Protecting Our Water Environment

Metropolitan Water Reclamation District of Greater Chicago

RESEARCH AND DEVELOPMENT DEPARTMENT

REPORT NO. 2000-10

FINAL REPORT ON

EVALUATION OF POTENTIAL ELECTRICAL ENERGY SAVINGS USING ON-LINE RESPIROMETRY FOR CONTROL OF AERATION AT THE JAMES C. KIRIE WATER RECLAMATION PLANT

May 2000

Metropolitan Water Reclamation District of Greater Chicago
100 East Erie Street Chicago, IL 60611-2803 (312) 751-5600

FINAL REPORT ON EVALUATION OF POTENTIAL ELECTRICAL ENERGY SAVINGS USING ON-LINE RESPIROMETRY FOR CONTROL OF AERATION AT THE JAMES C. KIRIE WATER RECLAMATION PLANT

By

Kamlesh K. Patel
Research Scientist II

Stanley Soszynski
Research Scientist I

Prakasam Tata
Assistant Director of Research and Development
Environmental Monitoring and Research Division

Jain S. Jain
Research Scientist III

Bernard Sawyer
Coordinator of Research

Cecil Lue-Hing
Director of Research and Development
(Retired)

James J. Bertucci
Research Scientist III
(Retired)

and

Keith Carns
Director
Electric Power Research Institute

David Perkins
Advisor
Electric Power Research Institute
Washington University
St. Louis, MO

Research and Development Department
Richard Lanyon, Director

May 2000

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ACKNOWLEDGMENT

The authors wish to thank District and non-District personnel who have contributed to a varying degree to this full-scale project; without their cooperation and teamwork, the project would not have progressed to the point of its conclusion.

Special thanks are due to Dr. James J. Bertucci, Research Scientist III (retired), for his initiative in developing this project and for his sincere and nurturing efforts in the early stages of the project.

The authors extend their heartfelt thanks to the following personnel from the District's Maintenance and Operations (M&O) Department who have contributed to this project at professional, semi-professional and trades levels: Mr. David Jaeschke, AETPO I; Mr. Gerald Greczek, AETPO III; Mr. Mohamedusman Baki, AETPO I; Mr. Edward Cameron, AETPO III; Mr. William Tamkevic, AETPO I; Mr. Gerald McGann, AETPO I; Mr. Jarrett Pasowicz, Senior Mechanical Engineer; Mr. Devidas Kapadia, AETPO I; Mr. Abdulsattar Shaikh, Senior Electrical Engineer; Mr. John Lazicki, Senior Electrical Engineer; Mr. William Munch, Assistant Chief Engineer and Mr. Thomas O'Connor, Chief of M&O, for their fullest cooperation with the technical and administrative demands of the project; Ms. Doris

Bernstein and Mr. Gary Deacon, Instrument Technicians, for their efforts in calibrating the air and liquid measuring devices installed in experimental and control tanks; all Treatment Plant Operators on duty (especially those who worked during non-business hours), for their courteous inspections of the respirometry set-up for its proper functioning and for diligently passing the plant data to Mr. Kamlesh Patel, Project Leader, on a daily basis; Messrs. Bob Maciaszek, Master Mechanic; Frank Prosczek, John Mathieu, Marvin Sato, Pat Hanrahan, and Sidney Sakoda, trades personnel; for their very creative plumbing set-up and amicable and timely expert help in different areas of trades such as plumbing, electrification, trailer renovation, communication set-up, and relocation and maintenance of submersible pumps, etc.

The authors appreciate the contribution of the following personnel from the District's Research and Development (R&D) Department: Messrs. George Richardson, Assistant Director of R&D, Analytical Laboratories Division; John Gschwind, Sanitary Chemist IV; John Chavich, Sanitary Chemist III; and their staff at the John E. Egan Laboratory for their analytical support; Messrs. Vinod Patel, Devanand Patel, Syed Hussaini, and Dr. Mohammed Zeb (temporary Laboratory Technicians), for their work at the experimental trailer; Mr. Claude Kendrick, Mr. John Szafoni and Ms. Jeanne Bradford, Laboratory Technicians,

for their need basis help at the trailer; Mr. Raymond LoVerde and Ms. Tunesia Dillard, summer workers, for their support in field work at the plant; Mr. Saeed Farooqui and Ms. Tiffany Tate, Laboratory Technicians I, for their help in data entry and data files transfer from Macintosh to PC platform.

The authors wish to thank the Community Environmental Center of Electrical Power Research Institute for its partial funding of this project in the amount of $50,000. Others who have contributed to this project in various capacities include personnel from Arthur Technology, Inc., Fond du Lac, Wisconsin; namely, Dr. Bob Arthur, Mr. Bob Arthur, Jr., and Mr. Paul Breister, and Dr. David Willcox of WillStein Software, Inc., Wilmette, Illinois. Arthur Technology personnel provided necessary help to maintain and modify the on-line respirometers and sequential samplers. Also, Arthur Technology, Inc., developed and provided the original version of LabVIEW® software. The software was debugged and modified by Dr. Willcox.

Numerous other individuals contributed their time to this project and the authors wholeheartedly acknowledge their help.

The authors also wish to thank Ms. Laura Franklin for meticulously typing the partial manuscript and applying the R&D Department's formatting criteria to make this report accept able.

DISCLAIMER

Mention of proprietary equipment, software, or chemicals in this report does not constitute endorsement by the Metropolitan Water Reclamation District of Greater Chicago.

INTRODUCTION

General Objective

The primary objective of this study is to evaluate the feasibility of applying on-line respirometry for aeration control in the activated sludge process for achieving potential electrical energy savings.

Literature Review

RESPIROMETRY AND DEVELOPMENT OF VARIOUS TYPES OF RESPIROMETERS

Respirometry directly measures the respiration rate of microorganisms. The microbial respiration rate is measured as oxygen uptake exerted by microorganisms per unit time from air or from an oxygen-enriched environment.

Because of a direct relationship between oxygen consumption and biomass growth and substrate removal, respiration rate can be used as a variable to model, operate, and control aerobic treatment processes. Consequently, efforts have been made to measure respiration rate by using respirometers.

In order to measure oxygen uptake rates, manometric, nonmanometric, and electrolytic techniques have been used in various types of respirometers since 1908. Improvements, modifications, automation and computerization of respirometers since then have been varied and numerous.

APPLICATION OF RESPIROMETRY IN WASTEWATER TREATMENT

Respirometry has been a very useful and promising tool in studying wastewater treatment problems since its early years because conceptually it is relatively simple, fast, and economical. Automation and state-of-the-art on-line respirometry have made respirometry's application more attractive and visible in recent years to researchers engaged in the field of wastewater treatment, and the design and control practices of these treatment processes.

A recent review of the literature (2, 4 through 6, 8, 15, and 19 through 26) reveals that respirometric techniques are useful in wastewater treatment engineering for assessing: biodegradation of specific chemicals or combination of chemicals, treatability of organic industrial wastes, effect of known amounts of toxic compounds on the oxygen-uptake reaction of a test wastewater or organic chemical, inhibition of pollutants or wastewater on biological activity of microorganisms, effect of various treatments such as disinfection, nutrient addition, and pH adjustment on oxidation rates, oxygen requirement for essentially complete oxidation of biologically oxidizable matter, biochemical oxygen demand (BOD_5) of a wastewater, toxicity in wastewater, predictability of effluent quality, and stability of sludge.

The following is a summary of major contributors whose work on respirometry is noteworthy in the field of wastewater treatment engineering.

As reported by Mahendraker and Viraraghavan (15), Warburg and then Sierp applied respirometry to the measurement of the oxidation of wastewater. During the 1950s, the development of an alternative respirometric method which would replace dilution BOD measurements spurred considerable interest in respirometry (26). Application of respirometry, therefore, remained limited to determination of BOD values.

During the 1960s, non-manometric techniques were developed and used in addition to manometric methods. Mahendraker and Viraraghavan (15) reported that the large-volume respirometers including electrolytic respirometers were developed and tested by Arthur, Abson et al. and Young et al. and that Lamb et al. used the oxygen electrode method to study aerobic degradation of wastewater. Arthur pioneered the application of respirometry to the determination of BOD, routine wastewater analysis, and design of wastewater treatment systems (2). According to the literature review done by Mahendraker and Viraraghavan (15), Arthur and Hursta demonstrated to the Federal Water Pollution Control Administration, in 1968, that accurate BOD values could be determined by using respirometric techniques. According to the same literature review, Bridie used his self-designed electrolytic respirometer for BOD measurement and biodegradability studies of refinery wastewater containing phenol.

In the literature review done by Mahendraker and Viraraghavan (15), they also cited the work of Young and Baumann, who developed an improved electrolytic respirometer and used it to determine three-day, 20°C BOD values equivalent to those from the standard five-day test. According to the same literature review (15), inhibition of nitrification was demonstrated respirometrically using 2-chloro-6-(trichloromethyl) pyridine (TCMP or N-Serve), a nitrification inhibitor, by Young and Baumann. Allyl thiourea, another nitrification inhibitor was used by Cech, King, and Dutka to demonstrate respirometrically the inhibition of nitrification (15). Spanjers et al. estimated short-term oxygen demand from respiration rates on a continuous basis (21). Spanjers et al. determined short-term BOD and respiration rate in an aeration tank by using respirometry (22).

During the 1970s and 1980s, application of respirometry expanded to wastewater treatability study, wastewater treatment plant design and its control, biodegradability of mainly organic compounds, determination of biokinetic parameters, and toxicity detection.

Mahendraker and Viraraghavan (15) also cited the work of Van Kessel who used dissolved oxygen (DO) and nitrate ion electrodes to simultaneously measure oxygen and nitrate uptakes to corroborate the fact that heterogeneous bacteria favor nitrate as a terminal acceptor under anaerobic conditions; Blok who used respirometry for calculating viability of activated sludge; Walker and Davies who studied the relationship between microbial activity and viability of biomass at different growth rates; Clarke et al. who used continuous respirometry to demonstrate the effect of different food to microorganism (F/M) ratios on oxygen uptake rates (OURs) by feeding synthetic and raw industrial wastewater.

In their literature review on respirometry, Mahendraker and Viraraghavan (15) described the work of Huang et al. who proved in 1985 that microbial activity was represented by specific oxygen uptake rates (SOURs). The SOURs were observed to be inversely related to solids retention time (SRT), and approached to low constant values at very high SRT values. The investigators also noted higher microbial activity based on respirometric techniques at lower SRT values, when compared with results by using other methods such as plate counting. This observation led the investigators to conclude that the respirometric technique was better than other available methods to assess microbial activity.

Again, according to Mahendraker and Viraraghavan (15), Arthur designed a full-scale wastewater treatment plant for the village of Eden, Wisconsin, and he indicated that respirometry may be used effectively for on-line control of the activated sludge process. Mahendraker and Viraraghavan (15) also cited the work of Edwards et al. in which they observed that exogenous respiration changes in direct proportion to influent loading at the beginning of an aeration basin, whereas endogenous respiration slows down and then becomes stable at the end of the basin. Due to fluctuations in the SOUR, Edwards et al. did not recommend the use of SOUR to control the activated sludge process. Ros provided a detailed methodology for designing an aeration tank based on OUR data, and recommended the use of respirometry for studying the effects of a wastewater being discharged into existing treatment plants for the first time (19).

According to the literature survey by Mahendraker and Viraraghavan (15), many researchers like Clarke, Arthur, and Ros recommended application of respirometry for activated sludge plant design and its control. Rozich (20) also made similar recommendations. However, very few actual field trials have been reported.

Temmink et al. developed a biological early warning system for toxicity based on activated sludge respirometry (24).

del Bel et al. applied respirometric techniques to monitor toxicity on a nitrifying sludge and the nitrification process itself (6).

During the 1990s, the focus of application of respirometry changed from the determination of BOD, nitrification inhibition in BOD measurement, toxicity detection, and biodegradability of organic chemicals to the control of aerobic processes and anaerobic processes.

Mahendraker and Viraraghavan (15) further cited the work of Young on the development of a respirometer to study the mechanism and kinetics of the anaerobic processes, and of Sollfrank and Gujer on simultaneous measurements of oxygen transfer coefficients and OUR in the activated sludge process using on-line respirometry. The same authors (15) cited the work of Colvin on the calibration of activated sludge models for process control using respirometry to successfully predict effluent quality and performance at the Patapsco Wastewater Treatment Plant in Baltimore, Maryland. Spanjers et al. presented a methodology to estimate biokinetic parameters (for high degradation) for heterotrophic and autotrophic process models and activated sludge models 1 and 2, developed by the International Association on Water Quality (IAWQ) (23). Witteborg et al. (25) presented a method for using an on-line respirometer to determine the concentration of readily biodegradable substrates in the influent of an activated sludge system of the municipal wastewater treatment plant of the city of Nijmegen (270,000 population equivalent), the Netherlands.

APPLICATION OF RESPIROMETRY FOR CONTROL OF AEROBIC PROCESSES (ACTIVATED SLUDGE TREATMENT)

Due to the potential use of respiration rate for process control strategies, it has generated much interest. At the same time, there has been reservation and confusion as to the utility of this parameter. Inadequate measurement and a good understanding of how to interpret the respirometric information for its use in process control are the chief reasons which make its application less appealing and attractive, and even controversial at times. Additionally, inconsistent implementation of respirometric information has created confusion. As a result, there is still a lack of well-documented respirometry-based control of aerobic processes at full-scale facilities. However, a few examples found in the literature are as follows.

Draaijer et al. (8) tested, on a short-term basis, an application of respirometry at full-scale for the control of aeration in an oxidation ditch (15,000 m^3/day dwf) in the Netherlands. In 1979, Arthur designed a full-scale wastewater treatment plant for the village of Eden, Wisconsin. The design of both the aeration tank and the blower were based upon respirometric information. Further, he recommended that respirometry can be used effectively not only for on-line control of the activated sludge process, but also for conservation of electrical energy for aeration control (2).

Based upon a review of the recent literature, it may be stated that the application of respirometry for aeration control has not been realized and implemented in full-scale treatment plants to any significant extent.

Potential Savings by On-Line Respirometry Study

Approximately 45 percent to 75 percent of the electricity consumption at a modern activated sludge wastewater treatment plant is for supplying air to various unit processes such as aerated grit chambers, mixed liquor tanks, and air lift pumps (1, 11, 12). More than half of the total electrical energy consumed is for aeration to provide oxygen to mixed liquor suspended solids (MLSS) in the aeration tanks. Wastewater treatment plants have not been systematically studied in regards to what extent the air supplied is utilized to satisfy the metabolic needs of the aerobic heterotrophs and nitrifiers in activated sludge systems. It is likely that there is a potential for savings in electrical energy by controlling and optimizing the aeration process if the air supply far exceeds the demand. However, in a system where excess air is not an issue, the opportunities for savings may be marginal and, hence, the use of respirometric technique for aeration control may not be attractive and/or justifiable.

The potential for savings in electrical energy for wastewater treatment can easily be estimated from the current use of electricity and corresponding dollar amount. The electrical energy consumption for the Metropolitan Water Reclamation District of Greater Chicago (District) for the last five years has been approximately 550 million kilowatt-hours (kWh) per year at a cost of nearly 27 million dollars per year. For the year 1997, the District consumed 553 million kWh at $0.04862 per kWh for a total electrical cost of 26.91 million dollars. The wastewater treatment industry in North America required approximately 17 billion kWh in 1993, and over the next 20 years electricity requirements for this industry are expected to increase to nearly 25 billion kWh per year (11). As stated above, given that 45 percent to 75 percent of the electricity consumption at a wastewater treatment plant is for aeration, usage for aeration in 20 years will be approximately 11.3 billion kWh per year to 18.8 billion kWh per year. The electricity usage for aeration nationwide would cost between 565 and 940 million dollars per year at a unit cost of $0.05 per kWh. Even if a small percentage of the aeration cost is saved by optimizing air usage through respirometric control, when compared to the existing method of aeration control, it would amount to a significant savings.

Application of On-Line Respirometry for Aeration Control

The District currently uses an established and widely used method of automated DO control for aeration control in its activated sludge treatment plants. (Detailed description is provided in the Materials and Methods section.) This system controls the air supply to the activated sludge treatment plant by responding to a DO concentration resulting after the oxygen demand of the wastewater is satisfied. This type of "after the fact" control would not be expected to be as accurate as "before the fact" control using on-line respirometry. On-line respirometers measure the oxygen demand of the wastewater entering an aeration tank. This information can be used to control aeration depending on the strength of the wastewater to be treated.

On-line respirometry may be used to measure the biological activity of activated sludge in terms of OURs. Using the OUR values as measured by on-line respirometers, it may be possible to predict the oxygen requirement of sewage entering the aeration tank before the treatment actually begins. Such an oxygen demand prediction allows the quantity of oxygen, and hence the quantity of air, needed to satisfy the carbonaceous and nitrogenous oxygen demand of a varying load of wastewater to the system. Based on these predicted air needs, aeration can be controlled to more efficiently match the air supply to the actual oxygen demand. Therefore, it is obvious that aeration control by an automated DO control system may not be as responsive and effective as on-line aeration control by respirometry.

In light of the potential benefit for aeration control by on-line respirometry, a study was conducted at the District's James C. Kirie Water Reclamation Plant (WRP) with the cooperation of the M&O Department. The project was partially funded ($50,000) by the Community Environmental Center of the Electric Power Research Institute (CEC-EPRI), and the study was jointly conducted by the R&D and M&O Departments of the District, and the CEC-EPRI.

MATERIALS AND METHODS

The major components of the Phase III Arthur Automatic On-line Respirometer and its appurtenances, the sequential sampler, and the LabVIEW® data acquisition and system control software are described below.

Description and Principle of Phase III Arthur Automatic On-Line Respirometer

The on-line respirometers (Model No. 010-5000) used in this study were manufactured by Arthur Technology, Inc., Fond du Lac, Wisconsin. These self-contained automatic instruments are used for measuring short-term respiration rates of microorganisms present in wastewater. The respiration rate is calculated by measuring the reduction in gas volume in a closed airtight system. The headspace volume of the airtight system is approximately three liters.

Major components of the on-line respirometer include a water bath jacket, sample chamber, sample chamber cleaning system, overflow pipe system, respirometer module containing a sensitive gas volume transducer (oil filled manometer), air pump, foam and trap reservoir, carbon dioxide scrubbing chamber, heat exchanger, antifoam system, control panel, base cabinet consisting of five printed circuit boards (on-line electronics board, solid state relay board, respirometer electronics board, automatic vent electronics board, atmospheric compensation auto calibration board), air compressor and air tank, pipe system equipped with pinch valves, and data output unit. A brief description of each of the components is provided in the following paragraphs. Figure 1 depicts some of the major components.

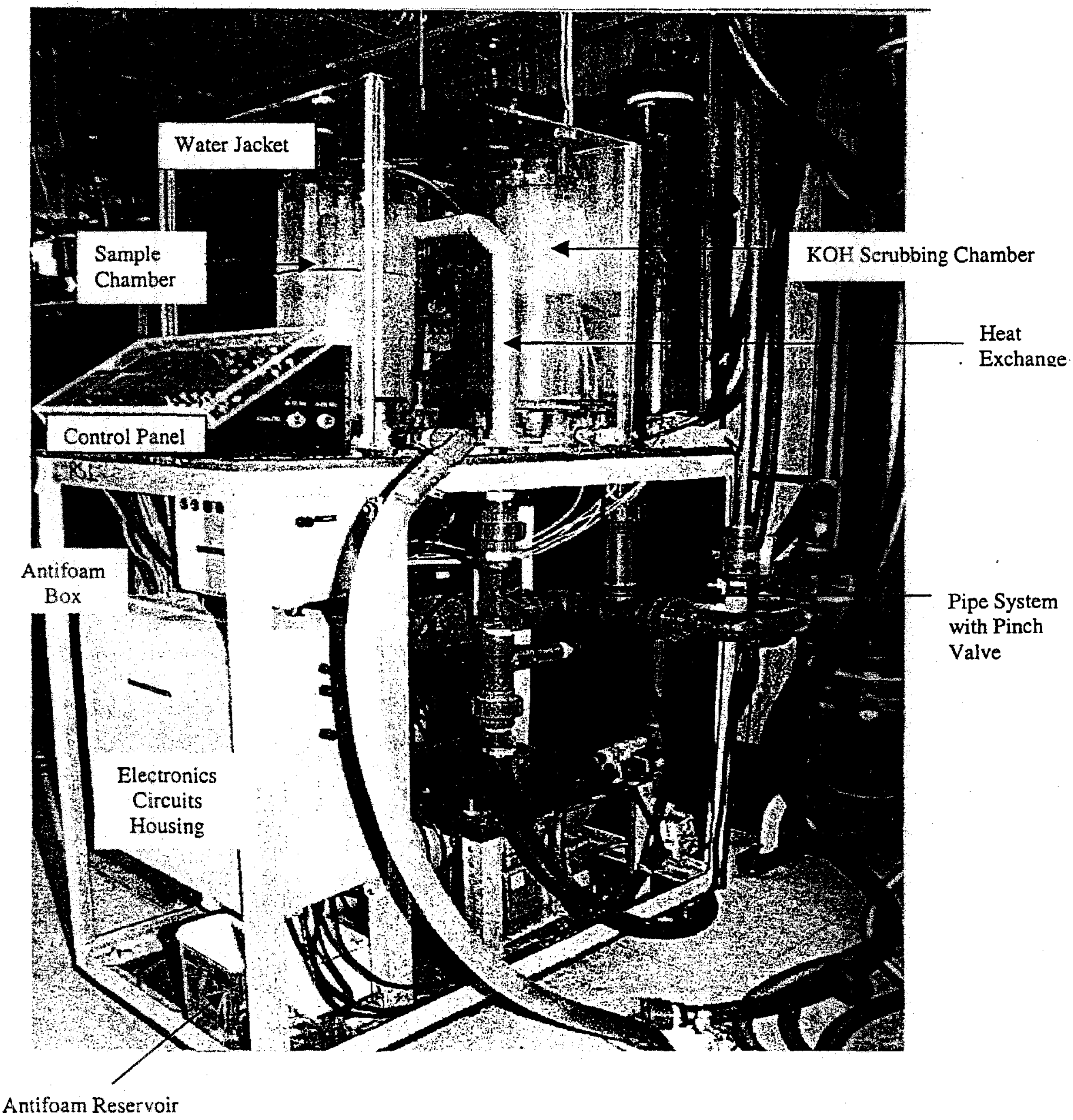
The sample chamber, respirometer module, carbon dioxide scrubbing chamber, and heat exchanger are located inside the water bath jacket and remain immersed in the water. Water in the water jacket adjusts the sample temperature to the system temperature and helps detect leaks in the closed system. Air leaks from the closed system are detected by the presence of bubbles at the water surface.

At the beginning of a defined time cycle, four liters of sample are drawn in the circular sample chamber which is made of transparent acrylic plastic. The amount of sample during each fill cycle is controlled by an overflow pipe system located in the rear of the water jacket. The sample chamber is designed to hold four liters of sample during normal operation.

The solids in the sample chamber are kept in suspension by using the air diffuser and airlift column. The airlift column is attached to the base of the sample chamber. At the end of each cycle, fresh water is sprayed at high pressure

FIGURE 1

MAJOR COMPONENTS OF PHASE III ARTHUR AUTOMATIC ON-LINE RESPIROMETER



(maximum pressure is 60 psi with a maximum consumption of 0.9 liter of water per five seconds) on the walls of the sample chamber to avoid contamination of the next sample and clogging by unwanted material. The tiny glass stopper attached to the lid of the sample chamber provides means for air suction and air injection in the closed system for calibration and air leak test of the respirometer.

A sensitive gas volume transducer senses the volume changes and converts them into electrical signals.

The air pump provides continuous air circulation through the sample and carbon dioxide chambers. The air and foam trap reservoir collects the foam transported from the sample chamber to the respirometer module, and thereby prevents malfunction of the instrument.

Because of the respiration of microorganisms in the closed system, carbon dioxide is produced and accumulated at the expense of the oxygen consumed in the head space air of the sample chamber. The air is pumped into 20 to 30 percent potassium hydroxide (KOH) solution contained in the carbon dioxide scrubbing chamber. The scrubbed air devoid of carbon dioxide is pumped further into the sample chamber through the air diffuser to sustain microbial respiration.

The sample is continuously pumped through the heat exchange column before it is diverted to the sample chamber for examination. The continuous circulation of sample narrows down the temperature variation between the sample and gas inside the closed system. Otherwise, variation in temperature would affect gas volume measurement and result in a misleading respiration rate.

The antifoam system, as the name suggests, is for controlling foam formation and its interference in the sample chamber. This system is equipped with a 5 RPM motor which drives a tubing pump and draws antifoam solution from a 1-liter reservoir, and pumps it into the pipe connected to the sample chamber at a rate of 4 mL per minute during the fill cycle. Variation in pumping time is possible by minor adjustments in the on-line printed circuit board. The antifoam pump is controlled by a solid state timer, which is operated by the on-line printed circuit board.

The control panel is located on the front of the instrument. This contains all the control switches for operating the instrument in either automatic or manual mode. The digital output meter is also located on the control panel and shows oxygen consumption within a range of 0-100 mL. It is designed to aid in calibrating the instrument. The cycle clock allows the operator to set a minimum cycle time of 1 minute and a maximum of 59 hours and 59 minutes.

The electronics assembly is housed in the base cabinet located in the front bottom portion of the instrument. It consists of five printed circuit boards (on-line electronics board, solid state relay board, respirometer electronics board, automatic vent electronics board, and atmospheric compensation auto calibration board).

The air compressor and air tank, both of which are located in the rear of the electronics assembly, provide necessary air pressure (approximately 30 psi) to the pinch valves of the respirometer, and the attached sequential sampler to help restrict flow movement through the pipe system.

The pipe system containing the pinch valves brings a sample of sewage or mixed liquor into the sample chamber via the heat exchanger, and drains out the sample and water used for cleaning the sample chamber at the end of each cycle.

The data output from the instrument consists of linear current and voltage signals in both a 4-20 mA-DC and 0-10 mV for recording analog outputs on the chart recorder. A RS-485 serial interface or computer interface capable of accepting a 4-20 mA input is used to feed the output signals to the computer.

Description of Sequential Sampler

The Arthur Sequential Sampler may be used in conjunction with an Arthur Automatic On-line Respirometer if multiple sample sources need to be tested in automatic mode. Because of this combination, multiple source samples (i.e., sewage, mixed liquor, return sludge, and effluent) can be tested in a sequence of preference without procuring as many respirometers as the number of sample sources. Only one source sample feeds the respirometer at a given time, and the rest of the lines remain in a dormant state until they are activated in the sequence of preference.

As shown in Figures 2 and 3, the major components of the Arthur Sequential Sampler include a control panel, a pipe system with pinch valves, and a solid state relay control unit. The control panel is located on the front of the instrument. It has all the control switches for operating the instrument in either automatic or manual mode.

