UNIVERSITY OF CALIFORNIA, LOS ANGELES

Civil & Environmental Engineering Department

ENERGY-CONSERVATION IN FINE PORE DIFFUSER INSTALLATIONS IN ACTIVATED SLUDGE PROCESSES

(Contract Number: 500-03-001)

Final Report 2005-2007

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Legal Notice

Acknowledgement

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

What follows is the final report for the **[Contract Name], 500-03-001,** conducted by the **University of California, Los Angeles**. The report is entitled **Energy-Conservation in Fine Pore Diffuser Installations in Activated Sludge Processes**. This project contributes to the **[PIER Program Area]** program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Abstract

Aeration is the most energy intensive unit operation in municipal wastewater treatment. To improve oxygen transfer rate, fine-pore diffusers have been wildly applied in aeration practice. However, during operation, this type of diffusers suffers from fouling and scaling problems, which rapid decline in performance and significant increase in energy costs. Diffusers must be cleaned periodically to reduce energy costs. The cleaning frequency of diffusers is site-specific, and is shown by the reduction of oxygen transfer efficiency (OTE) with time in operation. Off-gas testing, developed by Redmon et al., 1983, is the only technique that can measure real-time oxygen transfer efficiency. The main reason that prevents wide-scale installation of off-gas monitoring equipment in wastewater treatment plants is complexity and cost of operation. By using the classic instrument, at least two operators are required to conduct the analysis. Therefore, this project developed a low-cost, easy-to-operate instrument to monitor OTE and to provide guidance for calculating energy consumption and wastage. This instrument is auto-calibrated and its operation does not require trained experts. In addition, experiment results of real-time monitoring in several full-scale treatment plants were analyzed to demonstrate the benefits of cleaning and to predict cleaning frequency.

1.0 Introduction

1.1 Background and Overview

Aerobic bacterial processes are the most common technology for municipal wastewater treatment. This type of processes uses bacteria to consume/oxidize the organic pollutants in wastewater. Since the metabolism of bacteria highly depends on the accessibility of dissolved oxygen (DO) in the processing water, aeration is generally the most essential and costly unit operation in a wastewater treatment plant. According to the California Energy Commission published report in 2005, the amount of energy used for wastewater treatment in California is 1,911 kWh/MG; and among this energy spends, around 45 to 75% (Rosso and Stenstrom, 2005), or approximately 1000kWh/MG, is used in aeration (background of activated sludge processes and aeration detailed in Appendix - section 1.0).

Aeration systems are mainly full-floor configurations of fine-bubble diffusers, due to their favorable oxygen transfer rate (OTR, kgO2/hr) per unit energy required (i.e., kgO2/kWhneeded). The main pitfall of this aeration methodology is fouling/scaling, which causes a decrease in oxygen transfer efficiency (OTE, %) resulting in an increase in the energy cost per unit oxygen transferred (Rosso and Stenstrom, 2006a). To quantify the decreasing of OTEs in processing conditions, several techniques were developed; and after 15-year's investigation, American Society of Civil Engineers (ASCE) published *Standard Guidelines for In-Process Oxygen Transfer Testing* in 1997. The Guidelines recommended three types of in-process water testing methods for diffused aeration system, which are 1) the non-steady method; 2) off-gas; and 3) the tracer racer method. Among these techniques, the major advance described by the Standard Guidelines is the off-gas analysis method, which was developed by Redmon et al (1983) under US EPA and ASCE sponsorship.

The off-gas technique uses an oxygen gas sensor to measure the oxygen mole fraction in the off-gas. By removing the carbon dioxide and water vapor from the off-gas, and assuming no change in nitrogen fraction, Redmon et al (1983) showed that the OTE could be calculated directly from the mole fraction measurements, and did not rely one volumetric gas flow rate.

Figure 1 shows a schematic of a set-up to perform off-gas testing. A portable hood is floated on the liquid surface and captures the gas bubbles that reach the surface. The gas flows through an analyzer that measures total gas flow and the oxygen mole fraction of a small slip stream of the gas. Even though the total gas flow is not needed for OTE measurement, it is desirable to measure it, which is usually done by withdrawing a measured flow that precisely balances the pressure under the hood (theory of off-gas test detailed in Appendix - section 2.0).

The main reason that prevents a wide-scale installation of off-gas monitoring equipment in wastewater treatment plants is complexity and cost of operation. As mentioned, the set of equipments of a classic off-gas test including the floating hood and off-gas analyzer requires at least two operators to conduct the analysis. In addition, the classic off-gas analyzer requires sophisticated manual calibration to access accurate readings, thus a crew of trained experts were mandatory to the off-gas tests.

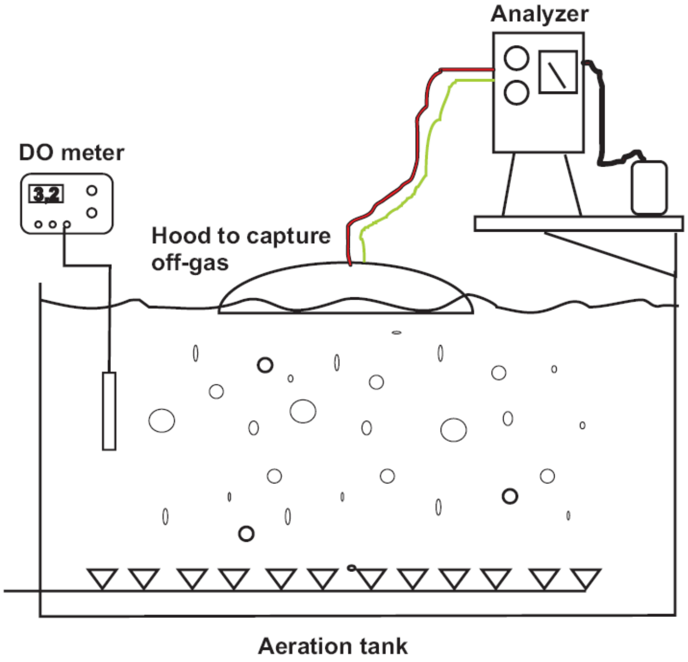

Figure 1. Off-gas test equipment schematic, showing hood, analyzer, DO meter and aeration tank.

1.2 Project Objectives

The goal of this project is to develop a portable, light-weight and simple to operate oxygen transfer efficiency monitoring device to help operators assess their aeration efficiency. To achieve this goal several objectives were performed:

- Develop and build lab-scale and field prototypes of OTE measuring devices
- Test extensively the prototypes in wastewater treatment plants (WWTPs)
- Build and test small-scale capture hoods
- Develop a field testing protocol for operators
- Verify the economic saving of cleaning frequency for fine-pore diffusers
- Create aerators' cleaning/maintenance schedules and protocols
- Utilize the OTE measurements for a process economic analysis

1.3 Report Organization:

1/1/2005-1/1/2006	Yearly report
1/1/2006-4/1/2006	Quarterly report
4/1/2006-7/1/2006	Quarterly report
7/1/2006-10/1/2006	Quarterly report
10/1/2006-1/1/2007	Quarterly report
1/1/2005-10/1/2007	Final report

2.0 Project Approach

In order to achieve the main goals of this project, following project approaches were accomplished by steps. Motoring protocols were first assembled and tested in the laboratory, where the experiment conditions are well-controlled and the lab-scale devices are more sensitive and can provide reference values to test the apparatus. Based upon the lab-scale tests, bread-board version field-scale analyzers were built. These prototypes were tested in the selected full-scale wastewater treatment plants of Northern and Southern California.

2.1 Lab-scale protocol and experiment

The lab-scale oxygen apparatus (shown in Figure 2) used in the lab-scale experiment is a full-featured unit with precise and accurate measurements for a wide range of measuring scales, thus allowing fine-tuning, debugging, and sensitivity analysis. The laboratory analyzer because of its sophistication, is rather costly. The portable, light-weight, and low cost fuel cell prototype unit to be used in the field will be tested by this apparatus.

The lab-scale protocol and experiment was set up as with the apparatus shown in Figure 3. A column 5-ft deep with 7-in diameter was used as batch reactor and a fine-pore membrane, collected from full-scale system was used as the air diffuser. A DO probe was placed in the water and a capture hood covered the top of the column. The hood collects and conveys the off-gas stream to an oxygen cell analyzer. Analog voltage signals were produced by both the DO meter and the oxygen cell and recorded by a data logger.

The experiment procedure basically follows the standard of clean water test published by ASCE, 2006. Sodium sulfite is used to scavenge dissolved oxygen according to the reaction:

$$Na_2SO_3 + \frac{1}{2}O_2 \xrightarrow{CoCl_2} Na_2SO_4 \tag{1}$$

Following the oxygen removal by oxidation of sodium sulfite which occurs almost instantaneously, the aeration device provides air to the batch system and oxygen continues to be consumed according to the stoichiometry in Eq.2, and when the excess sodium sulfite is completely converted into sulfate, the system experiences re-aeration. By analyzing the slope of the DO re-aeration curve or the oxygen fraction in the off-gas, the oxygen transfer coefficient kLa can be calculated.

Figure 2. Lab-scale off-gas testing apparatus (Teledyne 9070 O_2/CO_2 analyzer) used in our laboratory.

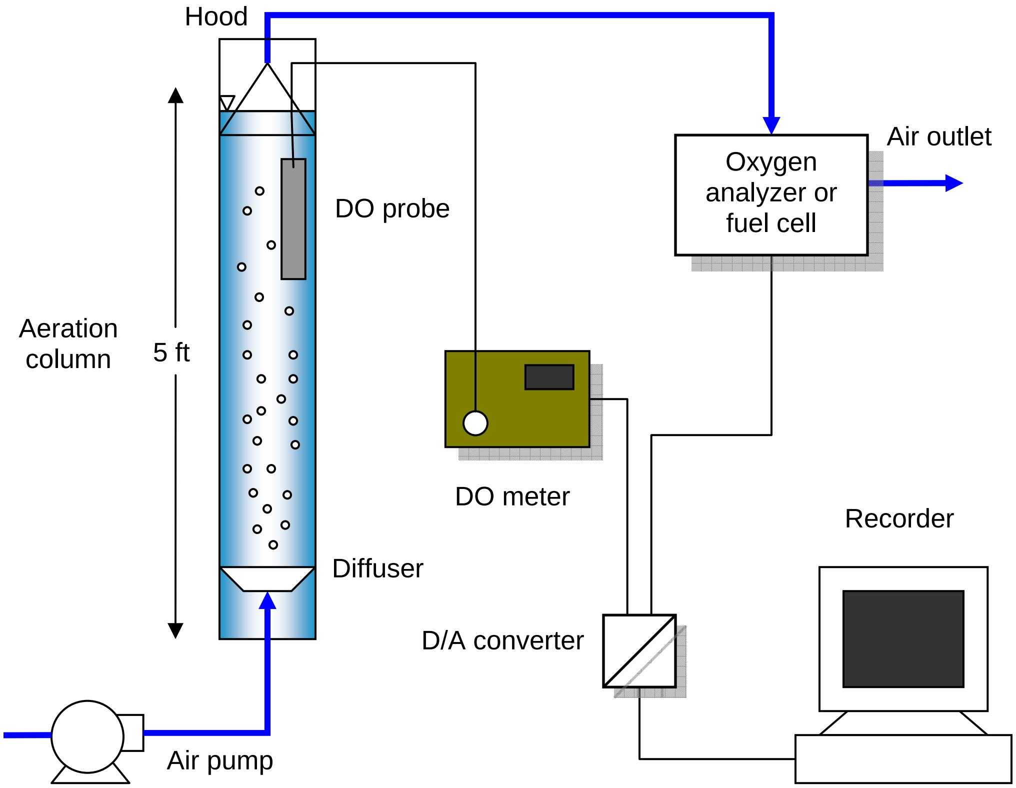

Figure 3. Schematic of a lab-scale off-gas testing apparatus

2.2 Design and Assembly of Field Prototype

Several units of field prototypes were assembled for plant testing and consequent distribution. The field unit will be designed and packaged for plant installation, i.e. it will be smaller (about the size of a shoebox), of simple design, user-friendly, and low-cost (~$2,000). This apparatus will be able to measure data in a narrower range than the lab-scale analyzer. The goal of the lab-scale system is to find and center the measuring range for the DO values to be used by the field unit within the ASP.

Figure 4 shows the schematic of the automatic off-gas analyzer. This design incorporates the highest simplification of off-gas measuring, hence maintains the measuring accuracy as the original device (Redmon et. al., 1986). A three-way valve controlled by a time-delay relay switches the connection in time-sequence from either the off-gas or the reference air into an O_2 fuel cell, which the air flow is driven by off-gas itself and a lab-scale vacuum pump (300 ml/min, or 2 in. Hg). The O_2 fuel cell returns a voltage proportional to the O_2 partial pressure in the gas stream. For each measuring event, reference air and off-gas are compared, which calibrates the instrument with each measurement. The off-gas flow rate is calculated by measuring the air velocity in the air hose and recorded for each measurement, to allow a flow-weighted average of the entire aeration tank. Our full-scale testing modules produced an aeration efficiency database, which complements our previous extensive off-gas experience (Rosso et al, 2005).

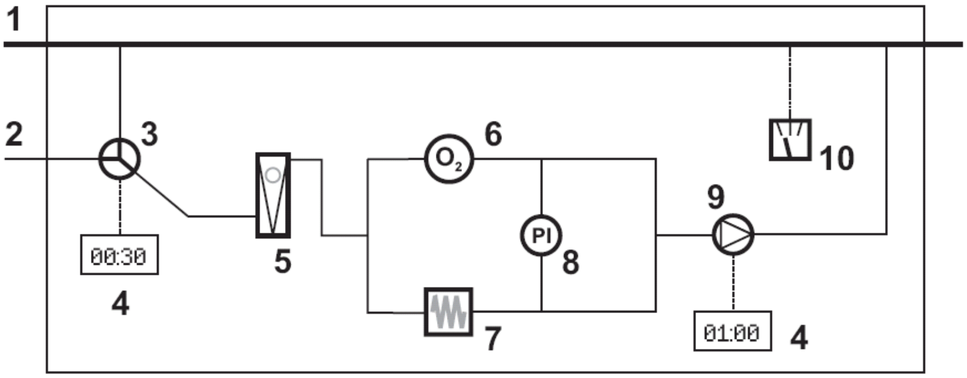

Figure 4. Schematic of the real-time automated off-gas analyzer. Key: 1) off-gas hose (from collection hood); 2) reference air intake; 3) 3-way valve; 4) time delay relay; 5) flow meter; 6) oxygen fuel cell; 7) resistance; 8) differential manometer; 9) vacuum pump; 10) air velocity meter. Solid lines are hydraulic lines, dashed lines are electrical connection

2.3 Field experiments – 24 hour test

Field experiments were performed in a full-scale WWTP to illustrate the capability of real-time off-gas monitoring and to test our field prototype. The volumetric flowrate of this plant is approximately 10MGD. Figure 5 shows the schematic diagram of this plant and the testing hood positions. The plant contains four process tanks (19 feet in depth), each with four small anoxic sections and two aerobic sections. Before secondary treatment, an extra basin equalizes the flow of primary effluent, and the MLE pumps to recycle the process water are equipped at the end of process tanks. Following the process tanks are two aerated polishing tanks (15 feet deep). The aerobic zones of process tanks and polishing tanks both are equipped with a fine-pore, strip type diffuser system.

Two 24-hour tests were performed using both the original (manual) and our bread-board field-scale prototype unit. The first test was performed on the aeration tank 5 months after the diffusers were installed and the second test was 8 months later, immediately after a cleaning process of diffusers. Both results were compared to a reference test performed 1 month later than the diffuser installation. The off-gas hood positions were in the middle position of the two aerobic sections and the first section of the polishing tank. The experiments measured the OTE, air flow, and off-gas temperature. Primary effluent samples were collected hourly to calculate the pollutant load as rate of oxygen demand. The power requirement and the potential costs/benefits were calculated by the integrated total oxygen transferred, where the main assumptions are $0.15/kWh of power cost and the annual interest rate = 4%.

