A COMPARATIVE ANALYSIS OF A BIOMIX SYSTEM AND A SUBMERSIBLE PROPELLER MIXER

Mixing in Anaerobic Zones at the F. Wayne Hill Water Resources Center Buford, Georgia

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1. Abstract

Bio^{M}x is a patented technology for mixing wastewater by releasing bursts of compressed air at the bottom of the water column at specific times and locations in anaerobic, anoxic and aerated treatment zones. Mixing in anaerobic and anoxic zones with no significant oxygen transfer is a critical step in meeting biological nutrient removal standards. This paper documents the results of testing performed at the F. Wayne Hill Water Resource Center (60 MGD), Gwinnett County Department of Public Utilities, in Buford, GA to compare mixing effectiveness, compatibility with anaerobic and anoxic environments, and electrical power requirements of Bio^{M}x and a conventional submersible propeller mixer.

Results of side-by-side comparisons of BioMx with submersible propeller mixers established that:

- *BioMx is effective in mixing wastewater to industry standards based on measured suspended solids and dye distributions.*
- *BioMx is fully compatible with anaerobic and anoxic environments based on measured Oxidation Reduction Potential. Reactors that maintain those environments are key treatment process components used to meet EPA and state-level nutrient removal limits.*
- *BioMx provides substantial power savings compared to submersible propeller mixers based on measured horsepower per volume of liquid mixed (0.097 vs. 0.243 hp/1000cf).*

An analysis of documented energy savings and projected savings in maintenance costs for the BioMx system as compared to submersible propeller mixers provides a solid basis for expected rapid return of capital and a payback period far shorter than the 10 year industry benchmark.

2. Introduction

Municipal wastewater treatment methodologies have evolved as our understanding of biological treatments to control wastewater chemistry has expanded. The accumulation of phosphorus and nitrogen in confined watersheds often results in eutrophication or algae growth in receiving water bodies and has increased the need for biological nutrient removal in wastewater treatment facilities that discharge into them. As an alternative to chemical treatment, biological phosphorus removal processes have been developed, such as the modified Bardenpho process utilized at the F. Wayne Hill Water Resource Center. Amounts of phosphorus removed by standard secondary wastewater treatment methods may range from 10 to 30 percent of the influent amount. However, by using a biological phosphorus removal process, removal much in excess of this range may be attained.

One key to biological phosphorus removal (BPR) in the activated sludge process is the initial exposure of the biomass to an anaerobic environment. This anaerobic step conditions the biomass to store phosphorus in excess of the amount needed for required cell maintenance, synthesis, and energy transport in the aerated portion of the process. Biomass containing the excess phosphorus is typically wasted for a net reduction. Anaerobic conditions require the absence of or a very minimal amount of dissolved oxygen, nitrates, and nitrites. Thus, mixing in anaerobic conditions must not introduce a significant amount of dissolved oxygen or the efficiency of the BPR process will be reduced.

Introducing oxygen by means of aeration was the traditional method of wastewater treatment because the bacterial populations in the wastewater utilizing oxygen were effective at consuming the organic material of the wastewater in short time periods. The high dissolved oxygen concentrations also reduced the levels of ammonia in the wastewater, which can be a fish toxin and algal fertilizer, by oxidizing them to nitrites and then nitrates. However, it soon became evident that the nitrates created also were an algal fertilizer. Denitrification to convert the nitrates created in the system to nitrogen gas became desirable for most watersheds. The cycling of nitrate-rich flows into anoxic environments for denitrification has become customary in wastewater treatment plant design.

Anoxic zones promote denitrification by combining organic material, the microbiological suspension, and the nitrates, without free oxygen present. The bacteria use the nitrate as an electron acceptor during the consumption of organic material. The result is the reduction of nitrate to nitrogen gas and the growth of the bacterial population. When oxygen is present, it is the preferred electron acceptor for the microbes, so exclusion of oxygen is critical to the removal of nitrate. Dissolved oxygen concentrations less than 0.3 mg/L are considered sufficient to promote denitrification in activated sludge mixed liquor because at that concentration much of the internal parts of the flocs will be anoxic or anaerobic under typical organic loading conditions. Proper mixing in an anoxic zone permits contact of the microbial population with the carbon and nitrate to accomplish the denitrification reactions.

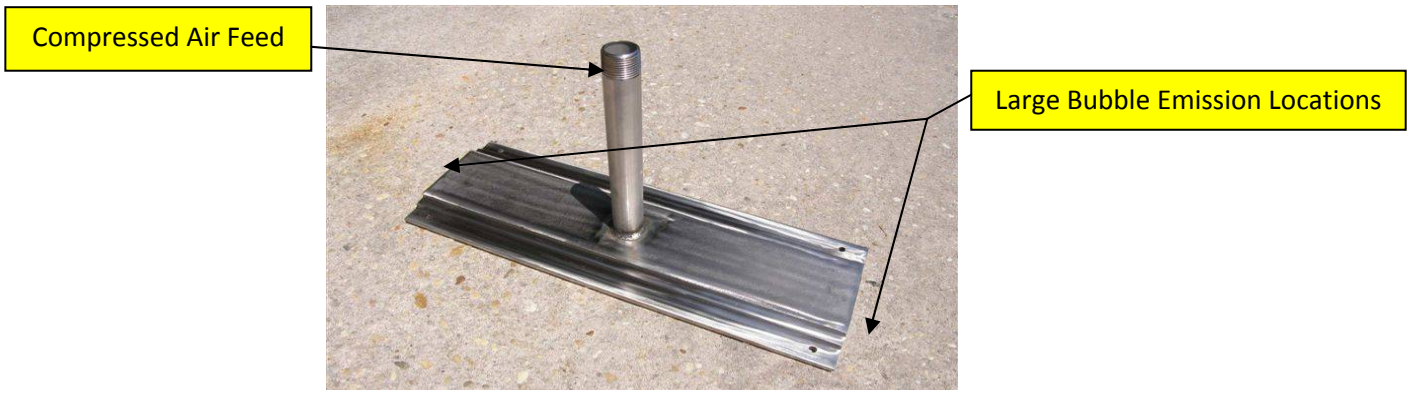
Effective mixing in anaerobic and anoxic zones is often accomplished with propeller mixers, either submersible rail-mounted or top-mounted, which operate continuously. **The power cost has often been viewed as a necessary consequence of the mixing requirements for anaerobic/anoxic zones, but these mixers experience disproportionately high levels of maintenance, relative to their role in the plant.**

This is primarily due to their continuous operation, often at high rpm with a submerged motor, in an early stage of the treatment process. The submergence of the motor with the equipment also makes maintenance events more problematic for the operators.

The proposed use of the intermittent release of compressed air (see Figure 1a) to generate mixing in anaerobic and anoxic environments has been met with concerns regarding the potential for introducing oxygen into the liquid. Oxygen transfer is determined by air-water surface interactions between the rising bubbles and the surrounding water. The surface area of the bubbles is significantly increased when the bubbles are smaller and more numerous for the same amount of air, so the use of uniquely-designed nozzles (see Figure 1b) to create large-diameter bubbles renders the oxygen transfer relative to mixing insignificant. The air bubbles made by Bio^{M}x nozzles range from marble to softball size; significantly larger than coarse bubble diffusers. Additionally, the more rapid rise of the large bubbles further reduces the oxygen transfer. **The use of large air bubbles with negligible oxygen transfer offers effective mixing with greatly reduced energy consumption as well as significantly reduced and simpler maintenance when compared to continuously operating submersed propeller mixers.**

Figure 1a – Animation - Large Bubble Mixing in Wastewater Treatment Basin

Figure 1b – Bio^{M}x Stainless Steel Nozzle



3. Mixing Study

This study evaluated the performance of the Bio^{M}x System compared to a submersible propeller mixer installed and operated in two anaerobic zones/cells of an operating wastewater treatment facility. The two mixing systems were installed, as shown in Figures 2a, 2b, 2c, and 2d, into the same anaerobic cells of a treatment train at the F. Wayne Hill Water Resources Center in Buford, Georgia (60 MGD, operating at approximately 30 MGD). Both mixing systems were installed as per manufacturer's recommendations. The first cell in the basin, A1, receives combined influent and recycle flows after primary clarification, as well as the return activated sludge (RAS) flow from the secondary clarifiers. The second anaerobic cell, A2, receives only the flow from A1 and discharges to the next cell, B1, downstream in the basin.

