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January 27, 2018

Carollo Engineers
Tanja Rauch-Williams
390 Interlocken Cresent, Suite 800
Broomfield, CO 80021

Re: Santa Fe Wastewater Treatment Plant - Report of Full Scale Offgas Analysis of Membrane Grid Aeration System

Dear Tanja,

Attached please find my report of the full-scale offgas tests conducted in November of this year; on the Sanitaire fine pore membrane disc aeration system at the at the Santa Fe WWTP.

Following your review, should you have any questions, please let me know.

Best regards,

REDMON ENGINEERING COMPANY

David T. Redmon, P.E.

FULL SCALE OFFGAS ANALYSIS
OF THE
SANITAIRE FINE PORE MEMBRANE GRID AERATION SYSTEM
AT THE
SANTA FE WWTP

SANTA FE, NEW MEXICO

PERFORMED ON BEHALF OF:
CAROLLO ENGINEERS

CONDUCTED
November 2017

PERFORMED BY:

REDMON ENGINEERING COMPANY
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REDMON
ENGINEERING COMPANY

FULL SCALE OFFGAS ANALYSIS
OF THE
SANITAIRE FINE PORE MEMBRANE DISC AERATION SYSTEM
AT THE
SANTA FE WASTEWATER TREATMENT PLANT
IN
SANTA FE, NM

December 2017

INTRODUCTION

Redmon Engineering Company was engaged as a subcontractor to Carollo Engineers to conduct an offgas evaluation of the Sanitaire fine pore membrane grid aeration system installed in the aeration basins at the Santa Fe WWTP in Santa Fe, New Mexico. The purpose of the tests was to measure the oxygen transfer efficiency of the existing membrane disc diffusers under process water conditions. A second portion of the aeration study was to conduct a laboratory evaluation of the existing membrane diffusers. This portion of the project is covered by a separate report.

The objective of the offgas evaluation was to provide site-specific measurements of oxygen transfer efficiency, alpha and oxygen transfer rate of the membrane disc aeration system that was installed in the two aeration basins approximately sixteen years ago.

On November 14, 15, and 16, 2017, David Redmon of Redmon Engineering Company conducted offgas tests on the aeration system at the Santa Fe WWTP. The results of this offgas evaluation are presented in this report.

BACKGROUND

The full-scale test involves placing a floating offgas collection device on the liquid surface of the basin(s) in question at various locations and to analyze the exiting gas for the partial pressure of oxygen compared to that of ambient air. In addition, the rate of offgas evolution is typically measured for each offgas collection hood sampling position employed and each test condition. These data are analyzed according to the procedures described in the paper, "Oxygen Transfer Efficiency Measurements in Mixed Liquor Using Offgas Techniques," by Redmon, et al. (WPCF November, 1983) and the ASCE “Standard Guidelines for In-Process Oxygen Transfer Testing,” (ASCE-18-96). The offgas paper is contained in Appendix I for the reader’s reference.

Aeration System

The aeration system tested at the Santa FE WWTP consists of two oxidation ditch aeration basins. Each of the basins is about 120 feet wide by about 260 feet in length and having a side water depth of 16.6 feet. Each basin consists of four channels, with each channel having a width of 29.25 feet. There are six (6) individual grids of membrane disc diffusers along the length of each basin. There are two grids in Channel #1, two grids in Channel #2 and two grids in Channel #3. There are no grids of diffusers installed in Channel #4. There is an approximate total of 3,800 diffusers installed in each basin. Figure 1 is a plan view drawing indicating the general layout of the basin and the diffuser layout. This figure shows that grids 4, 5, and 6 were turned of and not operating.

Test Parameters

The full-scale tests were conducted to measure oxygen transfer efficiency, alpha factor, and oxygen transfer rates under actual operating conditions.

Manufacturers of aeration systems typically quote performance based on clean water oxygen transfer test results. To compare data, the tests should best be conducted in large-scale tanks in accordance with standard procedures (ASCE Clean Water Test Standard, 1992). For a given basin geometry, diffuser type and layout, aeration equipment manufacturers can provide acceptable estimates of clean water standard oxygen transfer efficiency (SOTE) and equilibrium dissolved oxygen (DO) concentration at standard conditions as time approaches infinity ($C^*_{\infty 20}$). Standard conditions of temperature and pressure are 20°C and 1.0 atmosphere of pressure (29.92 in Hg or 760 mm Hg), respectively.

To estimate the oxygen transfer efficiency in the process water under actual operating conditions, the following equation is used (ASCE, 1992):

$$OTE_F = \alpha(SOTE)(\Theta^{T-20})(\Upsilon\Omega\beta C^*_{\infty 20} - C) / C^*_{\infty 20}$$

Where:

OTE_F = Process water oxygen transfer efficiency, mass fraction of oxygen transferred per unit of oxygen supplied, decimal fraction.

α = Alpha, the ratio of mass transfer coefficients, process water to clean water, decimal fraction.

Θ = Mass transfer coefficient temperature correction factor, generally taken to be 1.024, dimensionless.

T = Temperature of the process water, °C.

Y = Temperature correction factor (C^*_{bST}/C^*_{b20}) of the steady state DO saturation concentration, dimensionless.

Where:

C^*_{bST} = Tabulated DO surface saturation value at temperature T, taken from Standard Methods, mg/l.

C^*_{b20} = Tabulated DO surface saturation value at 20°C taken from Standard Methods, mg/l.

β = Ratio of steady state DO saturation concentration in process and clean water, dimensionless (basis total dissolved solids).

Ω = Pressure correction factor (P_b/P_s) for the steady state DO saturation concentration, dimensionless.

Where:

P_b = Local barometric pressure for the site, in Hg.

P_s = Standard barometric pressure, 29.92 in Hg (101.3 k Pa).

C = Dissolved oxygen concentration averaged over process water volume being evaluated, mg/l.

All of the factors involved in the conversion from clean water to process water, except alpha, and the fouling factor can be reasonably estimated from published or assumed values. The field studies were conducted at the Santa Fe WWTP in an effort to provide site-specific estimates of OTE and alpha(F), as well as OUR, for use in assessing the aeration performance of the aeration system under process water conditions.

RESULTS

General

The results of the full-scale offgas evaluation is summarized as Tables 1, 2, and 3. The field data sheets from which the summary tables were developed are contained in Appendix II. As mentioned earlier, Figure 1 is a plan view of one of the aeration basins and shows layouts of the fine bubble grid diffusers. Figure 2 shows the locations of the offgas collection hood sampling positions used in this evaluation. The offgas collection hood used was two feet wide by eight feet in length, thus having a total capture area of 16 square feet.

Table 1 summarizes the offgas results obtained on November 14, 2017. The first several columns of this table, including time, sampling station designation, mixed liquor temperature, gas-phase sensor output (Mog and Mr), DO concentrations (C), and offgas flow rate are obtained from the field data sheets. Knowing the dissolved oxygen (DO) saturation value from clean water testing of the equipment in question (C^*_{20}), the field saturation value (C^*_f) can be estimated by applying corrections for local atmospheric pressure, mixed liquor temperature and total dissolved solids, which are reflected in the beta factor. The column headed C^*_f-DO (Column 7) represents the DO driving force (saturation minus the DO concentration) at that sampling station.

Columns 8 and 9 are the float heights (in millimeters) for the two rotameters measuring offgas flow rate. Column 10 is the collection area of the offgas collection hood. Column 11 lists the measured offgas flux for the sample location in question. The offgas flux is determined by dividing the offgas flow rate by the offgas collection hood area (Column 10).

Column 12 is the calculated airflow per diffuser and is determined by dividing the offgas flux (scfm per square foot) by the diffuser density (the number of diffusers per square foot) beneath the hood.

Column 13 lists the total airflow to each of the test zones in the basin in question. In each zone the average offgas flux times the surface area of the zone in question yields an estimate of the total airflow to the zone in question. The total airflow for each cell and the basin overall is obtained by summing the estimated airflow in each zone.

The gas-phase oxygen transfer efficiency under process conditions is given by the columns headed OTE_F (Column 14), OTE_{SP20} (Column 15) and SOTEpw (Column 16). The field oxygen transfer efficiency (OTE_F) is the actual gas-phase transfer, as a decimal, under existing field conditions of DO concentration, barometric pressure, total dissolved solids, mixed liquor temperature and prevailing operating mode. OTE_{SP20} is the transfer efficiency per each mg/l of driving force, corrected to a 20°C mixed liquor temperature. SOTEpw is the oxygen transfer efficiency in process water corrected to standard conditions of one atmosphere of pressure, zero DO concentration and 20°C.

Column 17, SOTEcw, is an estimate of the clean water oxygen transfer efficiency based on the Sanitaire clean water test database.

Column 18 is the ratio of SOTEpw to SOTEcw. When diffusers are new this ratio is known as alpha. In this case, the aeration system had been in operation for many years so the ratio of SOTEpw to SOTEcw is known as alpha(F), where F is a fouling factor. The fouling factor accounts for changes in diffuser oxygen transfer efficiency due to fouling and changes in the membrane properties. When the diffusers are new the fouling factor is unity (1.00). Column 19 is the computed oxygen uptake rate (OUR) for each hood location based on a gas-phase mass balance. The mass balance calculation procedure used to calculate the OUR is presented in Appendix III.

Listed at the bottom of each table are the overall average values of DO concentration, offgas flux, diffuser air flow, alpha and oxygen uptake rate along with the total air flow and the mean weighted average OTE$_F$ and SOTEpw values for the entire basin.

Test Results

The first set of offgas data was obtained on Tuesday, November 14, 2017. Table 1 summaries of the offgas results for the first day of testing. Looking at the first line of data, it is seen that the first sample location (1.1N – Channel #1, hood location #1, in the North (N) Basin) was tested at 1026 hours. The mixed liquor temperature was 20.4

degrees Celsius and the dissolved oxygen concentration was 0.55 mg/l. The offgas flux for this location was observed to be 0.215 scfm per square foot of surface area, which is equivalent to an airflow rate of approximately 0.68 scfm per diffuser. The field oxygen transfer efficiency for sample location 1.1N is 21.74% when corrected to standard conditions is 29.51%. The alpha(F) value for this location is computed to be 0.66 and the oxygen uptake rate (OUR), based on the gas-phase mass balance, is 46.8 mg/l/hr. The results for each of the remaining test locations are presented in a similar matter.

At the bottom of each section of data is listed the average DO concentration, offgas flux, airflow per diffuser average transfer efficiency, alpha(F), and average oxygen uptake rate. Also presented is the total airflow to grid being tested. In Table 1 the first section of data only contains three hood locations in the first grid of Channel #1. These data points were gathered between 1025 hours and 1049 hours. Shortly after 1049 hours the airflow rate to the system was approximately doubled. As a result, the testing of the first grid in Channel #1 was restarted.

The second set of data in Table 1 is from the first grid in Channel #1 of the North Aeration Basin, while the third dataset in from the first grid in Channel #1 of the South Basin. It should be pointed out that the first grid in the North Aeration Basin had new membrane disc diffusers installed when the basin was recently drained and repaired, while the first grid in the South Aeration Basin had the original diffusers still installed in the grid. The summary data at the bottom of sections two and three (in red ink) indicate that the membranes in the first grid of the North Basin are more efficient than those installed in the South Basin. The overall average SOTEpw for the North Basin was observed to be 25.8% compared to 23.6% for the South Basin, even though the North Basin grid was operating at about 1.4 scfm per diffuser, while the South Basin was running at about 1.07 scfm per diffuser. Generally, the higher the airflow per diffuser, the lower the oxygen transfer efficiency. The data suggest that the North Basin grid is operating about 9.5% more efficient than the South Basin grid. The computed value of alpha for the new membranes (first grid in the North Basin) is 0.68, while the alpha(F) value for the first grid in the South Basin is 0.59. These are some of the highest alpha values measured by this writer, who has been conducting offgas analyses for over thirty-five years.

It was observed that there was a significant horizontal velocity in the channels due to the Banana Blade mixers installed in each basin. The writer was involved in a study in France that documented the improvement in fine bubble grid efficiency as a function of horizontal velocity across the fixed grids. This paper generated as a result of this study is contained in Appendix IV of this report. The results of this study in clean water demonstrate an oxygen transfer efficiency improvement at a horizontal velocity of about 1.2 feet per second on the order of 40%. In process water the improvement was approximately 20%. At lower velocities the improvement was less, but significant. Observations of the bubble patterns indicate that the horizontal velocity was on the order of about 1.0 to 1.5 feet per second. A differential velocity across the air discharge surfaces of the diffusers results in the bubbles being released from the diffusers at a smaller diameter due to the shear forces of the water flowing across the diffuser. This results in smaller bubbles with more interfacial area and lower rise rates, as smaller bubbles are less buoyant and therefore rise less quickly than do larger bubbles.

Table 2 is from Wednesday November 15th. On this day grid #3 in the North Basin was tested, and gird #1 of the North Basin was re-tested to see how consistent the offgas results were from one day to the next. The results of the re-test of grid #1 show nearly the same results as the previous day. The SOTEpw was observed to be 25.4% at an airflow of 960 scfm, compared to an SOTEpw of 25.8% at an airflow of 893 scfm. The alpha for grid #1 on day two was 0.64, compared to 0.68 on day one.

Grid #3 in the North Basin was observed to have an overall average SOTEpw of 22.8% at an airflow of 799 scfm. This results in a computed alpha(F) value of 0.60. Grid #3 also had the original membrane disc diffusers installed on the grid in question.

On the third day of testing (November 16th) grid #2 in the North Basin was tested. The overall average SOTEpw was observed to be 27.0% at an airflow of 900 scfm. This results in an alpha value of 0.71. This grid also has new membrane diffusers that were installed when the basin was drained to make repairs.

Table 4 is a summary of the offgas results comparing the performance of the new membrane disc diffusers against those grids with the original membranes still installed in them. The summary shows an average SOTEpw of 26.07% for the new membranes and 23.20% for the old membranes.

The writer believes the presence of significant horizontal liquid velocity across the fixed grids of fine bubble diffusers has resulted in enhanced oxygen transfer, when compared with fixed grids without velocity. This is the most likely reason for the high alpha values observed in the Santa Fe aeration basins. Field oxygen transfer efficiencies (corrected to standard conditions) under process water conditions in the range of 22% to 27% at a diffuser submergence of 16.6 feet are typically unheard of. These are transfer efficiencies in the range of 1.3 to 1.6% per foot of submergence, under process water conditions.

The writer has also observed that in looped reactors (oxidation ditches) that alpha values are nearly constant throughout the basin, as the loop time compared to the hydraulic retention time, is so small that the basin approaches that of a complete mix reactor.

The results are in general agreement with the laboratory diffuser tests, which indicated the used membranes, when tested head-to-head against new membranes, showed a loss in efficiency of about 6.2%. The existing membrane diffusers are approaching seventeen years old. If significant aeration system revisions are to occur in the future the best course of action would be to replace all of the diffusers with new membranes.