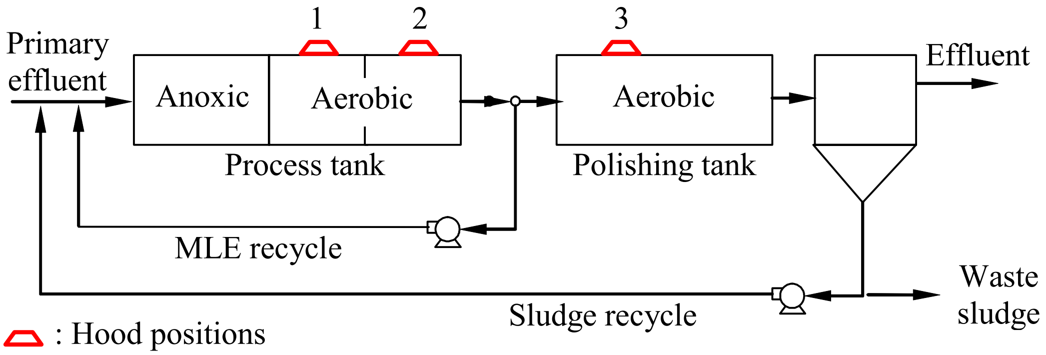

Figure 5. Schematic Diagram of the Nitrifying-Denitrifying Treatment Plant (headworks, primary clarifier, equalization basin and disinfection facilities not shown)

2.4 Applications in California

The off-gas field testing apparatuses will be tested in selected WWTPs. Table 1 summarizes the list of locations. Small (2x2') capture hoods will be built and placed in situ for data gathering. The final hood design will most likely integrate the field-scale analyzer onto the top of the hood as one single compact testing unit.

Table 1. Testing locations.

Plant	Location	Process layout	Aeration equipment
Proposed First Choice Plants			
LA Glendale	City of Los Angeles, Bureau of Sanitation, Glendale, CA	Conventional, NDN*	9" membrane and ceramic discs
Whittier Narrows	Los Angeles County Sanitation Districts, Whittier, CA	NDN	9" membrane and ceramic discs
Central Contra Costa	Central Sanitary District, Martinez, CA	Plug Flow Conventional	14" ceramic discs
SOCWA Regional Plant	Laguna Niguel, CA	NDN	Parkson panels
Simi Valley	City of Simi Valley, CA	NDN	Aerostrip panels
Alernates			
Tillman	City of Los Angeles, Van Nuys, CA	Conventional, NDN	Ceramic Domes and Discs
San Jose Creek	Los Angeles County Sanitation Districts, Whittier, CA	NDN	9" membrane and ceramic discs
West County	Richmond, CA	Nitrifying only	7" Norton Domes

*: NDN – nitrification and denitrification

3.0 Project Outcomes

In this section, the results of lab experiments and field tests were presented in § 3.1 and § 3.2, respectively. The lab experiments include a membrane cleaning study and the test results of the lab-scale protocol. The membrane test visualized and quantified the effects, and hence the importance, of diffuser cleaning. Field experiments were preformed in the selected full-scale wastewater treatment plants. The results of these 24-hour field tests were compared with our long-term observation (Rosso et al., 2005, 2006a, 2006b), which provided useful information to the development of our real-time monitoring system.

In addition, economic analysis of aeration costs was performed as a case study based upon our field experiments in the selected treatment plant. To clearly present the potential benefit of diffuser cleaning, energy savings was calculated and presented in total power and dollars. The design layout and field-scale prototypes built were presented in § 3.3; and § 3.4 shows the results of lab- and field- scale tests of these prototypes. In the final subsection § 3.5, several cases studies from full-scale WWTPs in California were presented. The potential energy savings that could be provided by the monitoring technique were performed in actual numbers, such as unit wastewater treated and capital cost in California.

3.1 Lab experiments

3.1.1 Membrane cleaning experiment

This experiment was performed to illustrate the improvement of aeration performance after diffuser cleaning. Figure 6 shows a half-cleaned diffuser. This diffuser was collected from a local treatment plant operating at low mean cell residence time (MCRT). Before cleaning, the membrane was covered by a layer of biomass and living worms (left side). Then half of this diffuser was cleaned by manual scraping and tap water rinsing. The result can be easily observed: totally different sizes of bubbles are produced from the same diffuser. Before cleaning, bubble diameters are about 4 mm, and reduced to 1-2 mm after cleaning. Smaller bubbles provide a larger specific surface area and therefore higher transfer efficiency.

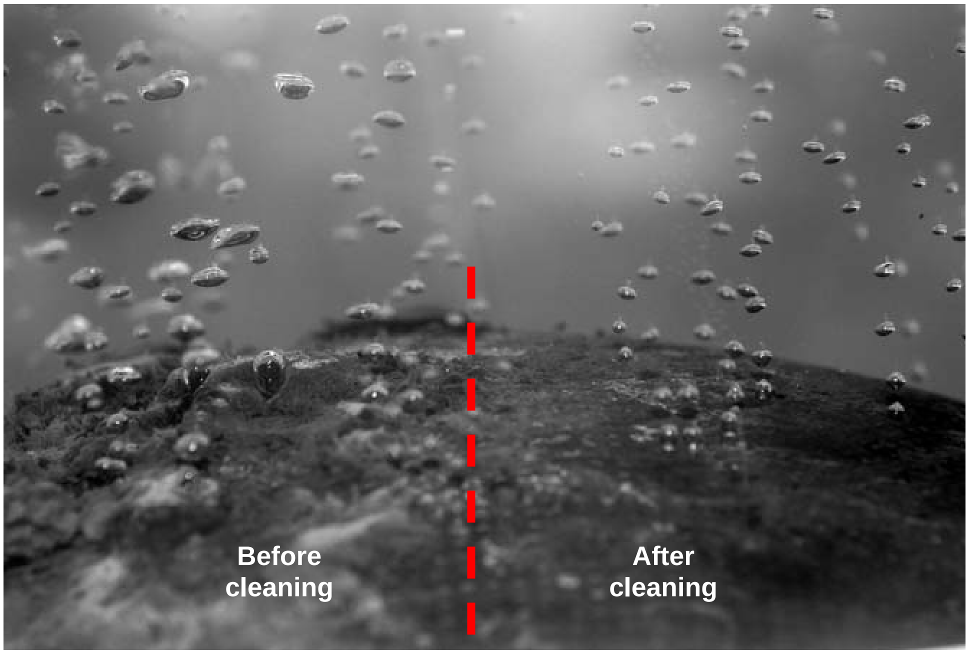

Figure 6. Photograph of a half-cleaned diffuser: before cleaned (left part of the diffuser) the diffuser was covered by a layer of biomass and the bubbles produced are big; after cleaned (right) the bubbles turn to smaller, similar to a new diffuser.

Clean water tests and dynamic wet pressure (DWP) tests were applied to confirm the former assumption. Same diffusers were tested before and after cleaning with tap water and acid. Figure 7 shows the results of this test. After cleaning, the gas transfer coefficient recovered significantly; acid cleaned diffusers recover their efficiency values and approach new diffusers' performance. DWP tests also show similar results for headloss variations: uncleaned diffusers show a dramatic increase in headloss, while cleaned diffusers maintain a more moderate increase (Figure 8). However, no significant difference was found between cleaning methods. Acid cleaning may not be effective for opening bio-fouled pores but effective for removing inorganic scales formed on the pores before complete fouling.

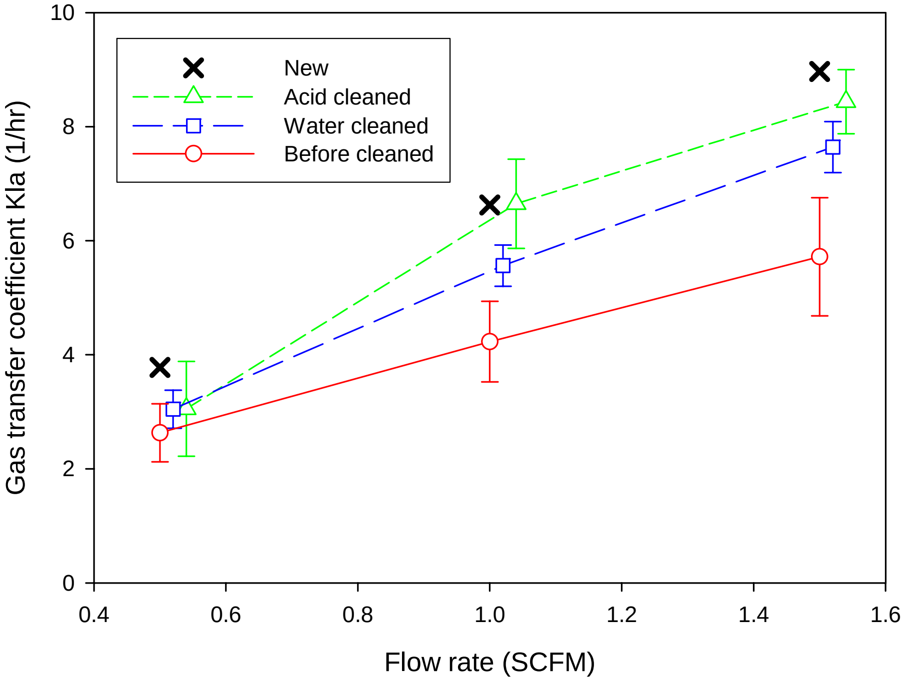

Figure 7. Comparison of oxygen transfer efficiency of uncleaned, water cleaned, and acid cleaned diffusers

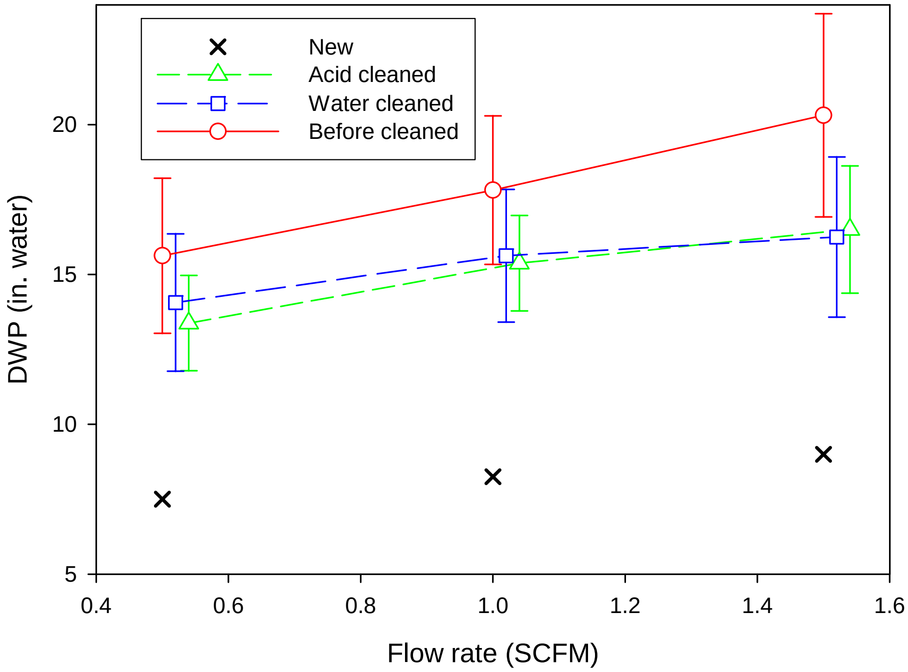

Figure 8. Comparison of headloss for uncleaned, water cleaned, and acid cleaned diffusers.

3.1.2 Lab-scale protocol

The dynamic status of the DO and the off-gas oxygen fraction is shown in Figure 9. Same patterns of DO and off-gas oxygen fraction can be observed, showing that the oxygen in the water is first segregated and then dissolved. In Figure 9, the first rapid decline of dissolved oxygen concentration corresponds to the addition of sodium sulfite and cobalt chloride. After a steady-state plateau, where the excess sulfite is converted to sulfate (Eq. 1), the DO concentration increases (re-aeration process).

Tank depth shows the most significant effect in our sensitivity analyses. Using a 5-ft deep reactor, during the steady-state oxygen scavenging (pink plateau in the graph) the oxygen fraction in the off-gas is 18.07% (green plateau in the graph). The difference between this value and the O_2 ambient concentration (20.99%) is large enough to be accurately recorded. Previous experiences using a 2-ft deep tank showed a difference in O_2 concentration between the off-gas and the ambient too small to be quantified. In a 2-ft tank, bubbles require less than 1 second transporting from diffuser to water surface. The short retention time makes the difference of off-gas and ambient not measurable. This difference becomes obvious when water is deeper than 5 feet. Since the depth of aeration tanks are much larger than 5 feet, the difference of oxygen concentration in influent air and off-gas is definitely measurable and serves well as an index of oxygen transfer.

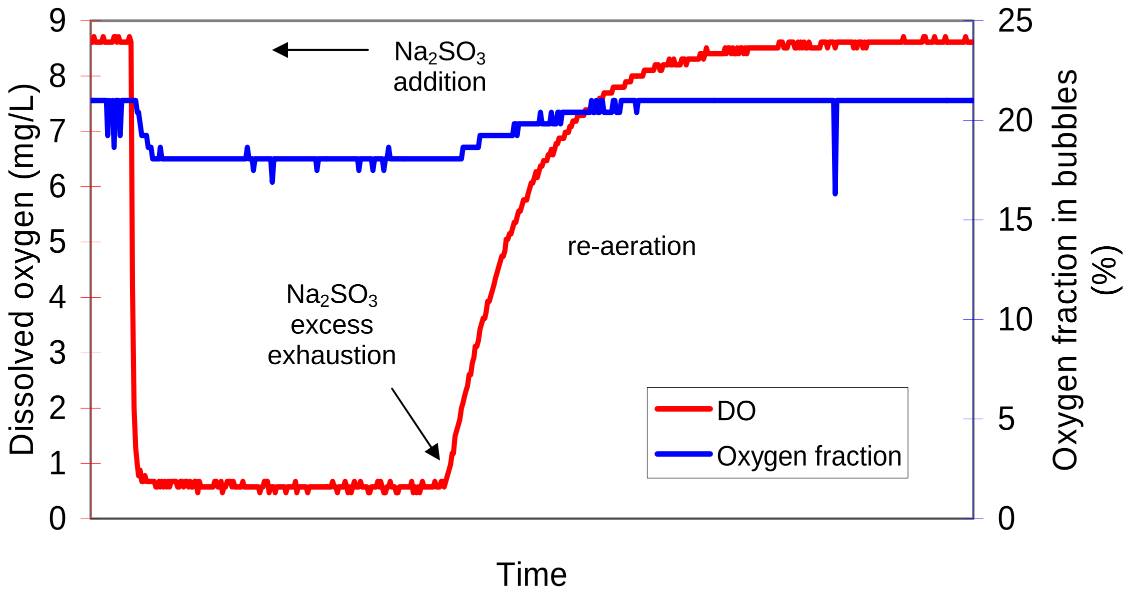

Figure 9. Dynamic status of dissolved oxygen and oxygen fraction in off-gas of a clean water test.

3.2 Field experiments

3.2.1 Results of 24-hour test

Figure 10 (a) shows the behavior of OTE compared to the air flow rate over a 24-hour cycle: when the air flow rate is at its maximum, OTE is at its minimum, and vice versa. The air flow rate is highest when the oxygen demand (i.e., the carbonaceous COD or C-COD) is highest, which is reflected in low OTE and low alpha values. In addition, alpha-factors calculated from αSOTE (measured with the off-gas technique) and manufacturer's clean water data (SOTE) are shown in Figure10 (b). Although diurnal cycles of OTE measurements were reported previously (Libra et al., 2002), this is the first report of time-series for alpha factors. The patterns of alpha and carbonaceous COD (C-COD) have analogous behavior as OTE vs. air flow rate (AFR). This result shows that the off-gas reading (OTE) carries valuable information on AFR and load. For a given load, the off-gas signal can be used as a feedback control to regulate AFR to its minimum possible value, yet achieving the same level of treatment, and to predict the influent load concentration.