Figure 2a – Basin 10, Cells A1 & A2

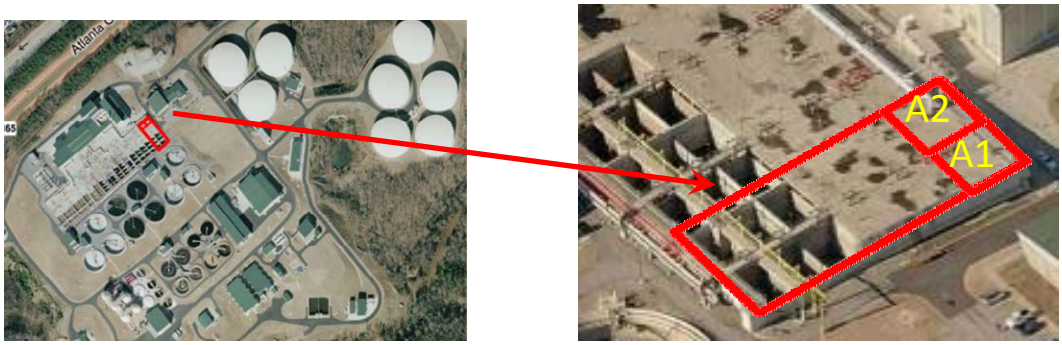
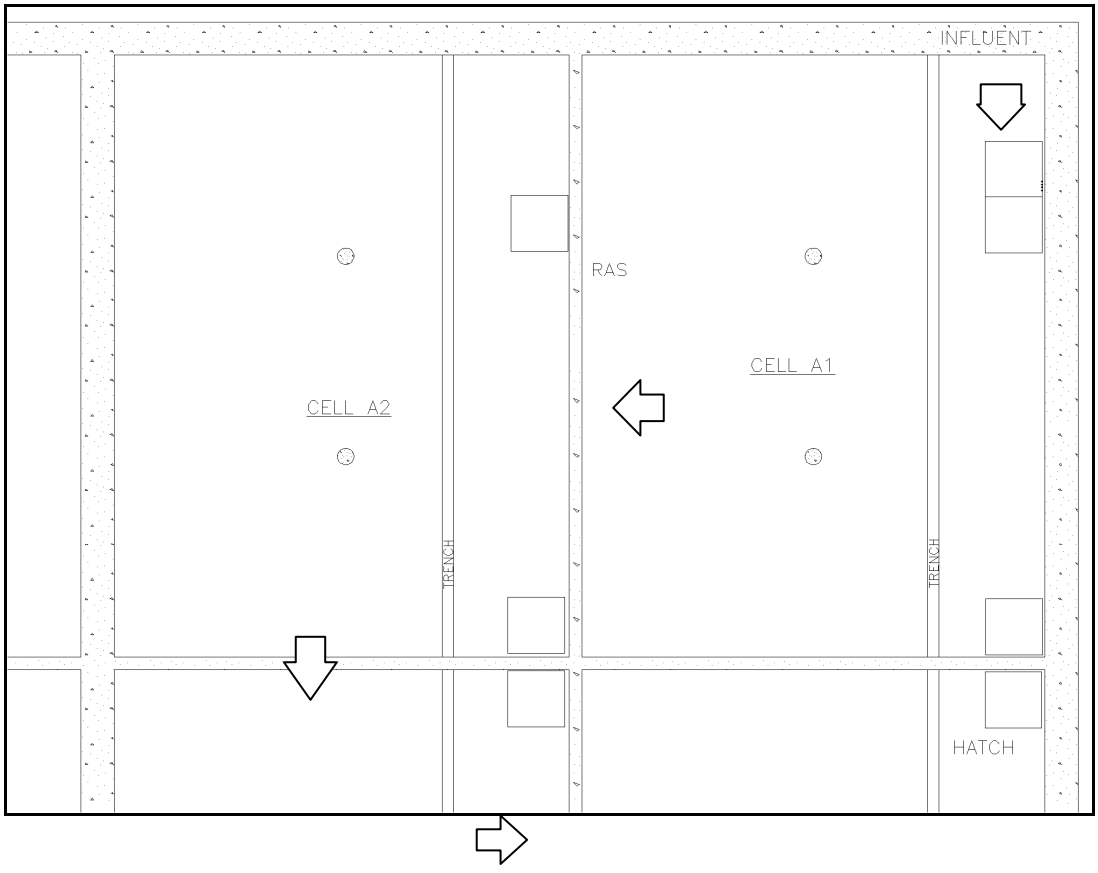


Figure 2b – Bio^{M}x Installation, Tank A1 (Dewatered) Partial View

Figure 2c – Bio^{M}x and Submersible Mixing Installation, Tank A2 (1' Water Level) Partial View

Figure 2d – Cells A1 & A2, RAS and Influent Flow



3.1 Test Area

The cells each measure 55 feet in width and 41 feet in length along the flow path, with an operating depth of 24 feet. A baffle wall with a height of 22 feet separates the two cells. In addition to flow over the baffle wall, there are openings along the floor that pass flow. The arrangement of the tanks is shown in Figure 2d. The influent weir gate is in the corner of cell A1, while the RAS flow enters the cell near the baffle wall as located in Figure 2d, through a pipe entering the head space above the water surface level and terminating 4' above side water depth. This drops the RAS flow into the cell, potentially entraining oxygen. Baffle walls also allow backflow from the swing zone downstream of the second anaerobic zone to come across the top of the two baffle walls at the corner where the anaerobic and swing cells meet. Since the swing cells were aerated during the mixing test, the higher water surface resulted in aerated backflow into the two anaerobic cells. The anaerobic and swing cells are also covered, with the only access through the hatches shown in Figure 2d. The volume of each anaerobic zone with the mixers is:

$$Tank\ Volume: \quad 55' x\ 41' x\ 24' = 54{,}120\ cu.ft.\ x\ 7.48 \frac{gal}{cu.ft.} = 404{,}818\ gallons$$

3.2 Evaluation Criteria

The performance of the two mixers was evaluated based on their abilities to:

- Sustain the suspended solids in the tank uniformly in the anaerobic volume
- Mix a tracer for a complete mix of the anaerobic volume
- Maintain acceptable Dissolved Oxygen (DO) concentrations and Oxidation Reduction Potential (ORP) values in the anaerobic cells*
- Limit power consumption

*Any discussion of modern wastewater treatment methods will include references to the need to provide mixing in anaerobic and anoxic zones. Maintaining acceptable DO levels and ORP values in these zones is crucial to successful treatment. **However, the standards for these levels in anaerobic zones are more difficult to reach and maintain than in anoxic zones, meaning that successful performance in an anaerobic environment automatically translates into successful performance in an anoxic environment.**

3.3 Rhodamine Dye Tracer Study

Dye was introduced into cell A-1 (0.405 MG) to compare the mixing resulting from the two systems. Rhodamine WT dye (approximately 20%) was introduced into the flow channel prior to the control gate entering the first anaerobic zone. A liter of dye was delivered into the channel in a single pulse. Data were collected from two points in the cell to follow the tracer concentration: the first point of collection was along the exit weir entering the next anaerobic zone by use of a probe recording at 30 second

intervals; the second point was by sample tube withdrawing samples from 12 feet below the surface near the center of the cell. A reciprocating pump was used to continuously draw from the mid-cell location, with samples collected at one minute intervals initially, then at increasing intervals as the test proceeded. Analysis of the grab samples was on stirred samples (not settled or filtered) to be comparable to the probe readings with interference from the solids of the cell.

The flows through the cell have an impact on the total mixing in the cell. Since dye testing had to be performed for the Bio^{M}x system and the submersible mixer separately, analysis of the hydraulic flows for the two testing periods was performed. Flow entering the anaerobic zone is not metered directly, but the recycle and influent flows prior to the dividing channel are metered. The RAS flow entering the zone near the exit baffle wall is metered, also. RAS flow is the only flow that is metered for an individual treatment train. A summary of the total flows recorded during the tracer study are in Table 1. These flows were calculated from the collection system and plant metered flows, and then assumed to divide equally between the four operating trains at the plant.