TABLE 1

SUMMARY DATA SHEET - FULL SCALE OFFGAS TESTS

DATE: November 14, 2017

SITE: SANTA FE, NM
SYSTEM: SANITAIRE MEMBRANES
SUBMERGENCE: 15.60 FT.
SWD: 16.60 FT.
DIFFUSERS/BASIN:

MLSS: 3,300 MG/L
MLVSS: MG/L
TDS: 1,000 MG/L (ASSUMED)
SRT: 12 DAYS
TOTAL AIR RATE: SCFM

LOCAL BAROMETER: 23.92 in. Hg.
BETA: 0.98
C^*_{20}: 10.70 MG/L
C^*_F: 8.20 MG/L

H_R: 0.00
H_{OG}: 0.00 LB H_2O/LB
B.D. AIR
CO_2: 0.00

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
TIME	STATION	ML TEMP °C	M(og) (mv)	M(r) (mv)	C (mg/l)	C^*_F-C (mg/l)	Rmm 1	Rmm 2	HOOD AREA (sq ft)	OFFGAS FLUX (scfm/sq ft)	SCFM PER DIFFUSER	TOTAL AIR FLOW (cfm)	OTE_F (decimal)	OTE_{SP20} (decimal)	SOTEpw	SOTEcw	ALPHA(F)	OUR (mg/l/hr)
NORTH AERATION BASIN - GRID 1																		
1025	1.1N	20.4	826	1007	0.55	7.65	133	0	16	0.215	0.68	145	0.2174	0.02815	0.2951	0.370	0.80	46.8
1037	1.2N	20.4	809	1009	0.55	7.65	98	0	16	0.163	0.52	110	0.2381	0.03083	0.3233	0.370	0.87	38.8
1049	1.3N	20.4	796	1011	0.60	7.60	134	0	16	0.217	0.69	147	0.2547	0.03320	0.3481	0.370	0.94	55.3
					$\bar{X}$ =					$\bar{X}$ =	$\bar{X}$ =	Σ =	MWA =		MWA =	$\bar{X}$ =	$\bar{X}$ =	$\bar{X}$ =
					0.57					0.198	0.63	402	0.2367		0.3222	0.370	0.87	47.0
NORTH AERATION BASIN - GRID 1																		
1334	1.1N	20.4	871	1000	1.20	7.00	0	58	16	0.436	1.38	147	0.1577	0.02232	0.2341	0.343	0.68	68.8
1309	1.2N	20.4	848	1002	1.30	6.90	230	0	16	0.361	1.15	122	0.1868	0.02682	0.2812	0.343	0.82	67.5
1252	1.3N	20.4	841	1003	1.60	6.60	0	65	16	0.474	1.50	160	0.1955	0.02934	0.3076	0.343	0.90	92.7
1211	1.4N	20.4	877	1002	1.25	6.95	0	80	16	0.556	1.77	188	0.1525	0.02173	0.2278	0.343	0.66	84.8
1225	1.5N	20.4	882	1003	1.65	6.55	0	60	16	0.447	1.42	151	0.1479	0.02237	0.2346	0.343	0.68	66.2
1239	1.6N	20.4	862	1003	1.70	6.50	235	0	16	0.368	1.17	124	0.1717	0.02617	0.2744	0.343	0.80	63.2
					$\bar{X}$ =					$\bar{X}$ =	$\bar{X}$ =	Σ =	MWA =		MWA =	$\bar{X}$ =	$\bar{X}$ =	$\bar{X}$ =
					1.45					0.440	1.40	893	0.1676		0.2581	0.343	0.76	73.9
SOUTH AERATION BASIN -GRID 1																		
1443	1.1S	20.5	871	1001	1.00	7.20	230	0	16	0.361	1.15	122	0.1589	0.02181	0.2287	0.350	0.65	57.4
1456	1.2S	20.5	853	1001	1.00	7.20	200	0	16	0.316	1.00	107	0.1800	0.02471	0.2591	0.350	0.74	56.9
1508	1.3S	20.5	853	999	1.00	7.20	220	0	16	0.347	1.10	117	0.1777	0.02440	0.2558	0.350	0.73	61.7
1520	1.4S	20.5	878	1000	1.00	7.20	235	0	16	0.368	1.17	124	0.1498	0.02056	0.2156	0.350	0.62	55.2
1534	1.5S	20.5	869	1002	1.00	7.20	200	0	16	0.316	1.00	107	0.1623	0.02227	0.2335	0.350	0.67	51.3
1545	1.6S	20.5	875	1002	1.00	7.20	195	0	16	0.308	0.98	104	0.1555	0.02134	0.2238	0.350	0.64	47.9
					$\bar{X}$ =					$\bar{X}$ =	$\bar{X}$ =	Σ =	MWA =		MWA =	$\bar{X}$ =	$\bar{X}$ =	$\bar{X}$ =
					1.00					0.336	1.07	682	0.1638		0.2357	0.350	0.67	55.1

TABLE 2

SUMMARY DATA SHEET - FULL SCALE OFFGAS TESTS

DATE: November 15, 2017

SITE: SANTA FE, NM
SYSTEM: SANITAIRE MEMBRANES
SUBMERGENCE: 15.60 FT.
SWD: 16.60 FT.
DIFFUSERS/BASIN:

MLSS: 3,300 MG/L
MLVSS: MG/L
TDS: 1,000 MG/L (ASSUMED)
SRT: 12 DAYS
TOTAL AIR RATE: SCFM

LOCAL BAROMETER: 23.99 in. Hg.
BETA: 0.98
C^*_{20}: 10.70 MG/L
C^*_F: 8.25 MG/L

H_R: 0.00
H_{OG}: 0.00 LB H_2O/LB
B.D. AIR
CO_2: 0.00

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
TIME	STATION	ML TEMP °C	M(og) (mv)	M(r) (mv)	C (mg/l)	C^*_F-C (mg/l)	Rmm 1	Rmm 2	HOOD AREA (sq ft)	OFFGAS FLUX (scfm/sq ft)	SCFM PER DIFFUSER	TOTAL AIR FLOW (cfm)	OTE_F (decimal)	OTE_{SP20} (decimal)	SOTEpw	SOTEcw	ALPHA(F)	OUR (mg/l/hr)
NORTH AERATION BASIN - GRID 3																		
1033	3.1N	20.1	902	1005	2.95	5.30	0	55	16	0.420	1.15	122	0.1264	0.02380	0.2495	0.347	0.72	53.1
1048	3.2N	20.1	909	1006	2.75	5.50	0	50	16	0.394	1.08	114	0.1189	0.02156	0.2261	0.347	0.65	46.9
1059	3.3N	20.1	911	1007	2.75	5.50	0	60	16	0.447	1.22	130	0.1177	0.02136	0.2240	0.347	0.65	52.7
1118	3.4N	20.1	908	1005	2.45	5.80	0	75	16	0.529	1.45	154	0.1189	0.02045	0.2144	0.347	0.62	62.9
1144	3.5N	20.1	905	1005	2.40	5.85	0	74	16	0.524	1.44	152	0.1223	0.02085	0.2186	0.347	0.63	64.1
1155	3.6N	20.1	900	1007	2.60	5.65	0	58	16	0.436	1.19	127	0.1309	0.02312	0.2424	0.347	0.70	57.1
					$\bar{X}$ =					$\bar{X}$ =	$\bar{X}$ =	Σ =	MWA =		MWA =	$\bar{X}$ =	$\bar{X}$ =	$\bar{X}$ =
					2.65					0.458	1.26	799	0.1224		0.2282	0.347	0.66	56.1
NORTH AERATION BASIN - GRID 1																		
1517	1.1N	20.2	873	1006	1.40	6.85	0	65	16	0.474	1.50	160	0.1615	0.02347	0.2461	0.340	0.72	76.6
1507	1.2N	20.2	852	1007	1.45	6.80	0	58	16	0.436	1.38	147	0.1868	0.02734	0.2867	0.340	0.84	81.5
1440	1.3N	20.2	844	1000	1.60	6.65	0	67	16	0.485	1.54	164	0.1894	0.02835	0.2973	0.340	0.87	91.9
1429	1.4N	20.2	878	1001	1.60	6.65	0	75	16	0.529	1.68	179	0.1502	0.02248	0.2357	0.340	0.69	79.5
,1401	1.5N	20.2	887	1002	1.75	6.50	0	62	16	0.458	1.45	155	0.1408	0.02155	0.2260	0.340	0.66	64.5
1416	1.6N	20.2	879	1001	1.60	6.65	0	62	16	0.458	1.45	155	0.1491	0.02231	0.2339	0.340	0.69	68.3
					$\bar{X}$ =					$\bar{X}$ =	$\bar{X}$ =	Σ =	MWA =		MWA =	$\bar{X}$ =	$\bar{X}$ =	$\bar{X}$ =
					1.57					0.473	1.50	960	0.1627		0.2539	0.340	0.75	77.1

TABLE 3

SUMMARY DATA SHEET - FULL SCALE OFFGAS TESTS

DATE: November 16, 2017

SITE: SANTA FE, NM
SYSTEM: SANITAIRE MEMBRANES
SUBMERGENCE: 15.60 FT.
SWD: 16.60 FT.
DIFFUSERS/BASIN:

MLSS: 3,300 MG/L
MLVSS: MG/L
TDS: 1,000 MG/L (ASSUMED)
SRT: 12 DAYS
TOTAL AIR RATE: SCFM

LOCAL BAROMETER: 23.94 in. Hg.
BETA: 0.98
C^*_{20}: 10.70 MG/L
C^*_F: 8.30 MG/L

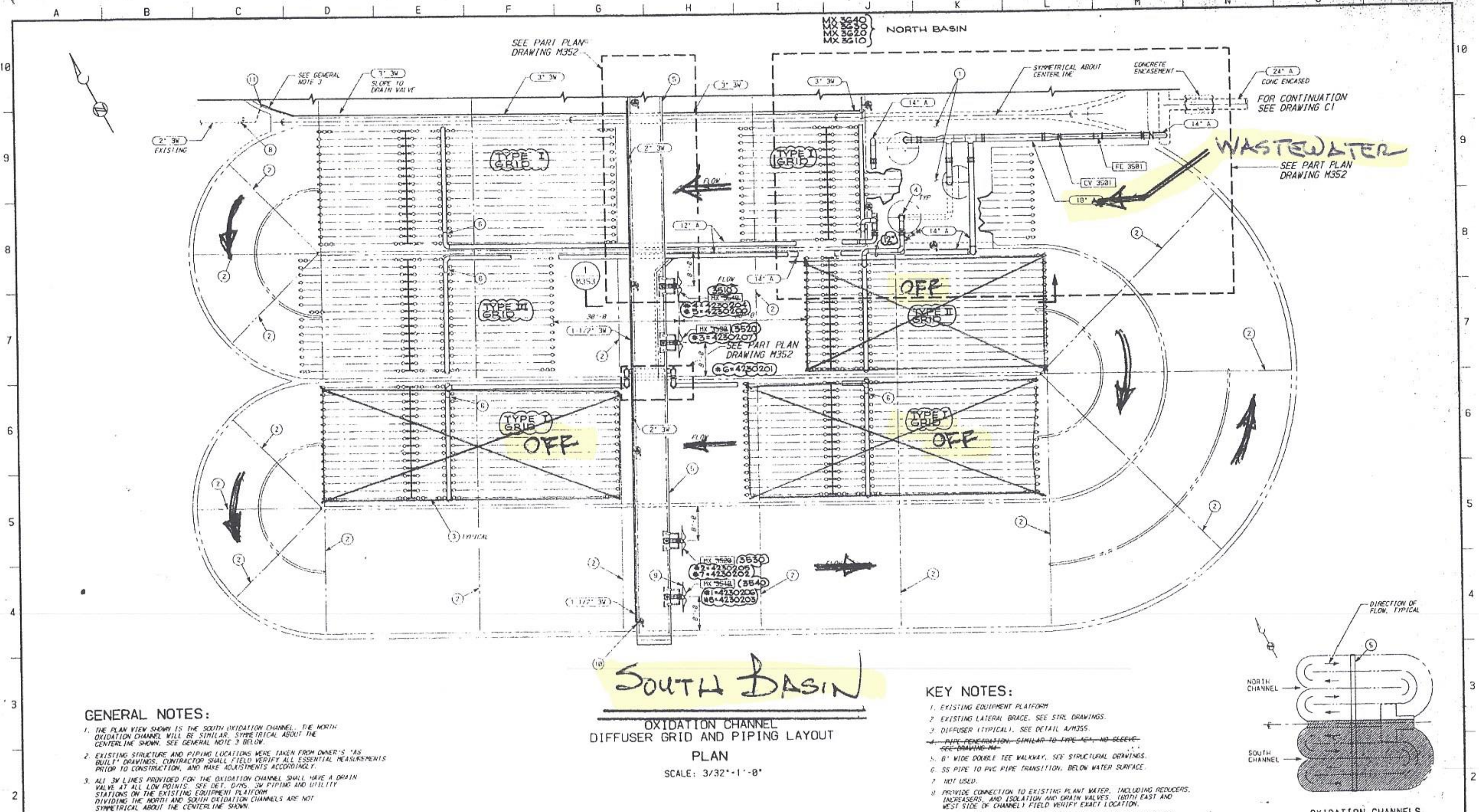
H_R: 0.00
H_{OG}: 0.00 LB H_2O/LB B.D. AIR
CO_2: 0.00

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
TIME	STATION	ML TEMP °C	M(og) (mv)	M(r) (mv)	C (mg/l)	C^*_F-C (mg/l)	Rmm 1	Rmm 2	HOOD AREA (sq ft)	OFFGAS FLUX (scfm/sq ft)	SCFM PER DIFFUSER	TOTAL AIR FLOW (cfm)	OTE_F (decimal)	OTE_{SP20} (decimal)	SOTEpw	SOTEcw	ALPHA(F)	OUR (mg/l/hr)
NORTH AERATION BASIN - GRID 2																		
1042	2.1N	19.9	886	1003	2.55	5.75	0	58	16	0.436	1.19	127	0.1430	0.02493	0.2614	0.343	0.76	62.4
1103	2.2N	19.9	893	1008	2.50	5.80	0	72	16	0.513	1.41	149	0.1400	0.02420	0.2537	0.343	0.74	71.9
1117	2.3N	19.9	882	1007	2.45	5.85	0	78	16	0.546	1.50	159	0.1521	0.02606	0.2732	0.343	0.80	83.1
1133	2.4N	19.9	882	1005	2.40	5.90	0	76	16	0.534	1.46	155	0.1498	0.02545	0.2669	0.343	0.78	80.1
1154	2.5N	19.9	875	1006	2.25	6.05	0	75	16	0.529	1.45	154	0.1593	0.02639	0.2767	0.343	0.81	84.3
1208	2.6N	20.0	870	1005	2.30	6.00	0	77	16	0.540	1.48	157	0.1638	0.02730	0.2862	0.343	0.83	88.5
					$\bar{X}$ = 2.41					$\bar{X}$ = 0.516	$\bar{X}$ = 1.41	Σ = 900	MWA = 0.1517		MWA = 0.2701	$\bar{X}$ = 0.343	$\bar{X}$ = 0.79	$\bar{X}$ = 78.4

TABLE 4 - OVERALL SUMMARY SANTA FE WWTP

Date	Basin	Grid	Diffuser Age	Airflow to Grid (scfm)	SOTEpw (%)
14-Nov	North	1	New	402	32.22
14-Nov	North	1	New	893	25.81
14-Nov	South	1	Old	682	23.57
15-Nov	North	3	Old	799	22.82
15-Nov	North	1	New	960	25.39
16-Nov	North	2	New	900	27.01
	Average		New		26.07
	Average		Old		23.20
	Ratio: New/Old				**1.124**

FIGURE 1 - SANTA FE
PLAN VIEW & DIFFUSER LAYOUT



OXIDATION CHANNEL
DIFFUSER GRID AND PIPING LAYOUT
PLAN
SCALE: 3/32"=1'-0"

OXIDATION CHANNELS
KEY PLAN
NO SCALE

GENERAL NOTES:

1. THE PLAN VIEW SHOWN IS THE SOUTH OXIDATION CHANNEL. THE NORTH OXIDATION CHANNEL WILL BE SIMILAR, SYMMETRICAL ABOUT THE CENTERLINE SHOWN. SEE GENERAL NOTE 3 BELOW.
2. EXISTING STRUCTURE AND PIPING LOCATIONS WERE TAKEN FROM OWNER'S "AS BUILT" DRAWINGS. CONTRACTOR SHALL FIELD VERIFY ALL ESSENTIAL MEASUREMENTS PRIOR TO CONSTRUCTION, AND MAKE ADJUSTMENTS ACCORDINGLY.
3. ALL 3W LINES PROVIDED FOR THE OXIDATION CHANNEL SHALL HAVE A DRAIN VALVE AT ALL LOW POINTS. SEE DET. D/M5. 3W PIPING AND UTILITY STATIONS ON THE EXISTING EQUIPMENT PLATFORM DIVIDING THE NORTH AND SOUTH OXIDATION CHANNELS ARE NOT SYMMETRICAL ABOUT THE CENTERLINE SHOWN.

