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Standard Guidelines for In-Process Oxygen Transfer Testing

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PREFACE

These guidelines for testing oxygen transfer devices in process water are the result of field testing by the ASCE Oxygen Transfer Standards Committee since about 1979. A significant portion of the early work by the Committee was supported by grants from the US Environmental Protection Agency.

Preparation of these guidelines was difficult. Side-by-side testing of a number of methods was used to verify reproducibility of the techniques and has led to substantial refinement in procedures and rejection of some techniques. The methods selected have proven to be most reliable under rigorous field conditions. The technology continues to remain dynamic, however, and modifications and/or new procedures are likely to occur in the future.

It is intended that these guidelines be used by engineers, owners, and manufacturers in evaluating the performance of aeration devices under process conditions. They are not intended for compliance testing of aeration devices insofar as performance under process conditions is affected by a large number of process variables and wastewater characteristics that are not easily controlled. In-process testing does provide the engineer with useful information that can be used in future design. It provides the owner with data that can be used for operation and

maintenance of the aeration equipment. These procedures provide manufacturers with a useful research and development tool for their equipment development and design.

The procedures as a whole are applicable for all oxygen transfer devices in suspended growth systems. They may also be applicable to testing oxygen transfer devices in lakes and streams. They are not applicable to fixed-film reactors, although modification of some of the methods might serve to provide data on these processes as well. The substance of the guidelines is based on the report, "Development of Standard Procedures for Evaluating Oxygen Transfer Devices," EPA 600/2-83-102, October 1983; however, other pertinent references are provided throughout this document dealing with more detail about the techniques. Section 5.0 provides a discussion on the comparison of the methods.

Since the original publication in 1996, the procedure that has gained the widest acceptance and use is the off-gas method detailed in Chapter 3. While still considered an accurate and reliable method for measuring oxygen transfer in process systems, the tracer technique described in Chapter 4 has not been used in recent years.

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The contributions of the EPA for workshops, laboratory, and field studies that support the development and refinement of these guidelines are gratefully acknowledged.

This standard was formulated through the consensus standards process by balloting in compliance with the procedures of the ASCE Codes and Standards Activity Council. Those individuals who serve on the EWRI Oxygen Transfer Standards Committee are

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CHAPTER 1

SCOPE

The methods described under these standard guidelines, which were first developed by ASCE (1996), provide several proven techniques for measuring oxygen transfer under process conditions. Nonsteady-state, off-gas, and inert gas tracer methods are described in Chapters 2, 3, and 4. Chapter 5 is a brief comparison among methods. The methods presented are considered to be well developed and provide satisfactory precision for a wide range of aeration processes in suspended-growth biological systems.

Because a wide range of process variables and wastewater characteristics that affect the precision (and accuracy) of these methods are difficult to control, the methods are offered as standard guidelines and are not recommended for compliance testing of aeration equipment. These guidelines use both the Système International (SI) units and common units. Symbols and nomenclature are defined in Appendix E. ASCE (1996) can still be obtained from the American Society of Civil Engineers in Reston, VA.

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CHAPTER 2 NONSTEADY-STATE METHOD

2.1 OBJECTIVE

This chapter describes a method to determine the average oxygen transfer coefficient, $K_L a_f$, for an aeration tank under actual process conditions by measuring the dissolved oxygen (DO) concentration over time after a perturbation from the steady-state condition. It is recommended that the perturbation be obtained using hydrogen peroxide, H_2O_2 , instead of changing the power level, to preserve hydrodynamics and allow higher incremental DO increases.

2.2 THEORETICAL BASIS

The theoretical basis for this method is derived from consideration of a mass balance around a completely mixed aeration tank under steady-state and nonsteady-state process conditions. The same mechanism applies (1) for oxygen transfer into wastewater, when the DO is less than the steady-state equilibrium value, and (2) for oxygen stripping from the wastewater, when the DO is greater than the steady-state equilibrium value. Note that this technique measures the oxygen transfer coefficient. It is not directly applicable for stripping other gases, which may have different molecular sizes and diffusion rates as well as significant gas side resistances. Kayser (1967, 1969, 1979) was the first researcher to apply this technique in testing aeration equipment under process conditions.

