Abstract

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Comparison of Oxygen Transfer Between an Integrated Fixed-Film Activated Sludge (IFAS) Process and a Conventional Activated Sludge Process (ASP)

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The T.Z. Osborne (TZO) Water Reclamation Facility (WRF) located in Greensboro, NC is a 40 million gallon per day (MGD) wastewater treatment plant that includes biological nutrient removal with surface-water discharge. Several process alternatives are being evaluated as strategies to meet forthcoming nutrient limits. Integrated fixed film activated sludge (IFAS) is one of the alternatives being considered for implementation. Due to the limited number of full-scale operating IFAS treatment facilities in the United States and the City of Greensboro's desire to experience operating the process, a thorough year-long study was conducted to quantify the nitrification kinetics, aeration requirements, process performance, and potential operational issues. As part of the full-scale evaluation, an off-gas test was performed in accordance with the American Society of Civil Engineers' (ASCE) Protocol. Previously, only one off-gas test had been performed, and it was conducted by another IFAS manufacturer. To our knowledge, the testing described in this report is the first independent off-gas test on an IFAS system to date. Results of the testing indicate that the IFAS process has higher air flux and air use per unit load treated compared to the activated sludge process (ASP), likely due to elevated mixing requirements and high dissolved oxygen (DO) specified by the process manufacturer, with associated lower oxygen transfer efficiency. The relative air use of the IFAS process is in the range of 1.3 to over 3.0 times that of the ASP, and the IFAS process has approximately 25 to 50% more air use for mixing when compared to the ASP.

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LIST OF ABBREVIATIONS

ASCE	American Society of Civil Engineers
ASP	Activated Sludge Process
BNR	Biological Nutrient Removal
DO	Dissolved Oxygen
IFAS	Integrated Fixed Film Activated Sludge
MGD	Million Gallons per Day
OTE	Oxygen Transfer Efficiency
OTR	Oxygen Transfer Rate
OUR	Oxygen Uptake Rate
SOTE	Standard Oxygen Transfer Efficiency
SOTR	Standard Oxygen Transfer Rate
TZO	T. Z. Osborne Water Reclamation Facility

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Chapter 1

Introduction

The T.Z. Osborne (TZO) Water Reclamation Facility (WRF) located in Greensboro, NC is a 40 million gallon per day (MGD) wastewater treatment plant that includes biological nutrient removal with surface-water discharge. Several process alternatives are being evaluated as strategies to meet forthcoming nutrient limits. Integrated fixed film activated sludge (IFAS) is one of the alternatives being considered for implementation. Due to the limited number of full-scale operating IFAS treatment facilities in the United States and the City of Greensboro's desire to experience operating the process, a thorough year-long study was conducted to quantify the nitrification kinetics, aeration requirements, process performance, and potential operational issues. This technology demonstration was conducted as a cooperative team effort between Hazen and Sawyer, CDM, and the City of Greensboro. An off-gas test was performed in accordance with the American Society of Civil Engineers' (ASCE) Protocol in addition to the pilot testing sampling and analysis.

The off-gas testing was conducted at TZO on January 18, 2010 and June 16-17, 2010 per ASCE Standard 18-96, Standard Guidelines for In-Process Oxygen Transfer Testing (1997). The goal of the initial January test was to determine the comparative oxygen transfer efficiency of the activated sludge process (ASP) and the integrated fixed-film activated sludge (IFAS) process. The June test was a repetition of the off-gas test conducted in January 2010 to confirm the results during the warm season. The plant has 12 aeration tanks, all of which are equipped with fine-pore diffusers except for the IFAS reactor cells, which are equipped with coarse-bubble diffusers. The IFAS process is operated in Tank 12, side-by-side to the ASP in Tank 11. Off-gas testing of the IFAS and ASP basins was performed in order to better understand the operational cost implications of each technology, to aid the City of Greensboro in selecting a process to help them meet their future nutrient limits.

1.1 Purpose of the Study

The IFAS manufacturer, AnoxKaldnes, required that a coarse-bubble diffuser system be installed in the IFAS cells. The design of the coarse-bubble diffuser grid for the IFAS reactor cells was performed by the manufacturer. The manufacturer also specified that the system should operate with an increased dissolved oxygen (DO) concentration relative to the activated sludge basins, to facilitate a bulk-liquid DO diffusion gradient through the biofilm such that the biofilm is fully aerobic. The idea that the IFAS media serves to split apart the coarse bubbles into fine bubbles and increases oxygen transfer in the system has been hypothesized by the manufacturers but has not been proven. Furthermore, the effects of operating an IFAS system at various dissolved oxygen concentrations has not been studied. The purpose of this study was to be the first independent investigation to identify oxygen transfer efficiency, air use, and oxygen uptake of an IFAS basin relative to an adjoining activated sludge basin. Previously, one off-gas test was performed by another IFAS manufacturer, Infilco Degremont (Viswanathan, 2008). To our knowledge, this is the only precedent that is published in literature. Our test is the first independent off-gas test on an IFAS system to date.

The one-year technology demonstration, conducted as part of the ongoing Master Plan, provided clear information on the biological process capability of the IFAS system, but little or no information is currently known about its oxygen transfer efficiency in comparison to the conventional activated sludge process. Energy use is a growing concern at wastewater treatment facilities and aeration has been identified as one of the most energy intensive processes on site (Rosso and Stenstrom, 2005). Furthermore, in the case of TZO, aeration energy may be the deciding factor in choosing between IFAS or expansion of the existing ASP when the plant is upgraded. It is therefore critical to characterize the current system efficiency and evaluate the potential to optimize aeration in attempts to maximize energy conservation and minimize operational costs. The overall goal of the testing is to increase our understanding of oxygen transfer rates in IFAS systems and ultimately use the knowledge gained in the decision making process for full-scale IFAS implementation at TZO.

Chapter 2

Background

2.1 IFAS Technology

The concept of integrating immobilized biomass in suspended biological reactors dates as early as the 1940's (Metcalf and Eddy, 2003). One of the more recent applications of this idea is the integrated fixed film activated sludge (IFAS) (Sen et al, 1994; Randall and Sen, 1996). IFAS involves the addition of fixed or free-floating media, either plastic or fabric, to an activated sludge basin. The IFAS process improves upon the activated sludge process by providing a larger biomass inventory in the aeration tank by facilitating biofilm growth on the media in addition to suspended solids which are present in the activated sludge process. The higher biomass inventory increases treatment capacity. The enhanced removal of chemical oxygen demand (COD) and nutrients has been demonstrated in IFAS applications (Randall et al., 1996). As conditions allow, attached biomass grows as a biofilm on the surface of the media simultaneously with suspended biomass (mixed liquor) in the activated sludge basin. The amount of biomass that is developed on the media depends on a host of factors, including loading, dissolved oxygen concentration, temperature, mixing energy, suspended-phase biomass concentration, and solids retention time. Biomass accumulates on the media until an approximate balance (steady state) is reached between biofilm growth rate and the rate at which solids are detached from the biofilm. Detachment is highly dependent on mixing turbulence and abrasion by other media. If biofilm solids grow more slowly than the detachment rate, the attached biomass will decrease. If biofilm solids grow more rapidly than they are detached, the attached biomass will increase.

In addition to the attached growth on the media, biomass will also develop in the suspended phase (mixed liquor), similar to conventional suspended growth systems. Because a portion of the total biomass is attached growth and retained in the aeration basin, only the mixed liquor suspended solids reach the final clarifiers. Therefore, the total biomass concentration achieved in an IFAS system will exceed the effective biomass concentration achievable by suspended phase only and increase the capacity of the system in the same reactor volume.

IFAS systems come with several physical requirements that must be accounted for in the system:

- Mixing – Adequate mixing must be provided for free-floating systems to ensure that the media remains uniformly distributed throughout the reactor and do not gather or concentrate at the effluent end of plug flow tanks. Additionally, free-floating media is slightly less dense than water, resulting in flotation when aeration systems are turned off. Mixing energy must be adequate to redistribute the floating media upon startup. The mixing requirement applies mainly to free-floating media.
- Turbulence/sloughing energy – In free-floating media systems like the one at the T.Z. Osborne WRF, the mixing and aeration provided by the aeration system is usually adequate for the sloughing of biological material from the biomass and for maintaining a thin, viable biofilm.
- Aeration – The buildup of biomass on the media requires a higher dissolved oxygen concentration in the suspended phase to ensure that the biofilm is aerobic throughout its thickness. Maas et al. (2008) found from oxygen uptake rate tests that the biofilm on

the media perform the majority of nitrification in an IFAS system. IFAS media manufacturers have identified target dissolved oxygen concentrations of a minimum of 3 mg/L and a preferable target of 4 mg/L.

- Effluent screens – For free-floating systems, effluent screens must be installed to contain media within the reactors. For aerobic systems, this is usually in the form of submerged, cylindrical screens. For anoxic systems, this is usually vertical wedge-wire screens. These effluent screens are designed for minimal head loss.
- Foam removal/ accumulation – Because of the need to retain the media within the IFAS cells, accumulation of foam in situations where foam can occur is a common issue with IFAS systems due to the decreased ability to collect and waste foam-causing bacteria. Most often, chlorinated water sprays are used to reduce and control foam. The use of screens to retain the media can allow the majority of the foam to pass through to downstream cells and on to the final clarifiers, where it can be removed from the system.

2.2 Nomenclature and Notation

The following definitions and special terms are used in this report: Their use is consistent with the American Society of Civil Engineers (ASCE) Standard (ASCE, 2007).

- DO = Dissolved oxygen concentration in mg/L.
- OTE = Oxygen transfer efficiency in percent. This is the percentage of the oxygen mass transferred from the gas phase to the liquid phase from the rising air bubbles. It is dependent upon the process conditions, such as dissolved oxygen (DO) concentration,

temperature, barometric pressure, salt concentration, and other constituents in the wastewater. This transfer efficiency is what is actually measured in an off-gas test.

- SOTE = Standard oxygen transfer efficiency in percent. This is the percentage of the oxygen mass transferred from the gas phase to the liquid phase from the rising air bubbles at standard conditions for dissolved oxygen (DO) concentration, temperature, barometric pressure, salt concentration, and clean water. One never obtains the SOTE in actual process operation. SOTE is determined by a clean water test, as described by ASCE (2007).
- OTR = Oxygen transfer rate in pounds of oxygen per hour. This is the rate of transfer of oxygen mass from the gas phase to the liquid phase. It depends upon the process conditions, such as dissolved oxygen (DO) concentration, temperature, barometric pressure, salt concentration, and other wastewater constituents. This transfer rate can be calculated from the OTE and the air flow rate, which is normally measured in an off-gas test.
- SOTR = Standard oxygen transfer rate in pounds of oxygen per hour. This is the rate of transfer of oxygen mass from the gas phase to the liquid phase at standard conditions for dissolved oxygen (DO) concentration, temperature, barometric pressure, salt concentration, and clean water. One never obtains the SOTR in actual process operation. SOTR is determined by a clean water test, as described by ASCE (2007).
- K_La = Volumetric mass transfer coefficient in units of hours^{-1}. This is a mathematical parameter calculated from transfer data to describe the rate of oxygen transfer from the gas phase to the aqueous phase. The SOTE can be calculated from the value of K_La and vice-versa.

- $C_\infty{}^*$ = Equilibrium DO concentration. This is the DO concentration that is achieved in clean water after being aerated for a very long time in order for the system to reach equilibrium (no changes in conditions over time). It is typically larger than the saturation concentration listed in handbooks, which results because of the increased hydrostatic pressure of the water column on the rising bubbles.
- α factor or α F factor = The α factor is the ratio of the value of K_La measured in process water to the K_La measured in clean water. The smaller the value of the α factor the greater the reduction in transfer rate due to contaminants in the process water. When the term α F is used, it refers to diffusers that have been in service for a period of time, which usually have additional reduction in transfer efficiency due to biofouling or changes in diffuser material properties, such as membrane hardening or softening.
- α SOTE or α FSOTE = Oxygen transfer efficiency (OTE) corrected for all process conditions such as DO, salinity, barometric pressure, etc., except for the α factor. This is the single most useful parameter to describe the performance of an aeration system under process conditions. The α SOTE divided by the SOTE is equal to the α factor. Again, when α F is used, it refers to used diffusers.
- β = salinity correction factor.
- Θ = temperature correction factor (1.024 for the ASCE Standard; ASCE, 1984).

2.3 Technical Description

One of the challenges with aerobic wastewater treatment process design is the correct specification of aeration capacity. A variety of techniques exist for estimating the oxygen transfer capacity of an aeration system. Methods for estimating transfer can generally be divided into three categories:

- Clean water testing and conversion to field rates with alpha, beta, and theta conversion factors.

- Testing under actual field conditions ("dirty water" testing) using methods to account for the biological consumption of oxygen during the transfer test.

- Material balance methods which attempt to determine differences between inputs and outputs of oxygen-consuming material.

All of these methods have advantages and disadvantages. When using clean water test results it is very difficult to accurately estimate the alpha factor (ratio of mass transfer coefficient in dirty water to its value in clean water). Dirty-water testing requires accurate estimation of the oxygen consumption rate, which is often very difficult, especially in oxygen-limiting conditions, which occur in overloaded treatment plants. Material-balance methods require long-term knowledge of process operating conditions such as sludge wasting rate, and are susceptible to error from sludge settling in the aeration basin or stripping of volatile oxygen-consuming compounds.

A technique which has none of the above shortcomings is off-gas analysis. This method requires the capture of a representative sample of the gas which exits the aeration basin surface, typically using a floating "hood" that provides a seal between the liquid surface and the headspace. The off-gas is analyzed for oxygen, carbon dioxide, and water vapor content. By knowing the flow rates of gas entering and exiting the liquid, mass transfer efficiency can be calculated. If flow rates are not known, the mass transfer efficiency can still be determined by knowing the partial volumes of the reacting or changing gas constituents (oxygen, carbon dioxide, and water vapor) and assuming that the inert gas constituents (nitrogen, argon) remain constant. It must be further assumed that the transfer at the fluid surface and the atmosphere is negligible when compared to the transfer caused by the aeration system, and that steady-state conditions exist during the test. Both assumptions are very good for wastewater treatment systems, especially over the short duration of off-gas testing.

The concept of off-gas analysis is not new and was originally described in 1939 by Sawyer and Nichols (1939). A number of later investigators continued the development of off-gas analysis, including Hover et. al. (1954), Pauling et al (1968), Prit and Callow (1958) and Downing (1960). Conway and Kumke (1966) and Leary et al. (1968) have also used off-gas analysis. The ASCE/EPA subcommittee on oxygen transfer testing asked Ewing Engineering (Redmon et al., 1983) to further develop the technique. Their results reported at the 1983 meeting of the Water Pollution Control Federation (now the Water Environment Federation) showed that the off-gas technique is an accurate and precise way of estimating aeration efficiency under process conditions. New developments which make this method more precise are advances in oxygen analyzers, and the use of large off-gas collection hoods which capture more representative samples.

Off gas analysis can be used for any subsurface aeration system regardless of the oxygen uptake rate and process conditions. Efficiencies of oxygen-limited systems can also be determined, although the transfer rate may be different than the transfer rate under normal operation. It has been documented that alpha factors can vary greatly (Stenstrom and Gilbert, 1981).

2.3.1 Analysis Theory

To determine oxygen transfer efficiency using off-gas analysis, a mass balance must be performed on the gas entering and exiting the liquid. The following description is provided, and is based largely on the analysis by Redmon et al. (1983). If the flow rates of gas entering and exiting the fluid are known, then the following mass balance can be made:

$$V_G \rho \frac{dY}{dt} = \rho(q_i Y_R - q_o Y_{og}) - K_L a(C_\infty^* - C)V \qquad (1)$$

where:

ρ density of oxygen at temperature and pressure of gas flow,

q_i, q_o = total volumetric gas flow rates of inlet and outlet gasses,

Y_R, Y_{og} = mole fractions (equivalent to volumetric fractions) of oxygen in the inlet (R, reference) and exit gasses (og, off-gas),

$K_L a$ = volumetric oxygen transfer coefficient,

C^*_∞ = equilibrium dissolved oxygen concentration in the test liquid at the given conditions,

C = dissolved oxygen concentration,

V = liquid volume, and

V_G = gas hold-up volume.

At steady state the equation reduces to:

$$\rho(q_i Y_R - q_o Y_{og}) = K_L a(C^*_\infty - C)V \qquad (2)$$

The left-hand side of equation 2 is the amount of oxygen transferred as determined from the change in oxygen mass and flow rate of the inlet and outlet gas streams. The right hand side of equation 2 is the familiar "K rate" based upon the mass transfer coefficient and driving force.

Since it is often difficult to measure the entering gas flow rate to an aeration system, a procedure which does not rely on gas flow rates is needed. If one assumes that the inert portions of the entering gas stream do not change, a mole fraction approach can be developed which does not require gas flow rate. This assumption means that the nitrogen, argon, and inert trace gases do not change as they pass through the aeration system. The alternative technique (Redmon et al., 1983) relies upon this assumption to calculate oxygen transfer efficiency (OTE).

OTE, expressed as a fraction, can be derived as follows:

$$OTE = \frac{\text{mass } O_2 \text{ in} - \text{mass } O_2 \text{ out}}{\text{mass } O_2 \text{ in}} \quad (3)$$

$$= \frac{G_i(M_o / M_i)MR_{o/i} - G_i(M_o / M_i)MR_{og/i}}{G_i(M_o / M_i)MR_{o/i}} \quad (4)$$

$$= \frac{MR_{o/i} - MR_{og/i}}{MR_{o/i}} \quad (5)$$

where:

G_i = mass rate of inerts, which is constant (by assumption) in both the inlet and off-gas streams

M_o, M_i = molecular weights of oxygen and inerts, respectively

$MR_{o/i}, MR_{og/i}$ = mole ratio of oxygen to inerts in the inlet and off-gas streams, respectively

The mole ratio of oxygen to inerts is calculated by subtracting the mole fractions of oxygen, carbon dioxide and water vapor, as follows:

$$MR_{o/i} = \frac{Y_R}{1 - Y_R - Y_{CO_2(R)} - Y_{W(R)}} \quad (6)$$

$$MR_{og/i} = \frac{Y_{og}}{1 - Y_{og} - Y_{CO_2(og)} - Y_{W(og)}} \quad (7)$$

where:

$Y_{CO_2(R)}, Y_{CO_2(og)}$ = mole fractions of CO_2 in the reference gas (R), or off-gas (og)

$Y_{W(R)}, Y_{W(og)}$ = mole fractions of water vapor in the reference gas (R) and off-gas (og)

The value of Y_R is the mole ratio of oxygen in air, and can be calculated by subtracting the humidity from the known (handbook) mole fraction of oxygen in dry air as follows:

$$Y_R = 0.2095(1 - Y_{W(R)}) \qquad (8)$$

The mole fraction of oxygen in the off-gas must be measured experimentally, as well as the CO_2 and water vapor mole fractions. For early Ewing Mark V devices the CO_2 was measured with an Orsat, which measures the CO_2 as a volume percent. In later instruments the CO_2 is absorbed with sodium hydroxide, which removes it from the calculations. The sample off-gas is also dried in the later version of the Mark V instrument, which means Y_W is zero. The oxygen mole fraction is measured with a Teledyne Model 320B analyzer, which provides a signal proportional to mole fraction, and can be calibrated directly at the pressure of the inlet air.