KEY NOTES:

1. EXISTING EQUIPMENT PLATFORM
2. EXISTING LATERAL BRACE. SEE STRL DRAWINGS.
3. DIFFUSER (TYPICAL). SEE DETAIL A/M355.
4. ~~PIPE PENETRATION. SIMILAR TO TYPE "E", NO SLEEVE. SEE DRAWING M4~~
5. 8' WIDE DOUBLE TEE WALKWAY. SEE STRUCTURAL DRAWINGS.
6. SS PIPE TO PVC PIPE TRANSITION, BELOW WATER SURFACE.
7. NOT USED.
8. PROVIDE CONNECTION TO EXISTING PLANT WATER, INCLUDING REDUCERS, INCREASERS, AND ISOLATION AND DRAIN VALVES. (BOTH EAST AND WEST SIDE OF CHANNEL) FIELD VERIFY EXACT LOCATION.
9. MIXERS WITH CABLE AND GUIDE RAILS. TOTAL OF 8 ARE REQUIRED (4 PER CHANNEL). SEE SPECIFICATIONS
10. UTILITY STATION. SEE DRAWING M5.
11. CORE DRILL AND GROUT FLUSH TO WALL AFTER MODULAR MECHANICAL SEAL IS INSTALLED. SEE PIPE PENETRATION TYPE "D" DRAWING M4.

RECORD DRAWING
DATE 8-1-94

15-486 8-5-91

BROWN AND CALDWELL
Consultants
Phoenix, Arizona

SUBMITTED: DATE: 8-22-91
Project Manager
APPROVED: DATE: 8-22-91
Brown and Caldwell
APPROVED: DATE:

LINE IS 2 INCHES AT FULL SCALE
(IF NOT 2"-SCALE ACCORDINGLY)

FILE 4132
DRAWN DRH
DESIGNED GLG & DHB
CHECKED PT & GLG
CHECKED RNW

SAMUEL A. EDMONDSON

ZONE	REV.	REVISIONS DESCRIPTION	BY	DATE	APP.

CITY OF SANTA FE
AIRPORT ROAD WASTEWATER TREATMENT PLANT

MODIFICATION / REPLACEMENT PROJECT

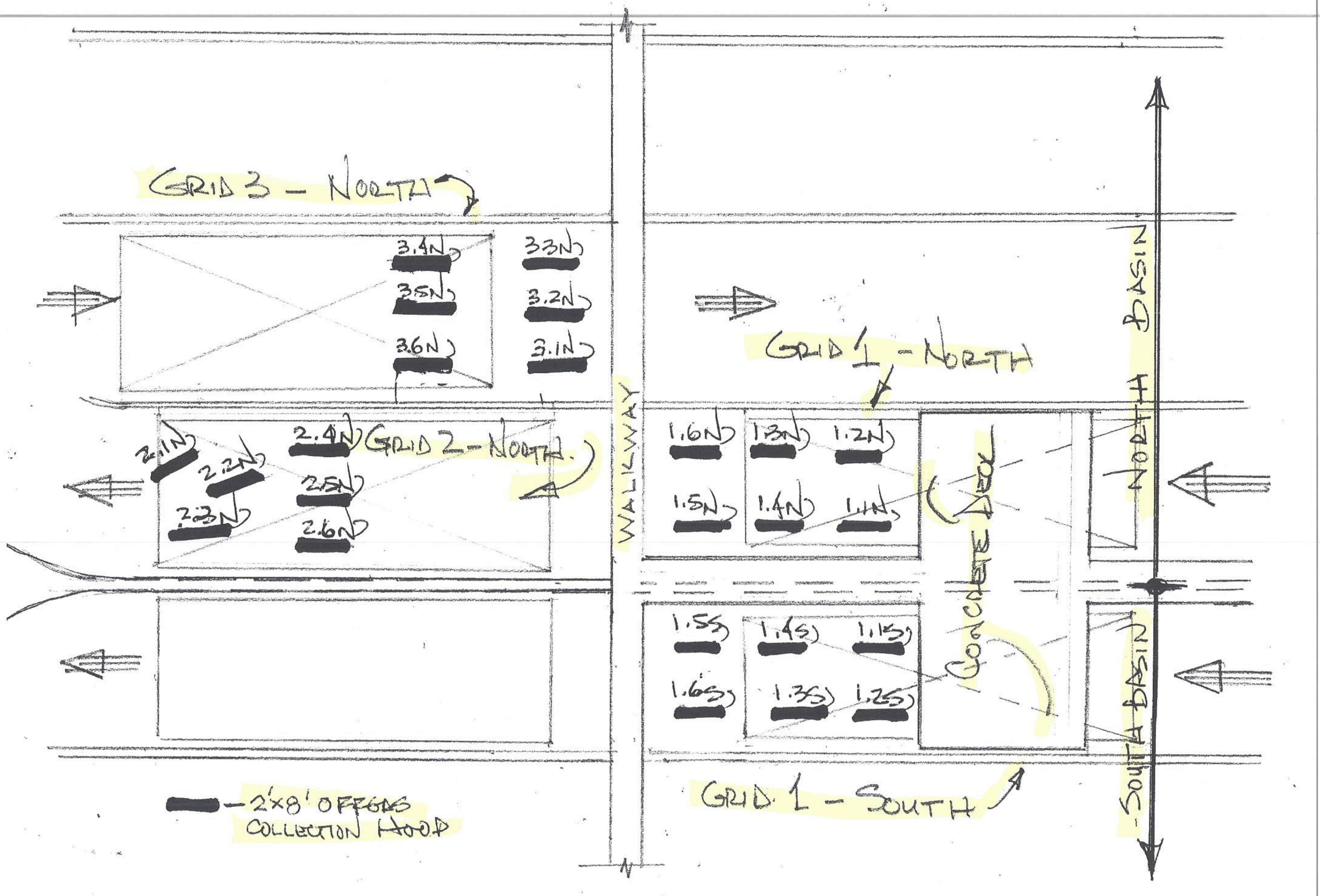
OXIDATION CHANNELS

DIFFUSER GRID AND PIPING LAYOUT

PLAN

DRAWING NUMBER M351
SHEET NUMBER 26

FIGURE 2 - OFFGAS SAMPLING PLAN



SYMBOLS AND NOMENCLATURE

DO = Dissolved Oxygen

C = DO concentration, mg/l

C^*_F = DO saturation value applicable for equipment in use and existing conditions, mg/l

C^*_F-C = DO driving force or effective DO deficit, mg/l

$C^*_{\infty 20}$ = DO saturation value in clean water for system tested at standard conditions as time approaches infinity

C^*_{ST} = Tabulated DO surface saturation value at temperature T, taken from Standard Methods, mg/l

C^*_{20} = Tabulated DO surface saturation value at 20 C taken from standard Methods, mg/l

EPDM = E-Ethylene, P-propylene, D-Diene comoners, M-polyMethylene backbone; synthetic rubber

AOTR = Actual Oxygen Transfer Rate in process water at existing conditions

fpm = Feet per minute

gpm = Gallons per minute

Hg = Mercury

Hood Area = Offgas Hood Collection Area, square feet

K_La = Apparent volumetric mass transfer coefficient of oxygen in clean water and/or process water

MLSS = Mixed Liquor Suspended Solids, mg/l

MLT = Mixed Liquor Temperature, °C

M(og) = Gas phase oxygen sensor output in millivolts for offgas stream

M(r) = Gas phase oxygen sensor output in millivolts for reference stream

MWA = Mean weighted average

Offgas Flux Rate = Rate of offgas evolution per square foot of collection area as measured by offgas rotameters, scfm/sq ft

OTE_F = Process water oxygen transfer efficiency, mass fraction of oxygen transferred per unit of oxygen supplied, decimal fraction

OTE_{SP20} = Oxygen Transfer efficiency per each mg/l of driving force under Standard Conditions

OUR = Oxygen Uptake Rate by mixed liquor, mg/l/hr

P_b = Local barometric pressure for the site, in Hg

P_s = Standard barometric pressure, 29.92 in Hg

Rmm 1 & Rmm 2 = Float Height in millimeters, from scale, for rotameters 1 and 2 in offgas analyzer scfm = Air flow rate, Standard cubic feet per minute

SOTE = Standard Oxygen Transfer efficiency at 20°C and zero DO

SOTEcw = Standard Oxygen Transfer efficiency at Standard Conditions and zero DO in clean water

SOTEpw = Standard Oxygen Transfer efficiency at Standard Conditions and zero DO in process water

SOTR = Standard Oxygen Transfer Rate in clean water at 20°C and zero DO

SRT = Solids Retention Time or Sludge Age, days

Standard Conditions= Barometric Pressure of 29.92 in Hg and 20°C

Submergence = Height of liquid above diffusers, feet

T = Temperature, °C

TDS = Total Dissolved Solids in mixed liquor, mg/l

wg = Water gauge

α = Alpha, the ratio of mass transfer coefficients (KLa), or standard oxygen transfer efficiency, process water to clean water, decimal fraction

β = Beta, the ratio of steady state DO saturation concentration in process and clean water, dimensionless (basis total dissolved solids)

Ω = Pressure correction factor (P_b/P_s) for the steady state DO saturation concentration, dimensionless

Θ = Mass transfer coefficient temperature correction factor, generally taken to be 1.024, dimensionless

Υ = Temperature correction factor (C^*_{ST}/C^*_{20}) for the steady state DO saturation concentration, dimensionless

APPENDIX I

1983 OFFGAS PAPER
BY
REDMON, ET. AL.

Oxygen transfer efficiency measurements in mixed liquor using off-gas techniques

David Redmon, William C. Boyle, Lloyd Ewing

It has been reported that approximately 1.75 million hp of aeration equipment is currently in place on the North American continent, in both municipal and industrial treatment facilities.[1] These facilities are being operated at a power cost exceeding $0.6 billion per year. Evidence suggests that the overall oxygen transfer efficiency for this equipment is low and the cost of power could be reduced by as much as 50% by improved design and operation.[1] Although there are many reasons for imperfect application of oxygen transfer devices in wastewater, one basic cause has been the unavailability of, or failure to use, optimal methods for the measurement of oxygen transfer.

The off-gas measurement technique may be a tool for obtaining more useful design data for aeration systems.

Consensus procedures for testing oxygen transfer devices in clean water are being developed.[2–4] Adequate test procedures for the assessment of aeration equipment under actual process conditions are less developed at this time. Several methods have been employed over the years to evaluate oxygen transfer in suspended growth systems. In a detailed review of these dirty water test procedures, the American Society of Civil Engineers (ASCE) Committee on Oxygen Transfer Standards outlined the assumptions required for these methods and the limitations for each procedure.[5,6] Table 1 briefly summarizes some of these constraints.

Most field test procedures may be classified according to two criteria: the presence or absence of wastewater flow (continuous versus batch tests); the rate of change of dissolved oxygen (DO) in the test volume (steady state versus unsteady state tests). In general, steady state tests are simpler to perform than unsteady state tests, but they do not provide an estimate of the effective DO saturation value in submerged aeration systems. Both procedures require an accurate determination of oxygen uptake rate (OUR) and test volume dissolved oxygen (DO) concentrations that are constant and greater than zero. In an effort to improve the accuracy of the OUR measurement and to ensure steady state conditions within the test cell with respect to DO, flow, and OUR, batch endogenous tests may be performed. These tests, however, often do not realistically project operating conditions.

Several other test procedures for field oxygen transfer are proposed to overcome some of these limitations. Tracer test methods have been used in both clean and dirty water oxygen transfer tests.[6–8] Although the procedure is very extensive and costly, the results obtained with this method are very precise and presumably accurate. The method does not require complete mixing in the test volume or aeration tank DO values greater than zero. In submerged aeration systems, however, this method suffers the same disadvantage as other steady state tests, which is the inability to estimate the effective DO saturation value.

The performance of a mass balance on oxygen in the gas phase under process conditions has been referred to as the off-gas method. This procedure offers a number of advantages over more traditional techniques currently used for this purpose. This paper describes this method, discusses its limitations, and provides data on recently conducted field studies.

HISTORICAL PERSPECTIVE

The use of off-gas measurements in biological reactors is not a new concept. Initially, off-gas analyses were performed to estimate the respiratory demand of biological cultures. As early as 1939, Sawyer and Nichols[9] described a volumetric method used in a closed system to determine the *in situ* oxygen uptake of activated sludge in the laboratory. Hoover *et al.*[10] in 1954 described a method of aeration control in a fermentation system using a paramagnetic oxygen analyzer developed earlier by Pauling *et al.*[11] Pirt and Callow[12] also used *in situ* respiratory demand measurements in studies on the continuous production of butanediol. Both oxygen and CO_2

OFFGAS PAPER

ERRATA: Page 1339

- In Equation (1), substitute $V\rho'\frac{dC}{dt}$ for $V\rho\frac{d\bar{Y}}{dt}$

- Substitute " = " for " − " between Y_{og} and K_La

- Add Definition of ρ' = density of liquid
  after ρ = density of oxygen

Table 1—Assumptions and limitations for dirty water oxygen transfer testing.

Major assumptions	Limitations
Test cell DO constant (spatial/temporal)	Estimate of OUR
Influent flow to cell constant	Estimate of effective DO saturation value
Influent DO to cell constant	DO must be greater than zero
Test cell OUR constant	Test performed under true process conditions
Effective $K_L{}^a$ in cell constant	

were monitored by Orsat analysis. Some of the first field studies that were reported on the use of off-gas techniques to evaluate aeration devices under process conditions were outlined by Downing[13] and Downing *et al.*[14] In this method, oxygen was captured with a light hood covering all or a portion of the aeration tank [capture areas varied from 2.3 to 13.8 m^2 (25 to 149 sq ft)] and the captured oxygen was determined with a paramagnetic oxygen analyzer. These authors calculated the effective overall transfer rate (αK_La), therefore, both captured gas flow rate and equilibrium saturation DO had to be estimated. Gas flow rate was measured by CO_2 injection and material balance calculation. The DO saturation value for these diffused air systems was calculated by a mid-depth correction. Barker *et al.*[15] described an off-gas method used to estimate the oxygen transfer efficiency of a turbine aerator under process conditions. An inverted 0.2-m^3 (55-gal) drum was used to capture the off-gas. Oxygen was determined by a paramagnetic oxygen analyzer and transfer was expressed as percent oxygen transfer efficiency (OTE). Off gas methods were also described by Conway and Kumke[16] for analyzing a sparged turbine in clean water. Similar to the method of Barker *et al.*, off-gas was captured with a 0.2-m^3 (55-gal) container. Gas analyses were performed by both a mass spectrometer and a direct reading oxygen analyzer. Results were reported as percent OTE. Leary *et al.*[17,18] conducted extensive off-gas analyses of the Milwaukee Jones Island aeration tanks from 1967 to 1968. A 46-cm (18-in.) diameter hood was used to collect off-gas, and analyses were performed using both Orsat and gas chromatographic techniques. Data was reported as both percent OTE and αK_La. More recently, off-gas techniques have again been proposed as a procedure for aeration control in field installations[19,20] completing the cycle initiated by Hoover *et al.* in 1954.