A liquid-phase mass balance for oxygen around a completely mixed aeration tank, as shown in Fig. 2-1, is determined by the following equation:

$$V \Delta C / \Delta t = Q C_i - Q C + K_L a_f (C_{\infty}^* - C) V - R V \quad (2-1)$$

Dividing by V and letting $\Delta \rightarrow 0$ yields the following differential equation:

$$\frac{dC}{dt} = \frac{(C_i - C)}{\theta_h} + K_L a_f (C_{\infty}^* - C) - R \quad (2-2)$$

where θ_h = detention time = V/Q and Q = total flow rate = $Q_P + Q_R$.

By setting dC/dt equal to zero in Eq. (2-2), the steady-state solution relates the oxygen uptake rate in the aeration tank, R , to the oxygen transfer coefficient and the steady-state deficit,

$$R = \frac{C_i - C_R}{\theta_h} + K_L a_f (C_{\infty}^* - C_R) \quad (2-3)$$

where $C = C_R$ at $dC/dt = 0$, the steady-state DO value in the tank at the in situ oxygen uptake rate, R . Substituting the steady-state solution, Eq. (2-3), into Eq. (2-2), yields

$$\frac{dC}{dt} = \frac{C_R - C}{\theta_h} + K_L a_f (C_R - C) \quad (2-4)$$

Integrating the above from “0” to “ t ,” assuming that conditions (θ_h , C_R , and $K_L a_f$) remain constant with time, yields

$$C_R - C = (C_R - C_0) e^{-Kt} \quad (2-5)$$

where

$$K = K_L a_f + \theta_h^{-1}$$

The previous equation is similar to the equation used for the nonsteady-state analysis of clean water (ASCE 2006), except that the saturation value has been replaced by the steady-state oxygen concentration, C_R , and detention time appears in the exponent for a flowing system. $K_L a_f$ is then calculated from the K value as

$$K_L a_f = K - \frac{1}{\theta_h} \quad (2-6)$$

in a completely mixed system.

For systems that are not completely mixed, modifications to the above approach are required, especially when different aeration densities exist in long, narrow aeration tanks (Hildreth 1983; Mueller 1985). A dual nonsteady-state method has been used to estimate accuracy of the nonsteady-state test (Mueller and Rysinger 1981; Mueller et al. 1983a); however, it requires a significant amount of process control to ensure constant conditions during testing.

2.3 ASSUMPTIONS AND LIMITATIONS

The assumptions made in the nonsteady-state analysis are the following:

1. Completely mixed system,
2. Constant R and $K_L a_f$ during the duration of the study, and
3. Probes located so that they sense equal tank volumes.

These assumptions require reasonable time periods, approximately $4/K_L a_f$, over which to conduct the tests and relatively constant process conditions. No dissolved or atmospheric oxygen limitation can exist in any portion of the tank immediately before or during the test because changing oxygen uptake rates would invalidate the results. This issue may require that the test be conducted on only a portion of the flow, so that conditions can be properly controlled. A change in the power level to obtain the perturbation from steady-state conditions must be made quickly to provide a response to a theoretically instantaneous change. This alteration can be obtained by changing the number of blowers on line or by changing the speed of surface aerators.

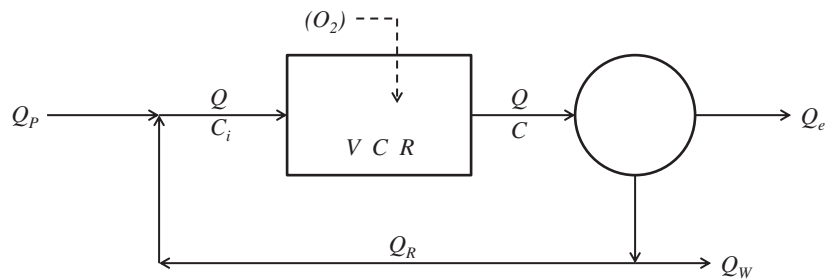


Figure 2-1. Schematic of a Completely Mixed System

It cannot be obtained by changing the blade submergence of a surface aerator by effluent weir level control because of the significant time required to change the tank volume.

