LAST COPY

Review and Evaluation of the Contractors' Oxygen Transfer Test Reports for the Total Barrier Oxidation Ditches at Opelika, Alabama

by

Peer Review Panel

William C. Boyle

Hugh J. Campbell, Jr.

Michael K. Stenstrom

February 28, 1987

TABLES OF CONTENTS

I. INTRODUCTION

In order to evaluate the applicability of the ASCE Clean Water Standard[1], Peer Consultants selected three Peer review panelists to assist the City of Opelika, its consultants, and interested equipment manufacturers in developing a field testing program for the Total Barrier Oxidation Ditch (TBOD).[2] Both clean and process water testing were envisioned. The Peer Review Panel was charged with the following tasks:[3]

1. Review project scope-of-work and attend a review meeting in Opelika, Alabama.

2. Prepare a summary report discussing technical feasibility, modify scope of work as needed, recommend modifications to existing test procedures as needed, and prepare a consensus report.

3. Review the Project Engineer's clean water testing plan, evaluating and recommending changes as necessary.

4. Witness clean water testing, providing advice and recommendations to resolve on-site disputes and alert the Project Engineer if non-acceptable test methodologies are being used.

5. Review the Project Engineer's process water testing plan, evaluating and recommending changes as necessary.

6. Witness process water testing, providing advice and recommendations as necessary. Provide a report summarizing clean and process water test results, reconciling differences, identifying problems and corrective actions, evaluating the accuracy of the various tests, and estimating apparent alpha factors.

During the initial meeting at Opelika, the scope-of-work and test program were expanded to include testing of a second TBOD at South Hill, VA. Previous reports were provided by the Peer Review Panel for Tasks 1 to 5. This report relates to Task 6, and is the summary of our evaluation of the test program for the TBOD's at Opelika, Alabama. A second report for Task 6 will be provided for the testing performed at South Hill.

The SOTR and αSOTR values reported herein refer to the entire aeration system, e.g. two turbines and however many blowers that were operating at the time of the test.

II. TESTING PROGRAM

A. PROGRAM OVERVIEW

The testing program for the TBOD aeration system involved two sites: Opelika, Alabama and South Hill, Virginia. Aeration testing was to be done in both clean water and process water situations. In the clean water programs, three different test methodologies were proposed: 1) the ASCE non steady state sulfite method, 2) the krypton/tritium radiotracer technique, and 3) the dissolved oxygen mass balance across the aeration unit (the so-called "delta DO" approach). For the process water situations, two approaches were recommended: 1) the "off-gas" technique and 2) the krypton/tritium radiotracer method. Prior to testing, all parties agreed to review the results of the Opelika testing to determine whether or not the radiotracer method, which is the most expensive test method, would be necessary at South Hill. Table 1 summarizes the overall testing strategy by site and method.

Table 1: Overview of the EPA Aeration Testing Program for the TBOD Systems

Test Site	Clean Water	Process Water
Opelika	ASCE Tracer DO Mass Balance	Off-Gas Tracer
South Hill	ASCE Tracer DO Mass Balance	Off-Gas

B. OPELIKA TESTING PROGRAM

The aeration testing program at Opelika, was performed in two phases. The clean water program was completed during July 7-11, 1986 and the process water testing was done during August 6-7, 1986. Table 2 summarizes the test conditions for each of these test programs. These conditions are consistent with the Peer Review Panel recommendations to BCM Converse in report dated February, 1986.[4] Table 2 also shows the Peer Review Panel's corrections to blower power for the clean water tests (see Section III.A for details). Analyses for the ASCE and DO mass balance approaches are discussed in a technical report issued to BCM Converse by Mixing Equipment Co, Inc. on September 9, 1986. The radiotracer analyses are discussed in a technical report issued to BCM Converse by Law Environmental Services in October 1986. Ewing Engineering Company documents the off-gas testing and analyses in process water in their report to BCM Converse dated October 23, 1986. All of these reports are reviewed in the following sections and this review is accompanied by an independent data analysis by the Peer Review Panel for each test program.

Table 2

Test Conditions

Test No.	Date	Time	Total Turbine horsepower (whp)	Total Blower horsepower (whp)+	No of Blowers in Service	Total Air Flow (SCFM)	Total horsepower (whp)
Clean Water*							
1	7/8/86	2:00 PM	120	45 (38)	2	1188	165
2**	7/8/86	7:30 PM	120	45 (38)	2	1195	165
3	7/10/86	4:50 PM	120	44 (38)	2	1177	164
3A	7/9/86	11:00 AM	120	45 (38)	2	1214	165
4**	7/9/86	3:30 PM	60	21 (19)	1	604	81
5	7/10/86	10:00 AM	122	20 (19)	1	624	142
6	7/11/86	9:30 AM	170	74 (57)	2	1710	244
Process Water* **							
1P**	8/6/86	9:50 AM	127	44	2	1117	171
2P**	8/7/86	5:15 AM	63	21	1	570	84
3P	8/7/86	10:30 AM	125	44	2	1133	169
4P	8/7/86	3:30 PM	174	77	2	1633	251

\+ Numbers in parenthesis are Computrack power measurements reported by Mixco which are inaccurate. The numbers used for this tabulation and subsequent calculations are estimated by the manufacturers recommended procedures.[5,6] See Appendix A for the procedure.

* Witnessed by Drs. Boyle and Stenstrom

** Radiotracers performed

*** Witnessed by the entire Peer Review Panel

III. CLEAN WATER TEST RESULTS

Clean water tests were conducted in Basin Number 2 at the Opelika Westside Treatment plant. The tests were conducted by Mixing Equipment Co. Inc. (Mixco) and Law Environmental Services (Law). This section will briefly critique the tests conducted by these two groups and will be followed by an analysis of the clean water tests by the Peer Review Panel.

A. MIXING EQUIPMENT CO.

The clean water tests were conducted in accordance with the ASCE Standard Measurement of Oxygen Transfer in Clean Water[1]. In general the test procedures were acceptable with respect to the standard. Some refinements in test procedures which are particularly suited to oxidation ditches are noted. We also note several deficiencies in reporting methods and power measurements.

A trial test was performed by Mixco on July 7, 1986. This test was not witnessed by the Peer Review Panel and the results are not included in the Mixco report. Nevertheless, this trial test was valuable in that it allowed Mixco and the Peer Review Panel to more precisely determine proper test conditions.

Sodium sulfite was dissolved prior to being introduced into the ditch. We concur with Mixco's recommendation that sodium sulfite needs to be thoroughly mixed in the ditch prior to testing for these types of systems. At Opelika this was accomplished by introducing the dissolved sulfite over several circulation times, followed by several additional circulations after sulfite addition to insure proper blending. It is significant to note that the amount of excess sulfite did not affect SOTR, K_LA or SAE as determined in replicate testing.

Initially, insufficient cobalt was added to the ditch to insure a cobalt concentration between 0.1 to 0.5 mg/L. More was added prior to official testing. There is no tabulation of the cobalt concentrations that were observed at the beginning and at the end of the test series (see ASCE 6.3.3). Furthermore there is no indication of the total dissolved solids concentration for this same period (see ASCE 6.3.3).

Chlorine addition to kill algal growths in the ditch was of some concern to the Peer Review Panel. Analysis of chlorine prior to the official test runs indicated concentrations at the trace level. No chlorine data were presented by Mixco.

Dissolved oxygen (DO) concentrations were monitored with six DO meters with three multipen recorders. Additionally, pumped samples were collected using BOD bottles followed by Winkler titrations. These samples were not officially used in estimating oxygen transfer.

There was need for a correction of Winkler thiosulfate normality. A value of 0.025 N was used on-site for probe calibrations. On the last day of testing, a sample of ditch water was aerated in the laboratory for one hour. The Winkler DO concentration determined for that saturated sample was 8.18 mg/L at 21.6°C as compared to 8.90 mg/L C^*_{sT} value corrected for barometric pressure. This represents an 8% error in the thiosulfate normality used in all probe calibrations. Mixco's report indicated a different error in thiosulfate normality and this difference will be discussed in more detail in the Peer Review Panel analysis.

In analyzing the data, we concur with Mixco, that if data are not collected continuously for ditches, it should be collected more frequently to insure that the "stair steps" do not bias the estimates of K_LA and C^*_∞. If DO concentration is not recorded continuously it should be measured more frequently than normally measured. For these types of geometries, Winkler testing is impractical due to the large number of samples required.

The power data collected for these tests were not collected in accordance with good practice. A Computrack recorder with four Hall effect transducers was used to monitor both mixers and blowers during the clean water testing. Additionally, a single channel three phase Esterline Angus recording Watt meter was used to monitor turbine power, and was moved back and forth between turbines during clean water testing. Mixco in their report indicated that the Computrack data are unreliable, and concluded that the only reliable power data were collected from the single Esterline Angus meter. Data from both Watt meters were noisy and power data were incompletely recorded and presented. It is difficult to assess the accuracy or precision of the power data. Raw data sheets in many cases were only partially completed. The raw power data were often confusing since the units (kW or hp) or the type (wire or brake) were not clearly delineated.

At the end of the process water testing it was noted that the blower power for nearly identical gas flow conditions during clean and process water testing varied considerably. The difference was traced to the Computrack Watt meter. In contrast to the blower power, turbine power, which was measured by the Esterline Angus meter for both clean and process water test conditions, agreed well. After considerable deliberation the Peer Review Panel decided not to use any Computrack power data, and to substitute calculated power measurements for the blowers during clean water testing. The procedure used was the blower manufacturer's recommended method.[5] After discussing the differences with Mixco they agreed that the calculation procedure provided the best estimates for clean water blower power.[6] Appendix A shows the calculation procedure, results, and Mixco's concurrence with the Peer Panel's calculations. The Peer Review Panel calculated blower power, and the Computrack measured power are both shown in Table 2.

