A Simplified Headspace Biochemical Oxygen Demand Test Protocol Based on Oxygen Measurements Using a Fiber Optic Probe

Booki Min, David Kohler, Bruce E. Logan

ABSTRACT: Batch respirometric tests have many advantages over the conventional biochemical oxygen demand (BOD) method for analysis of wastewaters, including the use of undiluted samples, a more rapid exertion of oxygen demand, and reduced sample preparation time. The headspace biochemical oxygen demand (HBOD) test can be used to obtain oxygen demands in 2 or 3 days that can predict 5-day biochemical oxygen demand (BOD₅) results. The main disadvantage of the HBOD and other respirometric tests has been the lack of a simple and direct method to measure oxygen concentrations in the gas phase. The recent commercial production of a new type of fiber optic oxygen probe, however, provides a method to eliminate this disadvantage. This fiber optic probe, referred to here as the HBOD probe, was tested to see if it could be used in HBOD tests. Gas-phase oxygen measurements made with the HBOD probe took only a few seconds and were not significantly different from those made using a gas chromatograph (t test; n = 15, R² = 0.9995, p < 0.001). In field tests using the HBOD probe procedure, the probe greatly reduced sample analysis time compared with previous HBOD and BOD protocols and produced more precise results than the BOD test for wastewater samples from two treatment plants (University Area Joint Authority [UAJA] Wastewater Treatment Plant in University Park, Pennsylvania, and The Pennsylvania State University [PSU] Wastewater Treatment Plant in University Park). Headspace biochemical oxygen demand measurements on UAJA primary clarifier effluent were 59.9 ± 2.4% after 2 days (HBOD₂) and 73.0 ± 3.1% after 3 days (HBOD₃) of BOD₅ values, indicating that BOD₅ values could be predicted by multiplying HBOD₂ values by 1.67 ± 0.07 or HBOD₃ by 1.37 ± 0.06. Similarly, tests using PSU wastewater samples could be used to provide BOD₂ estimates by multiplying the HBOD₂ by 1.24 ± 0.04 or by multiplying the HBOD₃ by 0.97 ± 0.03. These results indicate that the HBOD fiber optic probe can be used to obtain reliable oxygen demands in batch respirometric tests such as the HBOD test. Water Environ. Res., 76, 29 (2004).

KEYWORDS: biochemical oxygen demand, gas chromatograph, headspace biochemical oxygen demand, respirometric tests, fiber optic probe, oxygen measurement.

Introduction

The biochemical oxygen demand (BOD) test has been used to measure the amount of biodegradable organic matter in wastewaters since the late nineteenth century (Young and Clark, 1965). The procedures used for the test have changed little over time, except for the use of a probe to measure dissolved oxygen in the liquid sample. Ground glass-stoppered bottles are still used today for this dilution procedure conducted over a somewhat arbitrary time of 5 days. Relative to other measurements now performed in a water analysis laboratory, the BOD test is imprecise and its accuracy can only be gauged through interlaboratory comparisons and calibration tests using a glucose-glutamic acid (GGA) solution.

A variety of respirometric biochemical oxygen demand (RBOD) methods have been developed to assess BOD (O’Brien and Clark, 1962). Although RBOD methods are still listed as a proposed technique in Standard Methods, RBOD tests have been used for many years to assess treatment plant performance in the United States and elsewhere; additionally, they are approved as an alternative to BOD measurements in Europe. In RBOD tests, the wastewater does not have to be diluted because oxygen can be replenished from the headspace of bottles by sample mixing. The amount of oxygen consumed during the test is commonly measured indirectly from the pressure drop, introducing gas (bubbles) to equalize pressure, or through generation of oxygen directly in the chamber. In these types of RBOD tests, each sample requires its own dedicated oxygen or pressure measurement system, and the operation and interpretation of the system data can be relatively expensive and complicated.