2.4 PROCEDURE

To obtain nonsteady-state curves under process conditions, either of two approaches is taken, as shown in Fig. 2-2. The first approach (a) is to change power levels from either a lower to a higher level or vice versa to obtain a change in oxygen concentration with time and a new steady-state DO concentration, C_R . The alternative (b) is to add H_2O_2 to increase the DO to well above saturation while maintaining a constant power level. The oxygen will then be stripped out of solution until the C_R value is again obtained. Both curves will yield the same $K_L a_f$ and C_R values, providing that the uptake rate remains constant over the study. A nonlinear regression (NLR) technique, which is similar to the data analysis technique for clean water, is used to estimate C_R , C_0 , and K for analysis of the process data. The former provides not only best estimates for both C_R and K , but also the standard deviation of each in fitting the nonsteady-state data.

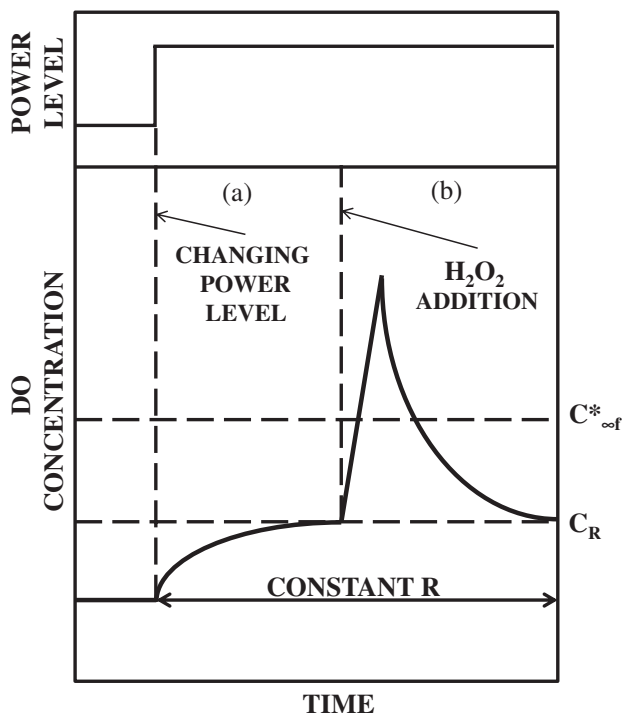


Figure 2-2. Nonsteady-State DO Curve for (a) Changing Power Levels and (b) H_2O_2 Addition

Constant load and oxygen uptake conditions should be maintained either by diverting some flow from the test basin or by testing during periods of approximately constant loading. Initially, DO concentrations should be monitored at several points throughout the test basin to define mixing patterns and ensure that the entire basin is aerobic. A minimum of four DO probes should be installed strategically within the aeration basin both vertically and horizontally to best represent the tank contents. Each probe should represent approximately equal tank volumes.

The recommended test procedure for nonsteady-state testing is the following:

1. Calibrate the DO probes in tap water at the same temperature as the test basin.
2. Place the probes at preselected vertical and horizontal positions in the aeration basin so that each probe senses an equal portion of the test volume. Stirred probes should be used, but if they are unavailable, locate the probes so that sufficient and regular velocity of mixed liquor across each is obtained. Probes should look upward to prevent bubbles from adhering to the membrane of the probe.
3. If recorders are used to continually monitor DO, calibrate the recorders to probe readings. Ensure that no change in probe signal occurs when probes are connected to recorders. This problem sometimes occurs when recorders are grounded.
4. For diffused-air systems, measure at regular intervals gas flow parameters, differential pressure readings, gas temperature, and pressure at the measuring device. For mechanical systems, measure power drawn.
5. Measure all influent, wastewater and return sludge flow rates, and DO concentrations.
6. Before and after tests, measure aeration basin temperature, air temperature, and barometric pressure—the last two by using a local (on-site) barometer and air temperature gauge, or by obtaining from the National Weather Service (www.weather.gov) and adjusting its sea level adjusted barometric pressure to a local station pressure based on the local altitude above sea level.
7. Change DO in basin by either (a) or (b):
 - (a) Change the power level by changing airflow distribution, turning a blower on or off, or changing power input to the mechanical aerator. A minimum DO difference of 2 mg/L should occur.
 - (b) Add H_2O_2 or high-purity oxygen to the tank. This procedure is recommended because a large difference in DO can be obtained; 10 mg/L is recommended. The H_2O_2 is dumped in using four to eight buckets, equally distributed around the tank. The full procedure is described in Kayser and Turner (1980). The method of adding high-purity oxygen.