Mixco's values of SOTR and $C^*_{\infty 20}$ are shown in Table 3. The values of K_LA, C_o, and C^*_∞ were estimated by Mixco's nonlinear least squares program (Version 1.3) which performs the analysis as outlined by ASCE. Timing criteria and data truncation employed by Mixco met the requirements stipulated by ASCE 6.8.3.3. Furthermore, all tests were run so that the DO concentration equaled or exceeded 98% of C^*_∞ ($4/K_LA$, ASCE 6.8.4) at the test conclusion.

In reviewing the Mixco data, the Peer Review Panel found that the spatial variation of average determination point K_LA_{20} values fell within ± 10 percent of the mean values as described by ASCE 8.2.1, indicating that the probe locations effectively described the oxygen transfer capability of the ditch. In addition, for the four replicate tests, the estimates of K_LA_{20}, fell within the ±15 percent of the mean values as specified in ASCE 8.2.2.

Accurate estimates of flow in the ditch were critical to the accuracy of the DO mass balance procedure. Flow was measured at 24 discrete points within a ditch cross-section using a Marsh-McBirney 201D magnetic flow meter. Analysis was in accordance with ISO report 748-1979. The Peer Review Panel measured velocity variation at a given point (near the surface toward the outside ditch wall) during one of the replicated test series and found a ±10% variation in velocity over a 10 minute period at a given point. Circulation times calculated by Mixco using the measured velocities gave values of 6.4 to 8.9 minutes for the six text conditions. These values check very well with circulation times calculated from tracer measurements made by Law (approximately 6 to 9 minutes).

Table 3

Mixco's Summary of Clean Water Test Results

Test No.	SOTR* (lb O_2/hr)	$C^*_{\infty 20}$ (mg/L)
1	272	11.5
2	272	11.2
3	299	11.3
3A	285	11.3
4	143	11.8
5	171	11.2
6	407	11.0

* The SOTR values reported in this table and hereafter refer to the entire aeration system, e.g., two turbines and however many blowers that were operating at the time of the test. Previous tests conducted by Mixco and the original equipment specifications sometimes refer to the SOTR of each turbine.

The DO mass balance analysis presented by Mixco produced highly variable results. These findings are largely due to the inherent error structure of the mass balance equations. The method of analyses used is somewhat different than that employed by the Peer Review Panel. Detailed discussion of this method of analysis appears in the Peer Review Panel analysis section.

In summary, the Mixco tests were performed in a manner consistent with the intent of the ASCE standard, although reporting procedures for power measurements and other data could have been improved.

B. LAW ENVIRONMENTAL SERVICES

Radiotracer tests were conducted simultaneously with clean water analyses during Test Runs 2 and 4 (Table 2). Results of the data analysis by Law are shown in Table 4. The Peer Review Panel concurs with Law's conclusion that the radiotracer analyses accurately describes aeration of water circulating in the ditch. Results of this test should therefore accurately depict oxygen transfer in a plug flow oxidation ditch.

Of concern to the Peer Review Panel, however, was the absence of a correction to the K_{Kr}/K_{ox} ratio to account for the gas side stripping which produces krypton partial pressure in the rising bubbles. This occurs in diffused air systems and has been documented by Baillod, et al[5]. The ratio of 0.83 used by Law was developed for surface aeration and must be corrected. This correction is described in the Peer Review Panel analysis section. The result of this correction is to reduce this ratio (to a value of 0.78) thereby increasing the values of K_{ox} that appear in Table 4.

Table 4

Radiotracer Oxygen Transfer Test Results - Clean Water
Law Environmental Services*

Run No	Station	Temp. (°C)	K_{Kr_T} (min^{-1})	$K^{**}_{ox_T}$ (min^{-1})	$K_{ox_{20}}$ (min^{-1})
2	A	30.8	.0320	.0386	.0298
	B	30.8	.0337	.0406	.0314
	C	30.8	.0325	.0392	.0303
	D	30.8	.0333	.0401	.0311
4	A	31.4	.0183	.0220	.0168
	B	31.4	.0171	.0206	.0157
	C	31.4	.0174	.0210	.0160
	D	31.4	.0173	.0208	.0159

* Table 17 from Law

**Calculated from $\frac{K_{Kr}}{K_{ox}} = 0.83$; $K_{ox} = K_L A$

The tritium tracer results produced useful information on the mixing characteristics of the ditch. The "plug flow" character of the ditch was clearly delineated from the analysis of this data. The circulation times predicted by this analysis were about 6 minutes for Test Run 2 and approximately 9 minutes for Test Run 4. These numbers compare favorably with those estimated by Mixco.

C. PEER REVIEW PANEL APPRAISAL

1. ASCE Procedure

The Peer Review Panel's data analysis produced results very similar to Mixco's results, differing only by a few percent. The differences in results are due primarily to corrections in probe calibration. Unfortunately, not all the probes were calibrated at the beginning of each test. Winkler samples were collected at the conclusion of each run. Mixco and the Peer Review Panel corrected probe calibrations by multiplying the indicated probe DO concentrations by the ratio of the final Winkler measured DO to probe measured DO concentrations. Alternatively one can correct the value of $C^*_{\infty T}$ by multiplying by the same ratio. Either procedure does not bias the results as long as the probes are not malfunctioning (linearity is preserved) and the error is a true calibration error, as opposed to probe drift.

During the last day of the Opelika testing, a check of sodium thiosulfate normality was performed. Verification of thiosulfate normality is not a requirement of the ASCE standard, but was done by Mixco on the advice of the Peer Review Panel. As indicated previously the difference produced an 8% error in DO analysis. After the test conclusion Mixco verified sodium thiosulfate normality with an independent laboratory, finding that the normality was 0.0256, which would only produce a 2.4% difference. Mixco rounded the normality to 0.026 and corrected all the data accordingly (a 4% difference).

The reasons for the difference in normality are unknown. The discrepancy between the saturation tests (8%) and the standardization (2.4%) might be explained by oxidation of the thiosulfate during its return to Rochester, NY. Sodium thiosulfate loses normality when exposed to air.

Table 5 compares the Mixco and Peer Review Panel results.

2. Dissolved Oxygen Mass Balance Procedure

From the outset of the project the manufacturers indicated that the plug flow nature of the system resulted in distinct changes in dissolved oxygen concentration as the liquid flowed through the turbines. The turbines in this application can be thought of as a pump. Figures 1 and 2 show the concept of a turbine pump. Figure 3 shows the typical "stair steps" that result. These steps are most distinct at the beginning of the test and gradually disappear as the test proceeds, due to dispersion and mixing. Additionally in the first step, excess sulfite may be oxidized if present at the turbine inlet which may result in a smaller change in DO. Consequently, the first step should be ignored when calculating oxygen transfer using this technique.

The mass rate of oxygen transfer can be calculated as follows:

$$OTR = Q(C_O - C_I) \tag{1}$$

The values of C_I and C_O should be displaced in time by the time of travel from the inlet probe, through the turbine to the exit probe. This was estimated to be one minute. Two sets of probes were placed at the inlet and discharge of the turbines in anticipation of this analysis. The volumetric flow rate Q was estimated from a series of ditch velocity measurements (described

Table 5

Comparison of Mixco and Peer Review Panel's ASCE Results

Test No	Mixco Results SOTR (lb O_2/hr)	Mixco Results SAE** (lb O_2/whp hr)	Mixco Results $C^*_{\infty 20}$ (mg/L)	Peer Review Panel Results SOTR (lb O_2/hr)	Peer Review Panel Results SAE (lb O_2/whp hr)	Peer Review Panel Results $C^*_{\infty 20}$ (mg/L)	Percent Difference* SAE	Percent Difference* $C^*_{\infty 20}$
1	272	1.65	11.5	270	1.64	11.4	0.6	0.9
2	272	1.65	11.2	283	1.72	11.7	-4.1	-4.3
3	299	1.82	11.3	296	1.80	11.4	1.1	-0.9
3A	285	1.73	11.3	291	1.76	11.4	-1.7	-0.9
4	143	1.76	11.8	150	1.85	12.1	-4.8	-2.5
5	171	1.20	11.2	178	1.25	11.6	-4.0	-3.4
6	407	1.67	11.0	435	1.78	11.8	-6.2	-6.8
Average			11.3			11.6	-2.9	-2.7

* Percent Difference = 100 (Mixco - Peer Panel)/Peer Panel

** Calculated from Mixco's SOTR's, Mixco's measured turbine horse power, and the Peer Review Panel's calculated blower horsepower