THEORETICAL DEVELOPMENT

The oxygen transfer capability of a submerged air device may be estimated by means of a gas phase mass balance over the aerated volume. A number of assumptions may be made to simplify this analysis. These include the following:

- Inerts, including nitrogen are conservative; that is, there is no net absorption or desorption of the constituents in question;
- There is negligible denitrification at the test location;
- The air flow rate to the basin is constant during the test;
- The barometric pressure is constant during the test,
- The off-gas humidity is equivalent to the saturated value at mixed liquor temperature where the latter is less than the instrument inlet temperature, though in other cases it will be equivalent to the saturated value at the instrument inlet temperature; and
- Negligible oxygen transfer is taking place at the liquid surface.

Referring to Figure 1, a gas phase mass balance over the liquid volume, V, may be written

$$V\rho \frac{d\bar{Y}}{dt} = \rho q_i Y_R - \rho q_o Y_{og} - K_La(C^* - C)V \quad (1)$$

where

ρ = density of oxygen at temperature and pressure at which gas flow is expressed (M/L^3),
q_i, q_o = total gas volume flow rates of inlet and outlet gases (L_3/t),
Y_R, Y_{og} = mole fractions (or volumetric fractions) of oxygen gas in inlet and outlet gases,
K_La = overall oxygen mass transfer coefficient, $(1/t)$
C^* = saturation concentration of oxygen in test liquid in equilibrium with exit gas (M/L^3),
C = equilibrium concentration of oxygen in test liquid, (M/L^3), and
V = test cell volume (L^3)

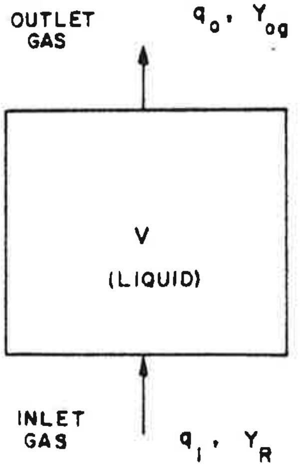


Figure 1—Gas phase mass balance.

At steady state

$$\frac{\rho}{V}(q_i Y_R - q_o Y_{og}) = K_L a(C^* - C) \qquad (2)$$

If one assumes that the volume of CO_2 produced and imparted to the gas stream just equals that of oxygen absorbed, and that nitrogen is conservative, this equation reduces to

$$K_L a = \frac{\rho}{V} q \frac{(Y_R - Y_{og})}{(C^* - C)} \qquad (3)$$

where $q = q_i = q_o$

The value of $K_L a$ may be estimated from Equation 2 or 3 provided that measurements are made of Y_R and Y_{og}, the inlet and outlet mole fractions of oxygen (q), the total gas flow rate, and C. In addition, an estimate must be made of C^* under test conditions.

Another method of reporting oxygen transfer is by the calculation of OTE expressed as a fraction.

$$\text{OTE} = \frac{\rho q_i Y_R - \rho q_o Y_{og}}{\rho q_i Y_R} \qquad (4)$$

Again, if one assumes CO_2 evolution is equivalent to oxygen absorption, this equation reduces to

$$\text{OTE} = \frac{Y_R - Y_{og}}{Y_R} \qquad (5)$$

Equations 4 and 5 simplify the computation of oxygen transfer in a given system because no estimate of C^* is required, although gas flow rates must be accurately monitored if a correction for CO_2 evolution is to be accounted for in Equation 4.

Gas flow measurements may be omitted from Equation 4 by using molar ratios of inlet and outlet oxygen to the inert gas fractions as given below:

$$\text{OTE} = \frac{\text{mass } O_2 \text{ in} - \text{mass } O_2 \text{ out}}{\text{mass } O_2 \text{ in}}$$

$$= \frac{G_i(M_o/M_i)MR_{o/i} - G_i(M_o/M_i)MR_{og/i}}{G_i(M_o/M_i)MR_{o/i}}$$

and

$$\text{OTE} = \frac{MR_{o/i} - MR_{og/i}}{MR_{o/i}} \qquad (6)$$

where

G_i = mass rate of inerts (including nitrogen & argon) (M/t),
M_o, M_i = molecular weights of oxygen and inerts, and
$MR_{o/i}$, $MR_{og/i}$ = mole ratio of oxygen to inerts in inlet and in off-gas.

The mole ratio of oxygen to inerts may be expressed by Equations 7 and 8 as

$$MR_{o/i} = \frac{Y_R}{1 - Y_R - Y_{CO_2(R)} - Y_{W(R)}} \qquad (7)$$

and

$$MR_{og/i} = \frac{Y_{og}}{1 - Y_{og} - Y_{CO_2(og)} - Y_{W(og)}} \qquad (8)$$

where

$Y_{CO_2(R)}$, $Y_{CO_2(og)}$ = mole fractions of CO_2 in inlet gas (R) or off-gas (og), and
$Y_{W(R)}$, $Y_{W(og)}$ = mole fractions of water vapor in inlet gas (R) or off-gas (og).

Equations 7 and 8 may be substituted into Equation 6 to estimate OTE. It may be noted in the rare case that the mole fraction of CO_2 produced just equals that of oxygen absorbed, Equations 6, 7 and 8 reduce to Equation 5.

Finally, the value of Y_{og} and Y_R may be calculated as follows:

$$Y_R = 0.2095\,(1 - Y_{W(R)}) \qquad (9)$$

and

$$Y_{og} = \left(\frac{MV_{(og)}}{MV_{(R)}}\right) Y_R \qquad (10)$$

where a sensor with linear response of millivolts to partial pressure of oxygen is used and where $MV_{(og)}$, $MV_{(R)}$ are the millivolt output readings of the oxygen sensor, which have been corrected as required for absolute sensor cell pressures and temperatures.

Additional refinements in these equations for nitrogen solution or volatilization may also be made, but preliminary calculations indicate that this correction is minor and may normally be omitted from the calculations.

INSTRUMENTATION

There seems to be general agreement among investigators that off-gas techniques offer substantial advantages over most other procedures for determining oxygen transfer efficiencies for submerged aeration systems under process condition. The greatest drawbacks have been related to the instrumentation. Two practical problems had to be overcome to make the method more acceptable. The first was the need for a gas collection device that was light and easy to handle, but large enough to collect a representative off-gas sample. The early work reported by Downing^{13} indicated that the smaller the hood the more variable was the measurement of $K_L a$. The second problem was the selection of an oxygen sensor that could precisely detect small differences in the partial pressure of oxygen, and be adaptable to *in situ* measurements. Over the years investigators have employed gas chromatography, paramagnetic oxygen analyzers and, more recently, polarographic probes and electrochemical galvanic cells.

The four major components of the off-gas equipment used in this investigation were a floating hood to capture the gas, a hose connecting the hood to the analytical circuit, an analytical circuit for monitoring off-gas composition, temperature, pressure, and gas flow rate, and a vacuum source to draw gas from the hood through the analytical circuit.

The hood used for these studies was a section of a 0.6-m (2-ft) diameter pipe cut longitudinally along the pipe diameter to a length of 2.67 m (8.75 ft), to provide a surface capture area of 1.62 m^2 (17.5 sq ft). The hood was provided with ballast tanks to ensure that it remained stable within a given sampling cross section. A 38-mm (1.5-in.) diameter connecting host carried the exhaust gases to an analytical circuit. Pressure under the hood was monitored by means of plastic tubing leading from a port on the hood to the analytical circuit. Suction of exhaust gas from the hood was provided by a vacuum cleaner. The suction line was valved to maintain a small, but constant negative or positive pressure (±0.2 in.) under the hood. A slight but constant vacuum on the order of −4.0 to −6.0 in. water was maintained in the analytical circuit when off-gas and reference air measurements were made.

The analytical circuit is depicted in Figure 2. A polarographic DO probe was used to measure oxygen partial pressure in the off-gas and reference air samples. Later, during the investigations, an electrochemical galvantic cell was used in series with the probe. Carbon dioxide was monitored batchwise by bleeding off gas flowing through the circuit to a volumetric CO$_2$ analyzer.

The gas was analyzed in this circuit by passing a small portion of the test gas through a flowmeter and past the oxygen probe. Gas temperature, humidity, and pressure were monitored and controlled within the circuit so that the difference in partial pressure of oxygen between the reference air and off-gas could be precisely obtained.

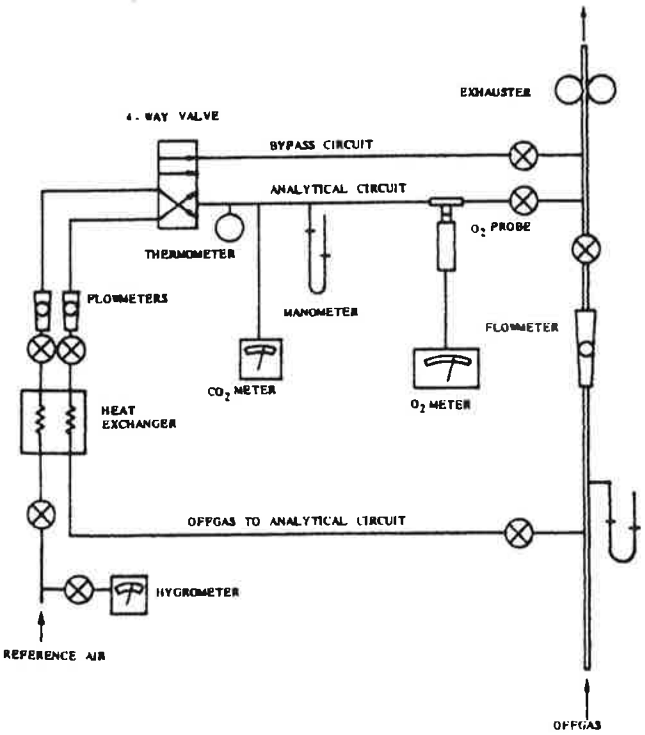


Figure 2—Schematic diagram of off-gas analyzer circuit.

CONDUCT OF THE TEST

Prior to the field test, the DO sensor was checked daily for accuracy with gases of certified composition. Pure nitrogen was also passed through the analytical circuit under test conditions to ensure that no leaks existed. These tests were normally conducted several times during the day.

The linearity of the probe was checked periodically by drawing the reference air past the sensor under various levels of reduced pressure while keeping the gas temperature constant. Under these circumstances the partial pressure of oxygen was directly proportional to the total absolute pressure. The criterion applied was that the ratio of absolute pressures for the two conditions divided by the ratio of the meter outputs fell in the range of 0.995 to 1.005.

Using this test for linearity, it was found that the calibration setting for probe output (in millivolts) was not critical, and essentially the same relative change in the voltage output occurred regardless of the setting with reference at ambient conditions. To obtain the maximum sensitivity, the reference output was set as close to full scale as was practical, because probe error is normally a fixed fraction of the full-scale reading. It should be emphasized that this procedure required precise measurement of the difference in the two gas streams and, therefore, it was not necessary to have an accurate determination of the absolute value of the partial pressure of oxygen in either stream.

Once the analytical circuit was checked, the gas collection hood was fixed in place at a predetermined location and a vacuum drawn at the instrument discharge. Reference air was first drawn into the analytical circuit and, a series of observations of temperature, humidity, pressure, and sensor millivolt readings were recorded over a period of about 5 minutes. A portion of the off-gas was diverted through the analytical circuit for a typical period of 5 to 10 minutes. During this time adjustments to the volume of off-gas drawn from the collection hood were made to obtain an equilibrium pressure condition beneath the hood at near ambient pressure (±0.2-in. water). Parallel measurements were recorded for off-gas temperature, humidity, pressure, CO$_2$ concentration, and sensor millivolt reading. Total off-gas flow rate was also recorded and used later in calculation of a bulk OTE for the entire tank volume. In addition to these measurements, mixed liquor temperature, DO, and local barometric pressure were also recorded. The hood was then moved to a new location and reference gas was again drawn through the circuit and measurements recorded. The reference gas check between each off-gas measurement provided a means for simple probe drift correction if required. This technique reduced errors in measuring the differences between off-gas and reference streams. The entire procedure for one determination required approximately 15 minutes.

The method involved sampling a sufficient number of locations within a given basin to obtain a representative sample of off-gas from the tank or tank element. A reasonable agreement between the applied and collected air flow rates was used to indicate a representative sampling layout. Initial field studies were conducted by drawing reference air directly from the plant air line. However, experience at a number of plants indicated that ambient air drawn directly within the vicinity of the analytical system yielded nearly identical readings to plant air. This approach greatly simplified the test procedure, and was adopted as a standard procedure thereafter.

The value of OTE for each sampling point was calculated using Equations 6, 7, 8, 9, and 10. Temperature corrections were made using the expression:

$$\text{OTE}_{20^\circ} = \text{OTE}_T\ 1.024^{(20-T)} \tag{11}$$

In order to estimate a weighted bulk average OTE for an entire tank or tank element, the following equation was used.

$$\text{OTE}_w = \frac{\sum_{0}^{n} \text{OTE}_n q_{an}}{\sum q_{an}} \tag{12}$$

where

OTE_w = weighted OTE
OTE_n = OTE value at sampling point, n, and
q_{an} = the collected gas flow rate per unit surface area at sampling point, n, (L^3/tL^2).

To provide comparisons between values of OTE measured for different systems, one may normalize the measured OTE by dividing it by $(C^* - C)$,

$$\text{OTE}_{sp} = \frac{\text{OTE}}{C^* - C} \tag{13}$$

In this equation, C^* is the calculated saturation value of oxygen in the wastewater. In diffused air systems C^* may be estimated by

$$C^* = C^*_{20} \frac{P_b}{P_s} \frac{C_{sT}}{C^*_{s20}} \beta \tag{14}$$

where

C^*_{20} = clean water saturation value in the same geometry at comparable air flow rate and at standard conditions (M/L^3),
P_b = atmospheric pressure during the test (f/L^2),
P_s = standard atmospheric pressure (usually 1.00 atm at 100% relative humidity (f/L^2),
C_{sT} = surface saturation book value for dissolved oxygen at the test temperature (M/L^3),
C^*_{s20} = the surface saturation book value for dissolved oxygen at 20°C (M/L^3), and
β = the ratio of process wastewater saturation value to that of clean water.

The value of C^*_{20} is often available from clean water tests of the diffuser system under the appropriate process configurations and gas flows. If it is not available it must be calculated using a gas-side correction model assuming some effective saturation depth.[2]

The data presented in this paper are uncorrected field measured OTE values except where subscripted as OTE_{20° or OTE_{sp}.

RESULTS

Off-gas field studies have been conducted during the past 3 years at over nine treatment facilities, including two industrial plants, and a variety of diffused air systems. Early tests were conducted at Whittier Narrows, California, Madison, Wisconsin, Brandon, Wisconsin, Ridgewood, New Jersey, and a DuPont facility. These tests were conducted in parallel with other field test procedures for comparative purposes. Other off-gas studies were conducted for a variety of purposes including:

- Evaluation of diffuser clogging problems,
- Evaluation of effectiveness of diffuser cleaning procedures,
- Evaluation of several diffuser types in side-by-side tests under process conditions, and
- Evaluation of aeration system control procedures.