An alternative RBOD approach called the headspace biochemical oxygen demand (HBOD) test that had the advantage of using a single measuring device to analyze a large number of samples just like the BOD test was introduced several years ago (Logan and Patnaik, 1997; Logan and Wagenseller, 1993). The HBOD test had several advantages over a BOD test: samples did not need to be diluted because oxygen was continuously added from the container headspace during sample shaking, only 2 to 3 days were necessary for sample incubation time to obtain values equivalent to the 5-day biochemical oxygen demand (BOD₅) test, and smaller sample bottles could be used (crimp-top test tubes). The major disadvantage of the HBOD test, however, was the method used to measure oxygen in a tube at the completion of the test. Either a gas chromatograph was necessary to measure oxygen in the tube headspace (Logan and Patnaik, 1997) or the tube solution had to be poured out of the tubes to measure the dissolved oxygen (DO) concentration (Logan and Wagenseller, 1993). These procedures either relied on equipment that was complicated to operate (in the case of the gas chromatograph) or somewhat messy (pouring samples for DO analysis, which could also aerate samples and produce inaccurate results). In both cases, the time required to measure the oxygen in the tubes was not substantially reduced compared with that necessary for the BOD test, although overall sample preparation time was reduced.
Nonconsumptive fiber optic probes have been developed recently that can measure oxygen in gas or liquid samples (Ocean Optics, 2005; Rosenzweig and Kopelman, 1995); however, these probes have not been tested for measurement of oxygen in HBOD tests. The probes work by using fiber optics to excite a sol-gel film on the probe tip. Fiber optic probes are then used to detect the fluorescent signal that is quenched in proportion to the concentration of oxygen molecules. We tested the accuracy of a fiber optic probe by comparing measurements of oxygen in heparin samples with gas chromatography. Based on the success of this comparison, we then used the probe in HBOD tests. The main objective of this comparison was to investigate whether tests conducted with the fiber optic probe (referred to here as the HBOD probe) could produce HBOD values comparable to those measured by the BOD test. To determine the suitability of the HBOD probe-based technique, we obtained HBOD and BOD measurements on samples from two different treatment plants. We show here that oxygen demands measured in 1-l or 3-day HBOD can be used to classify nearly all BOD samples and that HBOD tests using the HBOD probe provide a more precise estimate of BOD concentrations than those based on CHOD tests.

**Methods**

**Determining the Accuracy of the Headspace Biological Oxygen Demand Probe Using Gas Chromatography.** The accuracy of the HBOD probe was determined by measuring oxygen concentrations in the headspace (gas phase) of 28-ml HBOD tubes (crimp-sealed test tubes, Belco Glass, Inc., Vineland, New Jersey). A series of tubes containing different amounts of oxygen were prepared by first opening them in an anaerobic glove box (Coy Scientific Products, Grass Lake, Michigan) to completely remove all oxygen from the headspace in the tubes. The tubes were capped with a rubber stopper and immersed in the 30°C bath. Each tube was then opened in the laboratory for a different amount of time to introduce variable concentrations of oxygen into the tubes. The tubes were then crimp-sealed, and oxygen concentrations were measured in the headspace using a gas chromatograph and the HBOD probe.

**Oxygen Measurements Using a Gas Chromatograph.** Measurements of oxygen in the gas phase were conducted in previously described (Logan and Parnas, 1997) using a gas chromatograph (model 8610B, SRI Instruments, Torrance, California) equipped with a thermal conductivity detector (TCD) and a 0.4-ml-long, 3-mm-diameter packed silica column. Air was used as the carrier gas. A fresh sample (100 ml) was introduced using a gas-tight syringe equipped with a precision lock (Alltech Associates, Inc.) and a 22-gauge subcutaneous needle. REAKSIMPEL-E chromatography software (SRI Instruments) was used to analyze chromatograms.