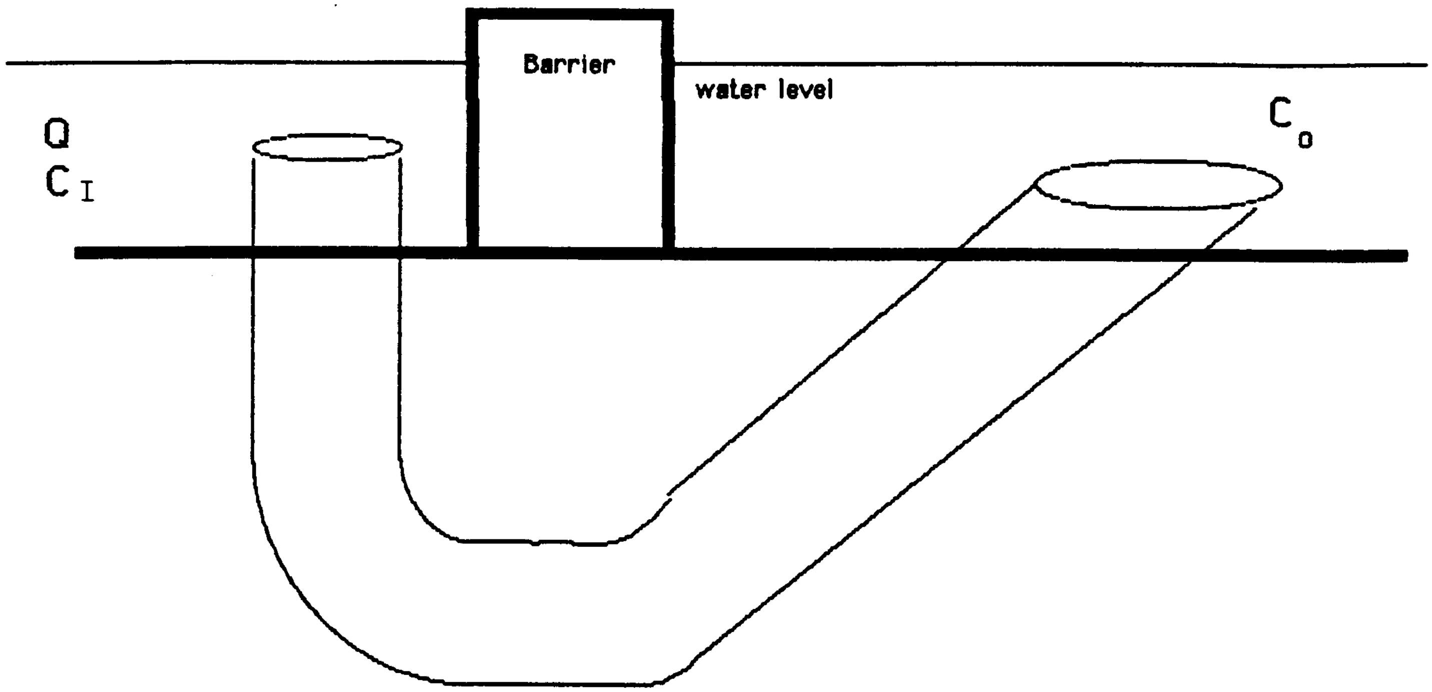

Figure 1. Schematic of the Total Barrier

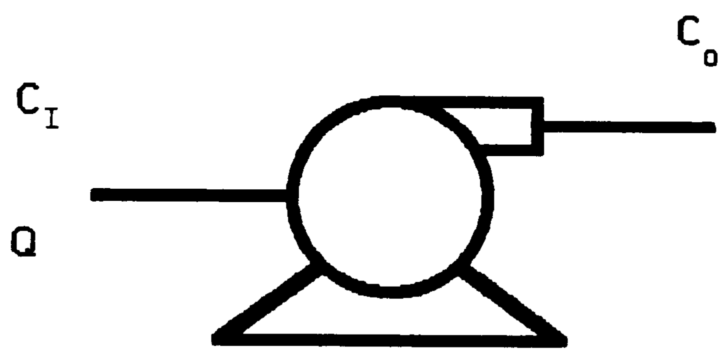

Figure 2. Pump Representation of the Turbine.

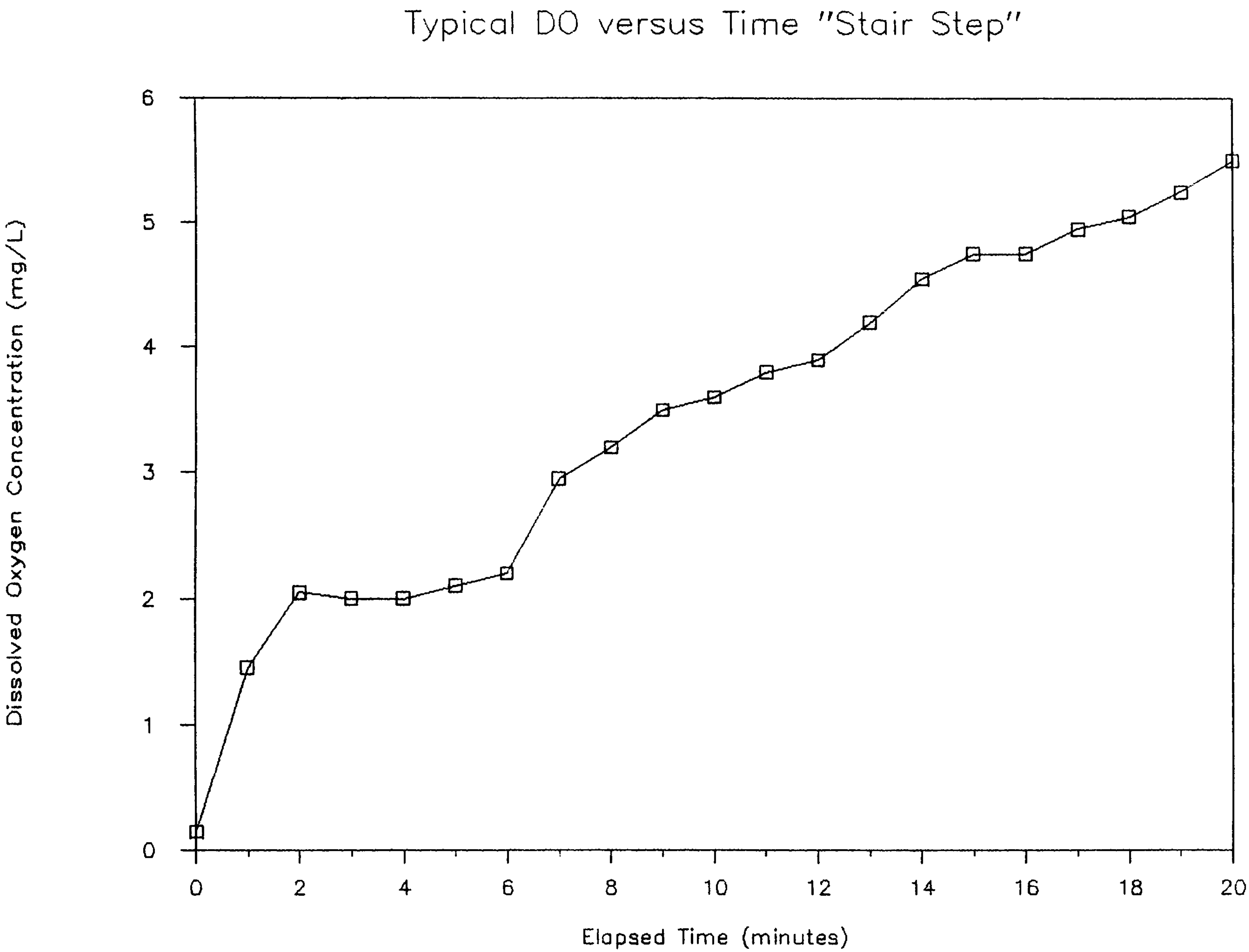

Fig. 3. Typical DO versus Time "Stair Steps"

previously). Correction of OTR to SOTR was performed as follows:

$$SOTR = \frac{OTR\ C^*_{\infty 20}}{\theta^{T-20}(C^*_{\infty T} - C)} \tag{2}$$

The definition of the terms in Equation 2 can be found in the ASCE Standard.[1] The ASCE Peer Review Panel clean water results (Table 5) were used to estimate $C^*_{\infty 20}$ (e.g. 11.4 mg/L for Test 1, etc). There are alternatives for choosing the value of C. The water enters the aeration zone at a concentration of C_I and leaves the zone at C_o. The Peer Review Panel chose to use the average of the two values.

This assumption can be explained using Figure 4. As a packet of water passes through the turbine it experiences a change in driving force. The driving force at any point is represented by a tangent to the dissolved oxygen versus time curve shown in Figure 4. The time of travel through the turbine is the interval over which one can draw a tangent. Tangents at the inlet or exit concentrations are shown as well as a tangent at the arithmetic average. The inlet and exit concentrations are the limits of possible driving forces, and neither is correct. The best estimator of driving force is an average of the inlet and exit concentrations, represented by a tangent to the curve midway between the inlet and exit concentrations.

It is important to note that in the early part of the curve, the exponential function is nearly linear. For a linear function, the location of the tangent (therefore the assumption for C) and driving force are independent. For higher concentrations, the location of the tangent has more effect on the driving force; however, for the DO mass balance procedure the higher concentrations cannot be used due to the errors in DO measurement and probe calibration.

