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## **Analysis of Oxygen Transfer at an Activated Sludge Plant: A Procedure for Monitoring Aeration Efficiency**

Benjamin Clyde Luke

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Analysis of oxygen transfer at an activated sludge plant: a procedure for monitoring  
aeration efficiency

By

Benjamin Clyde Luke

A Thesis  
Submitted to the Faculty of  
Mississippi State University  
in Partial Fulfillment of the Requirements  
for the Degree of Master of Science  
in Civil Engineering  
in the Department of Civil and Environmental Engineering

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In this investigation, two separate methods for determining oxygen transfer rates were applied to the oxidation ditches of an activated sludge plant. Steady state oxygen uptake rate testing and an oxygen mass balance technique were used to propose an in-process procedure for monitoring aeration efficiency using available resources. Although some overall averages offered promise, the testing results revealed that the mass balance analysis yielded results that do not accurately represent the oxygen transfer capabilities within the individual reactors due to shared variables that control the oxygen transfer rate. The steady state method provided more favorable results. Overall averages of daily oxygen transfer rates determined using the steady state method displayed a ratio of oxygen transfer rate between the reactors that corresponds to the expected ratio of 5/6 derived from the linear feet of aerator rotor present in each reactor.

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## LIST OF SYMBOLS AND NOMENCLATURE

$A$  = surface area of film,  $L^2$

$A_r$  = surface area of reactor,  $L^2$

$AE$  = aeration efficiency,  $m/t \cdot P$

$b$  = endogenous decay coefficient,  $t^{-1}$

$BOD$  = biochemical oxygen demand,  $m/L^3$

$BOD_5$  = 5-day biochemical oxygen demand,  $m/L^3$

$BOD_R$  = reduction in biochemical oxygen demand,  $m/L^3$

$BOD_R^{total}$  = total reduction in biochemical oxygen demand,  $m/L^3$

$BOD_t$  = biochemical oxygen demand at time  $t$ ,  $m/L^3$

$C$  = dissolved oxygen concentration,  $m/L^3$

$C_{avg}$  = average dissolved oxygen concentration in the reactor,  $m/L^3$

$C_i$  = influent dissolved oxygen concentration,  $m/L^3$

$C^*$  = saturation dissolved oxygen concentration,  $m/L^3$

$C_\infty^*$  = saturation dissolved oxygen concentration at time infinity,  $m/L^3$

$C_{\infty,20}^*$  = saturation dissolved oxygen concentration at time infinity and  $20^\circ C$ ,  $m/L^3$

$D_L$  = diffusion coefficient,  $L^2/t$

$DO$  = dissolved oxygen

$F$  = F-test statistic

$F_{crit}$  = critical F-test statistic

$f_d$  = fraction of biodegradable active biomass

$k$  = first order rate constant for BOD exertion,  $t^{-1}$

$K_L a$  = volumetric mass transfer coefficient,  $t^{-1}$

$m$  = mass, m

$MGD$  = million gallons per day

$MLSS$  = mixed liquor suspended solids concentration,  $m/L^3$

$MLVSS$  = mixed liquor volatile suspended solids concentration,  $m/L^3$

$NOD$  = nitrogenous oxygen demand,  $m/L^3$

$NOD_R$  = reduction in nitrogenous oxygen demand,  $m/L^3$

$OTR$  = oxygen transfer rate,  $m/t$

$P$  = power,  $mL^2/t^3$

$Q$  = volumetric flow rate,  $L^3/t$

$R$  = oxygen uptake rate,  $m/L^3*t$

$R_{ML}$  =  $MLVSS/MLSS$  ratio

$R_R$  = reaeration rate,  $m/L^2*t$

$SAE$  = standard aeration efficiency,  $m/t*P$

$SOD$  = sediment oxygen demand,  $m/L^3$

$SOTR$  = standard oxygen transfer rate,  $m/t$

$T$  = temperature

$V$  = volume of the liquid phase,  $L^3$

$V_i$  = volume of individual reactor segment,  $L^3$

$V_R$  = volume of the reactor,  $L^3$

$WWTP$  = wastewater treatment plant

$X_i^0$  = influent inert biomass concentration,  $m/L^3$

$Y$  = film width, L

$\alpha$  = alpha correction factor, unitless

$\beta$  = beta correction factor, unitless

$\Delta t$  = mass balance time step, t

$\theta$  = hydraulic retention time, t

$\theta_t$  = temperature correction factor, unitless

$\theta_x$  = solids retention time, t

## CHAPTER I

### INTRODUCTION

Wastewater treatment facilities implementing aerobic systems require oxygen in order to maintain a healthy and prosperous microbial population. Such systems must provide excess, or at the very least adequate, amounts of oxygen so that anoxic or anaerobic biological processes are minimized and aerobic processes thrive. The degree of aeration of the mixed liquor contributes directly to the effluent quality of a wastewater treatment facility.

The most common methods for achieving aeration are through mechanical or subsurface aerators. Specifically for oxidation ditches and aerated lagoons, mechanical aerators are the most widely-used. Mechanical aerators are commonly divided into three separate types: turbines, rotors, and aspirators. All three types provide mixing and air entrainment to varying degrees. Because of their widespread use in lagoons and oxidation ditches in the southeastern United States, rotors are the focus of this study. Due to loss of motor efficiency and damage to the aerator blades due to the degradation capabilities of wastewaters and high-speed contact with the mixed liquor, rotor aerators slowly become less efficient as they age. Less efficient aerators require more power to impart the same amount of oxygen into the wastewater. The aerators must eventually be replaced so that enough oxygen transfer potential can be maintained in the aerated reactor. However, the loss of oxygen transfer capability is often hard to measure or even

estimate at wastewater treatment facilities, and there is currently no accepted procedure for the long-term evaluation of surface aerators in wastewater under process conditions.

The primary parameters used to characterize the transfer capabilities of aerators are the oxygen transfer rate (OTR) and the aeration efficiency (AE). OTR and AE gauge how much oxygen is transferred into the wastewater over a period of time and how much oxygen is transferred into the wastewater per unit of power over a period of time, respectively. AE and OTR are also measured as standard values (SOTR, SAE). SOTR and SAE characterize the aerator's ability to transfer oxygen into clean water (tap water, 1 atm, 20 °C, zero salinity, zero dissolved oxygen, etc). Aerator manufacturers often provide standard values of transfer rate and aeration efficiency as to show no bias toward any one specific wastewater. Thus, by comparing an aerator manufacturer's specifications for a brand new rotor aerator in clean water to an estimation of the performance level of the rotor aerator experienced in process, an evaluation of the loss of aerator efficiency can be made. This would be useful in determining when and if the current aerators need repair or complete replacement.

The objective of this study is to analyze the oxygen transfer capabilities of the surface aerators at the Starkville wastewater treatment plant (WWTP) to assess different strategies for monitoring aerator performance. The Starkville plant is a 10 MGD activated sludge facility located within the city limits of Starkville, Mississippi, although the daily flow rarely exceeds 8 MGD. A flow schematic of the Starkville plant is shown below as Figure 1.1.

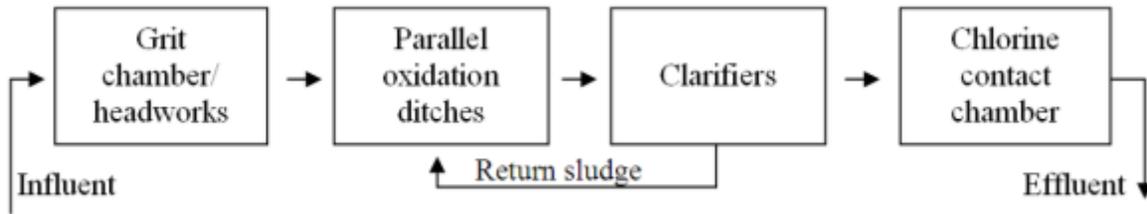


Figure 1.1 Flow Schematic of Starkville WWTP

The plant serves the citizens and industries of Starkville, campus of Mississippi State University, and some additional areas of Oktibbeha County. Typical influent concentrations of BOD<sub>5</sub> and suspended solids observed at the Starkville WWTP allow the wastewater to be characterized as a medium strength domestic wastewater as so described by Metcalf and Eddy (2003). Originally constructed as a 5 MGD plant in 1981 with two clarifiers and two parallel oxidation ditches, additional capacity was added with the construction of a third clarifier in 2001. However, the two approximately 2.30 million gallon oxidation ditches were deemed to be sufficient reactors during the upgrade.

Each oxidation ditch is a closed loop design with three dual rotor model 5300 Mammoth® aerators manufactured by USFilter/Zimpro, and each is powered by a 75 HP electric motor. The action of rotor aerators of this type on the mass of the mixed liquor is fourfold: (1) the water surface ripples and surges, (2) drops of water are thrown into the air, (3) air bubbles are introduced into the mixed liquor, and (4) agitation creates a mixture of air and water around the body of the aerator (Khadilkar, 1966). Each aerator assembly is reportedly capable of producing 152 lb O<sub>2</sub>/hr in clean water at the depth of submergence observed during the testing period (USFilter, 2002). Each shaft of the aerators has exactly 40 linear feet of rotors that are in contact with the mixed liquor. At the time of this study, one 20-foot aerator shaft in oxidation ditch #2 was not in working order. Thus, oxidation ditch #1 contains 120 linear feet of rotors while oxidation ditch #2

contains only 100 linear feet of rotors. This difference is noticeable when calculating the OTR as suggested by the manufacturer of the aerator. Photographs of the aerator assemblies and of the missing aerator shaft in oxidation ditch #2 can be seen in Appendix B.

There are several different methods for measuring the oxygen transfer rate, each of which offers distinct advantages and prominent shortcomings. Among them are the non-steady state method, off-gas method, the steady state method, the mass balance method, and the tracer measurement method (ASCE, 1997). Two methods will be performed in this study: the steady state method and a mass balance method. Both of these methods are relatively simple in procedure, at least compared to the other methods, and do not require sophisticated setups, procedures, or equipment. The steady state method requires a direct measurement of the oxygen uptake rate which can then be related directly to the oxygen transfer rate of the aerators due to the steady state assumption. For the alternate method, a simple mass balance is applied to the available substrate in each reactor and the various sources and sinks of oxygen in the system are considered. The theoretical basis for oxygen transfer and oxygen transfer measurement is presented in Chapter II.