Three or four different feed pipes and one outlet pipe with pinch valves make up the pipe network of the sequential sampler. The feed lines to the sequential sampler carry different source samples, and the outlet pipe which feeds the respirometer carries only one active sample source. Restriction of flow in the feed pipes is controlled by automatic

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FIGURE 2

MAJOR COMPONENTS OF ARTHUR AUTOMATIC SEQUENTIAL SAMPLER

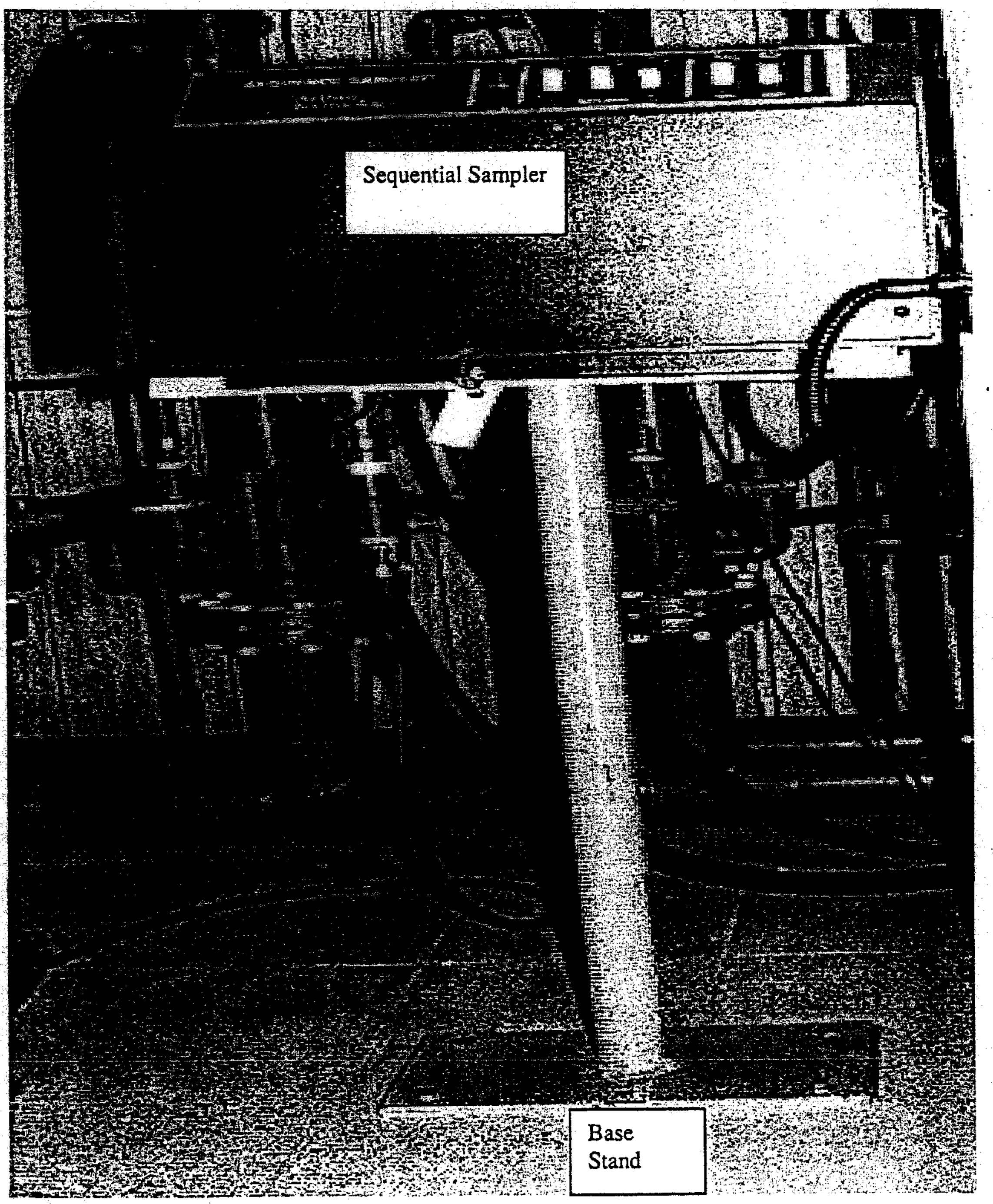
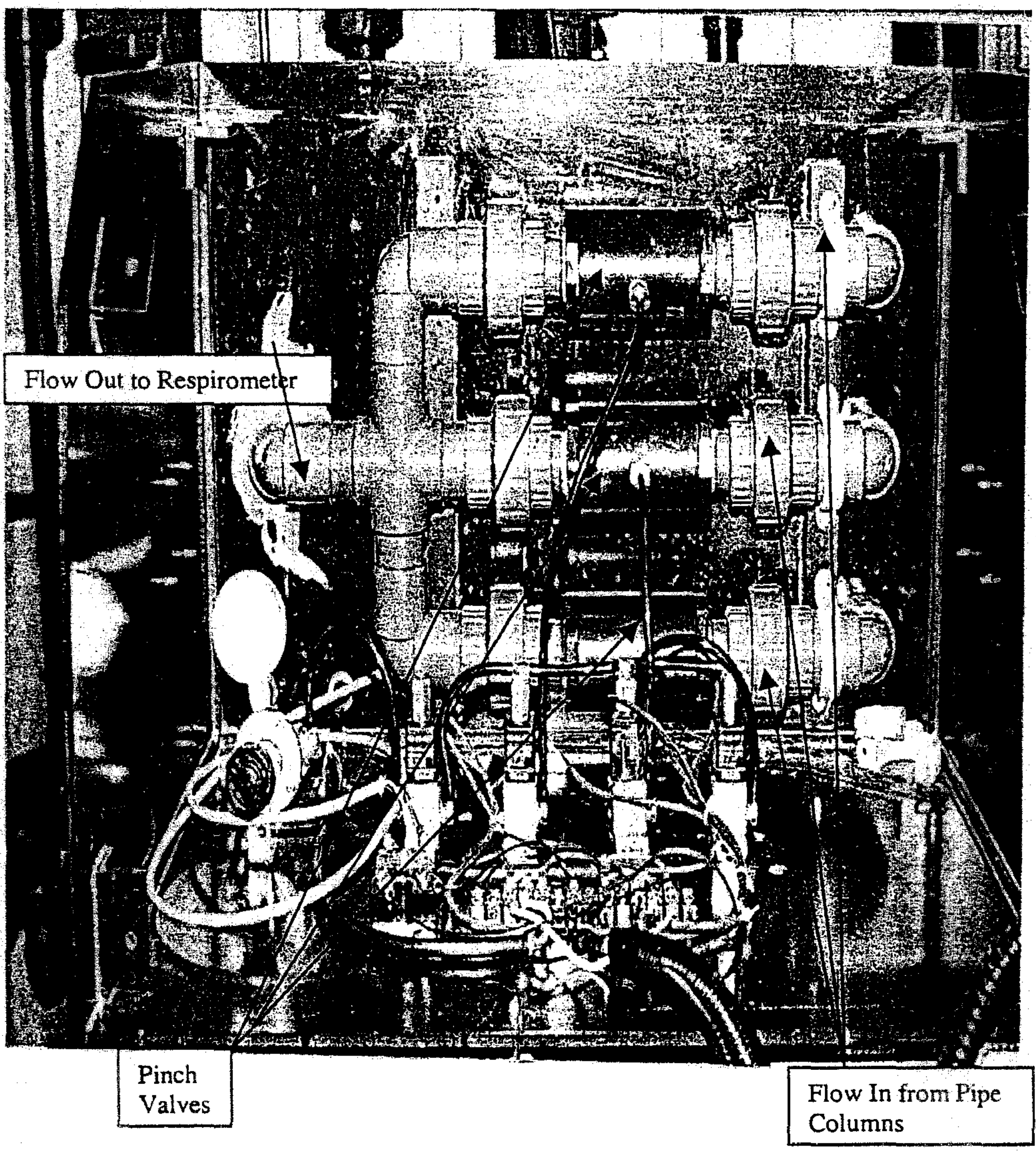


FIGURE 3

MAJOR INTERNAL COMPONENTS OF ARTHUR AUTOMATIC SEQUENTIAL SAMPLER



switches. The solid state relay (RS 3 type) regulates automatic switches.

Description of LabVIEW®

In 1986, National Instruments Corporation of Austin, Texas, introduced LabVIEW® (Laboratory Virtual Instrument Engineering Workbench), a graphical programming language, called "G," as an alternative to conventional programming. LabVIEW® is a robust program, well-known for its data acquisition, instrument control, data analysis, data management, and data presentation capabilities. Because of its features, LabVIEW® is functionally a complete programming language. LabVIEW® is a powerful and flexible instrumentation and analysis software for PCs running Microsoft Windows, Sun SPARCstations, and Apple Macintosh computers.

In LabVIEW®, programs called virtual instruments ("vis") are graphically created using the block diagram approach instead of writing the text-based programs. In the block diagrams, use of the natural design notation of scientists and engineers is permitted. After the block diagrams are completed, LabVIEW® compiles them into machine codes. Unlike text-based programs, the innovative feature of "vis" provides a high degree of freedom to the users to develop customized programs for virtually any situation ranging from bench-scale research testing to industrial plant testing, monitoring, and control.

A LabVIEW® "vi" consists of three main components, a front panel, a block diagram, and an icon/connector. The front panel is the user interface, the block diagram is the "vi" source code, and the icon/connector is the calling interface. A block diagram contains input/output (I/O), computational and sub-"vi" components, which are represented by icons and interconnected by lines directing the flow of the signal/data. I/O components communicate directly with plug-in data acquisition or General Purpose Interface Bus (GPIB) boards, and with external physical instruments (such as on-line respirometers). Computational components perform arithmetic and other operations. Sub-"vi" components call other "vis," passing data through their icon/connectors.

LabVIEW® can store data in ASCII or binary form. After acquiring, analyzing, and presenting the data, the data may be stored in a file, passed over a network, or passed to other applications such as Microsoft Excel for further processing or report generation.

Site Selection for Full-scale Experiment

One of the seven WRPs owned and operated by the District is the James C. Kirie WRP, which is located in Des Plaines, Illinois, a northwest suburb of Chicago. This WRP was chosen to conduct full-scale experiments for aeration control using on-line respirometry techniques. Several unique features of the Kirie WRP made it a better candidate for this experiment than the other WRPs of the District. Following are important features:

1. The average flow to plant was found to be around 30 million gallons per day (MGD) as against the design capacity of 72 MGD. This provided over 100 percent redundant capacity, which would essentially eliminate any potential adverse impact caused by the study on effluent quality.
2. The Kirie WRP happens to be the latest plant of the District, which became functional on May 12, 1980. In addition, the plant is equipped with the latest proportional integral derivative (PID) system for the purpose of aeration control using automated DO probes installed in the aeration tanks. This makes it more attractive for the study in which a comparison of the air rates

measured between on-line respirometry and conventional automated DO control technology is vital.

3. Variability in sewage characteristics at the Kirie WRP was judged to be very appropriate for this experiment because on-line respirometry is very sensitive to variability in sewage characteristics.

Aeration Control by Automated DO Probe System at the Kirie WRP

The Kirie WRP is equipped with an automated DO probe system for aeration control in its aeration tanks. The current operating protocols of the M&O Department suggest that a minimum of 2 mg of DO /L should be maintained in the aeration tank effluent. In order to do so, the DO probes are installed towards the end of all the six aeration tanks of Battery A; viz., 690 feet from the head end in a 750-foot-long tank. The DO probes continuously record DO concentrations in the mixed liquor, and feed these concentrations as analog signals to the control room computer. An algorithm scans the signals every sixth second and averages the scanned DO values every eighteenth second. The average DO value is compared against a set DO value of 2 mg/L. A change in air supply depends on the value of the average DO concentration. For example, if the average DO value falls below 2 mg/L, the algorithm determines to increase air supply until it reaches 2 mg/L and vice versa.

Description of the Arrangement of Arthur Automatic On-Line Respirometers, Sequential Samplers and LabVIEW® System

In April 1994, an experimental trailer was set up near Aeration Battery A at the James C. Kirie WRP (Figure 4). In addition to the basic amenities, the trailer was also equipped with a heating and air conditioning system to maintain normal room temperature and isothermal conditions in the water baths of the respirometers.

As shown in the floor plan of the trailer set-up in Figure 5, three on-line respirometers and two sequential samplers were set up in the trailer by the end of 1994. Respirometers 1 and 2 were connected to Sequential Samplers 1 and 2, respectively. Respirometer 3 was without any connection to Sequential Samplers 1 and 2. All three respirometers and two of the sequential samplers have computer interfaces, which allow the control of the entire system via an RS-485 connection. Commands are issued automatically by an Apple Macintosh computer, running a custom program developed in LabVIEW®. The LabVIEW® program controls the respirometers and sequential samplers, and collects and registers data.

The software made in LabVIEW® version 4.0.1 generates a maximum of 11 files per day, approximately 500 Kb each for the

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FIGURE 4

LOCATION OF EXPERIMENTAL TRAILER IN AN AERIAL VIEW

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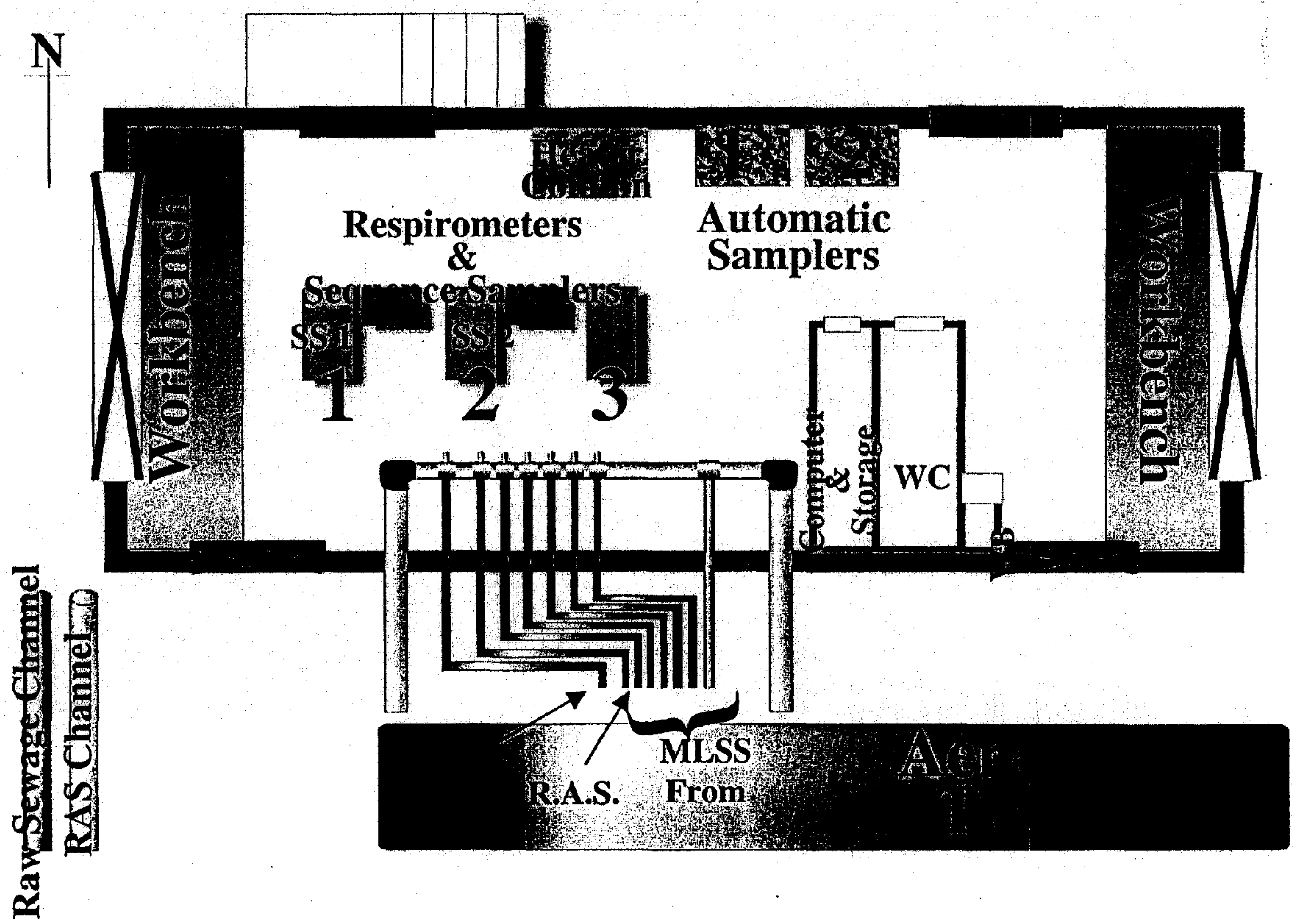
FIGURE 5

FLOOR PLAN OF THE EXPERIMENTAL TRAILER



purpose of data acquisition and data management. The software records information such as date, time of cycle start and cycle end, oxygen uptake volume in mL observed approximately every fifth second, final oxygen uptake rate as calculated by the program at the end of the cycle, and source of sample.

A maximum of eight different sources could be brought into the respirometers for respiration rate testing. These sources were pumped from a maximum distance of about 470 feet from the trailer by eight submersible pumps manufactured by ABS, Inc. The ABS pumps operated at a measured flow rate of about 18 gpm against a head of about seven feet in the appropriate pipe columns located inside the trailer. Of the eight submersible pumps, six submersible pumps are immersed in mixed liquor at different locations in the aeration tanks; one submersible pump in the return activated sludge in the RAS channel, and the last one in the raw sewage in the raw sewage channel.

The eight submersible pumps feed the eight pipe columns, which in turn supply the samples to respirometers via the sequential samplers. Samples could also be fed straight to the respirometers without passing the fluid through the sequential samplers if only one source needed to be examined.

From the respirometers, a sample flowed out to a 4-inch discharge pipe located inside the trailer. The discharge pipe opened at two far ends of the pipe columns, both of which were extended into pass 3 of aeration tank 1 for the final disposal of the sample. Bifurcation of the discharge pipe into two free falls on either side of the pipe columns was necessary to ensure an even flow distribution in the discharge pipe.

A typical pipe column is depicted in Figure 6. Each of the eight pipe columns has a diameter of 4 inches and four outlets of 1-inch diameter with control valves. With this multiple outlet feature in the plumbing system, the variability of oxygen uptake rate of the same source sample (as measured by three different respirometers) can be determined by testing the same source sample in three different respirometers. The fourth outlet allows the sampling of a wastewater or mixed liquor stream feeding the respirometers for any other analyses. Thus, the analyses of the desired parameters on the sample being tested by the respirometers can also be done by drawing the sample from the fourth outlet.

Flexible Nalgene® premium tubing of 1-inch diameter was used to carry the fluid flow either to the respirometers, or to the sequential samplers from the outlets of the pipe columns. The flow rate through each outlet was regulated by operating the control valves.

Because of the pressure exerted by the flow of wastewater or mixed liquor in the pipe column, a pressure release pipe

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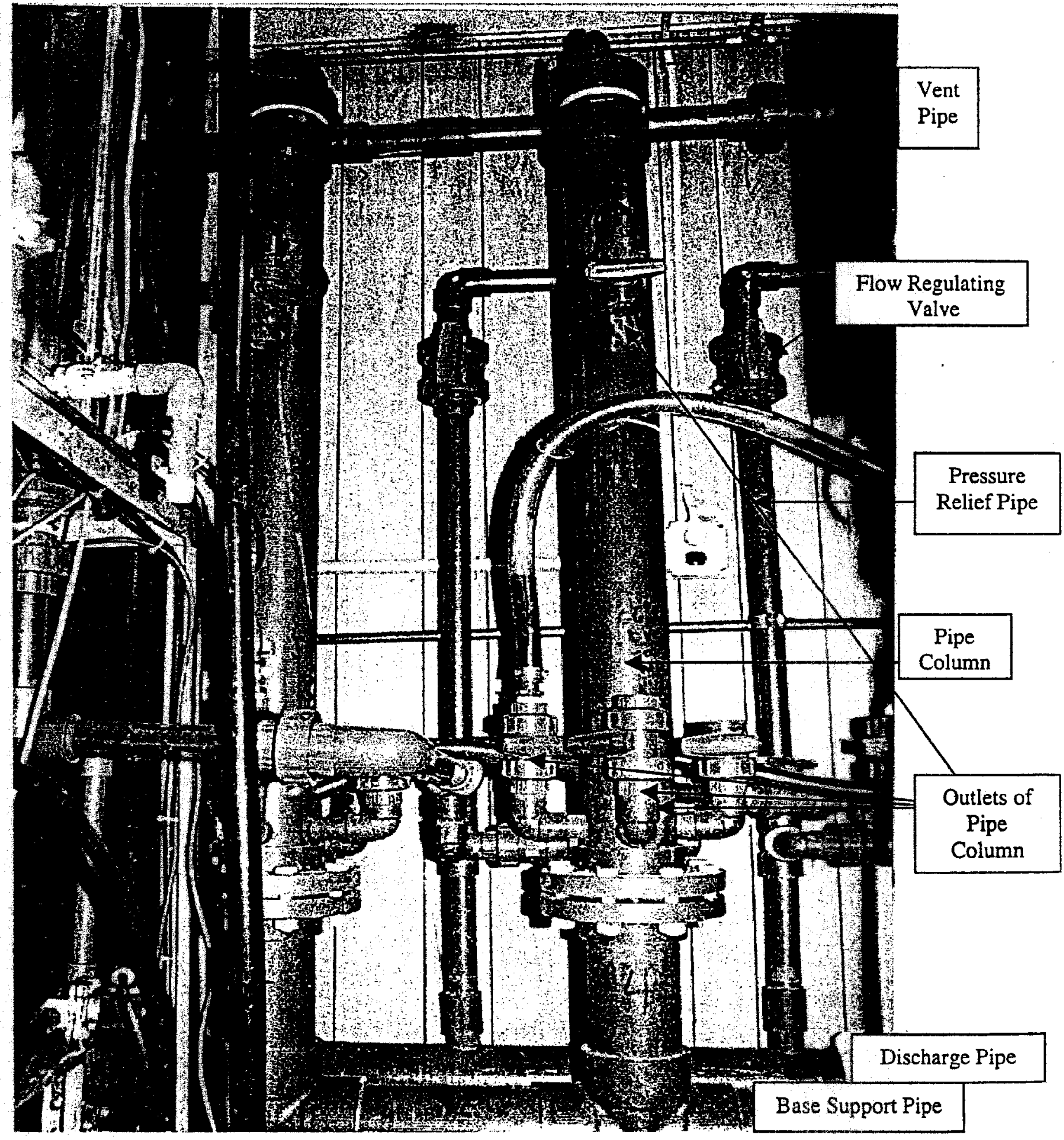
FIGURE 6

DETAILS OF THE PIPE COLUMN AND PIPE SYSTEM



was branched out to the discharge pipe for relieving the pressure in the pipe system. With this feature, the pressure in the pipe column was regulated, and the needed pressure head was maintained to feed the respirometer via the sequential sampler.

To ensure the flow of samples through the pipe system, the pipe column was extended to a common vent line as shown in Figure 7. The common vent line protrudes out of the end wall of the trailer and opens on the back side of the trailer.

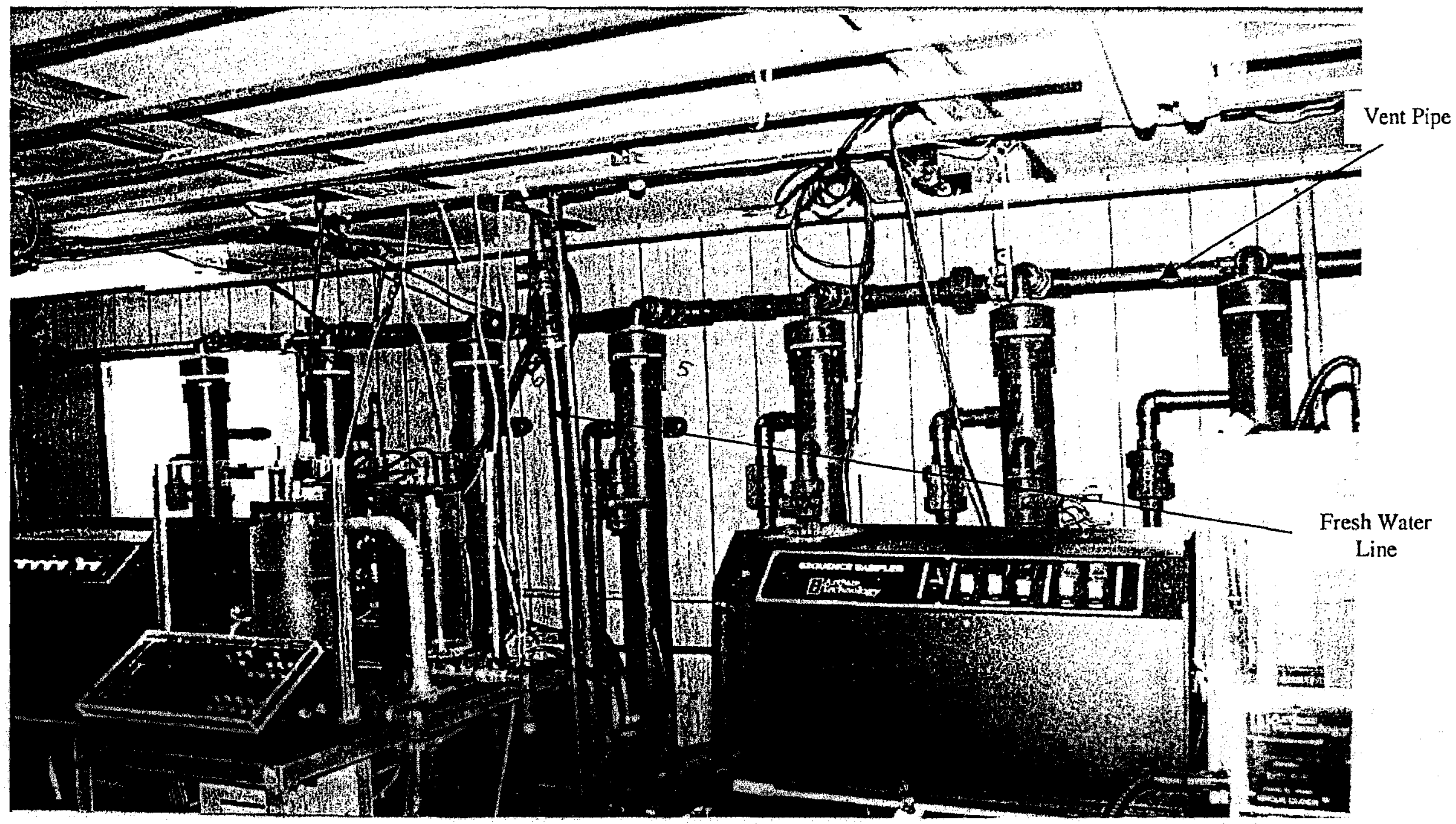
The base pipe at the bottom rests on the floor and provides the foundation support for all the pipe columns. The base pipe does not carry any flow.

A 1/2-inch fresh water line having three outlet connections above one respirometer was extended into the trailer (Figure 7). Each of these outlets provides water to clean the sample chamber of the respirometer at the end of a cycle, and also to backflush the pipe system of the respirometers and sequential samplers. The same water line was extended to different locations in the trailer for other uses.

A workbench on either side of the trailer provided space for laboratory and office work.

FIGURE 7

VIEW OF PIPE COLUMNS AND VENT PIPE



Automatic On-Line Respirometers - Sequential Samplers - LabVIEW® System: Calibration, Air Leak Test, Operation and Operational Protocols

The calibration and air leak tests on the respirometers are performed after they are properly assembled and started. The measurements of respiration rate in either manual or automatic mode of operation are performed on properly calibrated and leak-tested instruments. Computerized operation of the units in automatic mode is also possible by using a customized computer program.

The procedures for calibration, air leak testing, and operation are explained separately in different modes of operation.