2.3.2 Flow Weighted Averaging

The single value of OTE obtained from a single analysis represents the transfer at a single "point" in the aeration basin. The size of the point is equivalent to the size of the collection hood. In general, larger hoods provide more representative samples of the OTE of the entire tank.

If only a few hood locations are used, erroneous results may occur. For example, if the hood is located over a break in an air pipeline, very low OTEs will be measured. To obtain a representative single average value of OTE for an aeration tank, it is necessary to sample multiple locations and calculate an appropriate average. In an EPA sponsored research project (US EPA, 1989), a protocol was developed which required sampling at least 2% of the tank surface area.

To calculate an average OTE, the individual readings must be averaged. Since aeration basins are usually tapered (i.e., higher aerator density at the inlet end than at the outlet end), each hood location generally has a different gas flow rate. If the gas flow rate at each hood location is known, a flow-weighted average can be calculated. For this reason, the Ewing instruments include gas flow rate meters (rotameters) for measuring hood air flow rate, and a manometer to indicate hood pressure. When the hood pressure is stable, gas flow rate indicated by the instrument is equal to the hood collection flow rate.

In designing an off-gas experiment it is also necessary to select hood locations that are representative of specific areas of the tank. This is especially important if highly tapered aeration tanks, or tanks with irregular geometries, are being tested. To calculate a tank average, equation 9 is used:

$$\overline{OTE} = \frac{\sum_{i=1}^{m} A_i Q_i OTE_i}{\sum_{i=1}^{m} A_i Q_i} \qquad (9)$$

where

i = hood location (sample number)

m = total number of hood readings

A_i = the area covered by the hood at location i,

Q_i = air flux associated with hood location i (equals the gas flow rate measured by the analyzer divided by hood area),

OTE_i = oxygen transfer efficiency measured at location i, and

$\overline{OTE}$ = overall average OTE.

This equation represents a flow-weighted, area-weighted average OTE. In cases where the tank geometry is uniform, such as in an aeration tank with full floor coverage of fine-pore diffusers and equal sized grids, equal areas can be incorporated into the test design, and the area terms in equation 9 cancel.

If other indications of gas flow rate exist, they can be compared to the gas flow rate indicated by the instrument. The denominator of equation 9 represents the gas flow rate across all of the measured areas in the tank. The ASCE protocol specifies that a test is representative of a tank if at least 2% of the area is sampled. If reliable plant instrumentation exists, one should expect the hood and plant flow rates per unit surface area (air flux) to correspond very closely. The ability to accurately match the two flow rates in full scale aeration tanks has been demonstrated (Stenstrom and Masutani, 1990). One should not expect the air flux at each hood location to match the air flux indicated by the plant instrumentation; however, if the plant instrumentation is accurate, the average air flow rate indicated by the instrument and plant instrumentation should agree.

2.3.3 Correction to Standard Conditions

It is useful to calculate the OTE of the aeration system at standard conditions, insofar as this is possible. If the mixed-liquor dissolved oxygen, temperature and total dissolved solids (TDS) are measured at the same time OTE is measured, and if the equilibrium DO concentration (C^*_∞) is known, it is possible to calculate αSOTE The correction is made in the same way as clean water data are corrected to standard conditions, as follows:

$$\alpha SOTE = \frac{C^*_{\infty 20}}{(\Omega \beta C^*_\infty - DO)\Theta^{T-20}} \times OTE \qquad (10)$$

where:

$C^*_{\infty 20}$ = equilibrium DO concentration at 20°C, 760 mm barometric pressure, zero salinity,

C^*_∞ = equilibrium DO concentration at temperature T, 760 mm barometric pressure, zero salinity,

Ω = barometric pressure correction factor,

β = salinity correction factor,

Θ = temperature correction factor (= 1.024 for the ASCE Standard, 1984), and

T = temperature, °C

The pressure correction factor Ω accounts for the effect of non-standard barometric pressures. It is calculated as follows for basins less than 6.1 m (20 ft) deep:

$$\Omega = \frac{P_b}{P_s} \tag{11}$$

where:

P_b = barometric pressure during the test, psia

Ps = standard atmospheric pressure (14.7 psia at 100% relative humidity)

For deeper tanks a more elaborate procedure is required, as follows:

$$\Omega = \frac{P_b + 0.007\gamma_w d_e - P_{VT}}{P_s + 0.007\gamma_w d_e - P_{VT}} \tag{12}$$

where:

γ_w = specific weight of water at temperature T, lb/ft^3,

P_{VT} = saturated vapor pressure of water at temperature T, psia, and

d_e = effective saturation depth, at infinite time, ft

The effective depth, d_e, is defined as the depth of water under which the total pressure (hydrostatic plus atmospheric) would produce a saturation concentration equal C^*_∞ for water in contact with air at 100% relative humidity. The value of d_e can be calculated from clean water test data, as follows:

$$d_e = \frac{\left[\frac{C^*_\infty}{C_s}\left[P_s - P_{VT}\right] - P_b - P_{VT}\right]}{\gamma_w 0.007} \quad (13)$$

Generally for fine-pore diffuser systems that are mounted no more than 10% of the overall water depth above the tank floor, the value of d_e will range between 21 and 44% of the overall water depth (US EPA, 1989).

If the standard oxygen transfer efficiency (SOTE) of the aeration systems is known from clean water tests or from manufacturer's data, the α factor can be calculated, as follows:

$$\alpha = \frac{\alpha SOTE}{SOTE} \quad (14)$$

As noted above, the α factor is the ratio of the mass transfer coefficient, K_La, in process water to that in clean water. It is generally necessary to know its value when designing aeration systems, and therefore its measurement is often the goal of process water testing. A new factor, F, was introduced in 1989 in the US Environmental Protection Agency (EPA) design manual (USEPA, 1989). This factor represents the state of fouling of fine-pore diffusers. Generally, fine-pore diffusers foul and the α factor calculated after several years of operation, especially without cleaning, can be 50% of the α factor for a new diffuser. (Stenstrom and Masutani, 1989). When testing aeration systems that have been in operation for any considerable period of time, the αFSOTE is determined when using equation 10. To calculate overall, average, α F, or α SOTEs, equation 9 is used by replacing OTE with the desired parameter.

Chapter 3

Methods

3.1 Off-gas testing

In-process oxygen transfer testing, or off-gas testing, was conducted with the assistance of Dr. Diego Rosso, assistant professor at The University of California – Irvine and was performed in the same fashion as described by the US EPA (1989) and the ASCE (1997). It is based upon the original off-gas method developed by Redmon, et al. (1983). An extensive discussion of the test procedures and the mathematical basis are provided in Section 2.

Off-gas testing is accomplished by capturing a quantity of gas being released from the surface of the aerated mixed-liquor. This gas, called off-gas, is passed through an analyzer that measures oxygen partial pressure (equivalent to mole fraction). The carbon dioxide and water vapor in the off-gas can either be measured or removed from the gas by absorption and drying, respectively. In the tests performed at TZO, the carbon dioxide and water vapor were removed from the off-gas prior to analysis using a desiccant filled with silica gel (for drying) and sodium hydroxide pellets (for CO_2 absorption). Figure 1 illustrates the testing layout.

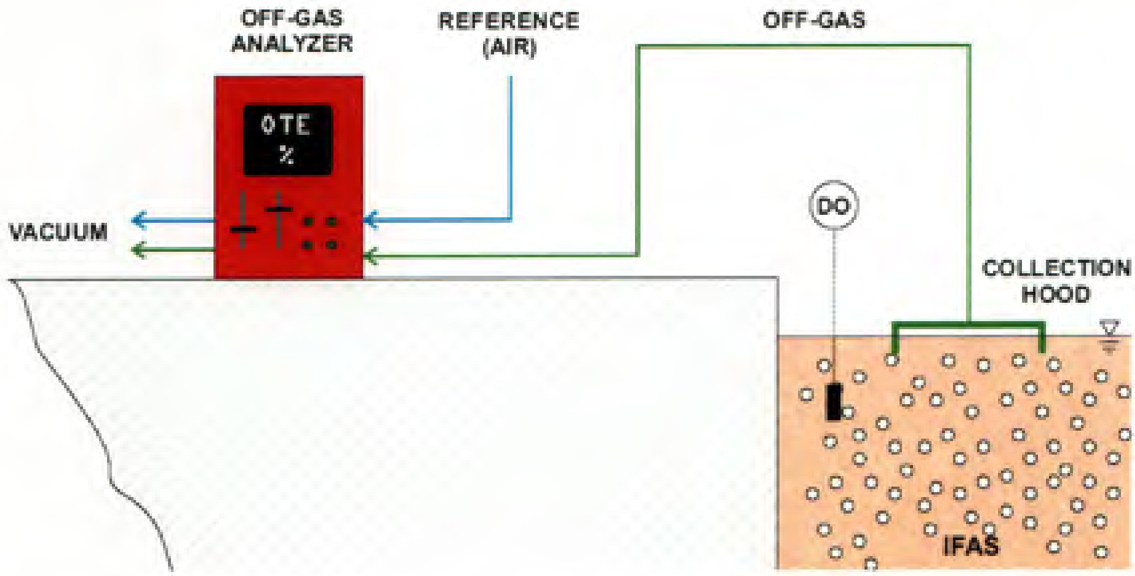

Figure 1. Off-gas testing layout. This non-invasive testing method allows the concurrent measurement of the actual oxygen transferred to the water (oxygen transfer efficiency [OTE, %], oxygen transfer rate [OTR, kgO_2/h], and oxygen uptake rate [OUR, $mgO_2/L/h$]).

The oxygen transfer efficiency can be calculated from the off-gas oxygen mole fraction and the known ambient air mole fraction (20.95%). The gas flow rate is not needed to perform this calculation, although it is desirable for performing flow-weighted averages over an aeration tank or across several aeration tanks (see Section 2.3.2).

The use of a compact analyzer, not the original Ewing instrument developed for this test, was necessary in order to facilitate Dr. Rosso's trip from Los Angeles to Greensboro. The smaller analyzer can use the Teledyne 320 oxygen analyzer or a zirconium oxygen fuel cell and gas drying cells. Instead of using dual rotameters for measuring gas flow rate, a Kurz Model 1440 mass flow meter was used. This instrument is a hot wire anemometer and is smaller and easier to transport than rotameters. The compact analyzer has been evaluated in parallel with the Ewing Mark IV and obtains identical results (D. Rosso, personal communication). The compact analyzer has an advantage for shipping but is less automated and can require a longer analysis time for each hood position. Appendix B has pictures of the test equipment. The City of Greensboro constructed an analyzer similar to the compact analyzer. At the time of testing, this analyzer was put into service and its performance was confirmed by matching measurements from this instrument with Dr. Rosso's instrument. Future testing will likely utilize this instrument. Tests were conducted on January 18, 2010 and June 16-17, 2010.

The off-gas was collected in a floating hood. Two hoods were constructed by the TZO staff; each were 8 ft by 4 ft in area, providing a capture area of 32 ft^2 per hood. The hoods were constructed from plywood with Styrofoam® for additional flotation. Photographs of the off-gas collection hoods are included in Appendix B.

Tests were conducted in each of two full-scale aeration basins, designated aeration tank 11 and aeration tank 12 (Figure 2). Aeration tank 11 is a conventional activated sludge basin with fine-bubble aeration, whereas aeration tank 12 is the IFAS basin. Tank 11 is divided into cells; concrete walls with submerged ports allow flow through the process. Tank 12 is also divided into cells by concrete walls but flow travels through submerged screens in the IFAS cells and submerged ports in the remaining cells. The purpose of the screens is to keep the IFAS media in place. Note that only the first half of the aerobic zone in aeration basin 12 contains IFAS media and coarse-bubble diffusers; the second half of the aerobic zone is identical to the second half of the aeration basin 11 aerobic zone and contains fine-bubble diffusers. Fine-bubble diffusers in tank 11 and tank 12 were installed at the same time.

Two testing locations were chosen in each aeration basin cell in order to gather a representative off-gas sample from each cell (Figure 2). The last cell of each basin was tested only in the middle. For each testing location, indicated with a yellow box and number on Figure 2, two readings were taken within an approximate 5 minute period. The testing hood was placed in the desired location and the analyzer was stabilized prior to the recording of an instantaneous value. A few moments were allowed to pass before another reading was taken. Two readings were taken at each location. Figure 2 shows hood placement and the testing locations. It is generally recommended that a minimum of 2% of the tank area be sampled (see Chapter 2). The combined hood positions provided approximately 3.3% coverage.

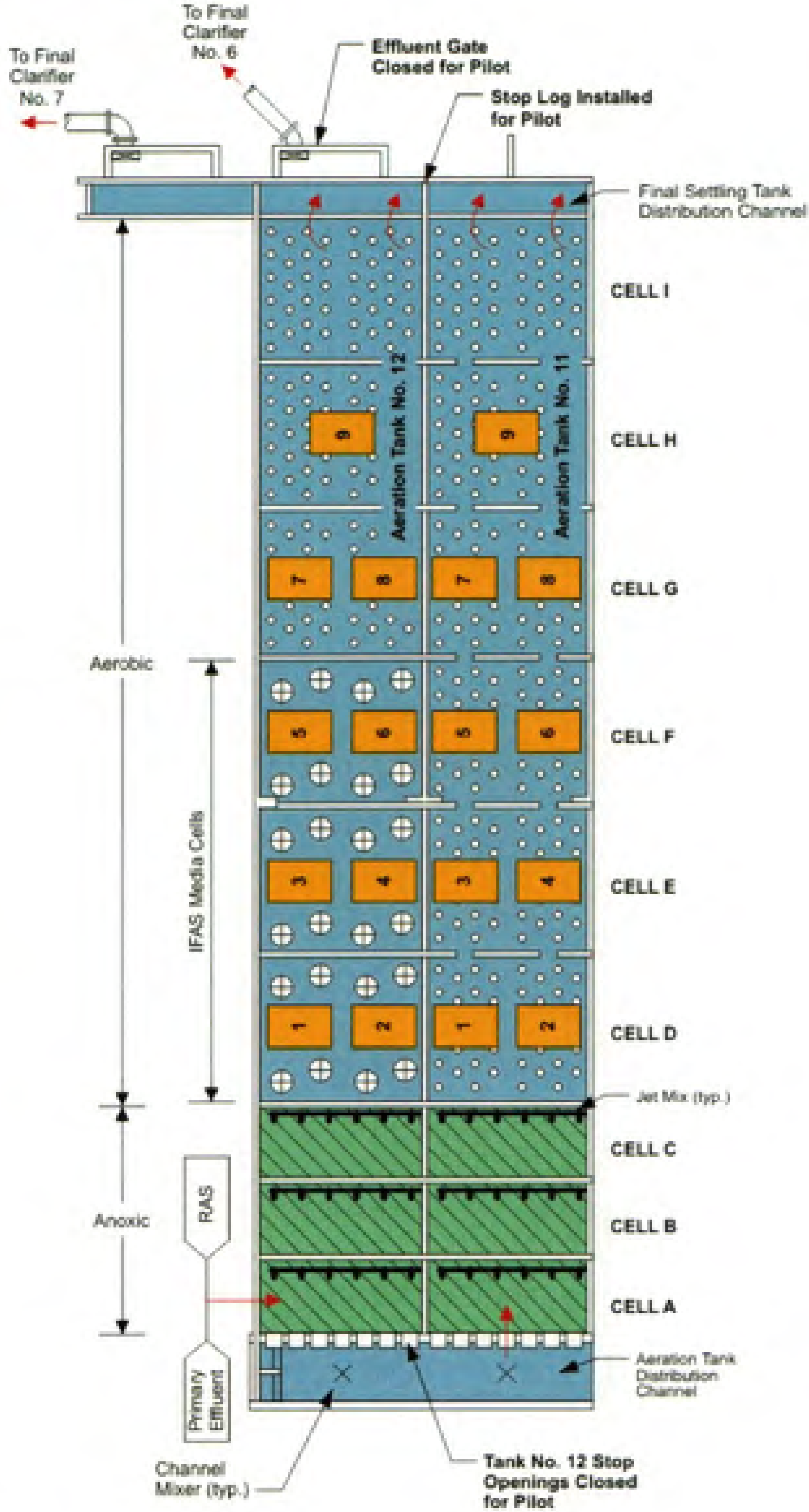

Figure 2. Testing Hood Positions. RAS = return activated sludge.

3.4 Plant Operation

Testing was first conducted on January 18, 2010; a second test was conducted on June 16-17, 2010. The outside air temperature at the time of testing was 63° Fahrenheit and 79° Fahrenheit for tests 1 and 2, respectively. At the time of each testing there were no unusual plant conditions. There were no rain events during test 1 and no wet weather flow events were being experienced at the facility at the time of testing. The second testing date was affected by inclement weather. A violent thunderstorm on June 16 interrupted testing after the bulk of the data had been collected. The positions measured pre-storm on June 16 included all the positions in aeration tank 11 and sampling locations 1-6 in aeration tank 12 (the IFAS process cells; see Figure 2). The remainder of the testing was completed on June 17 and included sampling of locations 7, 8, and 9.

Table 1 shows the key operating parameters for the plant at the time of each test. Most of the information in Table 1 does not enter into the aeration efficiency calculations but is very helpful to understand the results, because oxygen transfer efficiency can be dramatically affected by plant conditions. For activated sludge plants, the transfer efficiency is reduced at high loading rates (food:microorganism ratio, or F/M) or low mean-cell-residence time (MCRT). Since these were our first tests of an IFAS process, it is not well known how process conditions may affect transfer rates. However, one should expect the soluble substrates in the zones being aerated to suppress the α factor, therefore to depress αSOTE, as in a conventional activated sludge process. Soluble materials can include surfactants, which are known to suppress α factors (Rosso, 2006). It is well known that high-MCRT systems using fine-bubble diffusers have higher α factors and that the α factors at the effluent end of a "plug flow" aeration tank are higher than in the influent zone. Also, coarse-bubble diffusers are typically associated with elevated α factors but low SOTE values. The plant operating conditions should be noted when comparing performance to other test results or other plants. It is important to observe the difference in flows to each basin. During each testing event, flow, and subsequently load, to the IFAS basin was double the flow to the ASP.

Table 1. Plant Operating Conditions During Testing[1]

Parameter	January Tank 11	January Tank 12	June Tank 11	June Tank 12
Flow Rate, MGD[2]	2.9	6.0	3.0	6.0
COD (mg/L)				
Primary effluent	182	182	337	337
Final effluent	37.8	36.8	31.7	35.4
MLSS (mg/L TSS)	3,110[3]	1,215[3]	2,840	1,815
MLVSS (mg/L VSS)[2]	2,375[3]	928[3]	2,220[4]	1,390[4]
Temp, MLSS (°C)	14.2	14.5	26.8	26.8
NH_4-N (mg/L)				
Primary Effluent	12.9	12.9	23.8	23.8
Final Effluent	5.7	5.6	7.6	5.0

[1] COD = chemical oxygen demand; MLSS = mixed liquor suspended solids; MLVSS = mixed liquor volatile suspended solids; TSS = total suspended solids; VSS = volatile suspended solids.
[2] flow rate is combined primary effluent and RAS flow
[3] average of values collected Tuesday-Friday of testing week since testing day was a holiday
[4] MLSS values were 2,780 mg/L and 1,655 mg/L for Tank 11 and Tank 12, respectively, on June 16. MLVSS values were not recorded for that day. Data presented in the table are from June 17.