### **Scope of Work**

Surface aeration is implemented in a variety of applications from municipal wastewater facilities to industrial processes. Mechanical aerators used in such processes have a lifespan based on the efficiency of oxygen transfer that they are able to provide. Also, as energy costs continue to increase, mechanical aeration at less than maximum power can cut operational costs if there is excess aeration in place.

Because there is no widely accepted procedure for evaluating aerator performance and degradation due to age and other factors, a simple yet effective evaluation technique would be valuable to the wastewater engineering community. If the oxygen transfer rates of the aerators could be monitored over their life span, the need for rotor replacement, surface aerator submergence, power augmentation, or even power reduction would be apparent to the plant management. Such a procedure could save resources such as total plant power consumption and unnecessary replacement of the surface aerators. The steady state and mass balance methods are relatively simple and do not require large investments of time or money, making them attractive methods by which to perform oxygen transfer testing on a widespread scale as long as they are effective. By comparing the results of two methods to each other, the aerator manufacturer's specifications, and the literature, the effectiveness and accuracy of the procedure performed at the Starkville WWTP can be validated.

Although there are methods for determining the oxygen transfer rate of wastewater in-process, there is limited application of these methods pertaining to periodical evaluation of oxygen transfer capabilities in wastewater facilities. Many WWTPs, especially small rural facilities, are incapable of monitoring the oxygen transfer rate of aeration due to the time, cost, materials, and equipment involved in many approved procedures. However, the steady state method and mass balance method might provide a means for the reasonable estimation of the oxygen transfer rate of mechanical aerators with limited available resources. Hence, the goals of this study are to evaluate these methods, provide the results of these methods as they were performed at the Starkville WWTP, compare the results of both methods, and present the procedure as a

protocol for periodical monitoring of the efficiency of mechanical surface aeration at wastewater treatment facilities.

CHAPTER II  
LITERATURE REVIEW

Oxygen transfer into wastewater follows the same principles as any gas-liquid transfer phenomena. Two separate films, one gas and one liquid, must be penetrated by the gas when traveling between the bulk liquid and the bulk gas phases of a system (Lewis and Whitman, 1924). Because of the relative ease of transfer through the gas film in comparison to the liquid film, it is usually disregarded. The primary cause of the gas transfer relies on the gradient between the saturation concentration of the gas in the liquid and the actual concentration in the liquid, provided a constant concentration in the atmospheric gas phase, as is the case with oxygen. Figure 2.1 below provides a graphic illustration of the two-film theory.

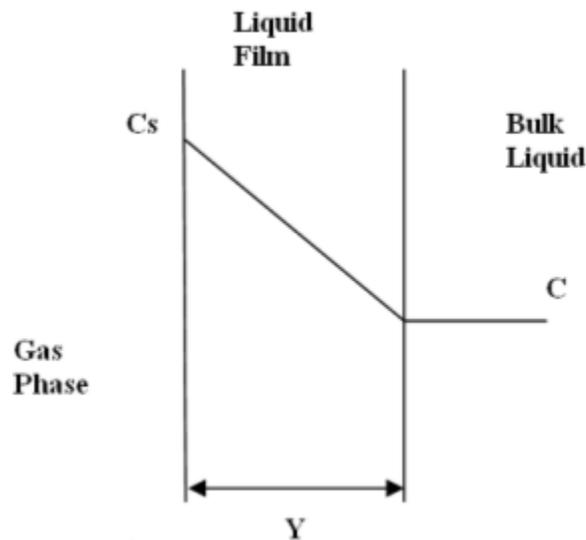


Figure 2.1 Two-Film Gas Transfer

The gas transfer phenomena above can be explained by Fick's first law of diffusion, manipulated to represent the particulars of oxygen transfer.

$$\frac{dC}{dt} = -D_L \frac{A}{V} \frac{(C_s - C)}{Y} \quad (2.1)$$

Because many of the variables are difficult or impossible to measure, the diffusion coefficient ( $D_L$ ), area of contact ( $A$ ), volume of the liquid phase ( $V$ ), and film width ( $Y$ ) are combined into one value, the volumetric mass transfer coefficient ( $K_L a$ ). A large concentration gradient will have much more potential for gas transfer, as indicated below as Equation (2.1) is rewritten into Equation (2.2), the rate of transfer relationship.

$$\frac{dC}{dt} = K_L a (C_s - C) \quad (2.2)$$

For oxygen, the gradient is limited because of its relatively low saturation concentration in water. As a result, the volumetric mass transfer coefficient has become a heavily-studied topic. However, it is often extremely difficult to estimate in-process water due to the different and simultaneous phenomena taking place (Garcia-Ochoa and Gomez, 2008). These processes include the influence of dissolved and suspended solids on gas transfer and the ever-changing dissolved oxygen concentration in the wastewater. In mentioning the volumetric mass transfer coefficient, the correction factors alpha, beta, and theta are also vital in the conversion of clean water oxygen transfer rates to process water oxygen transfer rates. The alpha factor is the ratio of  $K_L a$  in clean water to  $K_L a$  in process water. The beta factor is defined as the ratio of dissolved oxygen saturation concentration at field conditions to the dissolved oxygen saturation concentration experienced in clean water. The temperature correction coefficient theta accounts for the changes in oxygen transfer capability due to temperature. These three terms  $\alpha$ ,  $\beta$ , and  $\theta_t$  provide corrections between standard oxygen transfer rates provided by aerator

manufacturers and actual transfer rates occurring in operation (Gilbert, 1979). They are applied in Equation (2.3) below.

$$OTR = \alpha * SOTR * \theta_t^{T-20} * (\beta C^* - C) / C_{\infty,20}^* \quad (2.3)$$

Although this study will employ the steady state and mass balance methods for determining the oxygen transfer efficiency of surface aerators during wastewater treatment, there are numerous other credible methods (ASCE, 1997), though they require a more in-depth experimental procedure. The non-steady state method requires either a change in power levels of the aerators or increasing the dissolved oxygen well above saturation by using hydrogen peroxide while keeping the power level constant (Kayser, 1967, 1979). Dissolved oxygen is monitored during the test versus time and oxygen transfer rate is calculated from these observations.

A second method involves the use of a tracer to measure oxygen transfer. The transfer rate of an inert gas, usually krypton-85, can be monitored accurately and then be related to the transfer rate of oxygen by a constant (Tsivoglou, 1967). Because of the isotopes used in this procedure, it is not applicable for in-process conditions at operational facilities, but the inert tracer technique offers a high level of accuracy and precision (Boyle and Mueller, 1988).

Another accepted method is the off-gas technique that utilizes an off-gas analyzer to directly determine the oxygen transfer efficiency within a portion of the studied reactor. The off-gas method is popular in laboratory testing due to its accuracy and reuse ability. However, the off-gas method is not applicable to mechanical surface aeration, as the off-gas analyzer is designed to capture rising bubbles like those created by subsurface diffusion systems.

The downfall of using the non-steady state method, tracer method, or off-gas method is that specialized equipment, expensive materials, or complete control over the facilities operational parameters is required. Such resources are not commonly available when testing in-process conditions especially at small rural facilities. The two methods used in this study, steady state and mass balance, have the advantage of requiring no sophisticated equipment, complicated procedures, or control of the operational parameters of the wastewater facility.

The steady state method for determining the oxygen transfer rate of in-process wastewater is a direct measurement of the oxygen uptake rate in a suspended growth system. The steady state method, also called the BOD bottle test or biomass respirometry, involves an ex situ measurement of the oxygen uptake rate on-site either at the test reactor or on location at the operational wastewater facility to facilitate rapid-measurement of the oxygen uptake rate. Analysis needs to be performed immediately because removing the sample from the reactor isolates the biomass from the substrate. In a short period, the organisms exhaust their food and, subsequently, the oxygen uptake rate can be underestimated in the BOD bottle test by as much as 58%. Further oxygen will be depleted quickly. At low reactor DO concentrations, reaeration of the sample will be required for the test and this may result in oxygen uptake rate being overestimated (Chiese et al, 1990). Further literature supports the likelihood for the ex situ measurement of the oxygen uptake rate to underestimate the transfer capabilities from -5% to -43% in oxidation ditches using diffused aerators and slow mixers (Capela et al, 2004). Correspondingly, oxygen uptake rates obtained during the BOD bottle test have been reported as highly dependent on the reactor DO concentration with significant

underestimations of the oxygen uptake rate occurring at high DO and overestimations occurring at low DO (Mueller and Stensel, 1990).

The primary concern involving the BOD bottle test is that in the time that the sample is removed from the reactor, changes in oxygen uptake rate may be significant (EPA, 1983). Although the time from sample extraction to oxygen uptake rate (OUR) measurement can be minimized, the fact that the microbial population has been removed from its source of substrate is undeniable. In addition to the effects of DO and time on the BOD bottle test sample, small fluctuations in highly degradable organic and inorganic constituents normally found in industrial and municipal wastewaters can have a large impact on batch sampling results, like the BOD bottle test (Miller, 1979).

Nevertheless, the steady state test can provide some theoretical advantages. The BOD bottle test is a direct measurement of the uptake rate of the mixed liquor, albeit having been removed from its suspended growth environment. The limitations of the test arise due to its assumptions (constant oxygen uptake rate, DO,  $-K_L a$ , etc) and, as previously mentioned, the separation of the sample from the reactor, although the effects of this step can be minimized by performing the test extremely quickly. Meaningful results from the steady state method can be attained. Using model aerobic reactors, oxygen transfer rates obtained using both the off-gas method and the steady state method have been found to have mean variations between -2% and 22% under various operating conditions (Mahendraker et al, 2005). These variation percentages were found to be less for the steady state method than for either the non-steady state hydrogen peroxide method or the non-steady state changing power method.