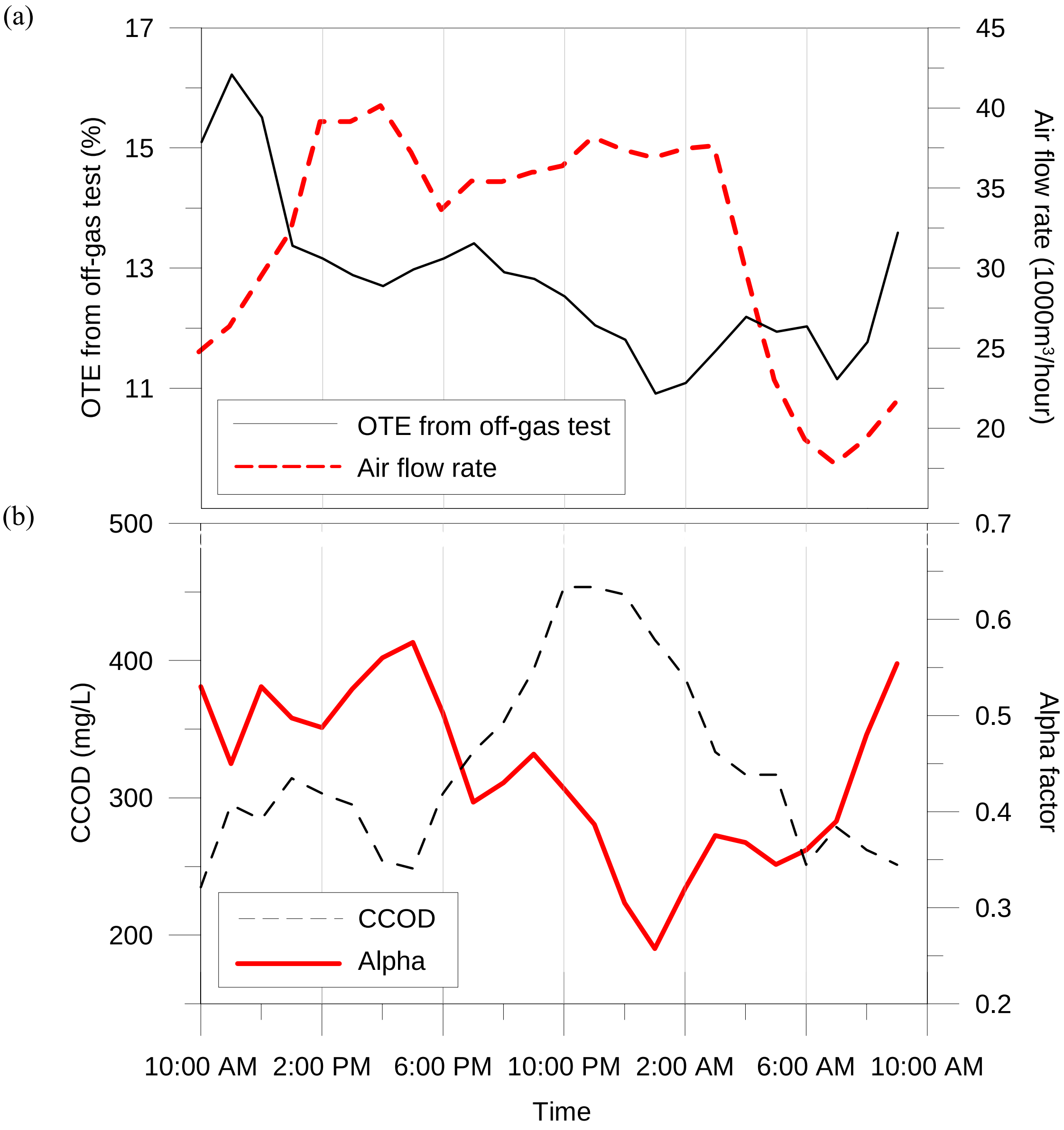

Figure 10. (a) Oxygen transfer efficiency (OTE) and air flow rate calculated from off-gas testing during a 24-hr. (b) Carbonaceous COD (C-COD) and alpha-factor estimated from off-gas analysis, during the same period.

3.2.2 Comparison of real-time data with long-term observation

Figure 11 shows the correlation between the alpha factor and air flux (air flow rate per unit of diffuser area, $m^3 \cdot s^{-1} \cdot m^{-2}$). The results were calculated from three different experiments: one clean water test and two process-water off-gas tests. In both off-gas tests, the results of a short term 24-hour measurements of αSOTE are negatively correlated with the air fluxes, which confirmed our previous long-term studies (Rosso et al., 2005). In addition, αSOTE is approximately half of the clean water SOTE (labels on the graph). The process water αSOTE has different pattern for different time in operation: diffusers that have been in operation for a longer period without cleaning are fouled, which is shown by a more rapid decline in performance with increasing air flux (labelled “before cleaning” in Figure14).

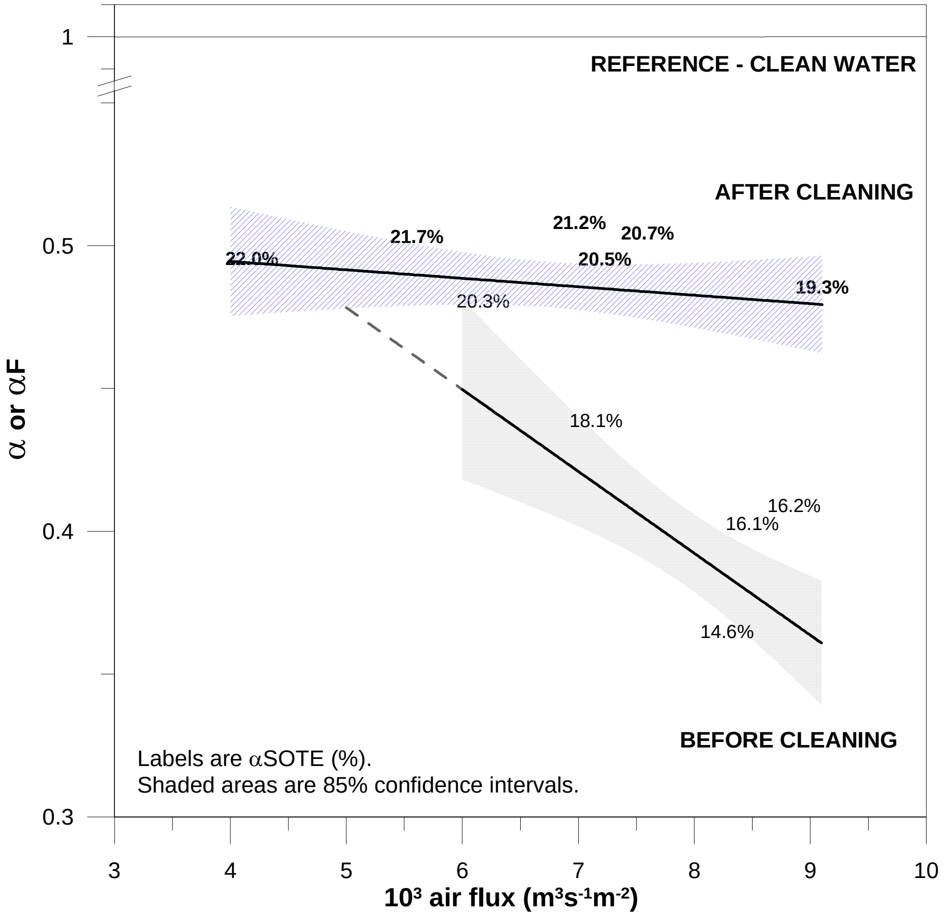

Figure 11. Correlation between standard oxygen transfer efficiency (SOTE) and diffuser air flux (curve zones represents 95% confidence, Leu et al., 2007).

3.2.3 Energy expenditure

Table 2 shows the aeration tank characteristics, the oxygen transfer data gathered from off-gas tests, and the energy consumptions calculated with our plant-cost algorithm (Rosso and Stenstrom, 2006a). Our results suggest that the cleaning procedure improves oxygen transfer efficiency from 16.1% to 18.6%, thus reducing demand requirements from 235kW to 193kW, or corresponding energy costs from $850 /day to $695/day (based on $0.15/kWh and 24 hours a day). Since the first test was performed 8 months before cleaning and the diffuser fouling could be more serious during this period, the actual total saving must be greater than the number calculated.

Table 2. Results of off-gas tests and energy cost estimation

Tests	Results or properties	Process Tank (×4)		Polishing Tank (×2)	Total
		Section 1	Section 2		
Background	Section dimension (m^2)	17.3 × 28.8	17.3 ×28.8	85.3×11.4	1969
	Depth (m)	5.8	5.8	4.5	-
	Number diffusers	71(×4)	56(×4)	127(×2)	762
Test 0 (Reference)	Air flow rate (m^{3}s^{-1})	1.49	0.87	0.38	2.74
	αSOTE (%)	17.5	18.3	18.9	-
	Power/OTR (kWh/KgO$_2$)	0.13	0.10	0.29	0.13
Test 1 (Before cleaning)	Air flow rate (m^{3}s^{-1})	1.34	1.01	1.00	3.35
	αSOTE (%)	15.8	16.3	13.4	-
	Power/OTR (kWh/KgO$_2$)	0.14	0.13	0.34	0.17
Test 2 (After cleaning)	Air flow rate (m^{3}s^{-1})	1.16	0.89	0.70	2.75
	αSOTE (%)	18.6	18.5	10.82	-
	Power/OTR (kWh/KgO$_2$)	0.13	0.12	0.44	0.15

The results of the 24-hour tests confirm our long-term observation that alpha factor is affected by load of contaminants, and OTE is negatively correlated with air flow rate (Rosso et al., 2005); detailed discussion has been shown in Leu et al., 2007. This paper further calculated the power costs of the experimental WWTP. Based upon our former studies (Rosso et. al., 2005, 2006), it is suggested that the fine-pore diffusers should be cleaned at least once per 1 to 2 years. Since diffuser fouling is a long-term process that the increase of power consumption is described in monthly basis; the results of our hourly measurement were integrated to calculate the daily oxygen supplied and transferred.

Figure 12 shows the total power consumption, the costs due to diffuser fouling, and the benefits gained by diffuser cleaning. The gray zone represents the total power consumption, which is equal to the basic power requirement (initial value, approximately 500kWh/million gallon wastewater treated in the figure) plus the power wasted due to diffuser fouling, and the dash line is the predicted value based on the current observations. The red bars represent the normalized costs of power wasted (e.g. annual cost in dollars per million gallon wastewater transferred per person). The potential saving of diffuser cleaning can be calculated by accumulating the costs times the interest rates (blue bars). Therefore, if we compare the benefit of cleaning to the cleaning costs, (e.g. tank drainage, diffuser replacement, and cleaning labor costs), then it is conceivable that we can predict an optimized time frame for diffuser cleaning.

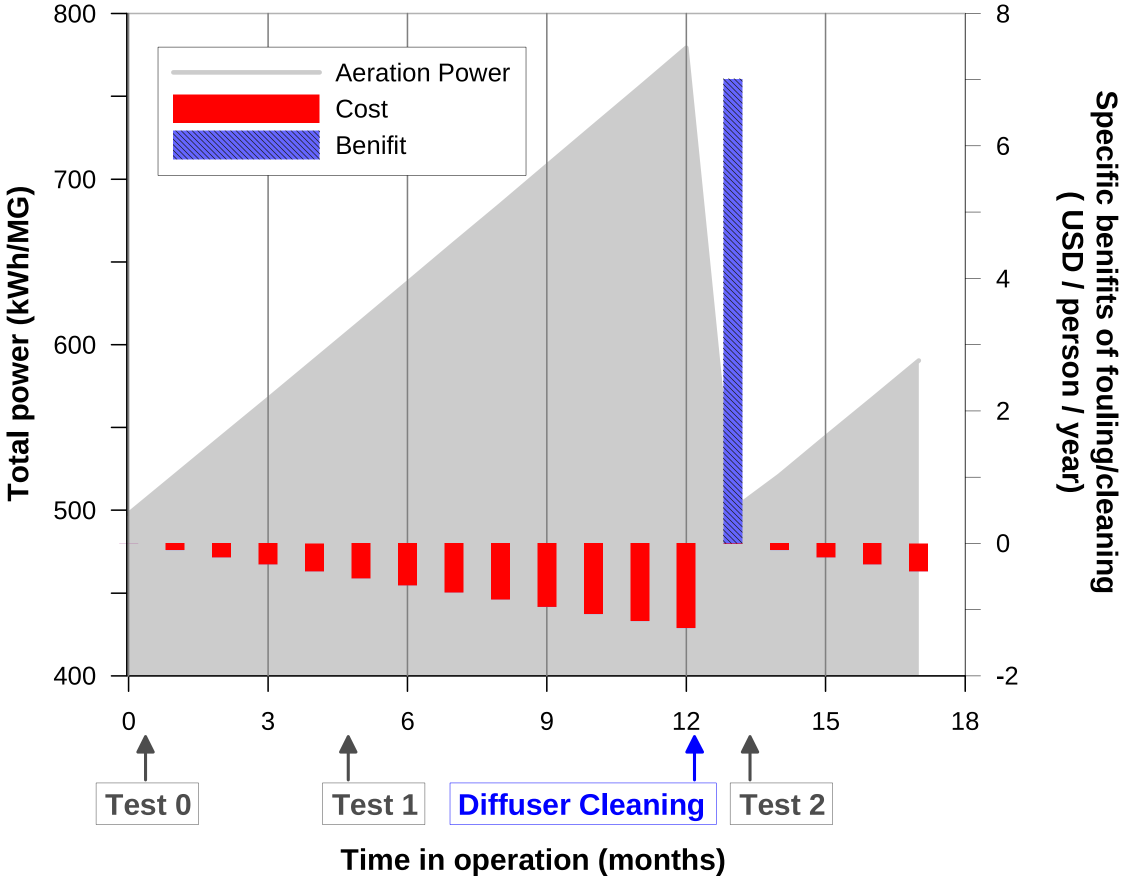

Figure 12. Energy expenditure of aeration cost. Total power consumption is calculated by the off-gas test results, in which total power = initial power + power wasted. Costs and benefits are calculated based upon the power wasted. The power cost is $0.15/kWh and the results are normalized by million gallon wastewater treated and the population served (100,000 people).

3.2.4 Potential application – operational control for energy saving

In addition to the long term diffuser fouling, the real-time off-gas test provides useful information for plant operation. Figure 13 shows the oxygen requirement and oxygen transferred within the treatment system in a 24-hour cycle. The oxygen requirement calculated by influent COD was considered as the input signal of the system, and the oxygen transferred was recorded as output by off-gas monitoring. The difference between the two values (the shade area) represents the wastage of oxygen supplied.

As shown in the former section, the treatment plant has an equalization basin to control the flow rate of primary effluent flowing into the aeration basin. The minimum flow and loading condition generally occurs at approximately 3am to 8am, when the equalization basin is empty. As shown in Figure 4, the over-aeration occurs in this period. Based upon equation (1), it can be suggested that the over-aeration is due to bacteria activities: during the minimum loading period, the bacteria consumes oxygen mainly for respiration instead of reproduction (reproduction requires more COD than respiration). A different plant operation strategy, by either changing the distribution of plant flow of equalized pumping rate and/or increase the pollutant concentration by sludge supernatant, could be designed to reduce the energy consumption.