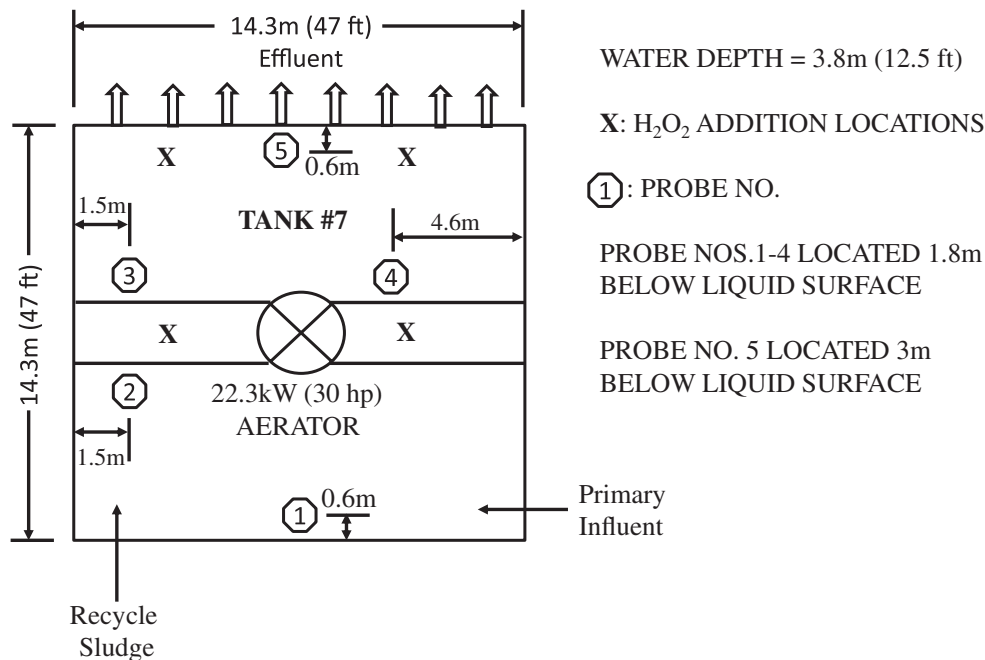


Figure 2-3. Dissolved Oxygen Probe Location during Haverstraw Test

Table 2-1. Test Conditions for Haverstraw Test No. 8

Surface aerator	22.4 kW (30 hp nominal)
Tank volume	783 m ³ (207,000 gal.)
Water depth	3.8 m (12.5 ft)
Power measurement	Three phase; assumed power factor = 90%
Voltage	200 V
Amperage	70 A
Wire hp	29.3 hp
Average Q_P	6,283 m ³ /d (1.66 million gal./d)
Average Q_R	3,444 m ³ /d (0.91 million gal./d) (from mass balance or steady state)
Total Q	9,727 m ³ /d (2.57 million gal./d)
C_i	2.3 mg/L (flow weighted average of return sludge and primary effluent)
Measured average oxygen uptake rate	19.4 mg/L-h
Mixed liquor temperature	20.0°C
Barometric pressure	101.3 kPa
Mixed liquor VSS	2,900 mg/L
Influent BOD ₅	90 mg/L
F/M	0.25/d

is described fully in ASCE/EWRI 2-06 *Measurement of Oxygen Transfer in Clean Water*.

- Monitor DO by recorder continuously during the test or at preselected time intervals to provide between 20 and 30 points during each test. The test duration should be $\sim 4/K_L a_f$, as recommended in the clean water standard of 2006.
- Analyze DO versus time data with the nonlinear regression program to obtain the best estimate of $K_L a_f$ and C_R .

- Calculate average $K_L a_f$ for the tank as follows:

$$K_L a_f = \frac{1}{n} \sum_{i=1}^n \frac{K_i V_i}{V_t} - \frac{1}{\theta_h} \quad (2-7)$$

or for equal volumes:

$$K_L a_f = \frac{1}{n} \sum_{i=1}^n K_i - \frac{1}{\theta_h} \quad (2-8)$$

where

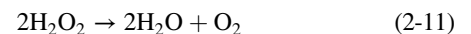
i = Each probe location;
 n = Number of probe locations;
 V_i = Volume of probe location i ; and
 V_t = Total volume.