Comparative test results. Table 2 presents the results of comparative tests conducted at four field sites. In general, the comparisons of the off-gas procedure with other currently-used field techniques are good. These tests reported were conducted under ideal conditions where the comparative test methods were applicable.

For example, field tests at Sites A and B were conducted at plants where mixed liquor DO values generally exceeded 0.5 mg/L and where approximate steady state conditions were achieved. Site A used both tapered aeration and step aeration thereby producing a wide variation in point values of OTE as measured by off-gas methods. Point values of steady state respirometeric tests versus off-gas data were, of course, not applicable, but overall bulk average values were comparable. At Site B, the small aeration tank was almost completely mixed with respect to DO. Point values of off-gas OTE varied substantially along test cross sections depending on off-gas flow rates (discussed later), but comparisons between tests were reasonable.

Results at Site C, another municipal plant, were also very favorable. At this plant, a non-steady state method with hydrogen peroxide was used for comparison. This

Table 2—Selected field test results off-gas versus other field methods.

Site	Diffuser system	Off gas analyses OTE-% (avg)	Off gas analyses OTE-% (range)	DO-mg/L (range)	OTE-% (comparison test)	Comparison method
A	Floor coverage ceramic	11.85	8.0–16.7	0.9–3.9	12.68	Respir. rate steady state
A	Dual roll coarse bubble	6.16	5.1–6.8	2.0–4.1	6.29	Respir. rate steady state
B	Jet aeration along longitud. wall (q = 67 L/s)	5.34	4.5–7.7	3.8[a]	5.31	Respir. rate steady state
	(q = 18 L/s)	9.58	8.7–11.1	1.1[a]	12.5	Respir. rate steady state
C	Spiral roll coarse bubble	3.2	—	1.8–4.1	3.3	H_2O_2/non-steady state
C	Spiral roll coarse bubble	1.1	—	6.8–7.2	1.7	H_2O_2/Non-steady state
D	Floor coverage coarse bubble	7.7	5.5–11.1	0	7.3–7.8[b]	Radioactive tracer

[a] Average DO in approximately CSTR system.
[b] Range of values depending on actual air flow rate.
[c] All OTE values calculated under field conditions and not corrected to 20°C.

method, described by Kayser,[5,21] must be performed under steady state conditions. Such conditions were established at Site C by diverting a substantial amount of the wastewater flow from the test system. Of special note, here, was the excellent agreement achieved between these two methods at an OTE value of 3.3%. The apparent poor agreement at the second test condition was not surprising considering the extremely low operating efficiency at that condition. The effectiveness of off-gas methods at low OTE values was of great concern to the investigators owing to the extremely small differences between reference air and off-gas oxygen concentrations. The excellent comparability of these methods at Site C was further reinforced by nonradioactive tracer tests performed at this site.

The tests conducted at Site D were reported by Campbell.[6] Here, the radioactive tracer technique using Krypton-85 and tritium was compared against the off-gas procedure. Excellent agreement was reported between the two methods in this highly loaded, single aeration tank where complete-mix conditions were approximated. The wide range of off-gas OTE point values measured at this facility was primarily the result of the variations in off-gas flow rates [3.4 to 4.5 L/m²/s (0.67 to 0.88 cfm/ft²)]. Even though the coarse bubble diffusers were distributed over the entire tank floor, there was a substantial localized boiling along the tank surface.

Important to note in all of these comparative tests, is the method of computation used to convert $\alpha K_L a$ values, which were estimated by all the other field test procedures, to OTE values measured by the off-gas procedure. The conversion was executed by the following general relationship,

$$\text{OTE} = \frac{\alpha K_L a(C^* - C)V}{q\rho} \tag{15}$$

To achieve this comparison, it was necessary to have good estimates of C^* for the diffuser system geometry in the process wastewater at the appropriate temperature, pressure, and q, the gas flow rate of the diffuser system.

Other test results. The value of off-gas measurements goes far beyond the ability to estimate bulk OTE values for a given system. No other field test for oxygen transfer can provide discrete point information for a given system. The analysis of oxygen transfer at a specified location can greatly benefit the design engineer and the operator. A few examples of this information are presented to illustrate this extra benefit of the method.

Figure 3 presents the results of OTE and off-gas flow rate measurements that were observed at twelve cross-sections along the aeration tank at Site A. Floor coverage ceramic diffusers were used at this site. Tapered aeration was employed and primary effluent was discharged in equal amounts at three points along this folded tank. Tapered air was achieved in these tanks by varying diffuser density and, to some extent, by throttling gas flow rates to the diffuser headers. Aeration control was accomplished through DO monitoring and manual shut-down or start-up of blowers. Figure 3 indicates that during this period, DO control appeared to be effective. Because OTE for ceramic diffusers are relatively insensitive to air flow rates per diffuser, it seemed that increases in OTE along each tank section were the result of increases in alpha values.

A similar plot for the cross roll configuration at this same site appears as Figure 4. These folded tanks were equipped with fine bubble tubes in the first bay and coarse bubble units in the last two bays. All diffusers were uniformly spaced and primary effluent was evenly split to three points. This data suggests that gas flow rates were not well distributed, perhaps because of ineffective throttling of air control valves. The decline in OTE values along the tank length was not expected and could not be

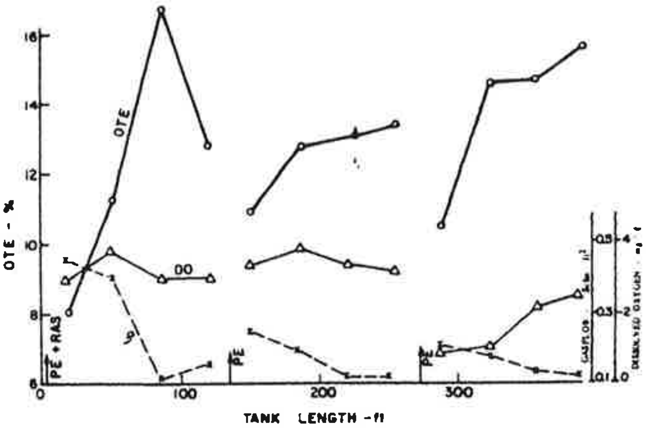


Figure 3—Gas transfer analyses along tank length—Site A. Floor coverage, ceramic domes, and tapered air.

entirely attributed to changes in gas flow rates. It is clear that operational corrections in this system were necessary.

An additional study was conducted near the discharge end of a three-pass cross roll system with various types of wide band tubular diffusers. A plan view of the tank indicating the header locations, diffuser locations and sampling plan is shown in Figure 5. The test results are presented in Table 3. Of particular interest was the apparent utility of the gas phase analysis which permits evaluation of several aerator types within a relatively small portion of a single tank. With tracers or liquid phase methods, such analysis is not possible.

The used units had been operating at the test plant for about 3 years. Comparing new and used Type C devices, there was a reduction in performance over that period. A similar reduction had most likely occurred with Type D diffusers, however, new Type D units were not available for test at that time.

It should be noted that the discharge end of the basin was selected to minimize potential alpha variations in the test region. The diffuser layout was such that the reference system, Type A, was on both ends of the test zone to pick up the relative apparent change in alpha across the test boundary. The data substantiated a constant alpha for the test region. Based on the above results, this method can be a useful tool in aeration system retrofitting consideration. It can measure the dirty water performance characteristics of various systems at a particular site under actual field conditions, with modest expenditure of time and effort. However, these systems should not be com-

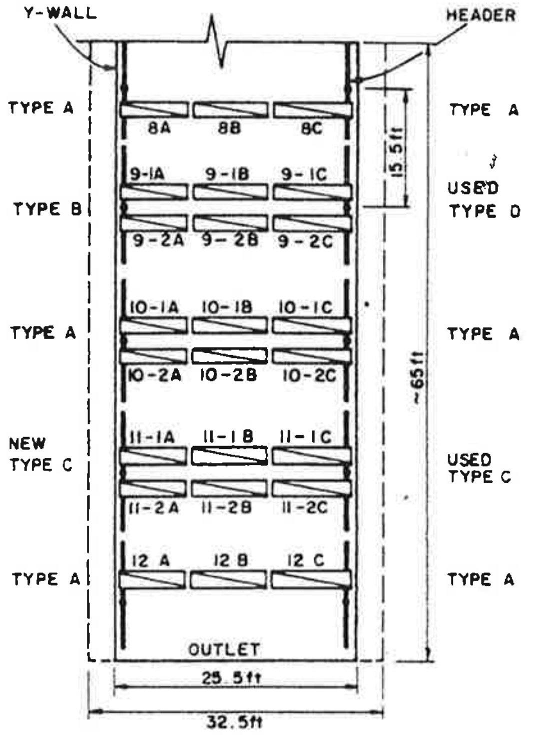


Figure 5—Aerator and sample site layout for comparative analysis of diffusers.

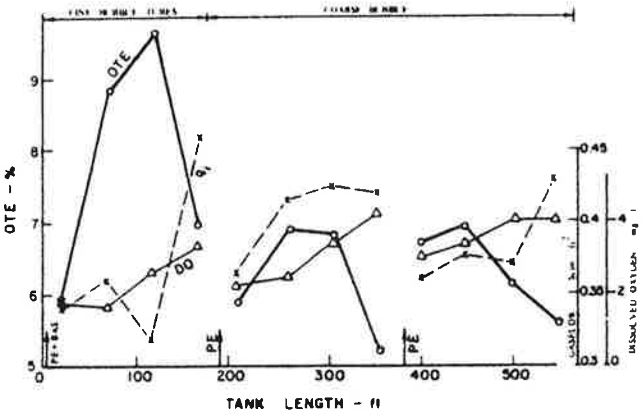


Figure 4—Gas transfer analyses along tank length—Site A. Cross roll, fine, and coarse bubble.

Table 3—In-process tubular diffusers comparisons with off gas procedures.

Diffuser	Location[a]	OTE-%[b]	DO-mg/L	$OTE_{20\text{-}0}$[c]
Type A	Station 8	7.95	0.9	8.29
Type B	Station 9	11.62	1.7	14.18
Used				
Type D	Station 9	9.17	1.7	11.33
Type A	Station 10	7.96	2.0	10.28
New				
Type C	Station 11	12.94	1.7	15.96
Used				
Type C	Station 11	9.05	1.7	11.00
Type A	Station 12	6.99	1.2	8.29

[a] See Figure 5.
[b] Field OTE.
[c] OTE corrected 20°C at 0 DO (Equations 11 and 13).

pared solely on the basis of OTE measurements when new, because other factors including back pressure, power, available driving force, and maintenance should also be considered.

Sample point selection in evaluating oxygen transfer data for a given system is critical to proper assessment of the system. Figure 6 presents a layout of the aeration tank at Site B that was equipped with jet aeration along one longitudinal wall directed across the tank. Although DO values were uniform in this small basin, off-gas flow rates and OTE values were not (Table 4). As would be expected, OTE values were generally higher over points of lower gas flow discharge. To estimate overall basin transfer efficiency using Equation 12, total captured gas flows were compared against measured values. Accordance between the two (±15%) indicates a reasonable sample point selection. In this particular study, gas capture flow rates were much higher than the rated capacity of the blowers. Further evaluation of the rating curves by the manufacturer revealed that the blower capacity had been seriously underestimated. No gas flow metering devices were available at Site B.

DISCUSSION

The results of 3 years of field experience with the off-gas procedure have been very encouraging. The procedure is relatively simple and straightforward, and the equipment required for precise and accurate *in situ* measurement is available. Hood designs will continue to improve so that they are lighter and more portable than the ones used in this study.

Table 4—Off gas analysis—Site B[a]

Station	q_A-L/m^2/s	OTE-%
1A	0.34	11.0
1B	0.80	9.3
2A	0.79	6.9
2B	0.75	8.8
3A	0.73	10.2
3B	0.40	11.1
Weighted Average	—	(9.58)
1A	2.21	4.5
1B	0.66	7.7
2A	2.27	4.9
2B	2.09	6.2
3A	2.61	4.4
3B	0.31	11.9
Weighted Average	—	(5.34)

[a] See Figure 6.

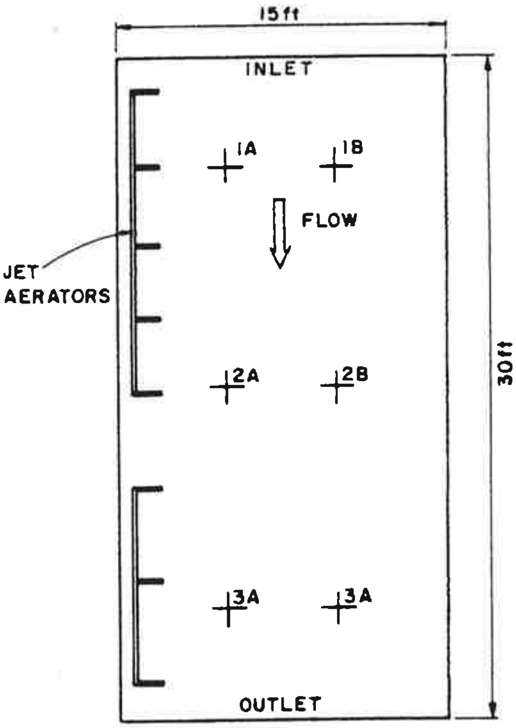


Figure 6—Aerator and sample site layout at Site B.

There is currently no way to effectively evaluate the precision of this method under process conditions because it is difficult to achieve constant performance of aeration equipment under field conditions. Under the most uniform aeration conditions, reproducibility seems to be well within acceptable ranges for this type of field measurement (less than ±10%). It should be noted that the estimate of the reproducibility of the method may be primarily the result of changing conditions at a given sampling point rather than the precision of the analytical system.

The accuracy of this technique cannot be determined because, to date, there is no standard against which to compare field OTE measurements. Many researchers feel that the radioactive tracer procedure described by Neal *et al.*[7] represents the state-of-the art available today for oxygen transfer rate measurement under process conditions. The results of the study at Site D were very encouraging in this regard. It should be remembered, however, that the tracer measurements provided a bulk average $\alpha K_L a$, whereas the off-gas measurements represented an average of local oxygen transfer efficiencies. It is also pertinent that where the objective of the test is to measure efficiency or predict air rate requirements, the off-gas method is significantly less subject to errors resulting from air rate measurement.

The accuracy of the off gas-measurement for prediction of local OTE is dependent on a number of measured variables including gas phase oxygen concentration, gas phase carbon dioxide concentration, gas phase humidity, gas phase temperature, gas phase pressure, and rate of off-gas flow. The accuracy of the oxygen sensor was continuously checked using certified gases or reduced pressure as described earlier. Results with the sensors used in this study were excellent, which indicates a high degree of precision and accuracy. Most sensors are temperature compensated. The effectiveness of this compensation varies, therefore each device should be carefully checked. Gas phase CO_2 and humidity seem to be the other major variables that influence computation of OTE. Off-gas flow rate measurement is used in Equation 12 primarily to weight OTE values. Its accuracy, therefore, is of secondary interest. On the other hand, if Equation 4 is used to estimate OTE values, a very accurate assessment of off-gas (and inlet gas) rates is required. Downing[13] employed CO_2 injection in the outlet gas with subsequent CO_2 analysis in the gas stream to ensure accurate estimates of gas flow. A sensitivity analysis of the parameters influencing the calculation of OTE will be published in the near future.