**Oxygen Measurements Using the Headspace Biological Oxygen Demand Probe.** Oxygen concentrations (percent) in the headspace of a HBOD tube were measured using the HBOD probe (FOXY R, Ocean Optics, Inc., Dunedin, Florida) and software provided by the manufacturer (ODIOXY oxygen sensor software, version: 1.0.18). Prior to measuring samples, the probe was calibrated with tubes prepared with 0% oxygen in an anaerobic glove box and 20% oxygen using laboratory air. To measure the partial pressure of oxygen in the sealed HBOD tube, the HBOD probe needle was inserted through the rubber stopper of the tube, and the oxygen concentration was read from the computer after a few seconds. Because oxygen measurements by the HBOD probe were affected by light, the tube was kept in the dark during oxygen measurement. A test tube holder that excluded light during oxygen measurements was constructed by drilling a block of wood to a diameter necessary to fully enclose the tube. The HBOD probe was constructed using a tube of stainless steel (1 cm o.d. diameter) and the film at the fiber optic tip of the probe is protected from wear by a coating. Thus, the probe was sufficiently sturdy so as to repeatedly pierce the rubber septa. New septa were used for each HBOD test and discarded after one test.

**Headspace Biological Oxygen Demand Tests.** Headspace biochemical oxygen demand measurements were conducted in triplicate as previously described (Logan and Parnas, 1997), with the exception that oxygen concentrations in the headspace was measured using the HBOD probe instead of a gas chromatograph (Min, 2001). Water samples were collected in 1000-ml bottles and dispensed into 28-ml HBOD tubes using a 5-ml-diameter pipette tip (Binkelman Instruments, Westbury, New York). The sample volume was selected based on the length of the water sample (using Table 1). Typically, a 23-ml water sample was used for oxygen demand measurements in the range of 7 to 5 log HBOD, while 20-ml water samples were used for measurements in the range of 5 to 36 log HBOD. After adding the wafer sample to the HBOD tube, the tube was immediately sealed with a rubber stopper and an aluminum crimp cap. Tubes were placed routinely in a plastic box and incubated on a shaker table (model 406s, Lab Line, Melrose Park, Illinois) at 100 rpm and constant temperature rooms of 20°C. The gas concentration in the headspace was then measured using the HBOD probe either every day or only on the second and third days. The DO concentration in each tube was made up to three times and the average was recorded for each tube; the three tube results were used to calculate an average and standard deviation for the sample. Prior to measuring using the HBOD test has shown that nitric acid is used to 1 ml in 3 day HBOD tests (Logan and Parnas, 1997). Therefore, nitric acid inhibition was not added to the tubes.

To calculate HBOD, oxygen concentrations, "lavate humidity," and temperature data were input an Excel (Microsoft Corp., Redmond, Washington) spreadsheet set up for input of HBOD data. As an example of a spreadsheet (available at the Web at http://www.mrrp.edu/eew/sm/d346a//bod.htm) is shown in Figure 1 for one sample. The HBOD value (in milligrams per liter) on day t was calculated in this spreadsheet using the following equation:

\[
\text{HBOD}_t = (P_0 - 0.0075p_{a2}) \left(1 - \frac{0.5}{P_0} \right) + \frac{\text{DO}}{500 - p_{a2}} \tag{1}
\]
This approach provides a more conservative estimate of the error than a typical sum-of-squares over approach.

Biochemical Oxygen Demand Tests. Biochemical oxygen demand tests were conducted in triplicate using 60-ml BOD bottles according to Standard Methods (APHA et al., 1998). Dissolved oxygen measurements were made with a DO probe (model 520, YSI Inc, Yellow Springs, Ohio). Samples (typically 2 or 3 ml sample volumes) were prepared with BOD nutrient pillows (HACH Co., Loveland, Colorado). Only bottles were left at least a residual dissolved oxygen of 1 mg/L and a DO charge of 2 mg/L were used to calculate the BOD5 (APHA et al., 1998).