- Calculate $SOTR_{pw}$, for the test as follows:

$$K_L a_{f20} = K_L a_f \theta^{(20-T)} \quad (2-9)$$

$$SOTR_{pw} = \beta C_{\infty 20}^* K_L a_{f20} V \quad (2-10)$$

2.4.1 The H₂O₂ Technique. Kayser (1979) indicated a convenient technique to raise the dissolved oxygen concentration in an aeration tank without changing power levels by using hydrogen peroxide. In the presence of a suitable catalyst—a reducing agent such as iron Fe⁺⁺—hydrogen peroxide dissociates to water and oxygen as given by the following equation:



Mixed liquor in an aeration tank contains significant amounts of reducing substances. They act as catalyzing agents, which allow the above reaction to take place within two minutes. Because mixing of aeration tank contents generally takes two to five minutes, this catalysis can be considered a slug dose of oxygen.

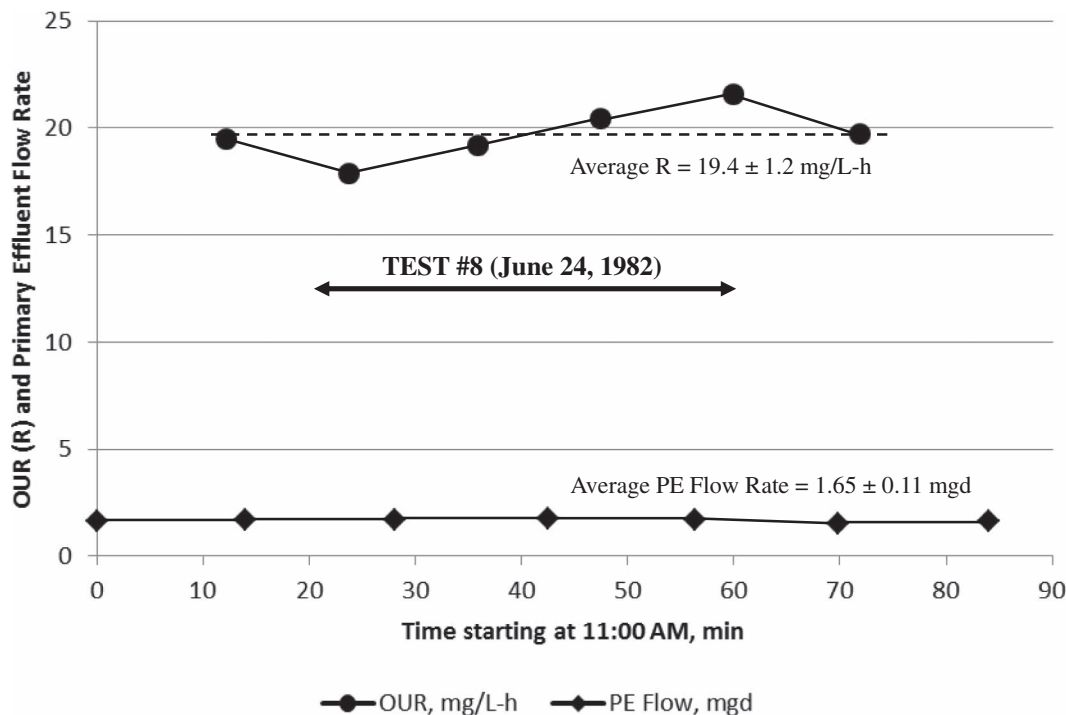


Figure 2-4. Flow and Oxygen Uptake Rate Variability during Haverstraw Test No. 8

into the system. Both laboratory and field studies have used an indicator to ensure that the peroxide did dissociate within two minutes. This technique cannot be used in clean water because dissociation generally does not occur or occurs over long time periods, or in wastewaters where enough catalyst may not be present. However, for aeration tanks with a significant amount of mixed liquor suspended solids (>1,000 mg/L), the technique is highly successful.