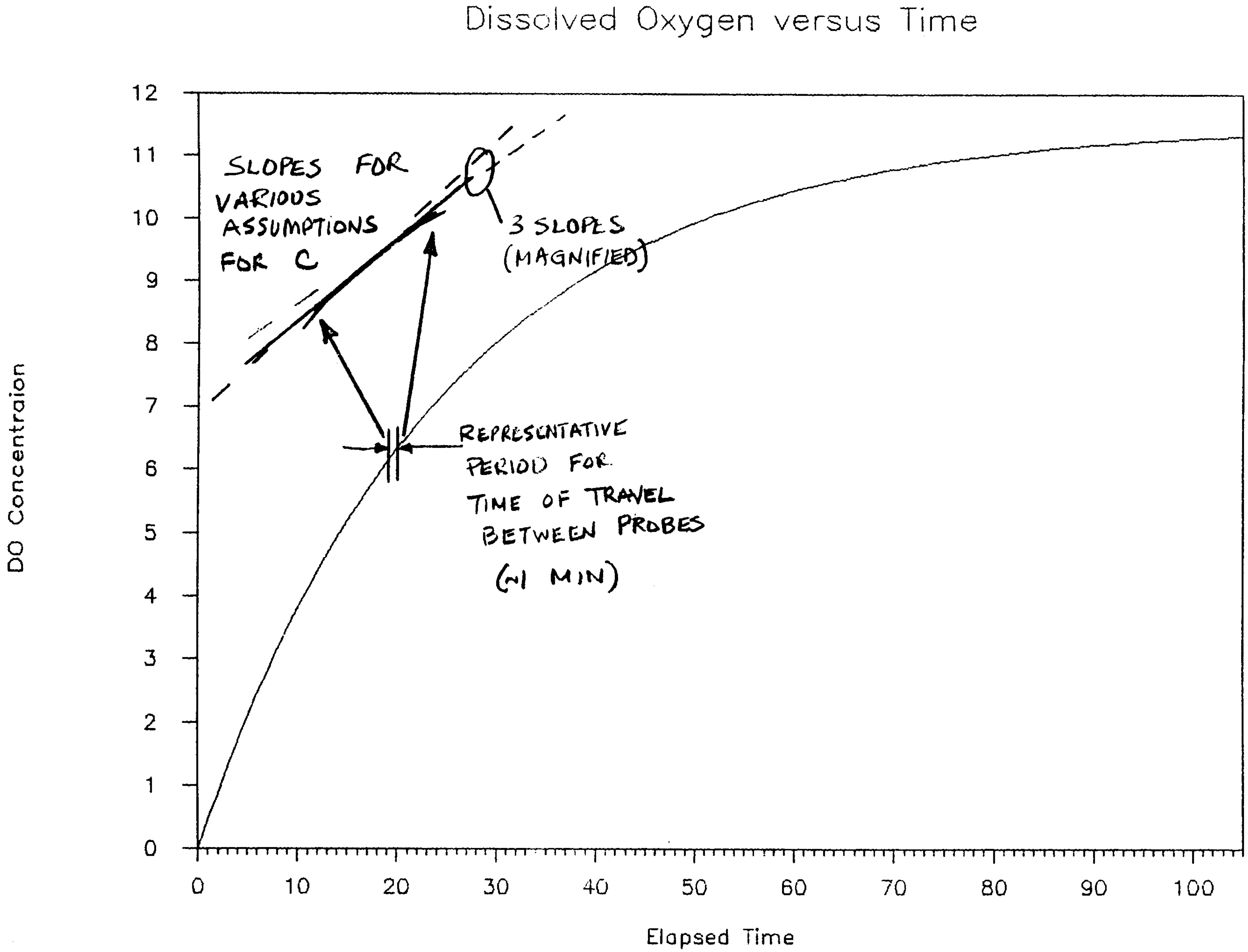

Fig. 4 Dissolved Oxygen versus Time Curve (typical), showing tangents to illustrate assumptions about C and the driving force. Note that the interval for tangents in greatly expanded for the sake of illustration.

The net calculation for SOTR from the mass balance procedure becomes:

$$SOTR = \frac{V \cdot A(C_I - C_o) \cdot C^*_{\infty 20}}{\theta^{T-20}\left[C^*_{\infty T} - \frac{C_I + C_o}{2}\right]} \tag{3}$$

The error structure of Equation 3 is problematic and produces significant variability in the results of the DO mass balance procedure. In subtracting the inlet and exit dissolved oxygen concentrations, probe calibration errors are introduced into the OTR calculation. Moreover there are two probes and the calibration errors can be additive. There is also significant error introduced in converting OTR and SOTR, due to probe calibration errors in the denominator term, $(C^*_{\infty T} - \frac{C_I + C_o}{2})$. This term tends to zero as the test proceeds. If there is positive error in the probe calibration, the denominator tends to zero too quickly and overestimates SOTR. If there is negative error SOTR is underestimated. To minimize the effects of probe calibration errors, only the early test results ($C \ll C^*_{\infty T}$) should be used. This constraint, combined with the inability to use the first step due to possible excess sulfite oxidation, renders a great portion of the data unusable.

Figure 5 shows typical results for the mass balance methods. As indicated previously the SOTR increases from zero at the test beginning. A plateau is reached where the best estimate of SOTR is obtained. As the dissolved oxygen increases, errors in probe calibration cause the denominator to vanish too quickly, resulting in drastic overestimation of SOTR, or vanish too slowly, underestimating SOTR. Results of the Peer Review Panel's DO mass balance are presented in the summary of this section.

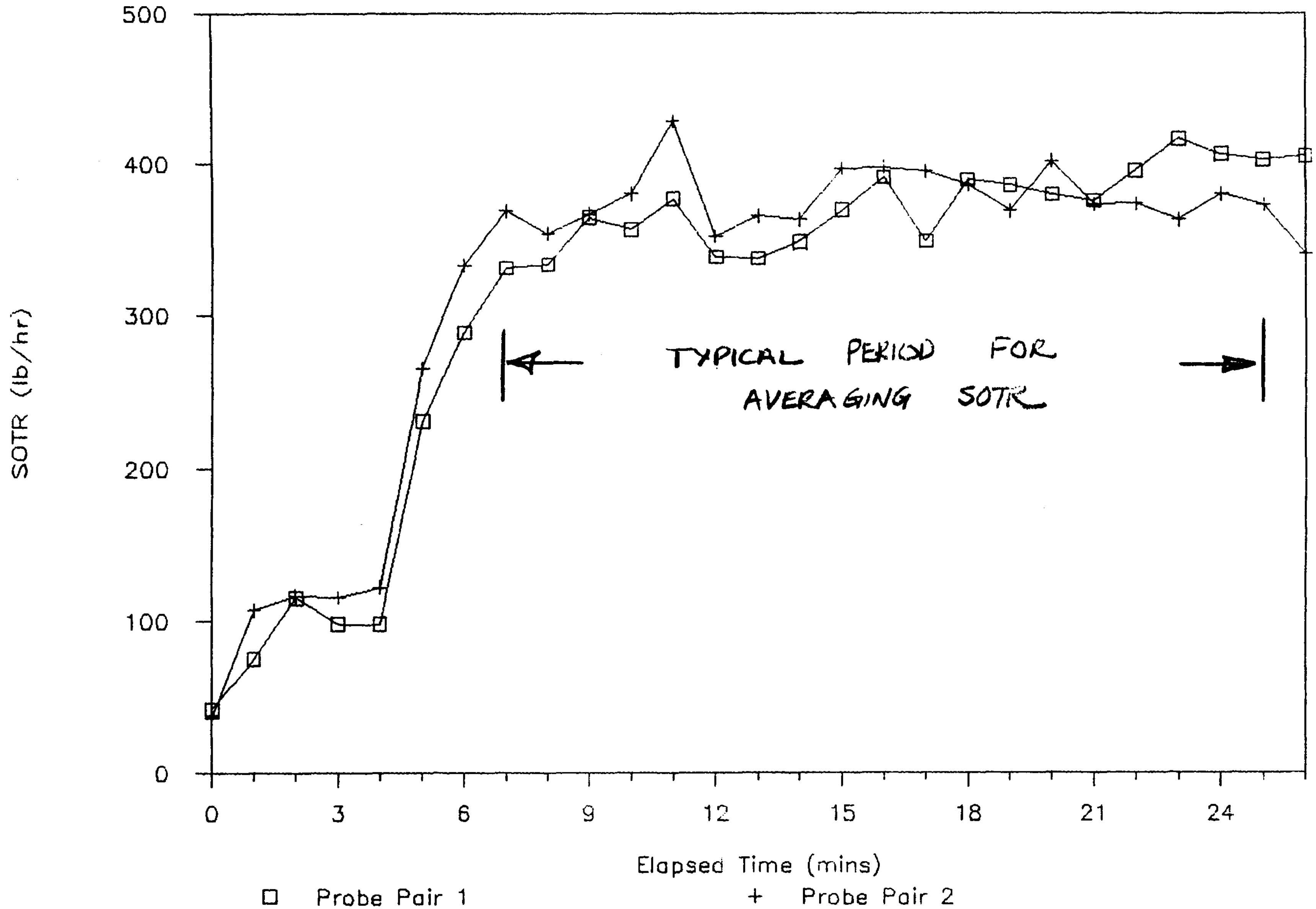

Fig. 5 Results of the DO Mass Balance Procedure (typical).

3. Radiotracer Procedure

The Peer Review Panel believes that the radiotracer procedure is currently the most accurate and precise method for assessing oxygen transfer in water and wastewater. Therefore, it serves as the referee method for all other test procedures. However, in order to provide accurate information on K_LA, it is necessary to correct the ratio $K_{Kr}/K_{ox} = 0.83$ to reflect stripping of krypton which takes place during bubble rise. Baillod, et al[5] have developed a methodology for calculating a correction factor, and corrections were developed for all tests by the Peer Review Panel. Appendix B summarizes the procedure. In both Test Runs 2 and 4 the correct ratio, K_{Kr}/K_{ox}, was 0.78. Table 6 shows the corrected values of K_{ox}.

4. Summary

Table 7 shows the SOTR and the standard deviation of SOTR for the radiotracer and ASCE methods as calculated by the Peer Review Panel. Also shown are the results of the DO mass balance procedure, applied to the data collected during the ASCE test. The standard deviations represent the standard deviations of the SOTR's obtained from each probe or sampling station in the case of the ASCE and radiotracer procedures, respectively. For the DO mass balance procedure, the standard deviation was calculated over all the points used in the analysis (typically 10 to 25).

The estimates of SOTR by the different procedures differ by only on a few percentage points. The agreement among methods is remarkably close. The difference in the results of the methods is not statistically significant, with the exception of the variability of the DO mass balance procedure, which is much higher than the other methods.

Table 6

Radiotracer Oxygen Transfer Test Results
Peer Review Panel Corrections

Run No.	Station	Law* K_{Kr_T} (min^{-1})	Law* SOTR** ($lb\ O_2/hr$)	Peer Review Panel K_{ox_T}*** (min^{-1})	Peer Review Panel $K_{ox_{20}}$ (min^{-1})	Peer Review Panel SOTR** ($lb\ O_2/hr$)
2	A	.0320	257	.0410	.0317	275
	B	.0337	271	.0432	.0333	290
	C	.0325	262	.0417	.0322	280
	D	.0333	268	.0427	.0329	286
			264 ± 6			283 ± 6
4	A	.0183	145	.0235	.0179	156
	B	.0171	135	.0219	.0167	145
	C	.0174	138	.0223	.0170	148
	D	.0173	137	.0222	.0169	147
			138 ± 4			149 ± 4

* See Table 4 for $K_{ox_{20}}$ $K_{ox} = K_L A$

** SOTR = $K_{ox_{20}}$ x $C^*_{\infty_{20}}$ x tank volume x conversion factors

= $K_{ox_{20}}$ x 11.6 mg/L x 1.5 MG x 8.34 x 60

*** Corrected by K_{Kr}/K_{ox} = 0.78 (Appendix B)

Table 7

Peer Review Panel's Comparisons of Different Methods (Clean Water)

Test No.	ASCE		Dissolved Oxygen Mass Balance			Radiotracer		
	SOTR ($lb\ O_2/hr$)	Std Dev*	SOTR ($lb\ O_2/hr$)	Std Dev*	% Difference with ASCE	SOTR ($lb\ O_2/hr$)	Std Dev*	% Difference with ASCE
1	270	10.8	313	23	+15.9			
2	283	5.7	292	45	+3.2	283	5.7	0
3	296	5.9	245	17	-17.2			
3A	291	7.3	312	26	+7.2			
4	150	6.9	168	12	+12	149	3.9	-0.6
5	178	3.4	174	15	-2.2			
6	435	6.9	375	17	-13.8			

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

IV. PROCESS WATER TESTING

A. EWING ENGINEERING

Ewing Engineering (Ewing) conducted four off-gas tests during August 6-7, 1986. The test results are summarized in Table 9 of Ewing's October 23rd report to BCM Converse. We have corrected a transcription error in Ewing's report and reproduced this revised table as Table 8.

