Oxygen transfer in clean and process water for draft tube turbine aerators in total barrier oxidation ditches

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ABSTRACT: Total barrier oxidation ditches (TBODs) have been installed over the past 5 years in the U. S. under the innovative provisions of the U. S. Environmental Protection Agency (EPA) Innovative and Alternative (I/A) Technology Construction Grants Program. One I/A feature of this system is the claimed energy savings due to high oxygen transfer efficiency of draft tube submerged turbine aerators (DTTAs). In an effort to evaluate the oxygen transfer performance of DTTAs in the TBOD configuration (with J-tube extenders to transfer aerated mixed liquor to the downstream side of the barrier wall), full-scale testing programs were conducted at two locations using a variety of clean and process water testing techniques. In clean water, the American Society of Civil Engineers (ASCE) sanctioned testing procedure was used and compared to the radioactive tracer (radiotracer) procedure and a dissolved oxygen (DO) mass balance across the DTTA/J-tube assembly. The radiotracer procedure was also used in process water testing and compared to the off-gas procedure and a long-term mass balance on oxygen demanding material. All test methods agreed very closely, indicating that the ASCE procedure can be used in noncomplete mixing geometries, such as oxidation ditches. The precision of the various methods was different. Specific recommendations are made to better adapt the ASCE procedure to this geometry. *J. Water Pollut. Control Fed.*, 61, 1449 (1989).

KEYWORDS: aeration, oxidation ditch, oxygen transfer, activated sludge, tests.

The Innovative and Alternative (I/A) Technology Construction Grants Program was legislated by Congress with the intent of encouraging utilization of promising new technologies in the nation's publicly owned treatment works (POTWs). Innovative construction grants are awarded by the U. S. Environmental Protection Agency (EPA) under the I/A Technology Construction Grants Program on the basis of savings of approximately 20% in primary energy consumption to the most energy-efficient conventional alternative, or approximately 15% in life cycle costs compared to the most cost-effective conventional alternative.

The total barrier oxidation ditch (TBOD) is a new oxidation ditch concept that utilizes draft tube turbine aerators (DTTAs). The TBOD differs from traditional oxidation ditch systems in that a vertical barrier wall is installed across the entire cross section of the ditch channel for the purpose of intercepting all circulating flow and forcing it through one or more DTTAs. Compressed air is introduced to the turbine assembly through a sparge ring located beneath the turbine blades. Aerated mixed liquor is discharged on the downstream side of the barrier wall through a J-tube extension of the basic draft tube downcomer, as shown in Figure 1. Thus, the turbine segment of the DTTA serves to impart sufficient energy to circulate liquid through the ditch at the proper velocity, while blowers deliver air to the DTTA for aeration.

A number of TBODs have been installed throughout the country under the innovative provisions of the I/A Technology Construction Grants Program. The EPA awarded these grants on the basis of the energy-savings criterion of the innovative stipulations. Estimated energy savings over conventional oxidation ditch processes were based on manufacturers' claimed standard oxygen transfer efficiencies (SOTE, percent mass oxygen transferred at 20°C and zero dissolved oxygen (DO) concentration in tap water at mean sea level) of 40 to 55%, depending on system operating depth. In a review of these installations, it appeared the claimed energy savings for the aeration system were not being realized, although many of these treatment systems were meeting or exceeding their National Pollutant Discharge Elimination System (NPDES) permits or design treatment efficiencies. Owners, manufacturers, and designers suspected a variety of causes, including the validity of oxygen transfer testing protocols.

To resolve the differences, a full-scale testing program was conducted at two treatment plants using different manufacturers' equipment. Both clean and process water testing was conducted using a variety of techniques. In particular, it was desired to evaluate the EPA sponsored clean water standard technique, developed under the auspices of the American Society of Civil Engineers (ASCE) Committee on Oxygen Transfer Standards,[1,2] and several process water tests.[3,4] Others[5] evaluated the accuracy and precision of the ASCE clean water method based on an analysis of existing data bases, which includes data for an oxidation ditch. Others[6,7] reported on comparisons between selected process water test procedures.

This manuscript describes the testing procedures and the results of five full-scale test programs. The ASCE method was used for clean water testing, in conjunction with a radioactive tracer (radiotracer) technique[3] and a

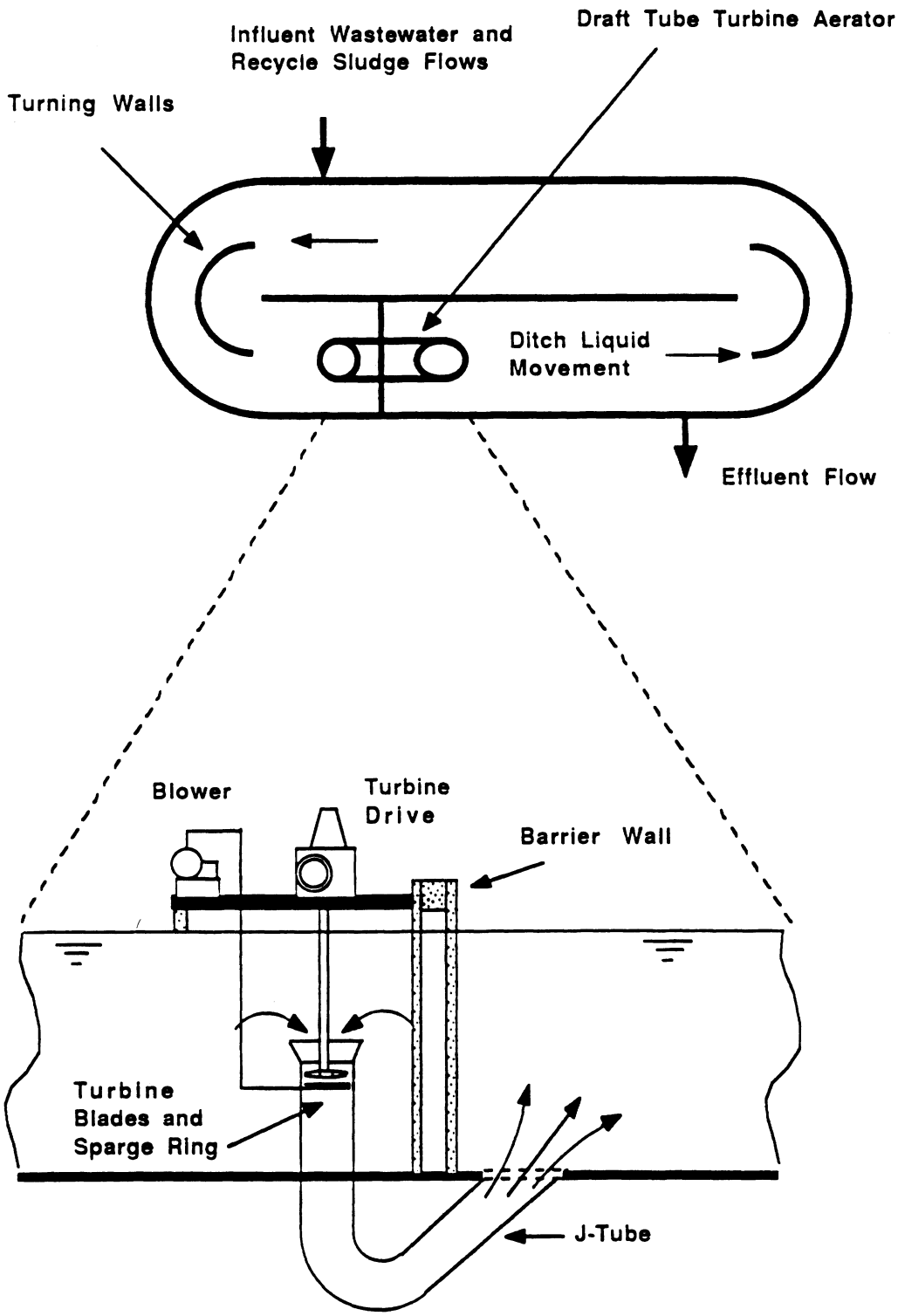

Figure 1—Total barrier oxidation ditch process concept.

DO mass balance procedure developed specifically for the TBOD application. The radiotracer technique was also used for process water testing, along with an off-gas method.[4] Additionally, a 4-week long process oxygen demand balance was conducted at one site to determine oxygen transfer rates over an extended period of normal process operation. Details of the testing procedures and the manufacturers' comments are reported by others.[8]

Site Descriptions

Two sites were selected for testing: Opelika, Ala., and South Hill, Va. These sites were selected in part because

of project timing, ditch design, and the equipment that each ditch utilized. Each site had two parallel ditches that facilitated clean and process water testing. Also the sites represented two major suppliers of DTTAs for TBODs.