In evaluating the off-gas procedure against other methods currently available, several advantages and disadvantages may be enumerated. Some off-gas methods are particularly suitable because they:

- Measure local performance,
- Yield OTE directly and are relatively insensitive to the precision of air flow measurement,
- Are applicable in tanks where spatial variation of gas flow rate, loading, DO, and alpha exist,
- Seem to have exceptionally good precision and accuracy as compared to other conventional methods,
- Produce relatively fast and inexpensively,
- Provide a simple and reliable means of measuring alpha values in aeration systems of known clean water performance,
- Provide a means for simultaneous side-by-side comparisons of different aeration systems under process conditions,
- Are applicable in anoxic tanks, and
- Do not require process interruption.

Off-gas methods can be disadvantageous because:

- Technique is not applicable to mechanical aeration systems;
- Tanks must be accessible to personnel,
- Severe foaming may complicate gas sampling,
- Severe turbulence may cause difficulty in hood placement, and
- Method requires accurate measurements of CO_2 and humidity of reference air and off-gas.

Additional field research continues with the off-gas procedure. The method has a wide list of applications that extend beyond the routine measurement of bulk transfer efficiency. As indicated previously, off-gas provides air distribution and transfer efficiency profiles that can be used to evaluate system operation and maintenance requirements. Furthermore off-gas may be used to monitor temporal changes in oxygen transfer caused by diffuser clogging, alpha variations, and gas flow adjustments. Recently the off-gas method has been used to evaluate a variety of diffuser devices in side-by-side tests under process conditions.

The translation of clean water oxygen transfer data to process conditions continues to produce a significant amount of uncertainty in the design of aeration systems. Through the use of field measuring techniques, a compilation of useful data will eventually be accumulated to provide the design engineer with better scale-up data. Hopefully, the off-gas technique will provide an additional tool to achieve that end.

ACKNOWLEDGMENTS

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APPENDIX I I

FIELD DATA SHEETS

PAGE: 1
DATE: Nov 14 2017
SITE: Santa Fe, NM
UNIT: North Aeration Basin

MLT: 20.4°C
BAROM: 24.00 in. Hg.
TDS:

Hood: 2'x8'

		ROTA	ROTA						
TIME	STATION	NO MM/P	TEMP	PRESS	CELL PRESSURE	DIGITAL OUTPUT	CELL TEMP	DO CONC	MISC DATA & COMMENTS
1020	DAA				-8.0	1005			
1022	1.1	1-135				829		0.55	
1023	''	1-133				822		0.53	20.4° C
1024	''	1-133				826		0.56	
1025	1.1	1-133✓				829		0.55	
1026	DAA				-8.0	1009			
1031	DAA				-8.0	1007			
1034	1.2	1-90				820		0.59	
1035	''	1-93				814		0.56	20.4°C
1036	''	1-94				801		0.57	
1037	1.2	1-98✓				800		0.56	
1038	DAA				-8.0	1010			
1044	DAA				-8.0	1008			
1046	1.3	1-135				791		0.58	
1047	''	1-135				800		0.57	20.4°C
1048	''	1-133				799		0.57	
1049	1.3	1-133				795		0.61	
1050	DAA				-8.0	1014			
1058	DAA				-8.0	1007-8			
1100	1.4	1-88				828		0.39	
1101	''	1-75							20.4°C
	''	AIR OFF!							
	1.4								

PAGE: 2
DATE: NOV. 14, 2017
SITE: SANTA FE, NM
UNIT: NORTH BASIN

MLT: 20.4°C
BAROM: 24.00 IN. Hg
TDS:

HOOD: 2'×8'

TIME	STATION	ROTA	ROTA		CELL PRESSURE	DIGITAL OUTPUT	CELL TEMP	DO CONC	MISC DATA & COMMENTS
		NO MM/P	TEMP	PRESS					
1205	DAA				-8.0	1003		1.09	
1207	1.4	2-90				873		1.20	
1208	"	2-73				875		1.26	20.4°C
1209	"	2-73				882		1.25	
1210	1.4	2-80				877		1.24	
1211	"	2-80 ✓				879		1.30	
1212	DAA				-8.0	1001			
1219	DAA				-8.0	1003-4			
1221	1.5	1-230				884		1.69	
1222	"	2-60				873		1.76	20.4°C
1223	"	2-60				889		1.57	
1224	1.5	2-60				884		1.68	
1225	"	2-60 ✓				880		1.66	
1226	DAA				-8.0	1003			
1233	DAA				-8.0	1003-4			
1235	1.6	2-70				861		1.68	
1236	"	2-67				863		1.76	20.4°C
1237	"	2-62				852		1.65	
1238	1.6	1-230				874		1.64	
1239	"	1-235 ✓				860		1.77	
1240	DAA				-8.0	1003			
1246	DAA					1004			
1248	1.3	2-67				835		1.63	
1249	"	2-69				844		1.50	20.4°C
1250	"	2-58				833		1.64	
1251	1.3	2-65				850		1.51	
1252	"	2-65 ✓				841		1.64	
1253	DAA				-8.0	1002-3			

PAGE: 3
DATE: NOV. 14 2017
SITE:
UNIT: SANTA FE, NM
NORTH BASIN

MLT: 20.4° C
BAROM: 24.00 IN. HG
TDS:

Hood: 2'x 8'

TIME	STATION	ROTA	ROTA		CELL PRESSURE	DIGITAL OUTPUT	CELL TEMP	DO CONC	MISC DATA & COMMENTS
		NO MM/P	TEMP	PRESS					
1303	DAA				-8.0	1002			AirFlow SO 1450
1305	1.2	1-250				845		1.35	AirFlow NO 1840
1306	"	1-250				845		1.24	
1307	"	1-250				846		1.41	20.4
1308	1.2	1-230				848		1.26	
1309	"	1-230				855		1.24	
1311	DAA				-8.0	1002			
1328	DAA				-8.0	1001			
1330	1.1	2-64				872		1.15	
1331	"	2-65				866		1.31	20.4°C
1332	"	2-66				874		1.04	
1333	1.1	2-58				873		1.30	
1334	"	2-58				870		1.18	
1335	DAA				-8.0	998			

PAGE: 4
DATE: Nov 14, 2017
SITE: Santa Fe, NM
UNIT: South Basin

MLT: 20.5°C
BAROM: 24.00 IN. Hg
TDS

Hood: 2'x8'

TIME	STATION	ROTA NO MM/P	ROTA TEMP	ROTA PRESS	CELL PRESSURE	DIGITAL OUTPUT	CELL TEMP	DO CONC	MISC DATA & COMMENTS
1437	DAA				-8.0	1000-1			
1439	1.15	1-220				873		0.95	
1440	"	1-210				873		1.04	20.5°C
1441	"	1-210				870		1.08	160°F
1442	1.15	1-220				868		1.01	AIRFLOW SO 1620
1443	"	1-230				871		0.94	
1444	DAA				-8.0	1002			AIRFLOW NO 1870
1450	DAA				-8.0	1002			
1452	1.25	1-190				863		1.05	
1453	"	1-190				844		1.01	20.5°C
1454	"	1-190				858		0.98	
1455	1.25	1-200				845		0.91	
1456	"	1-200				855		0.95	
1457	DAA				-8.0	1001			
1502	DAA				-8.0	1000			
1504	1.35	1-235				855		1.03	
1505	"	1-215				836		1.05	20.5°C
1506	"	1-215				867		1.09	
1507	1.35	1-215				843		0.89	
1508	"	1-220 ✓				865		0.99	
1509	DAA				-8.0	999			
1514	DAA				-8.0	1001			
1516	1.45	1-235				878		1.04	
1517	"	1-235				874		0.97	20.5°C
1518	"	1-235				879		1.06	
1519	1.45	1-235				880		1.03	
1520	"	1-235				879		0.99	
1521	DAA				-8.0	1000			

PAGE: 5
DATE: NOV. 14, 2017
SITE: SANTA FE, NM
UNIT: SOUTH BASIN

MLT: 20.5°C
BAROM: 24.00 IN. Hg
TDS:

HOOD: 2,80'

TIME	STATION	ROTA	ROTA		CELL PRESSURE	DIGITAL OUTPUT	CELL TEMP	DO CONC	MISC DATA & COMMENTS
		NO MM/P	TEMP	PRESS					
1528	DAA				-8.0	1003			
1530	1.55	1-160				874		1.10	
1531	"	1-165	↑			873		0.89	20.5°C
1532	"	1-200				866		0.97	
1533	1.55	1-210				871		0.89	
1534	"	1-200 ✓				862		1.00	
1535	DAA				-8.0	1001			
1539	DAA				-8.0	1001			
1541	1.65	1-208				856		1.05	
1542	"	1-195				877		0.96	20.5°C
1543	"	1-195				886		1.03	
1544	1.65	1-195				878		0.96	
1545	"	1-195 ✓				878		1.06	
1546	DAA				-8.0	1002			

AMBIENT 61F DEW POINT - 23F RH - 23%
30.08 IN. Hg BARO.

PAGE: 1
DATE: Nov. 15, 2017
SITE: Santa Fe, NM
UNIT: North Basin

MLT: 20.1°C
BAROM: 30.19-6.19=24.00 in. Hg
TDS:

Hood: 2'x8'

TIME	STATION	ROTA NO MM/P	ROTA TEMP	PRESS	CELL PRESSURE	DIGITAL OUTPUT	CELL TEMP	DO CONC	MISC DATA & COMMENTS
1026	DAA				-8.0	1005			
1028	3.1N	2-65				898		3.01	20.1°C
1029	"	2-64				903		2.87	
1030	"	2-50				902		2.90	
1031	3.1N	1-210				908		3.05	
1032	"	1-250				899		2.85	
1033	"	2-55				900		3.04	
1034	DAA				-8.0	1005			
1042	DAA				-8.0	1007			
1044	3.2N	2-70.+				909		2.72	
1045	"	2-70				910		2.76	20.1°C
1046	"	2-68				909		2.70	
1047	3.2N	2-63				909		2.91	
1048	"	2-50				912		2.75	
1049	DAA				-8.0	1006			
1053	DAA				-8.0	1007			
1055	3.3N	2-69				908		2.75	
1056	"	2-71				910		2.76	20.1°C
1057	"	2-70				912		2.69	
1058	3.3N	2-60				914		2.71	
1059	"	2-60				910		2.77	
1100	DAA				-8.0	1007			
1113	DAA				-8.0	1005			
1115	3.4N	2-79				909		2.64	
1116	"	2-85				910		2.37	20.1°C
1117	"	2-73				906		2.55	
1118	3.4N	2-77				910		2.45	
1119	"	2-75✓				906		2.37	
1120	DAA				-8.0	1005			

PAGE: 2
DATE: NOV. 15, 2017
SITE:
UNIT: SANTA FE, NM

MLT: 20.1°C
BAROM: 30.19 - 6.19 = 24.00 IN. HG.
TDS:

NORTH BASIN 2ND CHANNEL. HOOD: 2'x8'

		ROTA	ROTA						
TIME	STATION	NO MM/P	TEMP	PRESS	CELL PRESSURE	DIGITAL OUTPUT	CELL TEMP	DO CONC	MISC DATA & COMMENTS scfm.
1138	DAA				-8.0	1603			AIRFLOW SO - 1620
1140	3.5N	2-70				901		2.57	AIRFLOW NO - 1930
1141	"	2-72				905		2.49	
1142	"	2-75				909		2.27	20.1°C
1143	3.5	2-74				901		2.30	
1144	"	2-74✓				909		2.45	
1145	DAA				-8.0	1006			
1149	DAA					1006			
1151	3.6N	2-59				908		2.71	
1152	"	2-63				898		2.54	20.1°C
1153	"	2-63				895		2.58	
1154	3.6N	2-58				904		2.54	
1155	"	2-58✓				901		2.69	
1156	DAA				-8.0	1007			
1158	DO	END OF GRID 1				= 1.50 MG/L			20.1°C
1203	DO	END OF GRID 2							
						→ 1.95-2.0 MG/L			20.1°C
1208	DO	WALKWAY CHANNEL				0.40 MG/L			20.1°C

PAGE: 3
DATE: NOV 15, 2017
SITE:
UNIT: SANTA FE NM.
NORTH BASIN - GRID 1

MLT: 20.2° C
BAROM: 30.19 - 6.19 = 24.00 IN. Hg
TDS:

HOOD: 2' x 8'

TIME	STATION	ROTA	ROTA		CELL PRESSURE	DIGITAL OUTPUT	CELL TEMP	DO CONC	MISC DATA & COMMENTS
		NO MM/P	TEMP	PRESS					
1355	DAA				-8.0	1004			
1357	1.5N	2-65				887		1.81	20.2°C
1358	"	2-78				881		1.75	
1359	"	2-72				878		1.73	AirFlow So 1630
1400	1.5N	2-62				887		1.77	AirFlow No. 1920
1401	"	2-62 ✓				888		1.68	
1402	DAA				-8.0	1000			
1410	DAA				-8.0	1003			
1412	1.6N	2-62				849		1.56	
1413	"	2-62				869		1.62	20.2°C
1414	"	2-62				857		1.56	
1415	1.6N	2-62				861		1.63	
1416	"	2-64 ✓				857		1.56	
1417	DAA				-8.0	999-1000			
1423	DAA				-8.0	1003			
1425	1.4N	2-77				879		1.62	
1426	"	2-77				881		1.61	20.2°C
1427	"	2-76				878		1.68	
1428	1.4N	2-75				878		1.57	
1429	"	2-75 ✓				872		1.50	
1430	DAA					1000-1			
1434	DAA				-8.0	1001			
1436	1.3N	2-71				847		1.65	
1437	"	2-67				845		1.56	20.2°C
1438	"	2-67				843		1.64	
1439	1.3N	2-67				847		1.57	
1440	"	2-67 ✓				838		1.61	
1441	DAA				-8.0	998-999			

PAGE: 4
DATE: Nov 15, 2017
SITE:
UNIT: SANTA FE, NM
NORTH BASIN

MLT: 20.2°C
BAROM: 30.19 -6.19 = 24.00 IN. Hg
TDS

HOOD: 2'x8'

TIME	STATION	ROTA NO MM/P	ROTA TEMP	ROTA PRESS	CELL PRESSURE	DIGITAL OUTPUT	CELL TEMP	DO CONC	MISC DATA & COMMENTS
1459	DAA				-8.0	1006-7			
1503	1.2N	2-65				853		1.43	
1504	"	2-54				855		1.61	20.2°C
1505	"	2-65				856		1.33	
1506	1.2N	2-64				843		1.29	
1507	"	2-58✓				851		1.49	
1508	DAA				-8.0	1007			
1511	DAA				-8.0	1007			
1513	1.1N	2-58				870		1.30	
1514	"	2-64				874		1.50	20.2°C
1515	"	2-64				871		1.48	
1516	1.1N	2-66				877		1.34	
1517	"	2-65✓				873		1.45	
1518	DAA				-8.0	1006			

PAGE: 1
DATE: NOV. 16, 2017
SITE: SANTA FE
UNIT:
NORTH BASIN - FIRST CHANNEL - GRID 2 HOOD: 2'x3'