In analyzing the test data, Ewing discusses several items which are worthy of further comment. The first issue deals with Ewing's ability to balance the gas flow between that collected by the hoods (fixed and portable locations) and the air flow applied, as estimated from blower measurements. The first three test conditions demonstrate an excellent balance (98-99%) but in the last test run, at the highest air flow, there was initially a 10% discrepancy. Ewing attributes this imbalance to foaming created by the high air flow which resulted in difficulty obtaining accurate gas flow rate measurements for the portable hood placements. Thus, in determining the mean weighted αSOTE and αSOTR values, Ewing modified the portable hood gas flow rates (the more reliable fixed hood flow rate is unchanged) in order to make the collected gas rates approximately the same as the applied air flow (their alternative 3, their Table 8B). This revised estimate is shown in our Table 8. Based upon the Peer Review Panel's observations during this testing program, this correction is the most rational way of reconciling the test results.

The other significant issue is choosing the most appropriate driving force $(C^*_{\infty T} - C)$ to use in calculating the αSOTE and αSOTR values. Transfer at standard conditions can be calculated using the following relationships:

Table 8

Summary of Off-Gas Results by Ewing Engineering for Opelika, Alabama - August 6-7, 1986 (Revised Table 9 from Ewing Report)

Run	Condition	Applied Air Rate (SCFM) (% balance*)	Mean Wt. OTE(f)	Actual Transfer Rate (lb O_2/hr)	$\alpha SOTE$ (%)	Standard** Transfer Rate (lb O_2/hr)
1	1	1117 (99.1%)	16.7	194	19.3	223
2	2	570 (98.9%)	16.9	100	19.4	114
3	1 (Repeat)	1133 (98.3%)	16.9	198	19.2	225
4***	3	1633 (99.5%)	14.8	250	17.2	291

* % balance is the air flow rate measured from the hood divided by the blower air flow rate.

** Ewing Engineering used 11.5 mg/L for $C^*_{\infty_{20}}$ and not 11.6 as used by the Peer Review Panel. This difference will increase the Ewing Engineering SOTR's by 0.9%.

*** Ewing's third alternative, their Table 8B.

$$OTE = \frac{\alpha SOTE\ (C^*_{\infty T} - C)\ \theta^{T-20}}{C^*_{\infty 20}} \qquad (4)$$

or

$$\alpha SOTE = \frac{OTE\ C^*_{\infty 20}}{\theta^{T-20}(C^*_{\infty T} - C)} \qquad (5)$$

where

$C^*_{\infty T} - C$ = driving force[+]

The key question is: what is the most appropriate value to use for the DO (C) which the aeration unit is working against to transfer oxygen into the process water? This is most relevant for the fixed hood where the DO varies from zero at the entrance of the turbines to a finite level as the liquid is discharged. In practical terms, the OTE is a measured value and is independent of C; however αSOTE is a calculated value and is dependent upon measurement errors in OTE, T, C^*_{∞} and the interpretation of C. There are varied opinions on interpreting the value of C and the Peer Review Panel's viewpoint will be discussed in Section IV.C.1 to follow.

Ewing calculated αSOTE values using three different approaches for estimating the driving force. They use the following alternative methods for calculating the process water DO (C) level for the fixed hood which is used in the driving force calculation:

1. The DO level measured at the turbine exits (the DO sampling point was located at the corner of the barrier and ditch walls).

2. The log-mean of turbine inlet (0 mg/L) and exit (> 0 mg/L) DO concentrations.

[+] The value of β used in all process water equations to calculate $C^*_{\infty T}$ was 0.99

3. The arithmetic average of the DO concentration at the turbine exit and portable hood location 1 (i.e. at end of fixed hood).

Based upon their review, Ewing concluded that approach No. 2 using the log-mean of the turbine inlet and exit DO concentrations is the most reasonable alternative for corrections to standard conditions. The Peer Review Panel discusses another viewpoint in Section IV.C.1 to follow.

Ewing also concluded that the reproducibility of the off-gas method for this application is excellent. Since Test Run 3, which was a replicate of Test Run 1, yielded an αSOTR of 225 versus 223 lb O_2/hr for Test Run 1, the Peer Review Panel concurs with this conclusion.

As a final note on the Ewing report, there is a typographical error on page 12. The equation should read:

$$Mean\ wt.\ OTE_f\ x\ SCFM\ x\ 1.036 = \alpha K_L A(C^*_{\infty T} - C)W$$

B. LAW ENVIRONMENTAL SERVICES

Law reported on radiotracer testing (Law Test Nos. 3 and 4) that paralleled the off-gas testing Test Runs 1 and 2 (see Law report to BCM Converse, October, 1986). The results are shown in Table 9. The radiotracer approach has been used sparingly in the past (see the Law Report) as a double check on alternative aeration test methods in process water. As described previously, Law failed to make the necessary adjustments in the K_r/K_{ox} ratio (0.83) in their report, and therefore the values reported for K_{ox} are biased on the low side. The Peer Review Panel analysis section, IV.C.2, will show the quantitative significance of this correction.

Table 9

Radiotracer Oxygen Transfer Test Results - Process Water
(Law Environmental Services Report, Table 17)

Run No.*	Station	Temp.	αK_{Kr_T}	$\alpha K^{**}_{ox_T}$	$\alpha K_{ox_{20}}$
		(°C)	(min^{-1})	(min^{-1})	(min^{-1})
1P	A	28.2	0.0246	0.0296	0.0244
	B	28.2	0.0238	0.0287	0.0236
	C	28.2	0.0243	0.0293	0.0241
	D	28.2	0.0246	0.0296	0.0244
2P	A	28.1	-	-	-
	B	28.1	0.0110	0.0133	0.0109
	C	28.1	0.0118	0.0142	0.0117
	D	28.1	0.0122	0.0147	0.0121

* Test Runs 1P and 2P correspond to Law test numbers 2 and 4.

** Calculated from $\frac{K_{Kr}}{K_{ox}} = 0.83; \quad K_{ox} = K_L A$

Law also presents calculated values for α based upon direct comparisons between the clean water and process water test results for similar test conditions. For the high speed mixer, two-blower test, Law reports $\alpha = 0.79$ and for the low speed mixer, single blower test, α is calculated as 0.72 (actually Law incorrectly reports a value of 0.872 on page 54 of its report; this appears to be a simple calculation error). These values are incorrect since Law did not correct for the krypton partial pressure in the gas phase. The Peer Review Panel will show more accurate α calculations in the next section.

Law shows that complete mixing of the tritium takes nearly one hour. Based upon this observation Law concludes that analyzing the ratio of K_R / T_R is more appropriate than analyzing K_R concentrations for rate determinations. The Peer Review Panel concurs with this conclusion. Furthermore, Law concludes that since the ultimate K_R concentration in air is negligible, a linear least squares technique (rather than a non-linear least squares approach where the ultimate K_R concentration would be a variable determined in this analysis) would be the most reliable and meaningful method for data analysis. The Peer Review Panel supports this approach.

C. PEER REVIEW PANEL ANALYSIS

1. Off-Gas Procedure

The Peer Review Panel explored in detail the methodology which should be used for the off-gas method to convert actual oxygen transfer efficiencies (OTE's) to standard oxygen transfers ($\alpha SOTE's$ and $\alpha SOTR's$). As discussed in the Clean Water Testing section, the most appropriate estimate of the actual driving force across the aeration device should be calculated from the average of inlet and outlet DO levels (i.e. $C = \frac{C_I + C_o}{2}$). Thus, rather than using any of Ewing's alternatives for this conversion, the Peer Review Panel selected the average DO for calculating the driving force. Table 10 presents a comparison of Ewing's log-mean approach and the Peer Review Panel's average approach. Even though there is not a practical difference between the two approaches, the Peer Review Panel believes that the average DO provides the most representative and justifiable driving force. Appendix C contains the detailed calculations used by the Peer Review Panel to obtain the revised values for Table 10.

2. Radiotracer

The radiotracer results reported by Law for αK_{ox} ($\alpha K_L A$) are not accurate as mentioned earlier. Therefore, the Peer Review Panel recalculated the proportionality factor, finding it to be 0.79 (assumed by Law to be 0.83). The methodology for this calculation is presented in Appendix B and discussed in detail in Section III.3.C. Using this more appropriate factor, the Peer Review Panel recalculated the $\alpha K_L A$ values from the radiotracer results. Table 11 presents the revised $\alpha K_L A$ along with αSOTR values. As readily seen, the Peer Review Panel's calculations result in slightly higher αSOTR's.

3. Summary

A summary of the process water results based upon Peer Panel calculations is presented in Table 12. The comparison between radiotracer and off-gas method results indicates excellent agreement. The results compare favorably, within 1 to 5% of each other and are not statistically different. A comparison of process water and clean water results shows that α varies from 0.66 - 0.77.

Table 10

Log-Mean vs. Average DO Concentrations for Driving Force Calculations Used in Conversions to Standard Conditions

Run	Condition	Applied Air Rate (SCFM)	Ewing Engineering (Log-Mean)			Peer Review Panel (Average)		
			αSOTE (%)	αSOTR (*lb O_2/hr*)	α*SAE* (*lb O_2/whp–hr*)	αSOTE (%)	αSOTR (*lb O_2/hr*)	α*SAE* (*lb O_2/whp–hr*)
1P	1	1117	19.3	223	1.30	18.6	216	1.26
2P	2	570	19.4	114	1.36	18.8	111	1.32
3P	1 (repeat)	1133	19.2	225	1.33	18.7	220	1.30
4P*	3	1633	19.2	291	1.16	17.0	287	1.14

* From Ewing, Table 8B.