Start-Up of the Automatic On-Line Respirometer

After the respirometer is completely assembled according to the manufacturer's guidelines, it is ready to be turned on. Following are the steps for getting the instrument ready for calibration.

1. Place all switches in the position shown below (Figure 8):

    Control Power (8B): Off
    Sample Pump (7B): Off
    Antifoam (6B): Off
    Air Pump (5B): Off

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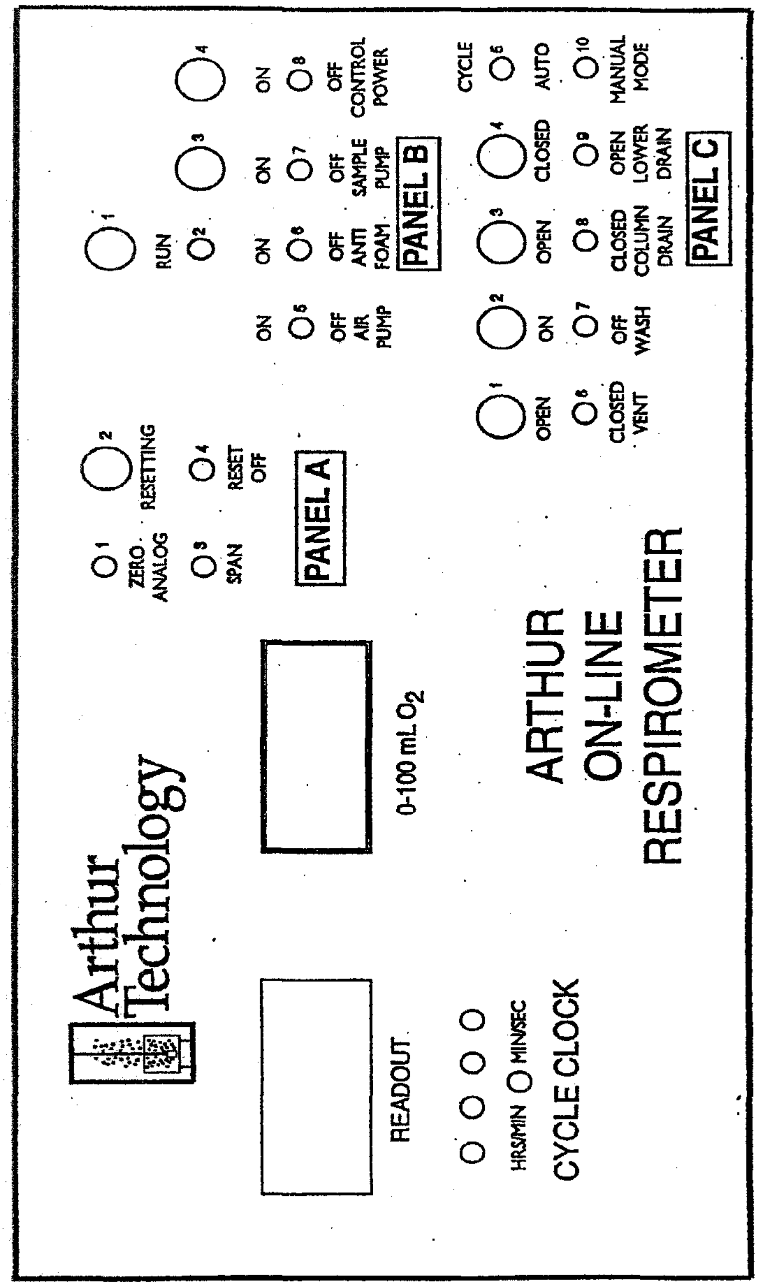
FIGURE 8

FRONT CONTROL PANEL OF ARTHUR ON-LINE RESPIROMETER



Mode	(10C):	Manual
Lower Drain	(9C):	Open (Off)
Column Drain	(8C):	Closed
Wash	(7C):	Off
Vent	(6C):	Closed

2. Plug the power cord into the wall outlet and turn the main power switch on.
3. Turn control power switch (8B) on. The indicator light (4B) comes on, indicating the on-line respirometer is operating.
4. Switch on the air pump (5B). Air should begin diffusing into CO_2 scrubber.
5. The respirometer is ready to examine the sample.

   One of the modifications made in the original design of the respirometer was the removal of the progressive cavity pump. The hydraulic head of the column is used to feed the respirometer instead of the progressive cavity pump.
6. Switch on the sample pump (7B). Check the drain line to verify that the sample is flowing through the respirometer.
7. Fill the water bath to the "tank fill" line.

8. Inspect the sample chamber and respirometer module for any possible air or water leaks. If water leaks into the volumetric transducer (it is heavier than the mineral oil), the water will have the appearance of shiny bubbles on the bottom of the transducer. Watch for rising water level in the sample chamber if it leaks.
9. Leave the instrument running for several hours. This will allow the sample flowing through the heat exchanger to equalize the water bath temperature.
10. Inspect the sample chamber and respirometer module after several hours for any possible air or water leaks. Now, the instrument is ready to be calibrated.

Principle of Calibration and Manual Procedure for Calibrating the Automatic On-Line Respirometer

The instrument is calibrated at the factory so that 10 mV (or 20 mA) full-scale on a 250 mm strip chart recorder is equivalent to 100 mL oxygen used. It may need to be recalibrated for different reasons, e.g., custom set-up or different size of chart strip, etc.

The principle of calibration is to simulate the removal of oxygen from the closed system. In an actual test, oxygen is removed from the system in the metabolic process. CO_2 is produced, but is absorbed by the KOH solution in the scrubbing unit. This results in a loss in volume created by the consumption of oxygen. A similar loss in volume can be accomplished by simply removing a known quantity of air from the closed system. This may be done with a calibrated syringe. The respirometer is calibrated when the removal of a given quantity of air from the system produces the correct reading on the recorder of the digital readout on the control panel.

Calibration beyond 100 mL of oxygen seriously limits the partial pressure of oxygen, and, therefore, the concentration of DO becomes limiting. Calibration must be done using the same volume of tap water as in the actual test.

The following details the calibration procedure.

1. Start calibrating the respirometer after cleaning the sample chamber, filling the water bath, and changing the diffuser.
2. Place all switches in the position shown below:

    Control Power (8B): On
    Sample Pump (7B): On
    Antifoam (6B): Off
    Air Pump (5B): On
    Mode (10C): Manual
    Lower Drain (9C): Open (Off)

Column Drain (8C): Closed
Wash (7C): Off
Vent (6C): Closed

3. Remove four liters of water from the water bath and save.

4. Switch vent (6C) to "open." The resetting (2A) and open (1C) lights will turn on. Remove sample fill tube plug and insert large funnel into the fill tube. Add the four liters of water previously removed from the water bath. Replace the sample fill tube plug; make sure that the syringe connector (stopcock) handle is in the horizontal position. Switch vent (6C) to "closed."

5. Measure the temperature of the water bath. Fill the water bath to "tank fill" line with soft or service tap water adjusted to within 0.2°C to 0.5°C of test temperature. If test temperature adjusted water is not available, the addition of any temperature water is acceptable; however, it will be necessary to wait until the test temperature becomes stable before continuing (i.e., 30 minutes or longer).

6. Once the temperature is stabilized, switch the vent (6C) to "open." Wait for the oil level in the volumetric transducer to equalize (about 30 seconds). Switch the vent (6C) to "closed."
7. Push reset button off (4A) to turn off the resetting (2A) light. Wait 15 seconds since the analog output will be held at zero for 15 seconds after resetting (2A) light turns off.
8. Depress zero analog button (1A).
9. Set calibration syringe to 0 mL mark, and connect syringe to syringe valve at the top of the fill tube plug.
10. If the recording device connected to output has a variable speed drive, adjust the drive so that the speed is the same as that to be used during the actual test, i.e., somewhere in the range of 5 to 10 cm/hour.
11. Turn syringe valve handle to vertical position and pull syringe plunger out to 55 mL. Close the syringe valve. This will remove 55 mL of air from the system. Allow 30 seconds for oil transducer to stabilize.
12. Adjust span knob (3A), if necessary, so that the digital display meter reads +55.0 greater

than the starting zero reading (e.g., if after depressing zero analog, the meter reads +0.5, then the final adjustment should be 55.0 + 0.5, or 55.5 mL).

13. Push syringe plunger in to 0 mL. Allow 30 seconds for oil transducer to stabilize. If digital display does not return to original starting point (0.5), press zero analog (1A).
14. Repeat steps 8, 9, 11, 12, and 13 until three consecutive calibration checks are made within 1 mL without adjusting the span knob (3A).
15. Close the syringe valve and remove the syringe.

Manual Procedure for Air Leak Test of Automatic On-Line Respirometer

After the respirometer is properly calibrated, the air leak test is performed as follows.

1. Place all switches in the position shown below:

Control Power (8B) : On
Antifoam (6B) : Off
Mode (10C) : Manual
Lower Drain (9C) : Open (Off)
Column Drain (8C) : Closed
Wash (7C) : Off
Vent (6C) : Closed

2. Push zero analog (1A). Withdraw 55 mL of air using syringe. Close syringe valve. This will make the indicator on the strip chart recorder and/or digital display meter move up-scale because the vacuum is drawn on the system.
3. Remove the syringe and reposition plunger to zero.
4. Allow the instrument to operate for a period of one hour to observe if air leaks are present. If the instrument is leakproof, the pen should draw a straight line on the chart. An acceptable test is defined as a graph trace that varies no more than ±2 mL from the initial point (i.e., 55 mL) for one hour. Repeat test if variance is greater than above tolerance.

Automatic Operation of the On-Line Respirometer without Computer Assistance

Once the respirometer is calibrated and air leak tested, the sample may be introduced into the sample chamber for measurement of the respiration rate. Following are the steps to run the instrument in automatic mode without computer assistance.

1. Set cycle clock switches to desired time interval (e.g., 20 minutes).

2. Place mode switch (10C) in "auto" position.
3. Press cycle button (5C). This will initiate a complete sample cycle.
4. Observe the instrument through the entire cycle. The existing fluid, if any, will drain out of the sample chamber and the clean water spray will clean the walls of the sample chamber. The sample fills to the red mark (four-liter line fixed by the manufacturer). The sample should be mixing well. When the vent is open (1C), the light goes off, and the cycle clock should begin counting down. If the sample does not reach the red mark, adjustment of the overflow pipe will be necessary. The sample level in the sample chamber proportionately changes with the adjustment of the height of the overflow pipe.
5. Observe that the oxygen consumption numbers on the digital display meter above the control panel are increasing.

Procedures for Computerized Calibration, Air Leak Test, and Operation of the Automatic On-Line Respirometer

Computerized calibration and air leak testing are improved versions of the manual procedures. The main difference between computerized and manual operation is in the automatic control of the instrument and recording the output signals. The use of the computer in calibration, air leak testing, and operation enhances the accuracy and reliability of these procedures. The output signals may be received on the computer hard disk drive, on the computer screen, or on the chart recorder.

Following are details of the computerized calibration and air leak test procedures.

Computerized Calibration Procedure

The "calibration" button on the "Chicago On-Lines.vi" screen causes the "calibration.vi" panel to be displayed as shown in Figures 9 and 10. Each of the three respirometers (units) can have its own calibration factor.

1. The top half of the "calibration.vi" screen in Figure 10 displays information related to all three units. It is not directly used in the calibration procedure. The "Zero" and "Span" for each channel are displayed. The "Raw Data" shows the readings from each unit as they are received, without correction. The "Corrected Data" is the result of converting the "Raw Data" into a mL reading. The formula for doing this is: Corrected Data = Span x (Raw Data - Zero).

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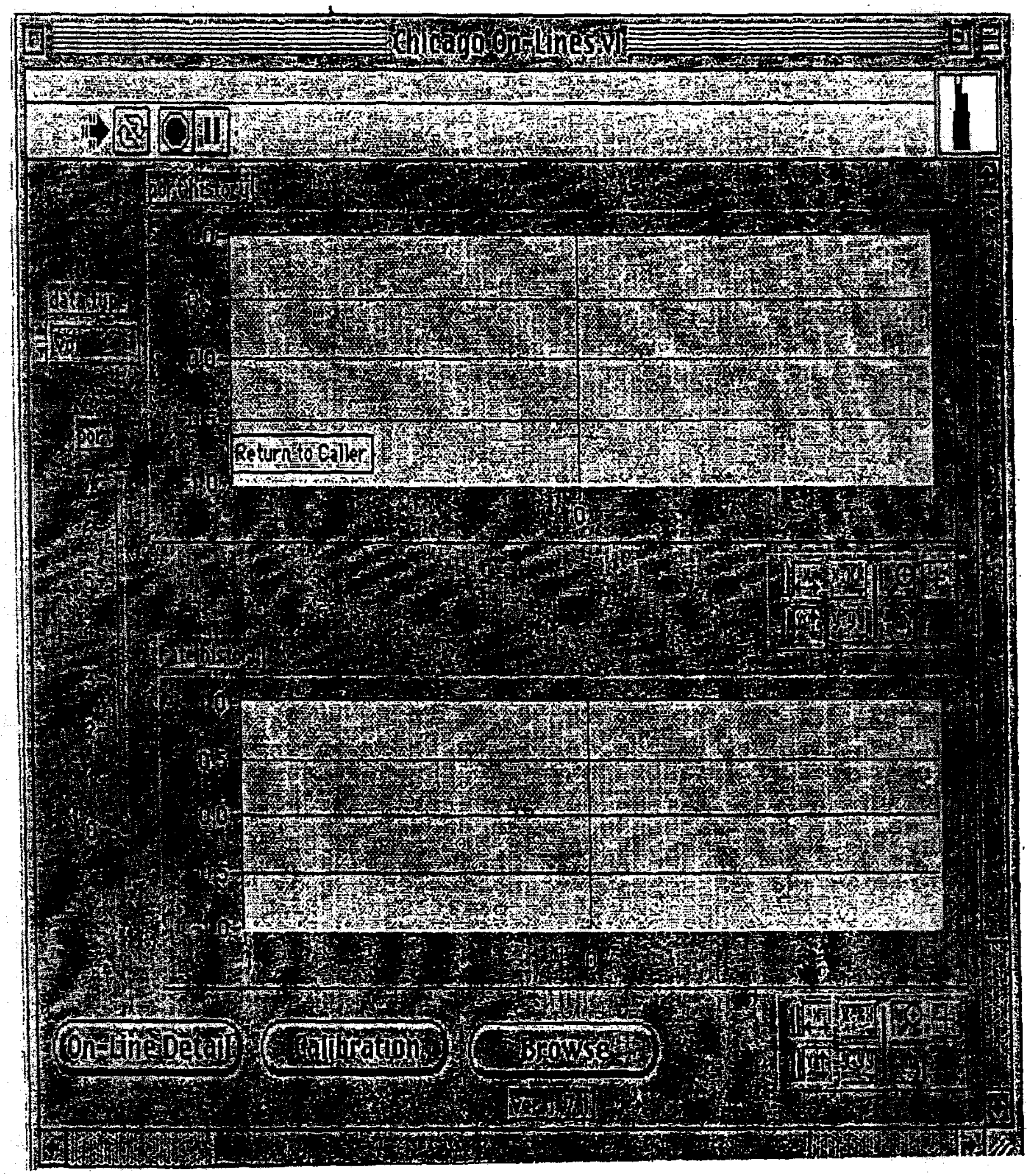
FIGURE 9

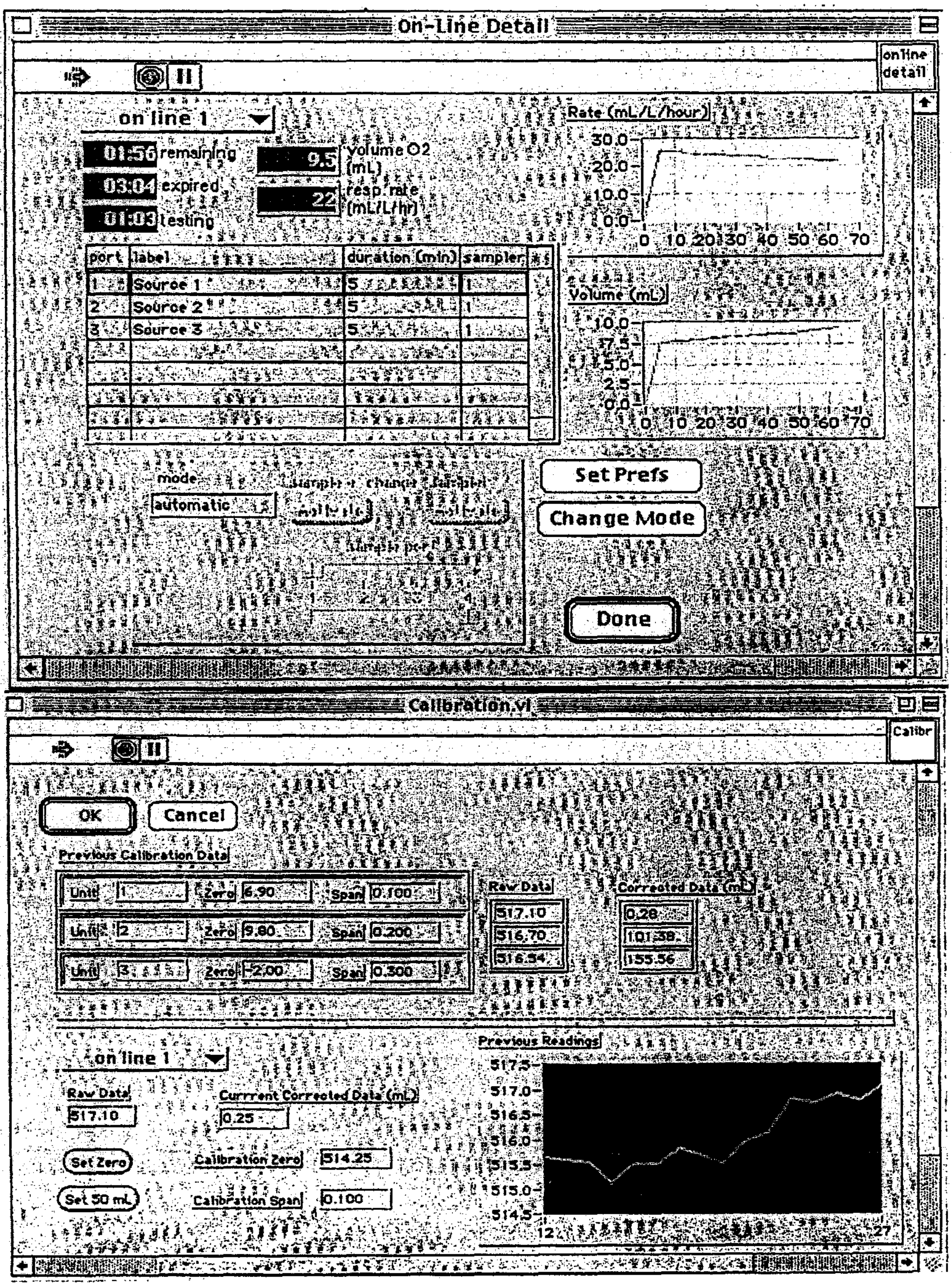
"CHICAGO ON-LINES.vi" SCREEN FROM LabVIEW® SOFTWARE



METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

FIGURE 10

"ON-LINE DETAIL" AND "CALIBRATION.vi" SCREENS FROM LabVIEW® SOFTWARE



01:56 remaining

03:04 expired

01:03 testing

Volume O2 (mL): 9.5

resp. rate (mL/L/hr): 22

port	label	duration (min)	sampler
1	Source 1	5	1
2	Source 2	5	1
3	Source 3	5	1

mode: automatic

Previous Calibration Data

Unit	Zero	Span
1	6.90	0.100
2	9.80	0.200
3	-2.00	0.300

Raw Data	Corrected Data (mL)
517.10	0.28
516.70	101.38
516.54	155.56

on line 1

Raw Data: 517.10

Currrent Corrected Data (mL): 0.25

Calibration Zero: 514.25

Calibration Span: 0.100

2. The bottom half of the screen is used to perform calibration on each unit individually as described below.
3. Select the unit to be calibrated using "On-line" pop-up menu. Wait for "Raw Data" reading to change to reflect the unit selected.
4. Follow the first eight steps as shown previously in the calibration procedure covered under the section entitled "Principles of Calibration and Manual Procedure for Calibrating the Automatic On-Line Respirometer," so that it gives a "zero" reading. Watch for a stable reading in the "Previous Readings" window. Press the "Set Zero" button when a stable reading is obtained. This will convert "Calibration Zero" to the current reading.
5. Set calibration syringe to 0 mL mark and connect syringe to syringe valve at the top of the fill tube plug in the respirometer being calibrated.
6. Turn syringe valve handle to vertical position and pull syringe plunger out to 50 mL. Close the syringe valve. This will remove 50 mL of air from the system. Allow 30 seconds for oil transducer to stabilize.

7. Watch for a stable reading in the "Previous Readings" window. Press the "Set 50 mL" button when a stable reading is obtained. This will convert "Calibration Span" to the current reading.
8. Repeat the procedure for other units.
9. Press "OK" button to save calibration factors in computer memory.

Computerized Air Leak Test Procedure

The air leak test should be performed subsequent to the computerized calibration. However, calibration of the instrument before performing the air leak test is not a prerequisite. The procedure for air leak testing is described in the following steps:

1. Select the unit that needs to be air leak tested using "On-Line" pop-up menu. Wait for "Raw Data" reading to change to reflect the unit selected.
2. Set calibration syringe to 0 mL mark and connect syringe to syringe valve at the top of the fill tube plug in the respirometer being air leak tested.

3. Turn syringe valve handle to vertical position and pull syringe plunger out to 50 mL. Close the syringe valve. This will remove 50 mL of air from the system. Allow 30 seconds for oil transducer to stabilize.
4. Watch for a stable reading in the "Previous Readings" window and "Corrected Data" to reflect the current reading of 50 mL.

   Allow the instrument to operate for a period of one hour to observe if air leaks are present. If the instrument is leakproof, the trend line in the "Previous Readings" window should draw a straight line and the number 50 should hold constant in the "Corrected Data." An acceptable test is defined as a variance of no more than ±2 mL from the initial point (i.e., 50 mL) for one hour. Repeat test if the variance is greater than the above tolerance.
5. Repeat the procedure for other units.

Computerized Operation of the On-Line Respirometer

The calibrated and air leak tested unit is desirable for computerized mode of operation. The "On-Line Detail" button on the "Chicago On-Lines.vi" screen (Figure 9) causes the "On-Line Detail" panel to be displayed as shown in Figure 10.

The pop-up menu allows the unit selection. A "remaining" window shows the remaining time in minutes and seconds for the current cycle. Time remaining is the time difference between the duration of the cycle and the "expired" time. An "expired" window shows the total amount of time expired in minutes and seconds, including the flushing time. The "testing" time is the amount of time in which measurements are made for the given cycle. It should be noted that the "testing" time is approximately 2 minutes less than the "expired" time. Therefore, if 20 minutes is the desired time for collecting data, then 22 minutes should be entered in the "duration."

The "Volume O_2 [mL]" window shows the oxygen consumption as the cycle progresses. The "resp rate [mL/L/hr]" window shows the current respiration or oxygen uptake rate. Both of these quantities are continuously updated until the cycle ends. To assess the trends during the cycle, they are also depicted in two different windows labeled "rate [mL/L/hr]" and "Volume [mL]." The scales in both the charts are self-adjusting.

The "Set Prefs" button allows the entry of the source of sample description under the title "label" for the appropriate port of the sequential sampler and the sample retention time in the sample chamber in minutes.

The "Change Mode" provides the choice of mode through a pop-up menu. In automatic mode, the computer controls the complete operation of the respirometer and sequential sampler. No manual control of the respirometer or sequential sampler is possible in automatic mode. Sample testing begins immediately and continues indefinitely. Data are logged to the computer disk and screen. In the standby mode of operation, manual control of only the respirometer is possible; no manual control of the sequential sampler is possible. Data are logged to the screen only in the standby mode of operation. In the manual mode of operation, all computer control is inactive. Data are only logged on the screen. In the off-line mode of operation, no contact exists between the computer and the respirometer or sequential sampler.

The "mode" window shows the current mode of operation. A sliding button in "sample port" allows control over the port activation of user's choice. The "Done" button brings the operator back to the "Chicago On-Lines.vi" screen.

The steps for computerized operation of respirometer in automatic mode are as follows:

1. Set the respirometer in automatic mode using switch 10C on the control panel.

2. Choose automatic mode from the pop-up menu. In order to choose the automatic mode, press the "Change Mode" button on the "On-Line Detail" screen. The program prompts the user for a password. Upon receiving the correct password, the program provides a pop-up menu to select one of the four modes of operation; namely, automatic, standby, manual, and off-line.
3. The computer immediately issues a command to the respirometer to start a new cycle. The computer controls all operations of the respirometer and sequential sampler.

Once the new cycle begins, the sample chamber pinch valve opens, which allows the existing sample to drain out of the chamber. Clean water spray from the city water line cleans the walls of the sample chamber for a few seconds. The pinch valve on the vent line also opens simultaneously, which allows a free exchange of air between the closed system and the atmosphere. By now, sample has been diverted into the sample chamber from the continuously pumped sample through the heat exchanger. A new sample fills the sample chamber to the four-liter mark. The excess flow of sample is diverted to the overflow pipe since its level is adjusted to the four-liter mark. At this time, the sample pump, the sample chamber, the lower drain, and the vent pinch valves are open. All this takes about two minutes.