The volume of peroxide required in an aeration tank to obtain an incremental change in dissolved oxygen concentration can be calculated as follows. The stoichiometry in Eq. (2-11) indicates that 2.13 mg of H_2O_2 is required for every 1 mg of oxygen produced. The volume of hydrogen peroxide solution, V_{PER} , can be calculated using the following expression.

$$V_{PER} = 2.13(\Delta DO)V / (10 C_{PER} \rho_{PER}) \quad (2-12)$$

where

V_{PER} = Volume of H_2O_2 solution, L;

2.13 = Hydrogen peroxide needed to increase the mass concentration of oxygen by one unit, mg H_2O_2 /mg O_2 ;

10 = Conversion factor;

ΔDO = Theoretical DO increase in aeration tank, mg/L;

V = Aeration tank volume, m^3 ;

C_{PER} = Hydrogen peroxide solution strength, wt%;

ρ_{PER} = Density of hydrogen peroxide solution at solution strength of C_{PER} , kg/L.

For field use, 35% by weight hydrogen peroxide is normally available in drums. The density of 35% hydrogen peroxide solution is 1.13 kg/L at 25°C (Sigma-Aldrich 2015).

The actual increase in DO is less than that calculated using the H_2O_2 dose in Eq. (2-12) because of the oxygen uptake rate and

the stripping that occurs during the time required to completely mix the tank contents. This difference is typically between 1 and 5 mg/L.

In field studies, hydrogen peroxide addition is straightforward. A drum is placed horizontally on a drum rack, and a spigot is used to fill the buckets. Four to eight 18-L buckets are filled from a drum of peroxide and placed on two sides of the aeration tank opposite each other. At a signal the peroxide is immediately dumped into the tank, allowing the aerators to mix it thoroughly with the tank contents. After five minutes, recording of data for analysis is generally begun. When using H_2O_2 , eye protection must be provided and plastic gloves are typically used to protect the skin. Immediate removal of H_2O_2 from the skin by washing prevents damage.

2.5 SAMPLE CALCULATION

An example test run using batch dumps of H_2O_2 is given for Test No. 8 conducted at Haverstraw, New York, on June 24, 1982 (Fig. 2-3). The test conditions for this run are given in Table 2-1. Five DO probes were used in the tank, as shown in Fig. 2-3, while the measured O_2 uptake rates and primary effluent flow rates are given in Fig. 2-4.

Table 2-2 and Fig. 2-5 show the recorder data and calculated nonlinear regression results for Probe No. 2 of Test No. 8. Table 2-3 gives the average $K_L a_f$ and C_R values for each probe. The data from this study were excellent, with the coefficient of variation of $K_L a_f$ generally less than 2% and the standard deviation on $C_R < 0.1$ mg/L. In all nine tests conducted at this site, Probe No. 4 was always low—located too close to the aerator and not exposed to the full circulation and aeration pattern. The results were deleted from the analysis. The probes were also not located at equal tank volumes during these tests because of ease of location off the walkways and side of the tank.

Table 2-2. Nonlinear Estimation for Nonsteady-State Oxygen Transfer: Haverstraw Run No. 8, Probe No. 2 Data for High Weir Level on June 24, 1982

Iteration Number	C_R (mg/L)	C_0 (mg/L)	K (1/h)	Sum of Squares
0	3	12	4	23.6218
1	3.43932	15.1658	4.42839	0.145039
2	3.42317	15.1712	4.33255	0.0719237
3	3.42315	15.1743	4.33539	0.0718862
4	3.42313	15.1743	4.33534	0.0718863
5	3.42313	15.1743	4.33534	0.0718863

Standard Deviations of Parameter Estimates

Absolute units	0.0412211	0.0958618	0.0663178
Percent of LSE	1.20419	0.631738	1.5297

Summary of Data	Time (min)	Concentration (mg/L)	Fit Value	Residual
1	4	12.176	12.2247	-0.0486956
2	6	11.008	11.0404	-0.0324011
3	8	10.144	10.0155	0.12854
4	10	9.104	9.12843	-0.0244293
5	12	8.32	8.36076	-0.0407534
6	14	7.792	7.69637	0.0956278
7	16	7.072	7.12139	-0.04386
8	18	6.624	6.62377	2.3222×10^{-4}
9	20	6.24	6.19311	0.0468936
10	22	5.76	5.82039	-0.0603924
11	24	5.52	5.49783	0.02217515
12	26	5.248	5.21867	0.0293322
13	28	4.96	4.97707	-0.0170693
14	32	4.56	4.58702	-0.0270233
15	36	4.256	4.29488	-0.0388803
16	40	3.952	4.07607	-0.124066
17	44	3.872	3.91218	-0.0401764
18	48	3.84	3.78942	0.0505767
19	52	3.776	3.69748	0.0785182
20	56	3.68	3.62862	0.0513816

Note: LSE = Least squares estimate.