The second method for determining oxygen transfer investigated in this study is the mass balance method. Although often used to determine the in-process oxygen

transfer rates of lagoon systems, the mass balance method may be used to obtain a rough estimate of the oxygen transfer capabilities of aerated basins in an activated sludge system (ASCE, 1997). In theory, the mass balance around an aerated basin can account for all sources and sinks of oxygen within the system by analyzing operational parameters and applying reasonable estimations to unknown or unattainable variables. The mass balance is then solved for the final unknown source of oxygen, the oxygen transfer rate of the aerators. Although theoretically sound, the mass balance approach relies heavily upon the values and coefficients chosen that are not directly measured during the test period. The aeration basin must be represented accurately by the selected physical, chemical, and biological parameters.

Only the dominating parameters are considered, including BOD load, mechanical aeration, surface reaeration, benthic oxygen demand, incoming DO correction, and the portion of substrate committed to cell synthesis. Photosynthetic effects within the oxidation ditches are not considered as the algae population of the system is considered to be minimal or even non-existent. A simple schematic of the mass balance can be seen below as Figure 2.2 with sources and sinks entering or exiting the system (although the BOD load is present in the influent of the oxidation ditches, it is shown exiting the system due to the fact that it is a major sink of oxygen).

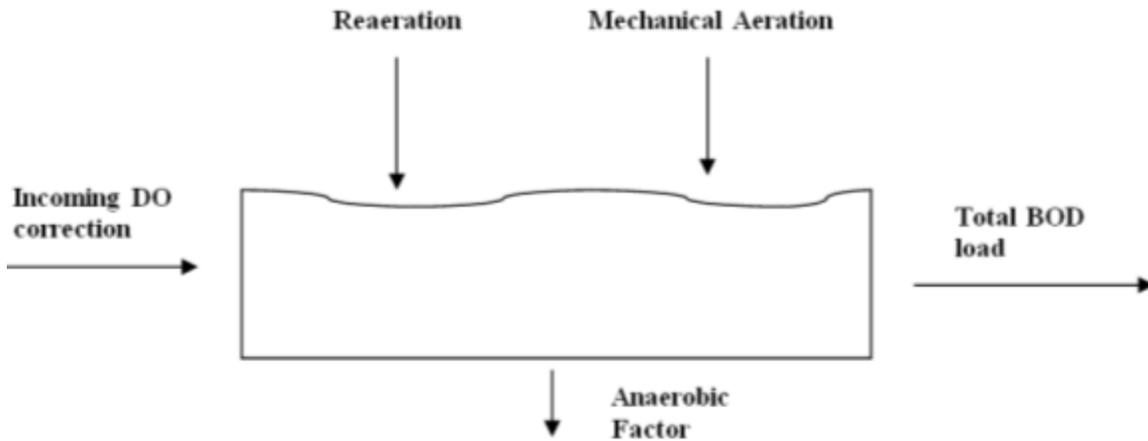


Figure 2.2 Oxygen Mass Balance

A simple mass balancing equation can now be applied to the above schematic. The specific relationship for the Starkville WWTP will be presented in the following chapter.

$$dm/dt = Q(C_i - C) + OTR + A_R(R_R - SOD) - Q(BOD_R^{total}) \quad (2.4)$$

As the total BOD load requires a consistent and robust unit, the  $BOD_5$  reduction, NOD reduction, and the portion of substrate used for cell synthesis must be converted into ultimate BOD ( $BOD_L$ ). Stoichiometric ratios are used for this conversion. For the conversion to  $BOD_L$ , Equation (2.4) is used.

$$BOD_t = BOD_L(1 - e^{-kt}) \quad (2.5)$$

The first order equation allows for the easily measured  $BOD_5$  to be converted to  $BOD_L$  if the first-order rate constant for BOD exertion ( $k$ ) is known. For original substrate, the first-order rate constant can be assumed to be  $0.23 \text{ d}^{-1}$  (McCarty and Rittman, 2001). This yields the widely accepted  $BOD_5 : BOD_L$  ratio of 0.68.

For aerobic processes, the empirical formula for cells generated has been estimated to be  $C_5H_7O_2N$ , which yields an oxygen demand of  $1.42 \text{ g O}_2/\text{g cells}$  (Porges et al, 1956). This ratio provides a conversion for the amount of oxygen demand consumed

by cell synthesis, which is a significant reducer of the total BOD load. The true empirical formula for cells within an aerated basin will depend on numerous factors including the biochemical makeup of the incoming wastewater. However, without laboratory testing, a representative formula for a particular wastewater is impossible to know to a certainty. Thus, the 1.42 g O<sub>2</sub>/g cells suggested by Porges et al. is commonly employed.

The nitrogenous oxygen demand must also be accounted for in the oxygen mass balance because of the significant reduction of nitrogen at many WWTPs. Its large demand of up to 4.57 g O<sub>2</sub>/g NH<sub>4</sub>-N coupled with significant influent concentrations make the nitrogenous oxygen demand vital in the mass balance around the aerated basins. Although the 4.57 ratio for oxygen demand of ammonium-nitrogen is a maximum and values of 4.33 g O<sub>2</sub>/g NH<sub>4</sub>-N have been reported (Davis, 2011), a truly accurate ratio would require intimate knowledge of the nitrifiers present in the wastewater. Because such knowledge is often unavailable and the limited effect of the ratio on the overall OTR, the maximum ratio of 4.57 is routinely used.

Given that the volatile fraction of solids is often not monitored at WWTPs, a conversion of total solids to volatile solids must be made in order to estimate the active biomass. The *MLVSS/MLSS* ratio ( $R_{ML}$ ) in the activated sludge process is usually 0.8-0.9 (McCarty and Rittman, 2001) but high solids retention times can drive the active fraction of the MLSS down (Joint Task Force, 1992). As a result, more conservative values of the *MLVSS/MLSS* ratio are often implemented for WWTPs operating with high solids retention times.

Because of the application limitations in the activated sludge process and more precise measurement procedures, the mass balance method has not been widely used to estimate oxygen transfer rates. Although the literature is limited, there have been

applications of the mass balance procedure for activated sludge systems. Mass balances have been applied to aeration basins of both diffused-air and mechanical type that show aerators operating at relatively high efficiencies in the United Kingdom (Boon, 1978). Applying mass balances around individual aerators has been shown to be successful in minimizing oxygen transfer parameters (Buckley and McKeown, 1971). Implementation of a flow-through measuring chamber coupled with mass balance equations around aeration basins has been reported to be superior to other techniques under dynamic process control in activated sludge systems (Gujer and Sollfrank, 1990).

The mass balance approach is occasionally used to compare results obtained using a more reliable and resource-intensive method. In two biological aerated filters, Rosso and Stenstrom (2006) reported mass balance approaches obtaining average oxygen transfer capabilities 8% and 43% larger than observed using the off-gas method. They considered the results reasonable (especially the filter showing 8% variation), but failed to mention that the ASCE in-process oxygen testing standard by which the experiment was based only recommends that the mass balance approach be applied to lagoon systems and activated sludge systems as an approximation of the oxygen transfer capabilities. The complex physical and biological mechanisms involved in biological aerated filters, including granular media and up-flow configuration, certainly would have some effect on the validity of the mass balance approach designed for lagoons and aeration basins.

Mass balances of oxygen around aerated basins are not limited in application to the analysis of aeration systems. The mass balance procedure has been useful in modeling the fate of volatile organic compounds so as to help predict air pollution caused by WWTPs (Zhu et al, 1997). When used in this fashion, the mass balance approach shows its true value as a somewhat rough estimator of the OTR. The procedure will

never consistently yield extraordinarily accurate values of the OTR, but it is capable of providing loose approximations to monitor and evaluate transfer performance.

The vast majority of literature pertaining to the mass balance method describe a procedure that is used either in conjunction with a more proven method or as an approximation on the true oxygen transfer rates experienced within the studied system. The latter is the way in which the mass balance method should be applied, according the ASCE in-process manual. The usefulness of the mass balance method in this study lies in the fact that it will be executed alongside the steady state method to provide both an approximation of the oxygen transfer rate and a verification of the manufacturer's specifications for the transfer capabilities of the Mammoth® aerators.

## CHAPTER III

### METHODOLOGY

#### **Steady State Method**

The experimentation for the steady state method was carried out at the Starkville WWTP. The primary objective of the experiments was to achieve a representative value of the ex-situ oxygen uptake rate for the biological reactor. This was accomplished by following a procedure that is slightly modified from the steady state method described in *ASCE-18-96: Standard Guidelines for In-Process Oxygen Transfer Testing* (ASCE, 1997). Because of the steady state assumption, many notable variables including volume of the reactor ( $V_R$ ) and volumetric flow rate ( $Q$ ) were easily determined from readings taken during the normal, day-to-day operation of the Starkville WWTP. However, the oxygen uptake rate required a direct measurement.

To determine the oxygen uptake rate, samples of mixed liquor were first collected at three different locations within each of the two reactors at the Starkville WWTP: immediately downstream of the final aerator assembly (1), immediately upstream of the final aerator assembly (2), and downstream of the second aerator assembly (3). The sampling configuration within the oxidation ditches can be seen below in Figure 3.1. Flow is counterclockwise around the ditch with the effluent weir on the extreme north end of the drawing. These locations were chosen to provide a representative sample of the entire reactor while allowing the influent and return sludge adequate time and space

to mix thoroughly. The six samples were drawn a total of 20 times each between the dates of March 23, 2012 and April 27, 2012.