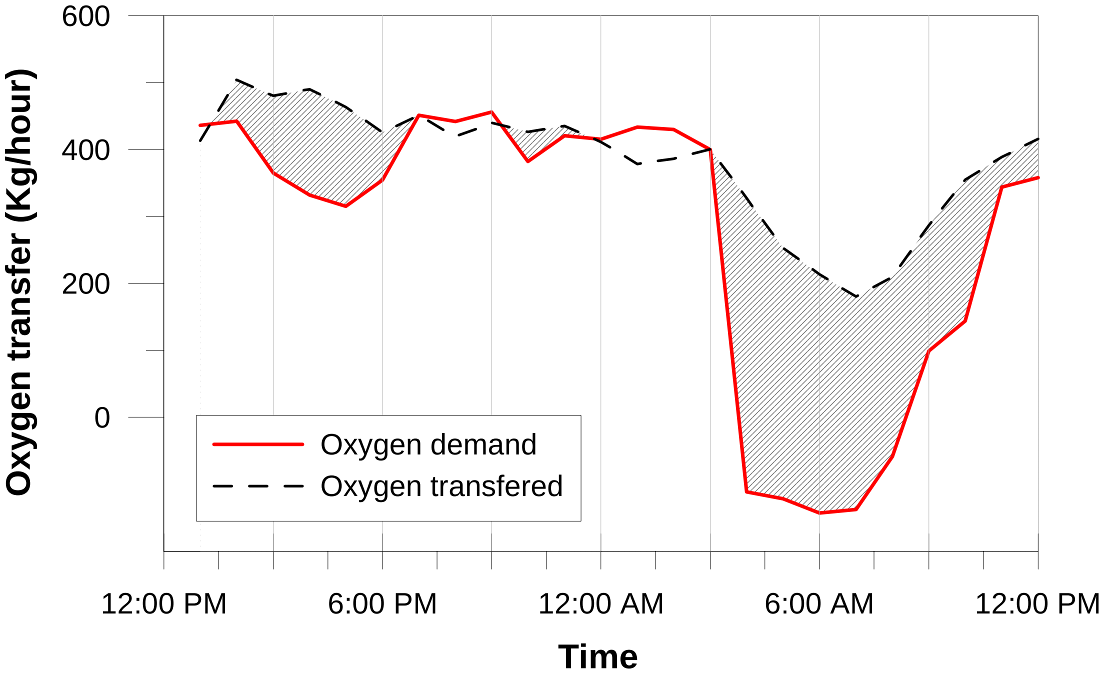

Figure 13. Rates of oxygen transfer and oxygen demand of a full-scale wastewater treatment plant during a 24-hour cycle. Oxygen transfer is calculated by the results of off-gas tests, and oxygen demand = CODtotal – CODsludge. The shade area represents the low loading/growing? growth period, and the oxygen is mainly consumed for endogenous respiration but not pollutant degradation.

3.3 Automated monitoring system

3.3.1 Field-scale prototype 1.0

The first field-scale prototype was built as shown in Figure 14. A Teledyne oxygen meter and a Kurz flow velocity meter were included in this device. In the later version, the Teledyne meter was removed and only the fuel cell was used. In further investigation of the flow velocity sensor we also considered the removal of the Kurz flow velocity meter in our later design. By so doing, we further diminish the size of the instrument to about half of the size shown in the picture (approximately 15”L×20”W×10”H).

Figure 14. Field-scale prototype 1.0

3.3.2 Field-scale prototype 2.0

The 2nd field-scale prototype (2.0) built is shown in Figure 15. The layouts of air flow and electronic connection are shown in Figure 16 (a) and (b) (two examples, one portable and the other wall-mounted are included in the appendix - section C). In prototype 2.0, instead of using the whole Teledyne oxygen meter, our latest design uses only the fuel cell to measure the oxygen fraction in the air sample. And since the air flow velocity can be measured by the plant air flow meters, the Kurz meter is not needed and is removed from the instrument and serves as an additional portable device. Two time-delay relays were used for system control and a NI data logger was used to record the measured signal to recorders (i.e. laptop computer) via a USB cable. By so doing, the size of the new instrument is reduced to about half of the prototype 1.0.

Figure 15. Prototype 2.0

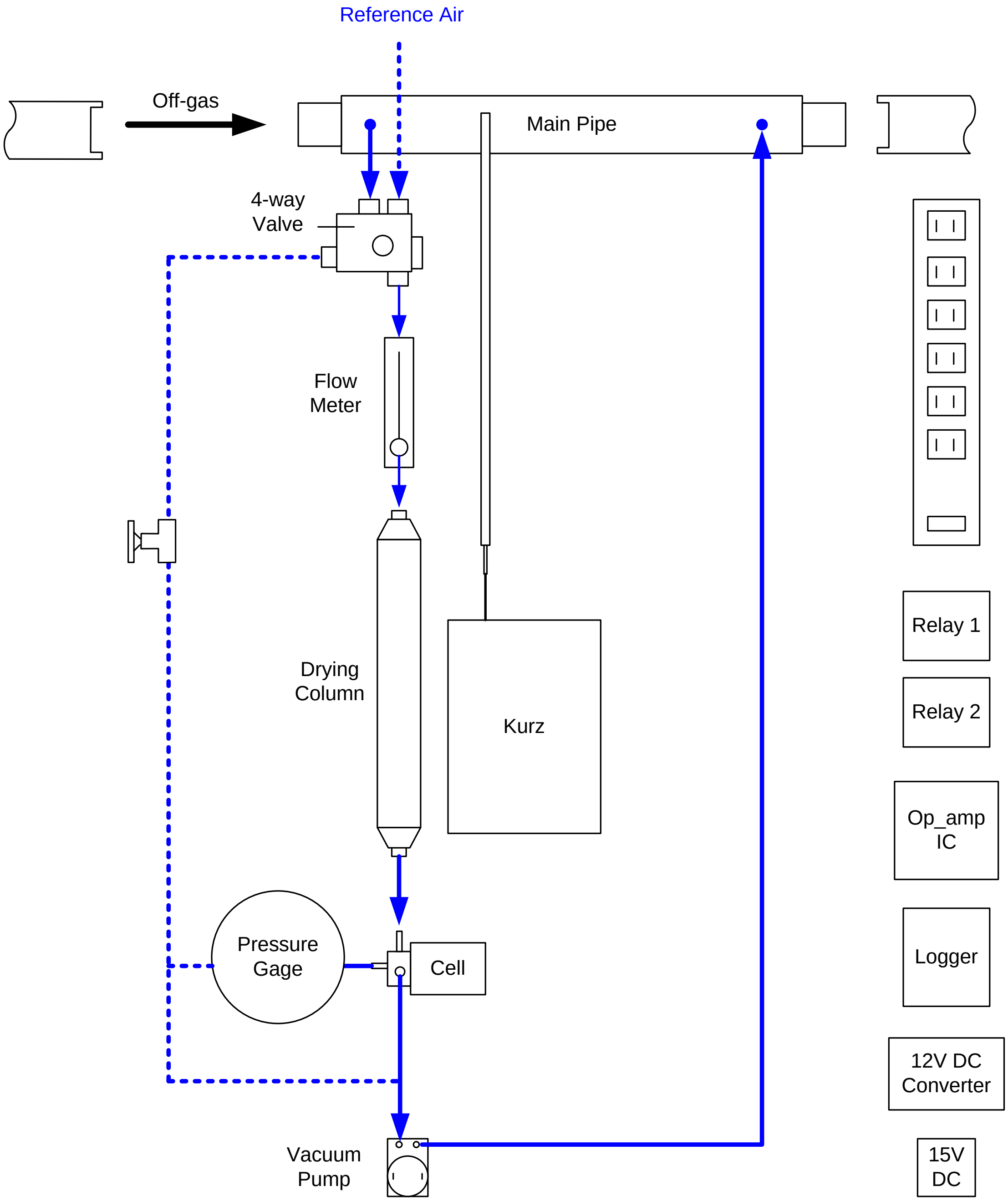

Figure 16 (a). Air flow layout of the field-scale prototype 2.0

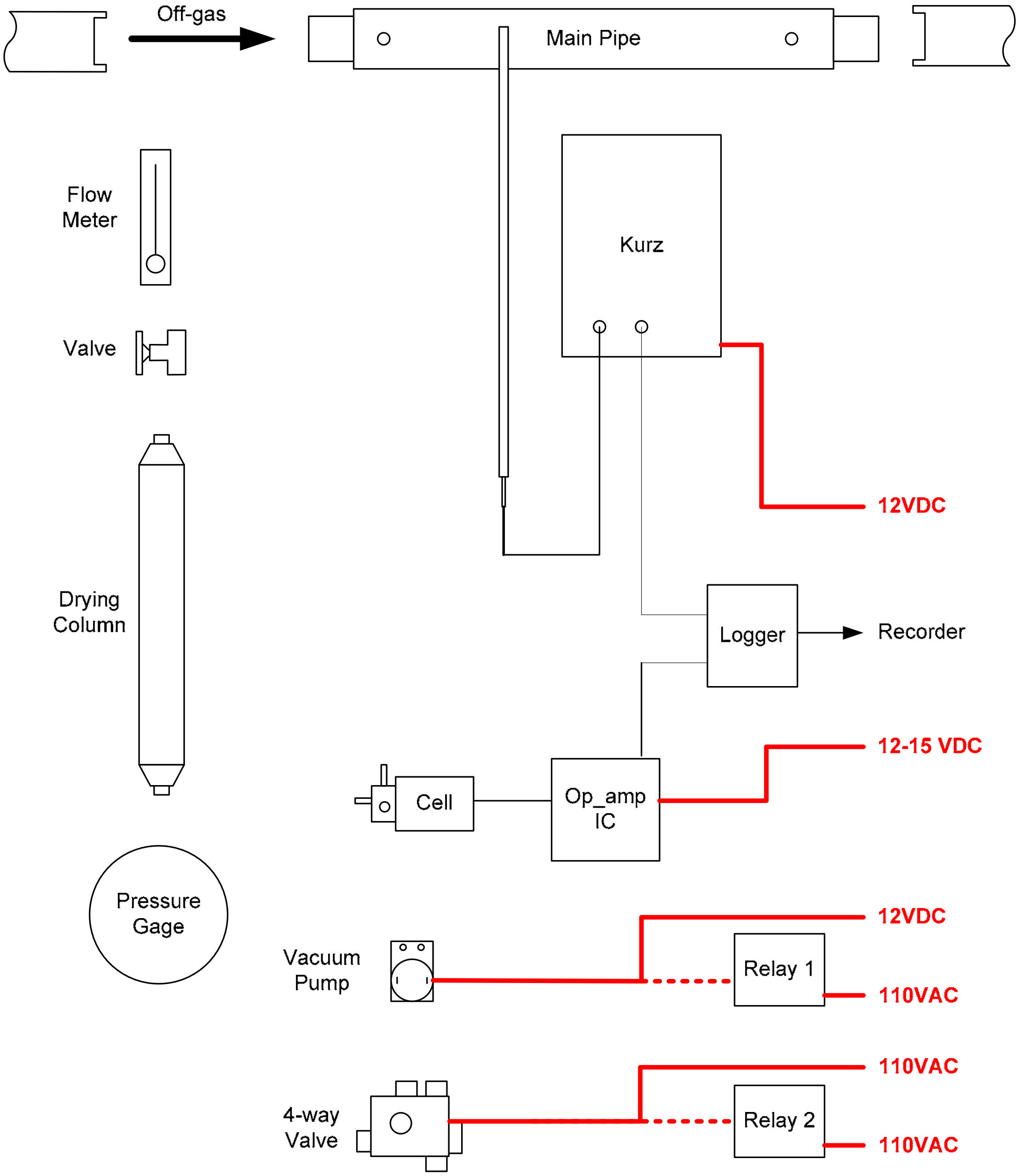

Figure 16 (b) layout of power connection in the field-scale prototype 2.0

3.4 Tests of the field-scale prototype

3.4.1 Lab-scale tests

Sensitivity analysis was applied to test the field-scale prototype. The prototype 2.0 was connected to the aeration column shown in Figure10, and clean water tests were performed to test the interferences caused by the running apparatus on the measurement results.

Figure 17 (a) shows the results of a classic clean water test with only the oxygen fuel cell and op-amp signal amplifier turned on (called test 1). The oxygen recovery curve shows a similar pattern as shown in Figure 11, where the oxygen fraction in air bubbles declines immediately after the sequestration of DO in process water, and then recovers as an exponential function of time. Since the driving force of air flow is from the air bubbles only, the measurement data are steady and show minimal noise.

Figure 17 (b) shows the results after the vacuum pump was on (test 2). The measured signal shows a much shorter response time to test 1. But additionally, significant noises were observed as well, possibly due to the non-steady pumping rate of the vacuum pump. The values of measurement readings are higher than in test 1. This can be explained by the changed total pressure in the system (i.e., when the total pressure is higher, the partial pressure is linearly biased as a higher measurement).

To reduce the noise, the off-gas sample must be compared with an ambient air sample. Figure 17 (c) shows the experiment results with the vacuum pump running and influent air flow switched on for a 30 second interval between off-gas sample and reference (air). As a result, noise was significantly reduced, and the instrument could be easily calibrated by comparing to the reference values. However, similarly to test 2, the data measured in this test have a much higher average value, and are continuously increasing. It could be due to the vacuum pumping in the system. In the laboratory, the air flow in the aeration column is adjusted to a minimum amount to produce enough oxygen reduction in air bubbles. Therefore the air flow rate in the analyzer provided by the vacuum pump may be higher than the total off-gas flow rate, which provides slightly vacuum piping system, causing the increase of fuel cell readings. In the field, the off-gas flow rate is recommended to be much higher than the pumping rate, so the bypass the bias formation.

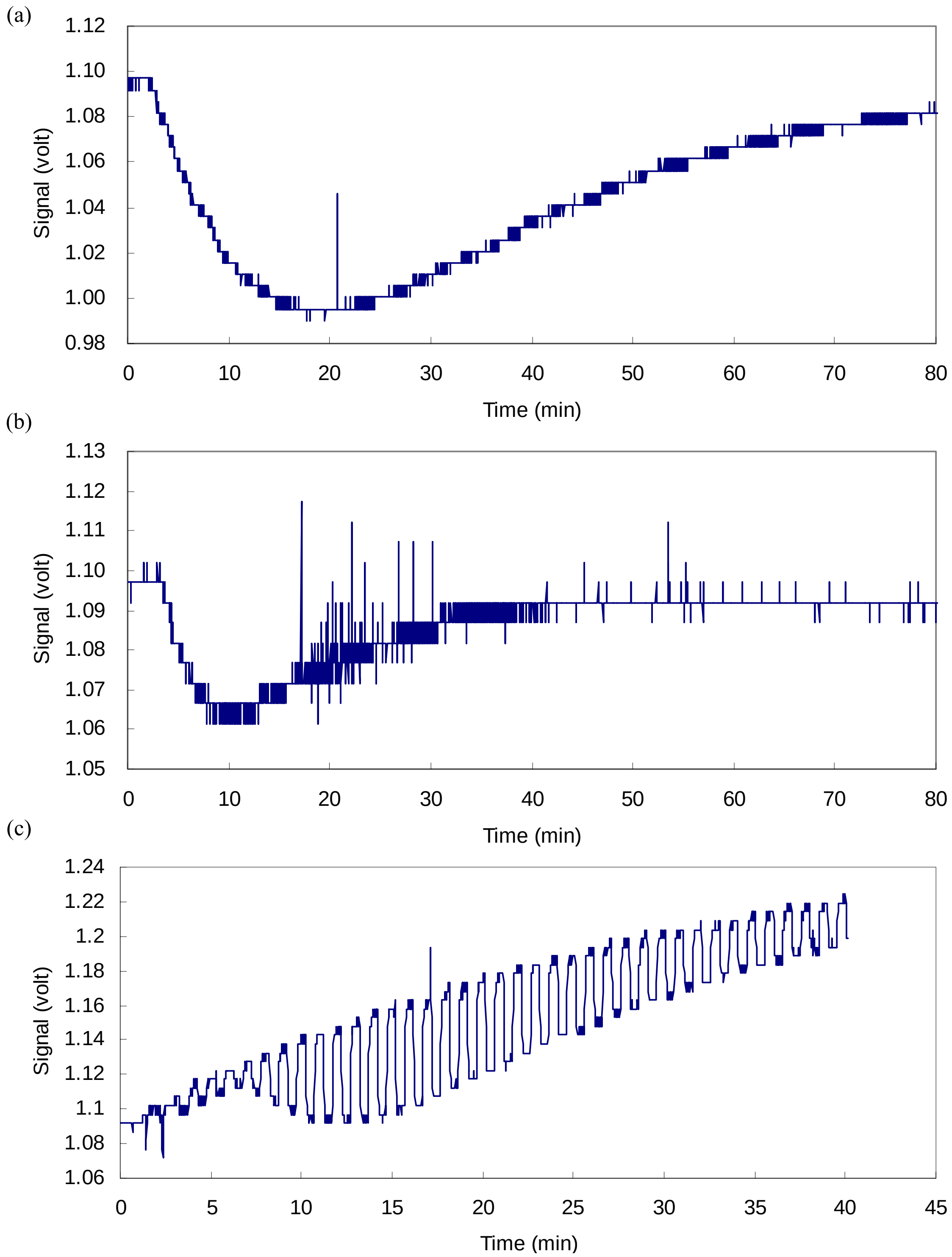

Figure 17 Lab experiment of field-scale prototype: (a) clean water off-gas test with no vacuum pump; (b) clean water off-gas test with vacuum pump; (c) clean water off-gas test with 4-way valve, time-delay relay, and vacuum pump

3.4.2 Field experiments

Figure 18 shows the signals recorded by the automatic analyzer in the selected WWTP. The plot contains both processed and unprocessed data (before noise filtering). The processed data have a step-pattern of 2 minutes duration period, due to the alternating sequence of reference air and off-gas measurements (2+2 minutes = 4 minutes per full measurement). The off-gas readings always have a lower value than reference air as expected, and the difference of the two readings is proportional to the oxygen transferred.