Field Tests Using University Area Joint Authority Wastewater Treatment Plant Primary Clarifier Effluent. Headspace biochemical oxygen demand and SOD measurements were made on samples obtained from the primary clarifiers effluent from the University Area Joint Authority (UAA) Wastewater Treatment Plant located in University Park, Pennsylvania. All BOD and BOD5 experiments were begun within 2 hours of sample collection and were run at 20 °C. All BOD5 measurements on UAA samples were performed by YSI Inc. using a battery-powered YSI 5000. Dissolved oxygen and headspace measurements were taken with a standard protocol (APHA et al., 1998). Split samples were also analyzed for COD either at UAA (investigator 1, or 3) or at The Pennsylvania State University (PSU) using the American Public Health Association (APHA) methods (2010). Samples were collected twice a week (Wednesday and Friday mornings). Samples collected on Wednesday were analyzed on Friday (BOD5), while samples collected on Friday were analyzed on Monday (BOD).
techniques for comparison with our BOD results. The PSUs samples were collected from the primary clarifier effluent (24-hour composite) and 1 L. Nalgene bottles (Nalgene Labware, Rochester, New York) by plant operators. Samples were split and either analyzed at the plant or transported to KEL and placed in a refrigerator. Samples were warmed and prepared for BOD and HBOD analysis within 2 hours in a constant-temperature (20 °C) room.

To obtain a wider range of BOD values, the secondary clarifier effluent (24-hour composite; coagulation/clarification) was also collected. Primary clarifier effluent samples collected at the same time were used to dilute the secondary effluent, and these samples were analyzed for BOD and HBOD as previously described.

**Glucose-Ulthane Acid Test.** Although there is no way to accurately measure the oxygen of BOD tests, a periodic check of benthic water quality, and effectiveness, and analytical technique can be obtained by conducting BOD measurements using a GGA solution (300 mg/L) (APA et al., 1995). A similar analysis can also be conducted with the HBOD test (Logan and Patnaik, 1997). The seed used for both tests was an equivalent from the PSU primary effluent after settling at room temperature for 1 day.

For HBOD tests, the GGA solution was used at full strength (300 mg/L) along with larger volumes of the seed solution. The HBOD of the seed solution (SHBOD) was determined by adding 10 mL of the seed solution to HBOD water. To determine the HBOD of the GGA and seed solution (THBOD), seed solution (4 mL) was put into the HBOD tubes containing 4 mL of GGA (9 mL total). The HBOD due to only the GGA (GHBOD) was calculated as a difference between the two samples after correction for sample volumes as

\[
\text{GHBOD} = \text{THBOD} - \text{SHBOD}
\]

Where,

- \( V_L \) = volume of liquid used in tubes containing GGA
- \( V_A \) = volume of air in the tubes containing only water
- \( V_G \) = volume of GGA added to the tubes.

**Results**

**Oxygen Measurements Using a Reduced-Pressure Biochemical Oxygen Demand Probe and Gas Chromatograph.** Oxygen measurements made using gas chromatography compared well with measurements made with the HBOD probe over a concentration range of 2 to 21% of oxygen in the headspace of samples as shown in Figure 2 (\( r = 0.987 \pm 0.002, r^2 = 0.990, n = 15, p < 0.001 \)). This oxygen concentration range is sufficient for the HBOD test because the final DO concentration in the headspace should be greater than 2 mg/L (Logan and Patnaik, 1997), which corresponds to a minimum oxygen concentration in headspace of 3 to 5% (depending on local air pressure). The manufacturer of the fiber optic probe does not report a minimum detection level of oxygen. Gas chromatographic measurements are typically accurate to 100 to 300 ppm. A minimum detection limit for either system was not further investigated since these would be substantially below the range needed for HBOD tests.