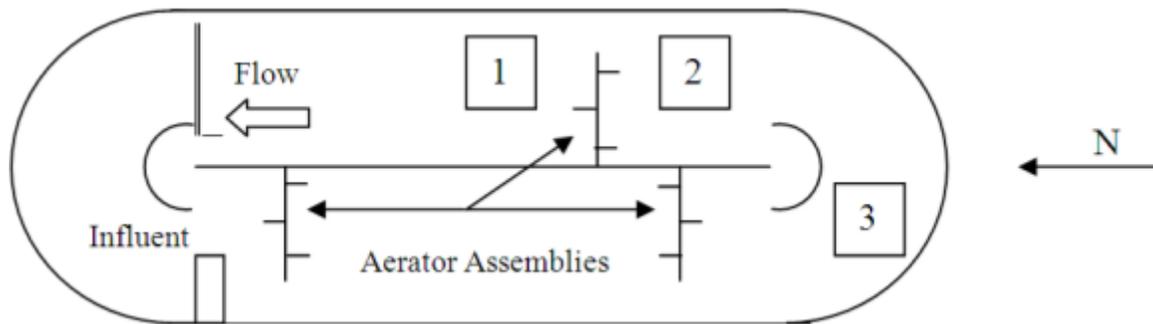


Figure 3.1 Oxidation Ditch Sampling Locations

The grab samples were taken using a PVC sampler with an approximately 500-mL capacity. Reaeration of the samples was not performed due to the fact that many of the samples already exhibited DO levels within the recommended range of 4 – 6 mg/L, the time between sampling and data collection was relatively short, and aerating the sample to achieve higher DO levels may significantly change the conditions under which the sample is metabolically functioning (Chiesa et al, 1990). The mixed liquor samples were poured into standard 300-mL BOD bottles and quickly tested for oxygen uptake rate using a YSI Model 5100 Dissolved Oxygen Meter calibrated daily using the manufacturer's specifications and equipped with BOD probe and stirrer. The total time between samples being pulled from the reactor and the DO meter insertion did not exceed one minute. After the DO meter was allowed to stabilize with the current sample temperature and DO concentration (approximately 30 seconds), the wastewater temperature and atmospheric pressure were noted, and the DO concentration was recorded at 15 and 30-second intervals for five minutes or until DO dropped below 1.0 mg/L, whichever occurred first.

Plots of DO concentration versus time were then created with linear least squared regression lines fitted to the data. The first two DO concentration readings (at 0 and 15 seconds) were omitted from the least squared regression due to the often large initial drop in DO caused by rapidly-oxidizing substrates. The slope of the regression lines at each test location reveals the oxygen uptake rate ( $R$ ) of the process water at that specific point in the reactor during the test period. From these measurements of the oxygen uptake rate, the volumetric mass transfer coefficient ( $K_La$ ), oxygen transfer rate ( $OTR$ ), and aeration efficiency ( $AE$ ) of the mechanical aerators can be determined by employing Equation (3.1), Equation (3.2), and Equation (3.3), respectively.

$$K_La = [R - (1/\theta)(C_i - C)]/(C_\infty^* - C) \quad (3.1)$$

$$OTR = RV_i \quad (3.2)$$

$$AE = OTR/P \quad (3.3)$$

The advantage of the steady state assumption becomes apparent in Equation (3.2). Under steady state, the oxygen transfer rate equals the measured oxygen uptake rate multiplied by the volume of the considered reactor segment ( $V_i$ ).

Each reactor was divided into three segments to aide in volume calculations. This was done in most part because three test points within the reactor would most likely be unable to yield a single representative value for the entire reactor. By dividing the oxidation ditches into segments based on the number of aerators encountered by the mixed liquor, the modeled reactor becomes simpler to analyze because each segment has been aerated by a steadily-increasing amount of horsepower. The aerator assemblies themselves serve as the dividers between the volume segments of the oxidation ditches.

Because the aerators were operated at a constant submergence of 8 inches during the entire test period, the volume of the reactor segments remained constant over the 20 samples collected. By knowing the depth of the water in the oxidation ditches and studying their construction drawings, an accurate estimation of the ditch volume during the test period could be made.

In these calculations, the saturation concentration of the DO ( $C^*$ ) is dependent on the temperature of the sample, the atmospheric pressure, and the beta factor. The saturation concentration of DO was selected to be identical to saturation concentration of DO at infinite time in process water ( $C_{\infty}^*$ ) due to the fact that the two values can be considered similar for a surface aeration model (Stenstrom et al, 2006). Barometric pressure was measured but not considered in the determination of the saturation concentration because of the proximity of observed values to standard pressure. However, the effects of temperature were considered. The following table was used to formulate appropriate dissolved oxygen saturation values from the range of temperatures encountered during this study. Intermediate values were interpolated linearly from the tabular values.

Table 3.1 Saturation Values of Dissolved Oxygen in Freshwater under Standard Pressure and a Saturated Atmosphere of 20.9% Oxygen

Temp., °C	Dissolved Oxygen, mg/L	Saturated Vapor Pressure, kPa
15	10.15	1.7044
16	9.95	1.8173
17	9.74	1.9367
18	9.54	2.0630
19	9.35	2.1964
20	9.17	2.3373
21	8.99	2.4861
22	8.83	2.6430
23	8.68	2.8086
24	8.53	2.9831
25	8.38	3.1617

(Whipple and Whipple, 1911)

The estimation of the correction factor alpha, which accounts for the transfer differences between clean water and a specific wastewater, is often a difficult task. The alpha factor depends on numerous variables including the composition of the wastewater, type of aerators, and reactor configuration. Because of its direct association with the clean water to process water conversion, alpha values have a large impact on the comparison of method OTRs to the aerator manufacturer's suggested OTRs. Values for alpha have been found to range between 0.3 and 1.1 under varying circumstances (Boyle and Mueller, 1988) and 0.6 to 1.2 for mechanical aerators (Downing et al, 1960). For this study, a preliminary value of 0.85 is chosen for alpha. This value falls within the reported ranges of alpha for mechanical aerators, and it will only affect the comparison of the steady state method and mass balance method to the manufacturer's equation. The OTRs found by steady state and mass balance remain unchanged by varying alpha.

Consequently, any change in aerator performance over a period of time would remain visible in the steady state or the mass balance method.

Similarly, beta represents a correction factor that accounts for the constituents of the water's effect on oxygen solubility. Municipal wastewaters often have a typical beta value of 0.95 (Davis, 2011). Because of its limited effect on the overall oxygen transfer rate of the system and narrow range of values for municipal wastewaters, beta is permanently chosen to be 0.98 for the purposes of this study in order to maximize the reported manufacturer value of the OTR.

The temperature correction factor theta ranges from 1.015 to 1.03 and is chosen to be 1.024 (EPA, 1983). These correction factors are applied to Equation (2.3) along with the SOTR reported by the manufacturer to yield an OTR that can be compared to the OTR values obtained from steady state analysis and the mass balance method.

### **Mass Balance Method**

Unlike the steady state method, the mass balance approach for determining the oxygen transfer rates of the oxidation ditches at the Starkville WWTP required no field measurements (although the average dissolved oxygen concentration of the reactors was calculated from steady state field measurements in order to provide a more encompassing value). Instead, daily monitored readings from the WWTP along with reasonable assumptions supported by literature were used to create an oxygen mass balance across each of the two oxidation ditches. The oxygen input into the oxidation ditches that could not be accounted for by the various sinks and sources of oxygen was assumed to have been applied to the system by the aerators. In order to provide comparative values to the steady state method, the mass balances were applied on the same twenty days between

March 23 and April 27, 2012 that oxygen uptake rates were measured at the Starkville WWTP. The individual time steps for each mass balance were chosen as one day to accommodate the daily readings of the WWTP.

The mass balance applied to each oxidation ditch considered the following factors as sources and sinks of oxygen: mechanical aeration, carbonaceous oxygen demand, nitrogenous oxygen demand, surface reaeration, sediment oxygen demand, driving force DO, and oxygen demand required for cell synthesis. Equation (3.4) below provides the mass balance across each reactor, accounting for the time step required for the processes to be performed. Equation (3.5) provides the MLVSS calculation.

$$OTR = [Q(BOD_R + 4.57 * NOD_R) - Q(C_i - C_{avg}) + A_R(SOD - R_R) - 1.42(MLVSS * f_d * V_R)/\theta_x]/\Delta t \quad (3.4)$$

$$MLVSS = (R_{ML} * MLSS - \theta_x X_i^0 / \theta) / (1 + (1 - f_d)b\theta_x) \quad (3.5)$$

The chosen ratios exhibited in Equation (3.4) and (3.5), namely the 0.68  $BOD_5/BOD_L$  ratio, the 1.42  $BOD_L/MLVSS$  ratio, the 0.75  $MLVSS/MLSS$  ratio, and the 4.57  $BOD_L/NH_4^+ - N$  ratio, are commonly used and widely accepted values and are further examined in the previous chapter. For the goals of this study, Equation (3.5) also assumes that there is no contribution to the volatile solids from influent inert biomass ( $X_i^0$ ). This is possibly a small source of error, but it is not a significant contributing factor to the overall OTR. Sediment oxygen demand ( $SOD$ ) and reaeration rate ( $R_R$ ) were assumed to be 5.5 g/m<sup>2</sup>\*d and 9.2 g/m<sup>2</sup>\*d, respectively (ASCE, 1997).

The endogenous decay coefficient ( $b$ ) represents several loss phenomena within the biomass including predation and death. Aerobic heterotrophs have  $b$  values between 0.1 d<sup>-1</sup> and 0.3 d<sup>-1</sup> (McCarty and Rittman, 2001). For this study, 0.1 d<sup>-1</sup> was chosen. The

biodegradable fraction ( $f_d$ ) was chosen as 0.8, a value common for a wide range of microorganisms (McCarty, 1975).

As with the steady state method, the influent dissolved oxygen concentration was assumed to be zero to maintain consistency, and influent DO values in oxidation ditches should be accurately estimated otherwise it is better to neglect them (Abusam et al, 2001). The average dissolved oxygen concentration was calculated as the average measured at the three test locations within each oxidation ditch during the steady state testing. The volume of the reactor was determined as the sum of the volume of the reactor segments calculated in the steady state analysis ( $V_R = \Sigma V_i$ ). As mentioned earlier, the volume of the oxidation ditches did not change across the test period, as a constant 8 inches of submergence was maintained on the aerator assemblies.

The volumetric flow rate, reduction of carbonaceous and nitrogenous oxygen demand, and solids retention time for the test period were determined from daily management reports that are used to record all relevant data at a wastewater facility on a daily basis. The daily management reports were provided by the Starkville WWTP for the 20 days considered in this study. Conversions from reduction of  $BOD_5$  and reduction of ammonia concentration to reduction of  $BOD_L$  by the ratios mentioned above were required.

The oxygen mass balance seen in Equation (3.4) was applied to the 20 days of operation at the Starkville WWTP that correspond to the same days that the 20 oxygen uptake rate tests were performed for the steady state analysis. This ensured that both methods were subject to basically the same volumetric flow rate, oxygen demands, and aerator parameters. The mass balance method subsequently yielded an OTR that could

be compared to the OTR determined by the steady state analysis and the OTR determined from the aerator manufacturer's specifications.