MLT: 19.9°C
BAROM: 30.13-6.19=23.94 IN. Hg
TDS

TIME	STATION	ROTA NO MM/P	ROTA TEMP	PRESS	CELL PRESSURE	DIGITAL OUTPUT	CELL TEMP	DO CONC	MISC DATA & COMMENTS
1036	DAA				-8.0	1001			
1038	2.1N	2-60				889		2.53	19.9°C
1039	"	2-66				884		2.56	
1040	"	2-65				886		2.59	
1041	2.1N	2-61				884		2.45	
1042	"	2-58✓				888		2.52	
1043	DAA				-8.0	1005			
1057	DAA				-8.0	1006			
1059	2.2N	2-66				892		2.58	
1100	"	2-66				895		2.47	19.9°C
1101	"	2-70				896		2.51	
1102	2.2N	2-70				890		2.44	
1103	"	2-72✓				892		2.50	
1104	DAA				-8.0	1009-10			
1111	DAA				-8.0	1005			
1113	2.3N	2-73				880		2.44	19.9°C
1114	"	2-80				878		2.54	
1115	"	2-78				880		2.51	
1116	2.3N	2-78				883		2.47	
1117	"	2-78✓				889		2.41	
1118	DAA				-8.0	1009			
1126	DAA				-8.0	1004			
1129	2.4N	2-70				887		2.37	
1130	"	2-75				878		2.50	19.9°C
1131	"	2-75				889		2.36	
1132	2.4N	2-74				874		2.38	
1133	"	2-76✓				880		2.37	
1134	DAA				-8.0	1005			

PAGE: 2
DATE: NOV. 16, 2017
SITE:
UNIT: SANTA FE, NM

MLT: 19.9°C
BAROM: 30.13 − 6.19 = 23.94 in. Hg.
TDS:

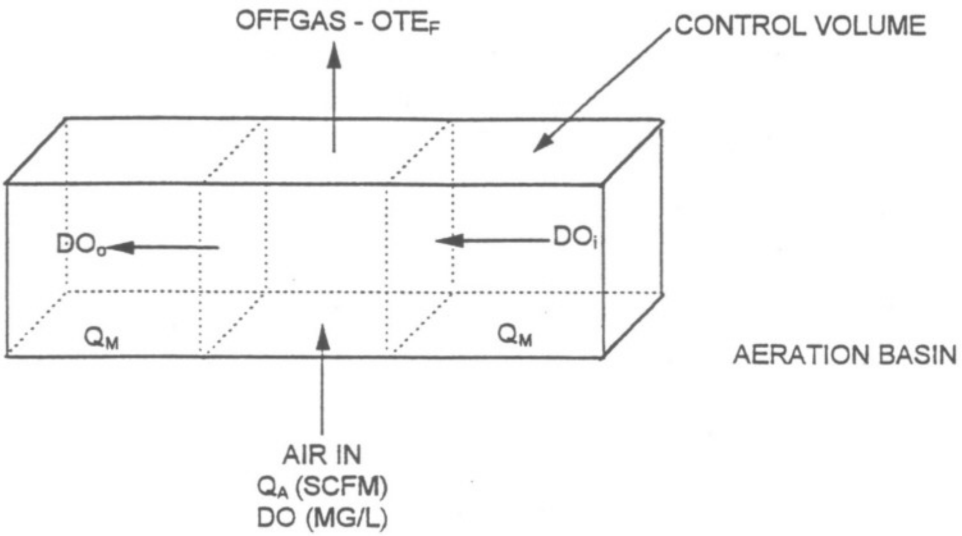
NORTH BASIN ~~SECOND~~ FIRST CHANNEL – GRID 2 HOOD: 2'x8'

TIME	STATION	ROTA NO MM/P	ROTA TEMP	PRESS	CELL PRESSURE	DIGITAL OUTPUT	CELL TEMP	DO CONC	MISC DATA & COMMENTS
1149	DAA				-8.0	1005			
1151	2.5N	2-72				870		2.34	
1152	"	2-74				875		2.27	19.9°C
1153	"	2-74				878		2.19	
1154	2.5N	2-75				879		2.26	
1155	DAA				-8.0	1007			
1202	DAA					1003			
1204	2.6N	2-74				872		2.23	
1205	"	2-78				864		2.32	20.0°C
1206	"	2-78				874		2.37	
1207	2.6N	2-80				874		2.31	
1208	"	2-77✓				868		2.28	
1209	DAA				-8.0	1007			
1215	DO	END GRID	3		2.20 mg/L		20°C		
1218	DO	END GRID	1		1.35 mg/L		20°C		
			AIRFLOW →		SOUTH			1530	SCFM
			AIRFLOW →		NORTH			1670	

APPENDIX III

MASS BALANCE PROCEDURE
TO CALCULATE
OXYGEN UPTAKE RATE

OUR BY GAS-PHASE MASS BALANCE



MASS BALANCE

$$\text{OUR} = \frac{\text{OTR - DO TRANSPORT}}{\text{VOLUME OF LIQUID IN CONTROL ZONE}} - \frac{\Delta \text{ DO CONCENTRATION}}{\text{TIME}}$$

WHERE:

OUR = OXYGEN UPTAKE RATE {MG/L/HR}

OTR = OXYGEN TRANSFER RATE {MG/HR}

= Q_A (1.036)(OTE_F)(454,000)

Q_A = AIR RATE TO CONTROL VOLUME IN SCFM

1.036 = LBS OF OXYGEN PER HOUR PER 1 SCFM

OTE_F = GAS PHASE OXYGEN TRANSFER EFFICIENCY UNDER PREVAILING CONDITIONS BY OFFGAS ANALYSIS LBS OXYGEN TRANSFERED/LBS OXYGEN SUPPLIED

454,000 = MG/LB

DO TRANSPORT = (DO_{OUT} - DO_{IN})(Q_M)(60)(3.785) {MG/LHR}

Q_M = LIQUID FLOW RATE THROUGH CONTROL VOLUME IN GAL/MIN

3.785 = LITERS/GAL

VOLUME OF CONTROL ZONE = LITERS

$$\frac{\Delta \text{ DO CONCENTRATION}}{\text{TIME}} =$$ END OF OBSERVATION PERIOD DIVIDED BY OBSERVATION TIME IN HOURS. AT STEADY STATE CONDITIONS THIS TERM IS ZERO SINCE DO IS ZERO.

APPENDIX IV

AERATION PAPER BY CEMAGREF

OXYGEN TRANSFER UNDER PROCESS CONDITIONS IN AN OXIDATION DITCH EQUIPPED WITH FINE BUBBLE DIFFUSERS AND SLOW SPEED MIXERS

OXYGEN TRANSFER UNDER PROCESS CONDITIONS IN AN OXIDATION DITCH EQUIPPED WITH FINE BUBBLE DIFFUSERS AND SLOW SPEED MIXERS

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ABSTRACT

Offgas tests were conducted at Milly la Forêt wastewater treatment plant, a low loaded oxidation ditch equipped with fine bubble diffusers and two banana blade mixers. These experiments showed a heterogeneity in Standard Oxygen Transfer Efficiencies along the tank. This can be related to differences observed on air flow rate per grid of diffusers. From a practical point of view, this implies that the offgas sampling pattern may include Oxygen Transfer Efficiency measurements on each grid of diffusers. Moreover, improvement in oxygen transfer due to horizontal liquid velocity was observed. The degree of Oxygen Transfer Efficiency improvement was approximately 20 % for a velocity of 0.4 m/s, which is less compared to the observed 40 % enhancement in clean water under the same aeration and mixing conditions. Presence of surface active agents may explain this difference. Finally, estimated alpha values are in the range of 0.60 to 0.64 with the mixers on and 0.75 to 0.78 with the mixers off.

KEYWORDS

activated sludge, fine bubble, horizontal velocity, off gas method, alpha factor, extended aeration

INTRODUCTION

Over the last few years, France has seen a multiplication of diffuser aeration systems (synthetic micro perforated membranes) coupled with mixers. The dissociation of the aeration and mixing functions has several advantages : it enables an improvement in mixing (DUCHENE and HEDUIT, 1990) and a greater elimination of nitrogen (DUCHENE, 1989). Moreover, it increases the oxygen transfer efficiency : in clean water, an increase in the oxygen transfer capacity of 40% to 50% was observed in different oxidation ditches by implementing a horizontal velocity of 0.4 m/s, for a water depth in the range of 2.2 to 4.65 m (DERONZIER *et al*, 1996). Few studies have been made on the influence of the mixed liquor rotation on oxygen transfer under process conditions.

The purpose of this paper is to present the initial results obtained in the oxidation ditch of Milly la Forêt. The oxygen transfer efficiency was determined by the off gas method (REDMON and BOYLE, 1981, REDMON *et al.*, 1983, EWING *et al.*, 1988 BOYLE *et al.*, 1989), which enables measurements to be taken without disturbing the operation of the aeration tank. This paper relates to the application of the off gas method to the particular case of oxidation ditches, of which few details can be found in the literature. The influence of various factors (horizontal liquid velocity, air flow rate, diffuser layout) on the oxygen transfer is then examined.

METHODOLOGY

The measurements were performed in an oxidation ditch operating as an extended aeration system at Milly la Forêt (France). The oxidation ditch, illustrated in diagrammatic form in Figure 1, is equipped with 720 SANITAIRE 9' EPDM diffusers, supplied with air by a ROBUSCHI/RB 80 blower. Agitation is provided by two FLYGT type 4430 mixers, 2 m in diameter, mounted side by side. A variable frequency drive (10 - 50 Hz) was used to adjust the horizontal liquid velocity.

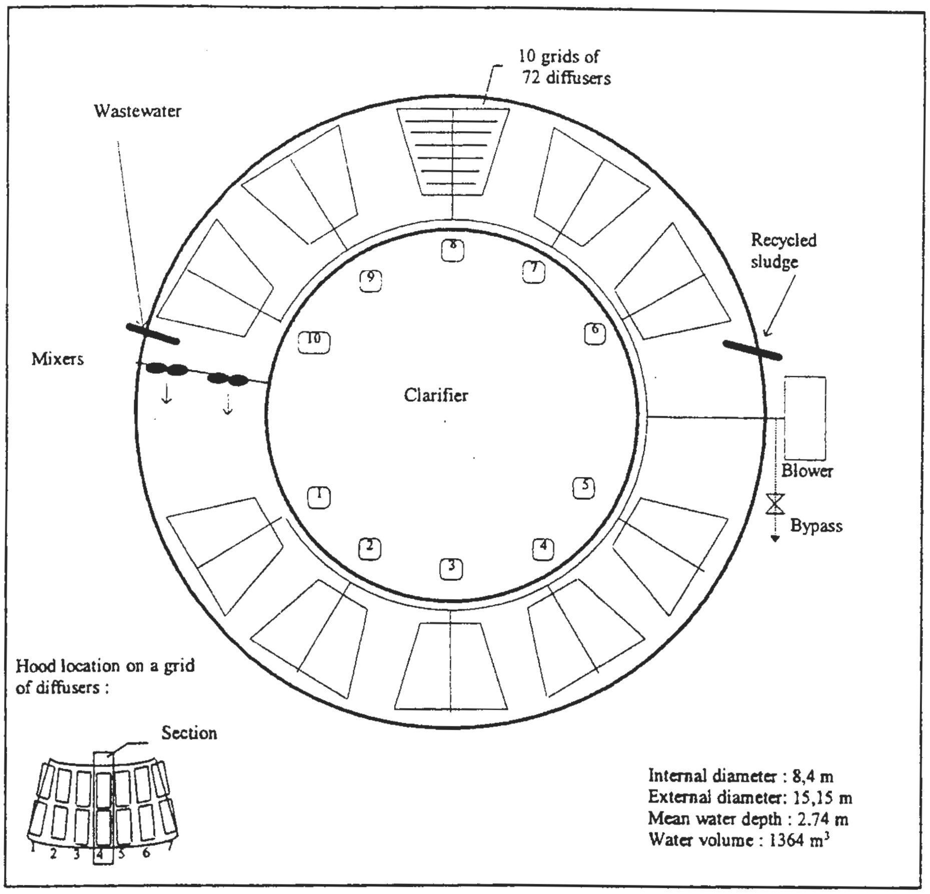

Figure 1. Milly la Forêt oxidation ditch

The velocity of the liquid (v) was determined using an OTT CE hydrometric propeller placed in one section of the ditch, away from all major perturbation. The measurements were recorded at 20 points, regularly distributed over the section, with the aeration stopped.

The air flow rate to the basin (q_e) was measured using an orifice plate. Results are expressed at 20 °C, 1013 hPa and divided by the number of diffusers to yield air flow rate per diffuser (m^3/h.dif.).

The Oxygen Transfer Efficiency (OTE) was measured from offgas analysis. Offgas was collected using a wood and polystyrene hood with a surface area of 2 m². The oxygen partial pressure of the gases, together with the offgas flow rate were determined by the EWING ENGINEERING MARK V analyzer, according to the procedure defined by REDMON *et al.* (1983). The dissolved oxygen concentration in the oxidation ditch was measured by 2 amperometric oxygen probes (YSI 57).

The Oxygen Transfer Efficiencies presented are expressed under standard conditions as Standard Oxygen Transfer Efficiencies (SOTEs), i.e. a dissolved oxygen concentration of 0 mg/L, a temperature of 20°C (or 10 °C), and a pressure of 1013 hPa.
The average Standard Oxygen Transfer Efficiency of a grid or of the aeration system was obtained by weighting the SOTE values by the offgas flow rates collected at each sampling point.

The first purpose of this work was, on the one hand, to study the variations in the Standard Oxygen Transfer Efficiency along a grid of diffusers, and on the other hand to determine the minimum number of gas sampling points and their location, to account for the average SOTE of the aeration system.

To reach these objectives, the variations in the Standard Oxygen Transfer Efficiency were studied :
- over one and the same grid, for different air flow rates :
    - with the 10 grids operating with mixers on ;
    - with the 10 grids operating with mixers off ;
    - with one grid out of two (1, 3, 5, 7 and 9) operating with mixers on ;
- over the entire oxidation ditch.

The influence of the horizontal flow velocity, of the air flow rate and of the diffuser layout on the oxygen transfer were then assessed for three configurations of the aeration system (see Figure 1) :

- configuration 1 : the 10 grids of 72 diffusers operating ;
- configuration 2 : one grid out of two operating (1, 3, 5, 7 and 9) ;
- configuration 3 : four consecutive grids operating (1,2, 3 and 4).

RESULTS AND DISCUSSION

1) Evolution of the Standard Oxygen Transfer Efficiency along a grid of diffusers

After verifying that the Standard Oxygen Transfer Efficiency was constant on one sampling point during the course of the test day, the SOTE was measured at different hood locations on a grid of diffusers (grid 2). Fourteen to sixteen sampling locations were required to collect all the offgas from the studied grid. Results are presented on Figures 2 to 4. Each point on the graphs represents a sampling point (2 per section, see sampling plan on Figure 1).

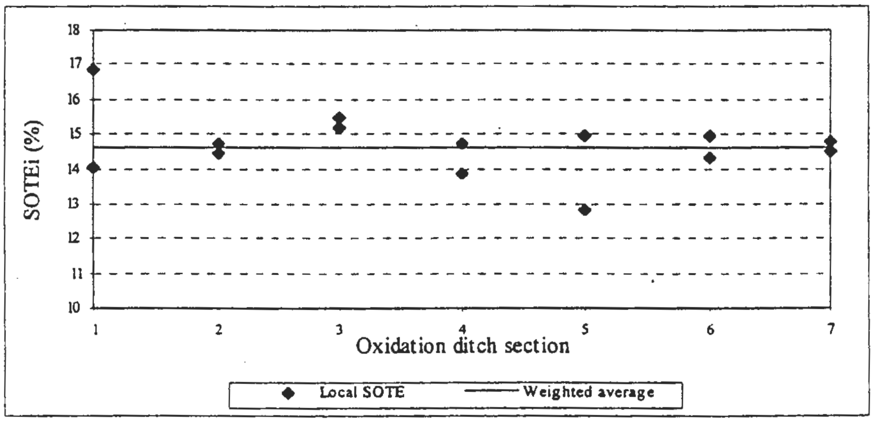

Figure 2. SOTE along grid 2 with all grids operating, v=0.33 m/s, q_e = 1.3 m^3/h.dif.