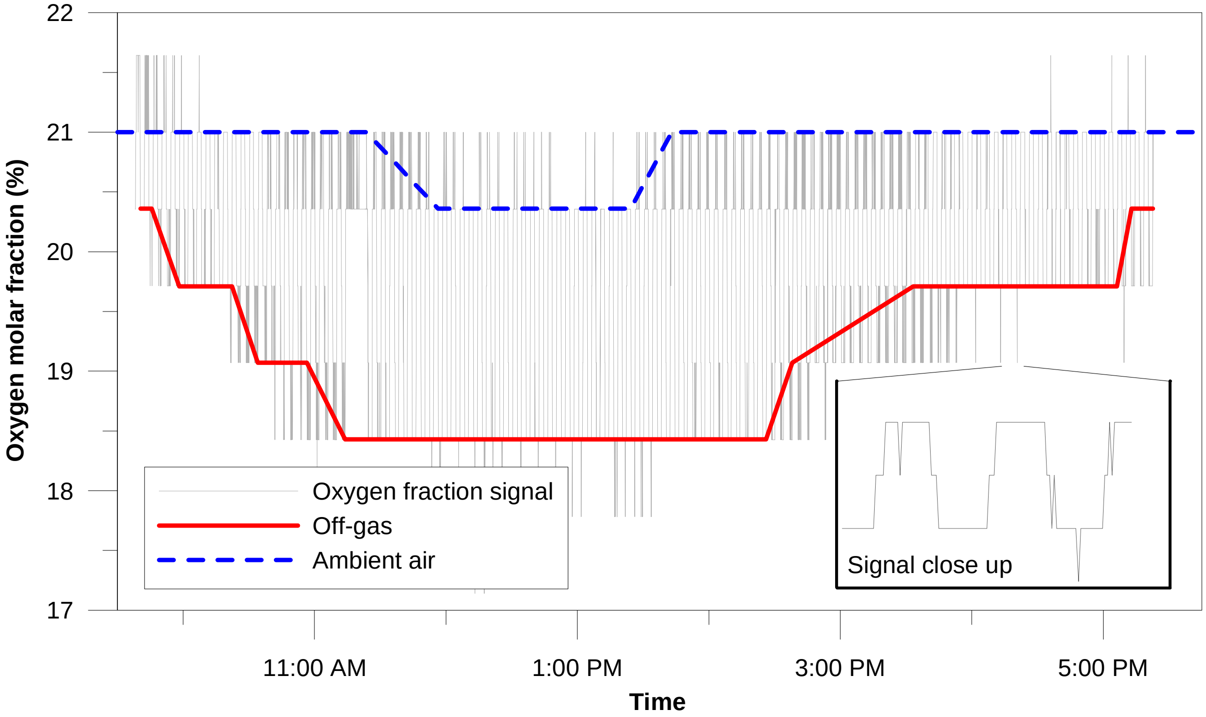

Figure 18. Continuous measurement record with the automated off-gas analyzer. The oxygen transfer efficiency (OTE) is measured by comparing the difference of oxygen molar fraction (%) between reference and off-gas.

3.4.3 Hood-size analysis

The hood dimensions are important when performing off-gas analysis in order to sample a representative area of the tank. For fine pore aeration systems, such as discs or domes, the spacing among diffusers may be less than several feet, but for coarse bubble diffusers or tanks that use diffusers to create strong mixing currents (i.e., spiral roll, cross roll), diffusers may be located more than 10 feet apart. Each portion of the tank area must be sampled representative to the entire area, so hood positions must include areas of low air flux (air flow per unit area of tank surface) and high air flux.

A small-size hood was also tested in the filed experiment. The surface area of the small hood is 2.67 feet in length and 1.34 feet in width. Comparing with the classic hood of 10 feet by 3 feet, (approximately 100 pounds in weight), the small hood has the benefit of maneuverability. As shown in Figure 19, single operator can measure the OTE at any spot of the aeration tank by moving the hood and the data could be easily recorded by the off-gas analyzer connected to a laptop.

The results of the field experiments using small-size hood shows consistent pattern as our long-term observation. However, the measurement errors were also extended. The small hood may not be able to cover the entire air plume generated by a diffuser, thus the OTE reading would not be steady unless with a long-term integration (i.e. in a daily or weekly basis) of measured data.

To reduce the number of separate analysis, a larger hood should be used to integrate over high and low flux areas of the tank. Hoods that are 10 feet by 2 feet or 8 feet by 4 feet in dimensions are common, but the specific size could be site-specific. In extreme cases, it is possible to construct a hood to cover an entire tank (Boyle, *et al.*, 1989).

Figure 19. Real-time off-gas test with field prototype no. 2 and a small hood

3.4.4 Remarks on air blowers and air distribution systems

Current control techniques for aeration systems are typically based on feedback signals provided by dissolved oxygen probes immersed in the aeration tanks. Dissolved oxygen concentration is an effect of oxygen transfer. DO is an important indicator of proper process conditions. When the DO is too low, bacterial metabolism can be inhibited. When that happens, the sludge composition may change, thus reducing treatment efficiency or even causing process failures (i.e., sludge bulking). Conversely, high DO may pose problems for denitrification (which requires anoxic conditions) and consumes excessive energy (Ferrer, 1998; Serralta et. al., 2002). Many studies have focused on the improvement of the DO control system (Ferrer, 1998, Ma et. al., 2004).

In fact, most plants have blowers that can generate only limited discharge pressure before surging or overloading the motors. The dynamic wet pressure required by fouled diffusers may be too high causing some diffusers not to release air, resulting in uneven bubble distribution throughout the tank. In other facilities, blowers may be able to discharge the DWP required by the fouled diffusers only when working outside their optimum efficiency region, resulting in increased power costs and possible damage to the blower.

To optimize the energy consumption of aeration systems, the best blower control strategy is to supply the minimum amount of process air to the wastewater treatment, yet meeting substrate removal requirements. The adoption of a low-cost on-line off-gas measurement should be considered. Off-gas testing measures the exact mass transfer, not only an effect of it, therefore offering a new tool for accurate energy calculations. In addition, a time-series of off-gas measurements offers a tool for monitoring the decline in SOTE with diffuser fouling**.**

When considering blower upgrades, several factors should be taken into consideration. Blower units must be chosen, accounting for redundancy, to allow scheduling shifts and operations and maintenance requirements. In order to avoid sudden increases in air flow rates (therefore of energy demand), blowers with tuning capability are always recommended (i.e., positive displacement blowers with variable frequency drives, or centrifugal blowers equipped guide vanes and/or variable frequency drives, etc.). These blower systems allow the variation in air flowrate within their operating range, which accommodates the variations of load in the treatment plant. When the variation exceeds the blowers' operating range, one more blower is activated, as in traditional systems. The benefit of tuning systems is a smoother transition within the range of air flowrates, which is reflected in an increased ease of management in terms of energy costs.

A classical problem that haunts operators and process control engineers is "hunting" that occurs with DO control systems. The basic problem is that the blower is treated as an "infinite" source by the control algorithm. An example explains it best.

> A treatment plant is composed of several, parallel aeration tanks. When one tank has low DO, caused by a flow imbalance or random effect, the controller calls for more air and opens an air valve, which provides more air to the affected tank. Ideally, the additional air should be provided by the blower, but in reality it is not. Instead it robs the supply air from an adjacent tank. This occurs because of pressure drops in the air distribution system as well as the nature of the blower. The loss of air in the adjacent tank causes the DO to drop, and the controller calls for even more air, which robs air from other tanks. Eventually all tanks are calling for more air and the control system finally responds by turning on an additional blower. Because the blowers have pre-set ranges of flow, and not a continuous distribution of flow rates, the air to all tanks increases and the DOs begin to increase. One tank will be first to reach excessive high DO and the control system will reduce the air flow. This does not reduce blower output, but only forces more air into other tanks. Very quickly all the tanks begin to have excessive DO, and the control system finally turns off the additional blower. Now the cycle starts over again and the DOs will decline until the blower is turned back on again, when all tanks will have excessive DO, yet again.

The impact of "hunting" is excessive energy consumption for starting and stopping of blower motors as well as an increase in wear and tear on the blowers. In cases where the operators become concerned about the impacts on plant performance, they may disable the DO control system altogether and causes over or under aerationx. Usually operators chooses over aeration to avoid effluent permit violations.

To mitigate this problem, several changes are needed. The first is to provide blowers by with larger "turn-up" and "turn-down" capabilities. The second is to provide a "smart" control system that would not consider the blower as an infinite source. This requires that the control system be equipped with a model for the blower (essentially the flow versus pressure curve and a time lag) that can be solved for each new state so that the new system pressure can be predicted and the air valves on all tanks can be adjusted appropriately. The more challenging part of the problem is providing blower flexibility (details of the blower study were presented in the additional report).

3.5 Off-gas tests in California

This section presents several case studies of energy savings in the selected WWTPs of California, based upon our off-gas analysis. Results of four sites were performed, including the treatment plants of Los Angeles Tillman, Glendale, Simi Valley, and Orange County. Aeration costs were presented in Table 3 as specific units of kWh/MG waste water treated and $/person/year. Pumping energy requirement was calculated by the adiabatic function of blowers (Metcalf and Eddy, 2003), as a function of total air requirement and diffuser head loss. Power cost was assumed to be 0.15$/kWh, and the field transfer efficiency of pumps was 75%.

Tillman wastewater treatment plant uses ceramic domes for aeration. Before 2000, this treatment plant was operated with conventional process, which removed only the carbonaceous pollutants but not ammonia. Off-gas tests were performed to evaluate aeration performance before and after diffuser cleaning. As a result, approximately 100 kWh/MG wastewater treated can be saved by diffuser cleaning. The plant later upgraded the system to NDN process to additionally remove nitrogenous pollutants. After upgrade, aeration performance is significantly improved. The new process provides better OTE and requires less air to oxidize the same amount of pollutants. If compare the two processes in the same base by converting the total oxygen transfer rate, approximately 500kWh per MG wastewater treated, or $2.3 to $2.9/person/year in energy cost can be saved.

Similar results were found in Glendale treatment plant, which used the same type of aerators (ceramic domes), and the plant also upgraded the operation process from conventional to NDN. Off-gas tests were performed before and after the upgrade of treatment system. Comparing to the results found in Tillman, the improvement on energy consumption in Glendale is slightly lower, approximately $1.2/person/year was saved. This difference should be caused by the scales of treatment plants and wastewater characteristics. Glendale is a smaller plant and has lower pollutant concentration (132mg/L) then Tillman (162mg/L).

In Simi Valley, off-gas tests were performed after the system being upgraded to NDN process. This plant uses strip-type membrane diffusers for aeration, and the specialty of this plant is that there are three polishing tanks following to the four new regular process tanks. The function of polishing tanks is to guaranty a steady effluent quality, e.g. when the treatment performance is low in process tank, extra air could be given in polishing tank. Due to this specialty, aeration costs in this plant were calculated by the "whole secondary treatment system", instead of each "tank" in the other cases. This plant has the lowest capital cost on aeration ($2.3/person/year) over the four WWTPs, possibly also due to the 2-stage aeration system. The energy savings on aeration before and after diffuser cleaning is approximately 100kWh/MG wastewater treated, which is close to the results of other WWTPs.

The wastewater treatment of Orange County use a disk-type diffuser made of EPDM (ethylene propylene diene monomer rubber). This plant has not yet been upgraded to remove ammonia due to overloading, i.e. more volumetric flow than designed capacity. In this plant, most of the fine-pores diffusers in the aeration systems (8 in 10 of the tanks) have never been cleaned, since the installation of diffusers (8 years, from 1997 to 2005). Therefore, the diffusers collected from the system were completely fouled (detail study see the membrane test in § 3.1.1), and has poor performance (i.e. low OTE, high DWP and air flux) on aeration. Based upon our off-gas analysis, up to $2403 on daily energy cost could be saved by diffuser cleaning.

Table 3. Summary of off-gas test results and energy saving of selected wastewater treatment plants in California

Plant	Population Served	Test Date	Process	Diffuser Condition	Required Air	Aeration Cost			
					scfm	kWh/MG	$/day	kWh/person/yr	$/person/yr
Tillman	800,000	1992/2/24	Conventional	Dirty	4296	638.2	7658	23.3	3.49
					6152	913.9	10967	33.4	5.00
		1992/6/29			7938	1179.2	14151	43.0	6.46
					6152	913.9	10967	33.4	5.00
		1993/12/10		New or Cleaned	5954	853.9	10247	31.2	4.68
					7144	1024.7	12296	37.4	5.61
		1994/7/11			4366	626.2	7515	22.9	3.43
					5160	740.1	8881	27.0	4.05
		2007/4/4	NDN	Cleaned	2628	377.0	4523	13.8	2.06
					2567	368.2	4418	13.4	2.02
					2812	403.3	4839	14.7	2.21
					2567	368.2	4418	13.4	2.02
		Average	Before Upgraded	Dirty	6135	911.3	10936	33.3	4.99
				Cleaned	5656	811.2	9735	29.6	4.44
			After Upgraded	Cleaned	2643	379.1	4550	13.8	2.08
			Upgrade savings		**3491**	**532.2**	**6386**	**19.4**	**2.91**
Glendale	220,000	1991/8/7	Conventional	New	4590	877.8	2633	29.1	4.37
					5472	1046.6	3140	34.7	5.21
					3531	675.2	2026	22.4	3.36
		1992/8/3		Dirty	4590	909.1	2727	30.2	4.52
					4060	804.2	2413	26.7	4.00
					3884	769.2	2308	25.5	3.83
					3707	734.3	2203	24.4	3.65
					5119	1014.0	3042	33.6	5.05
		2005/3/17	NDN	Dirty	4135	819.0	2457	27.2	4.08
		2007/8/16		New	3228	617.4	1852	20.5	3.07
				New	3115	595.7	1787	19.8	2.97
		Average	Before Upgraded	Dirty	4272	846.2	2539	28.1	4.21
				New	4531	866.5	2600	28.8	4.31
			After Upgraded	Dirty	4135	819.0	2457	27.2	4.08
				New	3172	606.6	1820	20.1	3.02
			Upgrade savings		**1100**	**239.6**	**719**	**7.9**	**1.19**
Simi Valley	100,000	2005/8/4	NDN	New	5810	499.4	622	15.1	2.27
		2006/1/11	NDN	Dirty	7107	615.9	767	18.7	2.80
		2006/9/19	NDN	Cleaned	5836	501.7	625	15.2	2.28
		Average	**Cleaning savings**		**1271**	**114.2**	**142**	**3.5**	**0.52**
Orange County	450,000	2002/10/22	Conventional	Cleaned	5330	487.5	2119	17.2	2.58
					4214	385.4	1675	13.6	2.04
		2005/10/22		Dirty	6074	579.1	2517	20.4	3.06
					6446	614.5	2671	21.7	3.25
					5454	520.0	2260	18.3	2.75
					5330	508.2	2209	17.9	2.69
					5816	503.4	6025	32.6	4.89
					6435	556.9	6666	36.0	5.41
					5816	503.4	6025	32.6	4.89
					5816	503.4	6025	32.6	4.89
		Average	Before cleaning		5898	536.1	4300	26.5	3.98
			After cleaning		4772	436.5	1897	15.4	2.31
			Cleaning savings		**1126**	**99.6**	**2403**	**11.1**	**1.67**

4.0 Conclusions and Recommendations

- Conclusions:
    - Wastewater treatment amounts to 3% of the energy consumption in California. Wastewater aeration is the most energy intensive process in wastewater treatment, accounting for 45-75% of the total energy cost for treatment. Due to the mandate to save 1 billion kWh/yr in California, there is a clear incentive to minimize the energy expenditure in wastewater treatment. Therefore, aeration is the first operation to be studied and optimized in the wastewater industry.
    - Existing control systems do not measure energy efficiency as an operating parameter. Therefore, a fully-automated real-time aeration efficiency monitoring analyzer was designed, built, and tested in several facilities. The results of the testing campaign met the project goal of measuring aeration efficiency with a relatively inexpensive analyzer (~ $3,000-5,000 for a prototype) which operates in fully-automatic mode without the need for supervision or operator training.
    - The analyzer built in this project measures the actual aeration efficiency and gives plant operators a real-time measurement (i.e., not just an estimate) of the energy required to perform wastewater aeration. This means that aeration will be optimized in real-time mode and will always be performed at the minimum energy cost.
    - The energy consumed by the wastewater industry in California is estimated to be about 2 billion kWh/yr. Assuming a market penetration of 50% and an average efficiency improvement of 15%, the large-scale implementation of aeration efficiency monitoring will allow energy savings potentially estimated in the range of 50-100 million kWh/yr.