Opelika, Ala., Westside wastewater treatment facility. The principle project test site was the Opelika Westside wastewater treatment plant. The city of Opelika is located on the eastern border in the middle of the state. The facility includes an influent pump station, screening, an aerated grit chamber, two parallel 5 700-m^3 (200 000-cu ft) TBOD basins, each designed to treat 315 m^3/h (2.0 mgd) under average flow conditions, two circular clarifiers, a dual chlorine disinfection chamber, postaeration, and a sludge lagoon.

Each of the two parallel TBOD basins is equipped with two 56-kW (75-hp) DTTAs and two 30-kW (40-hp) positive displacement blowers. Figure 2 shows the general plant layout and flow diagram for the Opelika facility. The sidewater depth during oxygen transfer testing was 3.49 m (11.46 ft). The J-tube is 2.13 m (7.0 ft) in diameter and extends 5.18 m (17.0 ft) below the tank bottom.

South Hill, Va., wastewater treatment facility. The second test site was at South Hill, Va., located in south central Virginia near the North Carolina border. The South Hill facility includes screening and degritting processes, two parallel 2 850-m^3 (100 000-ft^3) TBOD basins, each designed to treat 80 m^3/h (0.5 mgd) under average flow conditions, two intrachannel clarifiers, a chlorine contact chamber, a cascade postaeration chamber, an aerobic sludge digester, and sludge drying beds.

Each of the two parallel TBOD basins is equipped with a 37-kW (50-hp) DTTA. Air is supplied by two parallel 15-kW (20-hp) positive displacement blowers. The sidewater depth during oxygen transfer testing was 4.34 m (14.25 ft). The J-tube is 1.83 m (6.0 ft) in diameter and extends 5.87 m (19.25 ft) below the tank floor. Figure 3 illustrates the general plant layout and flow diagram for South Hill.

The two test sites differ in several ways. The Opelika ditch is in the shape of a single racetrack or oval, whereas the South Hill ditch wraps around itself in a folded flow arrangement. The South Hill channel is only 4.0 m (13.25 ft) wide compared to 9.6 m (31.6 ft) at Opelika. Each of South Hill's two ditches contains an intrachannel clarifier, which was isolated from the main basin flow during clean water testing. None of these differences were expected to affect oxygen transfer testing.

Experimental Methods

The testing programs for the TBOD aeration systems at both Opelika and South Hill were to be performed in both clean water and process water situations. Test programs were designed to evaluate the DTTAs over the expected range of operating conditions, from lowest to highest aeration rates. In the clean water programs, three different test methodologies were employed: the ASCE nonsteady-state method, the krypton/tritium radiotracer technique, and a DO mass balance across the turbine/J-tube. For the process water situations, three techniques were used at Opelika: the off-gas method, the krypton/tritium radiotracer technique, and a long-term process mass balance. Because of the expense of the radiotracer method, it was not performed at South Hill. The extensive data base required for the process mass balance was not available at South Hill, so that procedure was also not conducted there.

The aeration test program at Opelika was performed in two phases. The clean water test program was conducted during July 7–11, 1986, and the process water testing was conducted on August 6–7, 1986. Figure 4 illustrates the DO probe locations, tracer release point, and hood placements for the tests conducted at Opelika. Clean and process water tests were performed in Ditch 2.

The test program at South Hill was also performed in two phases. The clean water test program was conducted July 22–25, 1986. The process water testing was initially

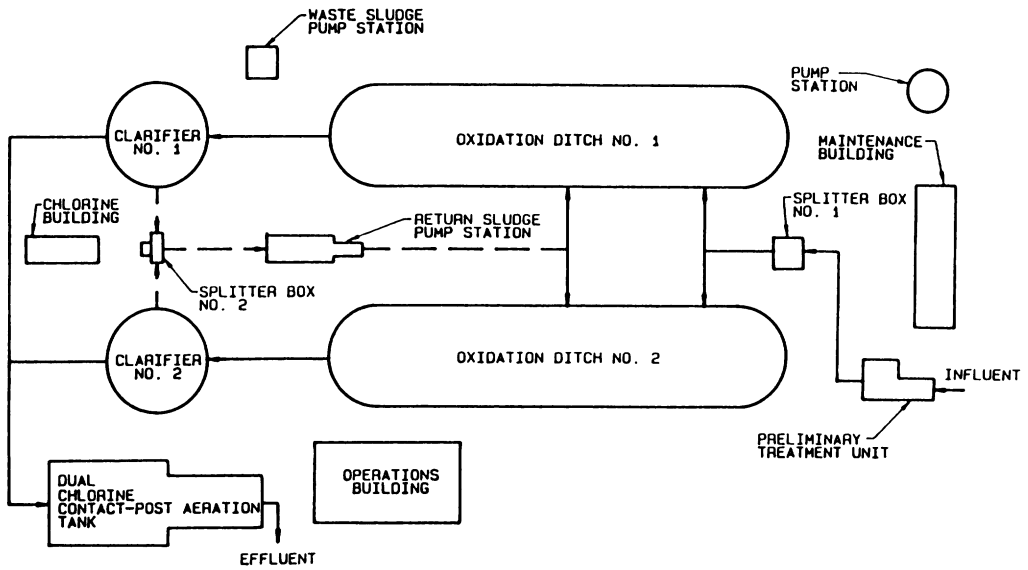

Figure 2—Opelika general plant layout and flow diagram.

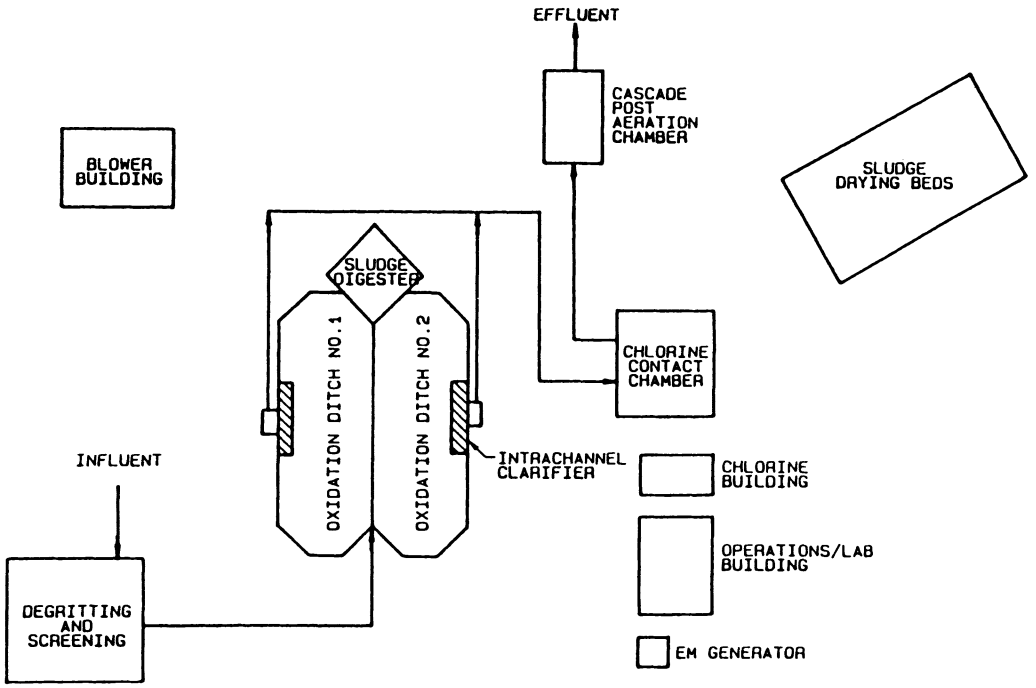

Figure 3—South Hill general plant layout and flow diagram.

conducted November 11–14, 1986. A follow-up test series was conducted May 20–22, 1987. Figure 5 illustrates the DO sampling points, tracer release points, and hood locations for the tests at South Hill. The clean water tests and the follow-up process water tests were performed in Ditch 1.