**Comparison of Daily Headspace Biochemical Oxygen Demand Measurements with 5-Day Biochemical Oxygen Demand.** Oxygen demand is typically exerted faster in respiratory tests such as the HBOD test than in a BOD test (Young and Barnaun, 1976, 1979). To determine the “best” day for HBOD and BOD comparison, the data for the HBOD of the BOD probe was measured over a 5-day period using primary clarifier effluent (PSU Wastewater Treatment Plant). This comparison (Figure 3) indicated that an oxygen demand determined using a BOD test was achieved in the HBOD test after 5.5 days, suggesting that either 2- or 3-day HBOD could be used to predict BOD. The value of BOD was 191 ± 29 mg/L, as shown by the horizontal line in Figure 1. The 2-day HBOD value (HBOD) was 168 ± 12 mg/L, and the HBOD was 2.2 ± 2 mg/L. Based on these results, both HBOD and HBOD data were collected for comparison to BOD results in the other tests. It was also shown in this test that HBOD was, on average, more precise than BOD. The standard deviation for BOD was 29 mg/L.
Figure 4—Comparison of BOD₅ values for UAIA wastewater samples with results by two different investigators (I and II): (a) HBBOD₅ (slope = 1.67 ± 0.07, n = 17, R² = 0.77, P < 0.001) and (b) HBOD₂ (slope = 1.27 ± 0.06, n = 24, R² = 0.66, P < 0.001).

Figure 5—Comparison of BOD₅ (analyzed at KEL) values with data for wastewater samples from PSU: (a) HBOD₅ (slope = 1.24 ± 0.04, n = 14, R² = 0.93, P < 0.001) and (b) HBOD₂ (slope = 0.97 ± 0.00, n = 28, R² = 0.91, P < 0.001).

University Area Joint Authority Headspace Biochemical Oxygen Demand Tests. Headspace biochemical oxygen demand tests made on UAIA primary clarifier effluent stage 2 (HBBOD₂) and 7 (HBOD₂) days by two different investigators (I and II) were compared to BOD₅ data. For data set I, the HBOD₂ value was 58 ± 3% of the BOD₅ value, while for data set II the HBOD₂ value was 62 ± 4% of the BOD₅ value. Based on t-test, the HBOD₂ data sets (I and II) were not significantly different (P < 0.001). An analysis of the combined data sets (I and II; Figure 4a) for this and the other figures throughout the manuscript indicated that the slope in a plot of HBOD₂ versus BOD₅ data was 1.67 ± 0.07, or that the HBOD₂ value was on average, 6% larger than the HBBOD₅ measurement for the UAIA Wastewater Treatment Plant. The HBOD₂ data were also, on average, more precise than the BOD₅ data, with an average standard deviation of only 5 mg/L for HBOD₂ data versus 29 mg/L for BOD₅ data.

An analysis of the two data sets (I and II) for the HBOD₂ results similarly indicated that there was no significant difference (P < 0.001) in results for the two investigators. For data set I, the HBOD₂ value was 73 ± 5% of the BOD₅ value, while for data set II the HBOD₂ value was 73 ± 4% of the BOD₅ value. An analysis of the combined data sets (Figure 5b) indicated that the BOD₅ value was, on average, 17% larger than the HBOD₂ value. The HBOD₂ data had a higher precision than BOD₅ data, with an average standard deviation of only 6 mg/L for HBOD₂ data versus 20 mg/L for BOD₅ data.

The Pennsylvania State University Headspace Biochemical Oxygen Demand Tests. Additional HBBOD₂ tests conducted on the PSU Wastewater Treatment Plant using primarily clarifier effluent, secondary clarifier effluent, and mixtures of the two samples were carried out to obtain a wider range of oxygen demands. Five-day biochemical demand measurements were made larger (24 ± 4%) than HBOD₂ measurements made on sample after a 2-day incubation period (Figure 5a). However, HBOD₂ values obtained at this treatment plant were nearly equal to BOD₅ values, with HBOD₂ only 3 ± 3% larger than BOD₅ (Figure 5b). Therefore, the results obtained from the precipitation of HBOD₂ or BOD₅ for these samples. The average standard deviations of test measurements...
Figure 6—Ratios of (a) BOD₅ and HBBOD₅ and (b) BOD₅ and HBOD₅ as a function of BOD₅ (calculations based on data in Figure 5). The solid line is the average of the ratio of BOD₅ to the HBOD₅, while the dashed lines indicate ± standard deviation.

were 10 mg/L for HBOD₅ and 1 mg/L for the corresponding BOD₅ data set and 6 mg/L for HBOD₅ and 7 mg/L for the corresponding BOD₅.