- Commercialization potential:
    - All treatment plants in California and elsewhere should be equipped with energy efficiency monitoring devices. The aeration efficiency monitoring analyzer is relatively inexpensive and has a payback period of a few months to a year, depending on plant size and energy savings. In any case, there is no economic obstacle for the installation of these analyzers, due to energy savings that far outweigh the analyzer's cost.
    - New designs and upgrades of existing facilities should include aeration efficiency monitoring as part of the design plan and the control system strategy. Therefore, the potential for commercialization is sustainable in the future, since this technology should be embedded in the wastewater industry as a necessary component for optimized operations.
    - The commercialization potential for this technology goes beyond California and a market will establish throughout the United States and abroad.

- Recommendations:
    - Implement aeration efficiency monitoring in every wastewater treatment plant. This means transferring to existing treatment facilities the aeration efficiency monitoring analyzer developed in this project. New designs of wastewater treatment plants should include this analyzer in the control system, therefore minimizing the energy expenditure from the first day in operation.
    - Power utilities, such as Southern California Edison or others, should establish a rebate system based on the energy efficiency measurements performed in wastewater treatment plants.

- Benefits to California:

- The benefits already enjoyed by California, during the course of this project, are multiple. Five treatment plants both in Northern and Southern California were tested and already adopted corrective measures to minimize energy losses. Moreover, the testing campaign, combined with conference presentation, gave this project exposure to the wastewater industry. The outcomes of this project were presented at the CWEA conference in Ontario, CA in March 2007, at the IWA Efficient conference in Jeju, Korea in May 2007, at the IWA LET conference in Singapore in June 2007, and were featured as keynote lecture at the CEE workshop in Long Beach, CA in January 2007. Several individuals belonging to organizations outside California already approached the project team, inquiring about the availability of the analyzer and volunteering their facilities for further testing. The Consortium for Energy Efficiency (CEE) offered to support the technology transfer by distributing all the information regarding this analyzer to their subscriber nationwide.
- After the project completion, when the aeration efficiency analyzer will be distributed throughout California, there will be a clear advantage for California to set the standard for energy efficiency in wastewater treatment. Moreover, there is a potential opportunity for California businesses to take part on the following phase of the project, i.e. manufacturing and distributing of the analyzer in the wastewater industry. Furthermore, and most importantly, the large-scale implementation of aeration efficiency monitoring will allow energy savings potentially estimated in the range of 100-150 million kWh/yr.

- Table 4. Project timeline

EDISON CONTRACT TIMELINE

Year	2005						2006							2007			
Date	1/1	3/1	5/1	7/1	9/1	11/1	1/1	3/1	5/1	7/1	9/1	11/1	1/1	1/1	3/1	5/1	7/1
Mo.	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32
	FORMATION OF PAC																
	---	---	---	---													
	ASSESSMENT OF TECHNOLOGIES																
	---	---	---	---	---	---	---										
			DEVELOPMENT OF NEW EQUIPMENT														
			---	---	---	---	---	---	---	---	---	---					
			PHASE I - lab scale equipment														
			5/31														
			design														
				6/31													
				materials acquisition													
					8/31												
					fabrication												
					8/31												
					test and debug												
							PHASE II - field prototype										
							1/31										
							field packaging										
								1/31									
								materials acquisition & fabrication									
									5/31								
									test and debugging								
							1/31				1/31						
							DEVELOPMENT OF TESTING PROTOCOL										
							---	---	---	---	---	---	---	---	---		
							7/1										
							Version 1										
									7/1								
									Version 2								
										7/31		7/1					
										TECHNOLOGY TRANSFER							
										---	---	---	---	---	---	---	---
												7/1					
																final report	

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Glossary

ASCE – American Society of Civil Engineers

ASP – activated sludge process

BOD – biological oxygen demand (mg oxygen/L)

C-COD – carbonaceous chemical oxygen demand, or carbonaceous COD (mg oxygen/L)

DO – dissolved oxygen (mg/L)

DWP – dynamic wet pressure (inch of water)

MCRT – mean cell residence time, the average time that bacteria staying in the treatment process

NDN – nitrification and denitrification

OTE – oxygen transfer efficiency (%)

OTR – oxygen transfer rate (kgO_2/hr)

SOTE – standardized OTE (%)

WWTP – wastewater treatment plant

α – alpha factor, a factor used to quantify the effect of contaminantion to oxygen transfer

αSOTE – the standardized OTE in contaminated water (%)

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Appendices

1.0 Literature Review of activated sludge process and aeration

Aeration is a key component of the activated sludge process (ASP). Aeration costs account for a large fraction of a wastewater treatment plant (WWTP) expenditure. Because of aeration, the ASP's electrical expenditure is in the range of 45-65% of the total plant energy cost (Reardon, 1995; Rosso and Stenstrom, 2005a; 2005d). There exist several methods for increasing energy-efficiency in the ASP, the most important being:

I. Utilization of fine-bubble aerators
II. Optimization of DO control systems
III. Implementation of diffuser maintenance/cleaning schedules

I. Fine-bubble aerators. Over the past 30 years, after the energy crisis of the 1970s, fine bubble (also referred to as fine-pore) aerators (also called diffusers) have experienced widespread application. Despite higher capital costs, increased energy costs make fine-bubble installations the most economically-viable solution in most cases. At present, fine-bubble aerators are the most commonly used aeration technology for municipal wastewater treatment in the United States and in Europe.

There are three main commercially-available aeration technologies: surface mixing, coarse-bubble, and fine-bubble aeration. Surface mixing are mechanical aerators that create a gas-liquid interface by shearing the liquid surface with a turbine or mixer. Coarse-bubble aerators inject air from open or slotted pipes, Venturi throttles, or sparger heads into the wastewater, with resulting bubbles larger than 50mm. Fine-bubble aerators differ from the former by releasing minute bubbles through the small pores of a sintered ceramic or the punched orifices of a polymeric membrane. The resulting bubbles have a typical diameter of 2-20mm, depending on diffuser type, airflow rate, and diffuser fouling/scaling conditions.

Fine-bubble diffusers exploit the advantages of mass transfer associated with small bubbles:

- larger mass-transfer interfacial area
- smaller bubble rising velocities (i.e., larger mass transfer contact time)
- lower specific energy required per wastewater unit volume

Furthermore, fine-bubble aeration devices have the additional advantages of lower stripping of volatile organics, and lower heat loss.

II. Optimization of DO control systems. Dissolved oxygen (DO) control is the most commonly used control parameter in WWTPs. This control system is based on a network of DO measuring probes. These probes are essentially fuel cells, with a semi-permeable membrane before the electrode. This membrane selectively allows the passage of oxygen molecules towards the electrode. The fuel cell burns the dissolved oxygen returning a voltage signal. The signal is proportional to the concentration of oxygen in the water solution.

When properly cleaned and maintained, DO probes offer instantaneous point readings of the dissolved oxygen concentration in the ASP. A major drawback of DO control systems is that they do not quantify the oxygen transfer efficiency, but only measure the local values of DO concentrations. Operators at WWTPs with DO control systems may use air line headloss and flowrate to estimate energy costs. Although, DO control systems measure an effect of mass transfer, they do not quantify the mass transfer itself. DO control systems do not provide information on the status of the diffusers, therefore on their operating efficiency, which is necessary to calculate energy requirements. The off-gas technique (see §3) is the only measurement that allows one to calculate the percent of oxygen transferred to the wastewater, and not an estimate of the energy requirements.

III. Implementation of diffuser maintenance/schedule. Fine-bubble diffusers have the disadvantage of experiencing aging (performance degradation) with time in operation (Rosso and Stenstrom, 2005b). Diffuser aging is due to:

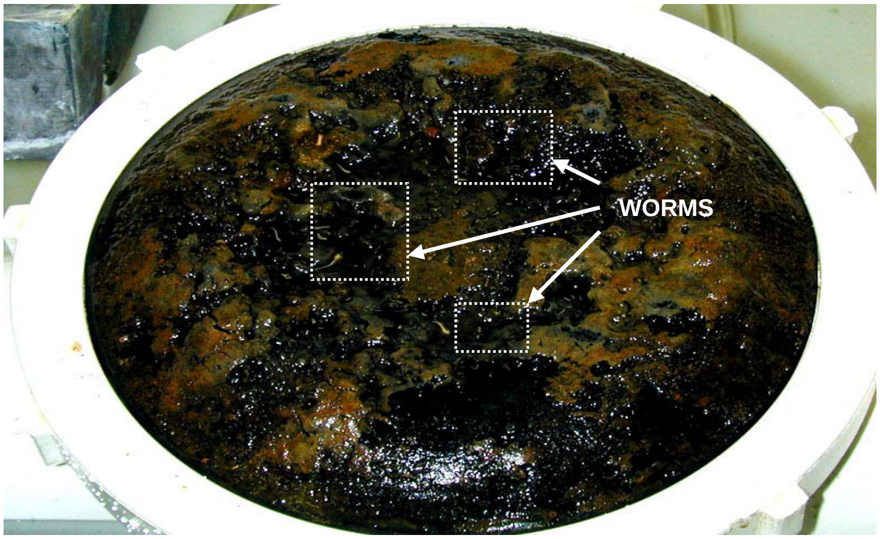
- inorganic scaling (precipitation of carbonates, sulfates, and silicates)
- biological fouling (attachment, formation and decay products of a microbial biofilm)
- a composite of scaling and fouling

The most commonly occurring scenario is a composite of scaling and fouling, with inorganic precipitated crystals embedded into a matrix of biological microbial polymers. After an extended time in operation without cleaning, fine-bubble diffusers typically show fouling/scaling visible to naked eye (Figure A-1).


a)

(caption overleaf)


b)



c)

Figure A-1. Typical fouling/scaling effect on a fine-bubble aerator ASP before cleaning (a) and after cleaning (b). Cleaning in this case was performed by tank-top hosing. A membrane diffuser from another plant 3 years after cleaning is shown in (c); note the superficial biological growth (highlighted are worms).

Figure A-2 shows the decline of the aerator efficiency with increasing time in operation. A recently published study found no evidence of different α factors for different makes or models of fine-bubble diffusers, but found that the key parameters affecting oxygen transfer efficiency are the microbial mean cell retention time, the airflow rate, diffuser depth and total bubbling area (Rosso et al, 2005). In an existing fine-bubble installation (where plant geometry is given) and for a given load, only the airflow rate can be manipulated so to maximize oxygen transfer efficiency.

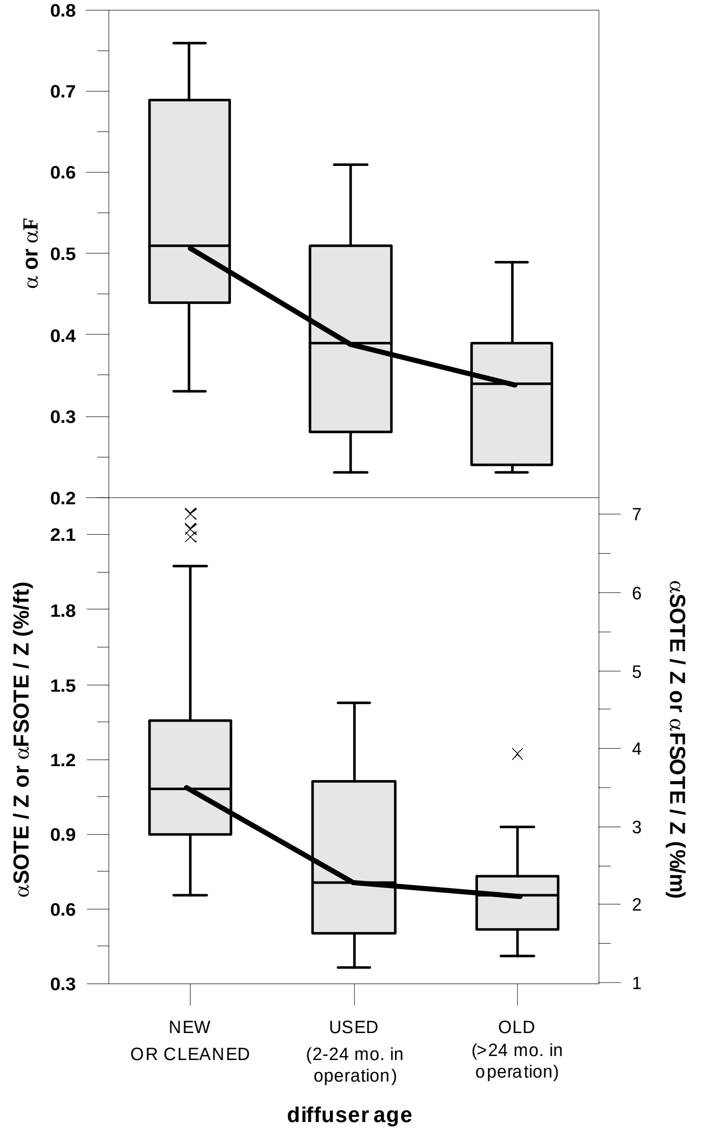


Figure A-2. Efficiency decline for fine-bubble diffusers (after Rosso and Stenstrom, 2005b and 2005c). Aerators are grouped in new (within 1 month from installation/cleaning), used (within 24 months from installation/cleaning), and old (over 24 months). α is the ratio of the mass transfer coefficient of process water to clean water. αSOTE/Z is the specific field oxygen transfer efficiency per unit depth. α and αSOTE/Z are used for new aerators; αF and αFSOTE/Z are used for used and old aerators

To accessing oxygen transfer efficiency, the Standard Guidelines of ASCE (1997) recommend three types of in-process water testing methods: 1) the non-steady method, using pure oxygen or hydrogen peroxide, for surface or diffused aeration systems; 2) off-gas analysis for diffused aeration systems, and 3) the tracer racer method for both surface and diffused aeration systems. It also describes but does not recommend two other methods, including methods based upon ex-situ oxygen uptake rate measurements and liquid-phase mass balances.