To perform the tests, contractors were used and, in the case of the ASCE method, the manufacturers performed

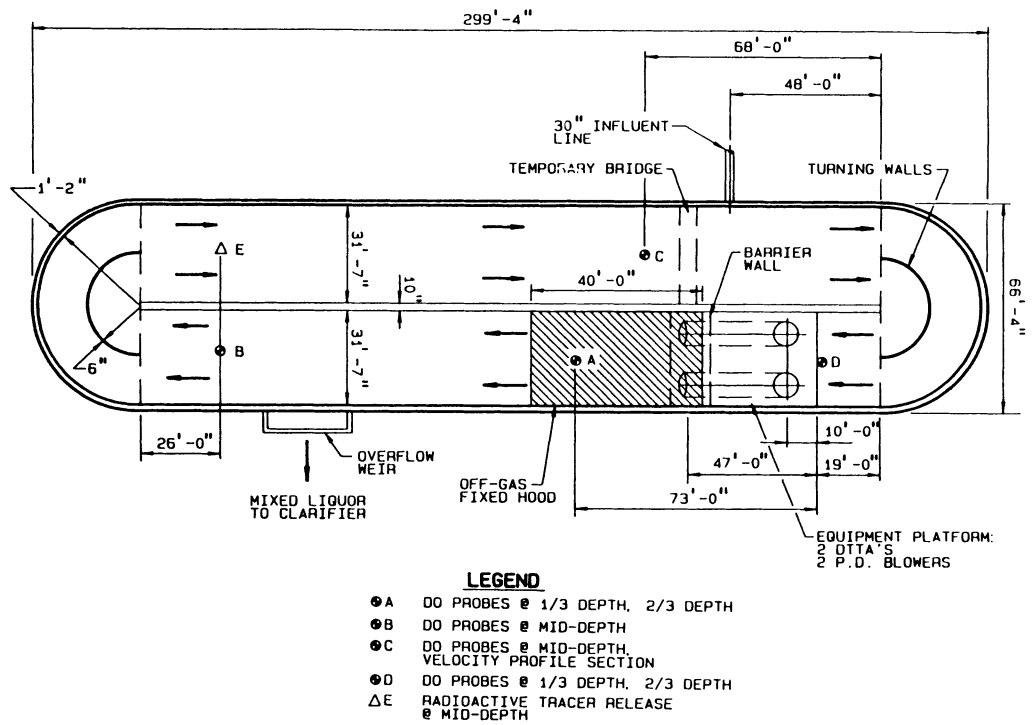

Figure 4—Opelika TBOD test locations.

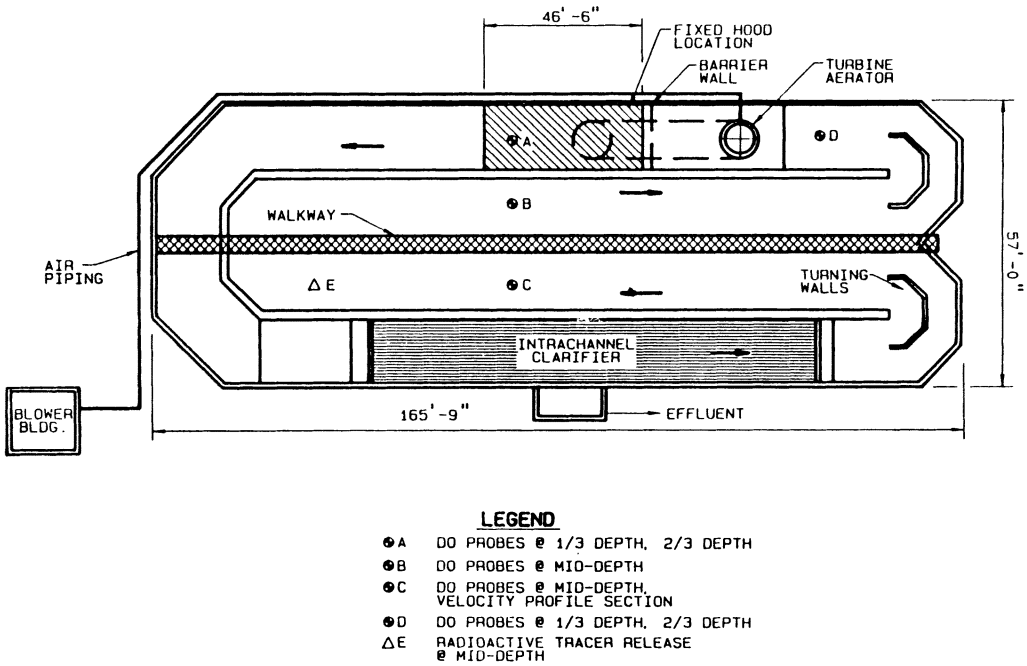

Figure 5—South Hill TBOD test locations.

the testing. The authors participated in the design of the tests, witnessed the testing, and performed independent data analyses.

ASCE nonsteady-state clean water test. The procedure, described in ASCE Standard Measurement of Oxygen Transfer in Clean Water,[2] was designed to measure oxygen transfer performance of diffused gas and mechanical oxygenation devices in clean water. It is applicable to laboratory-scale oxygenation devices with volumes of a few liters and to full-scale systems with volumes typical of those found in activated sludge treatment systems.

The test method is based on the removal of DO from the water by cobalt catalyzed sodium sulfite followed by reoxygenation to near saturation. The DO inventory of the water volume is monitored during reaeration by measuring DO concentrations at several determination points (probe locations) over the period of time required to achieve DO saturation. The data obtained at each determination point are analyzed by a nonlinear mass transfer model to estimate the apparent volumetric mass transfer coefficient, $K_L a$, and the steady-state DO saturation concentration, C^*_∞.

The oxygen transfer capacity of the aeration system is usually expressed as the rate of oxygen transfer predicted by the model at zero DO under standard conditions of pressure (1.0 atm) and temperature (20°C). This is termed the clean water standard oxygen transfer rate (SOTR) and is calculated as

$$\text{SOTR} = V \sum_{i=1}^{n} \frac{K_L a_{20} C^*_{\infty 20}}{n} \qquad (1)$$

Where

n = number of determination points, i;
$K_L a_{20}$ = volumetric oxygen transfer coefficient at i,
$C^*_{\infty 20}$ = steady-state DO saturation concentration at i, and
V = liquid volume of the reactor.

The clean water standard aeration efficiency (SAE) may be estimated by measuring the power consumed by the aeration equipment. It is calculated by Equation 2:

$$\text{SAE} = \frac{\text{SOTR}}{\text{wire power input}} \qquad (2)$$

All references to power in this manuscript refer to wire power, which includes all mechanical and compression losses.

Radiotracer procedure. The radiotracer method of measuring gas transfer in wastewater treatment plants has been described previously by others.[3] The principle of the tracer method is a direct measurement of mass transfer of an inert tracer gas, krypton-85. The mass transfer rate for krypton-85 is related to the oxygen transfer rate by a constant that has been derived from theoretical and experimental investigations. The method depends on the simultaneous use of two tracers in a single aqueous solution: a conservative dispersion/dilution radiotracer (tritiated water molecules) and a dissolved gaseous radiotracer for oxygen (krypton-85).

The tritiated water provides an accurate measure of dispersion and dilution because the changes in tritium concentration are caused by dispersion as a result of turbulent mixing and dilution by any influent flow to the aeration basin. Because the tritium is in the form of water molecules, it is an ideal conservative tracer for water.

The dissolved gaseous tracer (krypton-85) is subject to the same dispersion and dilution as the tritrium because both tracers are released simultaneously as a homogeneous

mixture. Also, the krypton gas is only lost from the aeration basin because of physical gas transfer, since it does not react with or adsorb to solids.

After the two tracers are released, samples from fixed points in the basin are taken over a sufficiently long interval to observe most of the krypton escape to the atmosphere. The escape of krypton can be described as follows:

$$\frac{dC_{Kr}}{dt} = -K_{Kr}C_{Kr} \quad (3)$$

Where

C_{Kr} = time dependent volumetric krypton concentration, and
K_{Kr} = krypton mass transfer coefficient.

In the case of noncomplete mixing systems, the ratio of krypton to tritium can be used to describe the loss of krypton as follows:

$$R = \frac{C_{Kr}}{C_h} \quad (4)$$

$$\frac{dR}{dt} = -K_{Kr}R \quad (5)$$

Where

C_h = time dependent tritium concentration, and
R = krypton:tritium ratio.

The krypton mass transfer coefficient, K_{Kr}, can be estimated from Equations 3 and 5 by linearizing the integrated form of the equations and finding the best fit estimate of K_{Kr} as follows:

$$\ln R = -K_{Kr}t + \ln R_0 \quad (6)$$

Where

R_0 = krypton:tritium ratio at $t = 0$.