Table 1. Flows During Test Periods

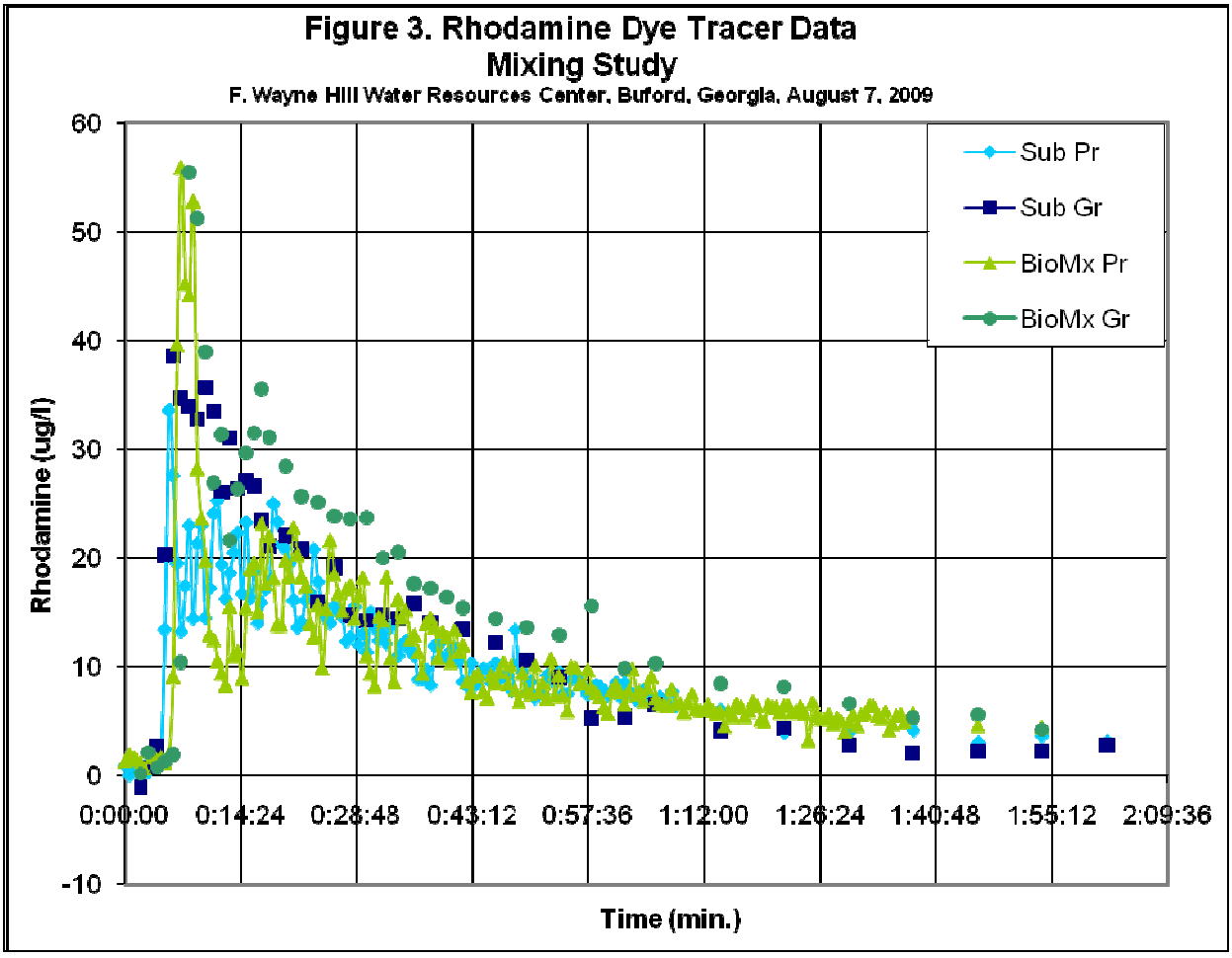
	Submersible Mixing Test Flows, MGD	Bio^{M}x Mixing Test Flows, MGD
Maximum	17.82	15.39
Average (Mean)	14.32	13.07
Median	13.79	13.35
Minimum	10.78	9.94
Standard Deviation	2.05	1.61
Count	24	21
Coefficient of Variation	14.3%	12.3%

The flows for the testing periods were statistically compared, and the variances cannot be differentiated at a 0.05 level of significance (α=0.05), but the means for the two periods were statistically different for the same level of significance. The average values for these periods were used to calculate the theoretical hydraulic detention time (t = V/Q) for the testing periods, as shown in Table 2. This value is used in the following analysis of the tracer study.

Table 2. Hydraulic Detention Times for the Test Periods

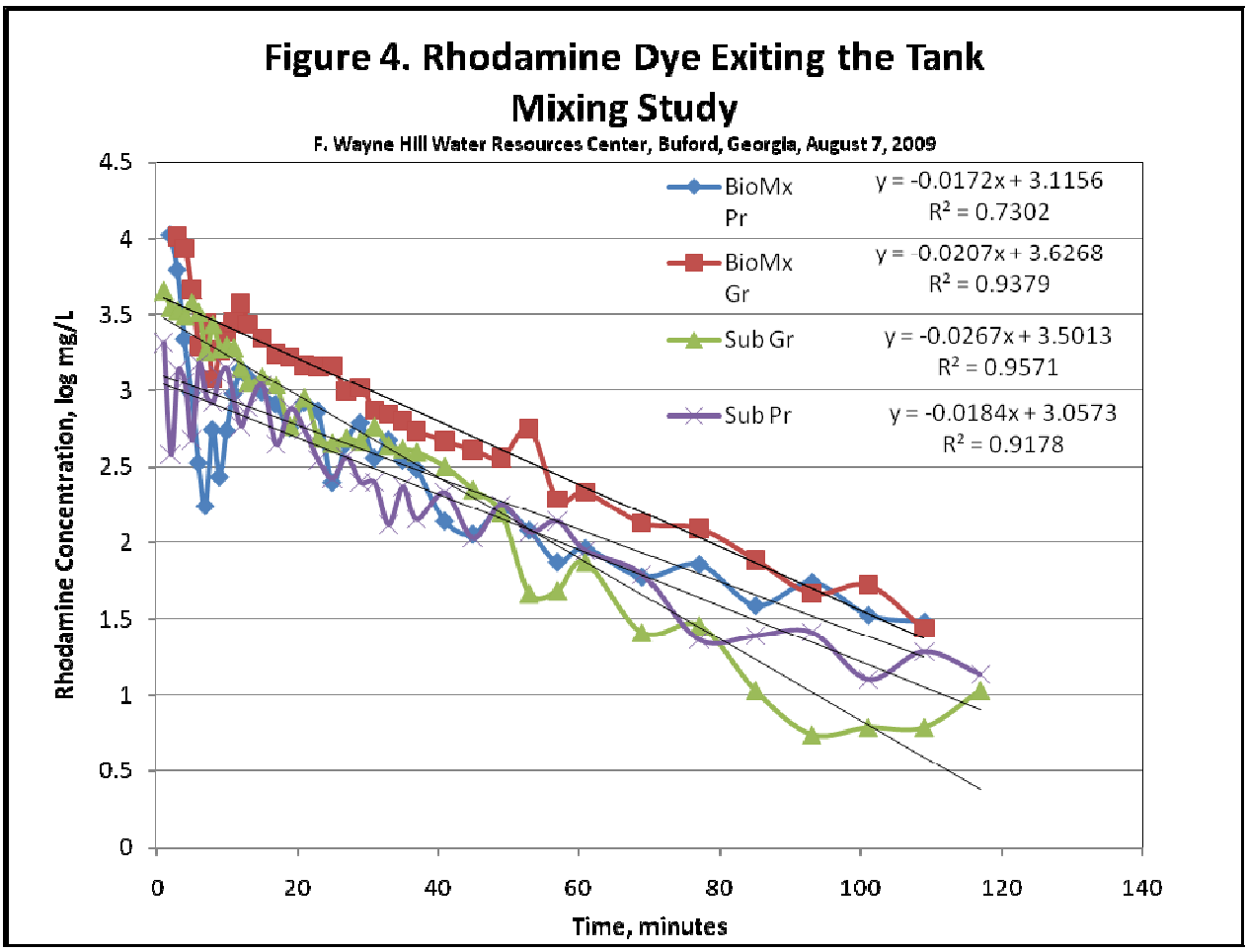
	Submersible Mixing Test	**Bio^{M}x Mixing Test**
Average Flow (Q), MGD	14.32	13.07
Tank Volume (V), MG	0.405	0.405
Hydraulic Retention Time, t (t=V/Q)	40.7 minutes	44.6 minutes

The data from the tracer study mixing periods were compared by several methods. The raw data are shown in Figure 3 for the four sets of collected data (*i.e.* the probe data at the exit of the tank and the grab samples from the middle of the tank with only the submersible mixer running, and the same data with only the Bio^{M}x running). The raw data show a similarity in pattern with an initial peak followed by the dilution of the dye with continued flow.