Methods based upon ex-situ oxygen uptake rate measurements, usually called the steady-state method, and using a BOD bottle for uptake measurement, have severe limitations on applicability because of the inability to simulate identical conditions in an aeration basin. The inability to measure an accurate oxygen uptake rate creates artificially low or high oxygen transfer estimates, which have sometimes been explained as biologically enhanced transfer (Albertson and DiGregorio, 1975). The problems and a history of the errors introduced by ex-situ measurements have been discussed in detail by Mueller and Stensel (1990), who concluded that there was no evidence for biologically enhanced oxygen transfer rates in the activated sludge process. In-situ oxygen uptake measurements, such as those taken by process respirometers ,have not been extensively used for in-process testing, and there is little or no long term experience in their use.

The major advance described by the Standard Guidelines is the off-gas analysis method, which was developed by Redmon et al (1983) under US EPA and ASCE sponsorship. The method uses an oxygen gas sensor to measure the oxygen mole fraction in the off-gas. By removing the carbon dioxide and water vapor from the off-gas, and assuming no change in nitrogen fraction, Redmon et al (1983) showed that the OTE could be calculated directly from the mole fraction measurements, and did not rely on volumetric gas flow rate. This technique improved on the methods used previously by a number of investigators, including Sawyer and Nichols (1939), Hover et. al. (1954), Pauling et al (1968), Prit and Callow (1958), Downing (1960), Conway and Kumke (1966) and Leary *et al.* (1968).

The main reason preventing a widely installation of off-gas monitoring in WWTPs is its complexity on operation. The classic instrument uses a vacuum cleaner to collect the off-gas stream from the aeration tank through a floating hood. The original manual off-gas setup, including the analyzer, the capture hood, and a vacuum pump, requires a crew of at least two to three skilled investigators to operate, thus considerably decreases the flexibility and applicability of this technique.

2.0 Off-gas test theory

The off-gas technique developed by Redmon et al. (1983) consists in measuring the partial pressure of oxygen in the gas stream leaving the wastewater. Since the oxygen partial pressure in the gas feeding line is known, the percent of oxygen transferred to the wastewater is:

$$\mathrm{OTE}(\%)=\frac{p_{O_{2,IN}}-p_{O_{2,OUT}}}{p_{O_{2,IN}}} \qquad (1)$$

with p_i = partial pressure of oxygen in the gas stream. The OTE is the ratio of oxygen transferred to oxygen fed to the ASP. It can be normalized to standard conditions (20°C, 0 $\mathrm{mg_{DO}/l}$, 1 atm, no salinity) to obtain a standard OTE, or SOTE (%) (ASCE, 1984, 1991). In order to quantify the deviations from clean water conditions, process-water mass transfer is characterized by an α factor, i.e. the ratio of the mass transfer coefficient of process water to clean water (Stenstrom and Gilbert, 1981). The product of α and SOTE gives the field oxygen transfer efficiency at standard conditions, or αSOTE (%). The SOTE of fine-bubble aerators is severely affected by fouling/scaling phenomena, with lower efficiency for diffusers with higher time operation, as shown in Figure 2 (Rosso and Stenstrom, 2005c). Figs. A-3, 4a, and 4b show an off-gas analyzer and different off-gas capture hoods.

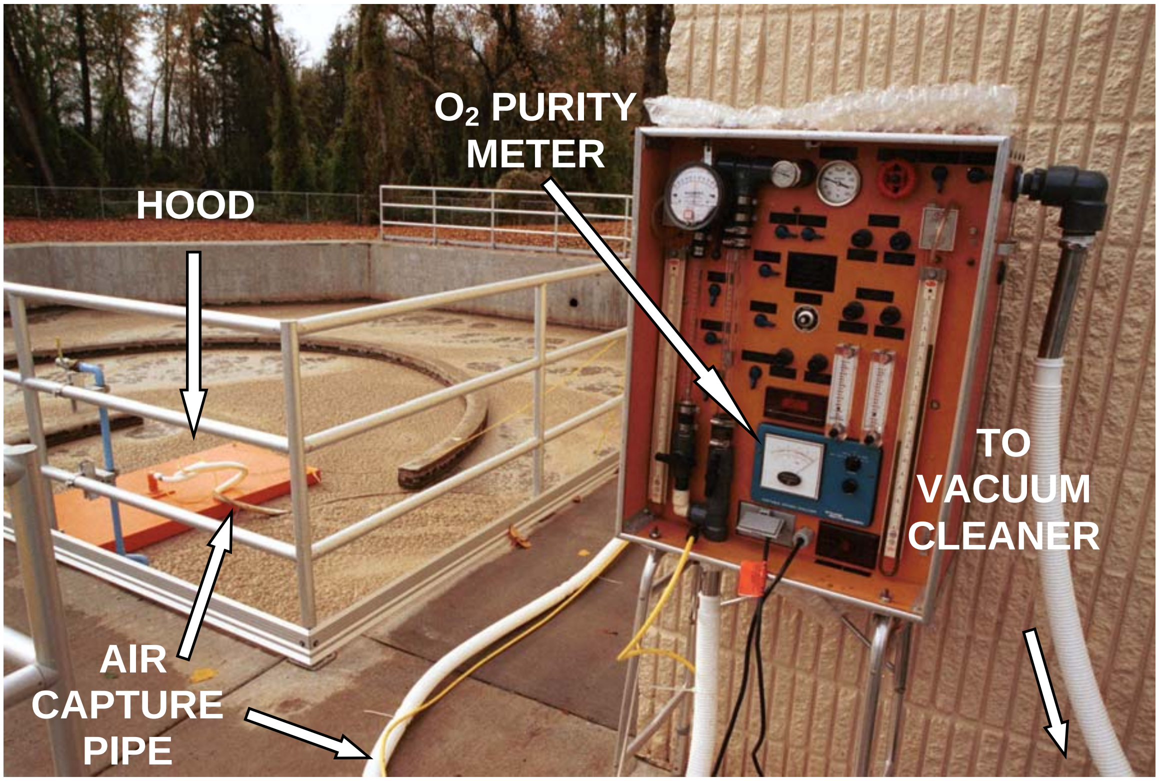


Figure A-3. An off-gas testing layout (apparatus, capture hood, air capture pipe, vacuum cleaner line).

The off-gas technique does not require flow measurements to calculate mass transfer. Yet, flow measurements are necessary to calculate a tank flow-average value. Capture hoods vary in sizes, from small (2x2') to very large (whole tank coverage). Larger hoods better represent the average tank efficiency distribution, while smaller hoods give a point measurement. Nevertheless, smaller hoods may be utilized for time-series harvest campaigns, and, when moved on the wastewater surface, can offer a space-and-time-integration for oxygen transfer efficiency.

Figure. A-4 (a), (b) Off-gas capture hoods. 2x10’, Styrofoam and aluminum frame (top); 5x8’, wood and plastic sheets, built *in situ* (bottom).

The available off-gas technology consists on a testing apparatus (Figure 3) and capture hoods (Figs. 4a, b) totaling about $20k, and an average cost per test of $5k-20k consulting fee for the expert investigator(s).

The key component of the off-gas testing apparatus is the oxygen purity meter, namely its fuel cell. Figure A-5 shows an existing off-gas testing apparatus, with details of the oxygen meter and its fuel cell. The field prototypes will only include the fuel cell instead of the whole oxygen meter.

Figure A-5. Manual off-gas testing apparatus (Manufactured by Ewing Co.). Details show the oxygen purity meter and its fuel cell.

3.0 PAC meeting

In this project, economic analyses were performed based upon the theoretical and experimental considerations. The results were compared with actual aeration costs in full-scale plants. A project advisory committee (PAC) was formed to oversee the research work and provide feedback and comments on the results. The PAC members were selected to review and recommend on: 1). field testing and protocol development and 2). plant operations improvement (i.e., operators training, cleaning frequency and methods, process upgrade, etc.).

The PAC was formed with the following expert candidates:

Dave Reardon	HDR Engineering Inc., energy audits specialist
Henryk Melcer	Brown & Caldwell, process designer
Rod Reardon	Camp, Dresser, and McKee Inc., process designer
Mike Selna	Sanitation Districts of L.A. Co., WWTP operations mgr.
Keith Carns	EPRI Solutions Inc., energy specialist
H. David Stensel	Univ. of Washington, Professor - Biological Processes
Omar R. Moghaddam	City of L. A., Bureau of Sanitation, manager
J.B. Neethling	HDR Engineering Inc., WWT technology director
Shahid Chaudhry	California Energy Commission, *Ex Officio*
Lory Larson	Southern California Edison, *Ex Officio*
Roger Sung	Utility Technology Associates, *Ex Officio*

3.1 1st PAC meeting

Summary

After the presentation of literature background and state-of-the-art equipment chosen for this project, the UCLA research group discussed with the PAC members the following issues:

- *Quantification of potential power savings*
  Energy savings can be calculated based upon the reduction of oxygen transfer efficiency of fine-pore diffusers. Due to different operation conditions, the diffuser cleaning schedule is plant-specific.
- *Comparison between power savings in fine-pore aerators and other existing technologies*
  Oxygen transfer efficiencies of different aerators are totally different. Off-gas method only valid for fine-pore diffusers, a more complex measurement method is required for surface aerators.
- *Challenges for the technology transfer*
  To convince operators to measure the oxygen transfer more frequently, the new off-gas apparatus should be easy to operate.
- *Cleaning schedules*
  The cleaning schedule can be developed by the oxygen transfer measurement. A spreadsheet has been build for this purpose.
- *Hood positioning and sizing*
  Bigger hood provides accurate measurement but difficult to operate. A sensitivity study of optimal hood size will be provided by UCLA research group after the protocol is built.

The UCLA research group addressed all of the above and satisfactorily answered them. PAC members' feedback input was recorded and will be incorporated into the project development phase.

Minutes of the discussion

1. ***Henrik Melcer:*** *Is the core of the instrument a fuel cell? If so, what's the operating principle?*

Michael Stenstrom: The core of the instrument is indeed a fuel cell, and the operating principle is as follows. The air mixture facing the cell diffuses through the porous membrane into the fuel cell, where oxygen will be consumed (as fuel) in an electrochemical reaction, which will produce a voltage. This voltage is recorded by a device connected to a computer. Known the composition of the air mixture (20.95% of oxygen, in standard conditions), the voltage can be immediately converted to a oxygen partial pressure scale.

2. ***J.B. Neethling:*** *How easy do you expect to be the installation of such a monitoring apparatus in a wastewater treatment plant?*

Michael Stenstrom: The hood size will be reduced from the manual, traditional off-gas testing, and the hood will be stationed in a fixed position. Also, the main goal of this study is to produce a simple, economical, operator-proof instrument. In the second part of this study, the filed-scale testing, we will work together with plant operations in selected locations, to include all the operators' feedback. This will maximize the user-friendliness of this system.

3. **Henrik Melcer:** *What actions can WWTP staff take to improve the efficiency of their aeration system?*

Diego Rosso: In the final part of this project, the technology transfer, we will include the outcomes of our recently published papers on aerators' efficiency and ageing in the tutorial seminars. Moreover, the results of our previous investigations will be transmitted to the wastewater treatment community in form of sample calculations and procedures.

Lory Larson: Also, at the very end of the project, we will host a day-long workshop in our Edison office where we will invite representatives of the whole treatment community. Mike, Diego, and Ben will then present their final results and show how to implement them at a plant scale.

4. **Keith Carns**: *Can you directly connect the fuel cell to a computer and read the oxygen concentration?*

Michael Stenstrom: Yes, the cell can be wired directly into a computer interface, thus bypassing the oxygen purity meter instrument. This simplifies the apparatus and has the big advantage to considerably reduce size and costs. (Follows a demonstration of a working oxygen fuel cell, performed by Diego Rosso)

5. **Henrik Melcer:** *Do you know yet how your proposed device will be calibrated, assuming that it will require calibration?*

Diego Rosso: one of the main features of this device is self-calibration, included in the design to simplify the operations of the device as much as possible.

6. **Henrik Melcer:** *If you permanently mount a hood in one location on an aeration tank, do you think you'll be able to develop approximate ratios between the measured OTE at that location and the overall tank efficiency? How many variables might affect such a ratio? Or will this have to be measured for each tank?*

Michael Stenstrom: hood positioning and sizing will be addressed in the field-scale sensitivity analysis included in the development of testing protocol, in 2006.

7. **Henrik Melcer:** *If OTE decays gradually over a period of years, is there any advantage to monitoring OTE continuously?*

Diego Rosso: The advantage of monitoring OTE continuously is that the rate of reduction in OTE is site-specific. We have collected an average rate of OTE decline over time for different operations (i.e., conventional, nitrification-only, nitrification/denitrification) and for different diffusers time in operation (new, used within 24 months, old over 24 months, cleaned within 1 month) and published them in our recent paper, Economic Implications of Fine-Pore Diffuser Ageing.

Michael Stenstrom: Field testing on a specific location provides the accurate OTE rate of decline value necessary for the economic analysis and the calculation of cleaning frequency.

3.2 2nd PAC meeting

Summary

In this meeting, the presentation provided by UCLA generally reemphasized the importance of diffuser cleaning schedules. The first version field-prototype was also introduced. Discussions and comments from PAC members focused on: the economic savings of cleaning frequency; cleaning methods; and the applications of the off-gas device. PAC members were interested in UCLA Research Group's curve method for defining the cleaning frequency provided. Members also provided their data on aeration costs as references. Other practical and useful suggestions such as the flexible hood was also favorably received by the PAC members.

Minutes of the discussion

1. ***Mike Selna:** Your main goal will be to convince operators to clean the diffusers more often. Although the cleaning frequency can be varied depending on each case, it is generally concluded that fine-pore diffusers should be cleaned at least once per year.*

   Diego Rosso: (A powerpoint slide is projected in this instance) A method to define the cleaning frequency for fine-pore diffusers in ASP was published by Rosso and Stenstrom (2005b and 2005c): Figure A-6 shows the generalized results of the economic analyses for a longer range of time in operation. Each curve is labeled according to off-gas test results. The upper-half of the graph shows the evolution over time of the ratio of actual power to initial power, i.e., the dimensionless power waste. The bottom-half plots the power waste to cleaning cost ratio versus time in operation. The characteristic saw tooth shape describes the evolution of costs over time. As the time in operation increases, the power waste to cleaning cost ratio grows and when it approaches 1, the algorithm sets a cleaning event with a steep decline in cost. An excel spreadsheet is provided to develop a specific curve for treatment plants.

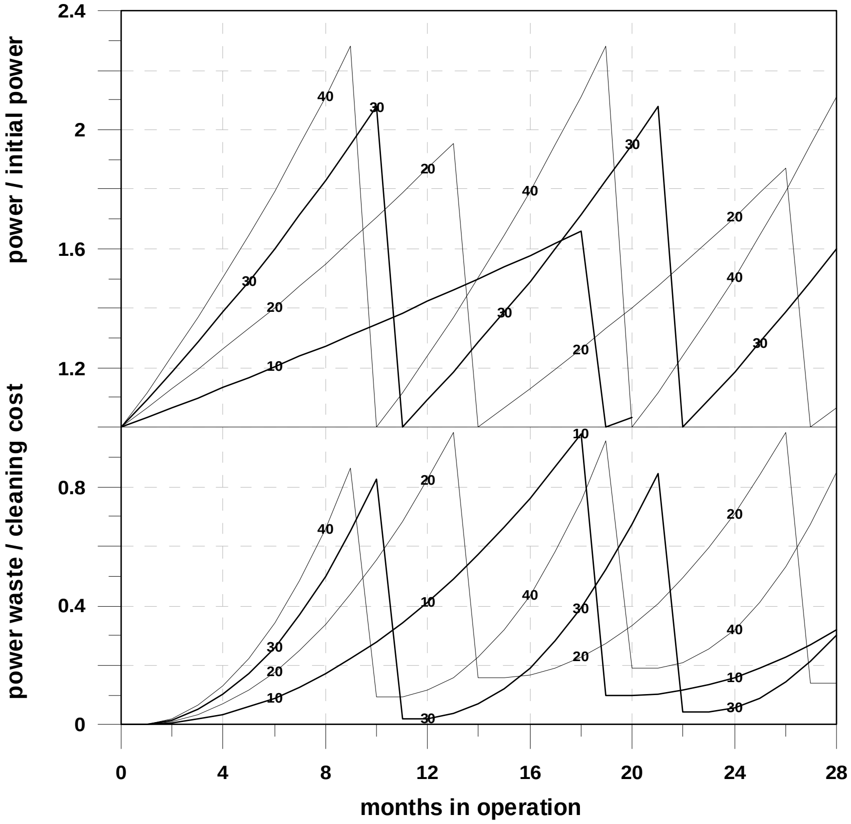


Figure A-6. Dimensionless cost ratios versus time in operation.