To use the radiotracer procedure for aeration system testing, it is necessary to know the ratio of K_{Kr} to K_La. It has been shown experimentally, and supported theoretically, that for surface aeration under identical mixing conditions

$$\frac{K_{Kr}}{K_La} = 0.83 \pm 0.04 \quad (7)$$

This ratio has been shown experimentally to be unaffected, over a large range of mixing conditions, by the presence or absence of a broken water surface or by the direction of gas movement in the temperature range of 10 to 30°C.

Equation 7 must be corrected for subsurface aeration to account for gas phase buildup of krypton due to stripping. This phenomenon is documented by others.[5] Using their correction procedures, the K_{Kr}:K_La ratios were found to be 0.78 and 0.79 for the Opelika clean and process water tests, respectively, and 0.79 and 0.78 for the two South Hill clean water tests. Detailed calculations of the corrections are available elsewhere.[5,7]

Dissolved oxygen mass balance. From the outset of the project, the manufacturers indicated that the plug flow nature of the TBOD system resulted in distinct changes in DO concentration as the liquid flowed through the turbines, producing "stair steps" in the DO concentration profile. These steps are most distinct at the beginning of the test and gradually disappear as the test proceeds due to mixing and dispersion. In addition, in the first step, excess sulfite, if present, will be oxidized at the turbine inlets, which results in a smaller change in DO. Figure 6 shows typical stair steps in the DO concentration during a reaeration test.

The mass rate of oxygen transfer (OTR) was calculated as follows:

$$\text{OTR} = Q_T(C_0 - C_1) \quad (8)$$

Where

Q_T = flow rate through the turbine(s),
C_1 = turbine inlet DO concentration, and
C_0 = turbine outlet DO concentration.

OTR was corrected to standard conditions using Equation 9 as follows:

$$\text{SOTR} = \frac{\text{OTR}\ C^*_{\infty 20}}{\theta^{T-20}\left(C^*_{\infty T} - \frac{(C_0 + C_1)}{2}\right)} \quad (9)$$

Where

$\theta = 1.024$;
T = basin temperature, °C; and
$C^*_{\infty T}$ = DO saturation concentration at the basin temperature and pressure.

The DO measurements for this procedure were performed just upstream and downstream of the turbines (see Figures 4 and 5). The same data collected for the

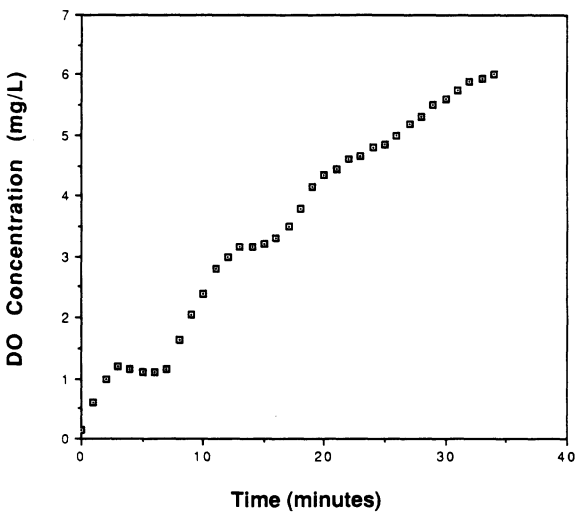

Figure 6—Typical "stair steps" observed in DO concentration in a TBOD clean water test.

ASCE procedure were used in this analysis. Flow rate was estimated using stream flow measuring techniques[9] and a magnetic flow meter. Other details of the procedure are presented elsewhere.[8]

Off-gas procedure. The oxygen transfer capability of a submerged aeration device, such as the DTTA, may be determined by means of a gas-phase mass balance over the aerated volume. Conducting such a mass balance on oxygen under process conditions is referred to as the off-gas method.[4]

The off-gas analysis procedure is a unique method of measuring the difference in the mole ratio of oxygen to inerts (conservative constituents, such as, N_2 and Ar_2) between the inlet and exiting gases from the aerator. As a result, unlike other methods, off-gas analysis measures oxygen transfer efficiency directly. The method employs measurement of the partial pressure of gaseous oxygen of atmospheric air and off gas under controlled conditions of pressure, temperature, humidity, and flow rate, using a gas-phase oxygen analyzer. The humidity of both atmospheric and off-gas samples are controlled by drying both gas streams with a desiccant. Carbon dioxide content, by volume, is measured only for the off-gas stream. A more detailed description of the procedure has been published elsewhere.[4]

Measurement of oxygen transfer efficiency by the off-gas method requires one or more off-gas collection hoods and an off-gas analyzer to measure the previously described constituents under controlled conditions. For the Opelika and South Hill TBODs, a fixed gas-sampling hood was placed over the entire cross section of the channel from the barrier wall downstream to the approximate end of the highly turbulent water surface. The configuration and location of these fixed hoods are shown in Figures 4 and 5. In addition to the fixed hood, a 1.2-m by 2.4-m (4-ft by 8-ft) portable hood was utilized for monitoring additional sampling positions downstream from the fixed hood until off-gas flows became insignificant.

For both systems tested, an in-line airflow measurement device was used to determine the applied airflow rate to the draft tube. At Opelika, the primary measuring element was a multiple-ported pitot tube; at South Hill, a sharp-edged, concentrically-bored orifice plate was used.

In order to accurately compute overall oxygen transfer efficiency and oxygen transfer rate, accurate measurements of the rate of off-gas flow from each sampling position are required. Off-gas flow from the fixed hood was estimated by observing the velocity profile from the discharge piping using a hot-wire anemometer. Off-gas flow from the portable hood was measured at different locations downstream of the fixed hood using variable-area glass rotameters at points in time when the rate of gas withdrawal from the hood was in equilibrium with the influx of gas to the hood from the aeration system.

The off-gas flow rates from the fixed and portable hood locations were corrected for temperature, pressure, humidity, carbon dioxide content, and oxygen depletion and then totalized. This total was compared to the airflow rate applied to the turbine(s), measured using the installed in-line instrumentation, to assess the adequacy of the off-gas hood placement and "capture" procedures. It is desirable to capture a high fraction of the off gas.

The oxygen absorption efficiency, or the fraction of oxygen transferred to the liquid as a ratio of that supplied by the compressed air, is commonly referred to as oxygen transfer efficiency (OTE). Since OTE is a function of the DO gradient ($C^*_\infty - C$), it is essential to observe the residual DO of the mixed liquor for each sampling location. Knowledge of the residual DO along with the actual gas-phase OTE, determined under existing field or process conditions, permits translation of field transfer efficiency data to other conditions, particularly the standard conditions assumed in clean water testing procedures. The overall weighted gas-phase OTE is computed as the summation of the product of OTE and off-gas flow rate for each hood location employed, divided by the summation of the total observed off-gas flow rates.

To translate OTE values to standard conditions, corrections can be made for all factors and conditions except the alpha factor (ratio of process to clean water mass transfer coefficients) as follows:

$$\alpha\text{SOTE} = \frac{\text{OTE}\ C^*_{\infty 20}}{\theta^{T-20}(\beta C^*_{\infty T} - C)} \qquad (10)$$

Where

β = ratio of process water DO saturation to clean water DO saturation.

In the more commonly encountered diffused aeration systems, where oxygen transfer and mixing are occurring within the same general zone, gradients in residual DO are typically very small. Unlike many submerged aeration devices, the DTTA has a distinct aeration zone and a distinct accumulation zone, resulting in a DO gradient. Therefore, some type of average DO value at the collection hood must be used in Equation 10 to estimate the effective DO driving force. For the TBOD, some question exists with respect to what the true effective driving force is across the aeration device.

For the Opelika tests, the αSOTEs of the fixed hood data were computed using both the log-mean average and arithmetic average of DO entering and leaving the J-tube. An insignificant difference was observed in the values of αSOTE for the fixed hood position using the two techniques. Therefore, the arithmetic average technique was employed for the fixed hood samples at both sites. This is consistent with the DO mass balance procedure described previously. For the portable hoods, DO was measured close to each hood location employed and this value was used in calculating αSOTE.

It should be pointed out that, due to the DO rise through the J-tube, it is not possible for this device to operate at an effective residual DO of zero. As a result, the values of αSOTE presented are unobtainable unless the entire basin is operated at zero DO concentration.

