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2–06

Measurement of Oxygen Transfer in Clean Water

This document uses both the
International System of Units (SI)
and customary units

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STANDARDS

In 2003, the Board of Direction approved the revision to the ASCE Rules for Standards Committees to govern the writing and maintenance of standards developed by the Society. All such standards are developed by a consensus standards process managed by the Society's Codes and Standards Committee (CSC). The consensus process includes balloting by a balanced standards committee made up of Society members and nonmembers, balloting by the membership of the Society as a whole, and balloting by the public. All standards are updated or reaffirmed by the same process at intervals not exceeding five years.

The following standards have been issued:

ANSI/ASCE 1-82 N-725 Guideline for Design and Analysis of Nuclear Safety Related Earth Structures
ASCE/EWRI 2-06 Measurement of Oxygen Transfer in Clean Water
ANSI/ASCE 3-91 Standard for the Structural Design of Composite Slabs and ANSI/ASCE 9-91 Standard Practice for the Construction and Inspection of Composite Slabs
ASCE 4-98 Seismic Analysis of Safety-Related Nuclear Structures
Building Code Requirements for Masonry Structures (ACI 530-02/ASCE 5-02/TMS 402-02) and Specifications for Masonry Structures (ACI 530.1-02/ASCE 6-02/TMS 602-02)
ASCE/SEI 7-05 Minimum Design Loads for Buildings and Other Structures
SEI/ASCE 8-02 Standard Specification for the Design of Cold-Formed Stainless Steel Structural Members
ANSI/ASCE 9-91 listed with ASCE 3-91
ASCE 10-97 Design of Latticed Steel Transmission Structures
SEI/ASCE 11-99 Guideline for Structural Condition Assessment of Existing Buildings
ASCE/EWRI 12-05 Guideline for the Design of Urban Subsurface Drainage
ASCE/EWRI 13-05 Standard Guidelines for Installation of Urban Subsurface Drainage
ASCE/EWRI 14-05 Standard Guidelines for Operation and Maintenance of Urban Subsurface Drainage
ASCE 15-98 Standard Practice for Direct Design of Buried Precast Concrete Pipe Using Standard Installations (SIDD)
ASCE 16-95 Standard for Load Resistance Factor Design (LRFD) of Engineered Wood Construction
ASCE 17-96 Air-Supported Structures
ASCE 18-96 Standard Guidelines for In-Process Oxygen Transfer Testing
ASCE 19-96 Structural Applications of Steel Cables for Buildings
ASCE 20-96 Standard Guidelines for the Design and Installation of Pile Foundations
ANSI/ASCE/T&DI 21-05 Automated People Mover Standards—Part 1
ASCE 21-98 Automated People Mover Standards—Part 2
ASCE 21-00 Automated People Mover Standards—Part 3
SEI/ASCE 23-97 Specification for Structural Steel Beams with Web Openings
ASCE/SEI 24-05 Flood Resistant Design and Construction
ASCE/SEI 25-06 Earthquake-Actuated Automatic Gas Shutoff Devices
ASCE 26-97 Standard Practice for Design of Buried Precast Concrete Box Sections
ASCE 27-00 Standard Practice for Direct Design of Precast Concrete Pipe for Jacking in Trenchless Construction
ASCE 28-00 Standard Practice for Direct Design of Precast Concrete Box Sections for Jacking in Trenchless Construction
ASCE/SEI/SFPE 29-05 Standard Calculation Methods for Structural Fire Protection
SEI/ASCE 30-00 Guideline for Condition Assessment of the Building Envelope
SEI/ASCE 31-03 Seismic Evaluation of Existing Buildings
SEI/ASCE 32-01 Design and Construction of Frost-Protected Shallow Foundations
EWRI/ASCE 33-01 Comprehensive Transboundary International Water Quality Management Agreement
EWRI/ASCE 34-01 Standard Guidelines for Artificial Recharge of Ground Water
EWRI/ASCE 35-01 Guidelines for Quality Assurance of Installed Fine-Pore Aeration Equipment
CI/ASCE 36-01 Standard Construction Guidelines for Microtunneling
SEI/ASCE 37-02 Design Loads on Structures During Construction
CI/ASCE 38-02 Standard Guideline for the Collection and Depiction of Existing Subsurface Utility Data
EWRI/ASCE 39-03 Standard Practice for the Design and Operation of Hail Suppression Projects
ASCE/EWRI 40-03 Regulated Riparian Model Water Code
ASCE/SEI 41-06 Seismic Rehabilitation of Buildings
ASCE/EWRI 42-04 Standard Practice for the Design and Operation of Precipitation Enhancement Projects
ASCE/SEI 43-05 Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities
ASCE/EWRI 44-05 Standard Practice for the Design and Operation of Supercooled Fog Dispersal Projects
ASCE/EWRI 45-05 Standard Guidelines for the Design of Urban Stormwater Systems
ASCE/EWRI 46-05 Standard Guidelines for the Installation of Urban Stormwater Systems
ASCE/EWRI 47-05 Standard Guidelines for the Operation and Maintenance of Urban Stormwater Systems
ASCE/SEI 48-05 Design of Steel Transmission Pole Structures

FOREWORD

This standard is a revision of the June 1992 standard and represents the current consensus of the ASCE Committee on Oxygen Transfer Standards after five years of monitoring the original standard.

Preparation of a standard general enough to be applied to all clean water unsteady-state tests and specific enough to incorporate all essential procedures was difficult. Users of this standard must give particular attention to use of the mandatory “shall” and advisory “should” terms. For particular applications of this standard, it may be advantageous for the user to elevate certain advisory steps to the mandatory level. The body of this standard is supplemented with Annexes and a Commentary, which follow the text. The Annexes provide *mandatory* information and include material that is an essential part of the standard but is too lengthy to place in the text. The Commentary that follows the Annexes provides *nonmandatory* information to supplement the standard. The Commentary is not a part of the standard.

It is intended that this standard be used by engineers in the preparation of specifications for compliance testing. When this is the case, the engineer should consider the costs of requiring extensive compliance testing in relation to the initial cost of the oxygen transfer system and present worth of future operating costs.

The substance of this standard is based on recommendations made in the report, “Development of Standard Procedures for Evaluating Oxygen Transfer Devices,” by the ASCE Oxygen Transfer Standards Subcommittee, Michael K. Strenstrom, Chairman. The user is referred to this document, which contains Refs. [1] to [4], Ref. [5] for background information, and Ref. [6] for a report on accuracy and precision of the method.

Formulas given in parentheses throughout the standard are for use with SI units.

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The contributions of U.S. EPA for workshops and for laboratory and field studies that supported the development and refinement of this standard are gratefully acknowledged.

This standard was formulated through the consensus standards process by balloting in compliance with procedures of ASCE's Codes and Standards Activities Committee. Those individuals who serve on the Standards Committee are:

Professor C. R. Baillod
Professor Edwin L. Barnhart
Mr. Henry Benjes, Jr.
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Mr. Arthur C. Boon
Mr. Robert Borneman, P.E.
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Dr. Martin Wagner
Mr. Robert Waltral
Mr. Jerome D. Wren
Mr. Shang Wen Yuan
Mr. Fred W. Yunt

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Commentary

Measurement of Oxygen Transfer in Clean Water

1.0 SCOPE

This method covers the measurement of the oxygen transfer rate (OTR) as a mass of oxygen per unit time dissolved in a volume of water by an oxygen transfer system operating under given gas rate and power conditions. Methods for measurement of gas rate and power are also described in the Annexes A and B, respectively. The method is applicable to laboratory-scale oxygenation devices with small volumes of water as well as the full-scale system with water volumes typical of those found in the activated sludge wastewater treatment process. The procedure is valid for a wide variety of mixing conditions.

The primary result of this test is expressed as the standard oxygen transfer rate (SOTR), a hypothetical mass of oxygen transferred per unit of time at zero dissolved oxygen concentration, water temperature of 20°C, and barometric pressure of 1.00 atm (101.3 kPa) under specified gas rate and power conditions. The method is intended primarily for clean water meeting the requirements of Sections 5.2 and 6.3. The results can be applied to estimate oxygen transfer rate in process water as described in Commentary G.

2.0 SUMMARY OF METHOD

The test method is based upon removal of dissolved oxygen (DO) from the water volume by sodium sulfite followed by reoxygenation to near the saturation level. The DO inventory of the water volume is monitored during the reaeration period by measuring DO concentrations at several determination points selected to best represent tank contents. These DO concentrations may be either sensed in situ using membrane probes or measured by the Winkler or probe method applied to pumped samples. The method specifies a minimum number, distribution, and range of DO measurements at each determination point.

The data obtained at each determination point are then analyzed by a simplified mass transfer model to estimate the apparent volumetric mass transfer coefficient, $K_L a$ and the steady-state DO saturation concentration, C^*_∞. The basic model is described in Ref. [1] and is given by

$$C = C^*_\infty - (C^*_\infty - C_0)\exp(-K_L a t) \qquad \text{(Eq. 2-1)}$$

where

C = DO concentration, mL^{-3};
C^*_∞ = determination point value of the steady-state DO saturation concentration as time approaches infinity, mL^{-3};
C_0 = DO concentration at time zero, mL^{-3};
$K_L a$ = determination point value of the apparent volumetric mass transfer coefficient, t^{-1}, defined so that
$K_L a$ = rate of mass transfer per unit volume$/(C^*_\infty - C)$.

Throughout this standard, the terminology for units will be shown as follows: m = mass units, l = length units, f = force units, and t = time units.

Nonlinear regression is employed to fit Eq. (2-1) to the DO profile measured at each determination point during reoxygenation. In this way, estimates of $K_L a$ and C^*_∞ are obtained at each determination point. These estimates are adjusted to standard conditions, and the standard oxygen transfer rate (mass of oxygen dissolved per unit time at a hypothetical concentration of zero DO) is obtained as the average of the products of the adjusted determination point $K_L a$ values, the corresponding adjusted determination point C^*_∞ values, and the tank volume. Recent developments that have the potential to be recognized in a future edition of this standard appear in Commentary A.

3.0 SIGNIFICANCE AND LIMITATIONS

Oxygen transfer rate measurements are useful for comparing the performance and energy efficiency of oxygenation devices operating in clean water. However, performance of these devices in process water may significantly differ from the performance in clean water, and the amount of difference will depend on the device, on how it is applied, and on the nature of the process water.

Agreement of this method has been evaluated by parallel testing with the radioactive tracer stripping method, and K_La by the two methods has been found to be within ±3% (Ref. [6]).

4.0 DEFINITIONS AND NOMENCLATURE

4.1 OXYGEN TRANSFER RATE

Mass of oxygen per unit time dissolved in a volume of water by an oxygen transfer system operating under given conditions of temperature, barometric pressure, power, gas rate, and dissolved oxygen concentration.

4.2 STANDARD OXYGEN TRANSFER RATE

OTR in clean water when the DO concentration is zero at all points in the water volume, the water temperature is 20°C, and the barometric pressure is 1.00 atm (101.3 kPa) (see Eq. 8-3).

4.3 AERATION EFFICIENCY

OTR per unit total power input. Power input may be based on either delivered brake or wire power, and this basis must be stated.

4.4 STANDARD AERATION EFFICIENCY

SOTR per unit total power input. Power input may be based on delivered, brake, or wire power, and this basis must be stated.

4.5 OXYGEN TRANSFER EFFICIENCY

Fraction of oxygen in an injected gas stream dissolved under given conditions of temperature, barometric pressure, gas rate, and DO concentration.

4.6 STANDARD OXYGEN TRANSFER EFFICIENCY

OTE in clean water when the DO concentration is zero at all points in the water volume, the water temperature is 20°C, and the barometric pressure is 1.00 atm (101.3 kPa).

5.0 APPARATUS AND METHODS

5.1 TANK

The geometry and tank size will depend on the particular oxygenation system to be tested. The test is applicable to tank volumes that may range from small laboratory vessels of a few liters to large tanks over 1 million gallons (3,800 m^3).

5.2 WATER

For determination of a standard oxygen transfer rate, the water to which oxygen is transferred should be equivalent in quality to a potable public water supply. Further specifications of clean water are given in Section 6.3.

The unsteady-state clean water test is occasionally conducted in clean water with detergent addition in an effort to mask the effect of trace contaminants in tap water or to roughly simulate transfer in municipal wastewater.

5.3 OXYGENATION DEVICE

This method is applicable to a wide variety of oxygenation devices installed in the tank including, but not limited to, the following:

Surface Aerators: high-speed, low-speed, and horizontal shaft rotors.

Subsurface Oxygenation Devices: diffused air, static tubes, submerged turbines, and jet aerators.

5.4 SAMPLING DEVICES

Submersible pumps and tubing are necessary when DO concentrations are to be measured on pumped samples in accordance with Section 6.8.2. They are also recommended to obtain samples for Winkler calibration of DO probes used in situ and samples for water chemistry analysis.

5.5 DISSOLVED OXYGEN MEASUREMENT

5.5.1 Wet chemical measurement of DO on pumped samples shall be in accordance with the azide modification of the Winkler method described in Section 4500-OC of the 20th Edition of *Standard Methods* (Ref. [7]).

5.5.2 Membrane electrode measurement of DO, either on pumped samples or in situ, shall be in accordance with Section 4500-OG of *Standard Methods* (Ref. [7]; see also Section 6.9.1).

5.6 TEMPERATURE MEASUREMENT

Water temperature measurement shall be in accordance with Section 2550 of *Standard Methods* (Ref. [7]).

5.7 DEOXYGENATION CHEMICALS

5.7.1 Sodium Sulfite

Either reagent- or technical-grade sodium sulfite (Na_2SO_3) shall be used for deoxygenation in accordance with Section 6.7. It is preferable that the sodium sulfite be free of cobalt. However, a chemical containing a known concentration of cobalt may be employed, provided that this cobalt is considered as part of the total cobalt addition discussed in Section 6.7.1.