The tank detention time is

$$\theta_h = \frac{V}{Q} = \frac{783}{9727 \text{ m}^3/\text{d}} \times \frac{24 \text{ h}}{\text{day}} = 1.93 \text{ h} \quad (2-13)$$

The average $K_L a_f$ is then

$$\begin{aligned} K_L a_f &= K - \frac{1}{\theta_h} \\ &= 4.31 - \frac{1}{1.93} = 3.79/\text{h} = K_L a_{f20} \end{aligned} \quad (2-14)$$

No temperature correction is required because the data were collected at 20°C. Using a β of 0.99 yields the following result:

$$\begin{aligned} \text{SOTR}_{pw} &= (0.99)(9.09)(783)(3.79 \times 10^{-3}) \\ &= 26.7 \text{ kg O}_2/\text{h} \text{ (58.9 lb O}_2/\text{h)} \end{aligned}$$

2.6 QUALITY CONTROL

As in clean water testing, DO probe calibration is important to determine the exact C_R values that are required in steady-state analysis. Although probe calibration is not necessary with nonsteady-state analysis because the results are related to the estimated values of clean water, and the estimate of $K_L a_f$ in nonlinear regression does not require exact DO concentrations, probe calibration is strongly recommended. It ensures probe stability and allows for evaluation of tank DO distribution, especially with respect to oxygen-limiting conditions, $\text{DO} < 0.5$ to 1.0 mg/L . If oxygen limitation occurs only at the end of a test, the data can still be analyzed to obtain estimates of $K_L a_f$ and C_R by truncating the data below the level at which oxygen limitation occurs. For nonnitrifying systems, data below 1.0 mg/L should not be used; for nitrifying systems, data below 2 to 3 mg/L should be truncated.

The major pitfall in nonsteady-state testing is oxygen-limiting conditions immediately before or during the test. These conditions cause marked changes in uptake rate during testing and should be avoided. Data demonstrating this effect are shown in Section 2.7.

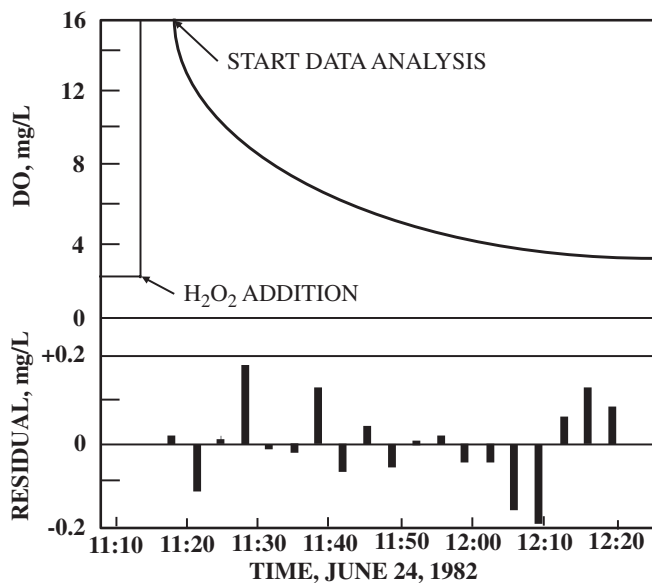


Figure 2-5. Nonsteady-State Oxygen Curve for Probe No. 2 at Site F during Test No. 8. The Curve Shows Residuals for Line of Best Fit

Table 2-3. Average Results for Test No. 8 at Haverstraw, NY, June 24, 1982

Probe	K (h^{-1})	$CV(K)$ (%)	C_R (mg/L)	σ
1	4.14	1.0	3.85	0.03
2	4.34	1.5	3.42	0.04
3	4.32	1.5	3.61	0.04
4	(3.90)	1.5	(3.11)	0.04
5	4.44	2.3	3.62	0.06
Avg. w/o Probe 4	4.31 ± 0.12		3.63 ± 0.18	

When oxygen limitation occurs only at the end of a test and DO falls to less than 0.5 mg/L, accurate results can still be obtained if the data below approximately 1.0 mg/L are not used.