Table 11

Peer Review Panel Revisions to Radiotracer
Oxygen Transfer Results

Run No.	Station	Law*		Peer Review Panel		
		αK_{Kr_T} (min^{-1})	$\alpha SOTR$** ($lb\ O_2/hr$)	αK_{ox_T}*** (min^{-1})	$\alpha K_{ox_{20}}$*** (min^{-1})	$\alpha SOTR$** ($lb\ O_2/hr$)
1P	A	0.0246	211	0.0311	0.0256	223
	B	0.0238	204	0.0301	0.0248	216
	C	0.0243	208	0.0307	0.0253	220
	D	0.0246	211	0.0311	0.0256	223
			209 ± 3			221 ± 3
2P	A	-	-	-	-	-
	B	0.0110	94	0.0139	0.0115	100
	C	0.0118	101	0.0149	0.0123	107
	D	0.0122	104	0.0154	0.0127	111
			100 ± 5			106 ± 5

* See Table 7 for $\alpha K_{ox_{20}}$

** $\alpha SOTR = \alpha K_{ox_{20}} \times 11.6\ mg/L \times 1.5\ MG \times 8.34 \times 60$

*** Corrected by $K_{Kr}/K_{ox} = 0.79$; $K_{ox} = K_L A$ (see Appendix B)

Table 12

Comparison of Process Water Test αSOTR
Results and α Calculations
Peer Review Panel

Run No.	Radiotracer* αSOTR (lb O_2/hr)	Off-Gas** αSOTR (lb O_2/hr)	Equivalent Clean*** Water SOTR (lb O_2/hr)	Calculated α
1P+	221 ± 3	216	285 ± 11	0.76-0.77
2P	106 ± 5	111	150	0.70-0.74
3P+	-	220	285 ± 11	0.77
4P	-	287	435	0.66

* From Table 11
** From Table 10
*** From Table 7
\+ Tests 1P and 3P are replicate tests

V. SUMMARY AND CONCLUSIONS

A comprehensive evaluation of downdraft submerged turbines in the total barrier oxidation ditch was performed at Opelika, Alabama. The ASCE standard procedure was compared to the krypton radiotracer method and a non-standard dissolved oxygen mass balance procedure ("delta DO"). All three clean water methods produced remarkably similar results. The estimates of SOTR for the different methods were within a few percent (usually less than 5) and were not statistically different. Figures 6 and 7 show the SOTR's and SAE for all clean water tests as calculated by the Peer Review Panel. The precision of the dissolved oxygen mass balance procedure is much less than the other methods, and for this reason is considered inferior.

The ASCE standard procedure is a valid procedure for testing total barrier oxidation ditches, and should also be valid for other types of oxidation ditches. Testing oxidation ditches is more difficult, due to the "plug flow" characteristics of the ditches. More care is required in introducing and mixing the sodium sulfite. Additionally, it is recommended that more frequent DO sampling be performed. The frequency of sampling makes Winkler analysis impractical.

In process water, off-gas analysis and the radiotracer method were used to estimate oxygen transfer. Both process water methods produced remarkably similar results. The estimates of SOTR for both methods were within a few percent (usually less than 6) and were not practically different. Figures 8 and 9 show the SOTR's and SAE's for all dirty water results, as calculated by the Peer Review Panel. The alpha factors for conditions tested ranged from 0.66 to 0.77.

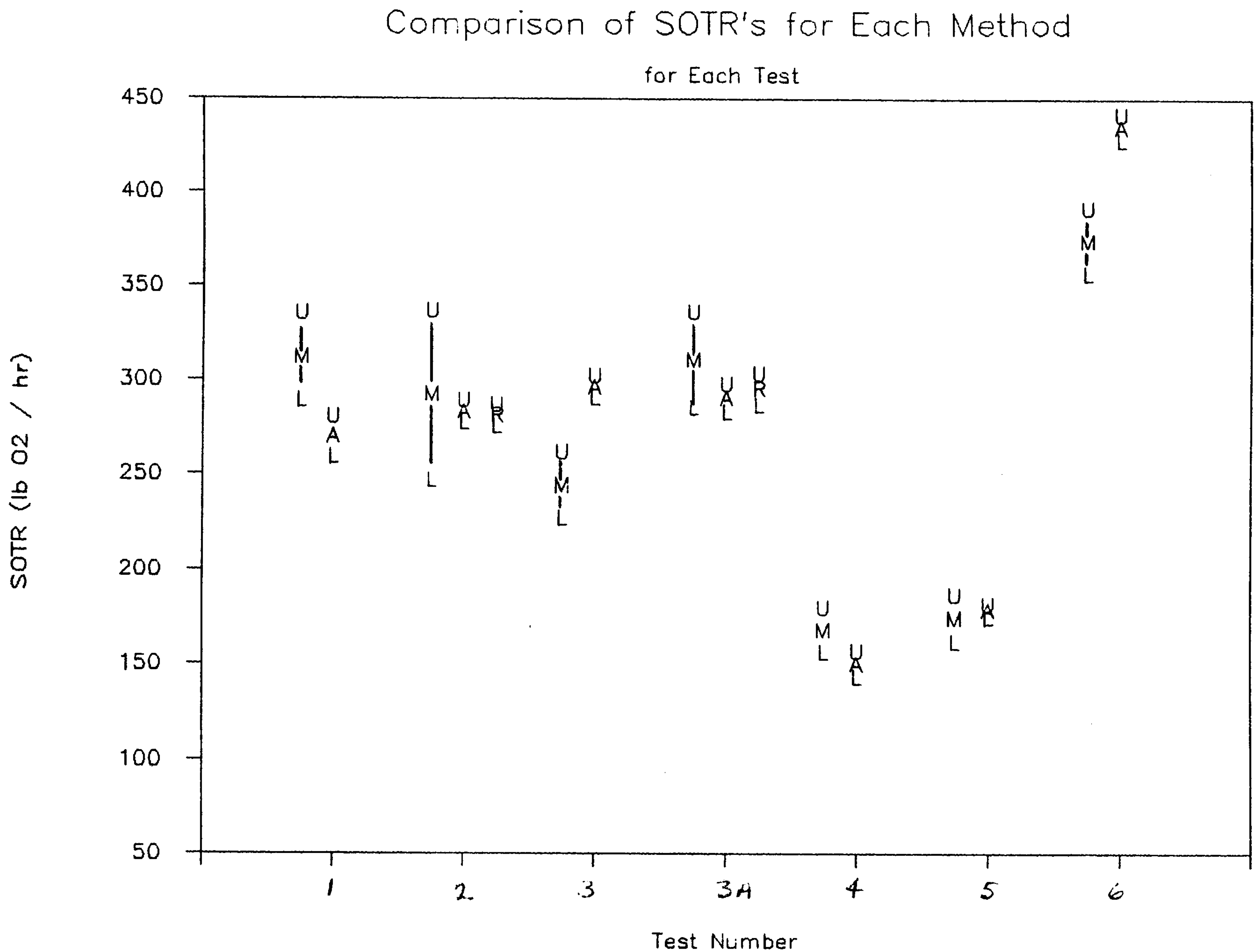

Fig. 6 Comparison of SOTR's for Clean Water (A = ASCE method, M = DO mass balance method, R = Radiotracer method, L = lower standard deviation, U = upper standard deviation. For the ASCE and radiotracer methods, the standard deviation is calculated over the probe or sample points. For the DO mass balance the standard deviation is calculated over sequential data points, typically 10 to 25).