Table 2 presents Supervisory Control and Data Acquisition (SCADA) data collected for the testing days and shows average values over a full 24-hour period.

Table 2. SCADA Data from Testing Day

Parameter	January Tank 11	January Tank 12	June Tank 11	June Tank 12
Average Airflow (scfm)	1,571	3,603	2,470	4,670
Average Dissolved Oxygen in Aerobic Cells (mg/L)	2.0	4.5	2.0	4.7

Chapter 4

Results and Discussion

4.1 Off-Gas Test Results

All data reported in this section were obtained with the compact analyzer described in Chapter 3. Tables 3 through 6 present the results for each hood location and flow-weighted averages for each tank for each of the testing days.

Table 3. Summary of January Results for Tank 11
(conventional activated sludge process with fine-bubble diffusers)

Position[1]	OTE[2]	αSOTE[2]	Air Flux	DO	OUR
	(%)	(%)	(scfm/ft^2)	(mg/L)	(mg/L-hr)
1	9.2	10.3	0.39	0.5	36.1
2	9.1	10.0	0.44	0.3	40.3
3	12.8	14.9	0.29	0.9	37.1
4	11.6	13.9	0.42	1.1	48.4
5	13.8	17.5	0.22	1.6	29.8
6	16.2	20.4	0.22	1.6	34.8
7	12.7	20.5	0.27	3.4	33.7
8	13.3	22.0	0.24	3.5	32.1
9	10.4	22.8	0.22	5.1	22.5
Avg Tank[3]	**11.5**	**13.5**	**0.4**	**1.0**	**39.0**

[1] refer to Figure 2 for position locations in the basin

[2] airflow-weighted average of two testingvalues

[3] only averages testing positions 1-6

Table 4. Summary of January Results for Tank 12

(IFAS, coarse-bubble diffusers for positions 1-6)

Position	OTE[1]	αSOTE[1]	Air Flux	DO	OUR
	(%)	(%)	(scfm/ft^2)	(mg/L)	(mg/L-hr)
1	4.1	7.2	1.45	4.0	58.8
2	5.0	9.0	1.76	4.1	86.3
3	6.9	11.2	1.81	3.5	123.8
4	7.5	11.2	1.13	2.9	84.3
5	6.9	11.4	1.08	3.5	74.1
6	6.9	11.2	1.00	3.4	68.6
7	9.2	20.5	0.29	5.2	26.8
8	8.3	18.9	0.29	5.3	24.0
9	8.4	22.8	0.24	6.0	20.1
Avg Tank[2]	**6.1**	**10.1**	**1.4**	**3.6**	**85.7**

[1] airflow-weighted average values

[2] only averages testing positions 1-6, which were in the cells containing coarse-bubble diffusers

Table 5. Summary of June Results for Tank 11 (ASP)

Position	OTE[1]	αSOTE[1]	Air Flux	DO	OUR
	(%)	(%)	(scfm/ft^2)	(mg/L)	(mg/L-hr)
1	10.0	10.7	0.44	0.5	43.9
2	13.7	14.6	0.60	0.5	80.7
3	11.2	12.1	0.46	0.5	51.0
4	13.8	15.7	0.46	0.9	62.7
5	12.0	15.8	0.55	1.8	65.2
6	12.2	16.0	0.52	1.8	63.1
7	9.9	24.2	0.28	4.6	27.3
8	9.0	21.3	0.28	4.5	25.0
9	5.7	15.9	0.33	5.0	18.6
Avg Tank[2]	**11.3**	**15.6**	**0.46**	**2.2**	**53.4**

1 airflow-weighted average values

2 only averages testing positions 1-6

Table 6. Summary of June Results for Tank 12 (IFAS)

Position	OTE[1]	αSOTE[1]	Air Flux	DO	OUR
	(%)	(%)	(scfm/ft^2)	(mg/L)	(mg/L-hr)
1	10.5	18.9	1.25	3.4	129.9
2	7.2	13.1	1.76	3.4	126.3
3	7.9	10.0	1.55	1.6	122.1
4	6.1	7.7	1.59	1.6	95.6
5	3.8	11.0	[3]	5.0	[3]
6	7.1	20.5	[3]	5.0	[3]
7	10.7	22.2	0.26	4.0	28.1
8	9.9	28.0	0.28	5.0	27.8
9	6.5	17.9	0.30	4.8	19.2
Avg Tank[2]	**7.9**	**13.4**	**1.41**	**3.8**	**106.8**

1 airflow-weighted average values, except DO

2 only averages testing positions 1-6

3 air velocity could not be measured due to weather

Figures 3 - 10 show the DO, OTE, αSOTE, OUR, and their relative ratios for both tanks tested, respectively. The differences between the IFAS tank and the ASP are apparent. The IFAS tank has higher transfer rates, DO and OUR, and lower αSOTE.

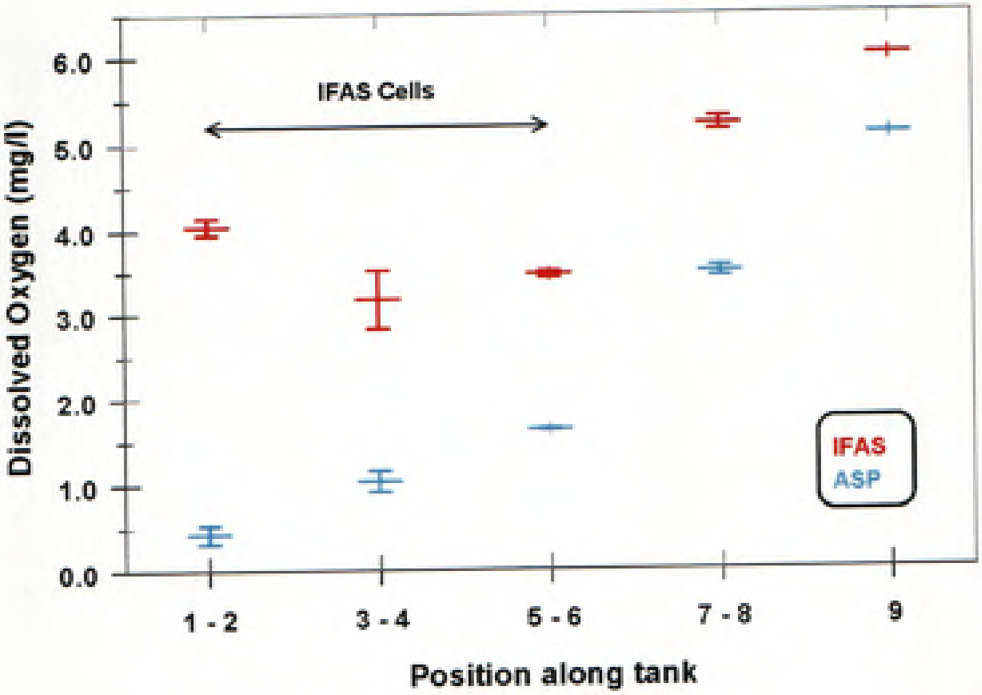

Figure 3. Dissolved oxygen profiles for the ASP and IFAS process in the January test. Error bars shown in the figure represents one standard deviation.

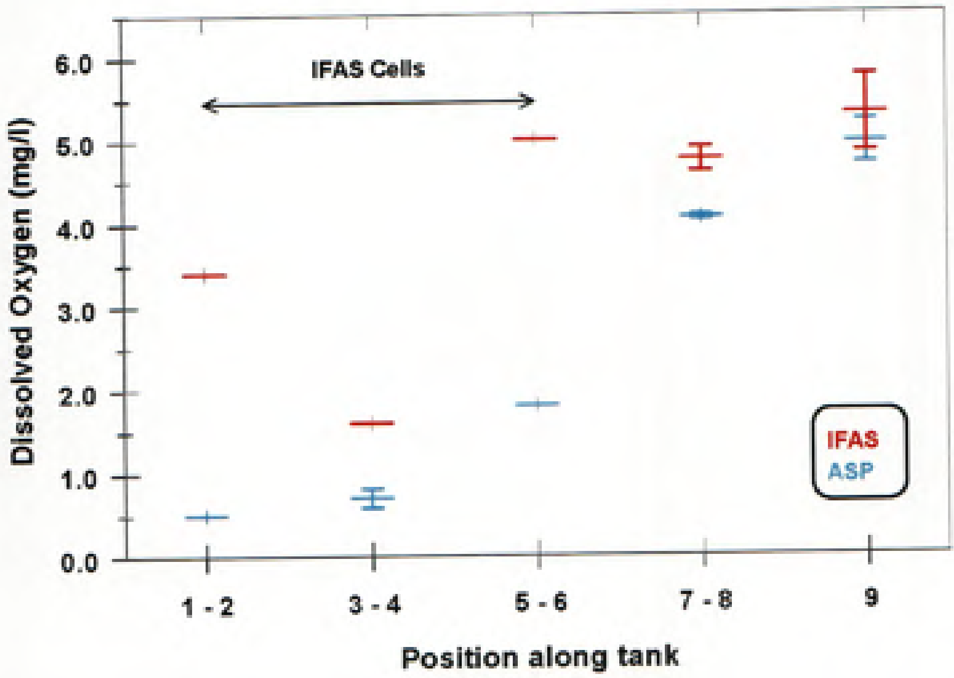

Figure 4. Dissolved oxygen profiles for the ASP and IFAS process in the June test. Error bars shown in the figure represents one standard deviation.

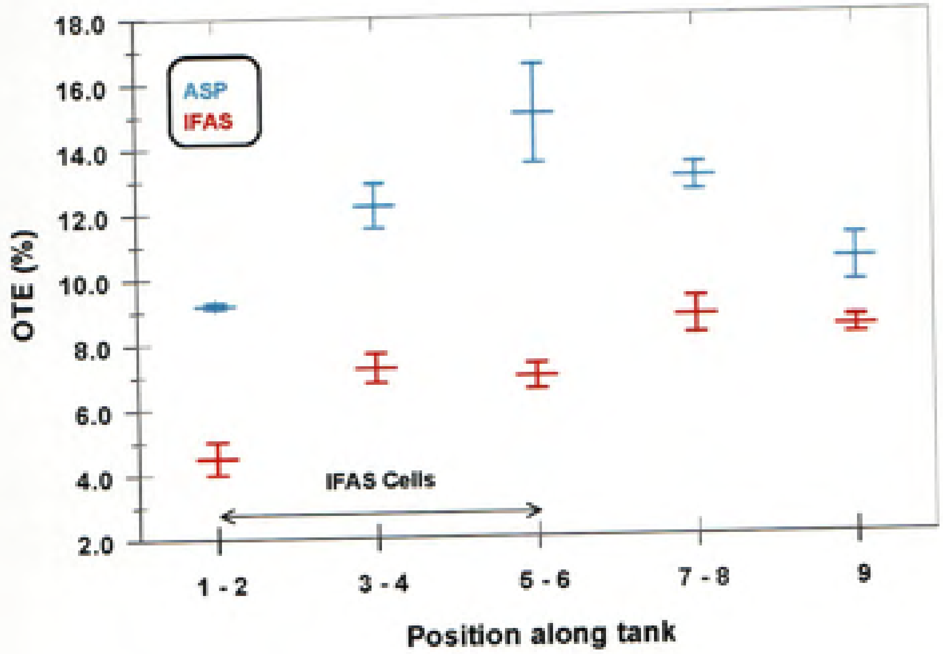

Figure 5. OTE profiles for the ASP and IFAS process in the January test. Error bars shown in the figure represents one standard deviation.

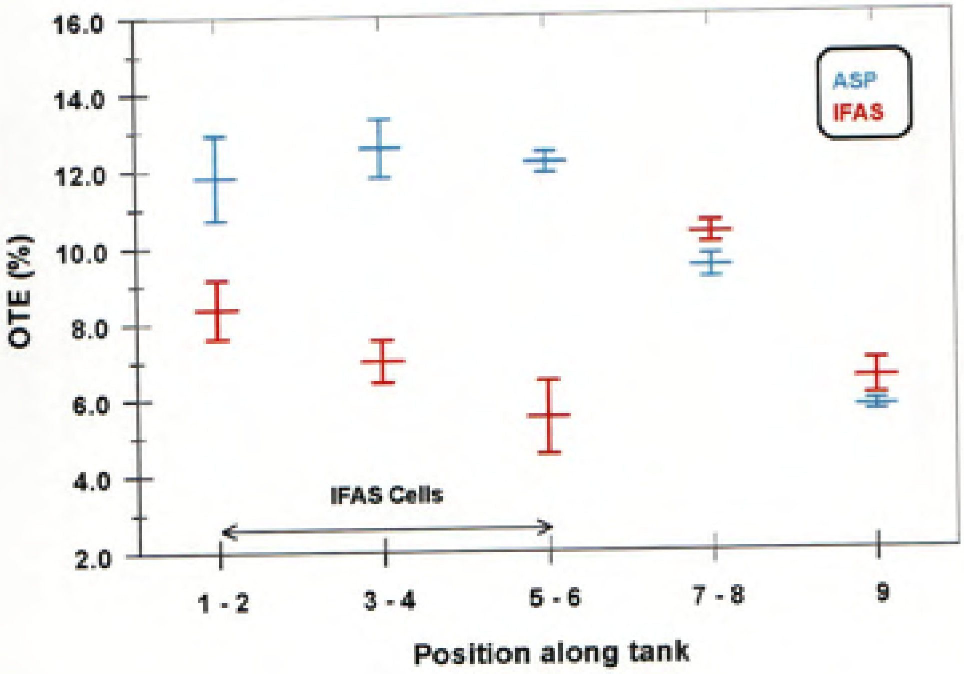

Figure 6. OTE profiles for the ASP and IFAS process in the June test. Error bars shown in the figure represents one standard deviation.

Figures 7 and 8 present αSOTE (%) for the two test basins. It is evident in Figures 5 and 6 that OTE is clearly different for the ASP and IFAS process in both tests. This is likely due to the elevated DO required for the IFAS process. In order to reach the elevated DO concentration in the tank, a high air flow rate is required, therefore lowering the OTE for IFAS. In addition, high DO concentrations are disadvantaged for OTE since the higher DO required is closer to saturation and results in a lower driving force for oxygen transfer. When calculated, αSOTE is compensated with a zero DO correction and therefore is expected to be in the same range for both processes.

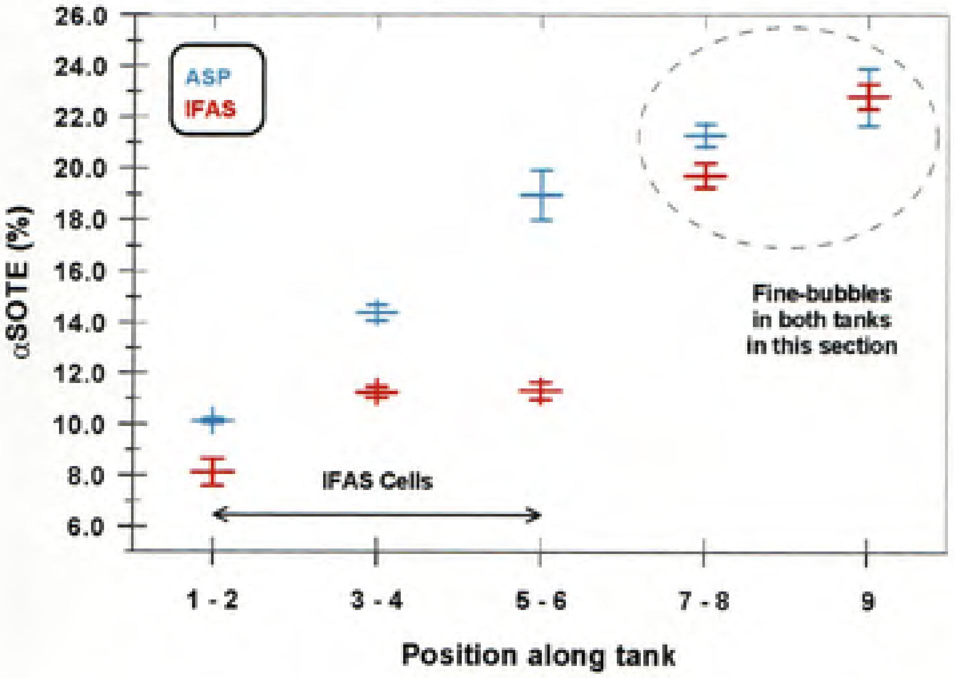

Figure 7. αSOTE profiles for the ASP and IFAS process in the January test. Error bars shown in the figure represents one standard deviation.

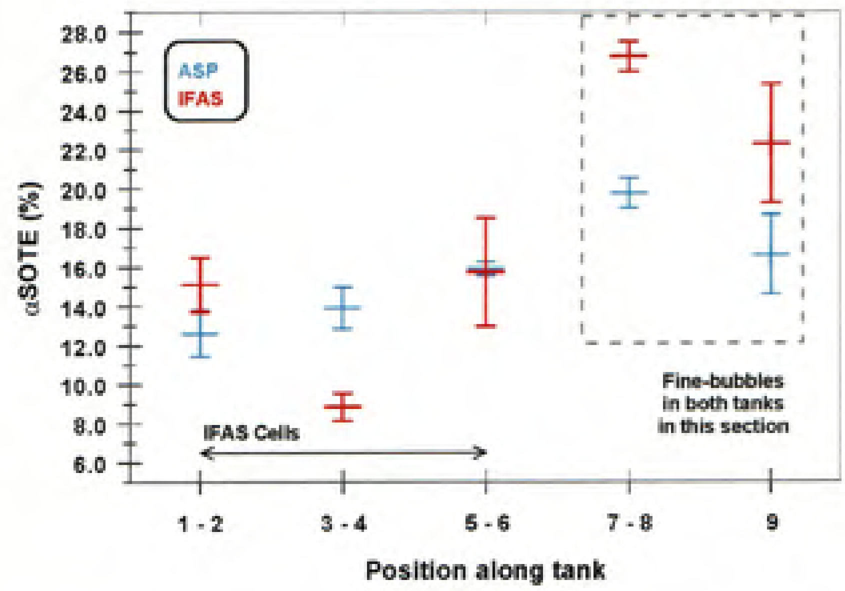

Figure 8. αSOTE profiles for the ASP and IFAS process in the June test. Error bars shown in the figure represents one standard deviation.

The only other published report of oxygen transfer efficiencies of an IFAS system states that IFAS media has little or no effect on oxygen transfer efficiencies when aeration systems are operated identically (Viswanathan, 2008). A comparison of average values calculated in the Viswanathan study at the Lakeview Wastewater Treatment Plant in Peel, Ontario, Canada to this study are presented in Table 7.

Table 7. Results Comparison

Study	αSOTE ASP	αSOTE IFAS
Lakeview WWTP[1]	14.7	11.7
T.Z. Osborne WRF January Test	13.5[2]	10.1[2]
T.Z. Osborne WRF June Test	15.6[2]	13.4[2]

[1] Viswanathan, 2008
[2] average for positions 1-6

The Viswanathan study attributes the difference in OTE values in their study to the difference in diffuser type (coarse bubble in IFAS vs. fine bubble in ASP). Results from both studies indicate that average αSOTE of the ASP is higher than average αSOTE for the IFAS process. It is important to note that, in both studies, airflow to the IFAS process was significantly higher than airflow to the activated sludge process. This is to be expected since an inverse proportionality exists between air flow rate and αSOTE (Rosso, 2005).