5.7.2 Cobalt Catalyst

Either reagent-grade or technical-grade cobalt chloride hydrate, $CoCl_2 \cdot 6H_2O$, or cobalt sulfate, $CoSO_4$, shall be used to catalyze the deoxygenation reaction in accordance with Section 6.7.

5.8 COMPUTER OR CALCULATOR

A computer or programmable calculator capable of handling the recommended methods of parameter estimation described in Section 7.2 is required.

5.9 GAS FLOW MEASUREMENT APPARATUS

For oxygenation systems based on subsurface gas injection, an apparatus capable of measuring the gas flow with an accuracy of ±5% in accordance with Annex A is required.

5.10 POWER MEASUREMENT APPARATUS

The apparatus required for power measurements will depend on the specific oxygenation device, but, in general, an apparatus suitable for measurement of total delivered power and total wire power in accordance with Annex B is required.

6.0 PROCEDURE

6.1 ADVANCE PREPARATION AND RESPONSIBILITIES

When this method is to be applied, the engineer-owner-manufacturer (EOM) representatives shall agree in advance on the specific system to be tested and the test conditions. The items upon which agreement must be reached include

1. test location (field installation or shop tank),
2. tank size and geometry,
3. aerator placement,
4. aerator power and gas rates,
5. temperature correction factor, θ if different from 1.024,
6. method of sealing partition walls, if used, and test procedures and tolerances acceptable for determining sealing effectiveness,
7. source and characteristics of test water including total dissolved solids concentration (TDS) and conductivity,
8. sodium sulfite addition procedure,
9. water temperature range, if different from 10–30°C, and
10. DO measurement method and locations.

Where field testing is to be conducted, the engineer-owner representative should provide the manufacturer with detailed drawings and specifications of the tank or tank section in which the test will be conducted. Information on the water supply source and available water chemistry data should be provided. Water samples should be made available to the manufacturer for laboratory experiments regarding the chemical additions that will be made.

Once the installation of aeration equipment is completed, provision should be made for EOM representatives to inspect the installation to verify placement and testing conditions. Systems employing diffused air aeration should be tested to eliminate leaks. Provisions for power and airflow measurement should be verified and modifications made as needed. It may be necessary to install equipment such as meters for power measurement, supplemental air piping, orifice plates, and manometers, as described in Annexes A and B.

Upon completion of the installation of the aeration equipment, the test tank should be cleaned prior to filling for testing. Once the tank is filled with the test water, chemical and biological contamination should be avoided. It may be necessary to dewater and refill the test tank during the testing, and adequate pumping and discharge arrangements should be made.

6.2 TEST TANK GEOMETRY AND AERATOR PLACEMENT

It is difficult to describe a required geometry or placement for testing conducted in tanks other than the full-scale field facility (Ref. [8]). Appropriate configurations for shop tests should simulate the field conditions as closely as possible. For example, water depths should be similar, if not identical, and, for certain systems, width-to-depth or length-to-width ratios should be similar. Potential interference resulting from wall effects and any extraneous piping or other materials in the tank should be minimized. The density of the aerator placement, air flow per unit volume, or area and power input per unit volume are examples of parameters that can be used to assist in making comparative evaluations.

Testing of tank sections is also useful in certain situations (e.g., long narrow diffused aeration tanks) where there is little water circulation between the adjacent sections. In this approach, a tank is divided into sections, and each section is tested individually. When this testing is performed, sealed partitions shall be installed between adjacent sections to prevent interchange of oxygen by advection and diffusion. This technique can provide information on spatial variation of K_La and SOTR in tanks designed for tapered aeration.

Consideration should be given to utilization of shop testing or testing of tank sections when full-scale facilities are very large (e.g., in excess of 1 million gallons) (3,800 m^3). Other criteria to be considered in making this judgment are

1. ease of distribution of deoxygenation chemicals (distribution may be difficult in certain tanks),
2. sampling requirements (very large tanks may be difficult to sample adequately), and
3. bulk flow and mixing patterns (shop or section testing should not be done when the mixing pattern in the shop or section tank would not be representative of the full-scale unit).

6.3 WATER QUALITY

6.3.1 General and Total Dissolved Solids

The water supplied for the initial test shall be equivalent in quality to a potable public water supply. The test water shall not be modified without agreement from EOM representatives. More than one test may be conducted in the same water, and, because of the addition of deoxygenation chemicals, the total dissolved solids concentration (TDS) will increase. Repetitive testing may be conducted in the same water, provided that the final TDS does not exceed 2,000 mg/L.

Note 1: In applying this method, a progressive increase in mass transfer efficiency has been observed in replicate tests when a number of tests have been performed in sequence without change of test water (Ref. [9]). Evidence supporting the theory that the phenomenon is associated with the increase in TDS resulting from the progressive addition of sodium sulfite has been advanced.

Note 2: A substantial amount of data from tests conducted on fine pore diffused aeration equipment has been used to develop a method for adjusting oxygen transfer test results (K_La) to a common TDS concentration. See Commentary B.

Note 3: Since increasing TDS may increase mass transfer efficiency, the order in which repetitive tests are conducted for more than one operating condition should be chosen so that increases are distributed randomly over the test series whenever possible (Ref. [10]).

6.3.2 Temperature

Water temperature should be between 10°C and 30°C, and as close to 20°C as possible. Testing outside this temperature range may be necessary in some situations and can be done with the approval of EOM representatives. Low temperatures slow the deoxygenation reaction, and this may introduce some error. It is recommended that a standard θ, temperature correction factor, of 1.024 be employed to adjust for temperature. Use of θ differing from 1.024 shall be permissible only when experimental data for the particular aeration system indicate conclusively that the value of θ is significantly different from 1.024. Water temperature shall not change by more than 2°C during a single unsteady-state test.

6.3.3 Water Quality Analyses

Initial analyses: Prior to beginning the testing program, a representative sample of the water from the test tank shall be analyzed for TDS and temperature. Additional analyses for parameters of concern, such as those listed in Note 1 below, may be desirable. EOM representatives should review these data to assess possible effects of water quality on the test results. Based on these data, EOM representatives should establish: (1) upper limits on the allowable TDS concentrations; (2) the concentration of cobalt to be employed; and (3) possible modifications of the test water quality.

As stated in Section 6.3.1, the quality of the test water should not be modified for clean water testing. However, a surface water may have to be treated because of a particular set of adverse field conditions. Factors that may be considered in agreeing upon any water quality modifications include any demonstrated oxygen transfer effects attributable to water chemistry differences between field conditions and prior test data used to predict field performance.

Note 1: Other water quality parameters including iron, manganese, residual chlorine, alkalinity, *p*H, total organic carbon, or chemical oxygen demand and surfactants (MBAS), may affect test results, but no definite limiting concentrations have been established to date.

Note 2: A very small amount of oil contamination can have a measurable effect on the oxygen transfer measurement. Oil spills or leaks around mechanical equipment shall be avoided.

Water quality analyses during testing: When repetitive tests are conducted in the same water, the water shall be analyzed for the various constituents and properties at the frequencies indicated in Table 6-1.

TABLE 6-1. Water Quality Measurements during Testing[a]

Measurement	Frequency of Sampling
Temperature[b]	Every test—beginning and end
Total dissolved solids[c]	Every test series—beginning and end (intermediate test values shall be calculated by mass balance)
Soluble cobalt[c]	Every test series—beginning and end

[a] All analyses in accordance with *Standard Methods* (Ref. [7]).
[b] Measured at test site during testing.
[c] Analysis conducted after completion of test series.

The cobalt concentration normally should not change during testing, but slight decreases may occur. If the concentration of cobalt is suspected to be insufficient, additional cobalt may be added to achieve a soluble cobalt concentration between 0.1 and 0.5 mg/L so as to assure complete oxidation of the sulfite (see Section 6.7).

6.4 SYSTEM STABILITY

The aeration system should be operated to achieve steady-state hydraulic conditions prior to starting the oxygen transfer evaluation. A steady-state power draw can indicate a steady-state hydraulic condition for mechanical aerators. Some mechanical and diffused air systems require 30 to 40 min to achieve a steady-state hydraulic regime. Where the power is input through speed reducers, it is important that the mechanical system be at a stable operating temperature. For gearboxes, the warm-up period may be as long as 8 to 12 hours.

For diffused air systems, water shall be displaced from the aeration system prior to beginning the test. Steady manometer readings for orifice airflow measurement and consistent airflow rate measurements for other flow measurement devices are indicative of this displacement. Lines with valves for purging water from the aeration system may be added for testing purposes.

For tests of fixed platform surface aerators and rotors, the water surface elevation shall be held constant so that the power draw is constant during the test. For other systems, the volume of water under aeration shall not vary by more than ±2% during any one test.

6.5 INITIAL TEST

Data anomalies have frequently been reported during the initial test conducted after filling the test tank. Therefore, this test is frequently not used as part of the oxygen transfer evaluation. Instead, it is often used to stabilize water chemistry and to overcome possible problems in test procedures including sulfite dispersion and sampling techniques. It also can provide an opportunity to check for possible analytical interferences, to assure proper probe zero and calibrations, and to verify adequate cobalt residual based on deoxygenation and reaeration patterns. The initial test may be used as part of the oxygen transfer evaluation with agreement of EOM representatives.

6.6 DEOXYGENATION CHEMICALS

Either reagent- or technical-grade sodium sulfite (Na_2SO_3) shall be used for deoxygenation. The concentration of cobalt in the sulfite shall be sufficiently low so that the concentration in the test tank following repetitive testing does not exceed limits set forth in Section 6.7.1. Sodium sulfite shall be added in solution. This may be accomplished by dissolving the sulfite in a separate mixing tank prior to its addition to the test tank. Saturated solutions contain 2.23 lb/gal (267.2 kg/m^3) at 20°C and 3.00 lb/gal (359.4 kg/m^3) at 30°C. If agreed to by EOM, sulfite may be added in powdered form. Annex C contains additional information related to dry sulfite addition.

Occasionally, impurities in technical-grade sulfite can cause erroneously low OTR values. See Commentary C for further guidance.

The sulfite deoxygenation reaction is catalyzed by cobalt. The cobalt source utilized shall be cobalt chloride hydrate, $CoCl_2 \cdot 6H_2O$, or cobalt sulfate, $CoSO_4$, reagent or technical grade (Section 5.7.2). The cobalt shall be dissolved prior to its addition to the test tank. Solubilities of $CoCl_2 \cdot 6H_2O$ and $CoSO_4$ are approximately 50 g and 36 g per 100 ml of water, respectively, at 20°C and increase with temperature. Care should be taken to ensure that complete dissolution of the cobalt salt is achieved, especially when it is added in the sulfate form.

6.7 ADDITION OF DEOXYGENATION CHEMICALS

6.7.1 Cobalt Addition

The cobalt catalyst should normally be added, once for each test water. A solution of cobalt salt shall be added to the test tank to achieve a soluble cobalt concentration between 0.10 mg/L and 0.50 mg/L in the test water.

The cobalt solution shall be added prior to the beginning of oxygen transfer testing with the aeration system operating. The solution shall be uniformly distributed into the test tank. Pumps and distribution systems may be required for large tanks. The cobalt solution shall be dispersed throughout the tank by operating the aeration system until completely mixed.

6.7.2 Sulfite Addition

The theoretical sodium sulfite (Na_2SO_3) requirement for deoxygenation is 7.88 mg/L per 1.0 mg/L DO concentration. Sulfite additions are made in excess of stoichiometric amounts. The amount of excess is dependent on the oxygen transfer rate of the aeration system and the size of the test tank. The amount of excess varies from 20% to 250% and increases for high transfer rate systems.

Sufficient sulfite solution shall be added to depress the DO level below 0.50 mg/L at all points in the test water. Consistent repetitive testing results have been observed where the DO concentration has reached zero at all sample points and remained at zero at least 2 min. Results from the initial test can be used to help establish the proper quantity to be added.

Sodium sulfite shall be dissolved in mixing tanks outside the test tank and distributed uniformly into the test tank. The use of pumps and flexible piping to distribute the solution throughout the tank volume is recommended. Extreme care should be exercised to assure adequate dispersion in the test tank. Testing in loop reactors (ditches) normally requires adding the sulfite over at least the time of travel of one revolution with additional revolutions utilized to provide adequate mixing prior to onset of the increase in DO with time response. If agreed to by the EOM, sulfite may be added in powdered form (see Annex C).

The ASCE procedure can be applied to loop reactors (e.g., oxidation ditches), and accurate and precise results can be achieved (Ref. [11]). Sodium sulfite must be added to the reactor over an integral number of loops in order to distribute it evenly over the length of the reactor. The loop time can be estimated by dividing the length of the reactor by the horizontal fluid velocity. The sodium sulfite addition pump flow rate must be adjusted to transfer the required sulfite into the reactor over an integral number of loops (preferably 3 or 4, but at least 1). Probes must be located in such a way as to measure the DO exiting and entering aeration devices. Data collection should begin while the reactor DO is still near zero. The data collected after all properly functioning probes show positive DO may be analyzed using the nonlinear method in the same fashion as with other aeration tank geometries.

6.8 DETERMINATION OF DISSOLVED OXYGEN AT VARIOUS POINTS IN THE TANK DURING THE UNSTEADY-STATE TEST

Dissolved oxygen concentrations shall be determined at various points in the tank and at various times during the unsteady-state test. This determination shall be carried out by one or both of the following procedures:

1. Samples pumped to biochemical oxygen demand (BOD) bottles followed by measurement of dissolved oxygen by either the Winkler method or the membrane probe.
2. In situ measurement of dissolved oxygen in the tank by membrane probes.

6.8.1 Location of Dissolved Oxygen Determination Points

The number and location of dissolved oxygen determination points will be dictated by the size of the test tank, aerator placement, and mixing pattern in the tank. The following criteria shall be used in establishing the number and location of points.

A minimum of four determination points shall be used. One should be at a shallow depth, one should be at a deep location, and one should be at mid-depth. The points should be at least 2 ft (0.6 m) from the walls, internal structures, floor, and surface, and no closer to the surface than 10% of the minimum tank dimension.