BioMx Pr – Bio^{M}x Unit Mixing, Probe Data; Gr – Grab Samples
Sub Pr – Submersible Propeller Unit Mixing, Probe Data; Gr – Grab Samples

For a perfect complete-mixed stirred tank reactor, the rate of dilution for the dye should follow a log-decay pattern, with the slope of the concentration decay being the negative reciprocal of the hydraulic detention time of the cell. Figure 4 shows the decay of the introduced dye for the measures taken as a log-concentration vs. time. The slopes of the lines and the resulting estimated hydraulic detention times are shown in Table 3. The estimated hydraulic detention times are compared with the flow-based times from Table 2 in the last column of Table 3. **The numbers suggest that the submersible mixer and the Bio^{M}x unit perform similarly in their mixing of the cell.**

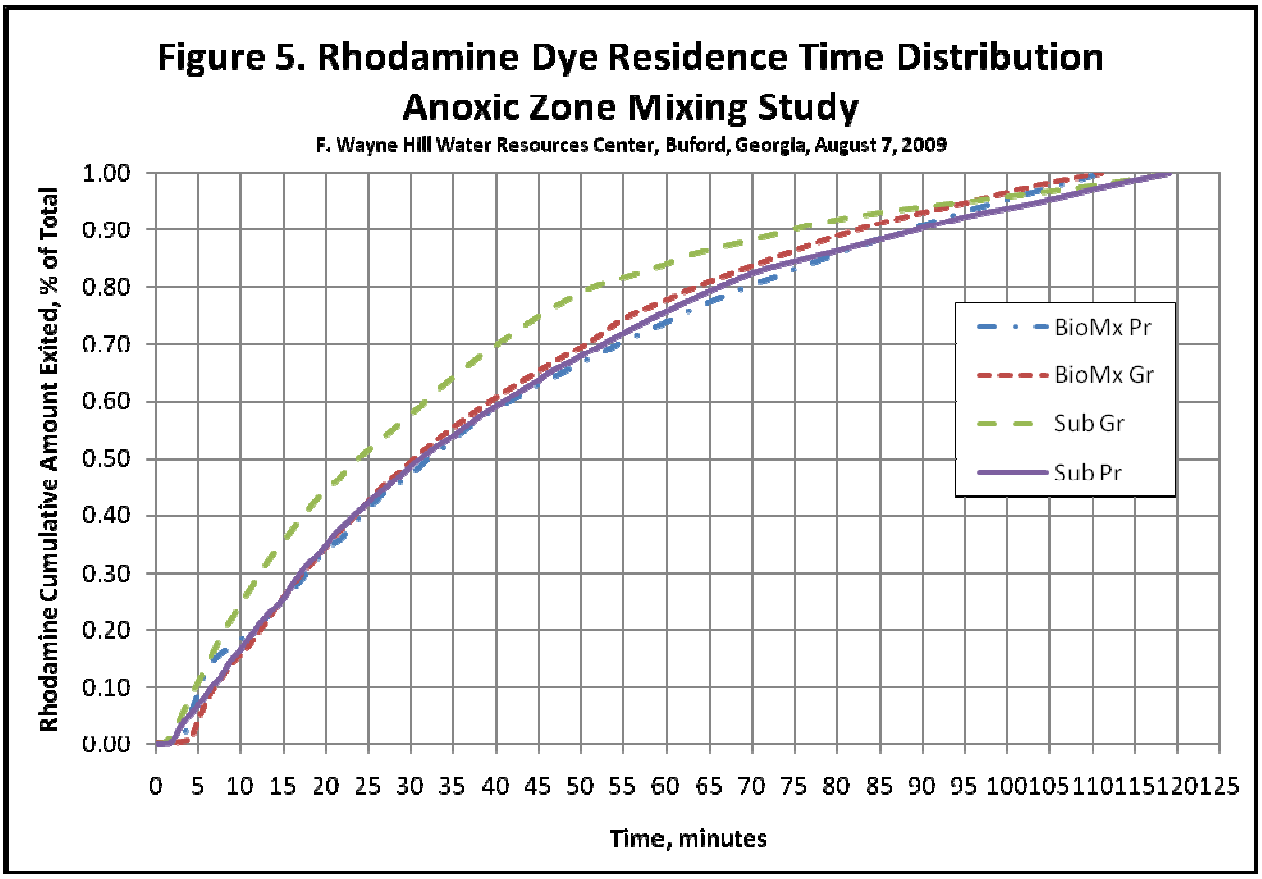


BioMx Pr – Bio^{M}x Unit Mixing, Probe Data; Gr – Grab Samples
Sub Pr – Submersible Propeller Unit Mixing, Probe Data; Gr – Grab Samples

Table 3. Retention Times: Decay-derived (τ) Compared to Flow-Derived (t)

Samples	Slope (Figure 4)	Retention Time, minutes		Change t to τ
		τ (-1/Slope)	t (from Table 2)	
Bio^{M}x Probe	-0.0172	61	45	+36%
Bio^{M}x Grab	-0.0207	48	45	+8%
Submersible Mixer Probe	-0.0184	54	41	+34%
Submersible Mixer Grab	-0.0267	37	41	-8%

For an additional analysis of the tracer data, the mean time of residence for the dye was calculated utilizing a Residence Time Distribution graph. (The calculations are presented in various texts and may be investigated there, e.g., Wastewater Engineering: Treatment and Reuse, Tchobanoglous, Burton, and Stensel, 4th Edition, McGraw Hill.) Representative results of this analysis are shown in Figure 5 and Table 4. **The results for the two mixing systems are similar, and the dispersion values and the mean residence time values suggest both mixers equally mix the hydraulic contents of the tank.**



BioMx Pr – Bio^{M}x Unit Mixing, Probe Data; Gr – Grab Samples
Sub Pr – Submersible Propeller Unit Mixing, Probe Data; Gr – Grab Samples

Table 4. Dye Study Residence Time Distribution Summary Numbers

	t', minutes mean residence time	Percentile Values, minutes			MDI[a]	t'/t[b]
		P_{10}	P_{50}	P_{90}		
Bio^{M}x Probe	40.3	5	32	90	18	90%
Bio^{M}x Grab	39.6	7	31	82	12	89%
Submersible Probe	40.5	7	32	90	13	100%
Submersible Grab	33.5	5	24	75	15	82%

[a] MDI is the Morrill Dispersion Index, a measure of dispersion. Theoretically a value of 1 would be a perfect plug-flow, and about 22 for a complete-mix reactor. Calculated by the 90 percentile value divided by the 10 percentile value.

[b] The mean residence time of the dye divided by the theoretical hydraulic detention time provides another measure of the ability of the mixing in the tank to achieve complete mixing.

The results of the tracer study conducted at the F. Wayne Hill Water Resources Center presented in Figures 4 and 5 and in Tables 3 and 4, show no meaningful difference in the mixing observed when the submersible mixer is operating compared to the Bio^{M}x unit.