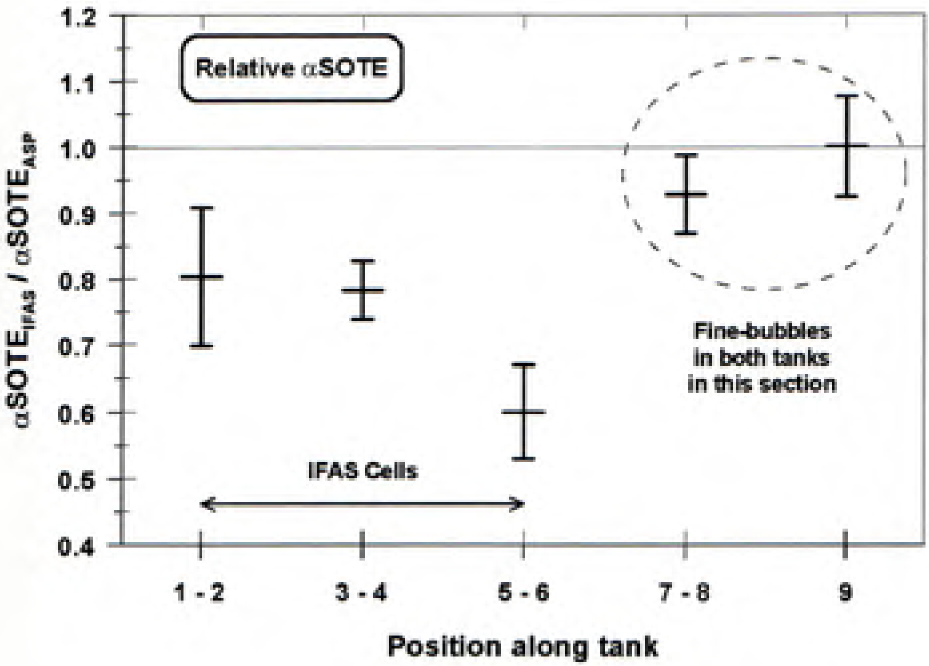

Figure 9. Relative αSOTE profiles for the ASP and IFAS process in the January test. Error bars shown in the figure represent standard deviations calculated using the propagation of error method.

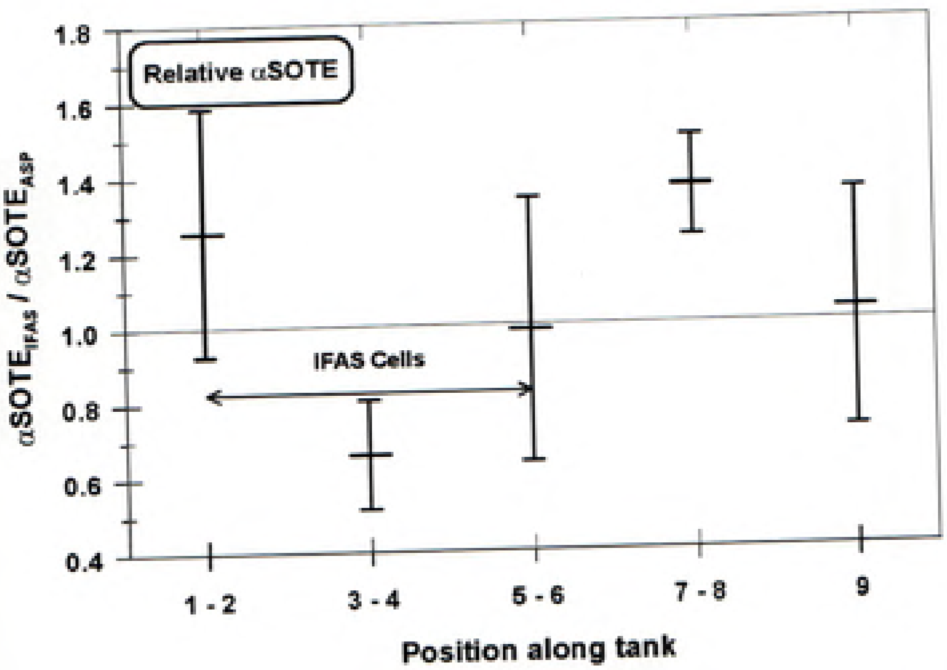

Figure 10. Relative αSOTE profiles for the ASP and IFAS process in the June test. Error bars shown in the figure represent standard deviations calculated using the propagation of error method.

Profiles of OUR in each test basin are shown in Figures 11 and 12, and the ratio between the basins is shown in Figures 13 and 14. The higher OUR for the IFAS basin is due to the higher loading of oxygen demand enabled by the higher total biomass concentration relative to the ASP.

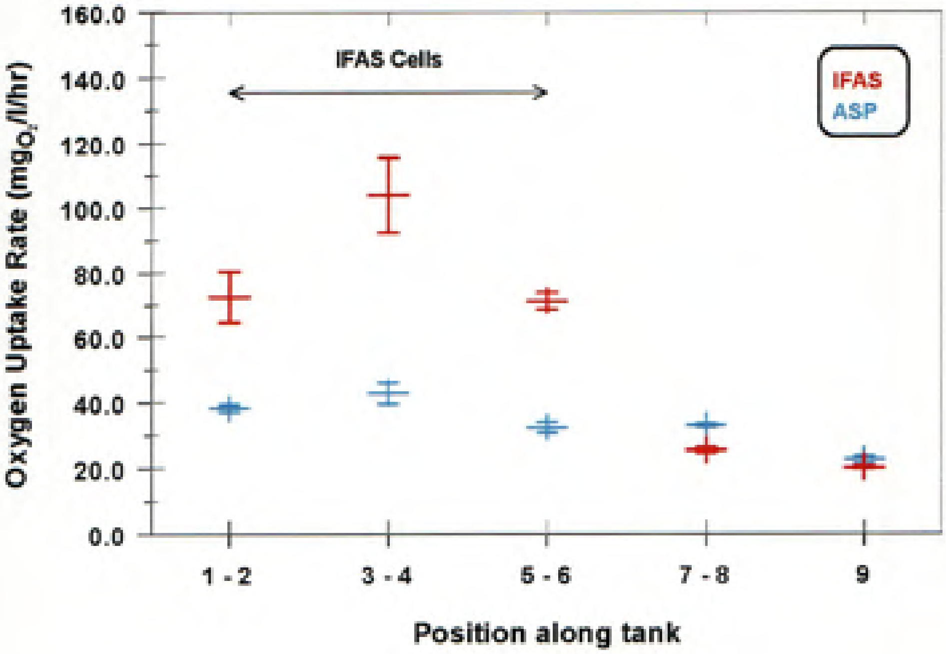

Figure 11. OUR profiles for the ASP and IFAS process in the January test. Error bars shown in the figure represents one standard deviation.

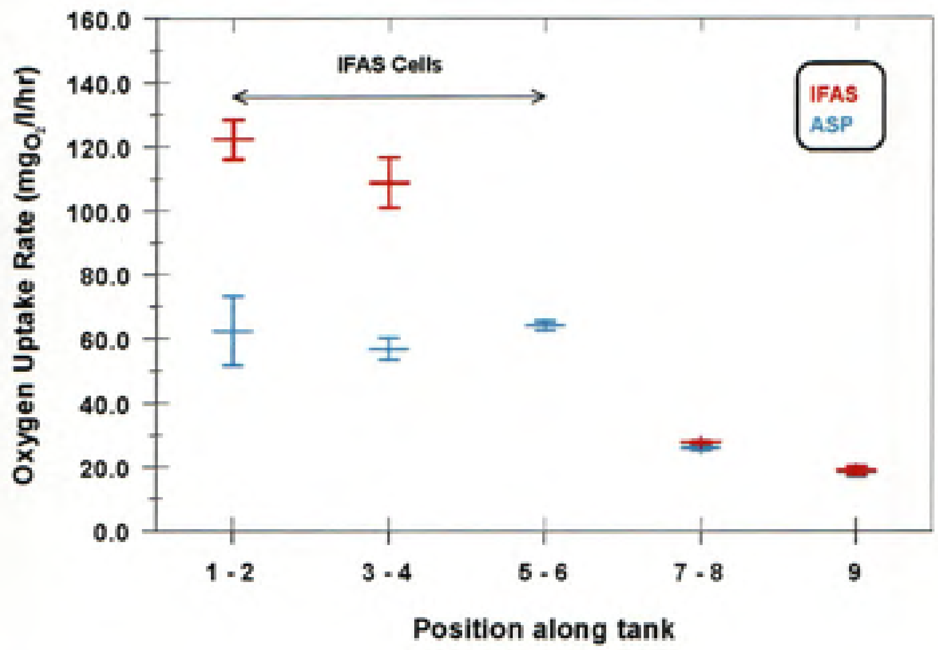

Figure 12. OUR profiles for the ASP and IFAS process in the June test. Error bars shown in the figure represents one standard deviation.

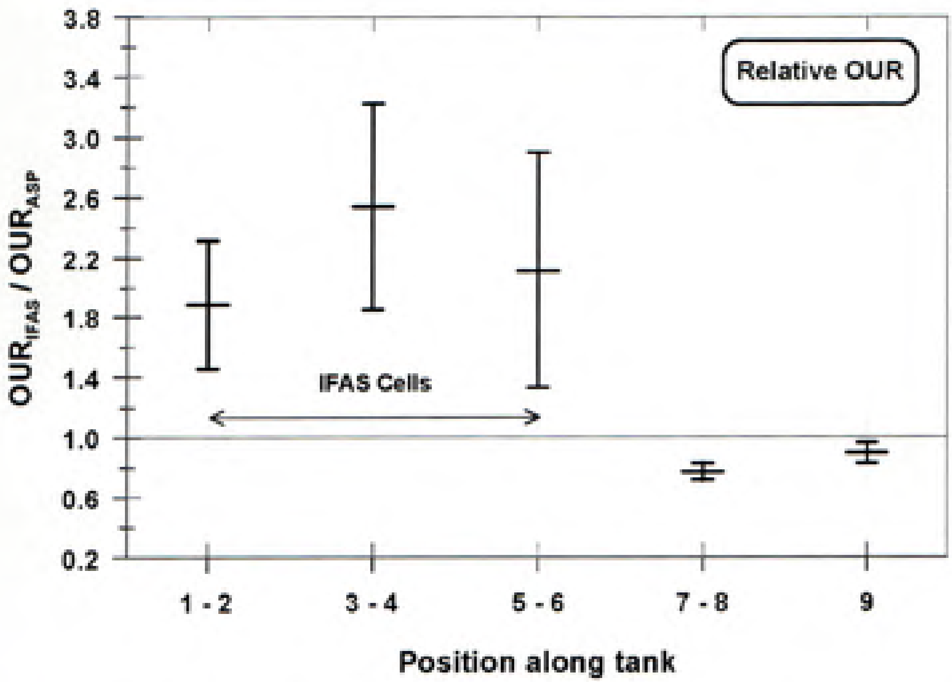

Figure 13. Relative OUR profiles for the ASP and IFAS process in the January test. Relative OTR is the same graph due to data normalization. Error bars shown in the figure represent standard deviations calculated using the propagation of error method.

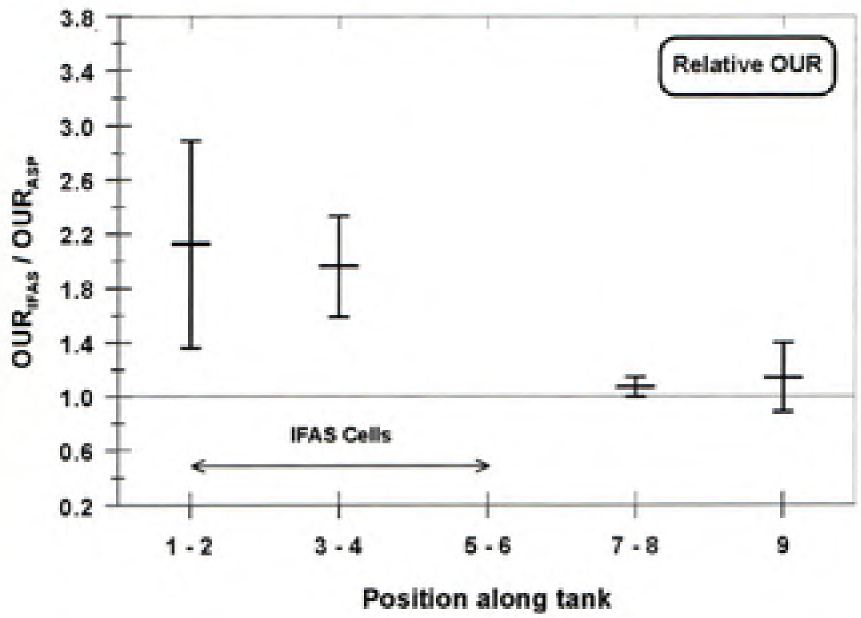

Figure 14. Relative OUR profiles for the ASP and IFAS process in the June test. Relative OTR is the same graph due to data normalization. Error bars shown in the figure represent standard deviations calculated using the propagation of error method.

Figures 15 through 18 present the air flux and the relative ratios for both tanks tested. The air flux in the IFAS basin can be as much as six times that of the activated sludge control basin,- which directly affects power consumption and the oxygen transfer efficiency. Moreover, during the coldest days of the year, it is possible that heat may be lost from the IFAS basin due to increased water vapor stripping, thus potentially affecting nitrification rates. It can be observed that at locations 7, 8, and 9, locations where both basins have fine-bubble diffused aeration, air flow rates for both basins were similar.

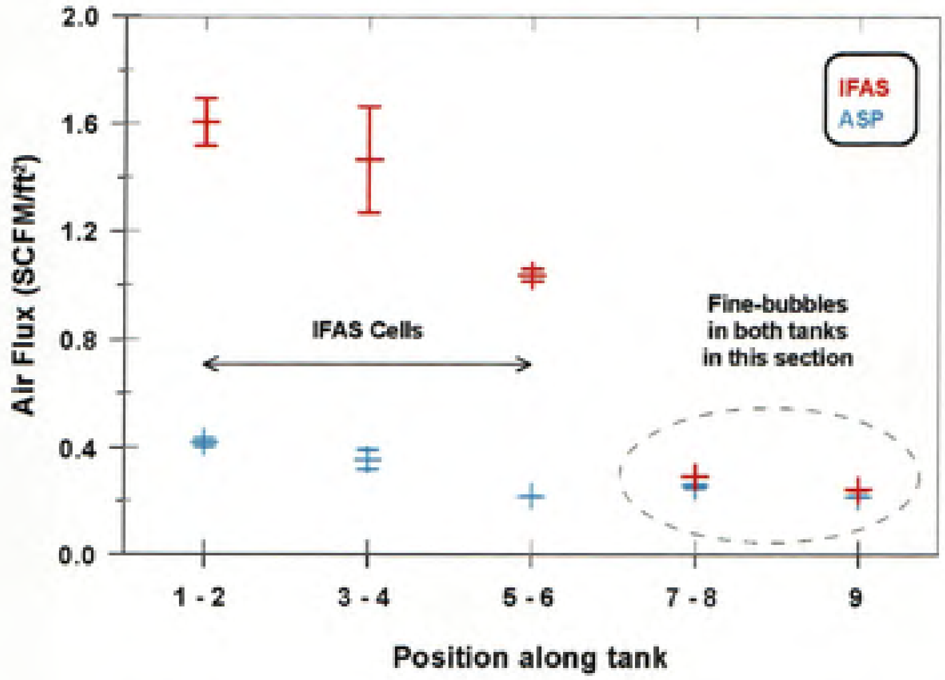

Figure 15. Air flux profiles for the ASP and IFAS process in the January test. Error bars shown in the figure represents one standard deviation.

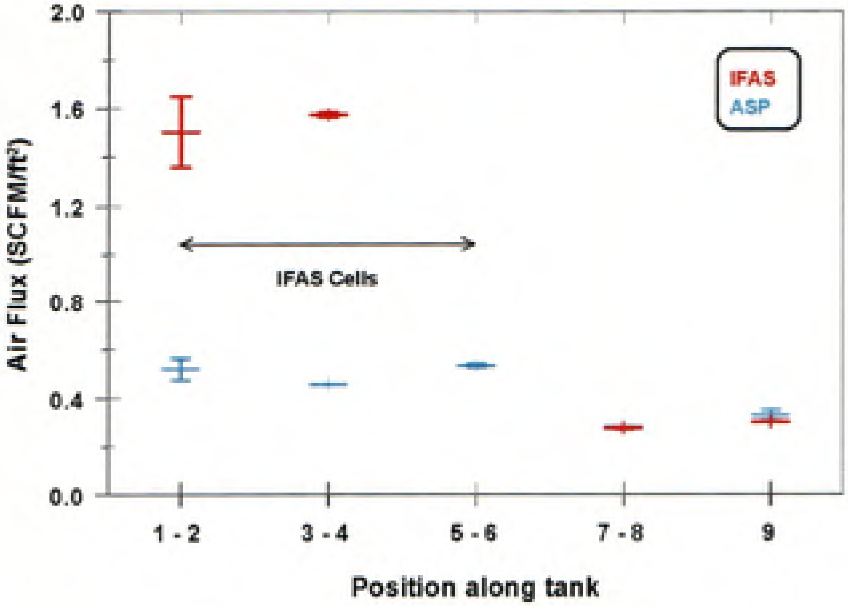

Figure 16. Air flux profiles for the ASP and IFAS process in the June test. Error bars shown in the figure represents one standard deviation.

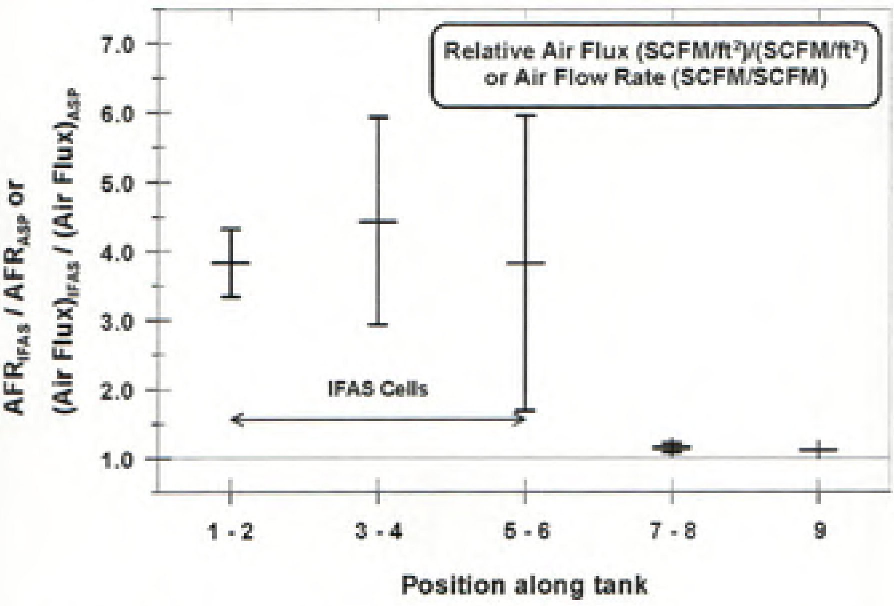

Figure 17. Relative air flux or air flow rate profiles for the ASP and IFAS process in the January test. Due to the normalization, the graph is identical for both air flux and air flow rate. Errors bars shown in the figure represent standard deviations calculated using the propagation of error method.