The determination points shall be located in an attempt to have each sense an equal portion of the tank volume and shall be distributed vertically and horizontally (or radially) to best represent the tank contents. More than four determination points should be used when the tank is large [e.g., >500,000 gal (1,900 m^3)] or when significant spatial K_La variations occur as described in Section 8.2.1.

DO probes should be secured by appropriate means to minimize movement due to water currents generated by operation of the aeration system during the tests.

6.8.2 Collection of Pumped Samples

When pumped samples are to be obtained for dissolved oxygen analysis, submersible pumps (discharging through tubing to BOD bottles) should be installed at the determination points. The pump inlet should be designed and located to avoid air bubble entrainment. The pumping rate and tubing lengths should be adjusted so that: (1) the transport times between the pump and bottle are equal for all determination points and not greater than 15 sec; and (2) the 300-mL BOD bottles fill in 6 to 10 sec. Sudden pressure drops in the sample line will degas the water and, thus, should be avoided.

With a pumped sampling system, the DO measurement may be made by a DO probe mounted in the sample line, by a DO probe with a stirrer placed into the sample bottle, or by Winkler titration of the DO in the sample bottle. The in-line probe system must be observed continuously to prevent line clogging or damage to the membrane. If individual bottle samples are used, they must be carefully stored to prevent temperature change and degassing. They should be analyzed for DO as soon as possible.

If the pumped sample−individual bottle technique is used, at least one recording DO probe system shall also be installed. This system would be used to help set sampling times, indicate when zero DO was reached during deoxygenation, and assist in determining the end of a test by noting a stable maximum DO concentration.

6.8.3 Times of Dissolved Oxygen Determinations

Dissolved oxygen concentrations shall be determined at various times during the unsteady-state test using one or both of the procedures described in Section 6.8.

6.8.3.1 DO Probes with Continuous Recorder

When DO probes with continuous recorders are used, a continuous record of DO versus time will be available at each determination point. In this case, a minimum of 21 discrete data values shall be selected from the continuous record for analysis. The values selected shall meet the timing criteria outlined in Section 6.8.3.3.

6.8.3.2 Individual Bottle Technique

When the pumped sample–individual bottle technique is used during the unsteady-state test, greater care and planning must be used in selecting the times for DO measurement. In this case, DO measurements shall be made such that a minimum of 12 DO values at each determination point are available for data analysis. Measurement of more values is desirable because of anticipated truncation and increased precision, but measurement of more than 25 DO values will not usually give a significant increase in precision. The values selected shall meet the timing criteria outlined in Section 6.8.3.3. A guide for determining the times of DO measurement is described in Commentary D.

6.8.3.3 Timing Criteria

The purpose of these criteria is to ensure that the data points are representative of the reaeration curve, and that an adequate number of points are obtained in sensitive regions of the curve. The rising part of the curve, up to about 85% of saturation, is sensitive for estimation of K_La, and the stationary part of the curve, above 90% saturation, is sensitive for the estimation of C^*_∞. Consequently, the timing of DO values used in the data analysis shall meet the following criteria for range and balance after preparation and possible low-end truncation as described in Annex E.

Range: The lowest DO value shall be not greater than 20% of C^*_∞, except when Annex E.3 permits values up to 30%. The highest DO value shall be not less than 98% of C^*_∞. Use of the alternate log deficit parameter estimate (Annex F), in lieu of the recommended nonlinear regression method (Section 7.2.1), will require additional data beyond 99.7% C^*_∞, which is reached at a time of $6/K_La$.

Balance: The data and timing shall meet *either* criteria (1) or (2) below.

1. The DO values are measured so that about two-thirds (58%–75%) of the values are evenly distributed over the rising portion of the curve between 20% and 86% of saturation, and about one-third (25%–42%) of the values are evenly distributed over the stationary portion between 86% and 98% of saturation. The Commentary gives guidance for estimating determination intervals to comply with this.
2. When 21 or more DO values are used, the values can be evenly spaced at approximately equal time intervals over the entire range between the first and last DO value.

In cases of rapid transfer, the minimum interval between measurements should be 0.4 min for collected samples. No minimum interval is specified for in situ probes.

6.8.4 Test Duration and Dissolved Oxygen Saturation

Dissolved oxygen data should be obtained over as wide a range as possible. Even though low-end values may be truncated to avoid lingering effects of the deoxygenation technique prior to analysis, it is important to collect low dissolved oxygen data so that these effects can be detected. The low dissolved oxygen data shall establish that the sulfite addition has depressed the DO concentration to less than 0.5 mg/L at all determination points. All tests shall be continued for a time so that the last measured DO value at each determination point is equal to or greater than 98% of C^*_∞ for that determination point. Use of the alternate log deficit parameter estimation method (Annex F), in lieu of the recommended nonlinear regression method (Section 7.2.1), will require additional data beyond 99.7% C^*_∞, which is reached at a time of $6/K_La$.

Tabulated values of dissolved oxygen surface saturation concentrations shall *not* be used as model parameters for calculation of oxygen transfer rates.

6.9 DISSOLVED OXYGEN MEASUREMENTS

The accuracy, reliability, and repeatability of the K_La determinations depend critically on the accuracy of DO measurements. The methods of measurement, detailed below, must be adhered to in all circumstances.

6.9.1 Measurement by In Situ and Sample Line DO Probes

The in situ DO probes shall be fast-response probes with a probe time constant of less than $0.02/K_La$ (see Commentary E) and should be equipped with agitators. If agitators are not employed, care shall be taken to ensure that there is sufficient water velocity past the probe. Probes shall be calibrated initially as well as following each test according to the methods outlined in Annex D.

Each probe should be equipped with a strip chart or digital recorder, which will permit reading of the DO concentration at appropriate intervals with a precision of ±0.05 mg/L. However, in the absence of recording devices, it is permissible to manually record probe data at the appropriate determination intervals.

If probes are placed in sample lines to measure DO, they need not be equipped with agitators. The velocity of flow past the probe shall be established and maintained to provide an accurate response from the probe. Calibration and recording requirements for sample line probes are equivalent to those for in situ probes.

Dissolved oxygen probes require considerable care and attention to provide continuous reliable data. Backup probes and meters should be available for replacement as needed.

6.9.2 Measurement by Probes in BOD Bottles

Probes used to measure the DO in 300-mL sample bottles shall be equipped with a stirrer. Probe manufacturer recommendations shall be followed for calibration. This procedure is not recommended for systems where degassing may affect measurement (e.g., subsurface systems, deep tanks).

6.9.3 Measurement by the Winkler Procedure

The modified Winkler DO analytical procedure of the 20th Edition of *Standard Methods* (Section 4500-OC) (Ref. [7]) shall be followed for DO titrations.

7.0 DATA ANALYSIS

7.1 PREPARATION OF DATA FOR ANALYSIS

The purposes of data preparation are

1. to obtain discrete numerical values from continuous probe readings, to plot and examine the data to determine if low-end truncation is necessary,
2. to truncate low dissolved oxygen values, and
3. to assure that the data values to be analyzed meet the timing criteria outlined in Section 6.8.3.

Details of the preparation of the data from either continuous probe records or discrete pumped samples may be found in Annex E.

7.2 PARAMETER ESTIMATION

The purpose of the parameter estimation procedure is to determine the best estimates of the three model parameters, K_La, C^*_∞, and C_0, so that the model given by Eq. (2-1) best describes the variation of DO with time at each determination point location in the tank. Parameter estimates shall be based on the nonlinear regression method unless the engineer/owner specifies the log deficit method. If the log deficit method is specified, data shall be collected over a time period at least 10 min greater than $6/K_La$ for each test, and the data shall be analyzed in strict accord with procedures detailed in Annex E. It should be noted that the nonlinear regression method requires data be collected over a time period greater than $4/K_La$. Accordingly, a decision by the engineer/owner to specify the log deficit method will require that each test be run and data be collected for a time roughly 1.5 times the test time that would be required for the nonlinear regression method.

7.2.1 Nonlinear Regression Method

This method is based on nonlinear regression of the model (Eq. 2-1) through the DO-versus-time data as prepared for analysis (Annex E). The best estimates of the parameters, K_La, C^*_∞, and C_0, are selected as the values that drive the model equation through the prepared DO concentration-versus-time data points with a minimum residual sum of squares. Here, a residual refers to the difference in concentration between a measured DO value at a given time and the DO value predicted by the model at the same time.

Application of this method requires a computer. User-oriented Turbopascal and Visual Basic/Excel spreadsheet programs, which will give the least square estimates, standard deviations of K_La, C^*_∞, and C_0, along with an output of the data, fitted values, and residuals, can be downloaded from http://www.seas.ucla.edu/stenstro. The programs are contained in self-extracting files and include brief instructions and an example data set.[1] To use these programs, the prepared data for a particular determination point are entered. The two programs will provide initial approximations of the three parameters. These initial estimates can be obtained by examining a plot of DO versus time. The programs adjust the initial approximations to minimize the residual sum of squares (see Annex E and Commentary D). Users can also write their own programs to perform the nonlinear regressions, and their answers can be validated with the provided programs.

For adequate convergence, the initial parameter estimate for C_0 should be within 2 mg/L of the final estimate. Frequently, data are taken with time zero defined early in the test sequence, and this can correctly result in large negative predicted values of C_0. In these cases, the initial parameter estimate for C_0 may be facilitated by redefining time zero so that C_0 is approximately zero. This redefinition of time zero does not affect the model predictions for K_La and C^*_∞.

The values of DO predicted by the model based on the final parameter estimates should be plotted along with the measured values and examined. A visual examination of such a plot will indicate any gross mistakes or false convergence in the nonlinear regression. False convergence occasionally occurs and can be easily remedied, improving the initial parameter estimates.

8.0 INTERPRETATION AND REPORTING OF RESULTS

8.1 STANDARD OXYGEN TRANSFER RATE

By convention, the oxygen transfer capacity of an oxygenation system is usually expressed as the rate of

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[1] Installation may conflict with Microsoft operating systems.

oxygen transfer predicted by the model at zero dissolved oxygen under standard conditions of temperature and pressure, usually 1.00 atm (101.3 kPa) and 20°C. This is termed the standard oxygen transfer rate (SOTR). It should be noted that SOTR is a hypothetical value based on zero dissolved oxygen in the oxygenation zone, which is not usually desirable in real oxygenation systems operating in process water. The SOTR value shall be determined by correcting the values of K_La and C^*_∞ estimated according to Section 7.2 for each determination point to standard conditions by

$$K_La_{20} = K_La\ \theta^{(20-T)} \qquad \text{(Eq. 8-1)}$$

$$C^*_{\infty 20} = C^*_\infty(1/\tau\Omega) \qquad \text{(Eq. 8-2)}$$

where

K_La = determination point value of apparent mass transfer coefficient estimated according to Section 7.2;
K_La_{20} = determination point value of K_La corrected to 20°C;
Θ = empirical temperature correction factor, defined by Eq. (8-1) (shall be taken equal to 1.024 unless proven to have a different value for the aeration system and tank tested);
C^*_∞ = determination point value of steady-state DO saturation concentration estimated according to Section 7.2;
$C^*_{\infty 20}$ = determination point value of steady-state DO saturation concentration corrected to 20°C and a standard barometric pressure of 1.00 atm (101.3 kPa);
τ = temperature correction factor = $C^*_{\mathrm{st}}/C^*_{\mathrm{s20}}$;
C^*_{st} = tabular value of dissolved oxygen surface saturation concentration, $\mathrm{mL^{-3}}$, at the test temperature, a standard total pressure of 1.00 atm (101.3 kPa) and 100% relative humidity (Ref. [7]);
C^*_{s20} = tabular value of dissolved oxygen surface saturation concentration, $\mathrm{mL^{-3}}$, at 20°C, a standard total pressure of 1.00 atm (101.3 kPa) and 100% relative humidity (Ref. [7]);
Ω = pressure correction factor
= P_b/P_s for tanks under 20 ft (6.1 m) [for deeper tanks or elevation changes greater than 2,000 ft (610 m), the more rigorous procedure given in Annex G shall be used];
P_b = barometric pressure at test site during test, $\mathrm{fL^{-2}}$;
P_s = standard barometric pressure of 1.00 atm (101.3 kPa), $\mathrm{fL^{-2}}$; and
T = water temperature during test, °C.

The average value of SOTR shall be calculated by averaging the values at each of the *n* determination points by

$$\mathrm{SOTR} = V/n\sum_{i=1}^{n} K_La_{20i}C^*_{\infty 20i} \qquad \text{(Eq. 8-3)}$$

$$\mathrm{SOTR} = 1/n\sum_{i=1}^{n} \mathrm{SOTR}_i \qquad \text{(Eq. 8-4)}$$

where

$$\mathrm{SOTR}_i = K_La_{20i}C^*_{\infty 20\mathrm{i}}\ V \qquad \text{(Eq. 8-5)}$$

V = liquid volume of water in the test tank with aerators turned off, L^3; and
SOTR = standard oxygen transfer rate, $\mathrm{mt^{-1}}$.

The individual values of K_La_{20}, $C^*_{\infty 20}$ (d_e, if required), the tank average values of K_La_{20} and $C^*_{\infty 20}$, actual test temperature, and unaerated liquid volume shall be reported along with SOTR.

$$C^*_{\infty 20} = 1/n\sum_{i=1}^{n} C^*_{\infty 20i} \qquad \text{(Eq. 8-6)}$$

$$K_La_{20} = \mathrm{SOTR}/C^*_{\infty 20} \qquad \text{(Eq. 8-7)}$$

For subsurface gas injections systems, the value of SOTE should also be reported (see Section 8.4). If possible, the standard deviations of the parameter estimates, K_La, C^*_∞, and standard error of estimate should also be reported.