While BOD₅ tests are always run in similar wastewater strengths (by diluting the wastewater sample), nephelometric samples are run at full strength. We, therefore, wondered if there were any differences in the average difference between the two measurements based on the absolute strength of the wastewater. The data from the PSU tests were replaced in Figure 5 as a dimensionless ratio of the two oxygen demands (BOD₅/HBOD) versus wastewater strength measured as BOD₅, as shown in Figure 6. For the HBOD₅ results, there was no difference in the BOD₅/HBOD ratio over the range of BOD₅ results, but all of the data except for one point was obtained on samples with BOD₅ greater than 50 mg/L. The analysis of the HBOD₅ data provided a wider range in BOD₅ values. These BOD₅/HBOD ratio results suggest that the BOD₅ results may have been disproportionately larger at BOD₅ values less than 50 mg/L than those at higher BOD₅ values. However, the large standard deviations of the BOD₅/HBOD ratios are so large that this difference could not be statistically proven.

Figure 7—Comparison of (a) BOD₅ data obtained by treatment plant technicians (PSU) with BOD₅ data obtained by KEL researchers (slope = 1.06 ± 0.07, n = 14, R² = 0.72, p < 0.001) and (b) HBOD₅ and BOD₅ (KEL) data (slope = 0.98 ± 0.04, n = 14, R² = 0.98, p < 0.001). Only data from Figure 5 for which there were BOD₅ values measured by PSU and KEL are included in these comparisons.

Accuracy of 5-Day Biochemical Oxygen Demand and Headspace Biochemical Oxygen Demand Measurements. In comparing the HBOD₅ values with BOD₅ data, it is inherently assumed that the BOD₅ data are accurate. However, the accuracy of the BOD₅ test results cannot be proven and the tests are not precise (relative to other types of modern laboratory measurements). For some of the data shown in Figure 5, BOD₅ measurements were made on the same samples by both the authors at KEL (BOD₅, KSL) and plant personnel (BOD₅, PSU). By comparing these data taken by different people, we can see the inherent error in BOD₅ results. The BOD₅ (KSL) values were slightly higher (6%) than those measured by PSU personnel, although this difference was not significantly different based on the slope shown in Figure 7a not being different than unity within a standard error.
The fiber optic HBO probe can rapidly and accurately measure the concentration of oxygen in the gas phase. A single gas chromatographic measurement of oxygen typically takes 2 to 5 minutes. Oxygen measurements using the HBO probe were not significantly different than those made with a gas chromatograph, and three HBO probe measurements took only a few seconds each. Although it was not tested here, the fiber optic probe can also be used to measure dissolved oxygen in water samples. The cost of the fiber optic probe is much less than that of a gas chromatograph, although the HBO probe currently costs somewhat more than a DO probe.

Oxygen demand is exerted faster in respirometric tests (Young and Baumann, 1976a, 1976b) than in BOD tests as a result of the higher concentration of substrate and microorganisms. Typically, an oxygen demand equal to BOD is exerted in 2 or 3 days in a respirometric test. In previous gas chromatograph-based BOD testing, an oxygen demand equal to the BOD was exerted in approximately 3 days at two different treatment plants in Arizona. It was similarly found here that HBOD was approximately equal to BOD at the PSU plant. The HBOD value was slightly lower than the BOD at the UAJA plant, and averaged only 71 ± 3% of BOD at that plant. Although we did not examine the reason for this difference, it is likely that a greater fraction of the oxygen demand was present in a more slowly degraded fraction in UAJA wastewaters than in wastewater samples at other sites. The slower exertion of oxygen demand could be due to compounds with high molecular weights that must be hydrolyzed (Grady et al., 1989; LeBlanc, 1974; Mathieu and Elieson, 2000) or to more particulate material in the UAJA wastewater than at the other plants. The soluble fraction of organic matter in respirometric tests is known to be more rapidly degraded, usually within 24 hours (Montgomery, 1967).