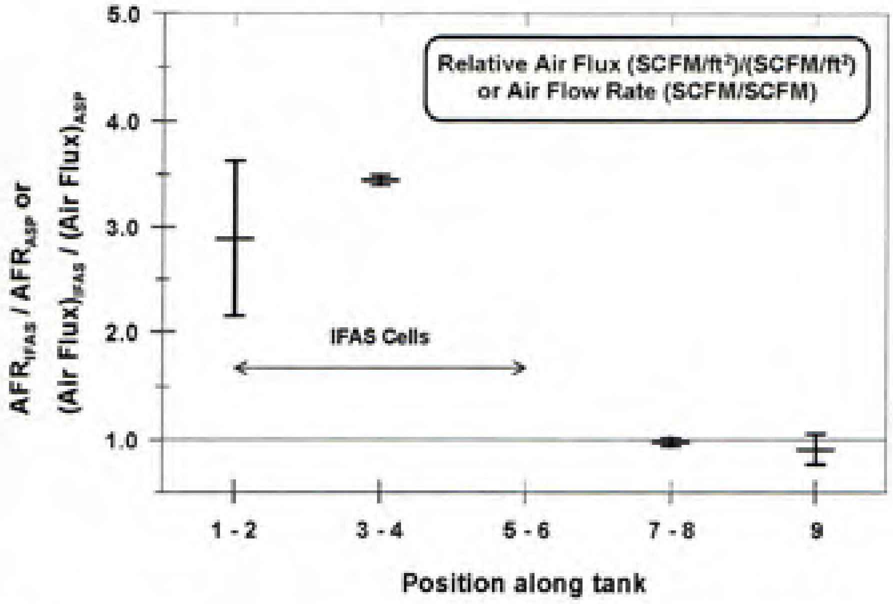

Figure 18. Relative air Flux or Air Flow Rate profiles for the ASP and IFAS process in the June test. Due to the normalization, the graph is identical for both air flux and air flow rate. Error bars shown in the figure represent standard deviations calculated using the propagation of error method.

Figures 19 through 22 present the air use (expressed as volume of air used per unit oxygen demand removed) and relative ratio for both tanks. Removal of oxygen demand considered both COD and nitrogenous oxygen demand, and they are collectively referred to as the "load" in subsequent discussion. In theory, when OTE is the same, the air required per unit of oxygen demand removed should be the same regardless of the process. Nevertheless, the mixing requirements specified by the IFAS manufacturers affect air use as evident in Figures 19 and 20. Throughout the coarse-bubble aeration zones (positions 1 to 6), the IFAS basin has elevated air flow rate and therefore the air use relative to that in the ASP basin is in the range of 1.3 to 3.0. The air use of the IFAS process is less than the ASP for locations 7 through 9. This is likely attributed to more oxygen demand consumed in the upstream IFAS cells than the ASP cells. Loads to each process were calculated from measured primary effluent and individual aeration basin effluent COD and ammonium-nitrogen (NH_4^+-N) values.

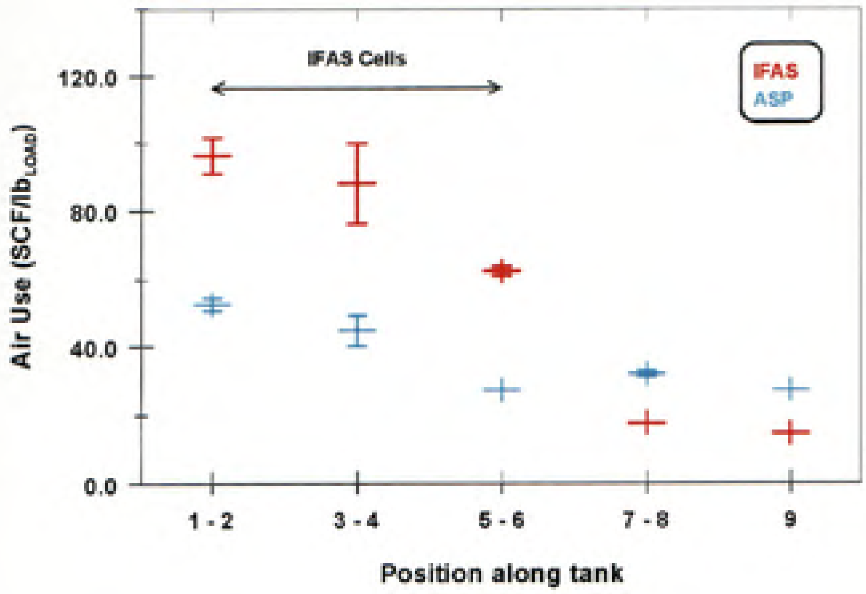

Figure 19. Air use (expressed as standard ft^3 of air used per unit load removed) profiles for the ASP and IFAS process in the January test.

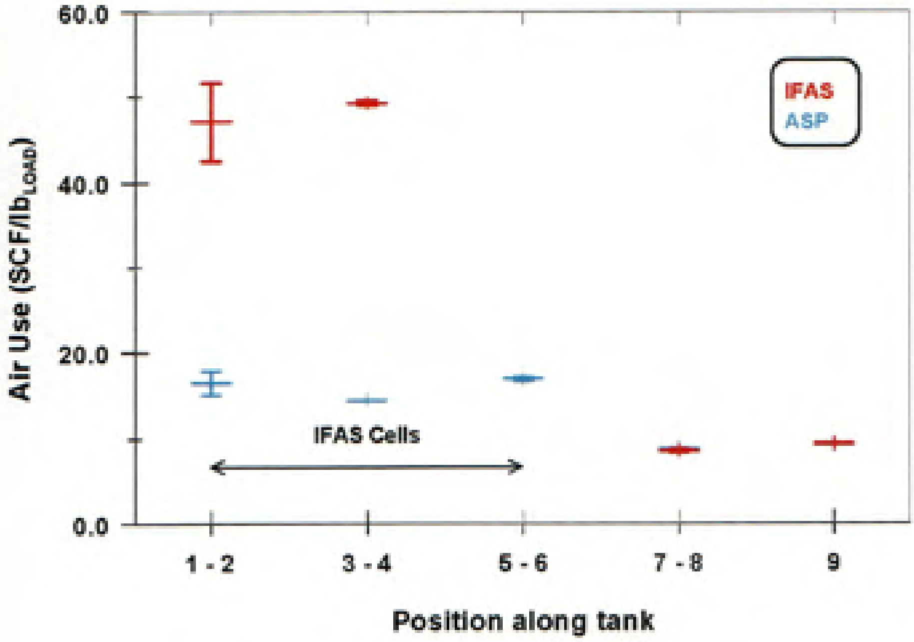

Figure 20. Air use (expressed as standard ft^3 of air used per unit load removed) profiles for the ASP and IFAS process in the June test.

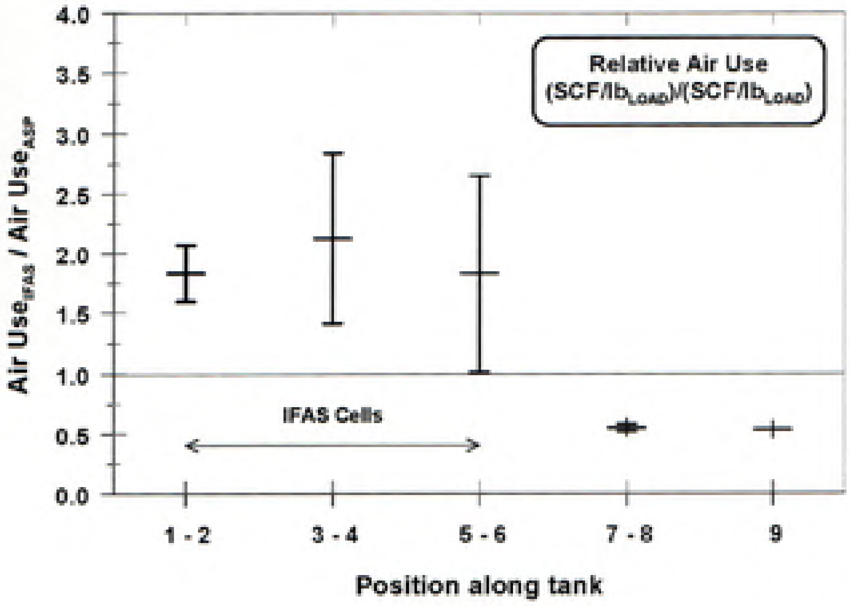

Figure 21. Relative air use profiles for the ASP and IFAS process in the January test. Error bars shown in the figure represent standard deviations calculated using the propagation of error method.

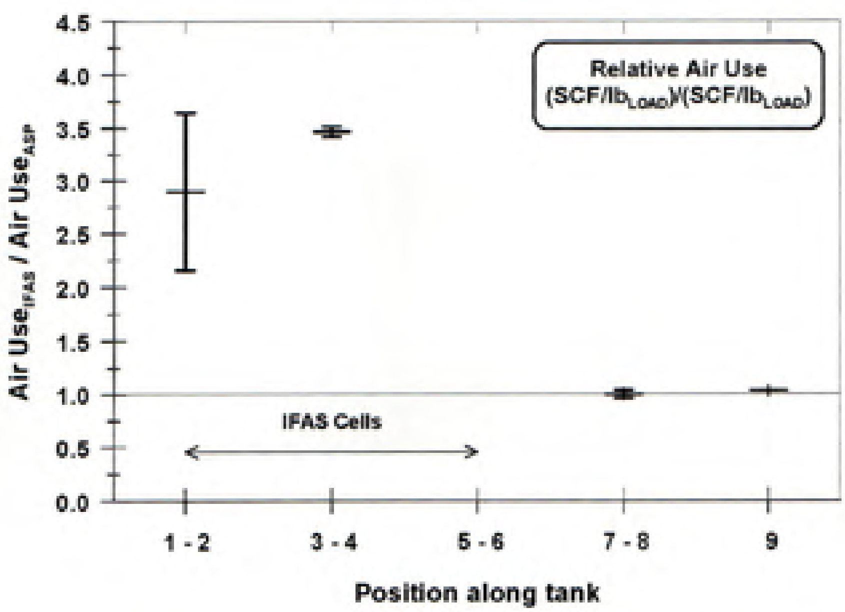

Figure 22. Relative air use profiles for the ASP and IFAS process in the June test. Error bars shown in the figure represent standard deviations calculated using the propagation of error method.

4.2 Nutrient Profiles

A nutrient profile was conducted at the same time as the off-gas testing. The goal of the nutrient profile was to quantify nitrification along the basin. Figures 23 - 30 present profiles of ammonium, nitrate, nitrite, and orthophosphate, respectively. Additionally, influent and effluent COD concentrations were measured in order to quantify COD load to each basin. The COD and ammonium influent values were used in the air-use calculations in order to normalize basin performance per unit loading of oxygen demand. Despite the higher hydraulic load on the IFAS basin, both basins achieved complete nitrification.

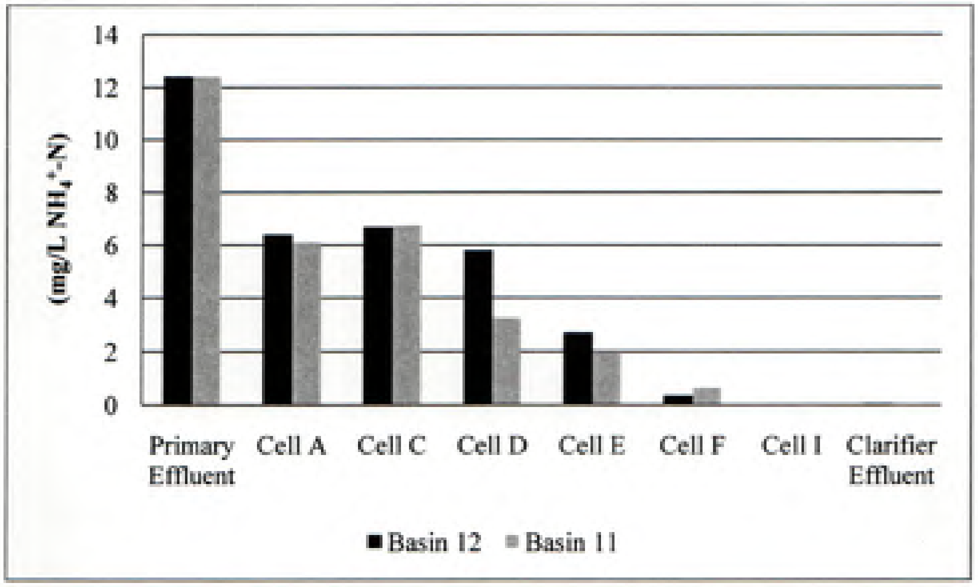

Figure 23. Ammonium-N profile in the January test.

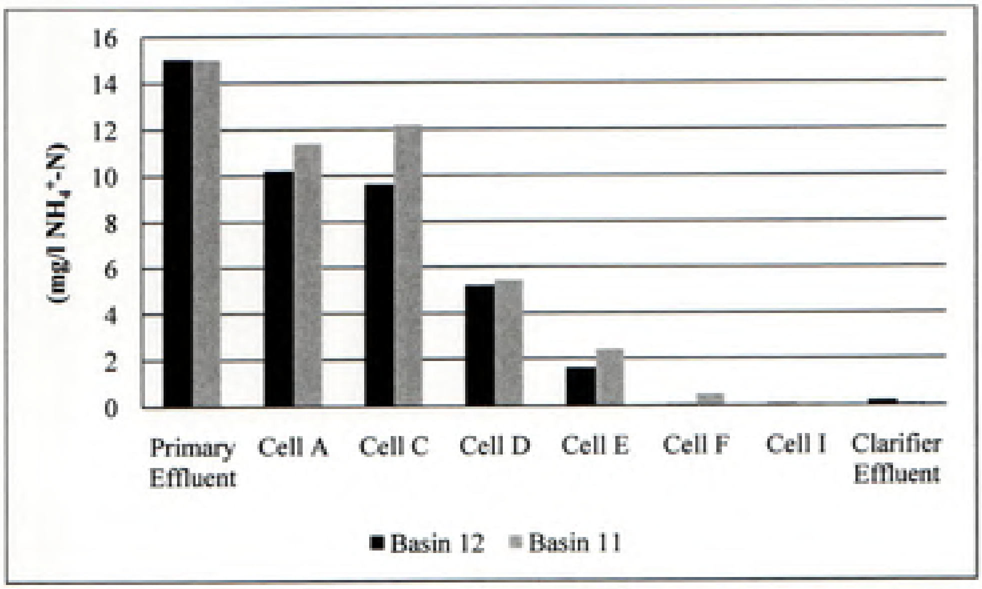

Figure 24. Ammonium-N profile in the June Test.

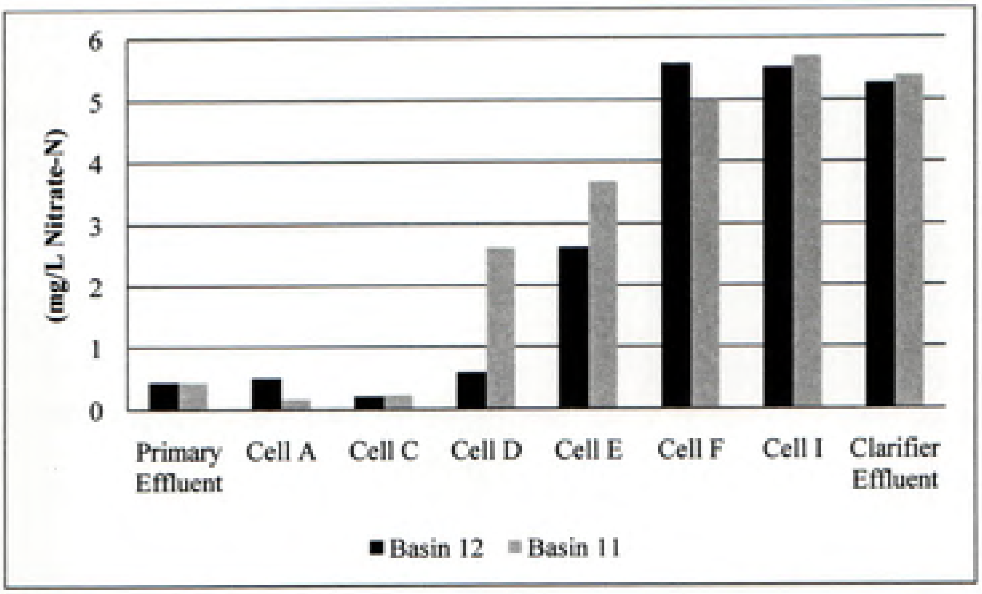

Figure 25. Nitrate-N profile in the January test.

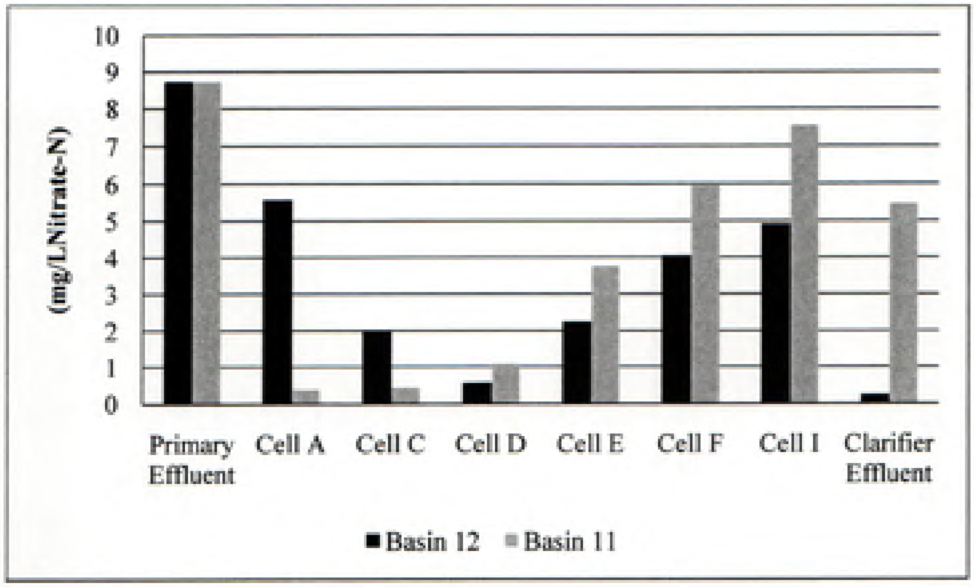

Figure 26. Nitrate-N profile in the June test. High nitrate concentration in the primary effluent is unexplainable.