## CHAPTER IV

### RESULTS

During the steady state testing regimen, respiration samples were taken at three specific locations within each of the two reactors. In order to properly analyze the steady state method, a representative daily value for the OTR within each ditch needs to be determined for the sake of comparison. Table 4.1 below summarizes the OTR values at each location within the oxidation ditches.

Table 4.1 OTR Statistics at each of the Testing Locations

	Location Number	20 Day Average OTR, lb O <sub>2</sub> /hr	Standard Deviation of OTRs
Oxidation Ditch #1	1	144.7	43.6
	2	111.3	42.6
	3	140.3	44.5
Oxidation Ditch #2	1	103.2	36.7
	2	99.7	38.6
	3	123.3	41.5

Between testing locations in both oxidation ditches, analysis of variance shows a  $F_{crit}$  greater than  $F$  for oxidation ditch #2 and a  $F$  slightly larger than  $F_{crit}$  for oxidation ditch #1. Thus, the means of the OTRs at the three test locations are statistically equivalent in oxidation ditch #2. OTR values at test locations in oxidation ditch #1 reject the null hypothesis that the means of the test points are equal, albeit by a small margin. The OTRs in oxidation ditch #1 narrowly fail to be characterized as having equal means.

The path of the mixed liquor around the oxidation ditches can provide an explanation for the failure of OTR means in oxidation ditch #1 to be statistically equivalent. As expected, elevated OTRs at location #3 are followed by suppressed OTRs at location #2 within each of the reactors because the high substrate conditions near the influent (location #3) slowly stabilize as the mixed liquor travels around the ditch (to location #2). However, the OTR mean at location #1 in oxidation ditch #1 is re-elevated due to the large input of DO caused by the final aerator assembly interacting quickly with the remaining substrate. The missing aerator assembly minimizes this effect in oxidation ditch #2.

Although the OTR means in oxidation ditch #1 are not statistically equivalent, the discrepancy is explained by the location of test point #1 within the reactor. The inhibition of OTR at location #1 in oxidation ditch #2 and the nearly identical  $F_{crit}$  and  $F$  values for oxidation ditch #1 support the use of overall averages for further analysis. Based on these findings, the need for consistency within the analysis, and the sake of argument, the average OTR across the three test points within each reactor is chosen as a daily representative value for the steady state analysis.

The steady state and mass balance methods along with the manufacturer's equation provide twenty representative values each for the OTR during the test period. As each method requires the OTR to be determined over a significant period of time, the twenty values representing daily OTRs between March 23 and April 27, 2012 are averaged to give an overall value of OTR over the test period for each method. A summary of overall averages is given below as Table 4.2.

Table 4.2 Comparison of Method Averages

Statistical Parameter	Oxidation Ditch #1		Oxidation Ditch #2	
	Steady State	Mass Balance	Steady State	Mass Balance
Average OTR, lb O <sub>2</sub> /hr	132.09	140.66	108.71	138.77
Standard Deviation of OTRs	40.88	39.10	39.05	37.86
Average AE, lb O <sub>2</sub> /hp-hr	1.76	1.75	1.45	1.51
Standard Deviation of AEs	0.55	0.58	0.52	0.44
Percent of Manufacturer's OTR, %	91.0	96.9	74.0	94.5

In both oxidation ditches, the mass balance method performed extremely well when compared to the manufacturer's reported OTR with total test period averages at 97% and 95% of the supposed oxygen transfer capability of the Mammoth® aerators. Many of the constants chosen for the mass balance across the reactors support those figures. Specifically, the 1.42  $BOD_L/MLVSS$  ratio and the 0.75  $MLVSS/MLSS$  ratio drive the portion of substrate used for cell synthesis to a maximum and thus the OTR values to a conservative minimum even though the relatively high solids retention times of the Starkville WWTP suggest these two ratios may be lower. Nevertheless, these relatively high percentages are due to the intense dependence of the manufacturer's formula on the alpha factor. Also, the DO concentration is present in both the mass balance equation and the manufacturer's formula, further intensifying their relationship.

A better measure of the accuracy of the OTRs is found by comparing the two oxidation ditches to one another. Because oxidation ditch #2 has only 100 ft of rotors, it should theoretically transfer 83.3% (100 ft/120 ft) of the oxygen transferred by oxidation

ditch #1. However, the percentage of average OTRs calculated by the mass balance method between oxidation ditches is 98.7%. Although they exhibit different DO concentrations, temperatures, *MLSS* concentrations, and other variables, the oxidation ditches are unmistakably linked in the mass balance method due to the overwhelmingly dominant variables that are assumed to be equal across both reactors: volumetric flow, BOD load, NOD load, and solids retention time.

The steady state test yields values of 91% and 74% of the oxygen transfer capabilities of the aerators reported by the manufacturer in oxidation ditches #1 and #2, respectively. The direct measurement of the OUR converted to OTR shows the greatest separation from the expected values, especially for oxidation ditch #2. However, some variation from the OTR calculated by the manufacturer's formula is expected due to its reliance on alpha and the fact that the rotor aerators at the Starkville WWTP most likely have experienced some degradation of oxygen transfer capability since their installation in 2002.

The percentage of average OTRs between oxidation ditch #1 and oxidation ditch #2 for the steady state tests is 82.3%. This percentage is almost identical to the expected percentage of 83.3% that corresponds to the linear feet of aerator rotor present in each oxidation ditch. The steady state method is thus able to accurately characterize a reduction of aerator performance. Figure 4.1 below illustrates the consistently lower steady state OTRs present in oxidation ditch #2 compared to those in oxidation ditch #1.

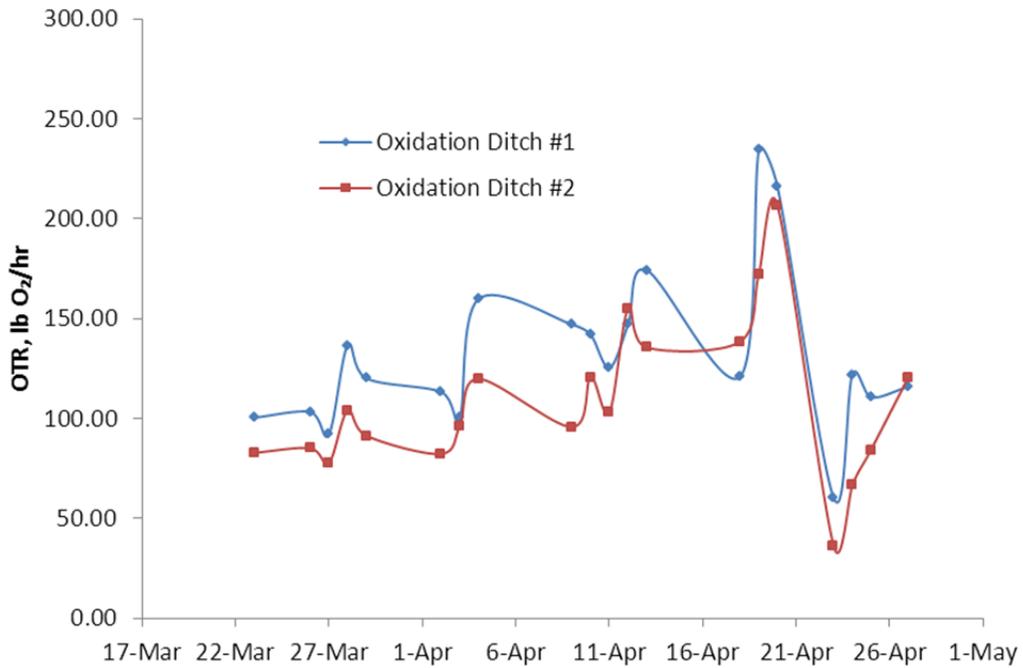


Figure 4.1 Steady State Daily OTR Averages in both Oxidation Ditches

Yet extensive variation is present in the time series of OTR values using both methods, particularly the steady state technique. OTR calculations using the manufacturer's equation show minimal change, as it depends solely on DO concentration. The OTR versus time plots are provided below as Figure 4.2 and Figure 4.3.