8.2 SPATIAL UNIFORMITY AND REPRODUCIBILITY OF K_La AND $C^*_{\infty 20}$ VALUES

In some cases, replicate tests are conducted sequentially under the same conditions of temperature and pressure, and the replicate K_La and C^*_∞ values can be compared directly without temperature and pressure adjustments. However, when temperature and pressure vary between replicates, comparisons should be made using the K_La_{20} and $C^*_{\infty 20}$ values.

8.2.1 Spatial Variation K_La_{20} and $C^*_{\infty 20}$ Values Related to Mixing and Data Adequacy

Although nonuniformity does not necessarily invalidate the test, it may suggest nonuniform aeration intensity or short-circuiting of the flow with some zones of the tank achieving higher oxygen transfer rates than others. Therefore, when nonuniformity is evident, care should be taken to ensure that a sufficient number of determination point locations are adequately placed to correctly sense the changes in dissolved oxygen inventory of the tank. See a detailed discussion of the spatial uniformity of K_La and $C^*_{\infty 20}$ values related to mixing and oxygen distribution in Commentary F.

The spatial variation of average determination point K_La_{20} values computed in each test can be used to judge the adequacy of determination point numbers and locations. When a minimal number of determination points (e.g., four) are employed, variation of these average point values should be limited so that three-fourths of the values are within ±10% of the mean value for the tank. When spatial variations greater than this are observed or expected, consideration should be given to using a greater number of determination points (e.g., six to eight) or to testing by tank sections.

8.2.2 Reproducibility Point K_La_{20} Values as a Criterion of Validity

When a series of at least three replicate tests are conducted, the determination point K_La_{20} values in each replicate shall not vary by more than ±15% from the mean value for that point. Replicate determination point K_La_{20} values that exhibit greater variation shall be considered as invalid and shall not be used for calculation of the measured SOTR. Deletion of data from a determination point shall invalidate the replicate test unless suitable data from a backup probe are available for that test.

8.3 STANDARD AERATION EFFICIENCY

Frequently the standard aeration efficiency, or rate of oxygen transfer per unit power input, is of interest and shall be computed from

$$\text{SAE} = \text{SOTR}/\text{Power Input} \qquad \text{(Eq. 8-8)}$$

where power may be expressed as delivered, brake, wire, or total wire power, and shall be specified. This parameter is normally expressed in units of pounds per horsepower-hour or kilograms per kilowatt-hour.

8.4 OXYGEN TRANSFER EFFICIENCY

Oxygen transfer efficiency refers to the fraction of oxygen in an injected gas stream dissolved under given conditions. The standard oxygen transfer efficiency (SOTE), which refers to the OTE at a given gas rate (see Annex A), water temperature of 20°C, and barometric pressure of 1.00 atm (101 kPa) may be calculated for a given flow rate of air by

$$\text{SOTE} = \text{SOTR}/W_{02} \qquad \text{(Eq. 8-9)}$$

where

SOTE = standard transfer efficiency as a fraction; and
W_{02} = mass flow of oxygen in air stream, mt^{-1} (see Annex A).

8.5 PERFORMANCE EVALUATION CRITERIA

Required oxygen transfer performance shall be stated as a required standard oxygen transfer rate (SOTR) for specified conditions of tank volume, placement geometry, power, and gas flow rate. System performance under the specified conditions shall be evaluated by a minimum of three replicate tests. Power and gas flow rate for each replicate test shall be within ±5% of the specified value. The measured SOTR for performance evaluation shall be determined as the average SOTR based on all valid replicate tests under the specified conditions, and this average shall equal or exceed the required value. Furthermore, the individual SOTR values determined from at least two-thirds of the valid replicate tests shall exceed the required value.

9.0 REPORTING

The test report shall include the following information:

9.1 A reference to the ASCE Oxygen Transfer Standard.

9.2 The purpose of the test, intended use of the results, and dates of testing.

9.3 A description of the test site including site evaluation.

9.3.1 A description of the aeration device, its placement, and operating conditions including drawings illustrating the placement.

9.3.2 Plan and section drawings of the test tank and a description of the test tank. If the test tank was partitioned, so indicate. Describe details of the partition wall construction, sealing methods, and basis upon which it is believed that leakage is not significant.

9.3.3 Photographs of the test tank and installation, if possible.

9.3.4 Source and quality of water used in testing.

9.4 A description and illustration of the air flow measurement system, if applicable. Calibration and source information shall be cited. Barometric pressure, system air temperature, and pressure readings and air flow rates for each test shall be cited.

9.5 Data utilized to provide horsepower results and the measurement procedures utilized including locations of measurement (pump, blower, turbine, etc.).

9.6 The name, type, source, and quantities of sodium sulfite and cobalt catalyst utilized.

9.6.1 The procedures utilized in making the sodium sulfite additions to the test tank.

9.6.2 Water chemistry information for each test including temperature and total dissolved solids concentrations and for each test series including cobalt.

9.6.3 Observations of water clarity, foaming, or color changes during testing.

9.6.4 Sequence of tests performed, identity, and quantity of chemicals added. Method of estimation of TDS (e.g., calculation or chemical analysis) for each test.

9.7 Tables of DO versus time or recording charts (digital or strip chart) of the DO response.

9.7.1 Location description of all DO determination points including a drawing.

9.7.2 Description of DO measurement procedures and calibration including type of probes and/or sample pump flow rates.

9.8 A summary of results listing K_La, K_La_{20}, C^*_∞, $C^*_{\infty 20}$, and d_e (where required) for each determination point, the values of K_La_{20} and $C^*_{\infty 20}$, and the calculated value of SOTR for each replicate test.

9.8.1 Water volume and depth during test.

9.8.2 Power measured for mechanical or combined systems.

9.8.3 Average air flow rates and variations for each test.

9.8.4 Brief description of the method of data analysis used along with values of τ, Ω, θ, densities, and pressures used in calculations.

9.8.5. Listing of or reference to any computer program used in the analysis of the data.

9.9 Persons involved and their areas of responsibility for various components of the testing. Witnesses of the tests with the periods they were present.

9.10 Any special details or uncertainties noted during the testing.

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ANNEXES (MANDATORY)

ANNEX A

Gas Flow Measurements. For oxygen transfer systems using subsurface gas injection as the source of all or part of the oxygen being transferred, the gas flow must be accurately and precisely measured. The gas flow must be known to determine the oxygen transfer efficiency (OTE) of the system. This Annex provides procedures for measuring and calculating gas flows. More detailed guidance and procedural assistance are provided in the references that are listed at the end of this Annex.

A.1 System Isolation

The system under test shall be isolated such that

1. all gas entering the volume of water being tested passes a suitable gas flow measurement device, and
2. no gas that passes a gas flow measurement device used for this test is diverted away from the volume of water being tested.

The intent of this requirement is to ensure that the full test gas stream, and only that stream, is measured. Splitting a measured gas flow to deliver a portion of that flow to the test tank and estimating the flow to the test tank using volumetric or area-served ratios is not acceptable for gas flow measurement.

A.2 Suitable Test Devices

Gas flow measurements shall be made using suitable primary measuring elements or elements that have been properly calibrated using a suitable primary measuring element. All primary measuring elements used for oxygen transfer system testing shall have a maximum absolute error of 5% of the measured value over the full range of gas flows measured. Potentially suitable test devices include

1. orifice plate meters
2. venturi tube meters
3. pitot tubes used with appropriate traversing methods
4. averaging pitot tubes (e.g., Annubars)
5. thermal anemometers

Most of these measurement devices are based on pressure differential across the device. Measurement of this differential shall be made using a device that has a maximum absolute measurement error of 5% of the differential over the full range of measurement. Potentially suitable measurement devices include

1. manometers
2. differential pressure gages

Regardless of the measurement device used, the accuracy and precision of the device shall be demonstrated under conditions comparable to those used for oxygen transfer system testing.

A.3 Measurement Device Placement

The gas flow measurement device shall be placed in a suitable section of gas piping so as to provide uniform approach and downstream conditions for the device. As a general rule, the device should be placed

1. in a straight pipe having no expansions, contractions, valves, or other appurtenances that may disrupt flow
2. in a straight pipe having a total length greater than or equal to twelve pipe diameters
3. with a straight length of pipe immediately upstream from the measurement device greater than or equal to seven pipe diameters
4. with a straight length of pipe immediately downstream from the measurement device greater than or equal to five pipe diameters

It is acceptable to use straightening vanes to improve flow conditions where ideal conditions are not available; however, the accuracy and precision of the measurement device under actual test conditions must be demonstrated. More comprehensive guidelines on measurement device placement are provided in the references furnished at the end of this Annex.

A.4 Measurement Conditions

The flow conditions shall be essentially constant during the test, as indicated by small instantaneous deviations from the average flow. The instantaneous deviation from the average flow shall not exceed 5% of the average flow.

Some gas delivery systems cause larger fluctuations in gas supply flow. For example, systems using positive displacement blowers that discharge directly to the gas delivery piping, rather than to a gas receiver, can have instantaneous flow deviations that exceed 5% of the average flow. For oxygen transfer system testing, temporarily increasing the head loss between blower and the flow measurement device, by partially closing valves or installing a pipe restriction, may be sufficient to control flow fluctuations. If flow fluctuations due to gas supply fluctuations cannot be held to a maximum of 5%, accurate OTE determination is generally not possible.

A.5 Calculations

The following calculations are for oxygen transfer systems using air as the oxygen source.

A.5.1 Conversion of Gas Flow to Inlet Conditions

Gas flows measured in the gas supply system are generally converted to equivalent gas flows under ambient (blower inlet) conditions. This conversion can be made using the following equation (refer to the following discussion regarding the relative humidity correction):

$$Q_1 = Q_p T_1 (P_p - R_{H,p} P_{V,p}) / T_p (P_1 - R_{H,1}\, P_{V,1}) \qquad \text{(Eq. A-1a)}$$

where

Q_1 = gas flow at the gas supply system, $\mathrm{ft}^3/\mathrm{min}$ (m^3/s);
Q_p = gas flow at the point of flow measurement, $\mathrm{ft}^3/\mathrm{min}$ ($\mathrm{m}^3/\mathrm{sec}$);
P_1 = ambient (gas supply inlet) atmospheric pressure, atm (kPa);
P_p = gas pressure at the point of flow measurement, atm (kPa);
T_1 = ambient (gas supply inlet) temperature, K (= °C + 273);
T_p = gas temperature at the point of flow measurement, K;
$R_{H,p}$ = ambient (gas supply inlet) relative humidity, percent;
$R_{H,1}$ = relative humidity at the gas supply inlet, percent;
$P_{V,p}$ = vapor pressure of water at the point of flow measurement, atm (kPa); and
$P_{V,1}$ = vapor pressure of water at the gas supply system inlet, atm (kPa).

Under typical operating conditions for oxygen transfer using diffused aeration, the effect of relative humidity is very small and can be neglected. The maximum error of the estimate of Q_1 likely to result from the simplification is approximately 1% (underestimation; for ambient relative humidities above 80%). Neglecting this small error, gas flows can be converted to inlet conditions using the following simplified equation:

$$Q_1 = Q_p (T_1 P_p / T_p P_1) \qquad \text{(Eq. A-1b)}$$

Ambient atmospheric pressure and relative humidity at the time of the test can generally be obtained from a nearby U.S. Weather Service station or commercial airport.

Many flow measurement devices operate on a pressure differential principle. The measurement of P_p must be made far enough downstream from the measurement device to avoid interferences that may be caused by the device. Generally, the downstream pressure measurement that is used for determining flow through the device is suitable for this purpose.

A.5.2 Conversion of Gas Flow to Standard Conditions

The gas flow measured in the gas supply system (and converted to the gas flow equivalent inlet conditions as described in paragraph A.5.1) must be converted to the equivalent gas flow under standard conditions. This conversion can be made using the following equation:

$$Q_s = Q_1 T_s (P_1 - R_{H,1} P_{V,1}) / T_1 (P_s - R_{H,s} P_{V,s}) \qquad \text{(Eq. A-2a)}$$

where

Q_s = gas flow at standard conditions, $\mathrm{ft}^3/\mathrm{min}$ ($\mathrm{m}^3/\mathrm{sec}$);
P_s = standard air pressure, 1.00 atm (101.3 kPa);
T_s = standard air temperature
= 293 K for U.S. practice
= 273 K for European practice;
$R_{H,s}$ = standard relative humidity
= 36% for U.S. practice
= 0% for European practice; and

$P_{V,s}$ = vapor pressure of water at standard air temperature, atm (kPa).

As with Eqs. (A-1a) and (A-1b), the error introduced by neglecting relative humidity is very small. The maximum error (which is an underestimation of Q_s) that is introduced by neglecting relative humidity is about 1% for U.S. practice and about 2% for European practice. Neglecting these small errors, gas flows can be converted to standard conditions using the following equation:

$$Q_s = Q_1 T_s P_1 / T_1 P_s \qquad \text{(Eq. A-2b)}$$

A.5.3 Calculation of Mass Flows of Air and Oxygen

Volumetric gas flows must be converted to mass flows. The conversions for air, measured at standard conditions, can be made using the following equations:

$$W_{\text{air},s} = 0.0750 Q_s \quad \text{(in U.S. units, for U.S. practice)} \qquad \text{(Eq. A-3a)}$$

$$W_{\text{air},s} = 1.20 Q_s \quad \text{(in SI units, for U.S. practice)} \qquad \text{(Eq. A-3b)}$$

$$W_{\text{air},s} = 1.29 Q_s \quad \text{(in SI units, for European practice)} \qquad \text{(Eq. A-3c)}$$

$$W_{\text{O2},s} = 0.23 W_{\text{air},s} \quad \text{(in consistent units)} \qquad \text{(Eq. A-3d)}$$

where

W_{air} = mass flow of air, lb/min (kg/s); and
W_{O2} = mass flow of oxygen in air, lb/min (kg/s).

REFERENCES—ANNEX A

[1] Spink, L. K. (1978). *Principles and Practice of Flow Meter Engineering,* Ninth Ed., Foxboro Company, Foxboro, MA.