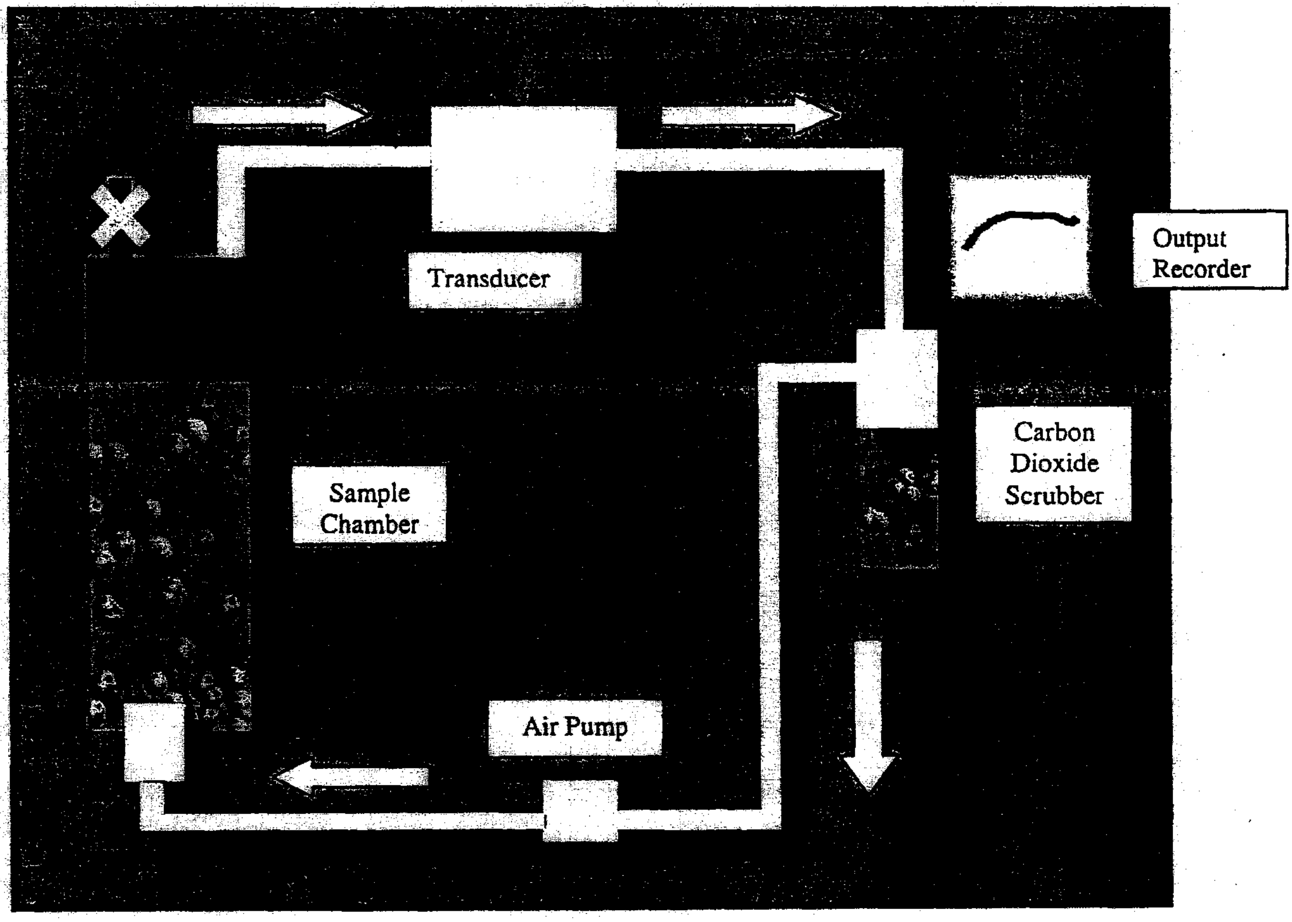
In a few seconds, the pinch valve on the sample chamber and vent line shuts off. Because of this, no new air or new sample fluid exchange is possible. In other words, the system is sealed. As soon as the vent and sample chamber pinch valves are closed, the system electronics are reset. Gas volume inside the closed system is measured by volumetric transducer and considered a zero reference point.

As the microorganisms in the sample metabolize the organic matter during the cycle time, oxygen from the closed system is utilized and carbon dioxide is produced and accumulated in the headspace of the sample chamber. The air pump continuously circulates the headspace air to the CO_2 scrubbing chamber. Scrubbing of CO_2 causes a change (decrease) in gas volume with respect to the initial gas volume measurement, cited above as a zero reference point. The net change in the gas volume at the end of the cycle time is equal to the volume of oxygen consumed by the microorganisms in the sample. All gas volume measurements during the cycle produce electrical signals in proportion to the gas volume (Figure 11).

Any effect on respiration rate due to temperature is insignificant, because the system assures that gas volume measurements are made at the sample temperature.

FIGURE 11

AIR FLOW PATH IN ON-LINE RESPIROMETER



A few seconds after the resetting of the system electronics, the backflushing solenoid switch is activated. At this time, the pinch valve on the active line of the sequential sampler (the line which just fed the sample chamber) remains open, but the sample pump and lower drain pinch valves remain closed. This ensures that the only exit available for the fresh water is to flow backwards into the pipe system. Thus, the pipe system is backflushed for about one minute with city water.

With the cessation of clean water backflushing, the pinch valve on the active pipe line of the sequential sampler is pinched and the next port of choice is automatically opened. Thus, approximately two minutes after the sample is filled, the next sample flows through the pipe system until the current cycle ends. At this time, the pinch valve on the recently activated line (the sample which is to be tested next), the sample pump and the lower drain pinch valves are open. This allows the flow to occur in the pipe system with the next sample to be tested. Such precirculation of sample through the pipe system avoids sample contamination due to the deposition of previous sample material in the pipe system and minimizes the temperature variations between the sample and water bath temperatures.

Backflushing with clean tap water helps overcome the problem of clogging and resuming the sample flow when the same source is activated again in rotation. When the given sample source line is deactivated, the sample can neither travel forward into the sequential sampler nor flow backward into the aeration tank. However, some of the sample which is trapped in the Nalgene® tubing (connected between sequential sampler and the pipe column) drains in the bends. The bends in the tubing are due to sagging. So, the fluid is trapped in the bottom curved portion and the air gets trapped in the top curved portion of the bends. Air locked inside the tubing bends prevents the sample flow from resuming when the same line is reactivated.

The clean water remains locked in the tubing bends when the tubing is backflushed. The water lock discourages air entrapment (air locks) in the tubing bends.

Protocols for Computerized Operation of Respirometer and Sequential Sampler System and Sampling Procedure During the Experiment

As explained earlier, respirometers 1 and 2 were calibrated and air leak tested with the help of the computer. Several trial runs were also carried out before actual data were collected.

Samples from the three sources; namely, the middle of the return activated sludge (RAS) channel, and 25 and 150 feet from the beginning of aeration tank 1 were collected through the Respirometer - Sequential sampler 1 system. Similarly, four source samples from 275, 400, 525, and 690 feet from the beginning of aeration tank 1 were collected through the Respirometer - Sequential sampler 2 system. The sample fluid would be pumped from different sources into the appropriate pipe columns. The pressure in the pipe columns would feed both sequential samplers through all the available ports.

Both the respirometer systems were operated in the automatic computerized mode. In this mode of operation, the sequential sampler allows only one sample to flow out to the respirometer at a given time. Thus, with the help of two sequential samplers, respiration rates on seven different sources were determined in an order of choice by only two online respirometers. The cycle time for each source was set at 20 minutes throughout the entire experimental time period.

Daily monitoring of the respirometers, and the system as a whole, was performed to ensure proper operation. All necessary maintenance was also performed as suggested by the manufacturer.

Computation of OUR by LabVIEW®

LabVIEW® software version 4.0.1 is made for system control, data acquisition, and data management. It utilizes a customized method to compute the OUR of a sample (mixed liquor or otherwise) from the data collected over a cycle time period. Intricacies involved in computing the OUR of a sample are explained in the following three paragraphs. The remainder of this section gives the details to better understand the computation of the OUR of the sample.

A discrete data set consisting of time period and the corresponding cumulative oxygen uptake volume in milliliters is produced at a certain time interval (approximately every fifth second) over the 20-minute cycle time period. Such a huge amount of information collected over the cycle time period needs to be reduced to one numerical value called the sample OUR. By obtaining a slope value using the least squares regression technique (9) for the data set exhibiting a linear pattern, the sample OUR may be obtained. However, a sophisticated algorithm must be used if the data set exhibits a non-linear pattern. An algorithm containing a moving interpolation function is used for this study (13).

It should be noted that there are many other ways to accomplish the same objective of data reduction to derive the OUR of a sample. No specific method is necessarily superior to others. It is, however, of utmost importance that whichever algorithm is used, it should produce a representative OUR of the sample. The inherent difference in various algorithms may largely be minimized by obtaining a maximum value of instantaneous OURs. Instantaneous OURs are the first refined condensation of the raw data. One instantaneous OUR is produced by the algorithm upon collecting any number of defined data points. For example, during this study, approximately 36 data points were collected over the first three minutes of a given cycle to calculate the instantaneous OUR of the cycle time. Subsequently, every fifth second, a new data point was added to the existing pool of data. The moving interpolation function slides with every new addition of volume-time data and calculates a new instantaneous OUR.

Thus, the sample OUR for this study is nothing but the highest value of all instantaneous OUR values compiled over the cycle time period. The sample OUR obtained by such an algorithm results in a very stable and robust sample OUR value which does not significantly change with an arbitrary alteration in the algorithm. The maximum value is preferred because it tends to be invariant with regard to modifications in interpolating function, moving window size, number of data points in the given window, etc.

In the actual study, the OUR value of several samples of mixed liquor in the aeration tank is obtained from specific locations in the aeration tank. The locations in the 750-foot long aeration tank were chosen at 25, 150, 275, 400, 525, and 690 feet from the head end. However, the OUR profiles representing different locations along the tank were studied before finalizing the above mentioned locations. For almost all of the OUR profiles, a characteristic of OUR profile as presented in Figure 12 was observed. Thus, it was evident that the OUR profile was not dependent on locations as long as the chosen locations are spaced properly to obtain the characteristic profile.

The only concern, however, with respect to the locations observed was mixing of raw sewage and RAS in the beginning of the tank. About 25 feet from the head end was found to be optimum to ensure adequate mixing. With respect to the first point thus defined, the subsequent locations were spaced 125 feet apart. This spacing was obtained by dividing the total length of 750 feet by the total number of submersible pumps (six) available for sampling. Instead of 750 foot point, the last location was selected at 690 feet to truly define the point of inflection in the OUR profile. The last (sixth) location was intentionally not placed at the end at 750 feet because of marginal differences observed in DO, OUR, and

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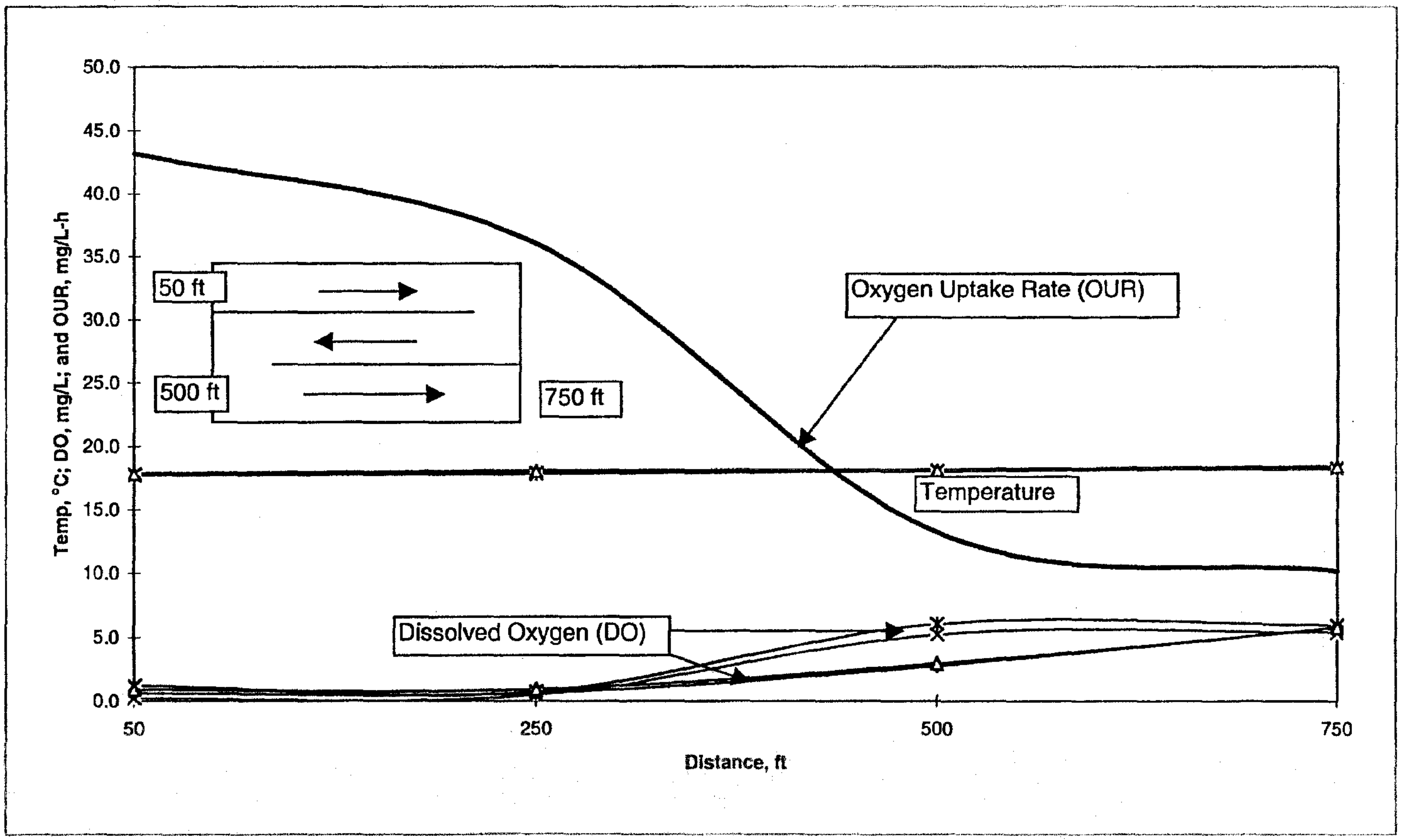
FIGURE 12

A TYPICAL OXYGEN UPTAKE RATES (OURs) PROFILE, BATTERY A, TANK 1 OF KIRIE WRP



ammonium nitrogen values at 690 and 750 foot locations (examine <u>Figure 12</u>), and due to inadequate aeration in the corners of the aeration tank towards the end. The location at 690 feet, therefore, has been interchangeably used in this report to reflect the outlet end of the aeration tank.

The mixed liquor samples were continuously obtained from the defined locations of the aeration tank for the determination of OURs. These six values of OUR make up a typical OUR profile (as shown in <u>Figure 12</u>). All six OUR values are used to obtain an average OUR value to represent the OUR of the tank as a whole. This average OUR value of the mixed liquor of the aeration tank is needed to estimate the air requirement for the entire aeration tank. Hence, a generalized model is developed in this study to obtain the average tank OUR. In the following sections, the average OUR is defined and discussed as the integral of the OUR profile curve (with details in <u>Appendix I</u>), and is used as an input value in the developed models (presented in the following sections) for predicting the air requirements for achieving carbonaceous and nitrogenous oxygen demands.

The "Rate (maximum).vi" is used to calculate the instantaneous rate at any point in time during the cycle measurement. This "vi" as it is called in the LabVIEW® program has two arrays. One array contains the measured oxygen uptake in milliliters as the Y axis, and the other contains the time values corresponding to the oxygen uptakes as the X axis. Approximately every fifth second, a new oxygen uptake measurement with its corresponding time value is added to the two arrays.

A new oxygen uptake measurement occurs only if a change in the gas volume reduction is sensed by the volumetric transducer. The gas volume reduction is not a steady state process because variations in many factors like type and strength of sewage, and strength of activated sludge affect the rate of gas volume reduction. Therefore, oxygen uptake measurements are not added to the arrays at a regular interval of five seconds.

Because of this inherent quality of respirometry measurement, the calculation of sequential OUR from the data set was preferred with a window of a variable number of data points collected in three minutes fixed time versus the alternative of a window of a certain defined number of fixed data points.

The window size of three minutes specified in "Rate (maximum).vi" was justified because a sufficient number of data points could be collected over three minutes duration which would reduce the effect of signal noise on the OUR calculations. At the same time, three minutes is a small enough interval that the respiration rate is roughly constant over the entire interval. For example, for a larger window size of ten minutes the respiration rate in this study was not constant, therefore, the optimum window size of three minutes was selected.

Since the OUR is calculated using a "sliding window" size of three minutes, the oxygen uptake measurement and time values are added to the arrays during the first three minutes. Each time a new measurement value is generated after the first three minutes, it is added to the arrays. Upon addition of the new value to the arrays, a new window is instantly formed, and the rate is recalculated. The window continues to slide until the end of the last measurement during the cycle. The window moves one data point at a time. Therefore, if there are 100 data points by the end of the cycle and only 20 data points were collected during the first three minutes, there will be a total of 81 windows to be examined. The slope value of linear fit is obtained for the data within each three minute sliding window and, the maximum value of all the slope values in the different windows correspond to the maximum OUR for the entire cycle.

Due to the algorithm used, the OUR value would either progressively increase in comparison to the value obtained from the previous window or stay the same as the experiment progresses in the given cycle time.

Sampling and Preservation of Samples

All samples were manually collected from different points in aeration tanks 1 and 2. The samples from aeration tank 1 were collected from inside the trailer through the sampling ports of two respirometer and sequential sampler systems. The samples from aeration tank 2 were manually collected directly from tank 2.

All the samples were collected in plastic (polyethylene or equivalent) bottles and preserved according to the guidelines provided by Standard Methods (10).

Before the samples were transported to the Egan Laboratory for analyses, they were temporarily stored in ice chests for a few hours. All analyses were completed within the time limit recommended by the Standard Methods (10).

Field and Laboratory Analytical Test Methods

Sludge Volume Index (SVI), Filament Count (Fil. Ct.), and DO tests were performed on-site. The samples were analyzed immediately after collection.

Tests performed in the District's Egan Laboratory on samples collected were mixed liquor suspended solids (MLSS), mixed liquor volatile suspended solids (MLVSS), BOD_5, carbonaceous biochemical oxygen demand ($CBOD_5$), Total Kjeldahl

Nitrogen (TKN), ammonium nitrogen (NH_4-N), nitrite nitrogen (NO_2-N), and nitrate nitrogen (NO_3-N).

The test methods used are shown in Table 1.

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TABLE 1

METHODS USED FOR FIELD AND LABORATORY TESTS

Name of Test	Method Used	Comments
MLSS	Standard Methods, 18th Edition, Method 2540 D	None
MLVSS	Standard Methods, 18th Edition, Method 2540 E	None
BOD_5 / $CBOD_5$	Standard Methods, 18th Edition, Method 5210	None
TKN	EPA Method 351.2	Automated version of test method using Lachat flow injection instrumentation
NH_4-N	EPA Method 350.1	"
NO_2-N	EPA Method 353.2	"
NO_2-N + NO_3-N	EPA Method 353.2	"

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TABLE 1 (Continued)

METHODS USED FOR FIELD AND LABORATORY TESTS

Name of Test	Method Used	Comments
SVI	Standard Methods, 19th Edition, Method 2710 D	In-situ analysis
Fil. Ct.*	A method used by Microbiology section of R&D Department	A sample aliquot of 1/10th of mL is spread and observed in 10 fields; expressed as meters of length per mL of sample
DO	Standard Methods, 19th Edition, Method 4500-O-G	In-situ analysis using YSI 58 meter and appropriate YSI probe system

*Filament count

RESULTS AND DISCUSSION

System Operation: Problems and Solutions

The respirometer and sequential sampler system was run during late June 1995 through October 1996 to become familiar with the calibration, operation, and maintenance of the equipment. During these trial runs and afterwards, a myriad of problems were encountered. Although frustrating and annoying, they were eventually resolved. The nature of the problems encountered and their remedies are discussed under two major groups, as follows.

Problems Related to Equipment and Plumbing System

During the trial runs in July 1995, the respirometers were found to be plagued by clogging problems. After a few months of continuous running, several spots in the pipe system (mainly bends, pinch valves, the rubber stator of the progressive cavity pump, the overflow pipe system, etc.) of the respirometers were identified as those where more frequent entrapment of a fibrous material would be found in substantial quantity. This was consistently observed in all three respirometers in a simultaneous run during the first few months of trial duration. Figures 13 and 14 show the fibrous material accumulated in the sample chamber, and on and around the submersible pump.

FIGURE 13

ACCUMULATION OF FIBROUS MATERIAL IN THE SAMPLE CHAMBER OF RESPIROMETER

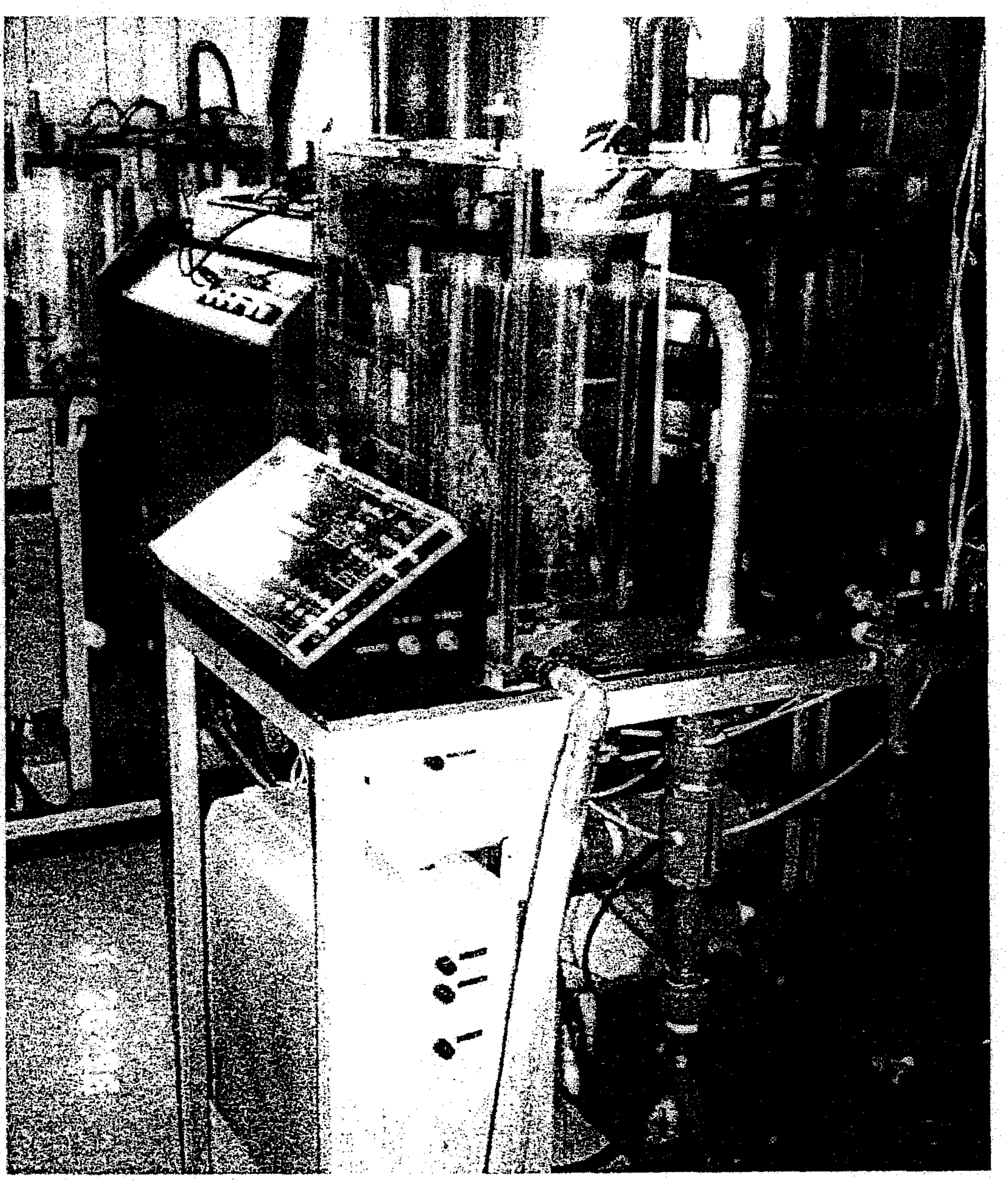

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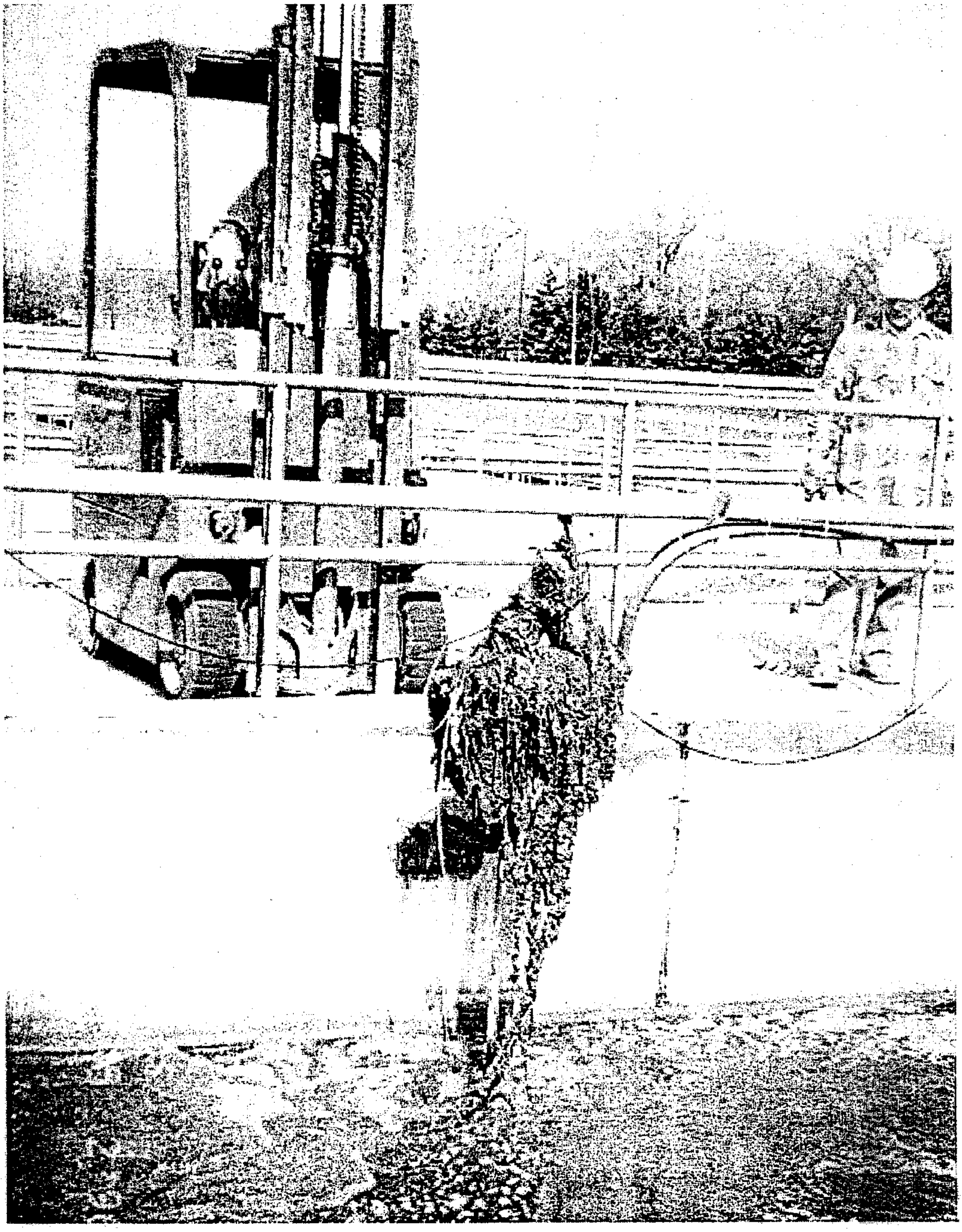
FIGURE 14

ACCUMULATION OF FIBROUS MATERIAL ON THE SUBMERSIBLE PUMP LOCATED IN AERATION TANK



Blockage in the pipe system was mainly attributed to the presence of a hairy, slimy, sticky thread-like floating material, and a high solids content in the mixed liquor aeration tanks. It should be noted that the Kirie WRP does not have primary treatment units or preliminary settling tanks. As a consequence, all settleable solids and fibrous material freely enter the aeration tanks, resulting in the clogging of the pump and pipe systems.

The solids and thread-like fibrous material resulted in the formation of a long sturdy mass because of repetitive swirling of the mixed liquor in the aeration tank. Even though the submersible pumps are equipped with rotating grinding blades, clogging of the respirometers persisted because the pumps did not have enough time to shred the fibrous material. As a result, the hairy material passed through the pump successfully and gradually accumulated in the pipe system. It was repeatedly observed that only a few hours to two days of continuous operation sufficed to clog the respirometers. On some occasions, respirometers were plugged after a few minutes of operation.