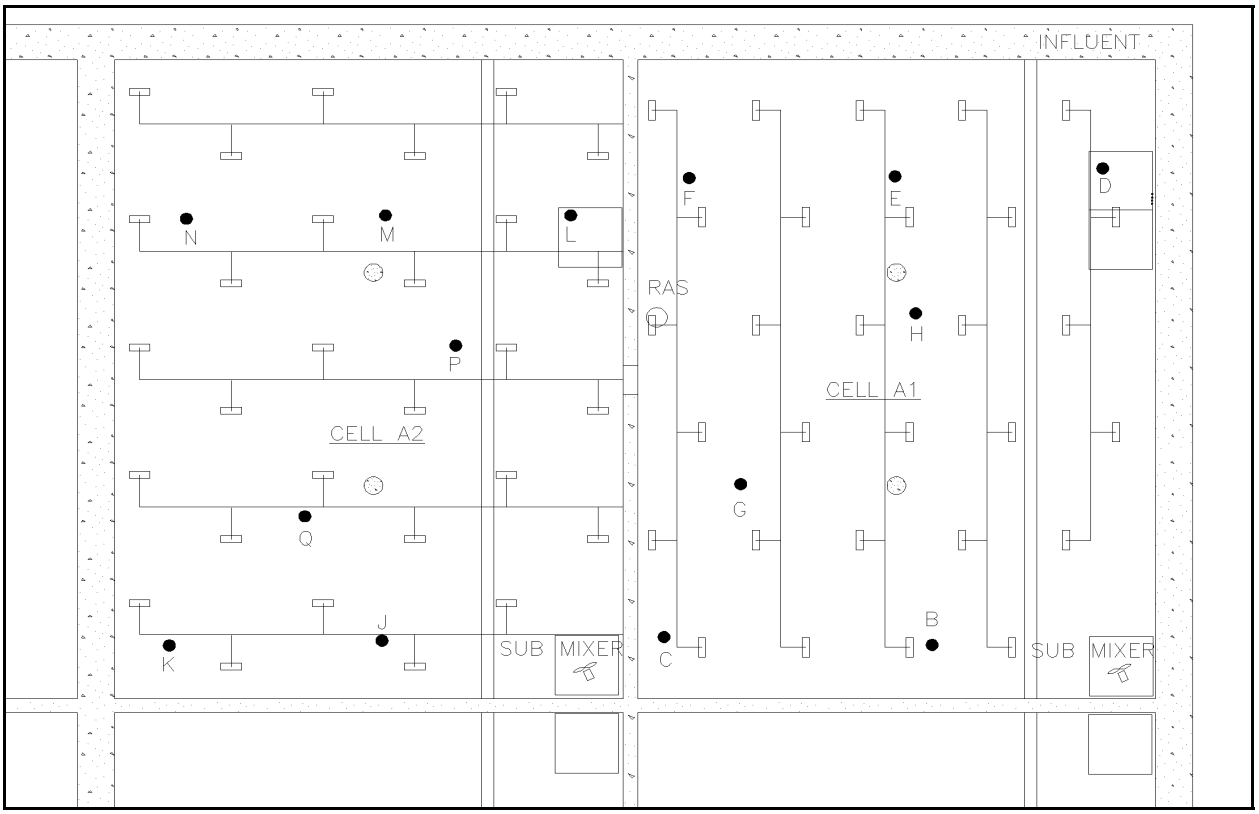
3.4 Total Suspended Solids Testing

Testing of both installed mixing systems was initiated with Total Suspended Solids (TSS) data collection. Ropes were positioned across the cell to deliver weighted sampling tubes to different locations (A-H) in cell A1 and (J-Q) in cell A2. Each location was sampled by an apparatus suspending tubes extending to three depths, approximately 2 feet below the water surface level, mid-depth at 12 feet below the surface, and 2 feet above the floor. Samples were drawn from the tubes with a diaphragm pump. Approximately one half gallon of sample was purged before sample collection. A diagram showing the locations in the cells is shown in Figure 6.

Note: The test apparatus at Location A became entangled in the submersible mixer and was destroyed at startup. Fibrous material attached to the propellers is the suspected cause. As a result, 21 locations in each cell were tested rather than the 24 planned locations.

Samples were collected in the anaerobic cells over four consecutive days with laboratory analysis for TSS performed by a commercial lab, Analytical Services, Inc., Norcross, GA. Each day, two rounds of sampling were performed; once in the late morning and once in the afternoon. This sampling time window was chosen due to the historically constant flow rates at the plant on any given day. Samples were preserved on ice and delivered to the lab at the end of each day.

Figure 6. Sampling Locations for TSS Samples



3.4.1 Total Suspended Solids Data

The collected data are presented in Appendix 1. The TSS varied widely for sample days. The average values for the cells ranged from 2351 mg/L to 5053 mg/L, requiring that day-to-day comparisons be normalized on the average suspended solids for the cells. This allowed compilation of the data, and is the basis for much of the following analysis.

The overall concentrations do not tell the entire story, however, as the incoming flows entering Cell A1 strongly influenced the D1 samples. This point, near the gate where the incoming flow enters, resulted in samples that had considerably lower concentrations than the adjacent samples, both in the water column (D2 and D3) and laterally (E1 and H1). Based on these observations, the layout of the sampling, and cursory analysis, the D1 data were omitted from analyses attempting to represent the basin contents.

The RAS flow entering in cell A1, along with the influent flow, presents a significant challenge for any mixing system attempting to homogenize the character of the cell contents. Figure 2d shows the close proximity of the RAS feed point to the cell effluent at the far end from the influent flow. As such, the variability of TSS concentration data for Cell A1 should be viewed as a 'stress test' of mixing capability while cell A2 presents fewer challenges and is a more normal operating condition for mixing performance evaluation.

Data are presented in Appendices 2 and 3 showing the TSS results from cells A1 and A2. Table 5 summarizes the data from both appendices and illustrates the greater variability expected for Cell A1. Cell A2 received the flow from Cell A1 and had no other influent flow from other sources and, therefore, would be expected to reflect the better mixing results shown in Table 5 if the mixing energy proved adequate.

Table 5 – Summary of Raw Mixing Data for Cells A1 and A2

	1/26/10 AM	1/26/10 PM	1/27/10 AM	1/27/10 PM	1/28/10 AM	1/28/10 PM	1/29/10 AM	1/29/10 PM
Cell A1	**Submersible Mixer**				**Bio^{M}x**			
Ave, mg/L	4309	3269	2796	3187	2380	2663	3134	3290
StdDev	264	305	255	344	265	297	334	324
CV	6%	9%	9%	11%	11%	11%	11%	10%
Cell A2	**Submersible Mixer**				**Bio^{M}x**			
Ave, mg/L	5053	4343	3281	3883	3631	4107	4663	4705
StdDev	107	219	96	135	187	231	60	165
CV	2%	5%	3%	3%	5%	6%	1%	3%

To make comparisons between the daily TSS concentrations, values were divided by the average value for the cell samples of that day (See Table 5 & Appendix 1). These normalized values are presented in Table 6. The difference in the mixing patterns within the cells is seen by the comparison of the lowest and highest values for each mixing system, which are shaded in the table.

Table 6 - Normalized TSS Data

	Submersible Mixer				**Bio^{M}x**			
Cell A1	26-Jan	26-Jan	27-Jan	27-Jan	28-Jan	28-Jan	29-Jan	29-Jan
B1	1.14	0.93	0.91	1.05	0.89	0.86	0.86	0.84
B2	1.04	1.08	1.11	1.10	0.91	0.90	0.92	0.93
B3	1.03	1.00	0.88	0.93	0.90	0.86	0.87	0.91
C1	1.03	1.29	1.16	1.21	0.89	0.90	0.86	0.91
C2	1.10	1.14	1.16	1.16	0.85	0.89	0.85	0.87
C3	1.07	0.91	1.13	1.09	0.86	0.91	0.86	0.87
D1	Deleted	Deleted	Deleted	Deleted	Deleted	Deleted	Deleted	Deleted
D2	0.94	0.94	0.94	0.93	0.95	0.98	1.05	1.01
D3	0.98	0.93	0.90	0.88	1.04	1.08	1.08	1.06
E1	0.93	0.93	0.94	0.90	1.04	1.07	1.07	1.04
E2	0.98	0.95	0.96	0.89	1.04	1.04	1.07	1.04
E3	0.97	0.92	0.89	0.90	1.11	1.07	1.12	1.08
F1	0.95	0.97	0.95	0.93	1.23	1.20	1.06	1.09
F2	0.94	1.02	1.01	0.94	1.01	1.04	1.05	1.04
F3	1.01	0.99	0.97	0.94	1.09	1.07	1.11	1.08
G1	1.07	1.08	1.10	1.22	1.00	1.00	0.90	0.89
G2	0.98	1.06	1.08	1.05	0.91	0.90	0.93	0.94
G3	0.99	0.95	1.04	0.98	0.92	0.87	1.06	1.13

Table 6. Normalized TSS Data (cont.)