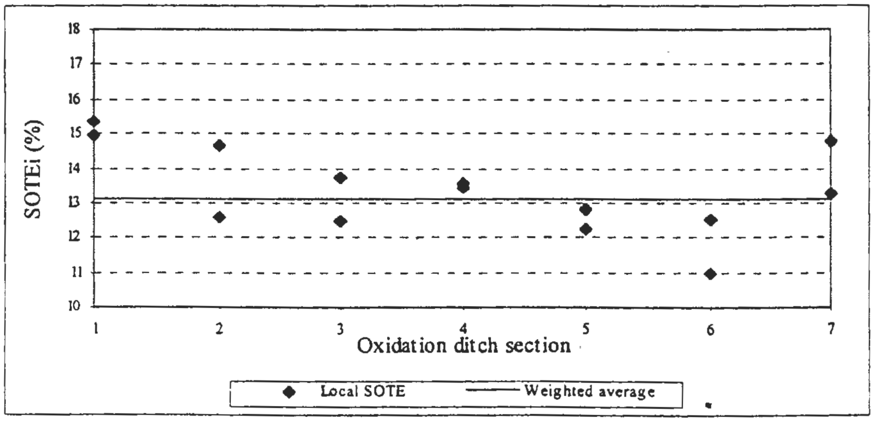

Figure 3. SOTE along grid 2 with all grids operating, v=0 m/s, q_e = 1.3 m^3/h.dif

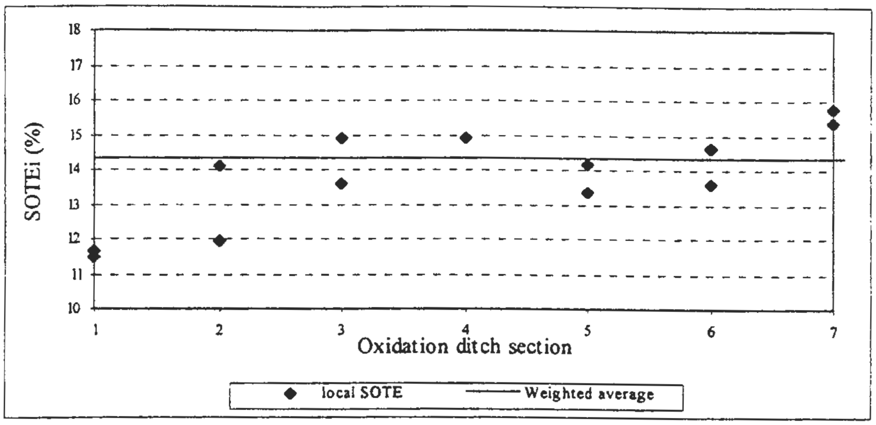

Figure 4. SOTE along grid 2 with 1 grid out of 2 operating, v=0.33 m/s, q_e = 2.2 m^3/h.dif.

When all the diffusers are in operation, in the presence of horizontal flow (Figure 2), the Standard Oxygen Transfer Efficiency is constant along a grid of diffusers. This is also the case with mixers off (see Figure 3), if the extreme points of the grid are excluded.

When one grid out of two is in operation (see Figure 4), the Standard Oxygen Transfer Efficiency increases in the direction of the current along the grid. It is, however, practically homogenous if the extreme points are excluded.

The number of sampling points required per grid of diffuser to obtain the average SOTE of the grid was determined in view of the results, taking initially 4 sampling points, on two symmetrical sections in relation to the center of the grid and excluding ends of the studied area : the differences between the average Standard Oxygen Transfer Efficiency obtained from 4 hood locations and the overall SOTE, determined from all the hood locations, are less than 3%.

These results obtained from measurements on grid 2 have been confirmed on grid 4.

2) Evolution of the Standard Oxygen Transfer Efficiency along the oxidation ditch

The Standard Oxygen Transfer Efficiency of the whole aeration system was determined from 4 hood locations per grid. Figure 5 presents weighted average SOTE values and air flow rates collected (q_s) on each grid.

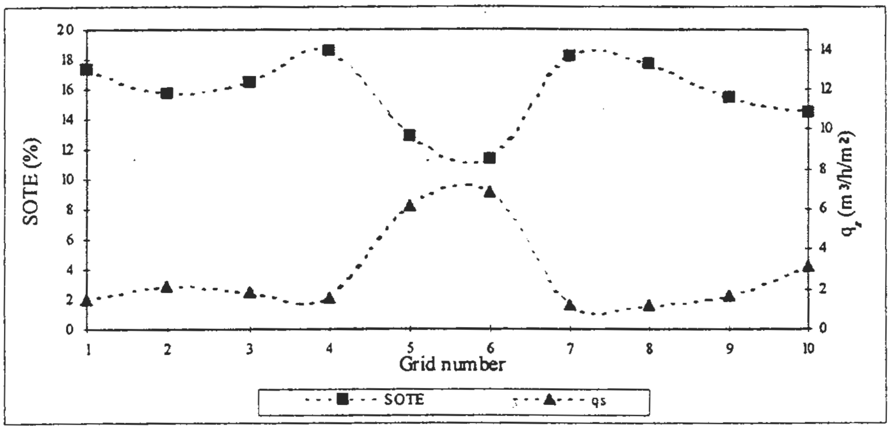

Figure 5. SOTE variation along the oxidation ditch, 10 grids operating ; v = 0.33 m/s; q_e = 1.3 m^3/h.dif.

The SOTE is not homogenous along the ditch. It depends on the air flow rate collected at each grid. The lower the air flow rate, the higher the Standard Oxygen Transfer Efficiency. For two identical air flow rates collected, the SOTE is the same. The weighted average SOTE corresponding to the entire aeration system is of 14.5 %.

3) Statistical influence of the number of grids investigated and of the number of sampling points per grid on the SOTE determination

Starting from the experimental data set consisting of 4 air flow rate/SOTE values per each grid (40 data), the weighted average ($SOTE_{wa}$) values of the aeration system were determined from random draws with replacement.
In the first case, $SOTE_{wa}$ was determined from a sample of 2 points (air flow rate and SOTE values) drawn on all the ten grids (20 draws with replacement). In the second case, $SOTE_{wa}$ was determined from a sample of 4 points (air flow rate and SOTE values) drawn on 5 grids previously determined from a random draw (20 draws with replacement).
Figure 6 presents histograms obtained from 500 draws in each case.

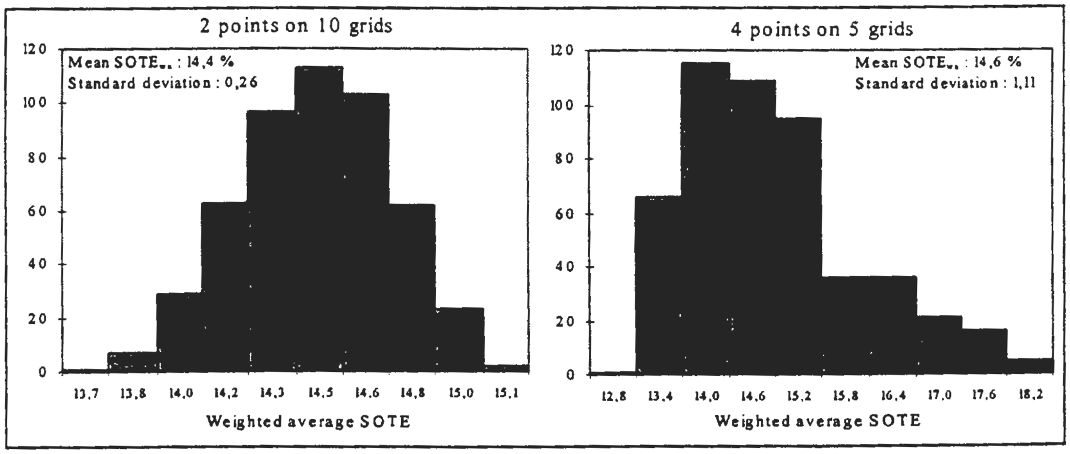

Figure 6. $SOTE_{wa}$ distribution in relation to sampling points

The confidence interval of 90% obtained from a random draw with replacement of 2 sampling points on 10 grids corresponds to a statistical accuracy (ratio of the difference of $SOTE_{wa}$ values limiting the confidence interval over the mean $SOTE_{wa}$ of the sample) of 5.9 %, whereas that obtained from a draw of 4 points on 5 grids corresponds to an accuracy of 25.5%

For an identical number of SOTE measurements, it is more advisable to sample each grid of diffusers, to take account of the heterogeneity of the oxygen transfer efficiencies along the ditch.

The distribution of the $SOTE_{wa}$ values obtained from a random draw with replacement of one, two, three or four sampling points per grid proves that the accuracy increases with the number of sampling points per grid. For a confidence interval of 90%, it is 8.4 %, 5.9 %, 4.9%, and 4.6% when 1, 2, 3 or 4 points per grid are taken. The statistical accuracy corresponding to 3 or 4 sampling points per grid are sufficient to determine the average Standard Oxygen Transfer Efficiency of the aeration system. Three sampling points correspond to 15% of the aerated area.

4) Influence of the horizontal flow, of the air flow rate and the diffusers layout on oxygen transfer

Figure 7 presents SOTE variations as horizontal velocity was increased from 0 to 0.45 m/s. Clean water measurements, previously performed according to non steady state clean water tests (DA-SILVA DERONZIER, 1994), are also reported on this graph.

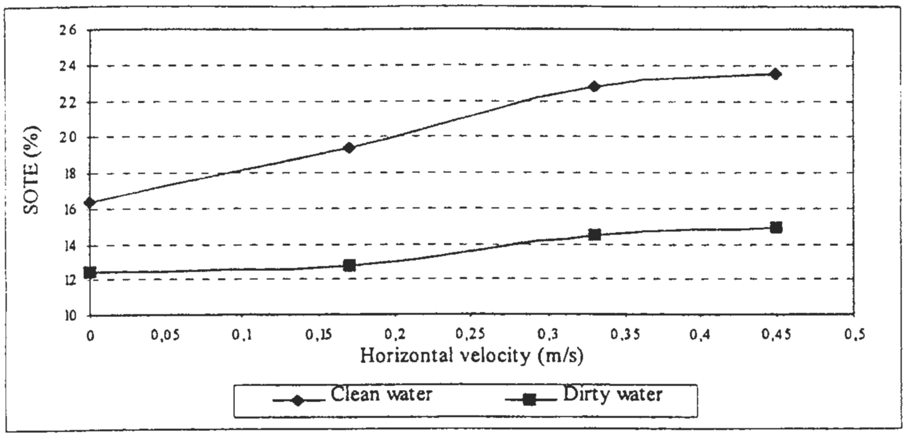

Figure 7. SOTE versus horizontal velocity, configuration 1, qe = 1.33 m^3/h.dif.

Oxygen transfer improvement due to a horizontal velocity of 0.45 m/s is of approximately 43 % in clean water and of 21 % under process conditions.

The influence of the number and the layout of the diffusers in operation and of the air flow rate per diffuser on the oxygen transfer is assessed by determining the alpha factor (See Table 1). The Standard Oxygen Transfer Efficiency under process conditions is compared to the clean water results.

Configuration	Air flow rate per diffuser (m^3/h)	Horizontal flow (m/s)	Alpha factor
1	1.3	0	0.75
1	1.3	0.17	0.63
1	1.3	0.33	0.61
1	1.3	0.46	0.62
2	2.2	0	0.78
2	2.2	0.33	0.64
3	3.4	0.33	0.61
3	4.5	0.33	0.60

Table 1. Alpha factor values determined at Milly la Forêt oxidation ditch

Alpha factor values are in the range of 0.75 to 0.78 when mixers are off. For a horizontal flow between 0.17 and 0.46 m/s, the alpha value is between 0.60 and 0.64, whatever the number of diffusers in operation and their layout, in the field of study concerned (immersion depth of the diffusers of 2.49 m, with an air flow rate per diffuser between 1.3 and 4.5 m3/h).

Such a decrease in the alpha factor, as a horizontal velocity is applied, may be induced by the presence of surface active agents.

In clean water, two mechanisms has been proposed to mainly explain oxygen transfer improvement with horizontal flow (DA SILVA-DERONZIER, 1994) :

- the specific interfacial area is enhanced by production of smaller bubbles, due to a shearing effect of the horizontal velocity on the nascent bubble ;
- horizontal velocity reduces the negative effect of spiral flows (increasing the upward velocity of the bubbles).

Both mechanisms yield to an enhancement of the air content and hence of the bubble residence time in the liquid.

Under process conditions, surface active agents, accumulated at the surface of gas bubbles, tend to make them smaller and more rigid, resulting in oxygen transfer decrease (STENSTROM and HWANG, 1979 ; HWANG and STENSTROM, 1985 ; BISCHOF *et al.*, 1993 ; WAGNER and POPEL, 1996). As a horizontal velocity is applied, several suppositions can be formulated :

- reduction of bubble size is lower compared to that in clean water, as it is already diminished by the effect of surface active agents ;

- bubble ascent is longer compared to no velocity. Surfactants have hence more time to be concentrated at the surface of gas bubbles, reducing oxygen transfer coefficient (K_L) ;

- threshold corresponding to the maximum oxygen transfer is reached for a lower horizontal velocity in dirty water than in clean water.

These remarks show that there is a need for further research work to better assess the influence of horizontal velocity on oxygen transfer.

CONCLUSIONS

The application of the off gas method to an oxidation ditch equipped with fine bubble diffusers and slow-speed mixers showed that :

- when all the diffusers are in operation, the Standard Oxygen Transfer Efficiency along a grid of diffusers is homogenous in the presence of an horizontal flow. Without horizontal flow, the SOTE is also homogenous except on the extremities of the grid.

- when the diffuser grids are spaced out (with one out of two operating), SOTE increases in the direction of the current in the presence of a horizontal flow.

- It may be necessary to sample each grid of diffusers, to take account of the heterogeneity of the Oxygen Transfer Efficiencies along the ditch. Two grids receiving the same air flow rate show identical efficiencies if they are symmetrically arranged in relation to the inlets of wastewater and recycled sludge, so initial measurements of the air flow supplied per grid would make it possible to minimize the number of grids to investigate.

- The statistical accuracy of the SOTE increases as the number of sampling points per grid of diffuser increases. At Milly la Forêt, three sampling points per grid are sufficient to determine the mean weighted Standard Oxygen Transfer Efficiency of the aeration system. This represents 15% of the aerated area.

- A horizontal velocity of approximately 0.4 m/s induce an oxygen transfer enhancement compared to no velocity. Under process conditions, the observed improvement is on the order of 20 %, substantially below the 40 % increase measured in clean water.

- The alpha factor determined when mixers are off is in the range of 0.75 to 0.78.

- With horizontal velocity, the alpha factor determined for different configurations of the aeration system reached 0.60 to 0.64 under process conditions. This value is independent of the number of diffusers in operation, of their layout and of the air flow per diffuser.
- These results are site specific and have to be confirmed on other aeration ditches.

ACKNOWLEDGMENTS

The authors would like to acknowledge ITT FLYGT for the modifications provided to Milly la Forêt oxidation ditch that allowed measurements to be carried out. They are also grateful to J. WREN (WATER POLLUTION CONTROL CORPORATION) and D.T. REDMON (EWING ENGINEERING COMPANY), for their help in conducting initial offgas tests at Milly la Forêt, and valuable discussion with them and W.C. BOYLE regarding the first results obtained.

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