It was felt that the high MLSS levels (~6,000 mg/L) in the aeration tanks might be responsible for the clogging problem as well. Hence, the plant manager was requested to operate the plant at lower MLSS levels of about 3,000 mg/L.

The clogging problem persisted even at the lower MLSS levels and at a higher velocity of 5 ft/sec accompanied by higher flow rates of the mixed liquor (a maximum of 22 gpm) and other liquid streams sampled. Flow meters and pressure gauges were installed on all eight pipes connected to the respirometry system that deliver various samples (e.g., influent, effluent, mixed liquor, etc.) to the respirometers.

Attention was also paid to the effects of location, alignment, and make of the submersible pumps regarding the clogging problem. With that goal, a comparison between two types of submersible pumps manufactured by ABS Inc. and KSB Inc. was made. The ABS pumps were found to be better in terms of allowing the fibrous material to be shredded into smaller fragments and allowing them to enter the piping system more freely.

In order to prevent the entry of the fibrous material into the respirometers, pumps equipped with sharp rotating blades or other mechanism to chop up the fibrous material were evaluated. These pumps were mainly placed in between the grinder pump and the respirometers. To provide more time for the pumps to further shred the fibrous material, extra pipe loops were also added to the existing pipe system, and the pipe system was specially configured such that the same mixed liquor would pass through the extra pump a few more times before it entered the respirometer. This approach of chopping the fibrous material was preferred since it does not alter the original characteristics of the MLSS.

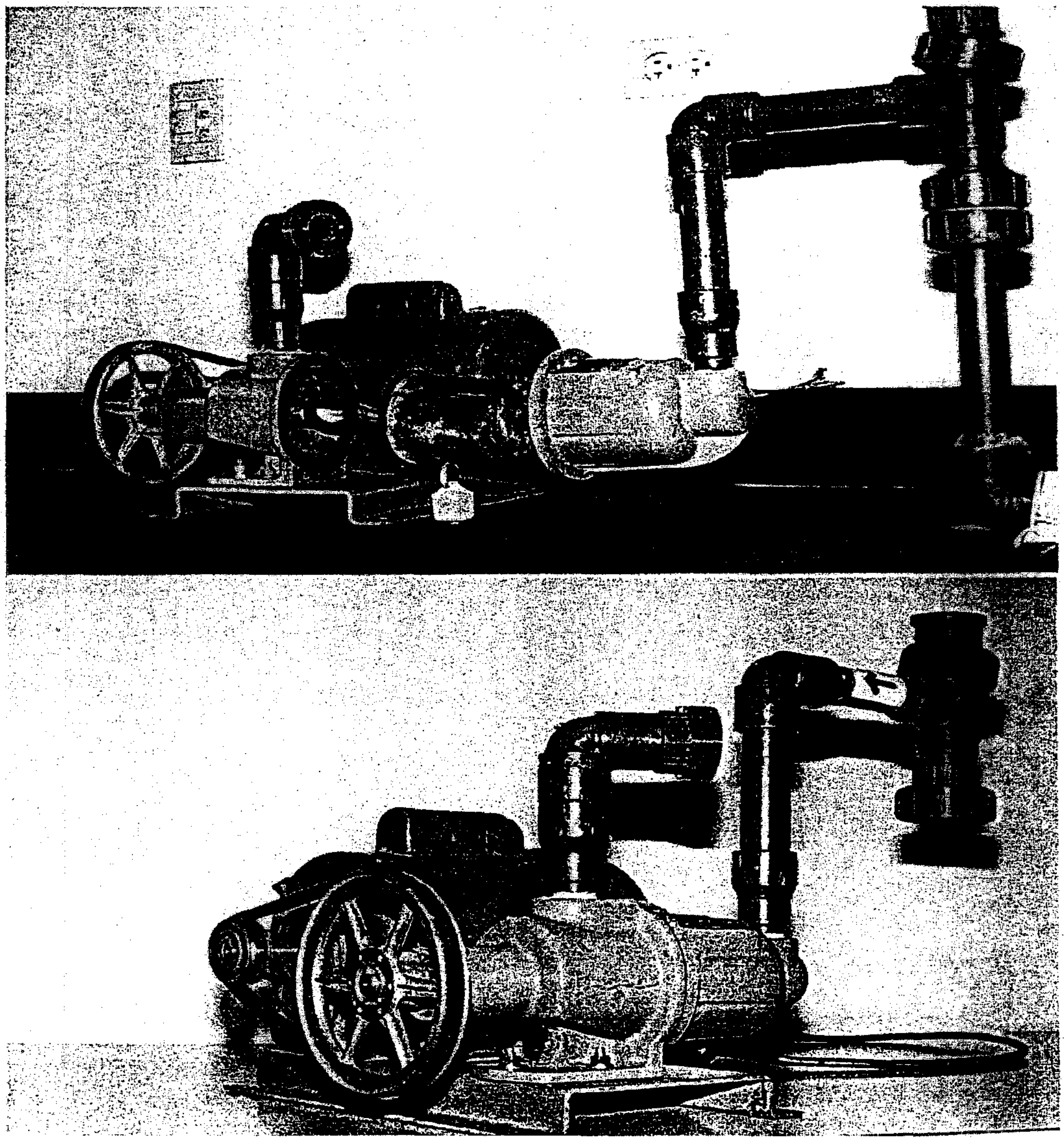
The Wastewater Treatment Research Section continued to make diligent efforts to eliminate the clogging spots and to redesign the necessary portion of the system. As a first step in that direction, the built-in progressive cavity pump was removed from the respirometer (Figure 15), and the respirometers were fed by pressure head available in the column. Along with a pressure feed system, the pipe system of all three respirometers were widened with installation of clear PVC joints (replacing the original gray HDPE pipe joints) to easily detect the clog. Also, backflushing with clean water at high pressure (25 psi) was introduced to minimize settling in the feed pipe after every sample exchange. With these three modifications to the system, the respirometers were made functional by the end of 1996. Thus, about 1 1/2 years were spent in the installation of respirometers and in devising ancillary equipment and devices to make the respirometers functional.

Thus, since the start of the project in June 1995, severe problems of clogging hampered the progress of the project during the remainder of 1995, and throughout 1996.

It had been observed that when more than six submersible pumps fed the pipe system, back-up pressure would build-up in

FIGURE 15

A PROGRESSIVE CAVITY PUMP - AN INTEGRAL PART OF RESPIROMETER



the pipe system. The pressure release occurred through the air vent by occasional discharge of mixed liquor. Installation of another discharge pipe relieved the back-up pressure in the pipe column. This was done during the first week of June 1998.

In order for the on-line respirometers to be used as reliable instruments, it is imperative that they be made free from clogging problems.

Problems Related to System Control by Computer and Their Solution

As indicated previously, all three respirometers and two of the sequential samplers have computer interfaces, which allow the control of the entire system via an RS-485 connection. Commands are issued automatically by an Apple Macintosh computer, running a custom program developed in LabVIEW®. The LabVIEW® program controls the respirometers and sequential samplers and collects and registers data.

The original version of the software contained a number of glitches in the computerized calibration of the respirometers, control of respirometers and the sequential sampler system, data collection and logging in proper files, etc. Even after several modifications were made in the original version of the software program, the problems with the computerized system control continued. For example, until December 1995, typical system-related problems included activation of the targeted sampling stream at the wrong time or failure to activate the desired port, activation of sources out of sequence, sudden freezing up of a computer program making the system control nonfunctional, lack of creation of new files, etc.

Finally, with the assistance of a consultant, the software was debugged and successfully completed and tested to our satisfaction during the first week of August 1997.

Effects of Air Reduction on OUR Profiles and Major Indicators of Wastewater Treatment

Progressive air reductions into passes 2 and 3 of the experimental tank ranged from 5 percent to 35 percent of the air being supplied into passes 2 and 3 of the control tank. The air supply into pass 1, and passes 2 and 3 combined, of the control tank ranged from 803 to 831 cfm with an average of 811 cfm and from 1430 to 2508 cfm with an average of 1754 cfm, respectively. A set percentage of air supply was reduced in the second and third passes of the experimental tank.

During this phase, both the tanks had practically similar organic and hydraulic loading as well as similar operating conditions. The effects of the reduced air supply into the second and third passes of the experimental tank on OUR profile and major indicators of wastewater treatment are discussed in the following paragraphs.

EFFECTS ON OUR PROFILE

The OUR profiles in the experimental tank were obtained using the on-line respirometers during the air reduction phase, but the OUR profiles could not be simultaneously obtained in the control tank using the on-line respirometers due to limited resources. However, the deficiency of simultaneously obtaining the OUR profiles in both the experimental and control tanks was overcome by manually drawing samples from the control tank and determining the OURs using the BOD bottle method (10).

The control tank OUR profile, as shown in Figure 16, is indicative of air supply based on the automated DO control system under normal operation. This profile follows a pattern observed over the entire experimental time period. In the identical experimental tank, the OUR profile observed is also depicted in Figure 16.

Figure 16 clearly shows that with a decrease in air supply, the SOUR patterns of the control and experimental tanks deviated towards the tail portion of the aeration tank. The SOUR pattern remained flat in the experimental tank, whereas it showed a declining pattern in the control tank, indicating the stabilization of the wastewater. This implies that the wastewater is not completely treated in the experimental tank (organic material and/or ammonium nitrogen are not completely

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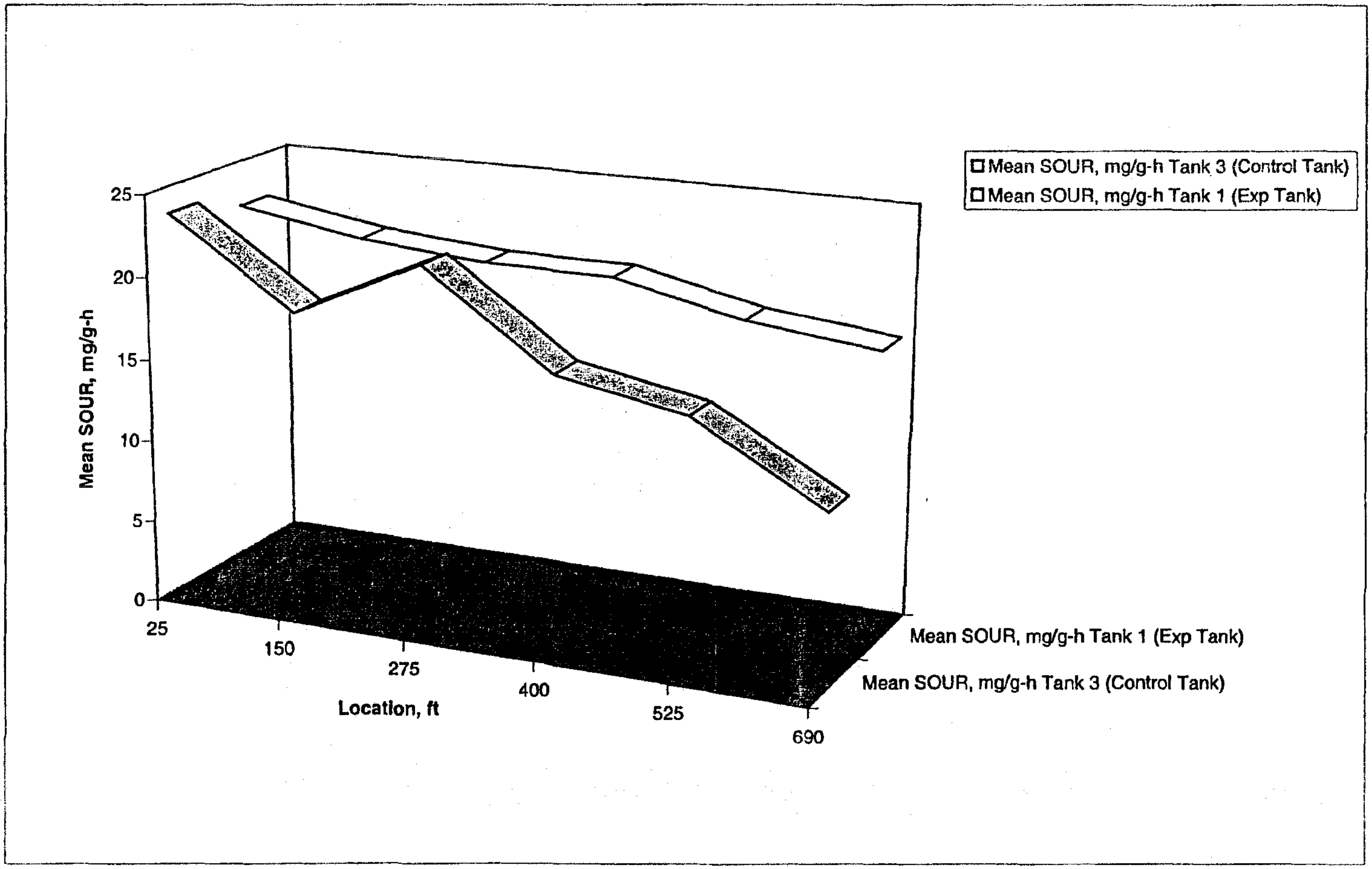
FIGURE 16

EFFECT OF 20% MEAN AIR REDUCTION ON SOUR IN EXPERIMENTAL TANK



oxidized). Food was still available to the organisms in the experimental tank, and the organisms did not reach the endogenous phase of respiration. Table 2 shows the comparative area under the curve for the control and experimental tanks. The area under the curves for the experimental tank at all air reduction levels except 9.31% is consistently higher than those of the control tank, indicating that the oxygen demand of the wastewater was still not satisfied to the same extent as that of the wastewater processed in the control tank.

EFFECTS ON DO IN EFFLUENT

During the progressive air reduction from 5 percent to 35 percent, the average DO concentration in the effluent (observed at 690 feet) of the experimental tank was consistently found to be at or below 1 mg/L, as shown in Figure 17. On the other hand, the average DO concentration in the effluent (observed at 690 feet) of the control tank was consistently observed to be over 2.5 mg/L. Figure 17 also shows that with as low as 5 percent mean air reduction, the DO in the experimental tank effluent decreased to below 1 mg/L. This is interpreted as meaning that the plant was supplying "just required" air for aeration in the control tank and, therefore, a little decrease in air supply in the experimental tank with respect to air being supplied in the control tank would cause the

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TABLE 2

COMPARISON OF CUMULATIVE AREA UNDER THE SOUR PROFILE CURVES AT DIFFERENT AIR REDUCTION LEVELS

% Air Reduction in Passes 2 and 3 of Experimental Tank	Location in the Exp Tank Feet from the Beginning of the Tank	Mean SOUR, mg/g-h		Area Under the SOUR Profile Curves, mg-g-ft/h	
		Tank 1 Experimental Tank	Tank 2/3 Control Tank	Tank 1 Experimental Tank	Tank 2/3 Control Tank
-6.49	25	31.66	20.17	31.66	20.17
	150	20.56	18.73	26.11	19.45
	275	17.88	16.30	19.22	17.52
	400	17.70	15.81	17.79	16.06
	525	16.66	13.93	17.18	14.87
	690	16.02	9.41	16.34	11.67
		CUMULATIVE AREA		128.29	99.74
-9.31	25	26.57	30.83	26.57	30.83
	150	23.46	23.67	25.01	27.25
	275	23.14	22.77	23.30	23.22
	400	23.10	28.21	23.12	25.49
	525	23.38	19.34	23.24	23.78
	690	17.17	8.02	20.28	13.68
		CUMULATIVE AREA		141.53	144.24
-18.96	25	22.22	23.39	22.22	23.39
	150	20.91	18.19	21.57	20.79
	275	20.24	21.89	20.58	20.04
	400	20.21	16.41	20.23	19.15
	525	18.51	14.99	19.36	15.70
	690	17.65	10.53	18.08	12.76
		CUMULATIVE AREA		122.04	111.84
-25.20	25	30.08	26.18	30.08	26.18
	150	22.09	19.90	26.09	23.04
	275	20.37	17.61	21.23	18.75
	400	19.13	17.13	19.75	17.37
	525	17.71	16.28	18.42	16.71
	690	17.34	10.09	17.52	13.19
		CUMULATIVE AREA		133.09	115.23
-35.85	25	25.16	17.87	25.16	17.87
	150	20.51	15.39	22.84	16.63
	275	19.67	14.59	20.09	14.99
	400	18.61	11.67	19.14	13.13
	525	17.41	8.69	18.01	10.18
	690	16.73	6.39	17.07	7.54
		CUMULATIVE AREA		122.31	80.33

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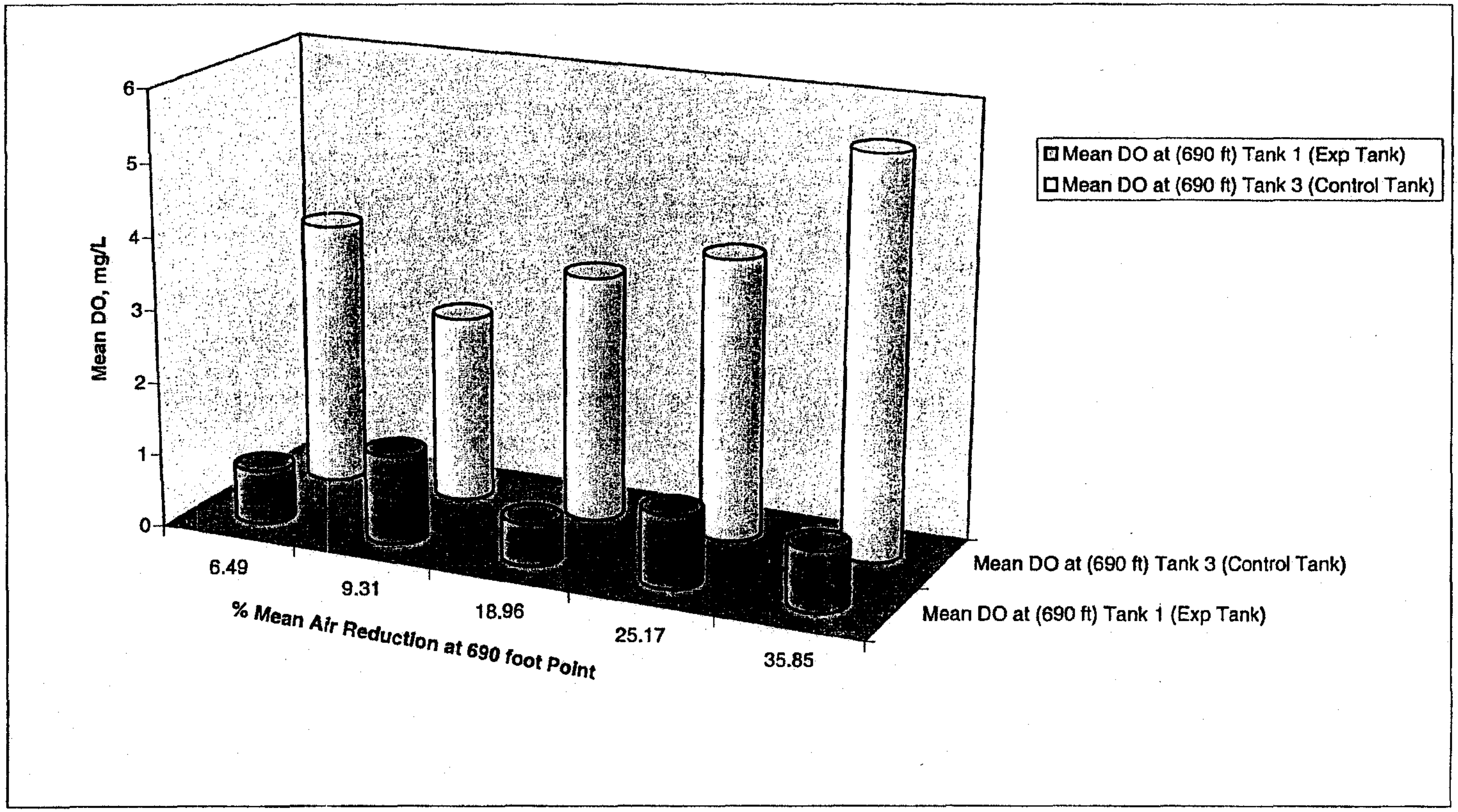
FIGURE 17

EFFECT OF MEAN AIR REDUCTION ON EFFLUENT DO IN EXPERIMENTAL AND CONTROL TANKS



effluent DO in experimental tank to drop below the plant operator's set point of 2.0 mg/L.

The plant operating protocols of the M&O Department were applied during the study to control aeration using the automated DO probe system in the control tank. Aeration control in the experimental tank was entirely dependent on the air rates being supplied in the control tank. A set percent of reduced air rates from 5 percent to 35 percent was supplied in the experimental tank in a progressively increasing fashion.

It is important to mention that the National Pollutant Discharge Elimination System (NPDES) permit issued by the State of Illinois does not require the Kirie WRP to maintain a minimum DO, or ammonium nitrogen value in the mixed liquor in aeration tank or in the effluent of the aeration tank. However, observations such as, ammonium nitrogen higher than 1.5 mg/L or DO lower than 2 mg/L in the effluent of the aeration tank are likely to result in a possible violation of unionized ammonium-nitrogen standard of the plant. The plant effluent DO, pH, NH_4-N, and temperature are used to calculate unionized ammonium-nitrogen concentration of the plant effluent. However, every effort was made during the study to maintain compliance with respect to the limitations imposed on the plant effluent.

During the progressive air reduction from 5 percent to 35 percent, the average DO concentrations in the experimental tank at all locations were also found to be barely above 1 mg/L (Appendix III). Comparative DO concentrations in the control tank at similar locations were observed to be slightly higher, especially in the first two passes. With increase in tank length from the head end, the oxygen demand did not decrease in the experimental tank as it did in the control tank. As a result, the average DO concentrations observed at similar locations in the control were higher than in the experimental tank. This indicates that air reduction at the Kirie WRP had a severe adverse effect on the DO concentration in the experimental tank, because air supply in the control tank was optimally controlled.

EFFECTS ON AMMONIUM NITROGEN IN EFFLUENT

The ammonium nitrogen concentration in the effluent of the experimental tank was consistently found to be at or over 4 mg/L, as shown in Figure 18. On the other hand, the ammonium nitrogen concentration in the effluent of the control tank was consistently observed to be under 1.5 mg/L. Figure 18 also shows that with as low as five percent mean air reduction, ammonium nitrogen concentration in the experimental tank effluent shoots up to 5 mg/L. This indicates that air

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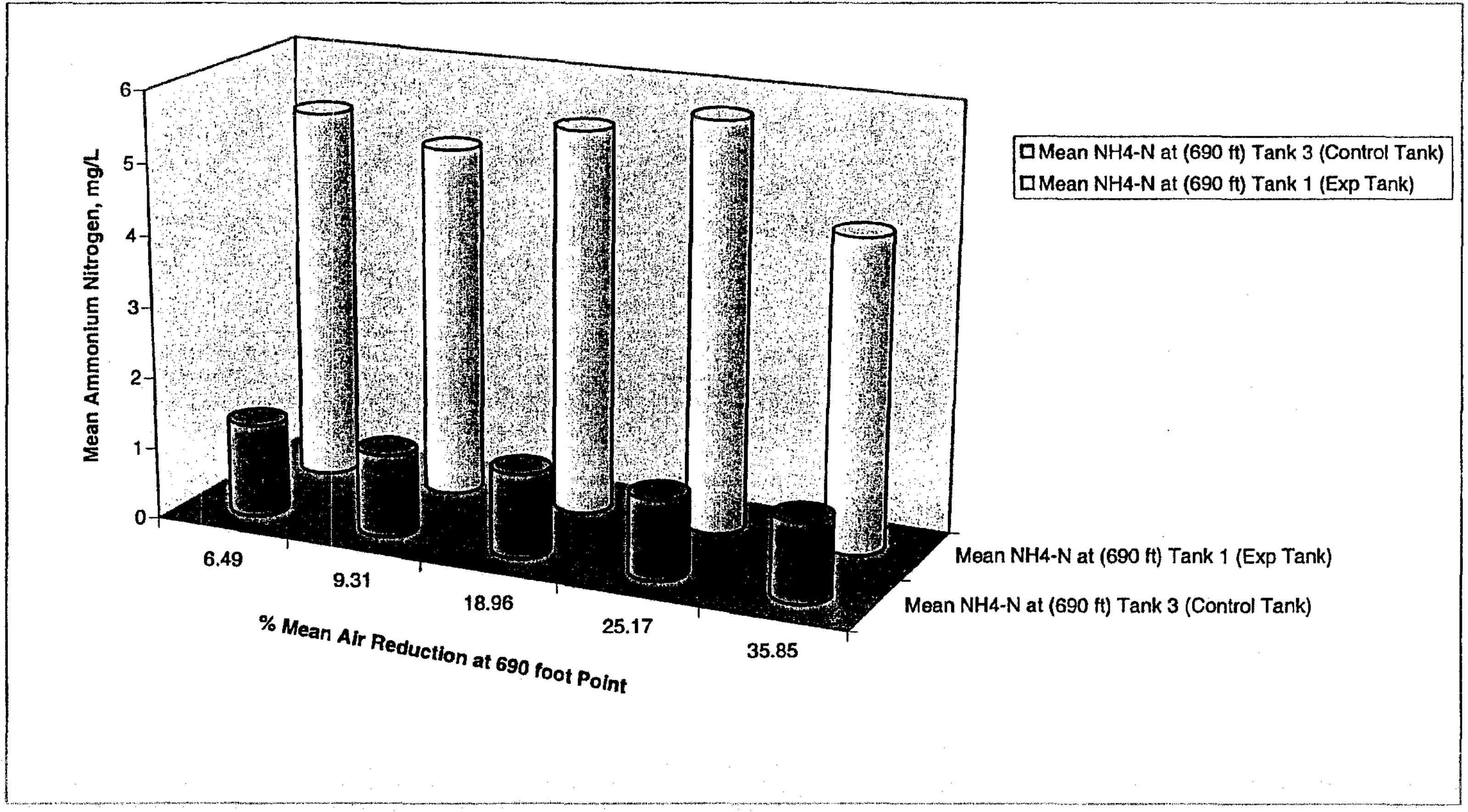
FIGURE 18

EFFECT OF MEAN AIR REDUCTION ON EFLUENT AMMONIUM NITROGEN IN EXPERIMENTAL AND CONTROL TANKS



reduction at the Kirie WRP, even at a modest level, severely affects the nitrification process. This observation corroborates the effects of air reduction on DO in the effluent of the experimental tank. Modeling efforts, as discussed later in this report, also provide an independent check of the dynamics of aeration rate and complete oxidation of organic matter and ammonium nitrogen in the control tank, and the lack of it in the experimental tank.

EFFECTS ON SVI AND FILAMENT COUNT

The effect of air reduction on the stability of wastewater treatment was found to be minimal during the period of this study. The settleability of the mixed liquor was evaluated by measuring SVI and filament count in the mixed liquor from both the control and the experimental tanks, and suspended solids of the effluent.

The SVI range observed in control and experimental tanks were 40 to 78 mL/g and 32 to 74 mL/g, respectively. The filament count ranged from 3 to 31 m/mL in the control tank and from 3 to 29 m/mL in the experimental tank. Table 3 presents SVI and filament count at each air reduction level in both the tanks.