Process mass balance. A process mass balance on carbonaceous oxygen demanding material was made for Opelika using the following mass balance equation:

$$\text{COUR} = Q(S_o - S_e)(1 - K_{ox}Y) + f_d K_{ox} b V X_a \qquad (11)$$

Where

COUR = carbonaceous oxygen demand satisfied, mass/t;
Q = influent wastewater flow rate, L^3/t;
S_o, S_e = influent, effluent COD or BOD concentration, mass/L^3;
K_{ox} = COD or BOD of waste solids, mass/mass;
Y = biological yield, mass/mass;
f_d = fraction biodegradable, mass/mass;
b = decay coefficient, t^{-1};
V = liquid volume of the reactor, L^3; and
X_a = active biomass concentration, mass/L^3.

Since nitrification and denitrification can both occur in a TBOD, it was also necessary to calculate nitrogenous oxygen demand satisfied at Opelika to permit estimates of process water oxygen transfer rate to be made using this procedure:

$$NOUR = [Q(TKN_I - TKN_E) - Q_W TKN_W]1.71 + Q(NO_{3_E})2.86 \quad (12)$$

Where

NOUR = nitrogenous oxygen demand satisfied, mass/t;
Q_W = waste sludge flow rate, L^3/t;
TKN_I = influent total Kjeldahl nitrogen (TKN) concentration, mass/L^3;
TKN_E = effluent TKN concentration, mass/L^3;
TKN_W = waste sludge TKN concentration, mass/L^3; and
NO_{3_E} = effluent nitrate plus nitrite concentration, mass/L^3.

The coefficient 1.71 is the net oxygen required to nitrify and denitrify TKN. The coefficient 2.86 reflects the additional oxygen required if denitrification does not occur.

Table 1—Test conditions for Opelika.

Test number	Total turbine power, kW	Total blower power, kW	Total air flow, m^3/h	Total power, kW
Clean water				
1	90	34	2018	123
2[a]	90	34	2030	123
3	90	33	2000	122
3A	90	34	2062	123
4[a]	45	16	1026	60
5	91	15	1060	106
6	127	55	2905	182
Process water				
1P[a]	95	33	1898	126
2P[a]	47	16	968	63
3P	93	33	1925	126
4P	130	57	2774	187

[a] Radiotracer tests performed.

Table 2—Test conditions for South Hill.

Test number	Total turbine power, kW	Total blower power, kW	Total air flow, m^3/h	Total power, kW
Clean water				
T	33	12	705	45
1[a]	33	12	705	45
2[a]	17	5.1	319	22
3	33	12	705	45
4	17	5.1	319	22
Process water				
1P	15	5.1	314	20
2P	36	12	683	47

[a] Radiotracer tests performed.

Necessary process data were collected 2 weeks prior to and 2 weeks after process water testing at Opelika to factor into the above equations. In general, the process was fully nitrifying and denitrifying during this period. Similar process data were not collected at South Hill. Details of this procedure are provided elsewhere.[8]

Test Results

The test data were analyzed by both the contractors and manufacturers performing the tests and the authors. In general, the contractors' and manufacturers' analyses were very similar to the authors' analyses. The small differences that existed were resolved, and the results presented herein represent a consensus. The clean and process water test conditions for Opelika and South Hill are shown in Tables 1 and 2, respectively. The results obtained with each test method are discussed in the following text, and comparisons are made later.

At South Hill, two series of process water tests were performed. The first series was performed in Ditch 2. Due to problems with gas flow rate measurements and differences in turbine performance, it was necessary to perform a second series of process water tests in Ditch 1. Results of Series 2 are reported herein; no results are reported for Series 1.

Clean water tests. *ASCE procedure.* The clean water tests were conducted in accordance with the ASCE Standard. The test results were consistent with the Standard, and probe-to-probe variability was low. Table 3 shows the results obtained using the ASCE method.

The spatial variation of average determination point values of $K_L a_{20}$ generally fell within ±4% of the average $K_L a_{20}$ values, which is well within the ±10% required by the ASCE Standard. This observation indicates that the probe locations were generally well selected and effectively described the oxygen transfer capabilities of the TBODs. In addition, the $K_L a_{20}$ values for replicate tests performed at each site (Tests 1–3, and 3A at Opelika; Tests T, 1, and 3 at South Hill) were also within ±4% of the mean values, which is significantly less than the required ±15% as specified in the Standard.

Table 3—Clean water test results using the ASCE standard method.

Opelika					South Hill				
Test number	SOTR, kg/h	SOTE, percent	SAE, kg O_2/kWh	$C^*_{\infty 20}$, mg/L	Test number	SOTR, kg/h	SOTE, percent	SAE, kg O_2/kWh	$C^*_{\infty 20}$, mg/L
1	123	21.9	1.00	11.4	T	40.9	20.9	0.90	10.6
2[a]	129	22.9	1.05	11.7	1[a]	43.2	22.1	0.95	11.4
3	135	24.2	1.10	11.4	2[a]	24.1	27.2	1.11	11.6
3A	132	23.1	1.07	11.4	3	45.0	23.0	0.99	11.5
4[a]	68.2	24.0	1.13	12.1	4	25.0	28.2	1.15	12.0
5	80.9	27.5	0.76	11.6					
6	198	24.6	1.22	11.8					

[a] Radiotracer tests performed on these runs.

Refinements in the ASCE test procedure that are particularly suited to oxidation ditch testing were revealed. Noteworthy among these are

- The flow properties of the TBOD, and by extension any oxidation ditch, make thorough mixing of the sulfite within the basin difficult. It is critically important to have thorough sulfite mixing to achieve a successful test. Addition of the sulfite solution at the turbine (without aeration) over several circulation times, followed by several circulations after sulfite addition, was practiced. This technique was successful and achieved excellent mixing.
- It is significant to note that the amount of excess sulfite used (100 to 150% of stoichiometric) did not affect SOTR, SAE, or K_La, as determined in replicate testing.
- In analyzing data from these sites, it is clear that frequent sampling (preferably continuous monitoring) is required to ensure that the previously described "stair steps" do not affect the estimates of K_La and C^*_∞. Winkler testing for this application is impractical due to the large number of samples required.
- The normality of the sodium thiosulfite used at Opelika was checked and found to be 0.026 N. This discrepancy, if undetected, would have biased the values of C^*_∞ and SOTR by −4%. This error is equal to the test-to-test variability of all other experimental differences. Therefore, it is extremely important to standardize thiosulfite during the testing program.

Radiotracer procedure. Radiotracer tests were conducted simultaneously with the ASCE clean water tests during Test Runs 2 and 4 at Opelika and Test Runs 1 and 2 at South Hill. As indicated previously, the K_{Kr} to K_La ratios were corrected from the value of 0.83 reported for surface aeration to 0.78 for Opelika Test Runs 2 and 4 and 0.79 and 0.78 for South Hill Test Runs 1 and 2, respectively. The radiotracer results for Test Runs 2 and 4 at Opelika were 128 ± 4 and 68 ± 3 kg O_2/h, respectively. At South Hill for Test Runs 1 and 2 the results were 47 ± 3 and 24 ± 2 kg O_2/h, respectively. The plus or minus variability represents the range of results from all four sampling points. These results compare very favorably with the ASCE method results.

The radiotracer test also provided useful information on the mixing characteristics of the ditches. Figure 7 presents typical radiotracer data that illustrate the plug flow nature of the TBOD. The time between peaks represents the circulation time for the ditch. Note that for these tests, only analysis of the krypton-to-tritium ratio (Equation 6) can provide meaningful results.

Table 4 compares the circulation times calculated for Opelika and South Hill using the radiotracer procedure

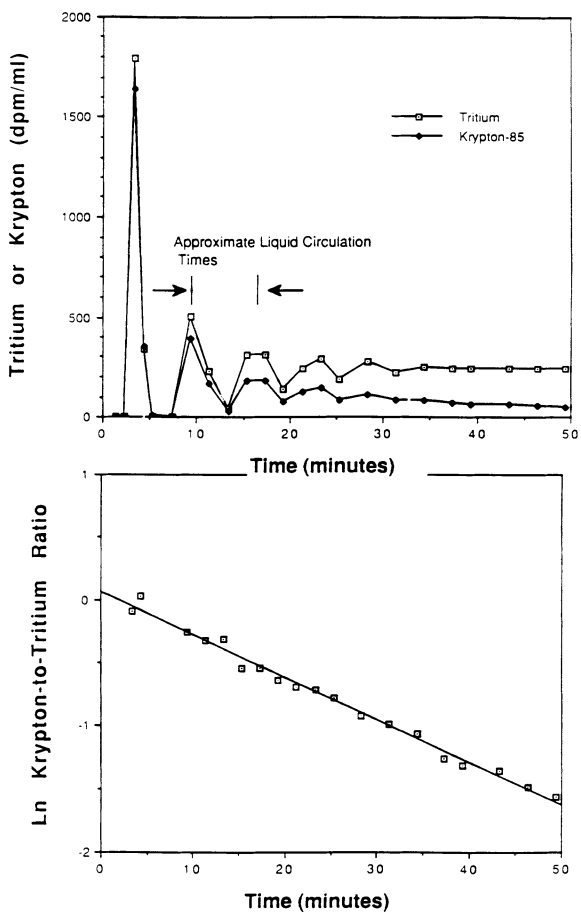

Figure 7—Typical radiotracer method results.