[2] Cusick, C. F. (1977). *Flow Meter Engineering Handbook*, Fifth Ed., Honeywell, Ft. Washington, PA.

[3] American Society of Mechanical Engineers. *Power Test Codes instruments and Apparatus Supplement,* ASME, 345 East 47th Street, New York, NY. Part 2. Pressure Measurement. (1987). PTC 19.2. Part 5. Applications, Part II of Fluid Meters. (1972). PTC 19.5.

[4] Miller, R. W. (1996). *Flow Measurement Handbook,* Third Ed., McGraw-Hill, New York, NY.

[5] *Handbook of Chemistry and Physics* (2005). 86th Ed., CRC Press, Boca Raton, FL.

[6] Stephenson, R. L., and Nixon, H. E. (1973). *Centrifugal Compressor Engineering*, Hoffman Air and Filtration Division, Clarkson Industries, Inc., New York.

ANNEX B

Power Measurements. Measurements of the power expended by oxygen transfer systems are required to determine system efficiency, such as the standard aeration efficiency (SAE). This Annex provides general procedures and guidance for measuring and calculating power. More detailed guidance and procedural assistance are provided in the references that are listed at the end of this Annex.

The power components to be measured or calculated depend on the specific oxygenation device and test conditions.

Measurement of power and related quantities should be in accordance with the following:

Shaft power measurement—ASME Power Test Code PTC 19.7 (i).

Electrical power measurement—ASME Power Test Code PTC 19.6 (i).

Pressure measurement—ASME Power Test Code PTC 19.2 (i).

Rotary speed measurement—ASME Power Test Code PTC 19.13 (i).

B.1 Definitions

B.1.1 Delivered Power

B.1.1.1 Delivered Blower Power

Theoretical power required at a blower discharge to deliver a given mass flow of gas at a given discharge pressure, calculated based upon adiabatic compression.

B.1.1.2 Delivered Turbine Power

Power delivered to a turbine, calculated based upon the turbine shaft torque and angular velocity.

B.1.1.3 Delivered Pump Power

Power delivered to a pump, calculated based upon the volumetric flow rate, fluid weight density, and total dynamic head.

B.1.1.4 Total Delivered Power

The sum of delivered blower, turbine, and pump powers.

B.1.2 Brake Power

Power developed or required at the shaft of a piece of rotating equipment.

B.1.3 Wire Power

The electrical power drawn by a motor.

B.1.4 Total Wire Power

The sum of blower, turbine, and pump wire powers.

B.2 Calculations of Delivered Power

B.2.1 Total delivered power is given as the sum of all the delivered power terms.

$$\text{Total Delivered Power} = \text{Delivered Blower Power} + \text{Delivered Turbine Power} + \text{Delivered Pump Power} \qquad \text{(Eq. B-1)}$$

Specific oxygenation devices may have only one or two delivered power terms, e.g., a surface aerator has only turbine power, whereas a submerged turbine has blower plus turbine power.

B.2.2 Delivered blower power shall be calculated based on adiabatic compression by Delivered Blower Power, hp (kW).

$$wRT_1/K[(P_2/P_1)^K - 1] \qquad \text{(Eq. B-2)}$$

where

w = mass flow of gas, lb/min (g/s);
R = gas constant for air, 1.62×10^{-3} hp-min/lb-°R (2.89×10^{-3} kW-s/g-K);
T_1 = absolute temperature before compression, °R (K);
P_1 = absolute pressure before compression, atm (kPa);
P_2 = absolute pressure after compression, atm (kPa);
k = ratio of specific heats for gas = 1.395 for air with adiabatic compression; and
$K = (k - 1)/k = 0.283$ for air with adiabatic compression.

B.2.3 Delivered turbine power should be based on direct measurement of torque and angular velocity delivered to the oxygenation device and shall be calculated from

$$\text{Delivered Turbine Power} = 2\pi T_q\,[N_r/(3.3 \times 10^4)] \qquad \text{(Eq. B-3)}$$

$$(\text{Delivered Turbine Power} = T_q N_r)$$

where

T_q = torque measured using either a cradled dynamometer (cradled motor, generator, pony brake) or surface strain dynamometer (surface strain, angular twist), ft lb (Nm); and
N_r = rotational speed, revolutions per min (rad/s).

When accurate conversion efficiencies are known, delivered turbine power may be calculated by multiplying the motor wire power by the appropriate efficiencies.

B.2.4 Delivered pump power shall be calculated as

$$\text{Delivered Pump Power} = Q_w(\text{TDH})(\text{SG})/3960 \qquad \text{(Eq. B-4)}$$

$$\text{Delivered Pump Power} = Q_w(\text{TDH})(W)$$

where

Q_W = liquid flow rate, gal/min (m^3/s);
TDH = total dynamic head, ft (m);
SG = specific gravity of water at test temperature; and
W = specific weight of water at test temperature (N/m^3).

When accurate conversion efficiencies are known, delivered pump power may be calculated by multiplying the motor wire power by the appropriate efficiencies.

B.3 Wire Power

Wire power is related to delivered power by

$$\text{Wire Power} = \text{Delivered Power}/e_a e_b e_c \ldots \qquad \text{(Eq. B-5)}$$

where

e_a, e_b, and e_c are the efficiencies of the various power conversion devices (motors, gear drives, reducers, blowers) used to transform electricity to delivered power.

Wire power should be measured using accurate recording polyphase watt meters capable of monitoring 10-cycle per second peaks. An ammeter can also be used if the voltage and power factor are measured. An expression for calculating the 3-phase power from current, voltage, and power factor measurements is

$$\text{Wire Horsepower} = (2.319 \times 10^{-3})EIF \qquad \text{(Eq. B-6)}$$

$$(\text{Wire Watts} = 1.7323EIF)$$

where

E = voltage, volts;
I = current, amperes; and
F = power factor.

REFERENCE—ANNEX B

[1] American Society of Mechanical Engineers. *Power Test Codes Instruments and Apparatus Supplement* ASME, 345 East 47th Street, New York, NY.

ANNEX C

Sections 6.6 and 6.7.2

Powdered Sulfite Addition to Aeration Tanks. The intent of sulfite addition is to achieve a condition in which the entire tank volume reaches near-zero DO and in which the entire tank volume begins the reoxygenation process at approximately the same point in time (Refs. [1] to [4]). The following points shall be considered when powdered sulfite is directly added to aeration tanks for deoxygenation:

1. For a tank in which the oxygenation rate is uniform over the volume (e.g., full floor coverage diffused aeration), sulfite should be uniformly distributed throughout the volume.
2. For a point source aerator/mixer, the oxygenation rate is generally higher in the vicinity of the aerator/mixer, and, therefore, relatively more sulfite should be added in the vicinity of the aerator/mixer.
3. For a looped reactor with a point source aerator, the sulfite shall be added during a fixed integer number of revolutions (1 to 4) of water. Multiple addition points should be used for large looped reactors (rotation times greater than 15 min).
4. In the case of high oxygen transfer rates or high power/volume ratios, consideration may be given to temporarily lowering the air rate or power during sulfite addition and then adjusting back to the required rate upon completion of sulfite addition.
5. Failure to achieve proper sulfite addition can result in erroneous estimates of K_La. A lack of sulfite in part of the tank can result in an underestimate of K_La, and excess sulfite in part of the tank can result in an overestimation of K_La.
6. Care should be taken to prevent addition of chunks or lumps of chemical. Sulfite shall be added as a shower and distributed uniformly, as opposed to "bag dumping."
7. Extra precautions for sulfite delivery must be taken on windy days.
8. Distribution points from the sides of the tank should not exceed 7 to 10 m (20 to 30 ft). Temporary access bridges or cranes may be required to reach the center of the tank.
9. Using shovels or scoops, one person can be expected to distribute approximately 100 kg (225 lbs) of sulfite in 4 to 6 min.

REFERENCES—ANNEX C

[1] Duchene, Ph., Schetrite, S., Heduit, A., and Racault, Y. (1995). *Comment reussir un essai d'aerateur en eau propre.* Cemagref, Antony, ed., France, p. 118.

[2] Vasel, J-L., and Juspin, H. (1995). *Convention pour la normalisation d'essais d'aerateurs.* Station pilote, Rapport Final, FUL, Arlon, Belgium, p. 124.

[3] ATV (1996). ATV-Merkblatt M 209: Measurement of the Oxygen Transfer in Activated Sludge Tanks with Clean Water and in Mixed Liquor, Gesellschaft zur Forderung der Abwassertechnik e.V. (GFA), Hennef.

[4] European Standard. (December 1999). Wastewater Treatment Plants—Part 15: Measurement of the Oxygen Transfer in Clean Water in Activated Sludge Tanks. Draft, prEN 12255-15.

ANNEX D

Probe Calibration. The basic method for calibrating dissolved oxygen probes consists of a zero check and a calibration adjustment.

D.1 Zero Check

There are two approaches to making the zero check. The first is the explicit method, outlined in Section D.1.1. The second is the deoxygenation method, described in Section D.1.2. The explicit method is recommended for an initial zero check before the probes are installed in the tank and may be used at any time when it is convenient to remove a probe from the tank. The deoxygenation method may be substituted for the zero check between tests when it is not convenient to remove the probes from the tank. Failure to attain the zero check indicates a faulty probe and requires corrective action.

D.1.1 Explicit Method

This is performed by placing the probe assembly in a sample of water containing zero dissolved oxygen, a condition that can be attained by the addition of excess sulfite, by stripping with pure nitrogen, or by biological utilization of oxygen. Upon exposure to zero DO, the probe shall indicate a dissolved oxygen concentration within 0.3 mg/L of zero over an exposure time of 5 min or less. Although it is desirable that the zero check reading be within 0.05 mg/L of zero, certain probe systems have a slow response rate in deoxygenated water and may indicate probe readings up to 0.3 mg/L at a response time suitable for higher DO values. Thus, a probe reading within 0.3 mg/L of zero (after an exposure time of 5 min or less) is generally acceptable for the zero check.

D.1.2 Deoxygenation Method

The basic oxygen transfer test procedure described in Section 6.7.2 requires that sulfite addition depress the DO to less than 0.5 mg/L at all determination points. Attainment of a probe reading of 0.5 mg/L or less during the deoxygenation procedure is a satisfactory zero check for that probe.

D.2 Calibration Adjustment

This shall be performed by

1. Measurement of DO meter response by exposing the probe assembly, either in situ or in vitro, to water containing DO at or near the saturation level.
2. Precise determination of the DO concentration in the water by an independent reference method.
3. Adjustment of the meter reading to agree with the DO determined by the reference method.

Five variants of the calibration adjustment procedure are permitted depending on the location of the probe (either in situ or in vitro) during the measurement of meter response, on the independent reference method (Winkler, calculation based on surface saturation, or calibrated reference probe) used for precise DO determination, and on the spatial variation in DO concentration. The variants are outlined in Sections D.2.1.1, D.2.1.2, D.2.1.3, D.2.2.1, and D.2.2.2, and one of these shall be followed.

Accurate probe readings generally require a liquid velocity of at least 0.3 m/sec near the sensor/water interface, and, for this reason, probes must be equipped with agitators or other suitable means must be provided to assure adequate liquid velocity past the probe. This is especially important if an in vitro calibration adjustment is to be employed.

D.2.1 In Situ Calibration Adjustments

The probe shall be located in the tank at the particular determination point to be used for the unsteady-state test. The tank shall be aerated to within approximately 0.1 mg/L of the steady-state saturation condition, the probe meter reading shall be noted, and the DO concentration at a point within 0.5 m of the probe location shall be measured using either the Winkler procedure (Section D.2.1.1) or a calibrated reference DO probe (Section D.2.1.2). A multiple probe calibration procedure (Section D.2.1.3) may be applied in cases where Winkler samples or calibrated reference probe readings taken from the various determination points indicate DO values within 0.2 mg/L of each other.

D.2.1.1 In Situ Calibration Adjustment Using the Winkler Procedure

This will normally require in-place tubing and a pump for withdrawal of a water sample from a location within 0.5 m of the probe. The probe reading at the time of sample withdrawal shall be noted, and a Winkler DO measurement shall be immediately performed on the water sample. The probe meter or recorder shall be immediately adjusted so that the indicated and measured values agree. Because samples withdrawn from deep locations may contain DO concentrations in excess of the surface saturation values, care must be exercised in handling the samples so that oxygen is not lost.

D.2.1.2 In Situ Calibration Adjustment Using a Calibrated Reference Probe

This procedure utilizes a portable calibrated reference DO probe in place of the Winkler method. The portable reference probe shall be calibrated according to one of the in vitro methods outlined below and lowered into the tank to within 0.5 m of the in situ probe to be calibrated. The meter reading of the probe to be calibrated shall be adjusted to agree with the DO indicated by the reference probe.

D.2.1.3 Multiple Probe In Situ Calibration Adjustment

In cases where it is demonstrated that a group of probe locations (up to four) shows steady-state saturation, Winkler DO values or calibrated reference probe readings within 0.2 mg/L of each other, a single centrally located measurement point may be used to calibrate a group of up to four probes. The spatial uniformity required to apply this method may be demonstrated by comparing the readings given by individually calibrated probes or by comparing the results of Winkler DO analyses performed on samples withdrawn from the various probe locations. When this method is applied, at least two Winkler DO values or calibrated reference probe readings shall be determined at the centrally located measurement point. The group of probes shall then be calibrated to read the average of the two or more values. The average value of the DO so determined shall be used for probe calibration and shall not be interpreted as the average value of C^*_∞ for the tank.

D.2.2 In Vitro Calibration Adjustment

This shall be performed by removing the probe from the tank and submerging it in a shallow (less than 0.3 m) aerated calibration vessel of water. The DO concentration in the vessel shall either be measured by the Winkler method (Section D.2.2.1) or be calculated based on surface saturation conditions (Section D.2.2.2), and the meter or recorder output shall be adjusted to agree with the measured or calculated value.