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TABLE 3

SVI AND FILAMENT COUNT IN CONTROL AND EXPERIMENTAL TANKS DURING AIR REDUCTION PHASE

% Mean Air Reduction	SVI, mL/g		Filament Count, m/mL	
	Control Tank	Experimental Tank	Control Tank	Experimental Tank
6.5	67	67	20	17
9.3	57	59	11	12
19.0	57	55	26	26
25.0	47	43	17	14
36.0	43	34	6	3

DEVELOPMENT OF MATHEMATICAL MODELS TO PREDICT "JUST-REQUIRED" OXYGEN DEMAND

With a view to automating the air flow adjustment in the mixed liquor aeration tanks commensurate with the variation in the strength or oxygen demand of the incoming sewage, the project experimental plan envisaged the development of model(s) to control the aeration of the mixed liquor as a function of OUR and other relevant operational variables. It also specified that the model partition the air supply rate requirement into carbonaceous and nitrogenous components.

During the entire experimental period, the maximum OUR was observed at the head end of the control aeration tank, and it gradually tapered off along the length of the tank to the endogenous level towards the end of the aeration tank as shown in Figure 12. Based on Figure 12, for the Kirie WRP, the OUR reaches an asymptotic level beyond the end of the second pass (each treatment tank consists of three passes - each pass is 250 feet long). The pattern of oxygen demand exertion, observed in this study, in the aeration tanks of the Kirie WRP is similar to the oxygen demand exertion pattern of plug flow reactors.

During periods when the respirometers were performing satisfactorily (May through July 1996 and May through October

1997) respirometric, analytical, and operational information was collected.

Based on the pattern of the OUR profiles observed along the tank length, the experimental data collected, and various published information (1, 7, 13, 14, 17), two semi-theoretical mathematical models had been developed for aeration rate as a function of OUR. A brief discussion of the two models is as follows; whereas the details on both models are presented in Appendix I.

Water Environment Federation (WEF) Model

The first model (Model 1) is the authors' modification of the model recommended by the WEF (formerly the Water Pollution Control Federation) for activated sludge based on the Lawrence and McCarty analysis for biological treatment systems in steady state (1, 7).

Dimensional Analysis Model

The second model (Model 2) is based on the direct conversion of OUR expressed as mg or mL of O_2 consumed per liter of mixed liquor per hour to aeration rate expressed as cubic feet of air per minute. This conversion of units is based on applied dimensional analysis.

Given equivalent input values, the two models provide equivalent output results. However, the first model (Model 1) allows a separation of aeration rate exerted by nitrogenous and carbonaceous components for the entire tank only. The second model (Model 2) allows the estimation of only total combined nitrogenous and carbonaceous aeration rate by integrating arbitrary subvolumes of the aeration tank along the length of the tank. In other words, Model 1 determines aeration rate individually for the nitrogenous and carbonaceous demand, whereas Model 2 determines aeration rate only for the total combined nitrogenous and carbonaceous demand with no individual separation of these two types of oxygen demands. Also, Model 1 determines aeration rate only for the entire aeration tank, while Model 2 is more flexible in this regard. In addition to being able to determine aeration rate for the entire aeration tank, Model 2 can also determine aeration rate for any subvolume of the tank (such as one of the three passes). Model 1 cannot determine aeration rates for subvolumes of the aeration tank.

Both models utilize the concept of average OUR for the entire aeration tank as an input variable. The average OUR is defined in terms of an integral of the OUR profile function over the tank length. Therefore, the OUR profile of an aeration tank is needed to obtain the average OUR of the aeration tank. The OUR profile could be developed, as described before, by acquiring multiple OUR values at different lengths of the aeration tank as measured by on-line respirometers.

In order to simplify this, a simple algebraic relationship between the average OUR and the initial OUR (measured at the head end of the tank) was developed. Because of this, the need to continuously obtain multiple OUR values, as measured by on-line respirometers, to develop an OUR profile of the tank could be avoided. Also, the need for numerical integration of the OUR profile could be avoided.

The initial OUR as measured by an on-line respirometer at the head end of the tank (25 feet from the head end) could be used as input into an algebraic function in order to calculate the average OUR of the entire aeration tank. This calculated average OUR then could be used as input to both models.

Both models described above are presented in detail in terms of basic and extended versions in Appendix I. These versions may be differentiated in a practical manner by considering the model variables. In addition to the average OUR as an input variable, the basic model versions (Model 1, Version 1 [M1V1] and Model 2, Version 1 [M2V1]) have the following as input variables: wastewater flow, solids retention time, oxygen transfer efficiency, endogenous decay coefficient, and cell yield coefficient. In addition to the above input variables, the extended model versions (Model 1, Version

2 [M1V2] and Model 2, Version 2 [M2V2]) have effluent ammonia concentration as an input variable. The output variable for both versions of each model is air requirement.

The basic versions predict the air requirement to satisfy the complete carbonaceous and nitrogenous oxygen demand, while the extended model versions predict the air supply rate requirement to satisfy partial carbonaceous and nitrogenous oxygen demand (contingent upon a specified ammonia concentration in the aeration tank effluent). When the ammonium nitrogen concentration is specified as zero, the extended model versions reduce to the basic model versions. However, the extended model versions with zero ammonium nitrogen as an input remain much more complex in structure in comparison to the basic model versions.

Model Adjustment

In the series of experiments conducted during July 14, 1998 through September 24, 1998, necessary respirometric, analytical and operational data were collected with a view to adjusting the models and to concluding the usefulness of on-line respirometry techniques for aeration control.

In an attempt to evaluate the usefulness of respirometry compared to the existing automated DO control system, progressive air reduction into passes 2 and 3 of the experimental tank was administered in lieu of using both the aeration control methods (respirometric and DO) in two side-by-side test tanks and comparing their air consumption for the given performance level.

The existing automated DO control system at the Kirie WRP maintains a minimum of 2 mg/L of DO in the aeration tank effluent. A DO probe which is located towards the end of the tank, viz., 690 feet in the control tank, records the DO value and continuously feeds the control room computer algorithm as analog signals. The algorithm scans the signals every sixth second and averages out the scanned DO values every eighteenth second. Comparing the average DO value against a set DO value of 2 mg/L, the algorithm determines change in air supply, e.g., if average DO value falls below 2 mg/L; then an algorithm determines to increase air supply until it reaches 2 mg/L and vice versa.

Two identical full-scale aeration tanks of Battery A were used as test tanks. Tanks 1 and 2 of Battery A were used as the experimental and control tanks, respectively. Necessary calibration of air and liquid flow rate measuring devices was performed before the experiment commenced. Modifications in the operations of the plant were also made to both test tanks such that they remained operationally identical.

The progressive air reduction into the experimental tank with respect to control tank approach (DO control) was chosen because of the anticipation that on-line respirometry would save some percentage of the air supplied to the control tank. The range of progressive air reduction would simulate what would occur in the aeration tank if it was respirometrically controlled for aeration purposes. Thus, this approach is a better choice because it is practical and would lead to the same conclusion in a shorter time.

Progressive air reduction was carried out using protocols developed. The developed protocols are presented in Appendix II. The air flow metering system at the Kirie WRP does not allow air flow rate measurement for each individual pass. However, air flow rate can be measured for the first pass as an individual quantity and for the second and third passes jointly. Because of this limitation, the test protocols called for the desired percentage of air reduction in the second and third passes of the experimental tank (first tank of Battery A) with respect to the air being supplied to the second and third passes of the control tank, while maintaining equal air supply in the first pass of the control and experimental tanks. The other important reason to keep the air reduction limited to the second and third passes was the consistent observation that a high demand for oxygen was always exerted in the first pass because of the plug flow pattern of the tank. It was prudent to be conservative by reducing air supply in only two passes so that the NPDES permit could be maintained during the course of the study without any violations.

During this experiment, both the control and experimental tanks were operated normally by following the M&O Department's operational protocols with the exception of the supply of air. As per normal operation protocols, the air supply in the control tank was controlled using the automated DO probe located towards the end of the third pass. With respect to the air quantity being supplied in the second and third passes of the control tank, desired air reductions in an increment of 5 percent per week were attempted in the second and third passes of the experimental tank. Air supply to the experimental tank was progressively decreased until the effluent NH_4-N breakthrough occurred. A breakthrough in NH_4-N as defined in the test protocols occurred during the course of the study because effluent ammonia nitrogen exceeded a value of 5 mg/L.

Applying insights gained from the data collected allowed the basic version models (M1V1 and M2V1) to be enhanced and transformed into the extended version models (M1V2 and M2V2).

The same data set collected during the air reduction phase also allowed model adjustment by optimizing the values of various model parameters. This optimization was done to tailor the models to plant-specific (aeration tank) conditions that existed at the Kirie WRP during this phase of the study. The optimization was performed with a Levenberg-Marquardt algorithm (18).

The model parameters chosen for optimization were: Y (Cell Yield Coefficient), k_d (Endogenous Decay Coefficient), E (Oxygen Transfer Efficiency), PO (an adjustable parameter related to the rate of effluent ammonium nitrogen removal), and K_1 (an adjustable lumped slack parameter). The lumped slack parameter K_1 lumps model errors from various unknown nonspecific sources into expression as one parameter in order to "pick up the slack" which limits model conformity with the data. It has no particular physical or geometrical interpretation. Its use is motivated entirely by two pragmatic considerations. One is to improve the model conformity with Kirie WRP aeration tank conditions, and the other is to provide a measure of model internal structure robustness and stability with regard to changes in parameter values from the optimization algorithm.

The model internal structure is considered robust and stable if the lumped slack parameter K_1 does not change much from the value of 1.0 under optimization that allows all five parameters (i.e., K_d, Y, E, K_1, and PO) to vary. The definition and interpretation of the lumped slack parameter, K_1, are crucial and important for quantitatively and objectively assessing model inner architecture and for defending and ensuring its validity.

The lumped slack parameter K_1 is a measure of model "looseness" when all the model parameters are optimized for model conformity with the data. If K_1 changes more than 10 percent from the value of 1.0, it is not a good sign for model validity. A metaphor may be helpful in comprehending the essential concept. If the data is likened to a person's foot, the model is likened to a shoe, and the parameters Y, K_d, E, and PO are likened to the shoelaces, then the lumped slack parameter K_1 is akin to the shoe size. If a person has a size 8 foot and a size 10 shoe, it doesn't matter how tight the shoelaces are tied; the fit will be poor and the person will not be able to walk or run effectively in those shoes. The shoe size simply has to be closer to the size 8 foot in order for it to be effective footwear. When $K_1 = 1$, the shoe size is equal to the foot size.

Table 4 shows the optimized parameters value estimates using model M2V2 (the same values are obtained if model M1V2 is used). For both the experimental aeration tank and the control aeration tank, the parameter value estimates are shown with all five parameters allowed to vary, and also with the

TABLE 4

ADJUSTED PARAMETER VALUES (MODEL M2V2)

	Experimental		Control	
Parameter	Observed[1]	Forced K_1[2]	Observed[1]	Forced K_1[2]
K_1 (-)	0.9535	1	0.9730	1
PO (-)	0.15	0.15	(0.15)[3]	(0.15)[3]
Y (-)	0.68	0.70	0.65	0.66
K_d (1/d)	0.037	0.031	0.047	0.043
E (%)	15.7	15.8	15.4	15.5

---

[1] Optimized values obtained with the Kirie WRP data.

[2] Optimized values obtained with the Kirie WRP data, but with the value of K_1 forced to equal 1.

[3] Optimized PO value obtained for the experimental aeration tank. An independent estimate of PO for the control aeration tank is not possible due to data range limitations which produce non-convergence in the optimizing algorithm.

lumped slack parameter K_1 set equal to 1.0 (being kept constant during the optimization). In both experimental and control cases, K_1 changes only very slightly from the value 1.0, which implies that the internal structure of the model is robust and stable. The value of parameter PO in the control case was assumed to be the same as in the experimental case, since the control data was inadequate to estimate this parameter related to the rate of effluent ammonia removal (the algorithm would not converge). The values of parameters Y and k_d are well within expected ranges as shown in Table 5. This table is from the WEF *Manual of Practice* (MOP) Number 8, *Design of Municipal Wastewater Treatment Plants* (7). The values without parenthesis were obtained from the technical literature, while the values with parenthesis were obtained from the major practicing consulting engineering firms in the USA (3, 16).

How the models look graphically (in a two-dimensional format) with these values of the optimizing parameters is shown in Figures 19 and 20. These figures show both the actual data used in optimization and traces from the model M2V2 with the optimized parameter values for the experimental tank. These traces (from the family of such curves) are drawn at constant values of flow and SRT (average values of flow and SRT observed during the course of the experiment are used:

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TABLE 5

COEFFICIENTS FOR THE ACTIVATED SLUDGE PROCESS

Coefficient	Units	Range*	Typical*
Y	g VSS/g BOD_5	0.4 - 0.8	0.6
		(0.6 - 0.84)	(0.71)
K_d	day^{-1}	0.004 - 0.075	0.06
		(0.02 - 0.10)	(0.064)

*The values without parentheses were obtained from the technical literature, while the values with parentheses were obtained from the major practicing consulting engineering firms in the USA.

FIGURE 19

FAMILY OF MODEL CURVES AS A FUNCTION OF OUR
(TOP: 75 mg/lh , MIDDLE: 65 mg/lh , BOTTOM: 55 mg/lh)

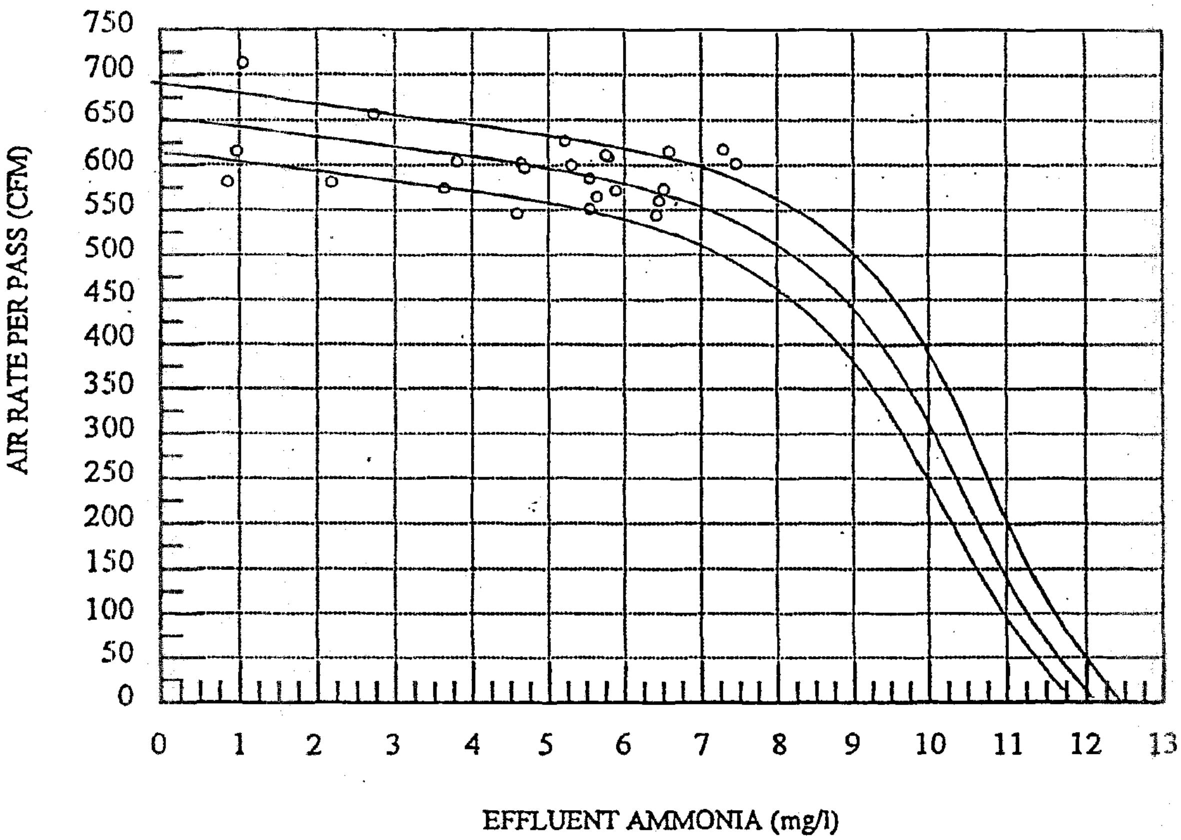

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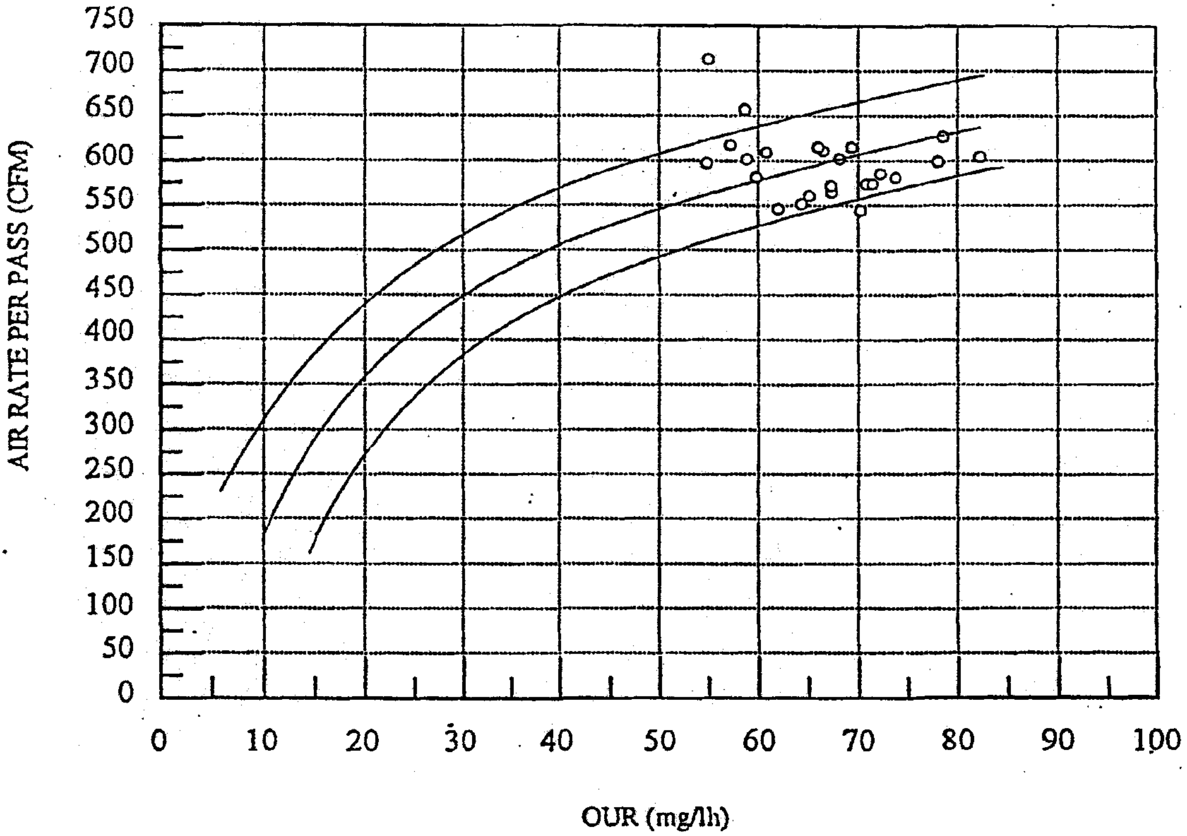
FIGURE 20

FAMILY OF MODEL CURVES AS A FUNCTION OF AMMONIA
(TOP: 0 mg/l , MIDDLE: 4.8 mg/l , BOTTOM: 7.5 mg/l)



4.3 million gallons per day per tank - a total flow for six tanks of Battery A would be ~26 million gallons per day, and 9.5 days, respectively). Both figures show the same data and the same model but from different perspectives.

Figure 19 illustrates the fact that even a very small air reduction produces a large increase in the effluent ammonium nitrogen at the Kirie WRP. It also illustrates that under existing protocol the Kirie WRP is not over aerating its mixed liquor and, therefore, any further reduction in the air supplied will not benefit the system in any substantial way. The current Kirie WRP aeration protocol is extremely satisfactory.

The average effluent ammonium nitrogen value for the control aeration tank during the air reduction period of the project was 1.09 mg/L. A comparison in air supply rate between the experimental and control aeration tanks can be made by inputting this value of effluent ammonium nitrogen into the models using the optimized parameter estimates (along with average values for flow and SRT).

The bottom part of Table 6 shows the air supply rates ($RATE_{TOT}$ [MCFD], $RATE_{PP}$ [CFM]) from model M2V2 for the experimental and control aeration tanks (with the parameter estimates obtained from optimization) required to obtain an effluent ammonium nitrogen value of 1.09 mg/L. The air supply rates are shown for the total tank in million cubic feet per

TABLE 6

AIR RATE ESTIMATION FOR EFFLUENT NH_4-N = 1.09 mg/L (MODEL M2V2)

Parameter	Experimental		Control	
	Observed[1]	Forced K_1[2]	Observed[1]	Forced K_1[2]
K_1 (-)	0.9535	1	0.9730	1
PO (-)	0.15	0.15	(0.15)[3]	(0.15)[3]
Y (-)	0.68	0.70	0.65	0.66
K_d (1/d)	0.037	0.031	0.047	0.043
E (%)	15.7	15.8	15.4	15.5
$RATE_{TOT}$ (MCFD)	2.721	2.732	2.796	2.804
$RATE_{PP}$ (CFM)	629.9	632.5	647.2	649.1

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[1] Optimized values obtained with the Kirie WRP data.

[2] Optimized values obtained with the Kirie WRP data, but with the value of K_1 forced to equal 1.

[3] Optimized PO value obtained for the experimental aeration tank. An independent estimate of PO for the control aeration tank is not possible due to data range limitations which produce non-convergence in the optimizing algorithms.

day (MCFD) and on a per pass (PP) basis in cubic feet per minute (CFM). There is little practical difference in the model air supply rate projections within each tank when the lumped slack parameter K_1 is either equal to 1 or not equal to 1. The difference (or error) in model air supply rate projections between each tank (experimental and control) is -2.6 percent when $K_1 = 1$ and -2.7 percent when $K_1 \neq 1$. If the optimized parameter values were averaged for the experimental and control tanks, a model would be obtained which would produce values midway between these two tanks, and the error would be cut in half (in both categories of $K_1 = 1$ and $K_1 \neq 1$) to - 1.3 percent and -1.35 percent, respectively.

It is apparent that these two differences in the air supply rate between tanks, although very small, are indicative of the different dynamics occurring within them. It is likely that all six aeration tanks in the two aeration batteries at the Kirie WRP would have similar minor air supply rate discrepancies due to the inability to reproduce the same dynamics within each tank. It will be shown, however, that this is no impediment to automating the adjustment of air flow to the tanks. This is because the model representing any arbitrary tank can be used to determine the air supply rate differences necessary for adjustment, and this adjustment difference is approximately the same no matter which tank (and its corresponding model) is picked for the air supply rate automation. The point is that it is not necessary to predict the actual air supply rate for each tank with a specific model, but what is necessary is to predict the air supply rate adjustment required for each tank (and to embed this into the computer control algorithm that will be used for the automated adjustment).

An example of this is illustrated in the next two tables, where model M2V2 for the experimental and control tanks is projected to estimate the air supply rate requirements for an effluent ammonia value of 0.0 mg/L, and where a comparison of the air supply rate adjustment values for the two tanks is provided.

The bottom part of Table 7 shows the air supply rates from model M2V2 for the experimental and control tanks (with the parameter estimates obtained from optimization) required to obtain an effluent ammonia value of 0.0 mg/L. The air supply rates are shown for the total tank in MCFD ($RATE_{TOT}$) and on a per pass basis in CFM ($RATE_{PP}$). As was the case with the values in Table 6, there is little practical difference in the model air supply rate projections within each tank (when $K_1 = 1$ or $K_1 \neq 1$). The difference (or error) in model air supply rate projections between each tank (experimental and control) is again -2.6 percent when $K1 = 1$ and -2.7 percent when $K_1 \neq$

TABLE 7

AIR RATE ESTIMATION FOR EFFLUENT NH_4-N = 0 mg/L (MODEL M2V2)

	Experimental		Control	
Parameter	Observed[1]	Forced K_1[2]	Observed[1]	Forced K_1[2]
K_1 (-)	0.9535	1	0.9730	1
PO (-)	0.15	0.15	(0.15)[3]	(0.15)[3]
Y (-)	0.68	0.70	0.65	0.66
K_d (1/d)	0.037	0.031	0.047	0.043
E (%)	15.7	15.8	15.4	15.5
$RATE_{TOT}$ (MCFD)	2.758	2.769	2.833	2.842
$RATE_{PP}$ (CFM)	638.3	640.9	655.8	657.7

[1] Optimized values obtained with the Kirie WRP data.

[2] Optimized values obtained with the Kirie WRP data, but with the value of K_1 forced to equal 1.

[3] Optimized PO value obtained for the experimental aeration tank. An independent estimate of PO for the control aeration tank is not possible due to data range limitations which produce non-convergence in the optimizing algorithm.

1. This equality of errors at different levels of effluent ammonium nitrogen shows that the models are equidistant between hyper-surfaces (or parallel in analogous two dimensional terms).

The bottom part of Table 8 summarizes the per pass air supply rate projections (in CFM) from Tables 6 and 7, and shows the air supply rate adjustment difference (delta) calculated for the experimental and control aeration tanks. The values of 8.4 CFM and 8.6 CFM for the air supply rate adjustment differences (in the experimental and control tanks, respectively) are an example of how these deltas are approximately the same regardless of the tank and its corresponding model parameter values. Table 8 also shows that there is no difference in delta values within the experimental and control tanks. Thus, for the purposes of applying the models in a computer control algorithm, the optimized parameter values with $K_1 = 1$ may be used. No advantage is gained by allowing K_1 to vary in the optimization, as far as calculating delta values is concerned.

TABLE 8

COMPARISON OF AIR RATE DELTA (FROM EFFLUENT NH_4-N = 1.09 TO NH_4 = 0 MG/L) BETWEEN EXPERIMENTAL AND CONTROL AERATION TANKS (MODEL M2V2)

	Experimental		Control	
Parameter	Observed[1]	Forced K_1[2]	Observed[1]	Forced K_1[2]
K_1 (-)	0.9535	1	0.9730	1
PO (-)	0.15	0.15	(0.15)[3]	(0.15)[3]
Y (-)	0.68	0.70	0.65	0.66
K_d (1/d)	0.037	0.031	0.047	0.043
E (%)	15.7	15.8	15.4	15.5
$RATE_{PP}$ (CFM) NH_3 = 0	638.3	640.9	655.8	657.7
$RATE_{PP}$ (CFM) NH_3 = 1.09	629.9	632.5	647.2	649.1
DELTA (CFM)	8.4	8.4	8.6	8.6

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[1] Optimized values obtained with the Kirie WRP data.

[2] Optimized values obtained with the Kirie WRP data, but with the value of K_1 forced to equal 1.

[3] Optimized PO value obtained for the experimental aeration tank. An independent estimate of PO for the control aeration tank is not possible due to data range limitations which produce non-convergence in the optimizing algorithm.