Table 4—Liquid circulation times in the TBODs.

Opelika			South Hill		
Test number	Circulation time, min velocity meter	Radio-tracer	Test number	Circulation time, min velocity meter	Radio-tracer
1	6.4[a]		1	7.6	9
2	6.4[a]	6	2	11.1	14
3	6.4[a]				
3A	6.4[a]				
4	8.9	9			
5	6.4[a]				
6	5.1				

[a] Calculated from a series of velocity measurements under identical conditions.

with circulation times estimated from velocity measurements. Excellent agreement between these two methods was obtained at Opelika. The agreement was poorer for South Hill, and no single explanation for the differences is known.

DO mass balance procedure. Equations 8 and 9 were used to calculate the oxygen transfer rate. Each data pair from the probes just upstream and downstream of the turbine produced one value of SOTR. To obtain meaningful results, a series of estimates must be averaged, as shown in Figure 8. For all tests, a "plateau" of nearly constant estimates exists that can be averaged to obtain meaningful estimates of SOTR. After the plateau as the DO increases, estimates for SOTR diverge, becoming very small, perhaps negative, or very large. This occurs because of probe calibration errors or random fluctuations in DO, which cause the denominator of Equation 9 to be too large or to vanish too quickly.

Table 5 shows the results derived using the DO mass balance procedure for all clean water tests at both sites. The standard deviation in SOTR estimates and the test-to-test variability clearly delineate the imprecision of this method. The test-to-test variability from the average of all replicates was +7.6% to −15.9% for Opelika and +10.2% to −11% for South Hill. The ASCE method produced individual test estimates of SOTR within ±4% of the mean for both locations.

The authors believe this is an inferior method to both the ASCE and radiotracer methods for purposes of clean water SOTR estimating. The accuracy of the method is directly proportional to the accuracy of measuring ditch velocity. Probe calibration errors directly affect the estimates of $K_L a$ and also introduce errors in converting to standard conditions.

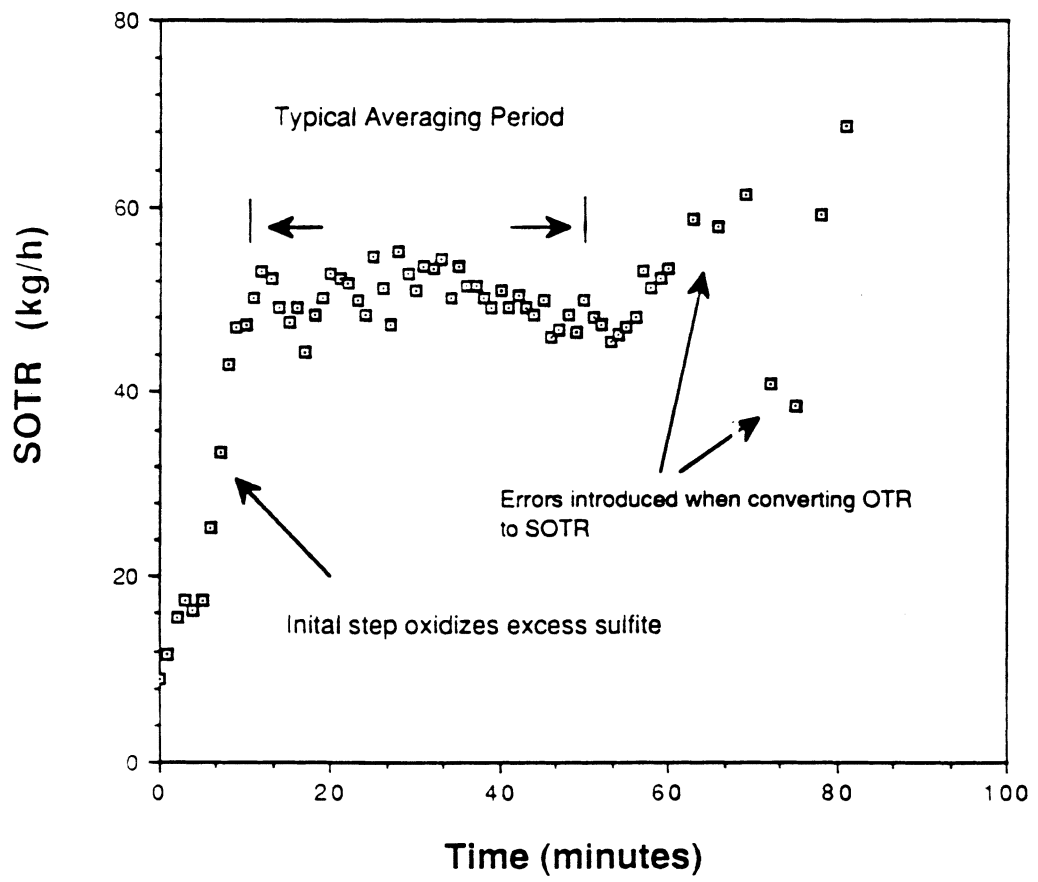

Figure 8—Typical DO mass balance procedure results.

Table 5—Clean water test results using the DO mass balance procedure.

Opelika				South Hill			
Test number	SOTR, kg O_2/h	Standard deviation	SAE, kg O_2/kWh	Test number	SOTR, kg O_2/h	Standard deviation	SAE, kg O_2/kWh
1	142	10.5	1.16	T	40	2.7	0.88
2	133	20.5	1.08	1	46	2.3	1.01
3	111	7.7	0.91	2	20	1.4	0.90
3A	142	11.8	1.15	3	50	2.7	0.82
4	76	5.5	1.26	4	25	1.8	1.12
5	79	6.8	0.75				
6	170	7.7	0.94				

Process water tests. *Off-gas procedure.* Off-gas analyses were performed several weeks (Opelika) to several months (South Hill) after clean water tests were concluded using the same test basins. Sufficient time was required to develop a nearly steady-state condition of the biological system prior to process water testing. As noted earlier, the first series of process water tests at South Hill were not successful due to gas flow metering problems and an apparent difference in performance characteristics between DTTAs in Ditches 1 and 2. These problems were avoided, however, in the second test series reported herein. Table 6 summarizes the off-gas test results for both sites.

At Opelika, excellent balances were obtained between gas flow rates collected by the hoods (both fixed and portable) and the airflow applied to the basin as estimated from airflow measurements. The first three tests demonstrated a balance ranging from 98 to 99%. In the last run (4P), severe foaming problems were encountered due to high turbulence. This caused difficulties in sampling with the floating hoods, producing errors in gas flow measurement. (It did not, however, affect αSOTE measurements.) In order to estimate αSOTR, floating hood gas flow measurements (the fixed hood values were felt to be very accurate) were increased so that the collected gas flow rates were comparable to the estimated applied airflow rates. Tests 1P and 3P at Opelika were replicates and produced estimates of αSOTR within $\pm 1\%$ of the mean value.

The gas capture efficiencies at South Hill were not as good as those at Opelika. This was due primarily to significant leaks from the fixed hood as demonstrated by smoke tests. Every effort was made to close the leaks; however, the leaks were along both sides of the hood, and it was difficult to seal the long seams. Calculated values of SOTR were based on metered gas flow rates in the air delivery line.

As indicated previously, calculation of the driving force $(C^*_\infty - C)$ is controversial. The value of C can be estimated by several methods. For the results shown here, the arithmetic average of the turbine inlet and exit DO concentrations was used. The magnitude of the effect of different assumptions for C will increase as the DO increases. For the cases reported herein, the magnitude of the difference in SOTR caused by using the arithmetic or log-mean average of inlet and outlet DO concentrations was insignificant.