Cell A1	26-Jan	26-Jan	27-Jan	27-Jan	28-Jan	28-Jan	29-Jan	29-Jan
H1	0.93	0.93	0.94	0.92	1.10	0.99	1.08	1.16
H2	0.93	0.99	0.94	0.95	1.04	1.11	1.03	1.00
H3	0.99	0.98	0.99	1.00	1.21	1.24	1.19	1.13
Ave	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
StdDev	0.06	0.09	0.09	0.11	0.11	0.11	0.11	0.10
CV	6%	9%	9%	11%	11%	11%	11%	10%
Cell A2	**Submersible Propeller Mixer**				**Bio^{M}x**			
J1	1.01	1.01	1.02	0.98	1.06	0.93	1.02	0.98
J2	1.02	1.00	1.03	1.01	1.02	0.93	0.99	1.00
J3	1.02	1.00	1.02	1.03	1.03	0.95	0.99	1.04
K1	1.00	0.98	1.01	0.97	1.07	0.96	0.98	0.99
K2	1.01	1.00	1.01	1.01	1.06	0.96	0.99	0.99
K3	1.01	1.02	1.01	1.00	1.04	1.00	1.00	0.98
L1	0.93	0.83	0.92	0.87	0.91	1.17	1.02	1.01
L2	0.99	0.97	0.95	0.99	0.90	1.00	1.01	0.99
L3	0.97	0.99	0.96	0.99	0.94	0.98	0.99	0.99
M1	1.00	1.02	1.01	0.99	1.01	1.10	1.00	1.00
M2	1.00	0.97	0.98	1.00	0.96	0.96	0.97	0.98
M3	1.01	0.97	1.02	0.99	0.91	1.01	0.99	0.99
N1	1.01	0.97	1.03	0.99	1.03	1.03	1.01	0.99
N2	1.04	1.03	1.02	1.04	1.01	1.03	1.00	0.98
N3	1.01	0.97	1.02	1.02	1.01	1.06	1.00	0.99
P1	1.00	1.04	0.99	1.03	1.04	0.99	1.02	1.13
P2	0.99	1.02	1.01	0.99	0.99	0.96	1.02	1.03
P3	1.00	1.01	0.99	1.01	1.03	0.99	1.00	1.00
Q1	0.99	1.06	1.00	1.02	1.03	1.00	1.00	0.96
Q2	0.99	1.08	1.01	1.03	0.97	0.97	1.00	0.97
Q3	1.00	1.05	0.98	1.04	1.00	1.00	1.01	1.00
Ave	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
StdDev	0.02	0.05	0.03	0.03	0.05	0.06	0.01	0.03
CV	2%	5%	3%	3%	5%	6%	1%	3%

Two highest values for test Two lowest values for test

The variability of the sampled suspended solids concentration is marginally greater in the Bio^{M}x system for A1. However, in A2, virtually all data points for both mixing systems fall within the goal of ±10% of the average value. Table 7 shows the values of the Coefficient of Variation for the different sampling days. This is calculated as the standard deviation of the samples divided by the average value and gives an indication of the variation of the suspended solids within the tank during the sampling event.

Table 7. Suspended Solids Concentration Variability

Submersible Mixer			Bio^{M}x		
Date	A1	A2	Date	A1	A2
26-Jan	6.1%	2.1%	28-Jan	11.1%	5.1%
26-Jan	9.3%	5.0%	28-Jan	11.1%	5.6%
27-Jan	9.1%	2.9%	29-Jan	10.7%	1.3%
27-Jan	10.7%	3.5%	29-Jan	9.8%	3.5%
Average	8.8%	3.4%	Average	10.7%	3.9%

The submersible mixing systems attempt to create a steady-state of currents and suspended material. Traditionally, this has been desired to keep solids from depositing on the floor of the tank, where they may be difficult to resuspend, as well as to assure contact of the microorganisms with their required nutrients. The Bio^{M}x system, by using timed firing of compressed air, continues to move the contents of the tank, but not with a constant and sustained velocity. The acceleration of the flow by the injection of air maintains the suspension of the solids, but, between firings, gravity and other currents are more significant than with a continuously-operated submersible mixer. Thus, the concentration of suspended solids might be expected to have more variability over time as the air injection cycles.

The data presented in Table 7 indicate that the Bio^{M}x unit is capable of mixing to homogeneity very similar to the submersible unit, with an increase in variation of samples only 2% greater in the A1 cell TSS concentrations and 0.5% greater in variation in the A2 cell. The variability of the Bio^{M}x unit may be a result of its cycling/intermittent operation, or there may be other confounding variables that have not been addressed in this study. Several samples were split and separate analyses run to provide an indication of the variation in the laboratory work. Samples averaged 1.5% difference in the two results, and it would be expected that duplicate samples would have increased this variability. The impact of the flow rate or the mixed liquor concentration on the variability of measured suspended solids or mixing homogeneity has not been isolated or controlled in the testing to allow firm conclusions about these variables.

Statistical comparison of the variances in the A1 cell for the two mixing systems, using an *F-statistic* at α=0.10, concludes it is justifiable to consider that the variation in the two mixing systems is the same. The same conclusion is reached in the A2 cell for the two systems. **Based on the information presented, the TSS data suggest that in the normal operating conditions tested, the mixing of the Bio^{M}x unit and the Submersible Propeller unit result in similar mixing of the mixed liquor.**

3.5 ORP in the Anaerobic Zone

Concerns regarding the introduction of air and the potential to transfer oxygen into an anaerobic zone and compromise the subsequent treatment in the zone must be addressed for the Bio^{M}x unit to reach general acceptance for nutrient removal applications.

Two measurements that indicate the impact of oxygen transfer from air on the environment in a biological wastewater treatment process are the dissolved oxygen (DO) concentration and the

oxidation-reduction potential (ORP). Biological nutrient removal biochemical processes do not require that DO concentrations always be zero, but that conditions in the reactor are always dominated by reactions that do not utilize oxygen as the electron acceptor. Under the anaerobic conditions used for these tests, the DO measurements of the mixed liquor were dominated by values less than 0.1 mg/L, which was the accuracy of the DO probe used (YSI ROX DO) . Therefore, for this evaluation, DO measurements were not taken, but ORP measurements were. ORP measures the ratio of oxidizing reactions to reducing reactions. The measurement provides a means of determining the chemical-biochemical nature of the reactor environment and, unlike DO concentration, can differentiate between an anoxic environment and an anaerobic one.

While the specific chemistry of the wastewater will determine the exact appropriate value, ORP measures below -100 mV are assumed to indicate anaerobic conditions.

The summary in Table 8 represents traces over periods of 12 to 28 hours of continuous monitoring. The 95th percentile values for ORP are shown in the Table, and indicate that anaerobic conditions dominate the cells with either mixing system. The 95th percentile values are most often below -150mV for ORP. These initial test results confirm that both Bio^{M}x and the submersible mixer are compatible with an anaerobic environment.

Table 8. Oxidation-Reduction Potential (ORP) in Anaerobic Environments

A1 Cell Mixing	**Date**	**ORP, mV** **95th Percentile**
Bio^{M}x	02/01/2010	-158
	02/17/2010	-196
	02/18/2010	-160
Submersible Mixer	01/29/2010	-117
	02/12/2010	-173
	02/14/2010	-179
A2 Cell Mixing		
Bio^{M}x	01/31/2010	-112
Submersible Mixer	01/30/2010	-102
	02/15/2010	-178

Two submersible mixer data sets were omitted from this presentation due to high ORP (-50 to -60) values and other factors which were so inconsistent with other collected data that they raised doubts

about their validity. Analysis of the impact of flow on the mixing of cell A1 and the measurement of ORP at multiple locations during testing would provide additional insights into this work and, perhaps, resolve the questions raised by the submersible mixer ORP observations.