Although HBOD values in our tests were typically lower in magnitude than BOD or than HBOD in other, either HBOD or BOD, could be used to predict BOD. In both statistical comparisons of HBOD and BOD (Figures 4 and 5), the R² values were generally lower for HBOD than for the BOD plots, but there were always more HBOD values used in these comparisons for the HBOD tests. In all cases, the correlation of HBOD and BOD data was significant (p < 0.001), proving that HBOD measured on either day could be used to predict BOD. To predict BOD at a treatment plant using HBOD, for example, the following equation should be used:

\[ \text{BOD} = m \times \text{HBOD} + b \]

where \( m \) is the slope of the line determined from HBOD and BOD correlation at the treatment plant. For example, at the PSU plant, \( m = 1.24 \) (Figure 5a) and, therefore, BOD equals 1.24 times HBOD. This shorter measurement time of an HBOD test can provide wastewater treatment plant operators an earlier assessment of wastewater strength, allowing operational changes to be made in the plant if necessary.

The use of a nontraditional technique often offers other advantages compared to a BOD test as well. Large changes in wastewater strength often do not get quantified with BOD analysis because of the lack of a sufficient number of dilutions of the wastewater sample by technicians. This is because the small oxygen demand range for each dilution in the BOD test make it likely that a sample could fall out of the given BOD range for that dilution. The oxygen demand range for a single HBOD tube is much larger than the range for a single BOD bottle, making it less likely that a HBOD test will provide inconclusive results. For example, a wastewater sample having an oxygen demand range of 7 to 501 mg/L can be successfully analyzed using only two liquid sample volumes in the HBOD test (5 mL, 7 to 30 mg/L, 18 mL, 51 to 364 mg/L, 28-mL tubes), while the same sample would require four different dilutions in the BOD test. Other advantages of the HBOD test relative to both BOD tests include less volume needed for a sample container, although similar volumes of wastewater may be used in the HBOD bottle compared to 300-mL BOD bottle; no wastewater overflow in the laboratory during oxygen sampling of the headspace; no contact of the oxygen probe with the liquid sample, reducing the potential for probe fouling; and reduced analysis time for oxygen measurements.

One of the main advantages of the HBOD test is that its precision is typically much higher than that obtained in a BOD test. For example, measurements using wastewater from the UAJA Wastewater Treatment Plant showed a variation in HBOD results that were typically in the range of 5 mg/L, but almost always less than 10 mg/L. This was much less than the typical bottle-to-bottle variation in the BOD, test of 20 mg/L, for this site. At the PSU plant, the average standard deviation for HBOD tests (6 mg/L for HBOD) and 50 mg/L for BOD was the same or less than the BOD measurements (7 and 19 mg/L) depending on where the tests were conducted (in our laboratories at The Pennsylvania State University or at the treatment plant). Although the accuracy of oxygen demand test remains problematic, the use of an HBOD test versus a BOD test could reduce sample preparation and analysis time and improve the prec
Chemistry and Geochemistry. Portions of this research were presented at WEFTEC 2000, the 73rd Annual Water Environment Federation Technical Exposition and Conference held in Anaheim, California, October 14-18.

Authors. Bruce E. Logan is the Kerpe Professor of Environmental Engineering, Johns Hopkins University, a graduate student in the Department of Civil and Environmental Engineering, and David Kolder was an undergraduate student in the Department of Chemical Engineering, at the Pennsylvania State University. Correspondence should be addressed to Dr. Bruce E. Logan, Department of Civil and Environmental Engineering, 212 Sacket Building, The Pennsylvania State University, University Park, PA 16802; e-mail: blogan@psu.edu.

Submitted for publication March 13, 2002; revised manuscript submitted February 24, 2003; accepted for publication February 27, 2003.

The deadline to submit Questions of this paper is May 15, 2004.

References