Radiotracer procedure. Process water radiotracer tests were conducted simultaneously with off-gas tests during Test Runs 1P and 2P at Opelika. Both tests required correcting the K_{Kr} to $K_L a$ ratio to 0.79. The SOTRs for Test Runs 1P and 2P were 100 ± 2 and 48 ± 3 kg O_2/h, respectively. The SAEs were 0.82 ± 0.02 and 0.80 ± 0.05 kg O_2/kWh. These results compare very favorably with the off-gas method results.

Process mass balance. The process mass balance results for Opelika are too detailed to be reported herein and can be found elsewhere.[8] Since the gas flow rates and turbine speeds varied during the 4-week period of observation, the most useful indicator to compare with the results of the other process water tests is αSAE. The αSAEs estimated using the process mass balance procedure varied

Table 6—Process water test results using the off-gas procedure.

Opelika					South Hill				
Test number	Applied airflow rate, m^3/h (percent balance)[a]	αSOTE, percent	αSOTR, kg O_2/h	αSAE, kg O_2/kWh	Test number	Applied airflow rate, m^3h (percent balance)[a]	αSOTE, percent	αSOTR, kg O_2h	αSAE, kg/O_2/kWh
1P	1897 (99.1)	18.6	98.2	0.77	1P	314 (84.8)	22.5	19.8	0.97
2P	968 (98.9)	18.8	50.5	0.80	2P	683 (89.7)	19.8	37.7	0.80
3P	1925 (98.3)	18.7	100	0.79					
4P[b]	2774 (99.5)	17.0	130	0.70					

[a] Airflow rate measured from hoods divided by blower airflow rate × 100.

[b] Reflects correction of floating hood capture rates (see text).

from 0.87 to 0.89 kg O_2/kWh (1.43 to 1.46 lb/wire hp/hr). This is approximately 13% higher than the mean αSAE value of all process water tests conducted at Opelika using the off-gas method. This agreement is considered favorable, given the large range of assumptions required to perform a process mass balance and the error inherent in measuring the COD of waste sludge and scum.

Discussion

Clean water tests. Table 7 summarizes the results obtained with all clean water test procedures for both Opelika and South Hill. The value and standard deviation of SOTRs are used as the basis of comparison.

The SOTRs determined using the different procedures are remarkably close. The SOTRs estimated using the ASCE and radiotracer procedures were within 0 and 0.6% of each other at Opelika and within 0 and 8.4% of each other at South Hill. These small differences are much less than the estimated precision of ±15% for the ASCE method. The DO mass balance procedure produced estimates of SOTR within −19 to 16% of the ASCE results. The precision of this method for replicated runs is poor, within ±20% of the mean of the replicate runs, as compared to ±4% for the ASCE method. As mentioned previously, the structure of the standardization equation magnifies the experimental error.

Based on these analyses, it is clear the ASCE Standard procedure represents a valid methodology for estimating the clean water oxygen transfer capacity of flow configurations and tank geometries represented by the TBOD. Testing of these systems is more difficult than for conventional rectangular tank geometries. Care must be exercised in the addition of sulfite, the collection of an adequate number of DO samples at appropriate locations within the system, and the analysis of the data collected.

The clean water estimates of SAE for both Opelika and South Hill ranged from 0.76 to 1.15 kg O_2/kWh (1.25 to 1.89 lb/wire hp/hr). These values were strongly affected by turbine power, blower power, and their ratio. The SOTE in clean water ranged from 21 to 28%, with a similar strong dependence on power. It is instructive to note that the values of SAE and SOTE in clean water were very similar at both sites, even though the DTTAs were furnished by different manufacturers and the ditch configurations varied significantly.

The utility of the ASCE method for noncomplete mixing regimes is surprising to some investigators. Its success is due to the large number (≥4) of determination points. The location of the determination points (probe locations) is important because, as a whole, they should represent the entire tank volume. They must be located at points of high and low DO compared to the mean basin DO.

The protocol for probe locations was subject to considerably debate in the development of the ASCE Standard. The debate addressed probe locations for testing surface or turbine aerators, which, like DTTAs in a TBOD, can produce gradients in DO concentration across the tank volume.

The debate was settled by visualizing a volume of liquid associated with the tank locations of high or low DO concentration. A probe must be located in such a way that it represents the DO of each liquid volume. The total DO mass can then be calculated as follows:

$$M_{DO}(t) = \sum_{i=1}^{n} V_i DO_i \qquad (13)$$

Table 7—Comparison of clean water test results.

Test number	ASCE SOTR, kg O_2/h	ASCE Standard deviation[a]	DO mass balance SOTR, kg O_2/h	DO mass balance Standard deviation[a]	DO mass balance Difference with ASCE, percent	Radiotracer SOTR, kg O_2/h	Radiotracer Standard deviation[a]	Radiotracer Difference with ASCE, percent
				Opelika				
1	123	4.9	142	10.5	+15.9			
2	129	2.6	132	20.5	+3.2	128	2.6	0
3	132	2.7	111	7.1	−17.2			
3A	132	3.3	142	11.8	+7.2			
4	68	3.1	76	5.5	+12.2	68	1.8	−0.6
5	81	1.5	79	6.8	−2.2			
6	198	3.1	170	7.7	−13.8			
				South Hill				
T	40.9	2	40	2.7	−2.2			
1	43	1.4	46	2.3	+6.3	47	2.1	+8.4
2	24	1.4	20	1.4	−18.9	24	1.4	0
3	45	0.6	50	2.7	+11.1			
4	25	0.6	25	1.8	−1.8			

[a] Standard deviations for the ASCE and radiotracer methods are calculated over probes or sample locations. Standard deviations for the DO mass balance method are calculated over observations.

Where

$M_{DO}(t)$ = total basin DO mass at time t,
i = determination point, or probe location,
V_i = liquid volume associated with point i,
DO_i = DO at point i, and
n = number of probe locations.

The basin volumes must be associated with each probe, subject to the constraint that

$$V = \sum_{i=1}^{n} V_i \qquad (14)$$

Where

V = liquid volume of the reactor.

The clean water testing programs at Opelika and South Hill were not designed to use this data analysis; otherwise, determination points might have been selected differently. Nevertheless, it is useful to analyze the data in this way. Figure 9 shows the results of Opelika clean water Test Run 3. These data can be analyzed using the same nonlinear exponential technique used in the ASCE procedure, except that the program estimates K_La, the product of basin volume, and mean basin DO concentration. Analysis of the data shown in Figure 9 produces a K_La_{20} of 1.99/h^{-1}, which compares favorably with 2.07/h^{-1} estimated using the ASCE procedure.

Process water tests. A summary of the process water test results for both sites is presented in Table 8. The agreement in αSOTR values estimated with the radiotracer and off-gas methods is excellent for both Test Runs 1P and 2P at Opelika (within 2 to 5% of each other).

The alpha factors calculated for the Opelika TBOD ranged from 0.66 to 0.77 with the majority of the test results ranging from 0.70 to 0.77. The South Hill alpha values were higher, ranging from 0.81 to 0.87. It is likely that the differences in alpha between these plant sites is attributable to plant loading. The instantaneous food:microorganism (F:M) loading at Opelika during process water testing was 0.14 day^{-1} (mixed liquor suspended solids (MLSS) basis), and the specific oxygen uptake rate (SOUR) was 7.3 mg O_2/g MLSS·h. The instantaneous F:M loading for South Hill during the second process water test series (Spring 1987) was 0.09 day^{-1} (MLSS basis), and the SOUR was only 3.5 mg O_2/g MLSS·h. The low values at South Hill were representative of extended aeration systems, whereas the values at Opelika were higher and representative of systems operating in the lower portion of the conventional activated sludge loading range. The alpha factors reported herein should be used with caution and should not be extrapolated to higher loaded systems.