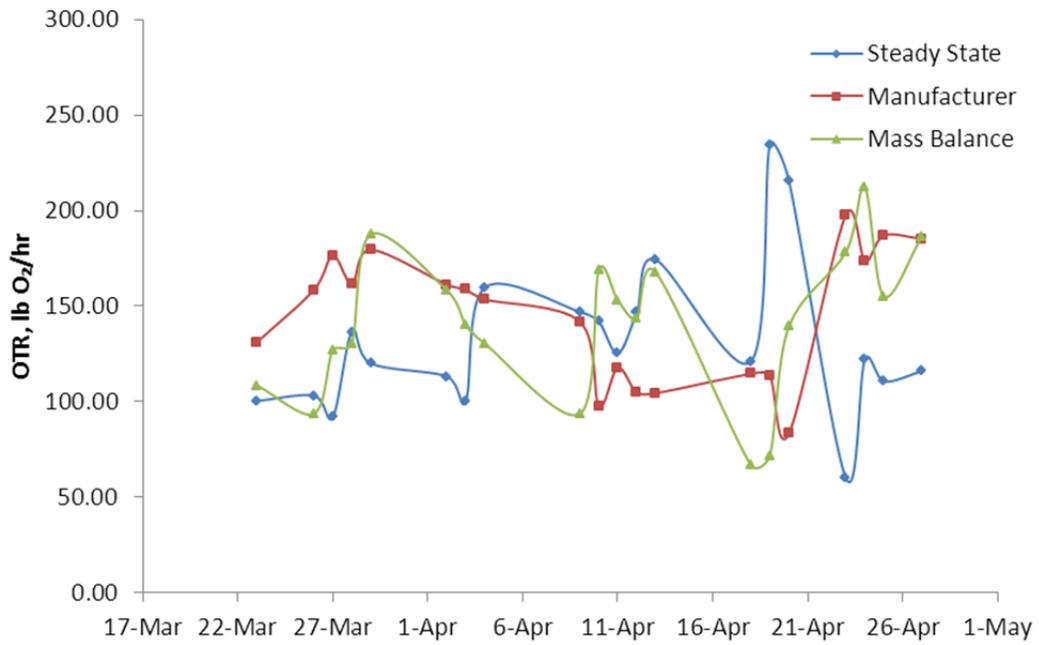


Figure 4.2 OTR versus Date Data for Oxidation Ditch #1

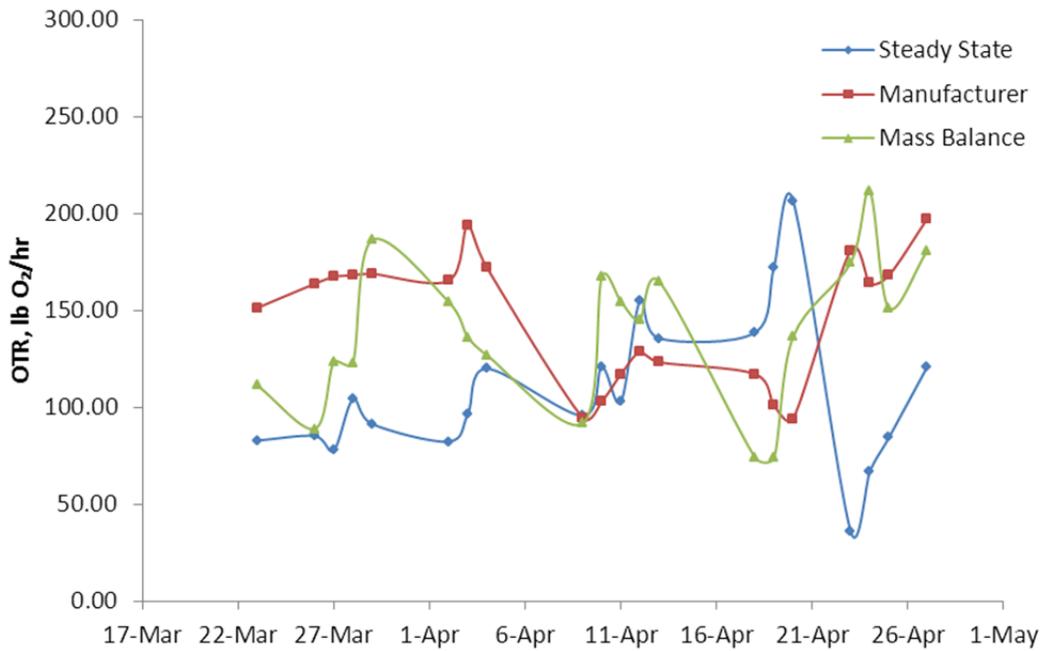


Figure 4.3 OTR versus Date Data for Oxidation Ditch #2

In ascertaining the validity of the test points, analysis of variance of the OTRs across both methods and the manufacturer's equation in both oxidation ditches is performed. Oxidation ditch #1 possesses an  $F_{crit}$  greater than  $F$ , meaning that statistically the method used to determine the OTR is irrelevant. For oxidation ditch #2, the opposite is true. Continuity between the methods and the manufacturer's equation fails in oxidation ditch #2 because of the large underestimation of OTR at certain points during the test period by the steady state method. A summary of the analyses of variance can be seen in Appendix A.

The steady state method shows erratic values, especially during the latter third of the testing period. A prominent spike in OTR on April 20 and subsequent plummet on April 23 have a large effect on the fit of the steady state testing values to the mass balance method and the manufacturer's formula. For both oxidation ditches, significant underestimations of OTR in the first third of the testing period and the considerable sag in the last third of testing are the cause of the lower average percentages of manufacturer's OTR than those calculated using the mass balance method.

The steady state and mass balance methods yield OTRs that may also be presented as a function of DO concentration. Generally, as DO concentration increases the ability of oxygen to be transferred into wastewater diminishes due to the DO nearing saturation concentration. The mass balance method and manufacturer's equation follow this pattern, but again the steady state values proved to be somewhat irregular. The DO series are shown below as Figure 4.4 and Figure 4.5.

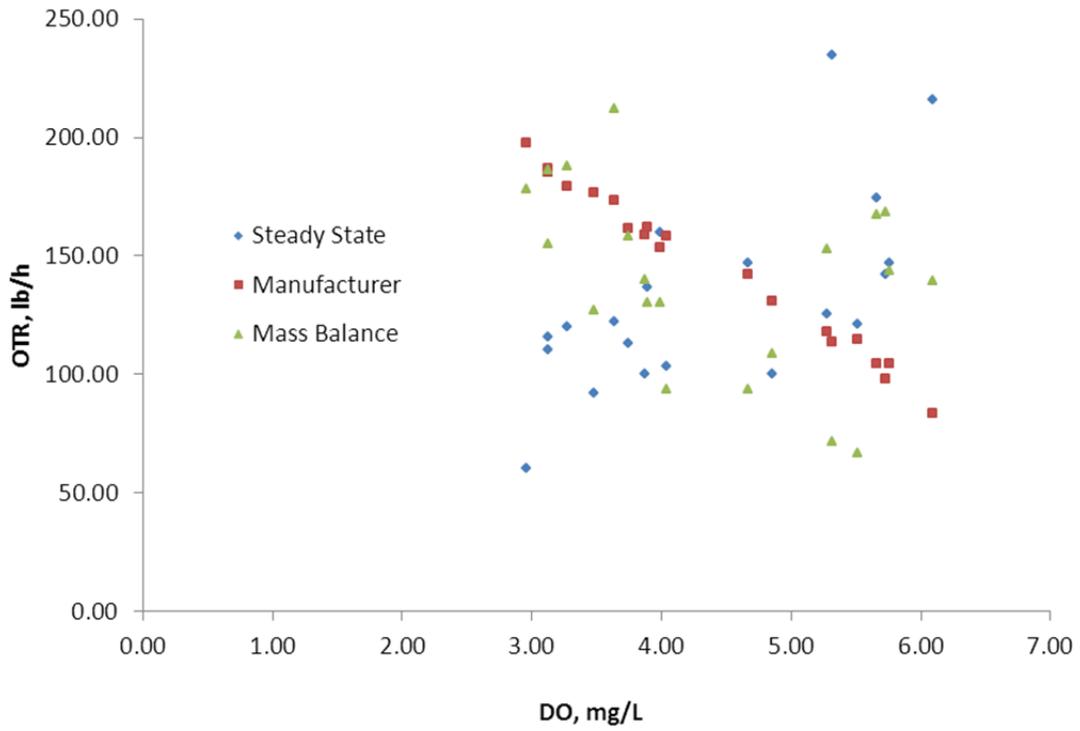


Figure 4.4 OTR versus DO Data for Oxidation Ditch #1

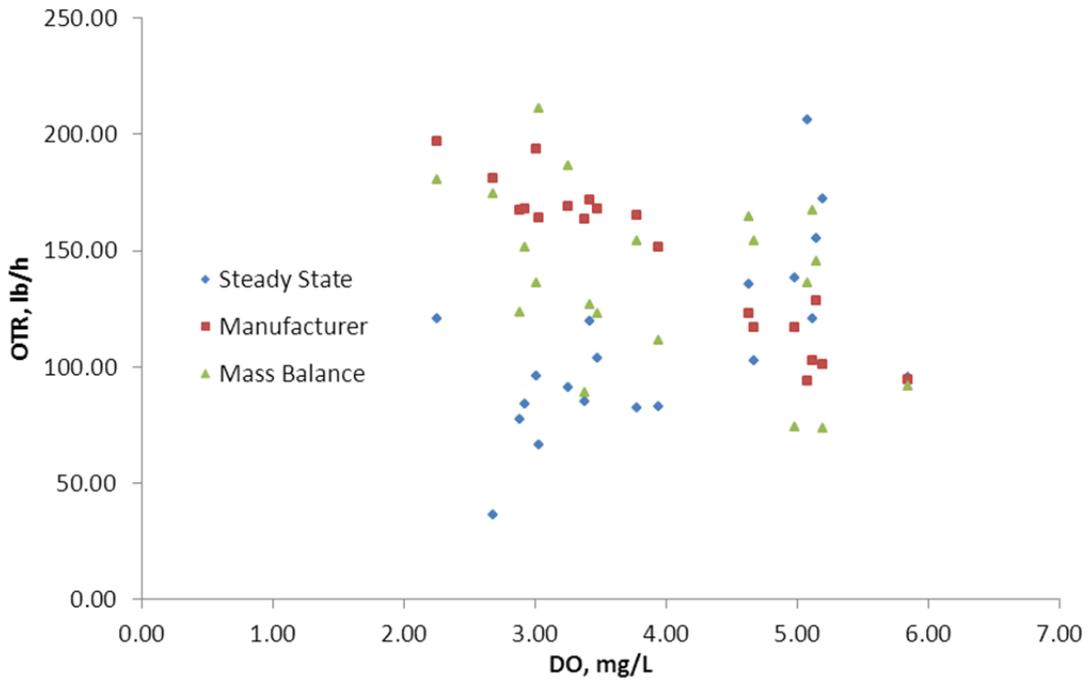


Figure 4.5 OTR versus DO Data for Oxidation Ditch #2

Due to the fact that the mass balance method and the manufacturer's recommended formula depend directly on the DO concentration in the reactor, both of these series display a downward linear trend as DO increases. Predictably, the mass balance series suffers from increased variation due to its overwhelming dependence on the ever-changing volumetric flow and total BOD load. However, the steady state method displays a more chaotic series. Low DO values are underestimating the OTR values while high DO concentrations are overestimating the OTR values. Moderate DO values seem to correspond to OTR values found in the other methods.

OTRs from the steady state method calculated at low DO concentration show significant discrepancy from OTRs obtained by the mass balance and manufacturer's formula. By not performing reaeration of the mixed liquor samples during the steady state procedure, low DO concentrations could be responsible for suppressed OTRs in the reactors if oxygen-limiting conditions were in place. Under such conditions, the respiration of the microbial population is limited by the availability of oxygen which would lead to an underestimation of the OTR.