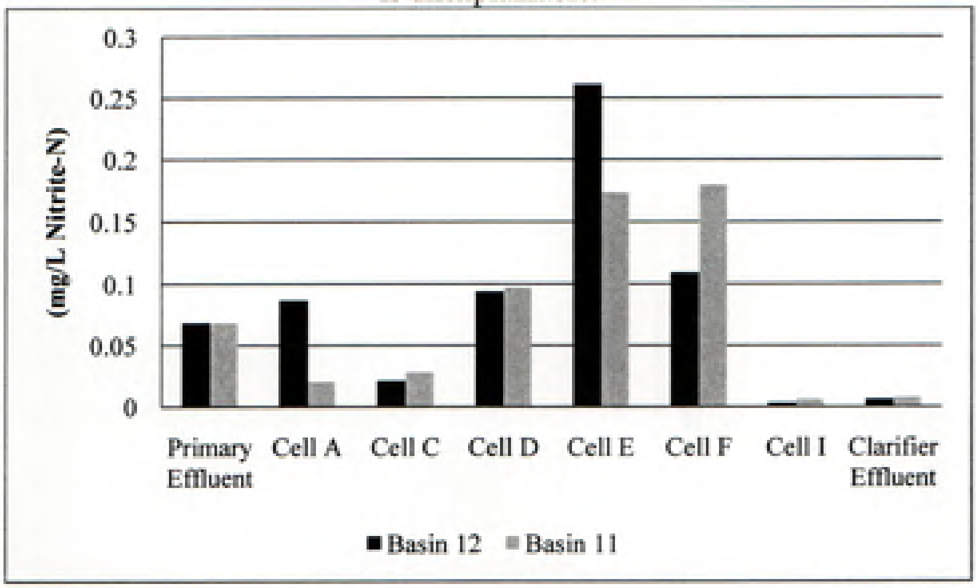

Figure 27. Nitrite-N profile in the January test.

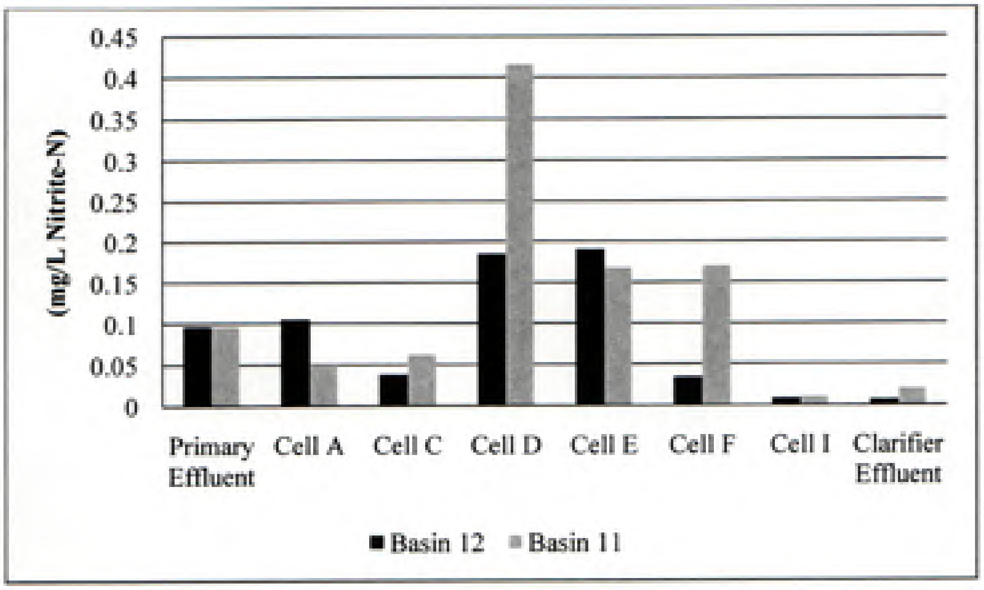

Figure 28. Nitrite-N profile in the June test.

Figures 29 and 30 show the orthophosphate profiles through each basin. Biological phosphorus removal can be observed and occurs more quickly in Basin 11. Cells A through C in each train are anoxic and phosphorus release in these cells is observed.

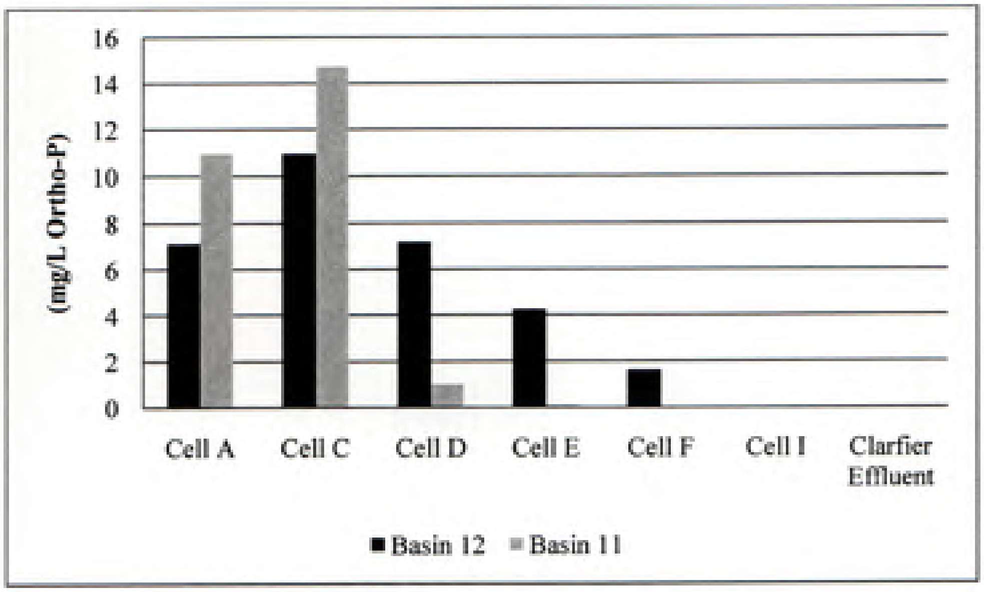

Figure 29. Orthophosphate-P profile in the January test.

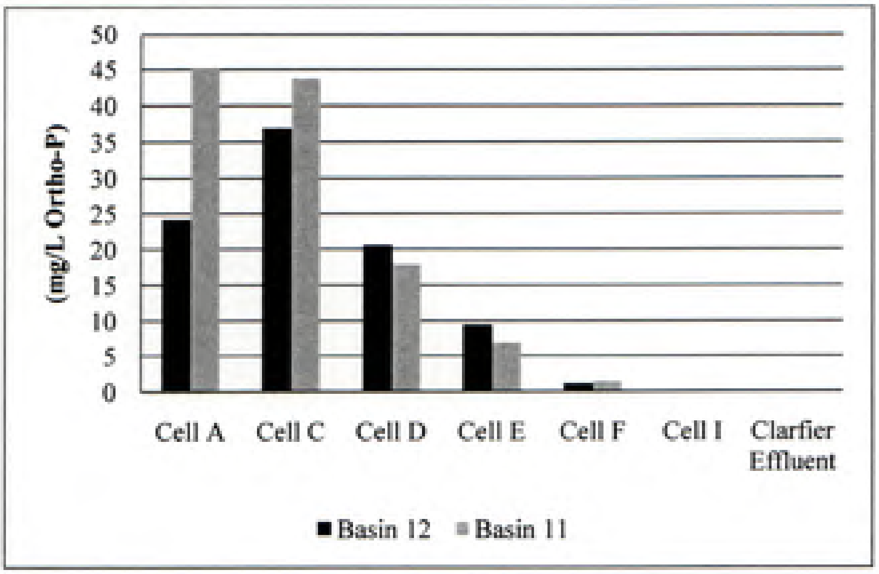

Figure 30. Orthophosphate-P Profile in the June test.

4.3 Mixing Considerations

Since mixing is a crucial component of the IFAS process, and since the elevated air flow rate for the IFAS process is driven by manufacturer's specifications for mixing, an attempt to quantify the fraction of aeration energy used for mixing was made. Although the exact fraction of air flow used for mixing cannot be quantified, it is possible to calculate the fraction of air flux used for oxygen transfer from off-gas data, then calculate the fraction of air flux used for mixing by subtraction from the off-gas air flux:

$$(\text{Air Flux})_{\text{Mixing}} = (\text{Air Flux})_{\text{Off-gas}} - (\text{Air Flux})_{\text{Oxygen Transfer}} \qquad (15)$$

Analogously, for air use the equation is:

$$(\text{Air Use})_{\text{Mixing}} = (\text{Air Use})_{\text{Off-gas}} - (\text{Air Use})_{\text{Oxygen Transfer}} \qquad (16)$$

Figures 17 to 24 show the results of this mixing air analysis.

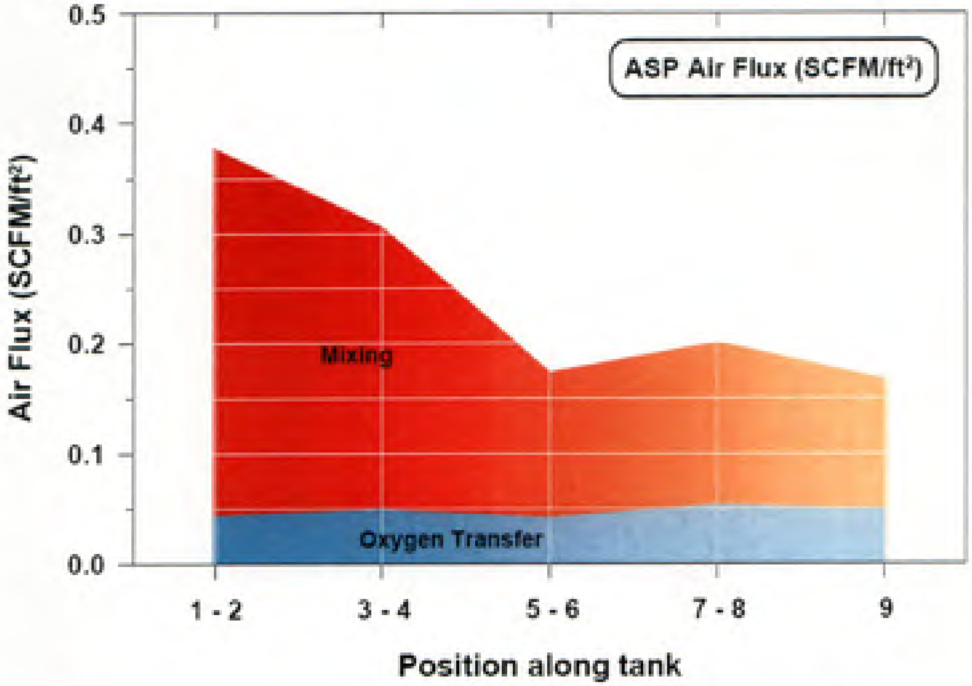

Figure 31. Air flux profiles for the ASP (Tank 11) in the January test. The fractions of air flux used in oxygen transfer and mixing were calculated using equation 15.

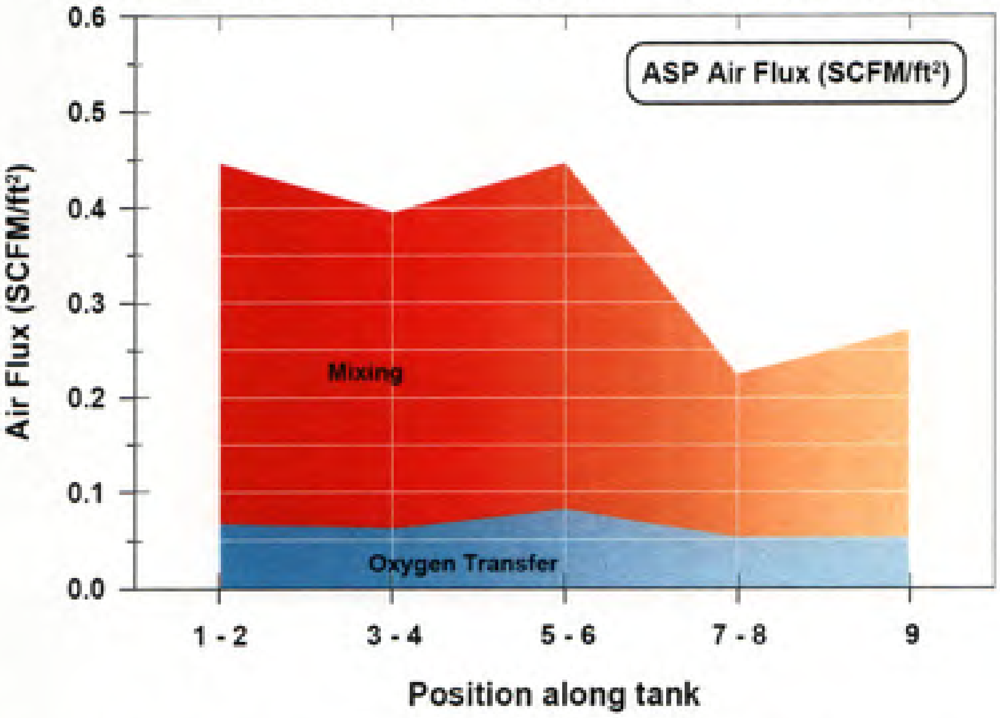

Figure 32. Air flux profiles for the ASP (Tank 11) in the June test. The fractions of air flux used in oxygen transfer and mixing were calculated using equation 15.

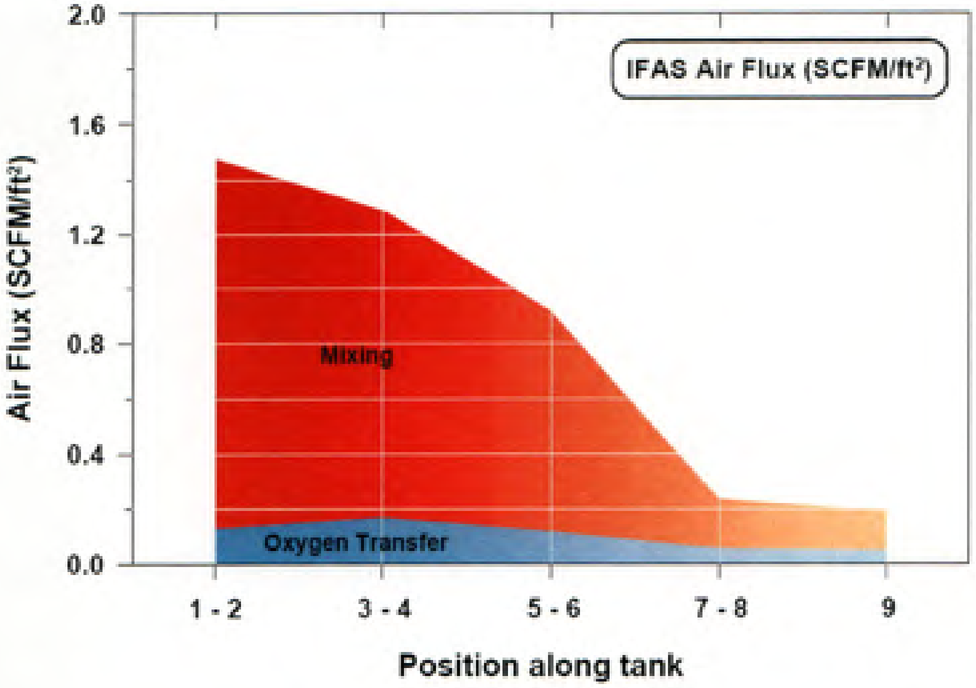

Figure 33. Air flux profiles for the IFAS (Tank 12) in the January test. The fractions of air flux used in oxygen transfer and mixing were calculated using equation 15.

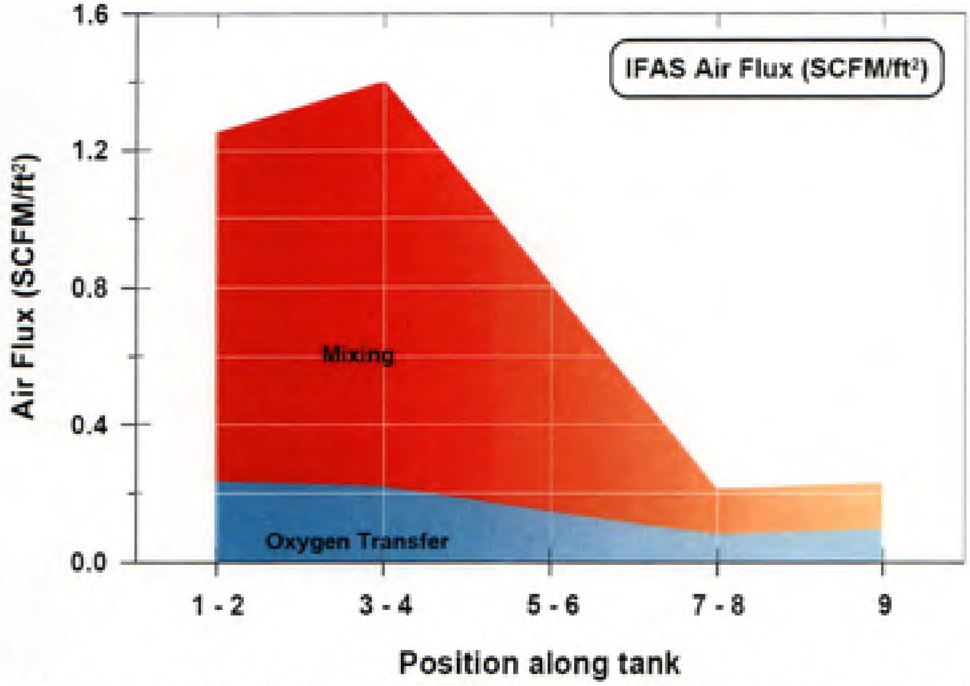

Figure 34. Air flux profiles for the IFAS (Tank 12) in the June test. The fractions of air flux used in oxygen transfer and mixing were calculated using equation 15.

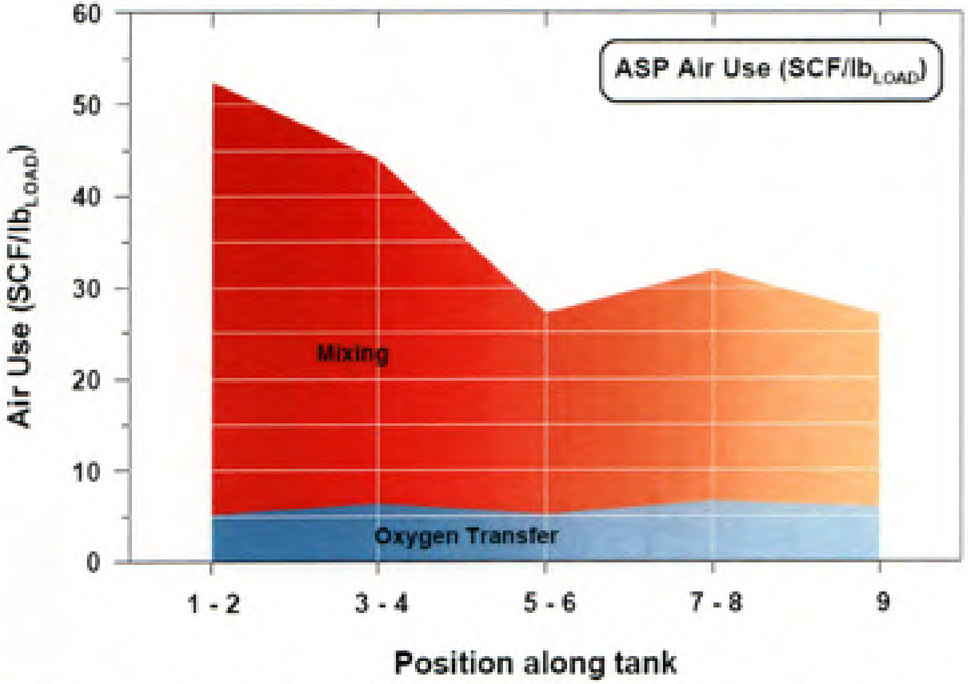

Figure 35. Air use profiles for the ASP (Tank 11) in the January test. The fractions of air use used in oxygen transfer and mixing were calculated using equation 16.