D.2.2.1 In Vitro Calibration Adjustment Using the Winkler Procedure

A water sample shall be siphoned from the shallow aerated vessel into a standard BOD bottle and analyzed for dissolved oxygen by the Winkler method. The remaining procedure is as described above in D.2.2.

D.2.2.2 In Vitro Calibration Adjustment Based on Surface Saturation Conditions

The following method shall be used for calculation of the DO concentration based on surface saturation conditions.

1. The water in the calibration vessel shall have been aerated by rapid stirring of a submerged diffuser for at least 20 min.
2. The water temperature shall be measured to within 0.50°C.
3. The local site elevation above sea level, H in ft, and the local barometric pressure corrected to sea level, P_{bsl}, shall be determined. These may be determined from topographic maps and the Weather Service, respectively. The barometric pressure, P_b, at the calibration site can then be calculated as

$$P_b = P_{\mathrm{bsl}}[1 - (3.5 \times 10^{-5})H] \qquad \text{(Eq. D-1)}$$

When the calibration site is at the same elevation as a nearby weather station, P_b may be taken equal to the station pressure.

The DO concentration in the calibration vessel is given as

$$C^*_{\mathrm{scal}} = C^*_{\mathrm{st}}\,(P_b/P_s)$$

where

C^*_{scal} = DO concentration in the calibration vessel;
P_{bsl} = local barometric pressure corrected to sea level; and
C^*_{st}, P_b, and P_s are as defined in Section 8.1.

D.3 Frequency of Probe Calibration

Although a well-functioning probe that is not calibrated will give data that will result in a correct value of K_La, proper determination of the oxygen transfer rate requires that the point value of the saturation concentration, C^*_∞, corresponding to each determination point be estimated from the oxygen transfer model. Because of this, it is important that the probes be properly calibrated and that this calibration be checked during testing.

During the collection of oxygen transfer data, the observed performance of the probes will generally identify malfunctioning if it exists. When the test system is deoxygenated, the dissolved oxygen probes should show the downscale response as deoxygenation is achieved, and the probes should have the anticipated near zero readout when complete deoxygenation is achieved. After reoxygenation to the steady-state saturation condition, the DO probe at a particular location should, if the water temperature is not changing, display essentially the same reading from run to run. A DO probe that does not track the anticipated pattern represents a potential malfunction and should be immediately recalibrated.

A zero check shall be performed on each probe at the beginning of each test. Inability of a probe to satisfy a zero check indicates a malfunctioning probe, and no data obtained from that probe shall be used to calculate the oxygen transfer rate.

It is recommended that probe saturation calibration be verified after each test; however, no more than three runs shall be made without checking the saturation calibration. This adjustment shall be performed frequently when observed saturation values indicate possible probe drift. If the indicated saturation adjustment is 0.2 mg/L or less, the data collected prior to the adjustment shall be accepted as valid and used to calculate the oxygen transfer rate. If the indicated saturation adjustment is greater than 0.2 mg/L, but less than 0.4 mg/L, the series of three tests shall be accepted as valid, but the DO data of the third test shall be adjusted to conform to the recalibrated value. If the indicated saturation adjustment is greater than 0.4 mg/L, the probe has drifted (i.e., malfunctioned), and no data from that probe shall be used to calculate the oxygen transfer rate.

D.4 Linearity Check

Linearity of probe response should be checked when there is reason to suspect that the response is not linear. Nonlinearity could be indicated by marked trends in the residuals resulting from nonlinear regression of the model to the data. A linearity check is performed by exposing a calibrated probe to a series of five or more water samples containing known values of DO concentrations distributed over a range of approximately 0 to 9 mg/L. The DO concentrations should be determined by the Winkler procedure. The probe response is plotted versus the known DO concentrations to demonstrate linearity. Linearity is a characteristic of a particular probe and meter combination. Generally, linearity does not change as long as the meter is kept in a stable operating environment.

D.5 Comments

A DO probe should theoretically produce identical readings in water-saturated air and air-saturated water at a given temperature. However, because of the influence of fluid velocity and evaporative heat loss, identical readings are not always obtained. Therefore, calibration of a probe in air is not recommended.

ANNEX E

Preparation of Data for Analysis

E.1 Continuous Probe Data

When DO probes, equipped with continuous strip chart recorders are used, a continuous record of dissolved oxygen versus time will be available at each determination point. When probes are equipped with digital recorders, printout should be at frequent intervals (about 0.25–0.5 min for concentrations below 86% C^*_∞, and 1.0 min, thereafter). In this case, a minimum of 21 discrete data values shall be used for the analysis. The data values selected shall meet the timing criteria outlined in Section 6.8.3.3. Commentary D gives guidance for selecting time intervals to meet these criteria.

The discrete data values shall be read directly from the recorder graph or digital output and shall not be subject to any smoothing or averaging procedure. (See Commentary D for experimental planning.)

The 21 or more data values selected at each determination point should be plotted as DO versus time, and the DO data should be examined for lingering effects of the deoxygenating chemicals. Following possible low-end truncation in accordance with E.3, the data plotted for each determination point shall be checked again for compliance with the timing criteria outlined in Section 6.8.3.3.

Occasionally, a DO probe will malfunction. Data from a malfunctioning probe shall not be used to calculate the SOTR. Frequently, malfunction will be obvious, but, in other cases, a malfunction may be only suspected. The following criteria should be employed to judge whether data from a suspected probe may be deleted:

1. Results of a probe calibration or check conducted immediately before, during, or immediately after the test.
2. Linearity check of suspected probe.
3. Comparison of the K_La_{20} value for the suspected test and point with the average of those obtained for the same point in at least three replicate tests (including the suspected test) as described in Section 8.2.2. Variation by more than 15% of the average suggests probe malfunction.
4. Deletion of data from a malfunctioning probe may invalidate the test in accordance with Section 8.2.2.

E.2 Discrete Sample Data

When discrete samples are analyzed, either by the Winkler method or by a membrane probe, the data consist of discrete DO concentration values at the intervals used for each determination point. In this case, it is crucial that the sampling times have been well planned in accordance with Commentary D.

The data shall be plotted as DO versus time and the low DO data should be examined for lingering effects of the deoxygenation chemicals as described in E.3. These effects are normally more difficult to detect in discrete sample data. Based on this examination, data values may be truncated as outlined in E.3. Following possible low-end truncation, the data plotted for each determination point shall be checked for compliance with the timing criteria outlined in Section 6.8.3.3. The discrete data values to be analyzed shall not be subjected to any smoothing or averaging procedure.

E.3 Truncation

The data values at each determination point should be plotted as DO versus time and the low DO data should be examined for lingering effects of the deoxygenation chemicals. These effects would be manifested by the rate of increase in DO being constant or increasing with DO up to an inflection point.

If either of these patterns is suggested, the DO data below 20% of the approximate C^*_∞ value may be truncated. Furthermore, when a clear inflection point is present, it is permissible to truncate data up to a concentration equal to 1.5 times the concentration at the inflection point, but in no case shall DO values greater than 30% $C^*_{\infty 20}$ be truncated.

ANNEX F

Log Deficit Parameter Estimation Method

This method relies upon the average of replicate DO measurements at saturation to estimate C^*_∞ at each determination point. It is based on a one-parameter linear regression of the logarithmic form of the model equation:

$$\ln(C^*_\infty - C) = \ln(C^*_\infty - C_0) - K_La(t - t_0) \qquad \text{(Eq. F-1)}$$

where

t_0 = time when $C = C_0$.

The value C^*_∞ at each determination point shall be estimated by averaging results of at least three DO measurements taken at 5 min intervals beginning at a time greater than $6/K_La$ beyond t_0. These measurements shall be collected using the same technique as that for reaeration DO measurements. The value of C_0 is the lowest value of DO selected for analysis in accordance with Section 6.8.3.3. Equation (F-1) shall be fitted to the data points, prepared in accordance with Section 6.8.3.3 and Annex D. However, the highest value of C employed in the linear regression shall not be less than 90% of C^*_∞ nor greater than 95% of C^*_∞.

To apply this method, the following steps shall be followed:

1. The prepared data, including the replicate measurements for estimation of C^*_∞, shall be plotted according to Annex C and shall be examined for consistency.
2. The quantity, $\ln(C^*_\infty - C)$, shall be computed for each of the values of C within the range to be analyzed, and a linear regression of this quantity versus time shall be made. (See any standard test on statistics or suitable electronic calculator instructions.) The regression coefficient is the slope of the plot of $\ln(C^*_\infty - C)$ versus time and is equal to $-K_La$.

In many previous studies, investigators have made assumptions regarding the value of C^*_∞, and methods have been developed considering water temperature and depth, transfer rate, along with other variables that affect the saturation DO value. These *a priori* methods, such as mid-depth saturation, have been used with the objective of determining the saturation concentration without actually measuring it. This is attractive since the time required to perform a test can be reduced.

Unfortunately, the precision of the *a priori* method of estimating the saturation value is much less than the precision required as a standard procedure. The only acceptable method of determining the saturation value is to measure it at the conclusion of a reaeration test, which requires that reaeration continue for at least $6/K_La$ units of time beyond t_0. If the test is terminated prior to $6/K_La$, estimates of K_La and SOTR will be biased in favor of a greater transfer rate than actually occurred in the test. It appears from analysis of numerous data sets that the calculated transfer rate will increase by 3% for every 1% decrease in the assumed saturation value. Boyle et al. (Ref. [1]) and Campbell et al. (Ref. [2]) have shown that a 10% bias in transfer rate may occur if the wrong *a priori* method of determining the saturation value is used. A 10% bias in transfer rate will often make the difference between failing and passing a compliance test.

If properly applied, the log deficit procedure generally produces K_La, C^*_∞, and SOTR values comparable to the recommended nonlinear regression procedure. However, the log deficit procedure requires additional time in testing, since long aeration times are required ($6/K_La$) to accurately estimate C^*_∞ from replicate measurements in saturation.

REFERENCES—ANNEX F

[1] Boyle, W.C., Berthouex, P.M., and Rooney, T.C. (1974). "Pitfalls in parameter estimation for oxygen transfer data," *J. Envir. Engrg. Div. ASCE,* 100(EE2), 391.

[2] Campbell, H.J., Ball, R.O., and O'Brien, J.H. (January 13, 1976). "Aeration testing and design—A critical review." 8th Mid-Atlantic Industrial Waste Conference, University of Delaware, Newark, Delaware.

ANNEX G

Calculation of $C^*_{\infty 20}$

A more rigorous method for calculating $C^*_{\infty 20}$ from Eq. (8-3) in Section 8.1 involves the more precise definition of the pressure correction factor, Ω. The value of the pressure correction factor may be expressed more explicitly as

$$\Omega = (P_b + \gamma_{wt} d_e - P_{vt})/(P_s + \gamma_{wt} d_e - P_{vt}) \qquad \text{(Eq. G-1)}$$

where

γ_{wt} = weight density of water at the test water temperature, fL^{-3};
P_{vt} = saturated vapor pressure of water at the test temperature, fL^{-2};
d_e = effective saturation depth at infinite time, L^2, defined by; and
$d_e = 1/\gamma_{wt}[(C^*_\infty/C^*_{st})(P_s - P_{vt}) - P_b + P_{vt}]$, and the other terms are defined in Section 8.1. A more detailed discussion of this calculation may be found in Brown and Baillod (Ref. [1] of this standard).

COMMENTARY (NON-MANDATORY)

COMMENTARY A

Section 2.0

Pure Oxygen Desorption Method. The following method is currently being used at sites outside of the United States. It has proven to be a successful alternative to the sulfite deoxygenation method in some cases. At this time, the method is being further evaluated as an alternative method for clean water oxygen transfer testing.

A.1 Fundamentals

The transfer of oxygen in clean water is described by Eq. (2-1). This equation can be used to express the increase in DO with time to steady-state DO saturation where sulfite is added to deoxygenate the water, or to express the decrease in DO down to steady-state DO saturation where excess DO is present in the water. In either case the values of K_La and C^*_∞ may be calculated for a given aeration system. In the first case, the method may be referred to as an absorption procedure and in the latter a desorption procedure.

A.2 Test Procedures

The proposed procedure is based on adding high purity oxygen gas to the air stream that feeds the aeration system in the aeration tank. The increase in DO in the test tank is monitored continuously. When a target concentration of DO is reached, the high purity oxygen feed is turned off. The DO is then measured and recorded the same as in the absorption procedure.

The target DO concentration should be at least 6 mg/L greater than the steady-state DO saturation concentration that would be achieved with atmospheric air. For example, if the steady-state DO saturation concentration for the air system was 10.5 mg/L, the target DO concentration while feeding the high purity oxygen should be at least 16.5 mg/L. For best results, the target increase in DO concentration should be higher, in the range of 10 to 15 mg/L. Higher oxygen concentrations are not necessary and should be avoided.

To achieve the desired increase in DO concentration in a reasonable amount of time, target DO concentration must be a point along the aeration curve and not the steady-state saturation concentration. This can be accomplished by increasing the oxygen content in the air stream so the resultant steady-state DO saturation concentration is increased by 5 to 20 percent.

The high purity oxygen feed rate can be calculated using the following equation:

$$Q_{O2} = Q_a(X_{O2} - 21)/(100 - X_{O2}) \qquad \text{(Eq. CA-1)}$$

$$X_{O2} = 21(C^*_{\infty HPO}/C^*_{\infty AIR}) \qquad \text{(Eq. CA-2)}$$

$$C^*_{\infty HPO} = (1 + f)(C^*_{\infty AIR} + \Delta C) \qquad \text{(Eq. CA-3)}$$

where

Q_{O2} = high purity oxygen flow rate, ft^3/min (m^3/hr);
Q_a = air flow rate, ft^3/min (m^3/hr);
X_{O2} = oxygen fraction in the enriched air stream, percent by volume;
$C^*_{\infty HPO}$ = steady-state DO saturation concentration in the test water that could be achieved with the oxygen enriched air, mg/L;
$C^*_{\infty AIR}$ = steady-state DO saturation concentration in the test water that could be achieved with atmospheric air, mg/L;
f = fractional increase in steady-state DO saturation concentration (typically 0.05 to 0.2); and
ΔC = target increase in DO, mg/L.