It is intended that the first model (M1) be used exclusively for partitioning the air supply rate requirement into carbonaceous and nitrogenous components, and that the second model (M2) be used exclusively for controlling the air supply rate in the aeration tanks. The equations of M1 are used to obtain the carbonaceous air supply rate fraction (F_C = $RATE_C/RATE_{TOT}$) and the nitrogenous air supply rate fraction (F_N = $RATE_N/RATE_{TOT}$), while the equations of M2 are used as part of a computerized control algorithm for actually adjusting air supply rate. If the plant operation concern is that the air supply rate requirement satisfy the complete carbonaceous and nitrogenous oxygen demand, then version 1 of both models should be coded into the control algorithm (M1V1 and M2V1). If the plant operation concern is that the air supply rate requirement satisfy the carbonaceous and nitrogenous oxygen demand only partially (with a non-zero specified effluent ammonia concentration) for reasons of economy, permit limits, or otherwise, then the more complex version 2 of both models must be coded into the control algorithm (M1V2 and M2V2). If air supply rate partitioning is of no interest, there is no need to code M1V1 or M1V2 in either case.

If stepwise aeration is used to supply more air at the beginning of the aeration tank and less air towards the end, models M2V1 and M2V2 can provide the air supply rate requirement necessary in each section of the aeration tank where the air supply rate can be independently varied. In such a case, an OUR profile function over the length of the aeration tank must be obtained, and the average OUR integral must be partitioned into separate individual integrals (with appropriate integration limits), each of which corresponds to a section of the tank where the air supply rate can be independently varied. Models M2V1 and M2V2 provide separate air supply rate requirements corresponding to each of the separate integrals which define the average OUR values in each of the tank sections. For example, at the Kirie WRP the air supply rate can be independently varied in the first pass of the aeration tank so that more air can be supplied in this pass while less air is supplied in both the second and the third passes. Thus, each aeration tank has two sections where the air supply rate can be independently varied, hence, the average OUR for each section can be obtained from two separate integrals. The integration limits for the first section would be 0 to 250 ft. (corresponding to the first pass length), while the integration limits for the second section would be 250 to 750 ft.

(corresponding to the combined length of the second and third passes).

A simpler approach, which would approximate the actual situation, would be to use the relationship between average tank OUR and initial tank OUR to obtain the air supply rate requirement from the models for the entire tank, and then to partition this total air supply rate between the two tank sections according to a fraction assumed to be constant under all circumstances. This would avoid both the need for obtaining an OUR profile function along the length of the tank each time air supply rate requirement is calculated from the models (this would require multiple respirometers simultaneously measuring OUR along the tank length), as well as the need to perform multiple numerical integration each time air supply rate requirement is calculated from the models. The partitioning fraction (assumed to be constant) would be obtained by the methodology previously described. This entails obtaining individual OUR values for the two tank sections from two separate integrals (with appropriate limits) using a generic or typical OUR profile function, and then obtaining two air supply rate requirement values from the models (one each for the two tank sections). The partitioning fraction for the first tank section (the first pass) would then be calculated as: $F_P = RATE_1/(RATE_1 + RATE_2)$. This partitioning fraction would then be used for all future partitioning of air supply rate from the models.

This type of analysis was done for the Kirie WRP using model M2V2 (details are in Appendix I - Partition Analysis). A general OUR profile function was developed whose coefficients are functions of the initial tank OUR (i.e., OUR at the head end of the aeration tank). This profile function was integrated over the two tank sections, using initial OUR values over the entire practical range of possible values. The average partitioning fraction for the first tank section (pass one) was 0.39 and for the second tank section (passes two and three combined) was 0.61, which is 0.305 per pass since the air supply rate cannot be independently varied in passes two and three. If the general OUR profile function is integrated over all three passes individually, the average partitioning fractions for the three passes, in sequence, are 0.39, 0.32, and 0.29. The two fractions from passes two and three add up to 0.61, which is the value obtained for the combined partitioning. It is of interest to note that the partitioning fractions in the control aeration tank were quite similar to those of the experimental tank, and they are 0.40, 0.30, and 0.30 for passes one through three, in sequence, during the time of sampling for the air reduction testing period of the project. This similarity indicates that no further air reduction is possible at the Kirie WRP, and the Kirie WRP operational personnel are doing an extremely satisfactory job in controlling aeration by the existing DO control approach.

Generic Control Algorithm Illustration

The control algorithm itself would be typically coded in an appropriate computer language at the WRP control room. An example control algorithm with flow chart and generic code is presented in Figure 21.

The following steps summarize the example algorithm:

1. The respirometer produces the raw data of oxygen uptake over time.
2. The computer calculates average OUR for the entire tank or for individual tank subsections.
3. The computer inputs current values of input variables (OUR, SRT, flow, etc.) into the model M2V2 or M2V1 (with model M1V2 or M1V1 if air supply rate partitioning is of interest), and calculates air supply rate requirement for the entire tank, or for individual tank subsections.
4. The computer subtracts the current calculated air supply rate requirement from the previously calculated air supply rate requirement (for the entire tank or for individual tank subsections).

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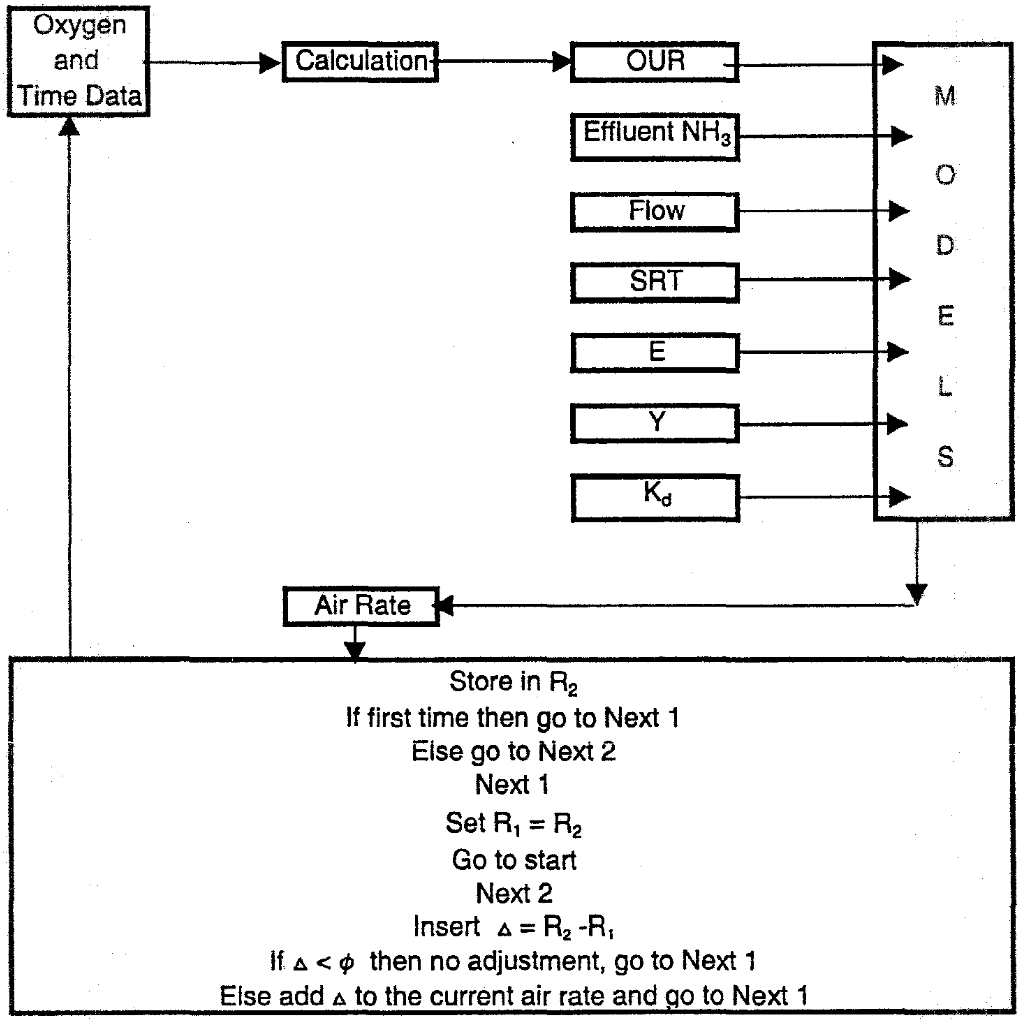
FIGURE 21

A TYPICAL CONTROL ALGORITHM FOR ON-LINE AERATION CONTROL



5. If the absolute value of a difference is less than a specified value, then the computer makes no adjustment and goes to step 1 to produce new raw data for the next air supply rate calculation. The specified value is the minimum air supply rate adjustment that can be made at a particular plant. This depends on the sophistication of the equipment employed.
6. Otherwise, if the absolute value of a difference is more than the specified value, then the computer makes the appropriate adjustment to the current air supply rate by adding or subtracting the increment as the case requires, and goes to step 1 to produce new raw data for the next air supply rate calculation.

Based on the air requirement computation, the information can then be fed to a program logic controller (PLC), which then would direct a blower to either reduce or increase the air supply. The increase or decrease in air supply can be achieved by the opening or closing of vanes on the blower. Alternatively, variable speed drive motors can increase or decrease the air supply as per the signals provided by the PLC.

CONCLUSIONS

The authors believe that the results of this study demonstrate that on-line respirometry has the potential for aeration control in the activated sludge process.

The conclusions which may be drawn from the results are:

1. The maximum OUR occurs at the head end of a plug flow aeration tank, and then it gradually tapers off to the endogenous level by the tail end of a plug flow aeration tank. This indicates that the highest oxygen demand occurs at the head end of the tank for oxidation of organic matter and ammonium nitrogen, and the oxygen demand decreases as the wastewater travels along the length of the tank.
2. For the Kirie WRP, the oxygen demand reaches an asymptotic level at any point beyond 500 feet, the end of the second pass (each treatment tank consists of three passes - each pass is 250 feet long). However, under the current operating conditions, air reduction in the third pass (i.e., 500 to 750 feet from the beginning of the tank) is not recommended since the air supply rate at which it is supplied is "just enough"

for both respiration of the microorganisms and to keep the MLSS under suspension.

3. Both the models developed in this study are comparable in the accuracy of predicting the air required for the oxidation of biodegradable organic matter and ammonium nitrogen.
4. Aeration control by on-line respirometry is technically possible. However, more work needs to be done using program logic controls, computer-coded algorithms, and blowers that can respond to such controls to actually demonstrate the applicability of on-line respirometry using the models developed in this study.
5. The reliability of on-line respirometry from an operation and maintenance point of view should be thoroughly investigated to ensure the robustness of this technology for consistent performance.
6. Automated DO probe system appears to be more practical than the respirometry system used in this study for aeration control with respect to ease of operation and maintenance, reliability, and skill requirements.

7. Air reduction of up to 35 percent had no appreciable effect on SVI and filament length, but resulted in elevated levels of effluent ammonium nitrogen and decreased DO.
8. As little as a 5 percent air reduction caused the experimental tank effluent ammonium nitrogen concentration to increase to nearly 5 mg/L, and the DO to decrease to under 1 mg/L throughout the experimental tank. This clearly indicates that aeration control using the automated DO probe system at the Kirie WRP provides optimum air supply, and further air reduction is not possible under current operating conditions. In WRPs where the air supply is not controlled by the automated DO probe system, energy savings may be accrued by installing such systems.
9. Aeration control using the automated DO probe system at the Kirie WRP provides optimum air supply and, therefore, the potentiality for electrical energy savings using on-line respirometry at the Kirie WRP is not substantial. As a result, application of on-line respirometry is not advantageous for the Kirie WRP under current operating conditions.

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APPENDIX I

MATHEMATICAL MODELS

MODEL 1, VERSION 1 (M1V1)

This model is a modification of the Lawrence and McCarty models for biological treatment systems in steady state (7). This is the basic version which predicts the air requirement to satisfy the complete carbonaceous and nitrogenous oxygen demand. It determines aeration rate individually for the carbonaceous oxygen demand and the nitrogenous oxygen demand. It also determines aeration rates for the entire aeration tank (it cannot determine subvolume aeration rates, such as in each pass). Thus, this model is only used when complete oxidation of carbon and ammonium nitrogen for the entire aeration tank is the goal, and separate quantities of air for carbonaceous and nitrogenous oxygen demand are to be computed.

$$\mathrm{RATE_{TOT}} = \mathrm{RATE_C} + \mathrm{RATE_N} \tag{1}$$

$$\mathrm{RATE_C} = (\mathrm{DELTA1})(\mathrm{RBOD})Q(\mathrm{KK})(\mathrm{KF}) \tag{2}$$

$$\mathrm{RATE_N} = (4.57)Q(\mathrm{DELTA2})(\mathrm{KK}) - (2.86)Q(\mathrm{DELTA2} - \mathrm{CF})(\mathrm{KK}) \tag{3}$$

$$\mathrm{DELTA1} = 52.58(\mathrm{OUR_{AVG}})^{0.3233}K_1 \tag{4}$$

$$\mathrm{DELTA2} = [(1 - \mathrm{RBOD}) / \mathrm{RBOD}](0.3335)(\mathrm{DELTA1})^{0.8209}K_1 \tag{5}$$

$$\mathrm{CF} = [(1 - \mathrm{RBOD}) / \mathrm{RBOD}](0.1204)(\mathrm{DELTA1})^{0.7921}K_1 \tag{6}$$

$$\mathrm{KF} = \left(\frac{1}{F}\right)[1 - (Z(\mathrm{AMR})\mathrm{FY}) / [1 + K_d(\mathrm{SRT})]] \tag{7}$$

$$KK = 8.34(100) / [E(DAIR)(FO_2AIR)] \quad (8)$$

Where,

$DAIR = 1.81 / ((0.082)T_K)$ density of air $\left(\frac{lbs}{ft^3}\right)$

$FO_2AIR = 0.232$ fraction of oxygen in air by weight (–)

$AMR = 1.42$ oxygen equivalent of cell mass (–)

$RATE_{TOT}$ = total aeration rate $\left(\frac{ft^3}{d}\right)$

$RATE_C$ = aeration rate due to carbon component $\left(\frac{ft^3}{d}\right)$

$RATE_N$ = aeration rate due to nitrogen component $\left(\frac{ft^3}{d}\right)$

Q = sewage flow (MGD)

RBOD = BOD ratio: $\frac{\text{carbonaceous}}{(\text{carbonaceous + nitrogenous})}$ (–)

OUR_{AVG} = average oxygen utilization rate for entire aeration tank $\left(\frac{mg}{lh}\right)$

F = ratio of BOD_5 to BOD_{MAX} (–) (typical value is 0.68)

Y = cell yield coefficient (–)

K_d = endogenous decay coefficient $\left(\frac{1}{d}\right)$

SRT = solids retention time (d)

E = oxygen transfer efficiency (%)

Z = model shape parameter (-)

T_K = temperature of ambient air (ºK)

K_1 = adjustable parameter (-)

Note: (-) indicates dimensionless quantity.

MODEL 1, VERSION 2 (M1V2)

This model is also a modification of the Lawrence and McCarty model for biological treatment systems in steady state (7). This is the extended version which predicts the air rate requirement to satisfy partial carbonaceous and nitrogenous oxygen demand (contingent upon a specified ammonia concentration in the aeration tank effluent). It determines aeration rate individually for the carbonaceous oxygen demand and the nitrogenous oxygen demand. Also, it only determines aeration rate for the entire aeration tank (it cannot determine sub-volume aeration rates such as in each pass). Thus, this model is only used when partial carbon and ammonium nitrogen oxidation for the entire aeration tank is the goal, and separate quantities of air for the partial carbonaceous and nitrogenous oxygen demand are to be computed.

$$\mathrm{RATE}_{\mathrm{TOT}} = \mathrm{RATE}_{\mathrm{C}} + \mathrm{RATE}_{\mathrm{N}} \tag{1}$$

$$\mathrm{RATE}_{\mathrm{C}} = (\mathrm{DELTA1})(\mathrm{RBOD})\mathrm{Q}(\mathrm{KK})(\mathrm{KF}) \tag{2}$$

$$\mathrm{RATE}_{\mathrm{N}} = (4.57)\mathrm{Q}(\mathrm{DELTA2})(\mathrm{KK}) - (2.86)\mathrm{Q}(\mathrm{DELTA2} - \mathrm{CF})(\mathrm{KK}) \tag{3}$$

$$\mathrm{DELTA4} = 52.58(\mathrm{OUR}_{\mathrm{AVG}})^{0.3233}\mathrm{K}_1 \tag{4}$$

$$\mathrm{DELTA2} = \begin{bmatrix} ((1 - \mathrm{RBOD}) / \mathrm{RBOD})(0.3335)(\mathrm{DELTA4})^{0.8209} \\ - (\mathrm{P}(\mathrm{NH3} / 0.1341))^{\left(\frac{1}{1.3868}\right)} \end{bmatrix} \mathrm{K}_1 \tag{5}$$

$$CF = ((1 - RBOD) / RBOD)(0.1204)(DELTA4)^{0.7921}(1 - P(NH3 / NH3Z))K_1 \quad (6)$$

$$KF = \left(\frac{1}{F}\right)[1 - (Z(AMR)FY) / (1 + K_d(SRT))] \quad (7)$$

$$KK = 8.34(100) / (E(DAIR)(FO_2AIR)) \quad (8)$$

$$DELTA1 = DELTA4 - DELTA3 \quad (9)$$

$$DELTA3 = DELTA4(P(NH3 / NH3Z))^{1.2279} \quad (10)$$

$$P = 1 + (PO - 1)EXP\left((NH3 / KNH3)^{10}(LOGN(0.5 / (PO - 1)))\right) \quad (11)$$

$$KNH3 = 0.7124(NH3Z) \quad (12)$$

$$NH3Z = 0.1341\left(((1 - RBOD) / RBOD)\left(0.3335(DELTA4)^{0.8209}\right)\right)^{1.3868} \quad (13)$$

Where,

$DAIR = 1.81 / ((0.082)T_K)$ density of air $\left(\frac{lbs}{ft^3}\right)$

$FO_2AIR = 0.232$ fraction of oxygen in air by weight $(-)$

$AMR = 1.42$ oxygen equivalent of cell mass $(-)$

$RATE_{TOT}$ = total aeration rate $\left(\frac{ft^3}{d}\right)$

$RATE_C$ = aeration rate due to carbon component $\left(\frac{ft^3}{d}\right)$

$RATE_N$ = aeration rate due to nitrogen component $\left(\frac{ft^3}{d}\right)$

Q = sewage flow (MGD)

RBOD = BOD ratio: $\frac{\text{carbonaceous}}{(\text{carbonaceous} + \text{nitrogenous})}(-)$

OUR_{AVG} = average oxygen utilization rate for entire aeration tank $\left(\frac{mg}{lh}\right)$

F = ratio of BOD_5 to BOD_{MAX} (–) (typical value is 0.68)

Y = cell yield coefficient (–)

K_d = endogenous decay coefficient $\left(\frac{1}{d}\right)$

SRT = solids retention time (d)

E = oxygen transfer efficiency (%)

Z = model shape parameter (–)

T_K = temperature of ambient air (ºK)

NH3 = ammonia concentration of aeration tank effluent $\left(\frac{mg}{L}\right)$

K_1 = adjustable parameter (–)

PO = adjustable parameter (–)

Note: (–) indicates dimensionless quantity.

MODEL 2, VERSION 1 (M2V1)

This model is based on the principles of applied dimensional analysis. This is the basic version which predicts the air requirement to satisfy the complete carbonaceous and nitrogenous demand. It determines aeration rate only for the total combined carbonaceous and nitrogenous oxygen demand (there is no separation into individual carbonaceous and nitrogenous components). It also determines aeration rate not only for the entire aeration tank, but for any subvolume of the tank, as well (such as one of the three passes). Thus, this model can be used only for predicting aeration requirements for the complete carbon and ammonium nitrogen oxidation either for the entire tank or for subvolumes of the tank.

$$RATE_{TOT} = (PR)V(100)(0.00354)/(E(DO_2)(FO_2AIR)) \tag{1}$$

$$PR = (0.8976)Q(OUR_{AVG})^{0.2963}\left(\frac{M}{F}\right)K_1 \tag{2}$$

$$M = 1 - (K)(N) \tag{3}$$

$$N = Z(AMR)FY/(1 + K_d(SRT)) \tag{4}$$

$$K = (0.5661) + (0.1632)/N \tag{5}$$

Where,

$DO_2 = 32/((0.082)T_K)$ density of oxygen $\left(\frac{mg}{mL}\right)$

FO_2AIR = 0.232 fraction of oxygen in air by weight (–)

AMR = 1.42 oxygen equivalent of cell mass (–)

$RATE_{TOT}$ = total aeration rate $\left(\frac{ft^3}{d}\right)$

Q = sewage flow (MGD)

OUR_{AVG} = average oxygen utilization rate for entire aeration tank $\left(\frac{mg}{lh}\right)$

F = ratio of BOD_5 to BOD_{MAX} (–) (typical value is 0.68)

Y = cell yield coefficient (–)

K_d = endogenous decay coefficient $\left(\frac{1}{d}\right)$

SRT = solids retention time (d)

E = oxygen transfer efficiency (%)

Z = model shape parameter (–)

T_K = temperature of ambient air (°K)

V = volume of aeration tank (gal)

K_1 = adjustable parameter (–)

Note: (–) indicates dimensionless quantity.

MODEL 2, VERSION 2 (M2V2)

This model is also based on the principles of applied dimension analysis, but this is the extended version which predicts the air rate requirement to satisfy partial carbonaceous and nitrogenous oxygen demand (contingent upon a specified ammonia concentration in the aeration tank effluent). It determines aeration rate only for the total combined carbonaceous and nitrogenous oxygen demand (there is no separation into individual carbonaceous and nitrogenous components). It also determines aeration rate not only for the entire aeration tank, but for any subvolume of the tank, as well (such as one of the three passes). Thus, this model can be used for predicting aeration requirements for a specified or partial carbon and ammonium nitrogen oxidation (specified effluent ammonium nitrogen concentration) and for subvolumes of the aeration tank.

$$\mathrm{RATE_{TOT}} = (\mathrm{PR})\mathrm{V}(100)(0.00354)/(\mathrm{E}(\mathrm{DO_2})(\mathrm{FO_2AIR})) \tag{1}$$

$$\mathrm{PR} = (0.8976)\mathrm{Q}(\mathrm{OUR_{AVG}})^{0.2963}\left(\frac{\mathrm{M}}{\mathrm{F}}\right)(\mathrm{KKN})\mathrm{K_1} \tag{2}$$

$$\mathrm{M} = 1 - (\mathrm{K})(\mathrm{N}) \tag{3}$$

$$\mathrm{N} = \mathrm{Z}(\mathrm{AMR})\mathrm{FY}/(1 + \mathrm{K_d}(\mathrm{SRT})) \tag{4}$$

$$\mathrm{K} = (0.5661) + (0.1632)/\mathrm{N} \tag{5}$$

$$KKN = 1 - (P(NH3 / NH3Z)) \tag{6}$$

$$P = 1 + (PO - 1)EXP((NH3 / KNH3)^{10}(LOGN(0.5 /(PO - 1)))) \tag{7}$$

$$KNH3 = 0.7124(NH3Z) \tag{8}$$

$$NH3Z = 0.1341(((1 - RBOD) / RBOD)(0.3335(DELTA\,1)^{0.8209}))^{1.3868} \tag{9}$$

$$DELTA1 = 52.58(OUR_{AVG})^{0.3233} \tag{10}$$

Where,

$DO_2 = 32/((0.082)T_K)$ density of oxygen $\left(\frac{mg}{mL}\right)$

$FO_2AIR = 0.232$ fraction of oxygen in air by weight (–)

AMR = 1.42 oxygen equivalent of cell mass (–)

$RATE_{TOT}$ = total aeration rate $\left(\frac{ft^3}{d}\right)$

Q = sewage flow (MGD)

RBOD = BOD ratio: $\frac{\text{carbonaceous}}{(\text{carbonaceous + nitrogenous})}$ (–)

OUR_{AVG} = average oxygen utilization rate for entire aeration tank $\left(\frac{mg}{lh}\right)$

F = ratio of BOD_5 to BOD_{MAX} (–) (typical value is 0.68)

Y = cell yield coefficient (–)

K_d = endogenous decay coefficient $\left(\frac{1}{d}\right)$

SRT = solids retention time (d)

E = oxygen transfer efficiency (%)

Z = model shape parameter (–)

T_K = temperature of ambient air (ºK)

V = volume of aeration tank (gal)

NH3 = ammonia concentration of aeration tank effluent $\left(\frac{mg}{L}\right)$

K_1 = adjustable parameter (–)

PO = adjustable parameter (–)

Note: (–) indicates dimensionless quantity.

AVERAGE OUR TANK ANALYSIS

All four model versions use the average OUR for the entire aeration tank. This is defined as follows:

$$\begin{bmatrix} \text{AVG} \\ \text{OUR} \end{bmatrix}_{\frac{mg}{lh}} = \left(\frac{1}{V_l^T}\right)\int_0^{V_l^T} [\text{OUR}]'_{\frac{mg}{lh}}\, dV_l$$

where,

V_l^T = total volume of aeration tank (l)

V_l = arbitrary tank volume (l) $\left(0 \le V_l \le V_l^T\right)$

$[\text{OUR}]'_{\frac{mg}{lh}}$ = OUR as a function of tank volume along the length of the tank

The average OUR is more convenient to work with in terms of aeration tank length rather than aeration tank volume. To this end the definition may be transformed as follows:

$V_l = 28.3168\, L_{FT}\, W_{FT}\, H_{FT}$

$dV_l = 28.3168\, W_{FT}\, H_{FT}\, dL_{FT}$

$$\begin{bmatrix} \text{AVG} \\ \text{OUR} \end{bmatrix}_{mg/lh} = \frac{28.3168 W_{FT} H_{FT}}{28.3168 W_{FT} H_{FT} L_{FT}} \int_0^{L_{FT}^T} [\text{OUR}]_{mg/lh}\, dL_{FT}$$

$$\begin{bmatrix} \text{AVG} \\ \text{OUR} \end{bmatrix}_{mg/lh} = \left(\frac{1}{L_{FT}^T}\right)\int_0^{L_{FT}^T} [\text{OUR}]_{mg/lh}\, dL_{FT}$$

Where,

L_{FT}^{T} = total length of aeration tank (ft)

L_{FT} = arbitrary tank length (ft) $\left(0 \leq L_{FT} \leq L_{FT}^{T}\right)$

W_{FT} = aeration tank width (ft)

H_{FT} = aeration tank height (ft)

$[OUR]_{\frac{mg}{lh}}$ = OUR as a function of tank length

In order to obtain a numerical value for the average OUR of the entire aeration tank, it is necessary to obtain an OUR profile of the entire aeration tank as a function of the tank length. The data from the OUR profile is fitted to an approximating function using a least squares algorithm, the function is substituted into the integral, the integration is performed numerically, and this value is divided by the aeration tank length to obtain the average OUR for the entire tank.

In the interest of simplicity (and routine, practical plant operations), it would be helpful if the average OUR could be obtained without the need for an OUR profile consisting of several values over the length of the tank. Such a simplification is possible by correlating the average OUR of the entire tank obtained from integration of OUR profile curves with the initial OUR obtained from one sample at the beginning of the aeration tank.

Average OUR values were obtained by integrating 15 sets of OUR profile curves (taken over a period of six months) and correlating them with corresponding 15 values of initial OUR, using a power function and estimating parameters with a least squares algorithm.

The correlation obtained is as follows:

$$[\mathrm{AVGOUR}]_{\mathrm{mg/lh}} = (1/750)\int_0^{750}[\mathrm{OUR}]_{\mathrm{mg/lh}}\,dL = a(\mathrm{OUR}_I)^b$$

Where,

$a = 0.06864$

$b = 1.5851$

$R^2 = 0.952029$

OUR_I = initial OUR, i.e., the OUR observed at head of tank (mg/lh)

Each of the aeration tanks consists of three passes with a length of 250 ft. per pass, which makes a total tank length of 750 ft. Therefore, the integration upper limit is 750 ft.