Comparison of test data with design basis for Opelika. In separating oxygen transfer performance from TBOD process performance, it is useful to review the process

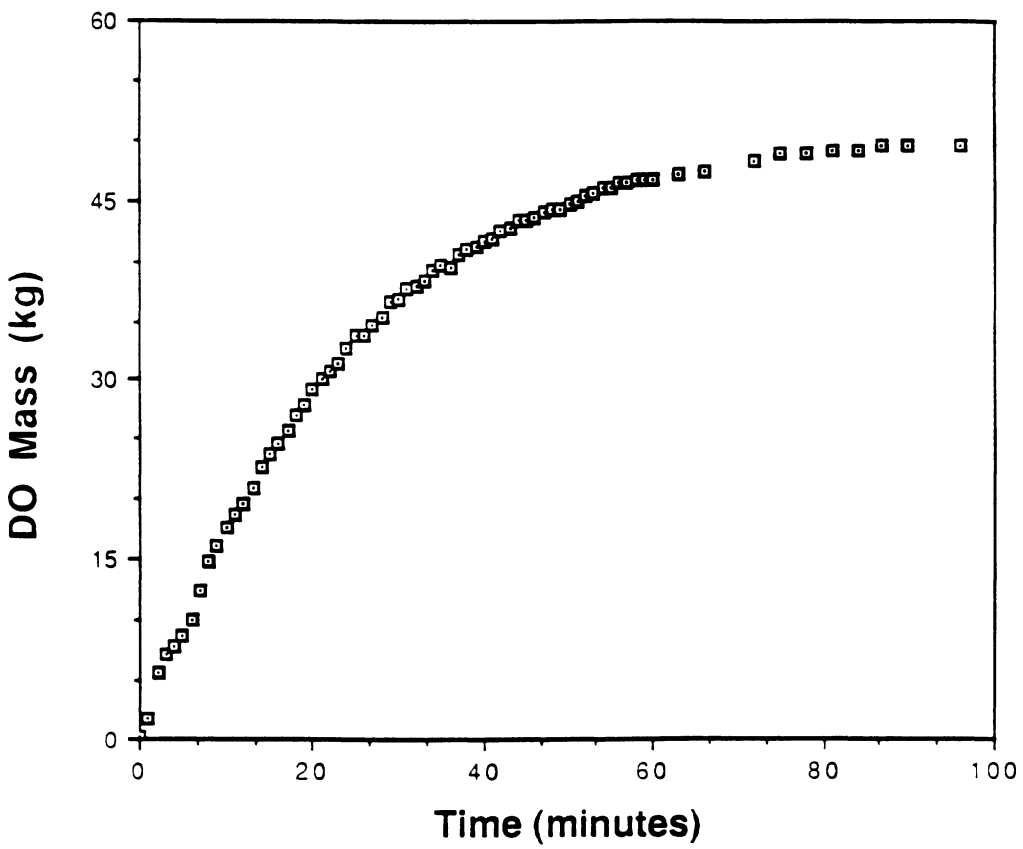

Figure 9—Total aeration basin DO mass versus time.

Table 8—Comparison of process water αSOTR values and alpha factors.

Test number	Radiotracer αSOTR, kg O_2/h	Off-gas αSOTR, kg O_2/h	Equivalent clean water SOTR, kg O_2/h	Alpha factor
		Opelika		
1P+	100 ± 1.4	98	130 ± 5.0	0.76–0.77
2P+	48 ± 2.2	50	68	0.70–0.74
3P+	—	100	130	0.77
4P	—	130	198	0.66
		South Hill		
1P	—	19.8	24 ± 0.5	0.81
2P	—	38	43 ± 2	0.87

design basis. Table 9 compares the Opelika design basis with actual plant operating data for a 4-week period in the summer of 1986. The design was based on Ten-State Standards criteria, which include no provisions for denitrification. The total oxygen required was calculated from the process mass balance described earlier.[8] The total oxygen requirement estimated by the process mass balance, 2454 kg/d (5410 lb/day), compares closely with that measured from replicate off-gas Test Runs 1P and 2P, 2138 kg/d (4713 lb/day).

The conservation built into the design procedures more than compensated for the shortfall in aeration system performance. The large difference in the O_2 required:5-day biochemical oxygen demand (BOD_5) applied ratio utilized for design compared with that experienced during actual operation (1.8 versus 1.34, respectively) and the lack of denitrification credits employed in the design procedure inflated the design basis total oxygen requirement by 1704 kg/d (3757 lb/day). Therefore, it is not surprising that the Opelika TBOD was meeting its summer effluent requirements at near design load, even though the measured OTR was much less than the equipment supplier's expectations.

Table 9—Comparison of the aeration requirements for the design basis and actual operation of the Opelika TBOD.

Parameter	Design basis/ ditch	Actual value/ ditch
Flow rate, m^3/h	315	284
Influent BOD_5, mg/L	204	250
Influent TSS, mg/L	200	195
Influent NH_4^+-N, mg/L	25	—
Influent organic N, mg/L	15	—
Influent TKN, mg/L	40	27.2
Effluent BOD_5, mg/L	30/15[a]	9
Effluent TSS, mg/L	30/15[a]	11
Effluent NH_4^+-N, mg/L	—/3[a]	
Effluent TKN, mg/L	0	2.7
Effluent NO_2^-/NO_3^--N, mg/L	—/—	0.3
Effluent DO, mg/L	—/5[a]	7.6
O_2 required/BOD_5 applied, kg/kg	1.8	1.34
Total O_2 required for nitrification/denitrification, kg/d	1382	171
Total O_2 required for BOD_5 removal, kg/d	2776	2283
Total O_2 required, kg/d	4158	2454
Peaking factor	1.5	—
Total peak O_2, kg/d	6237	—

[a] Winter/summer effluent requirements.

Conclusions

A comprehensive oxygen transfer evaluation of DTTAs was performed at two TBODs at Opelika and South Hill. Three different clean water oxygen transfer methods were utilized at each site. In addition, two process water oxygen transfer methods were used at Opelika and one at South Hill. Finally, a process mass balance was calculated at Opelika. Based on the test results, the following conclusions were reached:

- The ASCE nonsteady-state procedure for clean water oxygen transfer testing produced estimates of $K_L a_{20}$ at individual determination points that were generally ±4% of the mean value, indicating that probe locations at both test sites effectively described the oxygen transfer capacity of the ditches. The estimated values of clean water SOTR using the ASCE procedure were also generally within ±4% of the mean SOTR for replicate clean water tests performed at each site, well within the required ±15% variation from the mean specified by the Standard.
- The ASCE procedure and the radiotracer procedure produced estimates of clean water SOTR within ±1% of each other at Opelika and within ±8% at South Hill for parallel tests. This is well within the estimated precision suggested by the Standard of ±15%.
- The DO mass balance procedure produced estimates of clean water SOTR within −19 to +16% of the ASCE procedure for parallel runs. However, SOTR estimates for replicate runs for this method were only within ±20% of the mean SOTR. Precision of this method was poorer

than for the other methods, and, for this reason, the DO mass balance procedure is considered inferior for purposes of estimating clean water SOTR.

- Sulfite addition ranging from stoichiometric to 150% in excess of stoichiometric did not affect the estimate of clean water SOTR in the TBOD configuration even though the characteristics of the DO versus time curves were different.
- The ASCE procedure is a valid method for evaluating the clean water oxygen transfer capacity of TBODs and should be valid for other types of ditch configurations. Testing of these systems is more difficult, however, due to the plug flow nature of the configuration. More care is required in introducing and mixing sodium sulfite. Also, more frequent DO sampling is warranted.
- Under process conditions, the off-gas analysis and the inert gas tracer (radioactive krypton) procedures produced estimates of field oxygen transfer efficiency corrected to standard conditions (αSOTR) within 2 and 5% of each other for two parallel tests at Opelika. These results agree closely with the results of a process mass balance performed on data collected over a 31-day operating period.
- Alpha factors were estimated for the Opelika and South Hill TBODs. At Opelika, the alpha factors ranged from 0.66 to 0.77 with the majority of the test results ranging from 0.70 to 0.77. The F:M loading at Opelika during process water testing was 0.14 day^{-1} (MLSS basis), and the SOUR was 7.3 mg O_2/g MLSS · h. At South Hill, alpha factors ranged from 0.81 to 0.87. The F:M loading during process water testing at South Hill was 0.09 day^{-1} (MLSS basis), and the SOUR was only 3.5 mg O_2/g MLSS · h. The alpha values reported herein are valid only for the specific type of equipment, wastewater characteristics, and process conditions evaluated at each site. They should not be extrapolated to higher-rate systems.
- The SAE values measured at these two sites in clean water ranged from 0.76 to 1.15 kg O_2/kWh (1.25 to 1.89 lb/wire hp-h). These values depended on turbine power, blower power, and the corresponding ratio of these powers. SOTEs measured at these two sites in clean water ranged from 21 to 28%, again depending on the aforementioned variables of power. For sites employing DTTAs from two different manufacturers and exhibiting differences in aeration tank size and geometry, the values of clean water SAE and SOTE were remarkably similar.

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