4.0 Oxygen Transfer Study

A study of oxygen transfer was conducted with the Bio^{M}x unit by GSEE, an independent laboratory in Nashville, TN, widely accepted in the wastewater treatment industry as the leading test facility for testing OTE using the ASCE Standard clean water non-steady state test procedures. Membrane disk diffusers and a Bio^{M}x system were operated in a test basin both separately and together while unsteady-state oxygen transfer testing was performed. The result of the GSEE testing established that the oxygen transfer coefficient per unit volume, $K_L a$, for the Bio^{M}x unit was 0.25, while membrane diffuser testing resulted in values of 4.71-8.06. This lab facility work was continued in out-of-service basins at the F. Wayne Hill Water Resources Center at two depths, 15 and 22 feet. At the shallower depth, the Bio^{M}x $K_L a$ value was 0.14 and 0.70 for average and maximum operational settings, respectively. Values of $K_L a$ for the membrane diffusers were 2.44-4.67. At the twenty two foot depth, the testing data resulted in $K_L a$ values of 0.16 for the Bio^{M}x system and 2.70-2.97 for the diffusers.

This testing, conducted in clean water, demonstrates oxygen transfer rates and $K_L a$ values that would be decreased in applications with wastewater because of lower alpha and beta values. The trivial amounts of oxygen which might transfer in an operating facility would be consumed by the active biomass of the system, just as the diffused air from the basin surface is consumed, and the biomass would maintain the desired anaerobic environment. These findings are consistent with the observations made during full-scale testing at the F. Wayne Hill Water Resources Center, where even the A1 cell with the RAS flow falling into the basin maintains anaerobic conditions while mixing using the Bio^{M}x system.

5.0 Power Usage Study

The compressed air source for the Bio^{M}x system at the F. Wayne Hill Water Resources Center is an Ingersoll Rand variable speed rotary screw 15 hp compressor, which provides sufficient capacity to operate the Bio^{M}x equipment installed in three tanks, *i.e.*, the two tanks used for the mixing study plus one more tank, all identical in size. Each of these three tanks at the Center (along with many others in the plant) is equipped with a 15 hp submersible propeller mixer identical to those used for comparison with Bio^{M}x in the mixing study; these submersible mixers were all installed as original equipment at the plant.

Power readings were taken by connecting a Hioki Model 3196 Power Analyzer to the electrical supply for the equipment under test. Readings were taken for the submersible mixer at the control panel adjacent to the mixing tank. Power readings for the Bio^{M}x system were taken at the disconnect to the air compressor. The values presented below are representative of measurements automatically logged and averaged by the analyzer over several testing periods.

The initial phase of the power study was a direct comparison of the power required for operating Bio^{M}x in a single tank with the power required to operate the submersible mixer in the same tank. The Bio^{M}x

system and the submersible mixer were operated independently, *i.e.,* one at a time, each at the same operating settings as used for the mixing tests. **The results, summarized in Table 9, show that the Bio^{M}x system used approximately 55% of the horsepower required for the submersible mixer when operated to mix a single tank.**

Table 9. Power Usage in a Single Tank

Unit of Measure	Submersible Mixer	Bio^{M}x
Amps	22.05	7.26
Volts	467.6	479.3
Power Factor	0.56	0.91
Horsepower	13.14	7.32
HP/1000 ft^3	0.240	0.133
Kilowatts	9.8	5.46
Power Reduction		**45%**

Power measurements were also taken when the Bio^{M}x system was mixing in three tanks simultaneously. In this configuration, each tank was outfitted with similar Bio^{M}x components (control panels, piping, air control valves, and nozzles) but all equipment was served by the same single air compressor. This placed a load on the compressor nearing its maximum capacity.

Power measurements of the submersible mixers were not taken with three running simultaneously. This was not possible with the analyzer available, which was limited to measuring a single piece of equipment at any given time. Because all of the mixers were identical, *i.e.,* the same make, model, and capacity, the power to operate three at a time was assumed to be three times greater than the power required for a single unit.

The results of this phase of the study are summarized in Table 10 and show that when mixing three tanks simultaneously, the Bio^{M}x system used only 40% of the horsepower required to operate three submersible mixers.

Table 10. Power Usage in Mixing Three Tanks Simultaneously

Unit of Measure	Submersible Mixer calculated	Bio^{M}x measured
Amps	66.00	15.14
Volts	467.65	483.0
Power Factor	0.55	0.93
Horsepower	39.42	15.79
HP/1000 ft^3	0.243	0.097
Kilowatts	29.40	11.78
Power Reduction		**60%**

6.0 Maintenance Requirement Comparison

During the studies described above there were no equipment maintenance periods, so no direct assessment can be made regarding time and cost of maintenance of the equipment under test.

However, as noted in the introduction to this paper, submersible propeller mixers have a long history of requiring maintenance that is expensive, time consuming, and often entails unpleasant work for the operators. Due to this, it is not unusual for a submersible propeller mixer to be run until failure, with corrective maintenance costing much more than periodic maintenance. In addition, because the mixer must be removed from the tank for maintenance, the tank is out of service during the time that the mixer is being repaired. To prevent such service disruption, a spare submersible propeller mixer is typically kept in storage, introducing an additional capital expense.

While specific cost data for maintaining a single submersible propeller mixer were not collected during this study, interviews with wastewater treatment plant managers and operators indicate a range of $1,800-$5,000 per year per mixer as a representative cost. According to these operators, each mixer requires replacement at 5 – 7 year intervals.

Bio^{M}x provides a much different maintenance experience. The rotary screw compressors, typically housed indoors, require quarterly maintenance for oil and filters. Maintenance warranties are available from compressor manufacturers that cover all but repair labor for $3000-$5000 per year depending on compressor size, number and hours of use. Most notably, there is no routine maintenance required in the liquid and Bio^{M}x controls can be expected to operate with minimal maintenance. Because there are no motors, electrical components, or moving parts in the wastewater tank, any maintenance that is required is conducted above water level and typically involves the removal and replacement of a single

component. The only components in the Bio^{M}x system likely to need replacement are Air Control Valves, at a cost of less than $200 each; replacement takes just minutes without special tools. As with most component controls like submersible mixers, Bio^{M}x control panels include fault detection notification if valve failure occurs. These valves are rated at 25 million cycles, or about 15 years of normal use in a wastewater treatment plant. A key benefit is that the tank is out of service for only minutes rather than hours or days.

7.0 Conclusions

Based on all test results to date, demonstrated reliability of system components, and reported maintenance costs from knowledgeable sources, Bio^{M}x presents a more robust, cost-effective, and energy-efficient approach to mixing in anaerobic and anoxic environments than can be provided by submersible propeller mixers. With multiple Bio^{M}x systems added to a treatment process these advantages become more compelling, as each system further increases the overall efficiency of the plant.

Results of side-by-side comparisons of Bio^{M}x with submersible propeller mixers established that:

- Bio^{M}x is effective in mixing wastewater to industry standards based on measured suspended solids and dye distributions.
- Bio^{M}x is fully compatible with anaerobic and anoxic environments based on measured Oxidation Reduction Potential. Reactors that maintain those environments are key treatment process components used to meet EPA and state-level nutrient removal limits.
- Bio^{M}x provides substantial power savings compared to submersible propeller mixers based on measured horsepower per volume of liquid mixed (0.097 vs. 0.243 hp/1000cf).

An analysis of documented energy savings and projected savings in maintenance costs for the Bio^{M}x system as compared to submersible propeller mixers provides a solid basis for expected rapid return of capital and a payback period far shorter than the 10 year industry benchmark.