2. ***Keith Carns:*** *It is mentioned in the presentation that after cleaning the performance of fine pore diffusers recovers only around 80% of new or the latest cleaned ones. If this reduction can be accumulated, the performance of diffusers would be continuously decreased with time, even regular cleaning is provided.*

   Diego Rosso: Over the lifespan of the membranes, the reduction of performance is inevitable, because some of the severely fouled/scaled pores can not be cleaned. No membrane can recover to efficiency values comparable to new ones. Appropriate operations and cleaning management is helpful to increase the efficiency recovery and the overall diffuser lifespan. There exists a point in the lifespan of the diffusers where the recovery does not meet a sufficient value for operations, and the diffusers must be replaced. In order to quantify this turning point in time it is necessary to monitor the efficiency on-line for a prolonged time (i.e., months or years), which is one of the aims of this project.

3. ***Omar Moghaddam:*** *What's the general performance of acid cleaning (for both liquid and gas)?*

   Michael Stenstrom: Acid cleaning has shown better improvement on transfer efficiency and pressure loss than tap water cleaning. It is explained by the higher solubility in acid for some inorganic scaling compounds. Nevertheless, there may be a degradation of membrane properties. In our current database we have no significant number of facilities where acid cleaning.

   Diego Rosso: At this point, however, in our dataset we do not have an amount of data pertaining acid cleaning experiences large enough to quantify a difference.

4. ***Michael Selna:*** *Since the off-gas instrument can be set up as a permanent device for treatment plants, is it possible to develop a feed-back control system based upon off-gas readings?*

Diego Rosso: An off-gas device is a tool to assess the long-term performance of operating diffusers. Continuous off-gas monitoring may complete the information understanding the dynamic treatment status in the aeration tank. Therefore, a final goal of returning feedback to the aeration control system would be optimal.

5. ***Rod Reardon:*** *What* ***would*** *be the appropriate hood size?*

   Michael Stenstrom: In general, the hood reflects the performance of diffusers underneath its surface. Larger hoods provide information for more diffusers but are also more difficult to operate. Smaller hood is easier to operate but only collect the air sample from a smaller area of the tank, which is not representative to the whole tank. In this project, a movable minimum size hood will be investigated and designed. The mobility of the hood provides us the spatial information of diffusers and the whole-tank performance can be estimated by integration.

6. ***Michael Selna:*** *Aeration costs of $7.5 million/year and $110/million gallons are average, reasonable estimates for our county plants. How do they compare to theoretical values?*

   Michael Stenstrom: The recent paper we published, regarding economic analysis of conventional, nitrifying-only, and nitrifying/denitrifying operations returned results that can be roughly summarized as: $48/million gallons, $56/million gallons, and $36/million gallons for conventional, nitrifying-only, and nitrifying/denitrifying process, respectively. We will check the calculation assumptions that we used for this study and will discuss in the coming meeting the results.

3.3 3rd PAC meeting

Summary

Based upon the former meetings (1st at 06/27/2005 and 2nd at 11/02/2005), PAC members are all familiar with the main purpose and background of this project. Thus in this meeting, discussions of PAC members, UCLA research group, and Southern California Edison mainly focus on how to encourage the plant managers and operators to accept the concept and techniques to monitor aeration efficiency and power cost, in addition to the effluent quality. As by Mike Selna from Sanitation Districts of L.A., an advanced WWTP operation manager: operators always focus more on water quality instead of how to process the treatment plant correctly. Several options were recommended to link the power plant to the wastewater treatment plant, including:

- A one-day-long workshop in Edison office to present the final results and show how to implement them at a plant scale. Representatives of the whole treatment community will be invited and UCLA research group will be presenting.
- Since different rates of energy costs are counted for different purpose, i.e. rate of industrial is cheaper than residential; a rebate program could be ideal to encourage the WWTPs with the aeration energy monitoring system. However, this option requires good communication between power plants and treatment plants.

Questions from PAC members are all considerate and helpful. The comments will all be included in the project.

Minutes of the discussion

1. ***Henrik Melcer:*** *According to the description in slide #9, is the lab-scale experiment comparable to field-prototype?*

Michael Stenstrom: Yes. The lab-scale test is designed to test the apparatus used in the field-prototype. The basic theories of lab- and field- scale tests are the same.

2. **Lory Larson:** *What's MLE?*

   Diego Rosso: Modified Ludzack-Ettinger process, i.e. the simplest layout exploiting nitrification-denitrification.

3. **Henrik Melcer:** *What's happening to the 2nd part of the aeration basin in the treatment plant, Simi Valley, shown in the graph in slide #11?*

   Diego Rosso: The second tank is a polishing basin from the old system. The tanks are shallower but equipped with the same type of diffusers as the processing tanks.

   Michael Stenstrom: It is not a regular design. The plant is planning to change it to provide better treatment performance.

4. **Henrik Melcer:** *According to the picture in slide #18, is it possible that the floating hood can impact the surface aeration? Which diffusers are in place in Chino?*

   Michael Stenstrom: In most of the aeration tanks using fine-pore diffusers, the transfer from water surface is negligible comparing to the aeration from bubbles. Polyurethane membrane diffusers are used in the plant and there is no MLE pump in this system.

5. **Henrik Melcer:** *In the figure of slide #3, what are the numbers, 7%, 12%, and 11% represent? Those numbers seems too low if they are the OTEs of treatment plant of Chino.*

   Diego Rosso: Those are average OTEs adapted from the former experiment results. The detailed of this study was shown in our paper (2005b), which compiled the 15-year off-gas test results from treatment plants in California.

6. **Shahid Chaudry:** *The job reducing the size and complexity of off-gas test must be encouraged. What are the other sites?*

   Michael Stenstrom: LA City's Tillman and Glendale, LA County's Whittier and San Jose Creek, and the Central Plant of Contra Costa County in Northern California.

7. **Mike Selna:** *How do you document the cleaning frequency based upon the type of operation process? Is there any difference of the cleaning procedure between MLE and step-feed process?*

   Michael Stenstrom: The cleaning age of diffusers in Simi Valley is 6 month. One of the two aeration basins of Chino treatment plant is 1 year and the other is 1 month. Parallel tests may be performed to compare the effects of age of cleaning and develop the cleaning schedule.

   Diego's paper: The design of cleaning schedule is site specific. In general, the alpha SOTEs as shown in our papers (2005a and b) are 1.1% to 0.7% to 0.6% from new, clean, and old, respectively. With higher SRT and better bacteria composition, the diffuser condition of NDN process is generally much better than conventional treatment plant with low SRTs.

   Michael Stenstrom: After 2 year's operation the transfer efficiency reduced to about half.

8. **Henrik Melcer:** *How can we convince the operators to do oxygen transfer tests and establish a proper cleaning schedule, since everybody has a tight budget?*

Michael Stenstrom: Linking the power plant to wastewater treatment plant may encourage plant manager to focus on the issue of energy saving.

Lory Larson: At the very end of the project, we will host a one-day-long workshop in our Edison office where we will invite representatives of the whole treatment community. Mike, Diego, and Ben will then present their final results and show how to implement them at a plant scale.

9. ***Keith Carns:*** *What's the regulation from EPA on aeration costs of wastewater treatment? Could energy efficiency testing added to the regulation requirements? Is it possible to provide a discount or rebate program on energy costs to the plant accomplishes the OTE monitoring program?*

Lory Larson: Different rates of energy costs are counted for different purpose, i.e. rate of industrial is cheaper than residential. Rebate program is possible but it requires better communication between power plants and treatment plants.

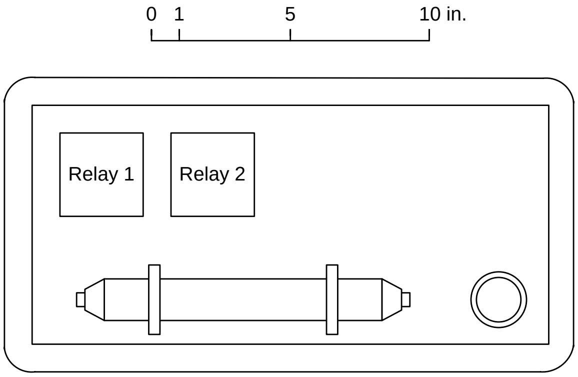
Diego: In some large municipalities, such as the City of LA, there is no way to track the source of energy consumption, since different entities perform operations and record expenses.

Mike Selna: Yes. Operators always focus more on water quality instead of how to process the treatment plant correctly.

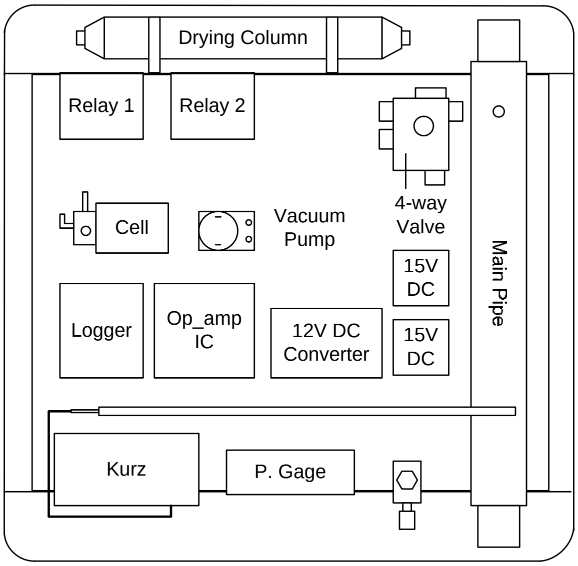
4.0 Example layouts of off-gas monitoring system

4.1 Layout of a portable off-gas monitoring system

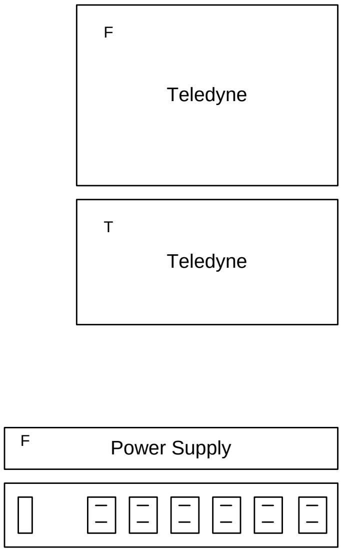
Back



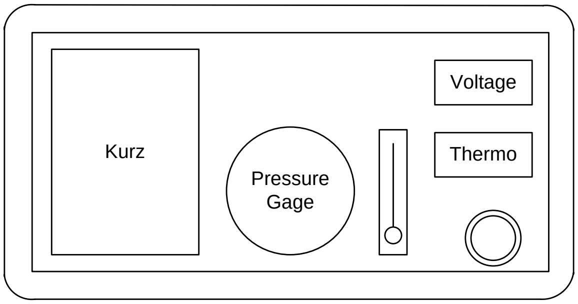
Top



Other Equipments

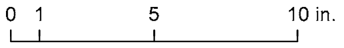


Front

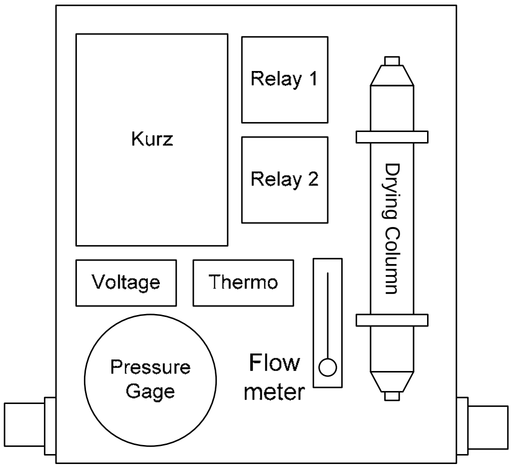


Note: This design is based on the 5U SKB musical rack as device box (inner W15" x L18.5 x H8.75"), which is slightly larger than the bread board version (W10.5 x L16" x H4.5")

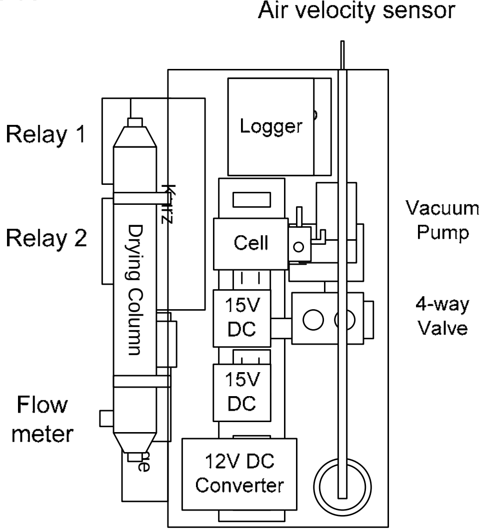
4.2 Layout of a wall-mounted off-gas monitoring system



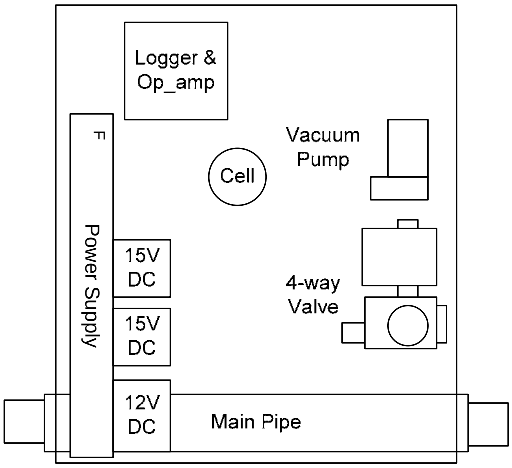
Front



Side



Inside



Note: This design is based on a normal size electrical enclosure with dimension W14" x L16" x D7.8"; the bread board version has dimension as W10.5" x L16" x D4.5" (Notice the length of air velocity probe is 16", which can be out of the box)

5.0 Project milestones and relative deliverables

DATE	%	MILESTONES	DELIVERABLES
10/1/2004			
		PAST	**PAST**
3/1/2005	2%	**1** formation of PAC	**1** letter describing pac members w/bios
		1.1 list of members	
7/1/2005	8%	**2** assessment of technologies	**2** ppts
		2.1 2-page summary of existing technology	technology summary letter
		2.2 summaries of 1st pac meeting	pac meeting minutes
		(minutes, comments, correspondence)	
9/1/2005	25%	**3** design and procurement of lab equipment	**3** equipment description letter
			ppt
1/15/2006	35%	**4** field prototype phase II-A	**4** summary letter
		4.1 design drawings	ppts
		4.2 description of the manufact	simi valley test report
		4.3 simi valley test	
3/1/2006	13%	**5** field prototype phase II-B	**5** summary letter
		5.1 design drawings	ppts
		5.2 description of the manufact	simi valley test report
		5.3 simi valley test	
		5.4 support tech-transfer	
7/1/2006	6%	**6** draft field testing protocol	**6** field testing protocol manual (draft)
11/1/2006	2%	**7** final field testing protocol	**7** field testing protocol manual (final)
		PRESENT AND FUTURE	**PRESENT AND FUTURE**
7/1/2007	7%	**8** final report (draft)	**8** final report (draft)
9/1/2007	2%	**9** final report (final)	**9** final report (final)