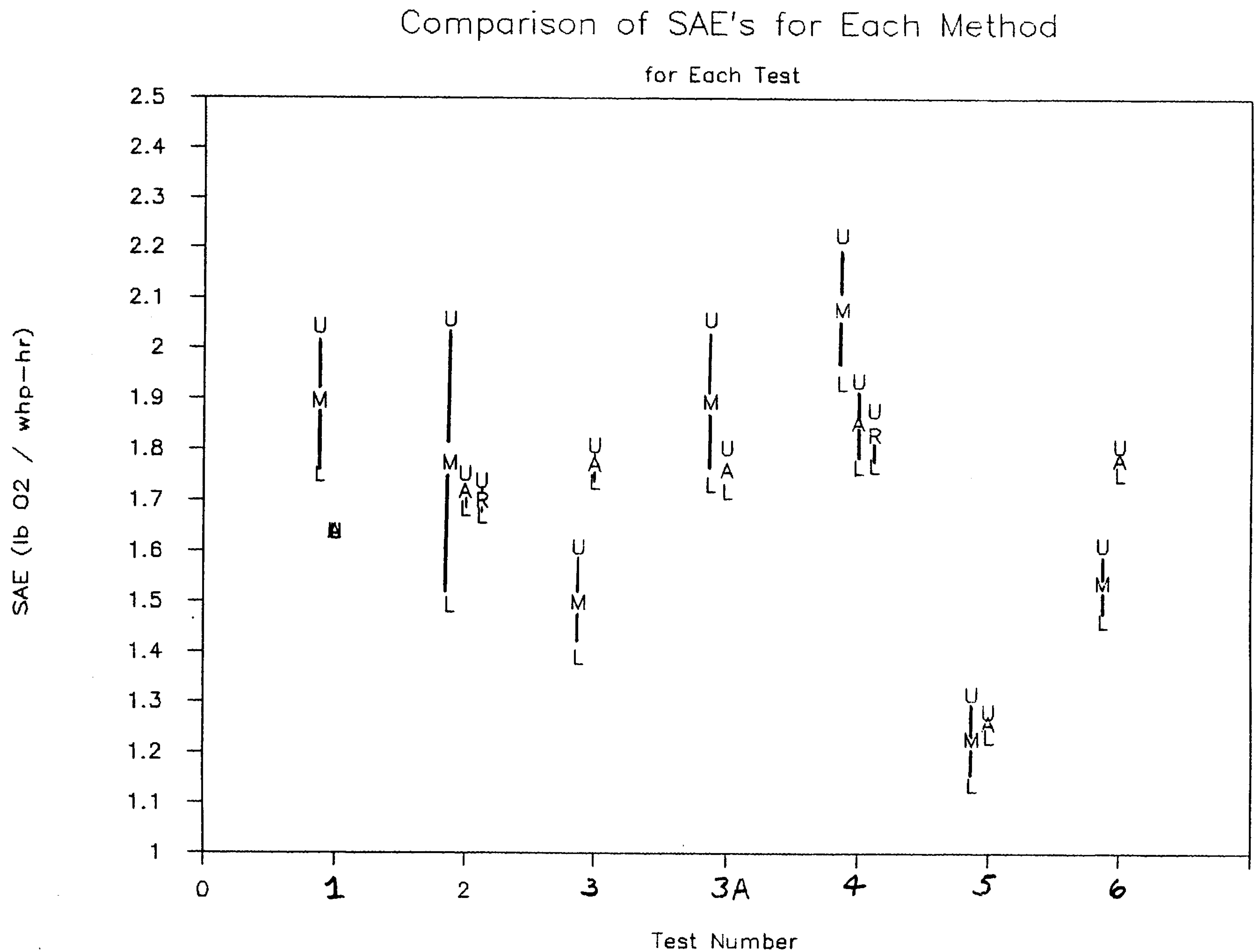

Fig. 7 Comparison of SAE's for Clean Water (A = ASCE method, M = DO mass balance method, R = Radiotracer method, L = lower standard deviation, U = upper standard deviation. For the ASCE and radiotracer methods, the standard deviation is calculated over the probe or sample points. For the DO mass balance the standard deviation is calculated over sequential data points, typically 10 to 25).

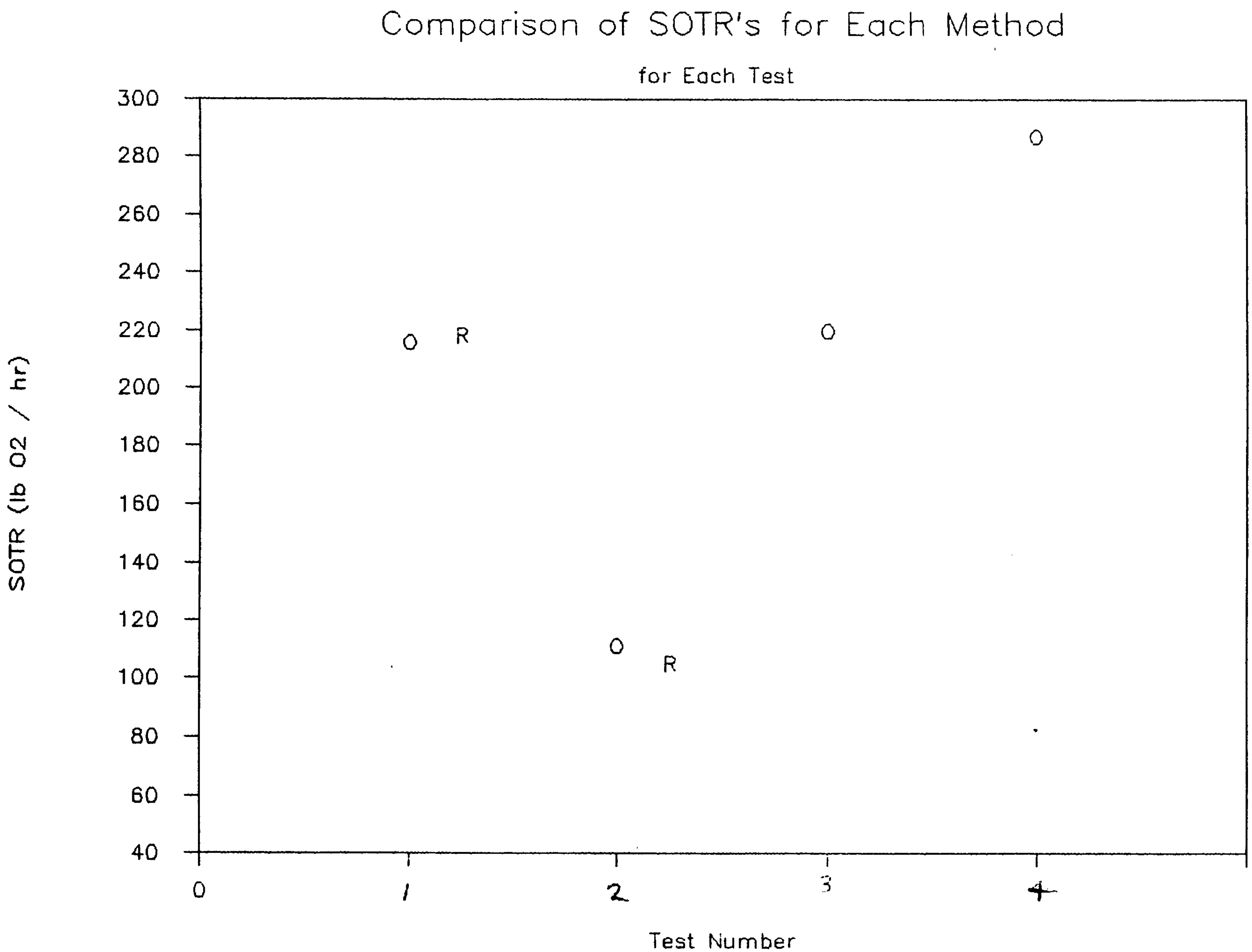

Fig. 8 Comparison of SOTR's for Process Water (O = offgas method, R = radiotracer method).

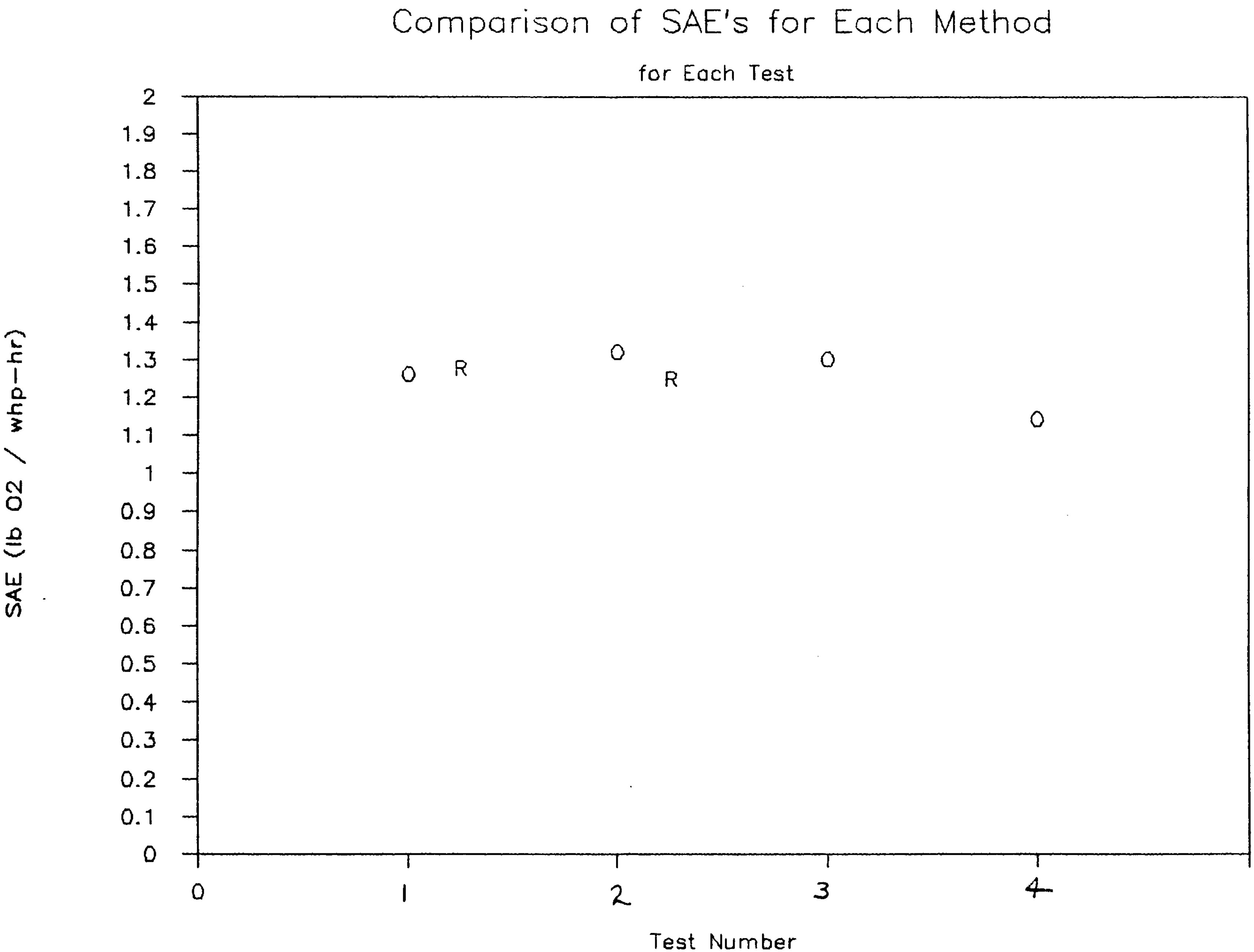

Fig. 9 Comparison of SAE's for Process Water (O = offgas method, R = radiotracer method).

VI. REFERENCES

1. ASCE, *A Standard for the Measurement of Oxygen Transfer in Clean Water*, ASCE, July 1984.

2. Letter from Lilia A. Abron-Robinson, Ph.D. to each Peer Review Panelist, January 15, 1986.

3. Letter from Dick Brenner to all project participants, January 28, 1986.

4. Peer Review Panel Report, "Evaluation of Oxygen Transfer Performance of Total Barrier Oxidation Ditches Equipped with Draft Tube Aerators, Opelika, Alabama - Summary Evaluation Report," February, 1986.