The length of time that the high purity oxygen must be fed into the air stream to achieve target DO saturation concentration is calculated by

$$t_{O2} = (-60/K_La')\ln[(C^*_{\infty HPO} - \Delta c - C^*_{\infty AIR})/(C^*_{\infty HPO} - C^*_{\infty AIR})] \qquad \text{(Eq. CA-4)}$$

where

t_{O2} = dosing time, min;
K_La' = apparent volumetric mass transfer coefficient for the air/oxygen mixture, hr^{-1}.

The value of K_La' can be estimated by

$$K_La' = K_La(Q_a' + Q_{O2})/Q_a \qquad \text{(Eq. CA-5)}$$

where

Q_a' = airflow rate (from blowers) during the high purity oxygen dosing time, ft^3/min (m^3/hr).

The quantity of high purity oxygen used in a given test can be calculated by

$$V_{O2} = Q_{O2}t_{O2} \quad \text{(in U.S. units)} \qquad \text{(Eq. CA-6)}$$

$$V_{O2} = Q_{O2}t_{O2}/60 \quad \text{(in SI units)}$$

$$M_{O2} = 0.089Q_{O2}t_{O2} \quad \text{(in U.S. units)} \qquad \text{(Eq. CA-7)}$$

$$M_{O2} = 1.43Q_{O2}t_{O2}/60 \quad \text{(in SI units for European practice)}$$

where

V_{O2} = volume of high purity oxygen used, ft^3 (m^3); and
M_{O2} = mass of high purity oxygen used, lb (kg).

The high purity oxygen would typically be delivered as a liquid and stored near the test tank in a mobile liquid-oxygen storage tank. The oxygen would be conveyed to a feeding flange via a vaporizer and flow measuring system. Personnel must follow all safety precautions when using high purity oxygen.

All other procedures to be followed for the pure oxygen desorption method are identical to those described in the sulfite deoxygenation procedures as written in Sections 6, 7, and 8. The advantage of this procedure is that no dissolved salts are added to the test water (sulfite and cobalt), and therefore no precautions need to be taken relative to buildup of TDS in the test water (Section 6.3.1).

A.3 Example

Testing Conditions and Assumptions (U.S. Units)

$Q_a = 5{,}000$ std ft^3/min
$C^*_{\infty AIR} = 10.5$ mg/L
$Q_a' = 5{,}000$ std ft^3/min
$K_La = 10\ hr^{-1}$
$\Delta C = 15$ mg/L
$f = 0.2$

Sample Calculations

$$\begin{aligned}
C^*_{\infty HPO} &= (1 + f)(C^*_{\infty AIR} + \Delta C)\\
&= (1 + 0.2)(10.5 + 15)\\
&= 30.6 \text{ mg/l}\\
X_{O2} &= 21(C_{\infty HPO}/C^*_{\infty AIR})\\
&= 21\%\ (30.6 \text{ mg/L}/10.5 \text{ mg/L})\\
&= 61.2\% \text{ oxygen in the air stream}\\
Q_{O2} &= Q_a(X_{O2} - 21)/(100 - X_{O2})\\
&= 5{,}000 \text{ std ft}^3\text{/min } (61.2\% - 21\%)/(100\% - 61.2\%)\\
&= 5{,}180 \text{ std ft}^3\text{/min of high purity oxygen}\\
K_La' &= K_La\ (Q_a' + Q_{O2})/Q_a\\
&= 10\ \text{hr}^{-1}\ (5{,}000 \text{ std ft}^3\text{/min} + 5{,}180 \text{ std ft}^3\text{/min})/5{,}000 \text{ std ft}^3\text{/min}\\
&= 20.36\ \text{hr}^{-1}\\
t_{O2} &= (-60/K_La')\ \ln[(C^*_{\infty HPO} - \Delta c - C^*_{\infty AIR})/(C^*_{\infty HPO} - C^*_{\infty AIR})]\\
&= (-60/20.36\ \text{hr}^{-1})\ \ln[(30.6 \text{ mg/L} - 15 \text{ mg/L} - 10.5 \text{ mg/L})/(30.6 \text{ mg/L} - 10.5 \text{ mg/L})]\\
&= 4.0 \text{ min}\\
V_{O2} &= (Q_{O2})(t_{O2})\\
&= (5{,}180 \text{ std ft}^3\text{/min})\ (4.0 \text{ min})\\
&= 20{,}900 \text{ std ft}^3\\
M_{O2} &= 0.089\ (Q_{O2})(t_{O2})\\
&= 0.089\ (V_{O2})\\
&= (0.089 \text{ lb O}_2\text{/std ft}^3)(20{,}900 \text{ std ft}^3)\\
&= 1{,}860 \text{ lb O}_2
\end{aligned}$$

REFERENCES—COMMENTARY A

[1] Wagner, M. R., Popel, H. J., and Weidmann, F. (1996). “Performance and evaluation of oxygen transfer tests in clean water.” *Korrespondenz Abwasser,* 43, 81.

[2] ATV. (1996). ATV-Merkblatt M 209: Messung der Sauerstoffzufuhr von Beluftungsreinrichtungen in Belebungsanlangen in Reinwasser und in belebtem Schlamm. (Advisory Guideline M 209, Measurement of Oxygen Transfer in Activated Sludge Aeration Tanks with Clean Water and in Mixed Liquor), Gesellschaft zur Forderung der Abwassertechnik e.V. (GFA), Hennef.

COMMENTARY B

Section 6.3

Effect of Total Dissolved Solids on K_La. Experience with conducting nonsteady-state reaeration tests in clean water using sodium sulfite for removing dissolved oxygen has shown that successive tests in a single batch of test water typically yield a progressive increase in the mass transfer coefficient, K_La. The effect was first noted by Benedek (Ref. [1]). The paper discusses causes for the effect and presents experimental data obtained using a 3-l, mechanically stirred fermentor. Several hundred tests were conducted in a single batch of water. Over the very wide range of total dissolved solids (TDS) concentrations, the data formed an S curve. The data were fitted to an equation of the form

$$(K_La)_s/(K_La)_0 = \gamma = \gamma_{\max}/(1 + p^{-rn}) \qquad \text{(Eq. CB-1)}$$

where

$\gamma_{\max}$ = the upper value of γ;
n = the number of tests conducted; and
p, r = arbitrary constants.

The results of Benedek are not applicable to current practice because of the very high concentrations of TDS concentrations tested. However, the effect has also been observed over the much smaller range of TDS concentrations typically encountered when conducting clean water oxygen transfer tests in accordance with this standard.

Ewing and Redmon developed a relationship similar to that of Benedek to correct clean water oxygen transfer test results to a total dissolved solid concentration of 1,000 mg/l (Ref. [2]). The TDS concentration of 1,000 mg/l was used as the reference concentration because it is one-half the maximum concentration of 2,000 mg/l allowed in this standard (Section 6.3.1). Furthermore, most municipal wastewater treatment plants seldom have TDS levels exceeding 1,000 mg/l.

Lee et al. (Ref. [3]) observed that standard oxygen transfer efficiency (SOTE) increased almost linearly as successive replicate tests were conducted in a single batch of water over the course of a day. They found excellent correlation between SOTE and TDS using both linear and exponential regression models. However, the exponential method provided a better fit at both ends of the data range. They also used 1,000 mg TDS/l as the reference concentration. Their relationship is nearly identical to the expression developed by Ewing and Redmon. The expression adjusts SOTE as follows:

$$\mathrm{SOTE}_{1,000} = \mathrm{SOTE} \exp^{[0.0000965\ (1,000\text{-TDS})]} \qquad \text{(Eq. CB-2)}$$

The more fundamentally correct adjustment for the TDS effect is to use the mass transfer coefficients as originally proposed by Benedek. The expression in terms of K_La is

$$K_La_{\ 1,000} = K_La \exp^{[0.0000965\ (1,000\text{-TDS})]} \qquad \text{(Eq. CB-3)}$$

This expression has been applied to both fine pore and coarse bubble diffused aeration systems tested in clean water. In each case, the relationship essentially eliminates the increasing trend seen in the raw test results. In addition, the variability among replicate tests as measured by the coefficient of variation (standard deviation divided by the mean) is reduced substantially.

While there appear to be sufficient data to support including the K_La adjustment (Eq. CB-3) for diffused aeration systems in the main body of the standard, Eq. (CB-3) has not been validated for mechanical aeration devices. A progressive increase in K_La (and SOTR) has also been observed when successive tests are conducted using mechanical surface aerators. However, the adequacy of Eq. (CB-3) or a similar relationship for adjusting raw test results to a common TDS concentration has not been verified.

The ASCE Oxygen Transfer Standards Committee requests that those who conduct clean water tests on mechanical aeration devices look for opportunities to gather data from a significant number of replicate tests. The data can then be used to determine whether Eq. (CB-3), or a similar equation, will provide a method for adjusting progressive K_La values to a common TDS concentration.

Researchers are encouraged to share their test results with the Committee. Communications can be sent electronically to Dr. Michael K. Stenstrom at UCLA. Dr. Stenstrom maintains a Web site at http://www.seas.ucla.edu/stenstro.

If sufficient data are collected and analyzed, methods for adjusting oxygen transfer test results to a common TDS concentration will be considered in the future for inclusion in the main body of the standard as a mandatory correction.

REFERENCES—COMMENTARY B

[1] Benedek, A. (1971). "Problems with the use of sodium sulfite in aerator evaluation." *Proc. of 26th Purdue Industrial Waste Conference,* Lafayette, IN, 947.

[2] Redmon Engineering Co., Milwaukee, WI, unpublished communication.

[3] Lee, J. S., Rieth, M. G., Jaccobson, R., DeFore, R. W., Voth, H. P., Edwards, J., Kuhn, P. A., and Popeck, J. R. (April 1997). "Twin Cities buy a fine aeration system." *Water Envir. Technol.,* 57.

COMMENTARY C

Section 6.6

Sulfite Quality Check. The quality of sulfite may be one of the causes for an unusual oxygen uptake response. The test sulfite may be evaluated by comparative laboratory or pilot-scale oxygen transfer tests. The oxygen transfer results (K_La values) obtained using analytical-grade sulfite or nitrogen-stripping deoxygenation can be compared to the results utilizing the test sulfite. The precision of the small-scale testing is such that if the oxygen transfer results are within ±10% of each other, the interference due to sulfite may be neglected.

COMMENTARY D

Sections 6.8.3.2 and 6.8.3.3

Guide for Estimating DO Determination Times. As described in Section 6.8.3.3, the timing of DO determinations is of importance in analyzing unsteady-state test data to ensure precision of the estimate of the oxygen transfer parameters.

It is convenient to plan a test based on 12, 15, 18, 21, or 24 measurements. Table D-1 shows the time intervals estimated to give the distribution of data values required by Section 6.8.3.3a. Use of Table D-1 requires an approximate value of K_La, which can be estimated from the expected value of OTR_0 as indicated in the table. However, K_La can more easily be approximated from an inspection of the DO-versus-time plot by noting the approximate value of the saturation concentration, C^*_∞, approached at infinite time. An approximate value of K_La is then given as the reciprocal of the time interval between dissolved oxygen concentrations of zero and 63% of C^*_∞. (For this method to be applied, the data may have to be extrapolated to zero DO.)

It should also be noted that the table assumes that sampling will begin at time zero, which is assumed to occur at a zero dissolved oxygen concentration. If zero DO is not attained, or if early truncation is to be practiced, the determination interval for zero to 86% saturation should be decreased by roughly 25% so that the required number of points are obtained in this region.

Table D-2 presents data value distributions for $0/K_La$ to $2/K_La$ and $2/K_La$ to $3.9/K_La$. This table can be used to check compliance with the timing criteria outlined in Section 6.8.3.3, whereas Table D-1 is used for experimental planning.

K_La = volumetric transfer coefficient, hr^{-1}, and may be approximated by

$$K_La = \text{OTR}_0/10W,$$

where

OTR_0 = expected oxygen transfer rate at zero DO, lb/hr; and
W = weight of water, 10^6 lb.

Table D-2. Distribution of DO Data Values Conforming to Criteria of Section 6.8.3.3

Total Number of Data Values	Time from 0 to $2/K_La$ Number of Values	Time from $2/K_La$ to $3.9/K_La$ Number of Values
12	7–9	3–5
13	8–9	4–5
14	9–10	4–5
15	9–11	4–6
16	10–12	4–7
17	10–12	5–7
18	11–13	5–7
19	12–14	5–7
20	12–15	5–8
21	13–15	6–8
24	14–18	6–10

Table D-1. Estimated Dissolved Oxygen Determination Intervals

	Time from 0 to $2/K_La$ (0%–86.5% Saturation)		Time from $2/K_La$ to $3.9/K_La$ (86.5%–98% Saturation)	
Total Number of Data Values	Number of Values	Determination Interval, hr	Number of Values	Determination Interval, hr
12	8	$0.285/K_La$	4	$0.500/K_La$
15	10	$0.222/K_La$	5	$0.400/K_La$
18	12	$0.182/K_La$	6	$0.333/K_La$
21	14	$0.153/K_La$	7	$0.285/K_La$
24	16	$0.133/K_La$	8	$0.250/K_La$

COMMENTARY E

Section 6.9.1

Probe Response Time. As a general guideline, the probe time constant should be less than $0.02/K_La$. The probe time constant can be estimated by transferring the probe from low DO water to high DO water and observing the time required for the probe to change from its old value to 63% of its new value. Error due to probe lag can be detected by observing the residuals. Probe effects are characterized by predominately negative residuals during the first part of the reaeration test and predominately positive residuals during the second part of the test (other factors can cause nonuniform residuals also). Truncation of early data up to 20% of C^*_∞ is sometimes helpful in reducing the effects of probe lag. For especially high rate transfer systems, it may be necessary to use 0.5 Mil membranes and select especially fast responding probes.