To explore this possibility, a supplementary series of respirometry tests were performed following the methodology of the steady state tests with one exception: reaeration of the samples was executed by vigorously shaking the mixed liquor in a 1000-mL Erlenmeyer flask for one minute before measuring the OUR. Because of the high DO concentrations at testing location #1 (due to being immediately downstream of the final aerator assembly), three samples were taken only from locations #2 and #3 within each oxidation ditch for a total of twelve samples. On the sampling day, June 1, 2012, the residual DO concentrations at the testing locations were between 3.51 mg/L and 3.90 mg/L, well within the range of DO values shown in Figure 4.4 and Figure 4.5 that

exhibited low OTRs. The samples were reaerated to a DO concentration above 5.00 mg/L before OUR was measured. Figure 4.6 below illustrates the results of the all of the reaeration tests compared to the OTR determined using the manufacturer's equation.

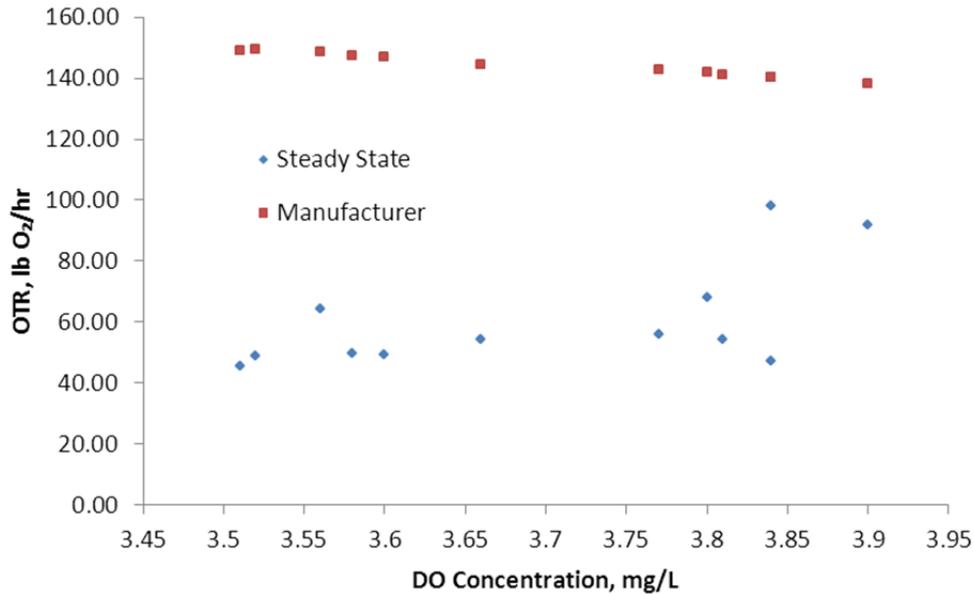


Figure 4.6 OTR versus DO Data for Reaeration Tests at all Locations

As experienced during the non-reaerated procedure, steady state testing at low DO yields a considerable underestimation of the OTR. It is unlikely that the OTR underestimations are caused by the inability of the aerators to transfer sufficient oxygen into the mixed liquor. Even at observed low DO concentrations, the biomass is not limited by oxygen. To further compare the non-reaerated and reaerated steady state tests, Figure 4.7 demonstrates all OTRs from samples taken at locations #2 and #3 in both oxidation ditches that have DO concentrations between 3.0 mg/L and 4.0 mg/L.

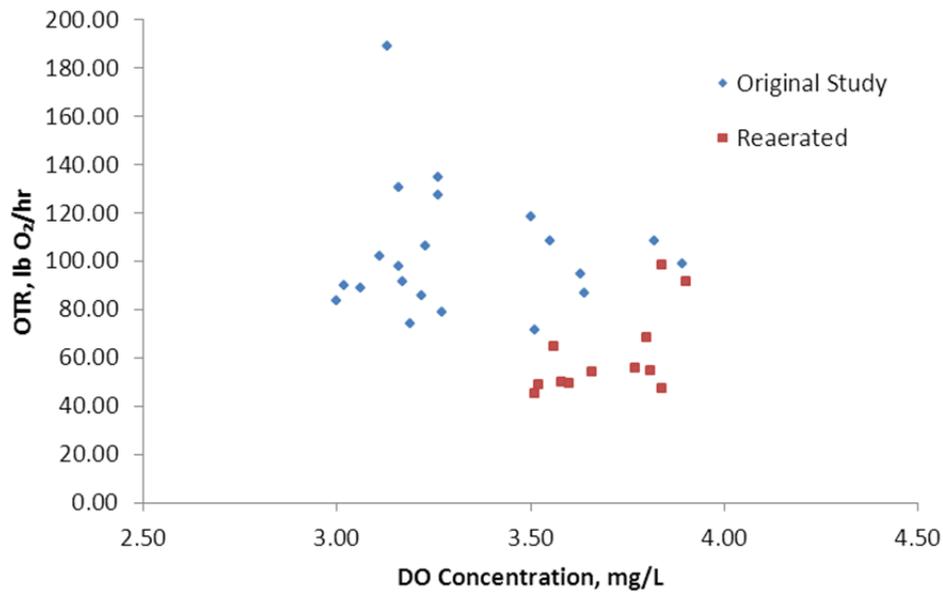


Figure 4.7 OTR versus DO Data for Reaeration Comparison

The reaerated samples are not comparable to the non-reaerated samples and display a lower overall OTR despite respiration testing being performed from an initial DO concentration above 5.0 mg/L instead of the in situ value of 3.0 - 4.0 mg/L. Although the operational conditions vary on a daily basis, the underestimation of OTR at low DO concentration by the steady state method can be explained by substrate-limiting conditions in the reactors.

Since sufficient DO exists in the oxidation ditches, optimal transfer rates are not achieved due to the lack of substrate and/or the rapid oxidation of substrate between the time the sample is removed from the reactor and when OUR is measured. This is supported by the lower overall OTRs in the reaerated samples seen in Figure 4.7. The reaerated samples were removed from their source of substrate for one minute longer than the non-reaerated samples while reaeration occurred. Thus, a portion of the substrate was likely oxidized before measurement of the OUR took place, even to an

extent beyond that seen during the original steady state methodology. A summarization of the reaeration testing can be seen in Appendix A.

In the steady state data set, a noticeable spike in OTR occurs on April 20 followed by a precipitous decline in OTR on April 23. Because the spike is nearly a statistical outlier lying 2.5 standard deviations away from the mean, an explanation of its existence is critical to the further development of the steady state method. A large storm event on April 18 produced volumetric flows almost double the observed average flow of 4.3 MGD and likely flushed the collection system of accumulated substrate. Experiencing increased substrate, the steady state method would develop elevated OURs and coinciding OTRs that would explain the large spike seen on April 20. The mass balance method may not have caught the spike because samples for each method were often taken at different times of the day.

## CHAPTER V

### CONCLUSIONS AND RECOMMENDATIONS

In attempting to provide a procedure for monitoring aeration efficiency at wastewater treatment facilities, the steady state and mass balance methods for the determination of oxygen transfer capability were applied to the oxidation ditches of the Starkville WWTP over a 20 day period from March 23 to April 27, 2012. The validity and robustness of these methods and their resulting data were evaluated through relationships and analysis of variance. Finally, the results from these methods were compared to OTRs calculated from the manufacturer's specifications of the Mammoth® aerators to evaluate their overall performance.

In Table 4.1, the mass balance method reveals total averages that represent oxygen transfer capability of 97% and 95% of the manufacturer's specifications for the Mammoth® aerators. However, the liquidity of these percentages becomes evident by altering the assumed alpha value. Using the lower limit of alpha values for mechanical aerators reported by Downing et al. ( $\alpha = 0.6$ ), the percentages of mass balance OTRs compared to manufacturer's equation OTRs explode to 137% and 134% in oxidation ditches #1 and #2 respectively. Similarly, when using the upper reported limit ( $\alpha = 1.2$ ), the percentages shrink to 69% and 67% in the respective ditches.

The volatility of the alpha value reveals the hazard of comparing the results from either the steady state method or the mass balance method to the OTRs calculated by the manufacturer's formula. A more reliable technique for evaluating OTR results lies in the

fact that oxidation ditch #2 should be 83.3% as effective as oxidation ditch #1 in regards to oxygen transfer due to the fact that it has less linear feet of rotor. The mass balance method cannot account for this reduction in OTR in oxidation ditch #2 because of its intertwining of the reactors with controlling parameters, such as volumetric flow, BOD load, NOD load, and solids retention time. At full aeration capacity as is seen in oxidation ditch #1, the mass balance method averages compare well to the steady state averages. However, when aeration is at diminished capacity as seen in oxidation ditch #2, the mass balance method fails to characterize the loss of transfer capability.

The steady state analysis provided sensible comparison of oxidation ditch #2 to oxidation ditch #1 (82.3%) despite experiencing the largest variation in values on a day-to-day basis. Much of the variation is found in low OTRs occurring at suppressed DO concentrations below 4.0 mg/L. Reaeration tests were performed to confirm that oxygen-limiting conditions did not cause the OTR repression at low DO concentrations, and, thus, more complex mechanisms were at work in the reactors, including a substrate-limiting environment.

The chaotic nature of the OUR readings taken during the respiration testing tend to question the effectiveness of the steady state technique. The principal causes of the variation in the OUR readings can be attributed to the unavoidable elimination of a feed source during testing, the tremendously complex behavior of the microbial population under process conditions, and the inability of three 300-mL samples taken per day to competently characterize the oxygen transfer capability of the multimillion gallon oxidation ditches, among others. While the OUR measurements have difficulty providing consistent estimations of OTR on a daily basis due to uncontrollable variation,

the overall averages of the steady state OTR values show promise in accurately representing the oxygen transfer capabilities of the aerators at the Starkville WWTP.

Analysis of variance across the steady state OTRs measured at the test locations did not produce equivalent means in oxidation ditch #1. However, the location of test point #1 within oxidation ditch #1 and the analysis of variance results suggest that the mean OTR of the three testing locations can be used as a representative daily value of overall OTR for each oxidation ditch. While of limited usefulness by themselves, these daily representative values constitute the pieces of the average OTR over a long period of time.