2.7 TEST VARIABILITY

Field studies were conducted at five locations using four generic types of aeration equipment at both municipal and industrial facilities (Table 2-4). All plants were full-scale facilities, except for the Stonewall, Virginia, plant, which was an 83.3-m³ (22,000-gal.) pilot facility. Plants A and D-S used contact stabilization processes, whereas the remaining plants used conventional activated sludge in either completely mixed or long, narrow aeration tanks. Plant D-S contained four completely mixed reactors in series, each reactor analyzed as a completely mixed system. Tank depths varied from 3.6 to 4.6 m (12 to 15 ft), except for the industrial facility (E-D and E-S in the table), which had a 9.1-m (30-ft) tank depth.

Dual nonsteady-state and steady-state testing were conducted at all plants. At Plant A, which contained a single-speed aerator, the power level was varied by changing the effluent weir level

and thus impeller submergence. H₂O₂ was required to conduct tests at this site, because instantaneous power level changes could not be obtained. Site B contained variable-speed surface aerators, which allowed testing using both H₂O₂ and instantaneous power level changes. H₂O₂ was also used at Site D. The plug flow analysis was used to analyze data from Site C in the middle and end sections of the aeration tank. The advective dispersive analysis was used for Site D-D, and the completely mixed analysis was used for all other locations. Clean water testing was conducted at Sites D and E providing the effect of wastewater characteristics on α . All diffused aeration tanks had full floor coverage except for the spargers at Site D, which were spiral roll.

Table 2-5 presents the nonsteady-state variability results for 84 field tests under various process conditions using both hydrogen peroxide (H₂O₂) and changing power level (CPL) techniques to generate the nonsteady-state curves. Goodness of model fit to the nonsteady-state data, expressed in terms of the coefficient of variation of the exponent $K_L a_f$, $CV(K)$, was always less than 2.6% for the four-test series—a total of 31 tests, conducted under flowing conditions using H₂O₂. Changing power levels under flowing conditions resulted in significantly greater $CV(K)$ values, ranging from 2.1% to 8.1% for 29 tests because of the relatively small DO change (1.5–6.9 mg/L) occurring during the tests as well as the changes in hydrodynamic conditions. Batch peroxide addition testing generally yielded better data fit to the exponential model, $CV(K) = 1.7\%$ to 5.4%, because of more stable conditions during testing.

In the earlier test series conducted at Plant E, field stirrers were not available for the DO probes. This resulted in “noisy” nonsteady-state curves. Results of model analyses using data both smoothed by eye and actually measured provided substantially the same $K_L a_f$ and C_R values; however, the model fit was much poorer for the actual data because of the large amount of noise present. Use of field stirrers with no data smoothing is recommended to minimize subjectivity involved in data analysis.

The standard deviation of the steady-state tank DO (C_R) value was generally less than 0.1 mg/L, typically considered the accuracy of the Winkler test. (*Standard Methods for the Examination of Water and Wastewater*, 23rd Ed., Method 4500-O/Azide Modification, is commonly known as the Winkler method, or test, APHA and AWWA 2017) For the low power levels in Plant A, the DO decreased to zero (predicted negative). Thus, poor estimates of C_R were obtained as evidenced by the high σ_{C_R} value of 0.17 mg/L.

The precision among multiple nonsteady-state tests, as measured by the coefficient of variation of OTE_f values, was generally better than 10%. The low power levels at Site A were less precise ($\pm 20.9\%$) because of the zero DO levels occurring in the tank. The flowing tests at Site D-S were also less precise because of the wide range in process conditions.

During a nonsteady-state test conducted under flowing conditions, some variability in process conditions is unavoidable. Fig. 2-6 shows the flow and oxygen uptake variability during the last set of tests conducted at Site D-S. Excellent flow control was maintained during Test No. 17; the oxygen uptake rate had a coefficient of variation, $CV(R)$, of 3%. However, during the next test, marked changes in uptake rate, $CV(R) = 10\%$, occurred because of organic load and flow perturbations during the test. The average $CV(K)$ for Test No. 17 was 1.1%, whereas it was 2.2% for Test No. 18 because of the perturbations. Nonsteady-state testing should obviously be conducted during portions of the day when process conditions are relatively constant.