Appendix 1. Anaerobic Mixing Study TSS Data (MLSS)

Cell A1	Submersible Mixer				Bio^{M}x			
	1/26/2010	1/26/2010	1/27/2010	1/27/2010	1/28/2010	1/28/2010	1/29/2010	1/29/2010
B1	4920	3040	2540	3360	2130	2300	2680	2760
B2	4490	3530	3090	3520	2160	2410	2870	3050
B3	4440	3280[a]	2470	2980	2140[a]	2300	2730	3010
C1	4450	4220	3240	3870	2130	2400	2700	3000
C2	4750	3730	3230	3690	2030	2360	2660	2850
C3	4600	2980	3155[a]	3490	2040	2420	2700	2860
D1	3260	1480	1280	1840	1350	1550	1925[a]	2380
D2	4050	3080	2640	2970	2250	2610	3280	3310
D3	4230	3050	2510	2790	2480	2880	3380	3500
E1	4020	3030	2640	2875[a]	2480	2840	3360	3430
E2	4220	3110	2690	2850	2480	2780	3350	3420
E3	4170	3020	2490	2870	2640	2860	3500	3540
F1	4090	3170	2650	2960	2930	3190	3320	3570
F2	4040	3330	2830	3000	2400	2780[a]	3280	3430
F3	4360	3230	2710	3000	2600	2840	3470	3540
G1	4610	3540	3080	3890	2390	2670	2820	2920
G2	4215[a]	3470	3020	3360	2170	2410	2910	3090
G3	4260	3100	2900	3110	2180	2320	3330	3710
H1	4010	3040	2640	2930	2620	2640	3370	3810
H2	4000	3240	2630	3030	2470	2950	3240	3285[a]
H3	4250	3190	2770	3200	2880	3300	3720	3720
Cell A2	**Submersible Mixer**				**Bio^{M}x**			
J1	5110	4400	3350	3820	3860	3840	4760	4600
J2	5170	4330	3390	3920	3700	3820	4610	4700
J3	5170	4350	3360	3990	3740	3910	4600	4910
K1	5040	4270	3310	3750	3880	3930	4580	4680
K2	5090	4340	3320[a]	3930	3860	3930	4630	4650
K3	5100	4430	3310	3880	3780	4100	4680	4600
L1	4720	3600	3010	3390	3320	4800	4750	4770
L2	4990	4200	3110	3850	3260	4120	4710	4670
L3	4880	4320	3150	3860	3400	4045[a]	4635[a]	4650
M1	5030	4430	3300	3860	3680	4500	4660	4720[a]
M2	5030	4210	3220	3870	3470	3950	4540	4630
M3	5120	4230	3350	3850	3310	4150	4600	4670
N1	5125[a]	4220	3390	3840	3740	4250	4700	4650
N2	5230	4470	3360	4050	3650	4250	4640	4590
N3	5090	4220	3350	3960	3650	4360	4650	4640
P1	5070	4520	3240	3990	3760	4080	4740	5310
P2	5000	4420	3300	3850	3580	3960	4740	4840
P3	5070	4390[a]	3250	3920	3750	4080	4660	4710
Q1	5020	4620	3290	3960	3740[a]	4100	4640	4510
Q2	5010	4700	3310	3980	3510	3980	4680	4580
Q3	5050	4540	3230	4020	3620	4100	4710	4720

a. These samples were spilt and analyzed in two analyses. The value shown is the average.

Appendix 2 – Cell A1 Results for TSS

Bio^{M}x

	1/28/2010		AM	1/28/2010		PM	1/29/2010		AM	1/29/2010		PM
	1*	2*	3*	1	2	3	1	2	3	1	2	3
B	2130	2160	2140	2300	2410	2300	2680	2870	2730	2760	3050	3010
C	2130	2030	2040	2400	2360	2420	2700	2660	2700	3000	2850	2860
D	Deleted	2250	2480	Deleted	2610	2880	Deleted	3280	3380	Deleted	3310	3500
E	2480	2480	2640	2840	2780	2860	3360	3350	3500	3430	3420	3540
F	2930	2400	2600	3190	2780	2840	3320	3280	3470	3570	3430	3540
G	2390	2170	2180	2670	2410	2320	2820	2910	3330	2920	3090	3710
H	2620	2470	2880	2640	2950	3300	3370	3240	3720	3810	3285	3720
Ave	2447	2280	2423	2673	2614	2703	3042	3084	3261	3248	3205	3411
StdDev	306	173	310	319	229	370	342	267	393	415	215	339
Total Ave		2380			2663			3134			3290	
StdDev		265			297			334			324	
CV		11%			11%			11%			10%	

Submersible Mixer

	1/26/2010		AM	1/26/2010		PM	1/27/2010		AM	1/27/2010		PM
	1	2	3	1	2	3	1	2	3	1	2	3
B	4920	4490	4440	3040	3530	3280	2540	3090	2470	3360	3520	2980
C	4450	4750	4600	4220	3730	2980	3240	3230	3155	3870	3690	3490
D	Deleted	4050	4230	Deleted	3080	3050	Deleted	2640	2510	Deleted	2970	2790
E	4020	4220	4170	3030	3110	3020	2640	2690	2490	2875	2850	2870
F	4090	4040	4360	3170	3330	3230	2650	2830	2710	2960	3000	3000
G	4610	4215	4260	3540	3470	3100	3080	3020	2900	3890	3360	3110
H	4010	4000	4250	3040	3240	3190	2640	2630	2770	2930	3030	3200
Ave	4350	4252	4330	3340	3356	3121	2798	2876	2715	3314	3203	3063
StdDev	373	276	149	473	236	114	288	240	253	471	319	233
Total Ave		4309			3269			2796			3187	
StdDev		264			305			255			344	
CV		6%			9%			9%			11%	

*1 Samples taken 2' below top
*2 Samples taken mid-depth
*3 Samples taken 2' above bottom

Cell Volume = 54,120 cf, 404,818 gal.

Appendix 3 – Cell A2 Results for TSS

Bio^{M}x

	1/28/2010		AM	1/28/2010		PM	1/29/2010		AM	1/29/2010		PM
	1*	2*	3*	1	2	3	1	2	3	1	2	3
J	3860	3700	3740	3840	3820	3910	4760	4610	4600	4600	4700	4910
K	3880	3860	3780	3930	3930	4100	4580	4630	4680	4680	4650	4600
L	3320	3260	3400	4800	4120	4045	4750	4710	4635	4770	4670	4650
M	3680	3470	3310	4500	3950	4150	4660	4540	4600	4720	4630	4670
N	3740	3650	3650	4250	4250	4360	4700	4640	4650	4650	4590	4640
P	3760	3580	3750	4080	3960	4080	4740	4740	4660	5310	4840	4710
Q	3740	3510	3620	4100	3980	4100	4640	4680	4710	4510	4580	4720
Ave	3711	3576	3607	4214	4001	4106	4690	4650	4648	4749	4666	4700
StdDev	186	190	183	336	141	135	67	67	40	261	88	101
Total Ave		3631			4107			4663			4705	
StdDev		187			231			60			165	
CV		5%			6%			1%			3%	

Submersible Mixer

	1/26/2010		AM	1/26/2010		PM	1/27/2010		AM	1/27/2010		PM
	1	2	3	1	2	3	1	2	3	1	2	3
J	5110	5170	5170	4400	4330	4350	3350	3390	3360	3820	3920	3990
K	5040	5090	5100	4270	4340	4430	3310	3320	3310	3750	3930	3880
L	4720	4990	4880	3600	4200	4320	3010	3110	3150	3390	3850	3860
M	5030	5030	5120	4430	4210	4230	3300	3220	3350	3860	3870	3850
N	5125	5230	5090	4220	4470	4220	3390	3360	3350	3840	4050	3960
P	5070	5000	5070	4520	4420	4390	3240	3300	3250	3990	3850	3920
Q	5020	5010	5050	4620	4700	4540	3290	3310	3230	3960	3980	4020
Ave	5016	5074	5069	4294	4381	4354	3270	3287	3286	3801	3921	3926
StdDev	137	93	92	335	172	113	124	94	79	199	74	66
Total Ave		5053			4343			3281			3883	
StdDev		107			219			96			135	
CV		2%			5%			3%			3%	

*1 Samples taken 2' below top
*2 Samples taken mid-depth
*3 Samples taken 2' above bottom
Cell Volume = 54,120 cf or 404,818 gal.