Although it failed to characterize the loss of aerator capability, further investigation into the ability of the mass balance method to evaluate the degradation of the aerators' transfer potential is needed. This research could be performed over long periods of time, ideally over years, to monitor the theoretical reduction of transfer performance. Furthermore, if specific parameters were known that could differentiate the transfer abilities present in each of the reactors, perhaps the mass balance method could be of some use beyond providing a rough approximation of the OTR.

The steady state method yields the most promising results in terms of expected average OTRs between the oxidation ditches. This study suggests that this technique can be applied over long periods of time to develop running or monthly averages of OTR that can characterize aeration performance. Monitoring aeration performance has application in a wide variety of systems that employ mechanical aeration equipment including rural WWTPs. Because the apparatus and calculation methods needed to perform the steady state testing are commonly used at WWTPs, the implementation of this method to insure effective aeration is feasible if not straightforward.

Finally, for the steady state method to have use, several issues will have to be addressed in developing a methodology. For example, to attain the most representative sample possible during a long term testing procedure, respiration samples should be taken daily at various times during the day in order to capture changing flow and temperature conditions encountered at the wastewater facility. Time between grab sampling and oxygen uptake measurement should be kept to a minimum in order to lessen the effects of removing the sample from available substrate. Also, the testing locations within the reactors should be chosen carefully, as analysis of variance suggested that the testing location within the reactor may impact the overall averages. Further research and testing is needed to complete a methodology that will provide the most representative average OTRs possible.

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APPENDIX A  
EXPERIMENTAL DATA

### Steady State OTR Values

Table A.1 Steady State OTR Values at each Location in Ditch #1

Date	OTR, lb O <sub>2</sub> /hr		
	Location #1	Location #2	Location #3
23-Mar	92.30	90.45	118.52
26-Mar	114.32	86.86	108.52
27-Mar	95.40	78.89	101.91
28-Mar	166.25	108.56	134.91
29-Mar	140.50	94.44	125.31
2-Apr	136.59	87.43	115.78
3-Apr	128.97	74.80	97.57
4-Apr	160.35	130.18	188.98
9-Apr	199.58	88.03	153.62
10-Apr	127.05	129.86	169.06
11-Apr	150.60	99.27	126.02
12-Apr	167.17	110.65	162.88
13-Apr	160.28	170.24	192.22
18-Apr	107.24	103.98	151.59
19-Apr	263.73	193.02	247.27
20-Apr	211.70	227.93	208.04
23-Apr	80.98	42.43	57.33
24-Apr	132.48	105.98	127.52
25-Apr	123.07	96.94	111.86
27-Apr	135.14	106.07	106.75
<b>Average</b>	<b>144.68</b>	<b>111.30</b>	<b>140.28</b>

Table A.2 Steady State OTR Values at each Location in Ditch #2

Date	OTR, lb O <sub>2</sub> /hr		
	Location #1	Location #2	Location #3
23-Mar	82.22	71.44	94.79
26-Mar	78.28	85.87	91.26
27-Mar	73.46	76.14	83.70
28-Mar	118.27	89.81	103.93
29-Mar	93.59	87.07	93.37
2-Apr	100.24	57.54	89.06
3-Apr	79.35	78.40	130.84
4-Apr	107.11	95.80	156.62
9-Apr	91.64	91.55	103.80
10-Apr	113.89	105.88	141.90
11-Apr	101.35	98.67	108.66
12-Apr	147.26	138.15	179.85
13-Apr	130.85	126.26	149.52
18-Apr	129.76	139.92	145.83
19-Apr	153.84	157.18	206.21
20-Apr	199.06	205.47	214.69
23-Apr	32.03	37.17	39.25
24-Apr	64.47	61.27	73.92
25-Apr	80.27	80.57	92.04
27-Apr	86.58	109.67	165.78
<b>Average</b>	<b>103.18</b>	<b>99.69</b>	<b>123.25</b>

## OTR Comparison

Table A.3 Comprehensive OTR Values in Ditch #1 for all Three Methods

Date	OTR, lb O <sub>2</sub> /hr		
	Steady State	Mass Balance	Manufacturer
23-Mar	100.42	108.58	131.08
26-Mar	103.23	93.81	158.50
27-Mar	92.07	127.20	176.45
28-Mar	136.57	130.33	161.82
29-Mar	120.08	187.69	179.53
2-Apr	113.26	158.36	161.29
3-Apr	100.45	140.00	158.72
4-Apr	159.84	130.45	153.58
9-Apr	147.08	93.69	141.94
10-Apr	141.99	168.73	97.93
11-Apr	125.30	153.09	117.77
12-Apr	146.90	143.85	104.72
13-Apr	174.25	167.70	104.49
18-Apr	120.94	66.92	114.63
19-Apr	234.67	71.64	113.87
20-Apr	215.89	139.33	83.34
23-Apr	60.24	178.25	197.74
24-Apr	121.99	212.22	173.48
25-Apr	110.62	155.23	187.00
27-Apr	115.99	186.17	185.28
<b>Average</b>	<b>132.09</b>	<b>140.66</b>	<b>145.16</b>

Table A.4 Comprehensive OTR Values in Ditch #2 for all Three Methods

Date	OTR, lb O <sub>2</sub> /hr		
	Steady State	Mass Balance	Manufacturer
23-Mar	82.82	111.34	151.23
26-Mar	85.14	88.81	163.69
27-Mar	77.76	123.31	167.28
28-Mar	104.00	122.95	168.09
29-Mar	91.35	186.34	168.82
2-Apr	82.28	154.34	165.27
3-Apr	96.20	136.09	193.79
4-Apr	119.84	126.81	172.01
9-Apr	95.66	91.58	94.57
10-Apr	120.56	167.20	102.87
11-Apr	102.89	154.45	117.01
12-Apr	155.09	145.31	128.44
13-Apr	135.54	164.85	123.21
18-Apr	138.50	74.21	117.12
19-Apr	172.41	73.76	100.88
20-Apr	206.41	136.37	94.07
23-Apr	36.15	174.49	180.98
24-Apr	66.56	211.29	163.96
25-Apr	84.29	151.27	168.05
27-Apr	120.68	180.60	197.09
<b>Average</b>	<b>108.71</b>	<b>138.77</b>	<b>146.92</b>

## Dissolved Oxygen Values

Table A.5 Actual Average and Saturation Dissolved Oxygen Concentrations in Oxidation Ditch #1

Date	Average DO Conc., mg/L	Average Temperature, C°	Saturation DO Conc., mg/L
23-Mar	4.857	20.8	9.02
26-Mar	4.043	20.6	9.06
27-Mar	3.480	21.4	8.93
28-Mar	3.893	20.9	9.00
29-Mar	3.270	21.5	8.91
2-Apr	3.747	21.6	8.89
3-Apr	3.870	20.9	9.01
4-Apr	3.987	21.6	8.89
9-Apr	4.663	20.3	9.12
10-Apr	5.727	21.6	8.89
11-Apr	5.280	20.2	9.14
12-Apr	5.757	18.8	9.39
13-Apr	5.660	20.6	9.06
18-Apr	5.510	19.7	9.22
19-Apr	5.317	21.5	8.91
20-Apr	6.097	21.7	8.88
23-Apr	2.957	18	9.54
24-Apr	3.633	19.6	9.24
25-Apr	3.127	21.7	8.88
27-Apr	3.127	23.6	8.59

Table A.6 Actual Average and Saturation Dissolved Oxygen Concentrations in Oxidation Ditch #2

Date	Average DO Conc., mg/L	Average Temperature, C°	Saturation DO Conc., mg/L
23-Mar	3.947	20.5	9.08
26-Mar	3.387	20.3	9.12
27-Mar	2.883	21.6	8.89
28-Mar	3.477	21.5	8.91
29-Mar	3.257	21.9	8.85
2-Apr	3.780	21.8	8.86
3-Apr	3.010	21.1	8.97
4-Apr	3.423	22.1	8.81
9-Apr	5.850	20.6	9.06
10-Apr	5.117	21.6	8.89
11-Apr	4.677	20.7	9.04
12-Apr	5.143	19.5	9.26
13-Apr	4.630	20.9	9.01
18-Apr	4.983	21.8	8.86
19-Apr	5.200	21.5	8.91
20-Apr	5.080	21.9	8.85
23-Apr	2.680	18	9.54
24-Apr	3.037	19.7	9.22
25-Apr	2.930	21.9	8.85
27-Apr	2.253	24.5	8.45

## Analysis of Variance Summary

Table A.7 Summary of Analysis of Variance across OTR Measured at Three Testing Points within each Oxidation Ditch

	Oxidation Ditch #1	Oxidation Ditch #2
Alpha	0.05	0.05
F	3.469	2.269
Fcrit	3.159	3.159

Table A.8 Summary of Analysis of Variance across all Three OTR Determination Methods

	Oxidation Ditch #1	Oxidation Ditch #2
Alpha	0.05	0.05
F	0.605	5.942
Fcrit	3.159	3.159

## Reaeration Summary

Table A.9 Summary of Reaeration Testing

		Test No.	Initial DO Conc., mg/L	Temp., °C	Reaerated OTR, lb O <sub>2</sub> /hr	Manufacturer's OTR, lb O <sub>2</sub> /hr
<b>Oxidation Ditch #1</b>	<b>Location #2</b>	1	3.80	23.6	68.07	142.04
		2	3.77	23.4	55.83	142.88
		3	3.84	23.9	47.19	140.30
	<b>Location #3</b>	4	3.90	24.0	91.73	138.17
		5	3.84	23.8	98.12	140.27
		6	3.81	23.8	54.43	141.19
<b>Oxidation Ditch #2</b>	<b>Location #2</b>	7	3.56	24.2	64.53	148.49
		8	3.60	24.6	49.21	147.11
		9	3.66	24.9	54.13	144.40
	<b>Location #3</b>	10	3.51	24.9	45.38	149.15
		11	3.58	24.7	49.88	147.47
		12	3.52	24.6	48.86	149.62

APPENDIX B  
SITE PHOTOGRAPHS



Figure B.1 Mammoth® Rotor Surface Aerator at Starkville WWTP



Figure B.2 Missing Aerator Assembly in Oxidation Ditch #2