REFERENCE—COMMENTARY E

[1] Philichi, T. L., and Stenstrom, M. K. (1989). “Effects of Dissolved Oxygen Probe Lag on Oxygen Transfer Parameter Estimation.” *J Water Pollution Control Fed.,* 61, 83.

COMMENTARY F

Section 8.2.1

Spatial Uniformity of K_La_{20} *and* $C^*_{\infty 20}$ *Values Related to Mixing, Oxygen Distribution, and Data Adequacy.* There are various types of mixing and oxygenation conditions important in the design and evaluation of processes into which oxygen transfer is incorporated. Here, “oxygenation condition” refers to the spatial pattern of oxygen addition, e.g., point source, or uniformly distributed over the volume. These mixing and oxygenation conditions can be related to the pattern of spatial variation in K_La and DO.

1. *Theoretical Complete Mixing:* This refers to a condition that would require an added component to be completely and instantaneously dispersed uniformly throughout the tank. Although this situation is not attainable in real oxygen transfer systems, it would require uniformity of DO concentrations at all points at any given time during the reaeration period. Consequently, K_La and C^*_∞ would be uniform throughout the tank. Furthermore, in an activated sludge aeration tank approaching this condition, the DO concentration will be uniform at all points in the volume for both point source and uniformly distributed oxygenation conditions.
2. *Complete Macro Mixing:* This refers to a condition requiring that all fluid elements in the tank participate equally in the bulk flow. There can be no stagnant or “dead” zones. This condition would be approached by turbulent flow in a looped tubular reactor and, to a lesser extent, by flow in a well-baffled oxidation ditch.

Addition of a point source of oxygen under this condition will result in dissolved oxygen gradients, and DO concentrations will not be uniform at all points at any given time during the reaeration test. Although the C^*_∞ values may vary with hydrostatic pressure, the values of K_La and C^*_∞ will tend to be uniform throughout the volume. However, in an activated sludge aeration tank approaching this condition, there will be considerable variation in DO concentrations between the inlet to and discharge from the point source aerator, and these concentrations should be averaged in determining the effective concentration for the oxygen transfer driving force for the process water condition.

Addition of a uniformly distributed oxygen source under this condition (e.g., full floor coverage diffused air) will result in uniform DO values as well as uniform K_La and C^*_∞ values.

3. *Complete Micro Mixing:* This refers to a condition requiring that all fluid elements in a tank *section* participate equally in the bulk flow of *that section.* In this case, there may be several cells of complete micro mixing incorporated into the same tank with little interaction between the cells. An ideal example would be two or more oxidation ditches connected by a small channel. Likewise, a tank containing several surface aerators could be approximated as containing several cells of complete micro mixing.

For point source oxygenation within each cell, DO gradients will exist within each cell, and if the aeration intensity varies between cells, as in tapered aeration, there will be DO gradients between cells. The values of K_La and C^*_∞ will be uniform within a cell but may change between cells if the aeration intensity varies between cells.

Addition of a uniformly distributed oxygen source to a cell will result in uniform DO values as well as uniform K_La and C^*_∞ values in that cell. If the oxygenation condition is uniform over all cells, the DO, K_La, and C^*_∞ values will be uniform over all cells.

4. *Incomplete Mixing:* This refers to a condition existing when all fluid elements do not participate equally in the bulk flow; i.e., there are stagnant or

dead zones. This condition would be approached by a looped reactor or oxidation ditch containing an added dead-end arm.

Addition of a point source of oxygen under this condition will result in nonuniform DO values as well as in nonuniform K_La values with stagnant zones manifesting the lower K_La values.

Addition of an oxygenation source uniformly distributed over the entire tank (including stagnant zones) would give uniform DO and K_La values.

Table F-1 summarizes the relationships between mixing and oxygenation conditions and spatial distribution of DO and K_La during unsteady-state oxygen transfer tests. It should be borne in mind that theoretical complete mixing cannot be achieved in practice, complete macro and micro mixing cannot be achieved in practice, and complete macro and micro mixing are difficult to approach. Likewise, perfect point source and perfectly uniformly distributed oxygenation conditions are difficult to attain in practice. Nevertheless, Table F-1 indicates that the spatial distribution of K_La and DO can give some information relative to the mixing regime in the tank.

Although appreciable nonuniformity of K_La values does not necessarily invalidate the test, Table F-1 shows that this condition is suggestive of either nonuniform aeration intensity or incomplete mixing. Therefore, when spatial nonuniformity of K_La is evident, or when a mixing condition known to produce nonuniform K_La values is suspected, care should be taken to ensure that a sufficient number of determination (sampling) points are adequately located to correctly sense the changes in DO inventory of the tank.

COMMENTARY G

Application of Clean Water Test Results to Estimate Oxygen Transfer Rates in Process Water at Process DO Levels. The SOTR value determined by clean water unsteady-state oxygen transfer tests may be applied to estimate the oxygen transfer rate, OTR_f, for the same oxygenation system operating in the same tank under the same conditions, but in process water at an average process level DO concentration and temperature. The estimated value of OTR_f shall be calculated by

$$\mathrm{OTR}_f = (1/C^*_{\infty 20})[\alpha(\mathrm{SOTR})\theta^{(T-20)}](\tau\beta\Omega C^*_{\infty 20} - C) \qquad \text{(Eq. CG-1)}$$

where

OTR_f = oxygen transfer rate estimated for the system operating under process conditions at an average DO concentration, C, and temperature, T;

α = average process water K_La/average clean water K_La $= K_La_{f20}/K_La_{20}$;

β = process water C^*_∞/clean water C^*_∞; and

C = dissolved oxygen concentration averaged over the entire process water volume and other symbols are as defined in Section 8.1 and Annex E.

Although the application of clean water SOTR values to estimate transfer rates in process water is conceptually straightforward, the estimate of OTR_f

Table F-1. Relation between Mixing and Oxygenation Conditions and Spatial Distribution of DO and K_La during Unsteady-State Tests

Mixing Condition	Oxygenation Condition	Spatial DO Distribution	Spatial K_La Distribution
Theoretical complete mixing	Point source	+	+
	Uniformly distributed	+	+
Complete macro mixing	Point source	−	+
	Uniformly distributed	+	+
Complete micro mixing	Point source		
	Uniform cells	−	+
	Nonuniform cells	−	−
	Uniformly distributed		
	Uniform cells	+	+
	Nonuniform cells	−	−
Incomplete mixing	Point source	−	−
	Uniformly distributed	+	+

\+ = uniformly distributed within tank during test

− = nonuniformly distributed within tank during test is subject to considerable uncertainty because of the uncertainty contained in the α value. This uncertainty is magnified when the process water application is based on tank geometries and temperatures that differ from those of the clean water test. Table G-1 is a guide to the application of Eq. (CG-1) and indicates the source of information for the parameters needed to estimate OTR_f. Values of $C^*_{\infty 20}$ and SOTR must be known from the clean water test. The average DO value, C, must be determined from the process water conditions and should be evaluated as the process level DO concentration averaged over the entire aeration volume. It should not be taken as the DO concentration in the influent to a point source aerator. The temperature correction factor, τ, and pressure correction factor, Ω, should be calculated based on the definitions in Section 8-1 and Annex G.

G.1 Alpha Factor, α

The alpha factor represents the ratio of the K_La in process water to the K_La in clean water, and this ratio can range from approximately 0.1 to greater than 1.0 (Refs. [1]–[5]). It is influenced by a great number of process conditions including surfactants, turbulence, power input per unit volume, geometry, scale, bubble size, sludge age, degree of treatment, and other wastewater characteristics. Ideally, the alpha factor would be measured by conducting full-scale oxygen transfer tests with clean water and wastewater, but this is normally impractical. Several studies have described small-scale [less than 50 gallons (190 L)] oxygen transfer tests for measurement of the alpha factor and a state-of-the-art method based on these studies has been suggested by Stenstrom (Ref. [5]). In selection of an alpha factor for use in Eq. (G-1), it should be borne in mind that, for a given wastewater stream, the alpha factor is normally not constant, and a range of alpha values should be considered.

Table G-1. Guide to the Application of Eq. (CG-1)

Parameter	Source of Information
$C_{\infty 20}$	Clean water test results
d_e	Clean water test results
SOTR	Clean water test results
C	Given by the process water conditions
T	Given by the process water conditions
τ	Calculated based on tabulated DO surface saturation values
Ω	Calculated
α	Estimated based on experience and on measured K_La values
θ	Calculated based on total dissolved solids measurements taken as 1.024 unless experimentally proven to differ

G.2 Beta Factor, β

The beta factor is defined as the ratio of the average saturation concentration, C^*_∞, in process water to the corresponding value in clean water. This ratio can vary from approximately 0.8 to 1.0, and is generally close to 1.0 for municipal wastewaters. Because it cannot be measured by a membrane probe and because many wastewaters contain substances that interfere with the Winkler method, it is difficult to measure accurately. For this reason, the value of beta for use in Eqs. (CG-1) and (8-1) is calculated as the ratio of DO surface saturation concentration in the process water to the DO surface saturation concentration in clean water. The corresponding surface saturation concentrations are interpolated from Table G-2 based on the total dissolved solids content of the process water and clean water.

G.3 Theta Factor, θ

The theta factor is employed to correct K_La for changes in temperature according to Eq. (CG-2). Values of theta reported in the literature have ranged from 1.008 to 1.047 and are influenced by geometry, turbulence level, and type of aeration device. There is little consensus regarding the accurate prediction of theta values, and, for this reason, clean water testing for the determination of SOTR values should be at temperatures close to 20°C.

The value of theta is taken equal to 1.024 in Eqs. (CG-1) and (8-1). Use of a theta factor differing from 1.024 is used only when experimental data for the particular aeration system indicates conclusively that the value of theta is significantly different from 1.024.

Table G-2. Solubility of Oxygen (mgL) in Water Exposed to Water-Saturated Air at Atmospheric Pressure = 101.3 KPa (Ref. [6])

Temp °C	Chlorinity*		
	0	5.0	10.0
0.0	14.62	13.73	12.89
1.0	14.22	13.36	12.55
2.0	13.83	13.00	12.22
3.0	13.46	12.66	11.91
4.0	13.11	12.34	11.61
5.0	12.77	12.02	11.32
6.0	12.45	11.73	11.05
7.0	12.14	11.44	10.78
8.0	11.84	11.17	10.53
9.0	11.56	10.91	10.29
10.0	11.29	10.66	10.06
11.0	11.03	10.42	9.84
12.0	10.78	10.18	9.62
13.0	10.54	9.96	9.41
14.0	10.31	9.75	9.22
15.0	10.08	9.54	9 03
16.0	9.87	9.34	8.84
17.0	9.67	9.15	8.67
18.0	9.47	8.97	8.50
19.0	9.28	8.79	8.33
20.0	9.09	8.62	8.17
21.0	8.91	8.46	8.02
22.0	8.74	8.30	7.87
23.0	8.58	8.14	7.73
24.0	8.42	7.99	7.59
25.0	8.26	7.85	7.46
26.0	8.11	7.71	7.33
27.0	7.97	7.58	7.20
28.0	7.83	7.44	7.08
29.0	7.69	7.32	6.96
30.0	7.56	7.19	6.85
31.0	7.43	7.07	6.73
32.0	7.31	6.96	6.62
33.0	7.18	6.84	6.52
34.0	7.07	6.73	6.42
35.0	6.95	6.62	6.31
36.0	6.84	6.52	6.22
37.0	6.73	6.42	6.12
38.0	6.62	6.32	6.03
39.0	6.52	6.22	5.93
40.0	6.41	6.12	5.84

*Salinity = 1.806 × Chlorinity (see *Standard Methods*, Ref. [7]).

REFERENCES—COMMENTARY G

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COMMENTARY H

High Purity Oxygen Activated Sludge Plants

The ASCE standard method can be used to estimate the oxygen transfer rate for aerators used in the high purity oxygen activated sludge process (HPO-AS). A shop or field test must be performed in the same way as other clean water tests for ambient air. For shop tests, the test will most likely be performed in an open top tank. For field tests, the reactors will most likely be covered to contain the HPO gas. These basins usually have only a few openings in the cover to allow access for maintenance and to insert a mechanical aerator. During the clean water test, the liquid will absorb oxygen from the headspace air, and care must be taken to avoid depressing the oxygen partial pressure in the headspace. Lower headspace oxygen purity will negatively bias the clean water test results. It will usually be necessary to ventilate the reactor headspace with fans or blowers. The blowers used to ventilate sewers and confined spaces during maintenance operations work well in this application. The headspace oxygen partial pressure can be easily monitored with a fuel cell type oxygen meter or similar device. It will be necessary to supply oxygen with the ventilators at a rate greater than the expected SOTR of the aerator. The first test in a series of clean water tests should be closely monitored with an oxygen sensor to ensure that headspace oxygen depletion does not occur. Analysis of test results will produce an SOTR and C^*_∞ corresponding to a headspace oxygen partial pressure of 0.2095 atm. The value of K_La obtained from this test is not a function of oxygen partial pressure.

To calculate the oxygen transfer rates at elevated oxygen partial pressures, the value of C^*_∞ must be increased to correspond to the expected HPO headspace oxygen partial pressure (the head space partial pressure is not the same as the feed partial pressure). The value of C^*_∞ is modified as follows:

$$C^*_{\infty \mathrm{HPO}} = C^*_\infty(\mathrm{O}_{2\mathrm{pp}}/0.209) \qquad \text{(Eq. CH-1)}$$

REFERENCE—COMMENTARY H

[1] Stenstrom, M. K., Kido, W. H., Shanks, R. F., and Mulkerin, M. (1989). "Estimating Oxygen Transfer Capacity of a Full Scale Pure Oxygen Activated Sludge Plant." *J. Water Pollution Control Fed.*, 61, 208.

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