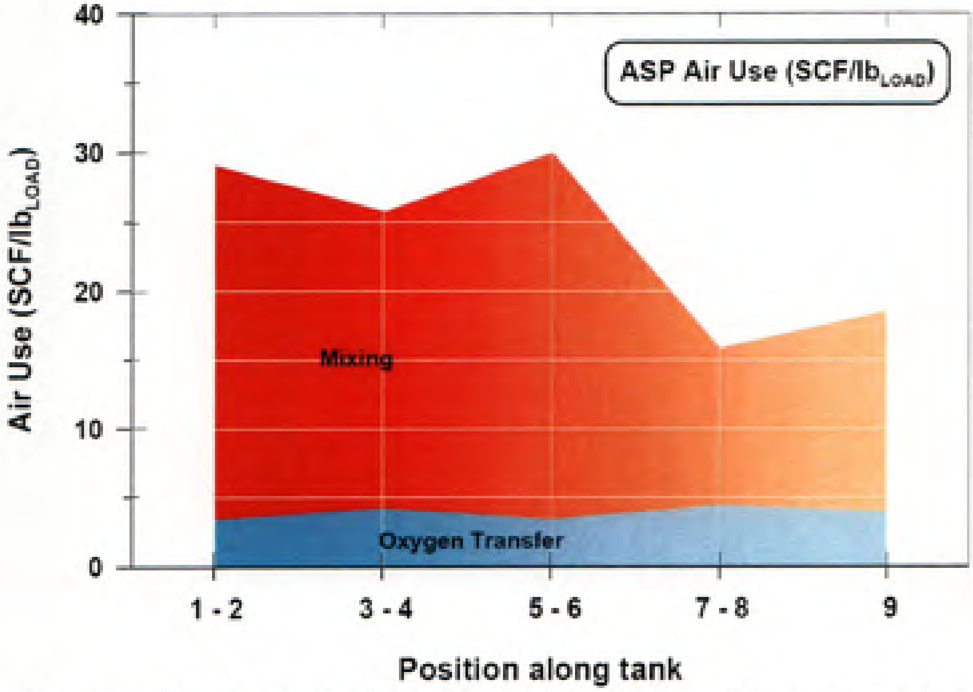

Figure 36. Air use profiles for the ASP (Tank 11) in the June test. The fractions of air use used in oxygen transfer and mixing were calculated using equation 16.

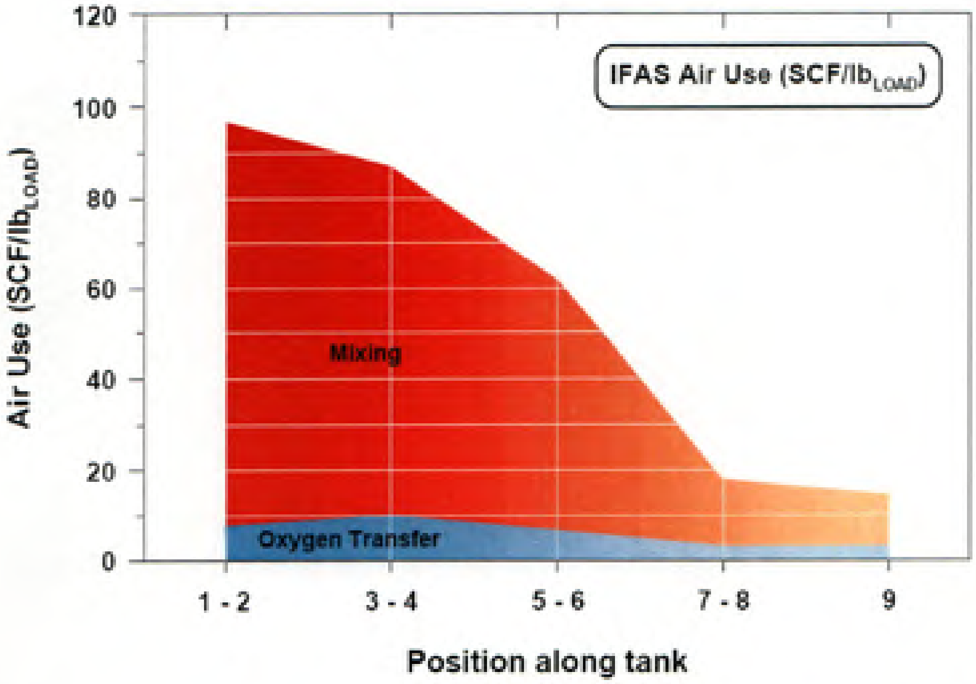

Figure 37. Air use profiles for the IFAS (Tank 12) in the January test. The fractions of air use used in oxygen transfer and mixing were calculated using equation 16.

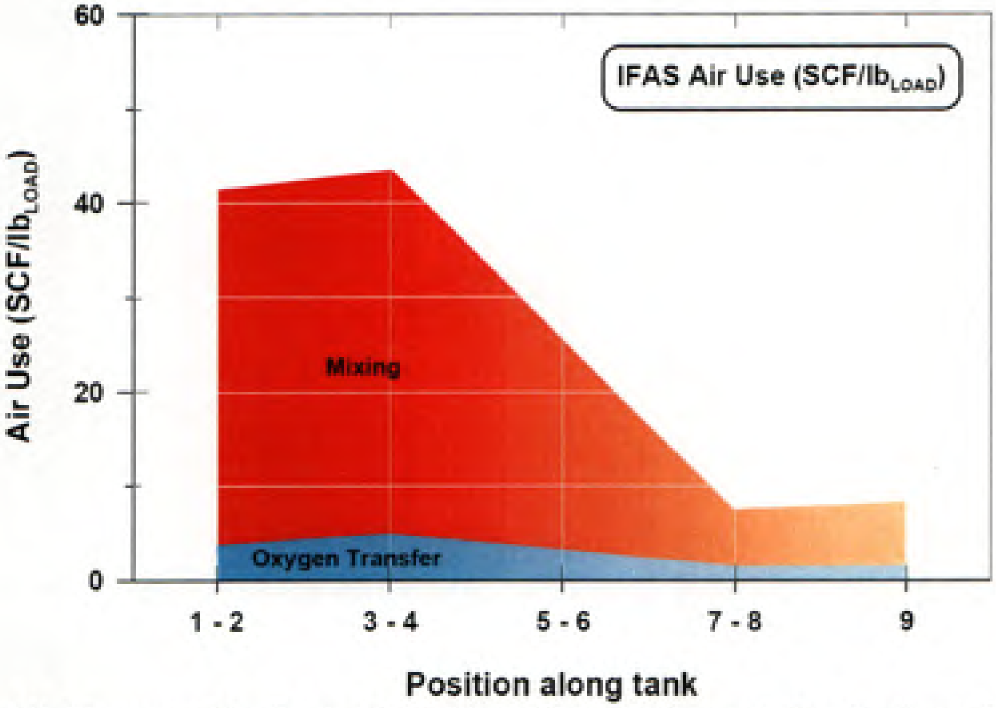

Figure 38. Air use profiles for the IFAS (Tank 12) in the June test. The fractions of air use used in oxygen transfer and mixing were calculated using equation 16.

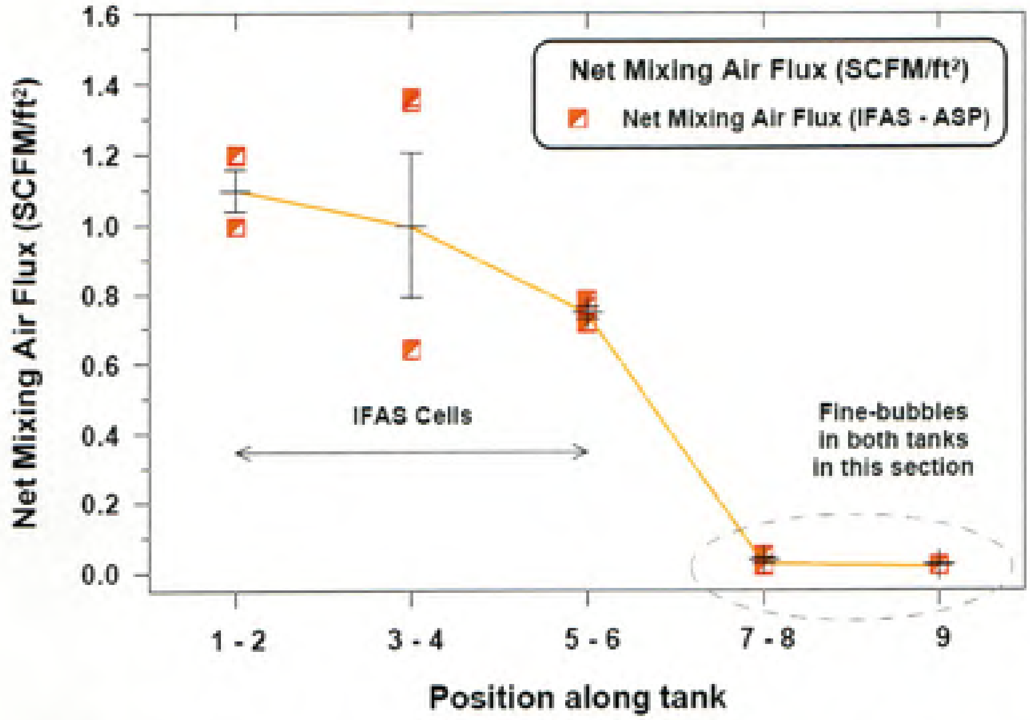

Figure 39. Net mixing air flux (difference between IFAS and ASP air fluxes) in the January test.

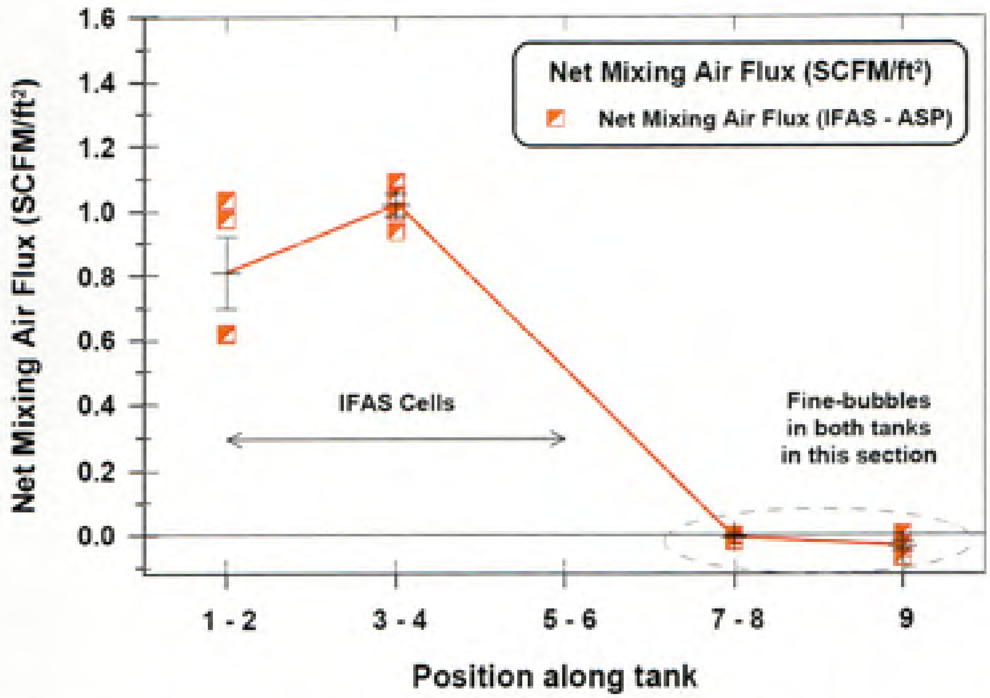

Figure 40. Net mixing air flux (difference between IFAS and ASP air fluxes) in the June test.

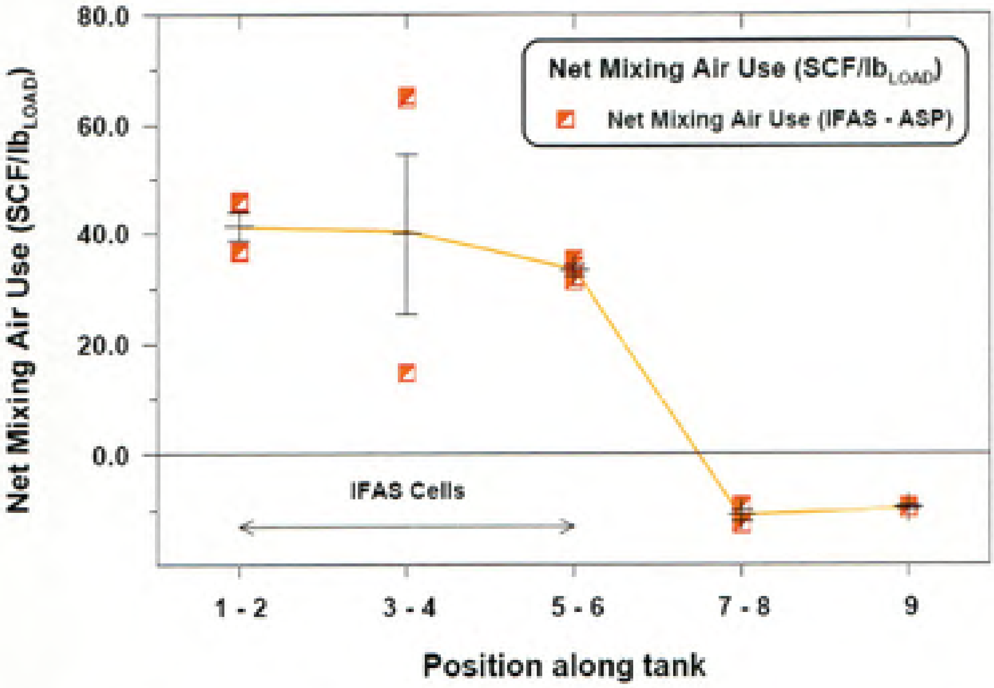

Figure 41. Net mixing air use (difference between IFAS and ASP air uses) in the January test.

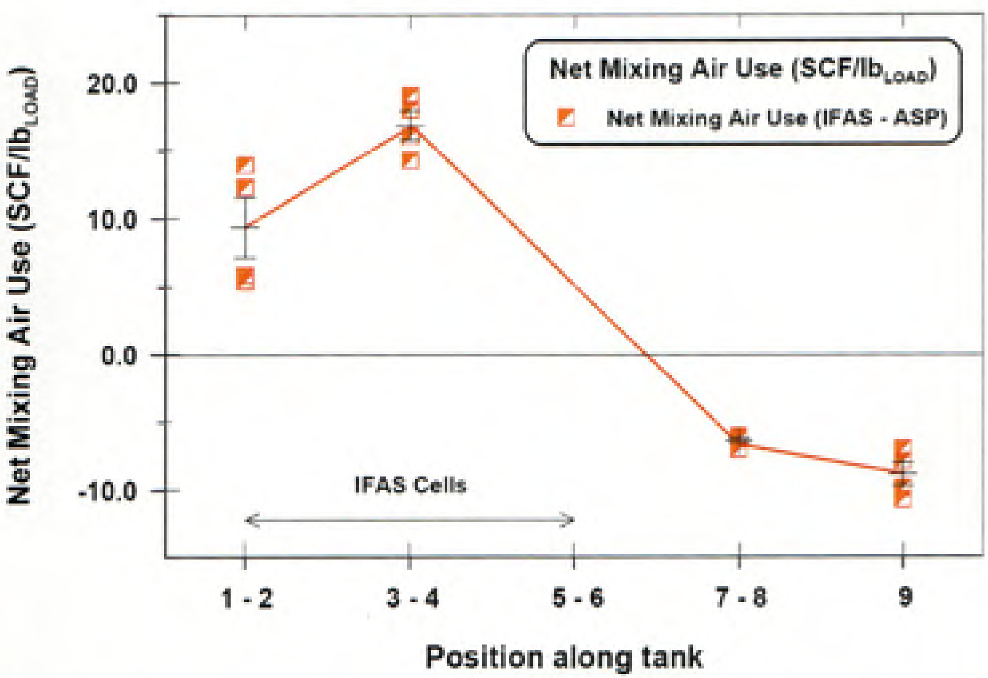

Figure 42. Net mixing air use (difference between IFAS and ASP air uses) in the June test.

Chapter 5
Summary, Conclusions, and Recommendations

The off-gas testing at the T.Z. Osborne WRF indicates that the IFAS process has a lower OTE when compared to the ASP. It is not appropriate to conclude that one process has a higher αSOTE relative to the other; higher IFAS αSOTE compared to the ASP in the June test is attributed to adjustment of the OTE value to standard conditions during warm weather when the DO saturation point in water is lower. The IFAS process requires more air per unit of COD removed. The IFAS process also exhibited higher air flux and air use compared to the ASP. This is attributed to the higher DO concentration required in the IFAS process. It can be deduced that, because of the higher DO concentration required by the media manufacturer, operation of an IFAS process is more expensive than operation of an ASP. Calculations to attempt approximation of air required for oxygen transfer and mixing (keeping media in suspension) within both test basins indicates that DO concentrations could be lowered within an IFAS process to provide just enough air for oxygen transfer and mixing with none wasted to the atmosphere. Further testing would be required to calculate precise air requirements for seasonal and load variations.