5. *Roots Rotary Blower Manual*, Roots-Dresser, Connersville, Indiana.

6. Grinnell, D., Mixco, personal communications, February 9, 1987.

7. Baillod, C.R., Paulson, W.L., McKeown, J.J., and H.J. Campbell, Jr., "Accuracy and Precision of Plant Scale and Shop Clean Water Oxygen Transfer Tests," *JWPCF*, Vol. 58, No. 4, pp. 290-299, 1986.

VII. APPENDICES

APPENDIX A

Table 13.

Peer Review Panel Calculated Blower Horsepower for the Clean Water Test

Test No	RPM	Discharge Pressure (psi)	Gear Speed	Friction Horsepower	Brake Horsepower	Motor Efficiency (Fraction)	Sheave Efficiency (Fraction)	Wire Horsepower	No Blowers In Service	Total Wire Blower Horsepower
1	2215	5.35	2611	1.7	21.6	0.98	0.99	22.3	2	44.6
2	2215	5.40	2611	1.7	21.8	0.98	0.99	22.5	2	44.9
3	2220	5.29	2617	1.7	21.4	0.98	0.99	22.1	2	44.2
3A	2215	5.36	2611	1.7	21.7	0.98	0.99	22.3	2	44.6
4	2217	5.04	2614	1.7	20.5	0.98	0.99	21.1	1	21.1
5	2219	4.70	2616	1.7	19.2	0.98	0.99	19.8	1	19.8
6	3080	6.24	3631	3.5	35.8	0.98	0.99	36.9	2	73.8

Notes: Pressure drop was obtained using Mixco's discharge pressure with an assumed inlet pressure drop of 0.1 psi.

Horsepowers calculated according to recommended procedures from manufacturer's design manual[5] for Roots/Dresser Model 412 blower, as follows:

$$BHP = FHP + (0.00436)\ CFR\ N\ \Delta P$$

where:

FHP = Frictional Horsepower, taken from the Roots figure on page 14 of their manual.

CFR = Displacement per revolution = 0.333 for blower model 412.

N = RPM, taken from your report

ΔP = Pressure drop

LIGHTNIN

MIXING EQUIPMENT COMPANY • 135 MT. READ BLVD. • P.O. BOX 1370 • ROCHESTER, NEW YORK 14603-1370
PHONE: 716-436-5550 • TELEX: 97-8244 • CABLE "Mixco" • TELECOPIER 716-436-5589

February 17, 1987

Michael K. Stenstrom, Ph.D.,P.E.
Professor, Civil Engineering Department
School of Engineering and Applied Science
University of California, Los Angeles
Los Angeles, California 90024

Subject: Blower Horsepower

Reference: Opelika/EPA Oxygen Transfer Test Program

Dear Mike:

Dave Grinnell and I have reviewed your letter of February 5, 1987 and appreciate your efforts to resolve the discrepancies in blower power data. We concur that the calculated power levels for the clean water tests closely agree with those measured during the dirty water testing, and represent performance more accurately than the Computrac data.

We will revise our test report accordingly and transmit a copy to you for your records.

Please do not hesitate to call should you have any further comments on this or any other items.

Very truly yours,

MIXING EQUIPMENT COMPANY

Paul M. Kubera
Manager, Market Development
Waste and Water Treatment

dmg

xc:
D. Grinnell (Mixco)

Dr. Wm. C. Boyle
Dept. of Civil & Environmental Engrg
3230 Engineering Building
University of Wisconsin
Madison, Wisconsin 53706

Richard C. Brenner, P.E.
Water Engineering Research Lab
Wastewater Research Division
U.S.Environmental Protection Agency
26 W. St. Clair Street
Cincinnati, Ohio 45268

Hugh J. Campbell, Jr., Ph.D.,P.E.
Senior Consultant - Engineering Dept.
Louviers Building 1382
E. I. DuPont de Nemours & Company
Wilmington, Delaware 19898

Robert C. Borneman, P.E.
BCM Converse
108 St. Anthony Street
Mobile, Alabama 36633

MIXING EQUIPMENT COMPANY, A DIVISION OF GENERAL SIGNAL CONTROLS, INC.

APPENDIX B

Corrections to K_{Kr}/K_{ox} Ratio for Krypton Stripping

(See Baillod, et al[7] for details)

During the development of the inert gas radiotracer procedure for oxygen transfer measurement, the ratio K_{Kr}/K_{ox} was determined experimentally in laboratory studies using surface aeration experiments. The value obtained, 0.83, has been proven accurate for surface transfer systems. Baillod et al.[7] have shown that in subsurface aeration there is a deviation in the K_{ox} (K_LA) values away from the "true" K_{ox} values by virtue of gas-side oxygenation (or stripping in the case of krypton) as the bubble rises through the transfer fluid. In order to properly use this ratio, one must correct the "true" K_{Kr}/K_{ox} ratio for this gas-side stripping.

The equations developed for these corrections follow:

$$\frac{K_{Kr}}{K_{ox}} = \frac{K_{Kr}^*}{K_{ox}^*}\,\frac{\phi_k}{\phi}\,\frac{2\phi + \dfrac{2\phi K_{ox}}{2\phi - K_{ox}}}{2\phi_k + \dfrac{K_{Kr}^*}{K_{ox}^*}\,\dfrac{2\phi K_{ox}}{2\phi - K_{ox}}} \tag{7}$$

where

$\phi \quad = \quad \dfrac{M_o \rho_a Q_a}{M_a H_o V (P_b + \gamma\, de)}$

$\phi_k \quad = \quad \dfrac{M_k \rho_a Q_a}{M_a H_k V (P_b + \gamma\, de)}$

$\dfrac{K_{Kr}^*}{K_{ox}^*} \quad = \quad$ true ratio of $\dfrac{K_{Kr}}{K_{ox}}$

$K_{ox} \quad = \quad$ apparent K_LA value, t^{-1}

M_o	=	molecular weight of oxygen
M_a	=	molecular weight of air
M_k	=	molecular weight of krypton
$\rho_a Q_a$	=	mass rate of air, m/t
H_o	=	Henry's constant for oxygen - m, $L^{-3}f$, L^{-2}
H_k	=	Henry's constant for krypton - m, $L^{-3}f\,L^{-2}$
ρ_b	=	barometric pressure, $f\,L^{-2}$
de	=	effective depth, L
γ	=	weight density of water, $f\,L^{-3}$
V	=	water volume, L^3

Table 14 illustrates the application of these equations to the calculation of the apparent K_{Kr}/K_{ox} ratios for both the clean and process water tests at Opelika, Alabama. The entire test volume, 5680 m^3, was used in these calculations since K_{ox} was estimated for that volume. The K_{ox} values used were those obtained from clean water test data for Runs 2 and 4. The K_{ox} values for the process water test data (Table 17 - Law Environmental Service) initially were estimated from K_{Kr} using a value of 0.79 for K_{Kr}/K_{ox}. Subsequent values were obtained by using iterations. Convergence was obtained in two iterations.

Table 14

Parameters Used to Calculate Apparent K_{Kr}/K_{ox} Ratio

Parameter	Clean Water Run 2	Clean Water Run 4	Process Water Run 1	Process Water Run 2
Temp, °C	30.8	31.4	28.2	28.1
M_o	32	32	32	32
M_a	29	29	29	29
M_{Kr}	83.8	83.8	83.8	83.8
$\rho_a Q_a$, kg/min	40.74	20.6	38.1	19.4
V, m^3	5680	5680	5680	5680
P_b, KPa	102.2	102.2	99.5	99.5
de, m	2.9	3.42	2.9	3.42
H_o, mg/L atm	36	36	37.9	37.9
H_k, mg/L atm	169.5	169.5	178.6	178.6
K_{ox}, min^{-1}	.0419	.0216	.0307	.0148
ϕ	.170	.0828	.154	.0760
ϕ_k	.0944	.0460	.0844	.0421
$\frac{K_{Kr}}{K_{ox}}$	0.7824	0.7799	0.791	0.792

Appendix C

Table 15. Peer Panel's Revisions to the Off-Gas Results

Ewing's Revised Table 5

Zone	Off-gas Rate Zone	Mean Wt. OTE f	Mean Wt. α SOTE	Avg. DO	Wt. SOTE	SOTR
Fixed	777	0.129	0.146	1.31	113.44	
1	147.5	0.219	0.240	1.02	35.36	
2	88.6	0.235	0.265	1.37	23.46	
3	55.7	0.304	0.333	1.0	18.52	
4	21.6	0.392	0.405	0.5	8.75	
5	16.5	0.396	0.408	0.5	6.74	
Total	1106.9				0.186	215.6

Ewing's Revised Table 6

Zone	Off-gas Rate Zone	Mean Wt. OTE f	Mean Wt. α SOTE	Avg. DO	Wt. SOTE	SOTR
Fixed	509	0.156	0.177	1.26	89.84	
1	41.8	0.276	0.287	0.59	11.98	
2	12.4	0.334	0.343	0.05	4.26	
Total	563.2				0.188	111.1

Ewing's Revised Table 7

Zone	Off-gas Rate Zone	Mean Wt. OTE f	Mean Wt. α SOTE	Avg. DO	Wt. SOTE	SOTR
Fixed	777	0.132	0.149	1.28	115.77	
1	146.2	0.229	0.256	1.24	37.46	
2	94.4	0.242	0.263	0.95	24.79	
3	68.1	0.284	0.303	0.8	20.61	
4	28.7	0.341	0.359	0.7	10.31	
Total	1114.4				0.187	220.1

Ewing's Revised Table 8b

Zone	Off-gas Rate Zone	Mean Wt. OTE f	Mean Wt. α SOTE	Avg. DO	Wt. SOTE	SOTR
Fixed	1128	0.117	0.136	1.47	153.18	
1	206.1	0.193	0.223	1.5	45.96	
2	118.5	0.196	0.224	1.4	26.48	
3	84.6	0.226	0.254	1.27	21.50	
4	49	0.273	0.305	1.2	14.95	
5	38.3	0.339	0.365	0.9	13.97	
Total	1624.5				0.170	287.4