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APPENDIX A

Position	aSOTE (ASP)	aSOTE (IFAS)	aSOTE (IFAS/ASP)	OUR (ASP)	OUR (IFAS)	OUR (IFAS/ASP)	Air Flux (ASP)	Air Flux (IFAS)	Air Flux (IFAS/ASP)	Air Use (ASP)	Air Use (IFAS)	Air Use (IFAS/ASP)	Air Use (ASP)	Air Use (IFAS)
	(%)	(%)	-	mg/l/hr	mg/l/hr	-	SCFM/ft2	SCFM/ft2	-	SCF/lbCODrem	SCF/lbCODrem	-	SCF/lbLOAD	SCF/lbLOAD
1	10.3	7.1	0.69	36.3	57.9	1.60	0.39	1.45	3.69	60.0	106.2	1.77	49.3	87.2
1	10.2	7.3	0.72	35.9	59.8	1.67	0.39	1.45	3.69	60.0	106.2	1.77	49.3	87.2
2	10.0	8.9	0.89	40.5	85.3	2.10	0.44	1.76	3.95	67.6	128.3	1.90	55.6	105.4
2	9.9	9.1	0.92	40.0	87.4	2.18	0.44	1.76	3.95	67.6	128.3	1.90	55.6	105.4
3	15.2	11.7	0.77	37.9	128.8	3.40	0.29	1.81	6.17	44.6	132.0	2.96	36.7	108.4
3	14.6	10.8	0.74	36.4	118.7	3.26	0.29	1.81	6.17	44.6	132.0	2.96	36.7	108.4
4	13.8	11.1	0.80	48.1	83.0	1.72	0.42	1.13	2.69	63.8	82.3	1.29	52.5	67.5
4	14.0	11.4	0.82	48.8	85.7	1.76	0.42	1.13	2.69	63.8	82.3	1.29	52.5	67.5
5	17.2	12.2	0.71	29.4	79.3	2.69	0.22	1.08	4.95	33.1	78.6	2.38	27.2	64.5
5	17.7	10.6	0.60	30.2	69.0	2.28	0.22	1.08	4.95	33.1	78.6	2.38	27.2	64.5
6	21.5	11.1	0.52	36.7	68.0	1.85	0.22	1.00	4.60	33.1	73.0	2.21	27.2	60.0
6	19.3	11.3	0.59	33.0	69.2	2.10	0.22	1.00	4.60	33.1	73.0	2.21	27.2	60.0
7	20.3	20.6	1.02	33.3	26.9	0.81	0.27	0.29	1.09	40.8	21.4	0.53	33.5	17.6
7	20.8	20.4	0.98	34.2	26.6	0.78	0.27	0.29	1.09	40.8	21.4	0.53	33.5	17.6
8	22.3	19.0	0.85	32.5	24.1	0.74	0.24	0.29	1.21	36.9	21.4	0.58	30.4	17.6
8	21.7	18.8	0.87	31.7	23.9	0.75	0.24	0.29	1.21	36.9	21.4	0.58	30.4	17.6
9	23.9	23.3	0.98	23.6	20.6	0.87	0.22	0.24	1.12	33.1	17.7	0.54	27.2	14.6
9	21.6	22.3	1.03	21.4	19.7	0.92	0.22	0.24	1.12	33.1	17.7	0.54	27.2	14.6
Flow Weighted Average	**15.7**	**11.0**	**0.79**	**36.5**	**80.0**	**1.97**	**0.3**	**1.34**	**3.73**	**49.7**	**97.9**	**1.79**	**40.9**	**80.4**

Air Use (IFAS/ASP)	OTR (ASP)	OTR (IFAS)	OTR (IFAS/ASP)	Air Use OT (ASP)	Air Use OT (IFAS)	Air Use MIX (ASP)	Air Use MIX (IFAS)	Net Air Use MIX (IFAS-ASP)	Air Use MIX (IFAS/ASP)	AFR OT (ASP)	AFR OT (IFAS)	AFR MIX (ASP)	AFR MIX (IFAS)	Net AFR MIX (IFAS)	AFR MIX (IFAS/ASP)
-	lbO2/hr	lbO2/hr	-	SCF/lbLOAD	SCF/lbLOAD	SCF/lbLOAD	SCF/lbLOAD	SCF/lbLOAD	*(Per unit load)*	SCFM/ft2	SCFM/ft2	SCFM/ft2	SCFM/ft2	SCFM/ft2	*(Flux)*
1.77	314	501	1.60	5.1	6.2	44.2	81.0	36.8	1.8	0.04	0.10	0.35	1.35	1.00	3.82
1.77	310	517	1.67	5.0	6.4	44.3	80.8	36.6	1.8	0.04	0.11	0.35	1.35	0.99	3.81
1.89	351	738	2.10	5.6	9.4	50.0	96.0	46.0	1.9	0.04	0.16	0.40	1.60	1.20	4.00
1.89	346	756	2.18	5.5	9.6	50.1	95.8	45.7	1.9	0.04	0.16	0.40	1.60	1.20	3.99
2.96	328	1115	3.40	5.6	12.7	31.1	95.7	64.6	3.1	0.04	0.21	0.25	1.60	1.35	6.42
2.96	315	1027	3.26	5.3	11.7	31.3	96.7	65.4	3.1	0.04	0.19	0.25	1.61	1.36	6.44
1.29	416	718	1.72	7.2	7.5	45.2	60.1	14.8	1.3	0.06	0.12	0.36	1.00	0.64	2.77
1.29	422	742	1.76	7.3	7.7	45.1	59.8	14.7	1.3	0.06	0.13	0.36	1.00	0.64	2.77
2.37	255	686	2.69	4.7	7.8	22.5	56.7	34.2	2.5	0.04	0.13	0.18	0.94	0.76	5.25
2.37	261	597	2.28	4.8	6.8	22.4	57.7	35.3	2.6	0.04	0.11	0.18	0.96	0.78	5.38
2.21	317	588	1.85	5.8	6.7	21.4	53.3	32.0	2.5	0.05	0.11	0.17	0.89	0.72	5.21
2.21	286	599	2.10	5.3	6.8	21.9	53.2	31.3	2.4	0.04	0.11	0.18	0.89	0.71	5.06
0.52	288	233	0.81	6.8	3.6	26.7	14.0	-12.8	0.5	0.05	0.06	0.21	0.23	0.02	1.09
0.52	296	230	0.78	7.0	3.6	26.5	14.0	-12.5	0.5	0.06	0.06	0.21	0.23	0.02	1.10
0.58	281	209	0.74	6.8	3.3	23.6	14.2	-9.3	0.6	0.05	0.06	0.19	0.24	0.05	1.26
0.58	274	206	0.75	6.6	3.3	23.8	14.3	-9.5	0.6	0.05	0.06	0.19	0.24	0.05	1.25
0.54	204	178	0.87	6.5	3.4	20.7	11.2	-9.5	0.5	0.05	0.06	0.17	0.19	0.02	1.12
0.54	185	170	0.92	5.9	3.2	21.3	11.3	-10.0	0.5	0.05	0.05	0.17	0.19	0.02	1.11
1.79	**316**	**692**	**1.97**	**6.0**	**8.2**	**34.9**	**72.2**	**30.4**	**1.87**	**0.05**	**0.14**	**0.28**	**1.20**	**0.71**	**3.90**

Position	aSOTE (ASP)	aSOTE (IFAS)	aSOTE (IFAS/ASP)	OUR (ASP)	OUR (IFAS)	OUR (IFAS/ASP)	Air Flux (ASP)	Air Flux (IFAS)	Air Flux (IFAS/ASP)	Air Use (ASP)	Air Use (IFAS)	Air Use (IFAS/ASP)	Air Use (ASP)	Air Use (IFAS)
	(%)	(%)	-	mg/l/hr	mg/l/hr	-	SCFM/ft2	SCFM/ft2	-	SCF/lbCODrem	SCF/lbCODrem	-	SCF/lbLOAD	SCF/lbLOAD
1	10.0	18.9	1.90	41.1	130.1	3.17	0.44	1.25	2.82	15.6	44.3	2.83	14.1	39.2
1	11.3	18.8	1.66	46.8	129.6	2.77	0.44	1.25	2.82	15.6	44.3	2.83	14.1	39.2
2	14.4	15.5	1.07	79.7	106.6	1.34	0.60	1.25	2.10	21.0	44.3	2.11	18.9	39.2
2	14.8	12.3	0.83	81.8	118.9	1.45	0.60	1.76	2.95	21.0	62.2	2.97	18.9	55.0
3	11.8	13.9	1.18	49.6	133.7	2.69	0.46	1.76	3.84	16.1	62.2	3.87	14.5	55.0
3	12.4	10.2	0.82	52.4	124.0	2.37	0.46	1.55	3.40	16.1	55.1	3.42	14.5	48.7
4	15.9	9.9	0.62	63.3	120.2	1.90	0.46	1.55	3.40	16.1	55.1	3.42	14.5	48.7
4	15.6	7.3	0.47	62.1	90.8	1.46	0.46	1.59	3.48	16.1	56.4	3.51	14.5	49.8
5	15.6	8.1	0.52	64.4	100.5	1.56	0.55	1.59	2.92	19.2	56.4	2.94	17.3	49.8
5	16.0	10.8	0.68	66.0	--	--	0.55	--	--	19.2	--	--	17.3	--
6	15.2	11.1	0.73	59.9	--	--	0.52	--	--	18.3	--	--	16.5	--
6	16.8	21.0	1.25	66.3	--	--	0.52	--	--	18.3	--	--	16.5	--
7	21.3	20.0	0.94	27.8	--	--	0.28	--	--	9.8	--	--	8.8	--
7	20.6	24.8	1.21	26.8	27.3	1.02	0.28	0.26	0.95	9.8	9.4	0.95	8.8	8.3
8	19.3	26.3	1.37	25.9	29.0	1.12	0.28	0.26	0.94	9.9	9.4	0.95	8.9	8.3
8	17.8	28.2	1.58	24.0	28.0	1.17	0.28	0.28	1.01	9.9	10.0	1.02	8.9	8.9
9	13.2	27.7	2.10	16.0	27.5	1.72	0.29	0.28	0.97	10.2	10.0	0.98	9.2	8.9
9	19.9	28.0	1.41	21.2	17.4	0.82	0.36	0.30	0.82	12.8	10.6	0.83	11.5	9.4
Flow Weighted Average*	**15.3**	**13.8**	**0.68**	**53.5**	**108.5**	**1.26**	**0.5**	**1.42**	**1.85**	**16.3**	**50.1**	**1.86**	**14.6**	**44.3**

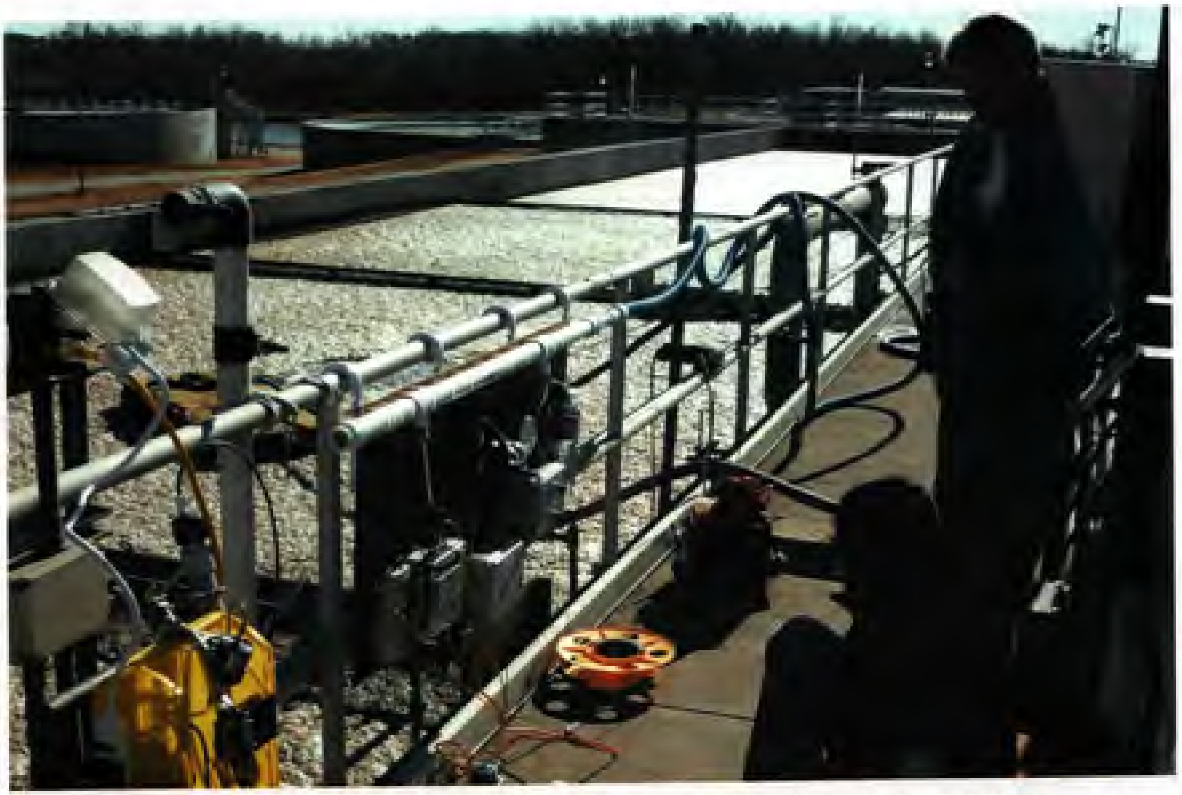
*missing data excluded from weighted averages

Air Use (IFAS/ASP)	OTR (ASP)	OTR (IFAS)	OTR (IFAS/ASP)	Air Use OT (ASP)	Air Use OT (IFAS)	Air Use MIX (ASP)	Air Use MIX (IFAS)	Net Air Use MIX (IFAS-ASP)	Air Use MIX (IFAS/ASP)	AFR OT (ASP)	AFR OT (IFAS)	AFR MIX (ASP)	AFR MIX (IFAS)	Net AFR MIX (IFAS)	AFR MIX (IFAS/ASP)
-	lbO2/hr	lbO2/hr	-	SCF/lbLOAD	SCF/lbLOAD	SCF/lbLOAD	SCF/lbLOAD	SCF/lbLOAD	*(Per unit load)*	SCFM/ft2	SCFM/ft2	SCFM/ft2	SCFM/ft2	SCFM/ft2	*(Flux)*
2.79	355	1126	3.17	1.4	7.4	12.7	31.8	19.1	2.5	0.04	0.24	0.40	1.02	0.62	2.54
2.79	405	1122	2.77	1.6	7.4	12.5	31.8	19.3	2.6	0.05	0.24	0.39	1.02	0.62	2.58
2.08	690	922	1.34	2.7	6.1	16.1	33.1	17.0	2.1	0.09	0.19	0.51	1.06	0.55	2.07
2.92	707	1028	1.45	2.8	6.8	16.1	48.2	32.1	3.0	0.09	0.22	0.51	1.54	1.03	3.03
3.80	430	1157	2.69	1.7	7.6	12.8	47.4	34.6	3.7	0.05	0.24	0.40	1.51	1.11	3.75
3.36	453	1073	2.37	1.8	5.0	12.7	43.7	31.0	3.4	0.06	0.16	0.40	1.40	1.00	3.49
3.36	548	1040	1.90	2.3	4.8	12.2	43.9	31.7	3.6	0.07	0.15	0.38	1.40	1.02	3.64
3.45	537	785	1.46	2.3	3.6	12.2	46.2	34.0	3.8	0.07	0.12	0.39	1.48	1.09	3.83
2.89	558	870	1.56	2.7	4.0	14.6	45.8	31.3	3.1	0.09	0.13	0.46	1.46	1.00	3.18
--	571	--	--	2.8	--	14.5	--	--	--	0.09	--	0.46	--	--	--
--	519	--	--	2.5	--	14.0	--	--	--	0.08	--	0.44	--	--	--
--	574	--	--	2.8	--	13.7	--	--	--	0.09	--	0.43	--	--	--
--	241	--	--	1.9	--	6.9	--	--	--	0.06	--	0.22	--	--	--
0.94	232	236	1.02	1.8	2.1	7.0	6.2	-0.8	0.9	0.06	0.07	0.22	0.20	-0.02	0.90
0.93	224	251	1.12	1.7	2.2	7.2	6.1	-1.1	0.9	0.05	0.07	0.23	0.20	-0.03	0.86
1.00	207	242	1.17	1.6	2.5	7.3	6.4	-0.9	0.9	0.05	0.08	0.23	0.20	-0.03	0.88
0.96	138	238	1.72	1.2	2.5	8.0	6.4	-1.6	0.8	0.04	0.08	0.25	0.20	-0.05	0.81
0.81	184	151	0.82	2.3	2.6	9.2	6.7	-2.5	0.7	0.07	0.08	0.29	0.22	-0.08	0.74
1.83	**462**	**939**	**1.26**	**2.2**	**5.5**	**12.4**	**38.8**	**16.0**	**1.85**	**0.07**	**0.18**	**0.39**	**1.24**	**0.20**	**1.87**

APPENDIX B

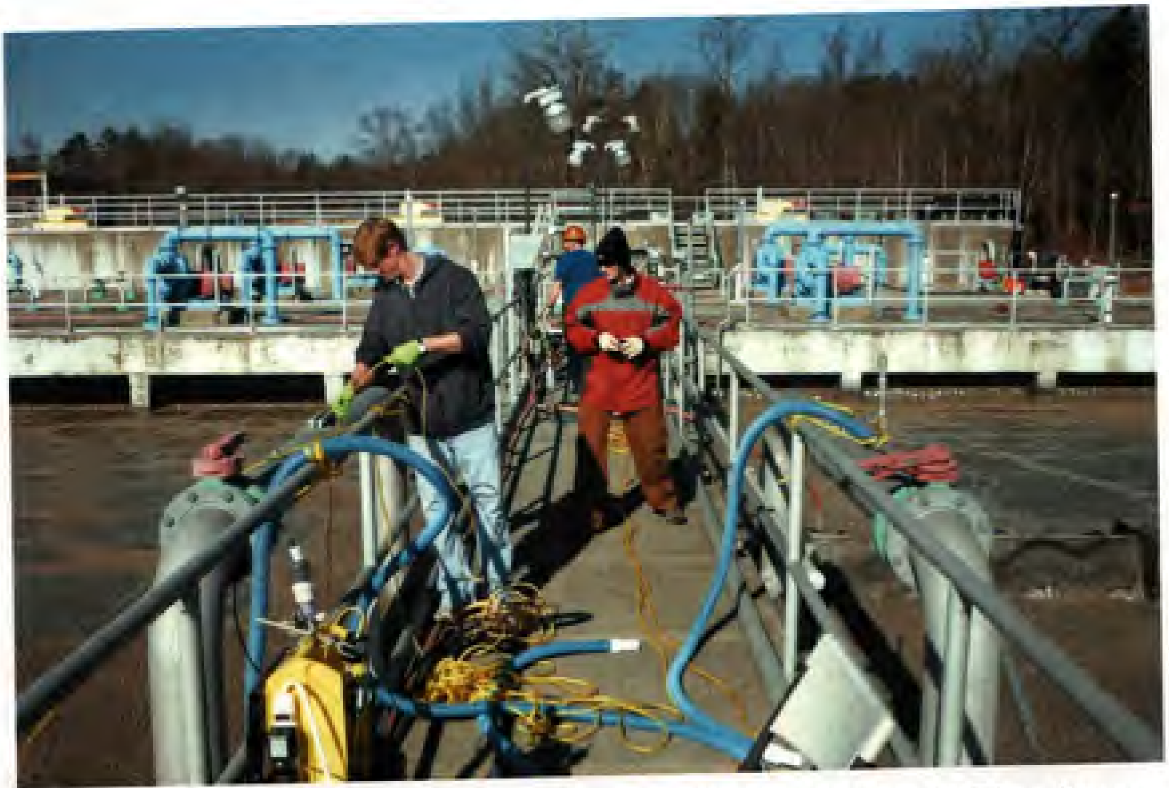
Photograph 1. IFAS (left) and ASP (right) during testing (January). Photograph taken by the author.

Photograph 2. Off-gas hood floating on the ASP Tank 11 during testing (January). Photograph taken by the author.



Photograph 3. The author and Mike Adcock during testing. Note the two off-gas analyzers: yellow used for this test, and the board-mounted analyzer built by TZO Staff (January). Photograph taken by Diego Rosso.

Photographs 4a,b. Details of Dr. Rosso's analyzer (left) and TZO's analyzer (right). Photographs taken by the author.



Photograph 5. The team during testing (January). Photograph taken by Diego Rosso.

Photograph 6. The team during testing (January). Photograph taken by Diego Rosso.

Photograph 7. During testing (June). Photograph taken by Diego Rosso.

Photograph 8. Dr. Rosso's off-gas analyzer during the testing. Photograph taken by Diego Rosso.

Photograph 9. The author during June testing. Photograph taken by Diego Rosso.

Photograph 10. Detail of IFAS media in Reactor 1 of Tank 12. Photograph taken by Diego Rosso.