The following figures (Figures AI-1 and AI-2) show the relationships between average OUR vs. initial OUR (OUR_I). The correlation between AVGOUR and OUR_I has been found to be

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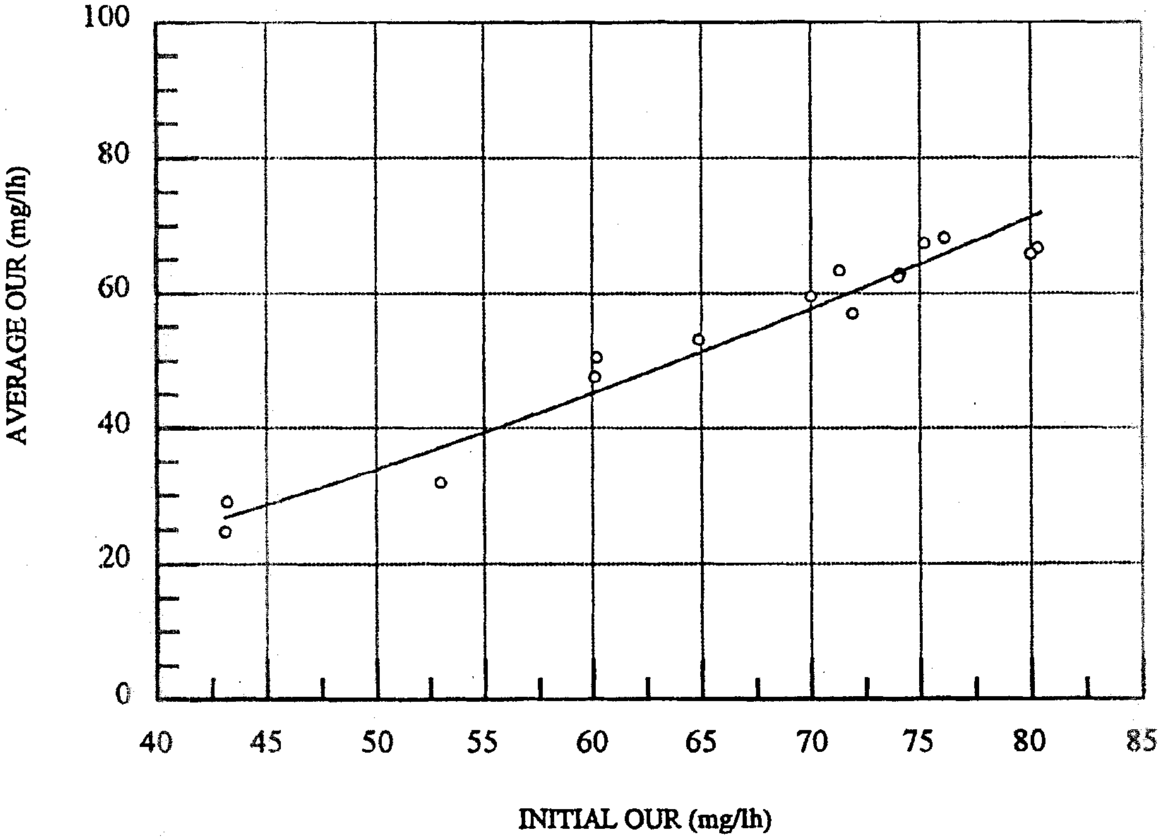
FIGURE AI-1

CORRELATION PLOT OF AVERAGE OUR vs. INITIAL OUR*

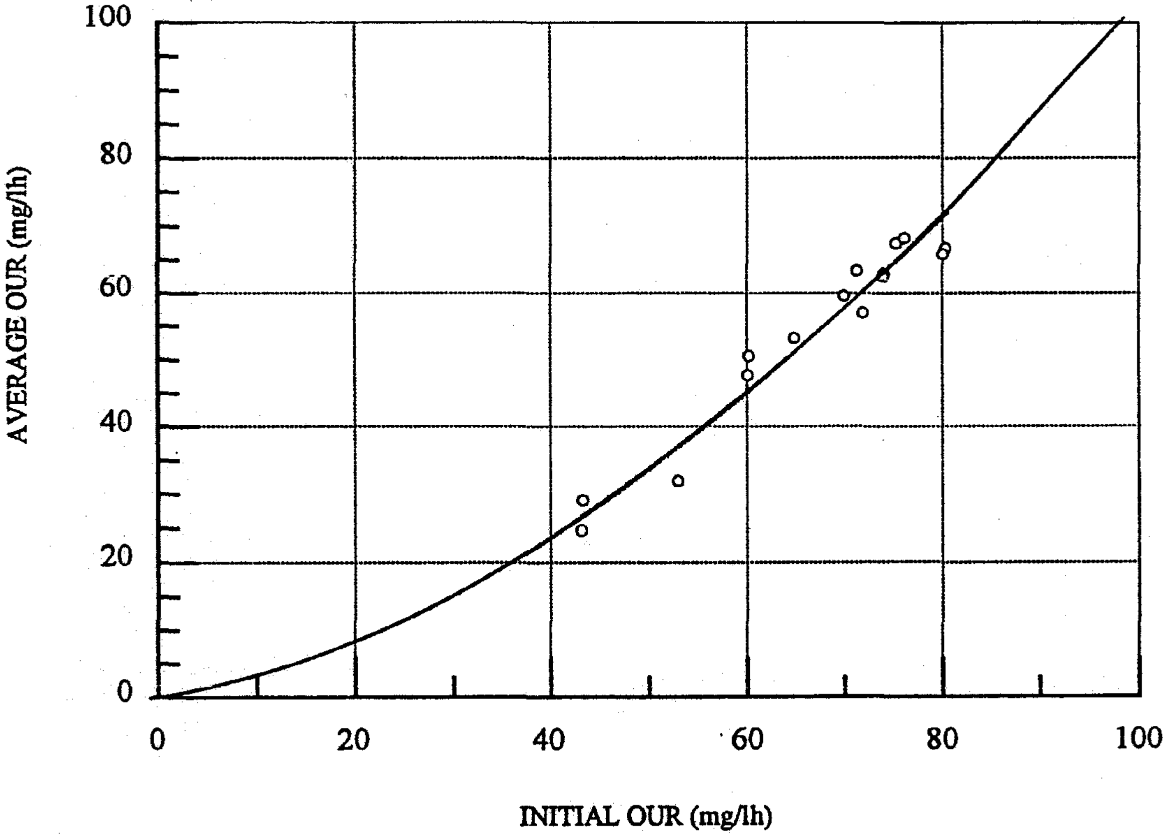


* VALUES OBTAINED BY INTEGRATING 15 SETS OF OUR PROFILE CURVES TAKEN OVER A PERIOD OF 6 MONTHS

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

FIGURE AI-2

CORRELATION PLOT OF AVERAGE OUR vs. INITIAL OUR WITH EXPANDED SCALE AND CURVE EXTENSION*



* VALUES OBTAINED BY INTEGRATING 15 SETS OF OUR PROFILE CURVES TAKEN OVER A PERIOD OF 6 MONTHS

statistically very highly significant ($P << 0.001$). The approximating function applied to integrate the OUR profile data is as follows:

$$[OUR]_{mg/1h} = K1 + (K2 - K1)/(1 + K3(L/375)^{6})$$

Where,

$[OUR]_{mg/1h}$ = OUR at any length in the aeration tank, L (mg / 1h)

L = tank length at which OUR sample is taken (FT)

K1, K2, K3 = least squares algorithm fitting parameters

After integration (using this function) and division by the total tank length to obtain the average OUR for the entire tank, the parameter K2 is used as the value of initial OUR to obtain a data pair in order to determine the correlation power function with 15 such data pairs. All 15 data pairs obtained in this manner (and plotted in Figures AI-1 and AI-2) are shown in Table AI-1. The values in the "Average OUR" column are obtained by dividing the values in the "Integral" column by 750 (the total tank length). This is the data used to obtain the correlation power function presented.

The first model presented (M1) requires a value for RBOD (BOD ratio of carbonaceous divided by total carbonaceous and nitrogenous BOD) and so an empirical value of this ratio was

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TABLE AI-1

CALCULATION OF AVERAGE OUR BASED ON INITIAL OUR OBSERVATIONS

Initial OUR	Integral	Average OUR
74.100	47179	62.905
71.300	47569	63.425
70.000	44722	59.629
64.900	39925	53.233
60.100	35803	47.737
60.200	37845	50.460
43.100	18544	24.725
43.200	21798	29.064
53.000	23949	31.932
80.300	50015	66.687
80.000	49431	65.908
75.200	50660	67.547
76.100	51214	68.285
74.000	46775	62.367
71.900	42783	57.044

obtained from 57 experimental values shown in Table AI-2. The RBOD value obtained is 0.50 with 95 percent confidence limits of (0.47, 0.53).

The value of Z (the Shape Parameter) appears in both models presented (M1 and M2). It is intended to be used to make adjustments to the models for any given WRP. As an example, Metcalf and Eddy provide a small modification to the WPCF (WEF) recommended model of Lawrence and McCarty.

This modification is based on their many years of experience with this model, and in effect their modification provides a "Safety Factor" for practical and trouble free routine plant operations with aerobic biological wastewater treatment systems. This safety factor is incorporated into the models when the value of the Shape Parameter is Z = 1. If the safety factor is not considered useful, then it may be removed using a value of the Shape Parameter Z = 1.431664. This transforms the models into the original Lawrence and McCarty versions. Thus, the models may be modified very easily by changing the value of the Shape Parameter Z. The Lawrence and McCarty design equations, along with the functional form from dimensional analysis, are provided for reference. The Lawrence and McCarty model is obtained from Design of Municipal Wastewater Treatment Plants (7).

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AI-2

CALCULATION OF RBOD VALUES BASED ON BOD_5 AND $CBOD_5$ OBSERVATIONS

BOD_5	$CBOD_5$	RBOD
37	15	0.41
31	10	0.32
33	11	0.33
37	11	0.30
25	12	0.48
31	10	0.32
33	11	0.33
41	22	0.54
25	13	0.52
25	13	0.52
23	10	0.43
23	11	0.48
24	11	0.46
23	13	0.57
25	11	0.44
28	13	0.46
28	14	0.50
30	15	0.50
29	15	0.52
20	11	0.55
32	18	0.56
15	11	0.73
29	18	0.62
24	13	0.54
26	13	0.50
26	14	0.54
24	13	0.54
28	16	0.57
29	14	0.48
55	35	0.64
43	24	0.56
37	20	0.54
46	27	0.59
44	23	0.52
40	22	0.55
43	18	0.42
47	30	0.64

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TABLE AI-2 (Continued)

CALCULATION OF RBOD VALUES BASED ON BOD_5 AND $CBOD_5$ OBSERVATIONS

BOD_5	$CBOD_5$	RBOD
41	26	0.63
47	28	0.60
37	18	0.49
34	23	0.68
29	20	0.69
35	22	0.63
20	11	0.55
28	14	0.50
18	12	0.67
30	15	0.50
30	12	0.40
32	12	0.38
29	13	0.45
30	13	0.43
25	11	0.44
25	12	0.48
23	11	0.48
30	12	0.40
27	11	0.41
27	12	0.44

LAWRENCE AND McCARTY DESIGN EQUATIONS

$$\Theta = V / Q = \text{hydraulic detention time} \tag{1}$$

$$\Theta_c = VX / Q_w X_r = VM / Q_w M_r = \text{mean cell residence time} \tag{2}$$

$$1 / \Theta_c = [YkS_e / (K_s + S_e)] - b \tag{3}$$

$$XV = \Theta_c QY(S_o - S_e) / (1 + b\Theta_c) \tag{4}$$

$$Y_{OBS} = Y / (1 - b\Theta_c) \tag{5}$$

$$M = (\Theta_c / \Theta)\{[Y(S_o - S_e) / (1 + b\Theta_c)] + Z_{io} + Z_{no}\} \tag{6}$$

$$P_x = Q\{[Y(S_o - S_e) / (1 + b\Theta_c)] + Z_{io} + Z_{no}\} \tag{7}$$

$$\alpha = Q_r / Q = X / X_r - X = M / M_r - M \tag{8}$$

$$R_c = Q(S_o - S_e)((1 + b\Theta_c - BY) / (1 + b\Theta_c)) \tag{9}$$

$$R_n = 4.57Q(N_o - N) - 2.86Q(N_o - N - NO_3) \tag{10}$$

V = aeration tank volume, L^3

Q = wastewater forward flow, L^3/t

Q_r = sludge recycle flow, L^3/t

X = reactor biological solids, m/L^3

Y = true cell yield, m/m

S_o = influent soluble biodegradable substrate, mg/L

S_e = effluent soluble substrate, m/L^3

Q_w = sludge waste flow, L^3/t

K_s = half-velocity coefficient, m/L^3

k = maximum rate of substrate utilization per unit weight of biomass, 1/t

b = endogenous decay coefficient based on biomass in aerated zone, 1/t

Y_{OBS} = observed cell yield, m/m

M = total mixed liquor suspended solids, m/L^3

Z_{io} = influent nonvolatile suspended solids, m/L^3

Z_{no} = influent volatile nonbiodegradable solids, m/L^3

R_c = mass of oxygen required per unit time to satisfy carbonaceous oxygen, m/t

R_n = mass of oxygen required per unit time to satisfy nitrification oxygen demand, m/t

N_o = influent oxidizable nitrogen, m/L^3

N = effluent oxidizable nitrogen, m/L^3

NO_3 = effluent nitrate-nitrogen, m/L^3

P_x = mass of total activated sludge solids generated or wasted per day, m/t

B = oxygen equivalent of cell mass, often calculated as 1.42 mass O_2/mass VSS, mg/mg

DIMENSIONAL ANALYSIS FORM

$$\begin{matrix}\text{AIR}\\ \text{RATE}\end{matrix} = \left(\frac{K}{F_{OXY}\;\;E_{\%}}\right)\left(\frac{D_{OXY}}{D_{AIR}}\right)V\ (OUR)$$

Where:

D_{OXY} = density of oxygen

D_{AIR} = density of air

F_{OXY} = mass oxygen/mass air

$E_{\%}$ = oxygen transfer efficiency

V = tank volume

OUR = oxygen uptake rate

K = constant

$\begin{matrix}\text{AIR}\\ \text{RATE}\end{matrix}$ = air demand

PARTITION ANALYSIS

For the aeration tank subsection partitioning analysis, a general OUR profile function was developed whose coefficients are functions of initial tank OUR. This general OUR profile function is based on the OUR approximating function presented previously, but the least squares algorithm fitting parameters (K1, K2, K3) are modified appropriately:

$$[\mathrm{OUR}]_{\frac{mg}{lh}} = K1 + (K2 - K1)/\left(1 + K3(L/375)^6\right)$$

Where,

$[\mathrm{OUR}]_{\frac{mg}{lh}}$ = OUR at any length in the tank $\left(\frac{mg}{lh}\right)$

L = tank length at which OUR is required (ft)

$K1 = OURF = 0.1191(OURAVG)^{1.4501}$

$OURAVG = 0.06864(OURI)^{1.5851}$

$K2 = OURI$

$$K3 = \left(\frac{OURI}{OURF} - P\right)\left(\frac{1}{P-1}\right)$$

$P = 1.32$ (if $OURI \leq 80$)

$P = 2.52 - 0.015(OURI)$ (if $OURI > 80$)

OURI = initial tank OUR $\left(\frac{mg}{lh}\right)$ $(0 \leq OURI \leq 100)$

OURF = final tank OUR $\left(\frac{mg}{lh}\right)$

The function would appear as follows when coded in a computer language similar to BASIC:

$$OURAVG = 0.06864(OURI)^{1.5851}$$

$$OURF = 0.1191(OURAVG)^{1.4501}$$

If OUR ≤80, then P = 1.32

else P = 2.52 - 0.015(OURI)

$$\phi = \left(\frac{OURI}{OURF} - P\right)\left(\frac{1}{P - 1}\right)$$

$$[OUR]_{\frac{mg}{1h}} = OURF + (OURI - OURF)/\left(1 + \phi(L/375)^{6}\right)$$

These transformations produce a general OUR profile function which has two independent variables: L and OURI. This function (call it F(L,OURI)) can be used to obtain the average OUR values for the entire tank, and for each of the three passes as follows:

$$[AVGOUR]_{TOT} = \left(\frac{1}{750 - 0}\right)\int_{0}^{750}(F(L, OURI))\,dL$$

$$[AVGOUR]_{PASS1} = \left(\frac{1}{250 - 0}\right)\int_{0}^{250}(F(L, OURI))\,dL$$

$$[AVGOUR]_{PASS2} = \left(\frac{1}{500 - 250}\right)\int_{250}^{500}(F(L, OURI))\,dL$$

$$[AVGOUR]_{PASS3} = \left(\frac{1}{750 - 500}\right)\int_{500}^{750}(F(L, OURI))\,dL$$

These average OUR values can be used as input to the models in order to obtain aeration rates for the total tank, and each of the three passes individually. The partitioning fractions (PF) can then be calculated as follows:

$$PF_{PASS1} = \left(\frac{RATE_{PASS1}}{RATE_{TOT}}\right)$$

$$PF_{PASS2} = \left(\frac{RATE_{PASS2}}{RATE_{TOT}}\right)$$

$$PF_{PASS3} = \left(\frac{RATE_{PASS3}}{RATE_{TOT}}\right)$$

These partitioning fractions can be obtained for various initial OUR values. If this is done using initial OUR values taken over the entire practical range of possible values, and then the partitioning fractions obtained are averaged, the average partitioning fractions for all three passes are determined:

$$AVGPF_{PASS1} = 0.39$$

$$AVGPF_{PASS2} = 0.32$$

$$AVGPF_{PASS3} = 0.29$$

The validity of the general OUR profile function can be demonstrated by the application of the following equation:

$$[AVGOUR]_{TOT} = \left(\frac{1}{750}\right)\int_{0}^{750}(F(L, OURI))\, dL$$

This is the first of the equations presented previously for obtaining average OUR for the total tank in the determination of partitioning fractions. It states that the average OUR for the total tank is related to the initial OUR of the tank. This relationship was determined directly from data as the simplifying correlation presented previously, both as a graph and as a power function:

$$[\mathrm{AVGOUR}]_{\mathrm{TOT}} = 0.06864(\mathrm{OURI})^{1.5851}$$

If the general OUR profile function developed is valid, then this simplifying correlation and the above integral equation should give equivalent results. It will be shown that they do.

By solving the integral equation for average OUR with various values of initial OUR (over the range of zero to 100), data points are obtained which may be plotted as a graph. A power function which approximates the integral equation can then be fitted to these data points applying a least squares algorithm. Figure AI-3 shows both the data points obtained from the integral equation, and the power curve that is fitted to these data points. Table AI-3 compares the power function coefficients for the simplifying correlation with the coefficients of the power curve fitted to the data points from the integral equation (which uses the general OUR profile

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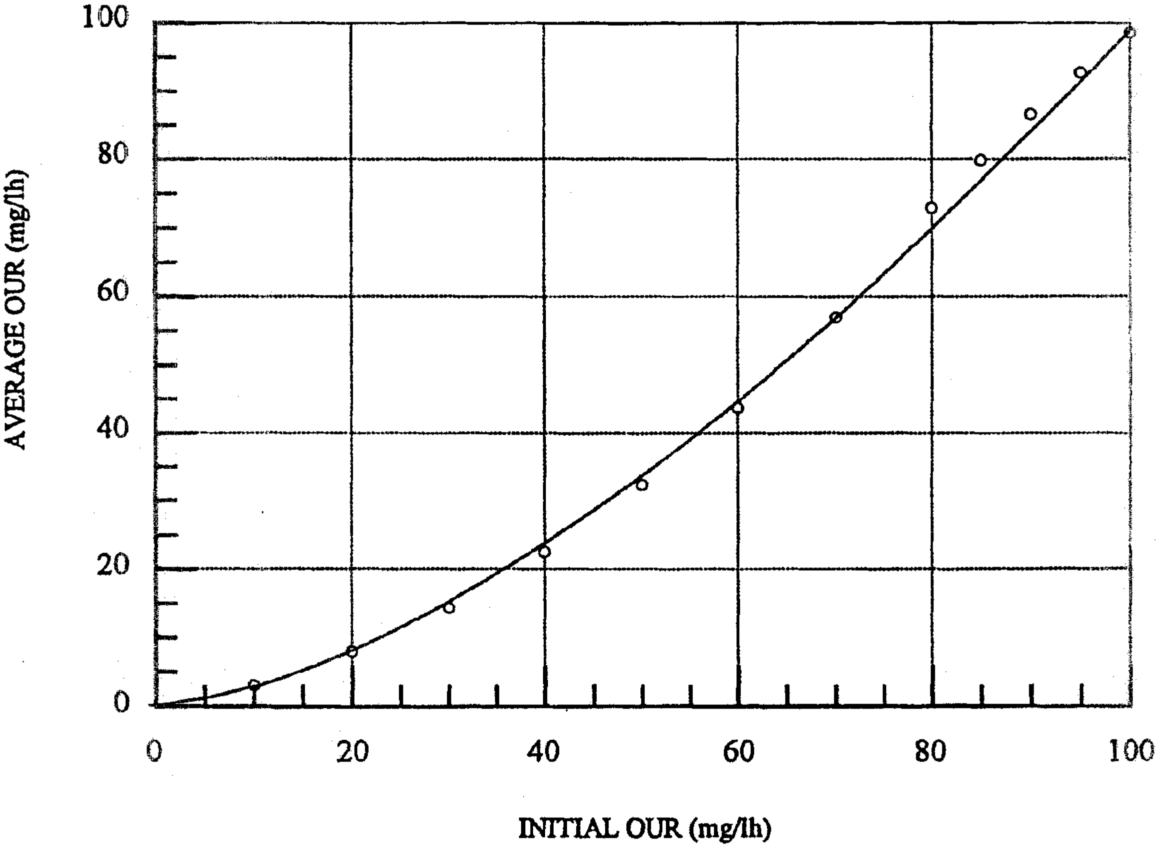
FIGURE AI-3

PLOT OF AVERAGE OUR vs. INITIAL OUR FROM THE INTEGRAL EQUATION WITH THE GENERAL OUR PROFILE FUNCTION*



* VALUES OBTAINED FROM THE INTEGRAL EQUATION WITH THE POWER CURVE THAT IS FITTED TO THESE VALUES

TABLE AI-3

COEFFICIENT COMPARISON OF POWER FORMS

Previous Simplifying Correlation[1]	Integral Equation Approximation[2]
$A = 0.06864$ $B = 1.5851$ $R^2 = 0.952029$	$A = 0.07758$ $B = 1.5528$ $R^2 = 0.998552$

[1] $[\text{AVGOUR}]_{\text{TOT}} = A(\text{OURI})^B = 0.06864(\text{OURI})^{1.5851}$

[2] $[\text{AVGOUR}]_{\text{TOT}} = A(\text{OURI})^B = 0.07758(\text{OURI})^{1.5528}$

$$= \left(\frac{1}{750}\right)\int_0^{750}(F(L, \text{OURI}))dL$$

function). The power form is defined as follows: [AVGOUR] = A(OURI)^B. The coefficients A and B are very similar, which implies that the two curves are very similar. Figure AI-4 is a visual comparison of the two curves superimposed on each other (shown individually in Figures AI-2 and AI-3). It shows that the two curves are almost identical except in the upper region, above initial OUR values of 80 mg/lh.

A more quantitative comparison of the essential equivalence of the two curves is obtained by plotting average OUR values from the simplifying correlation versus the average OUR values from the integral equation (which uses the general OUR profile function). This plot should produce a line passing through zero with a slope of 1 if the output OUR values from the two curves are equal. Figure AI-5 shows the plotted data points and the line fitted to these data points applying a least squares algorithm. The functional form for the line is: Y = K X. The least squares estimate of the slope (K) is 1.00662 (with R^2 = 0.998574), which shows the essential equivalence of the two curves and which validates the general OUR profile function developed.

An important insight into the dynamics of aeration arises from the fact that such a general OUR profile function can describe the typical aeration tank state. In essence, the

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FIGURE AI-4

COMPARISON OF CURVES TAKEN FROM FIGURES AI-2 AND AI-3

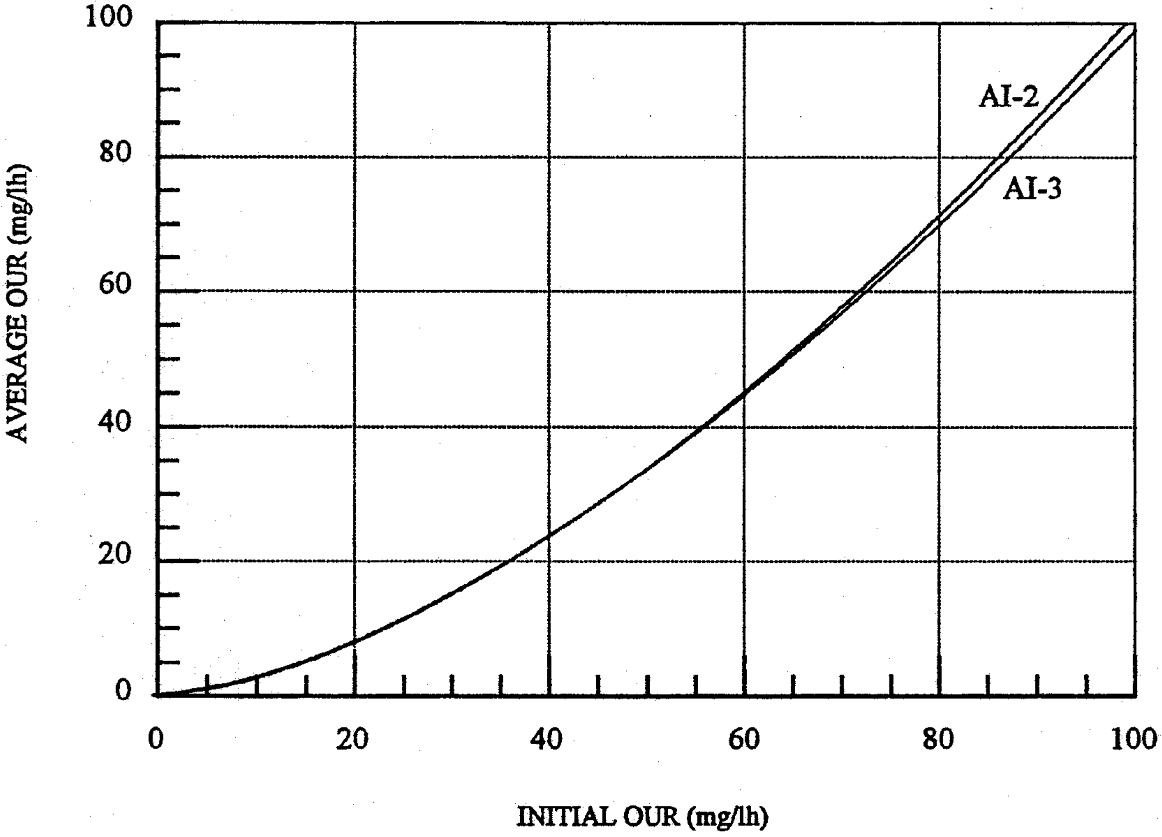

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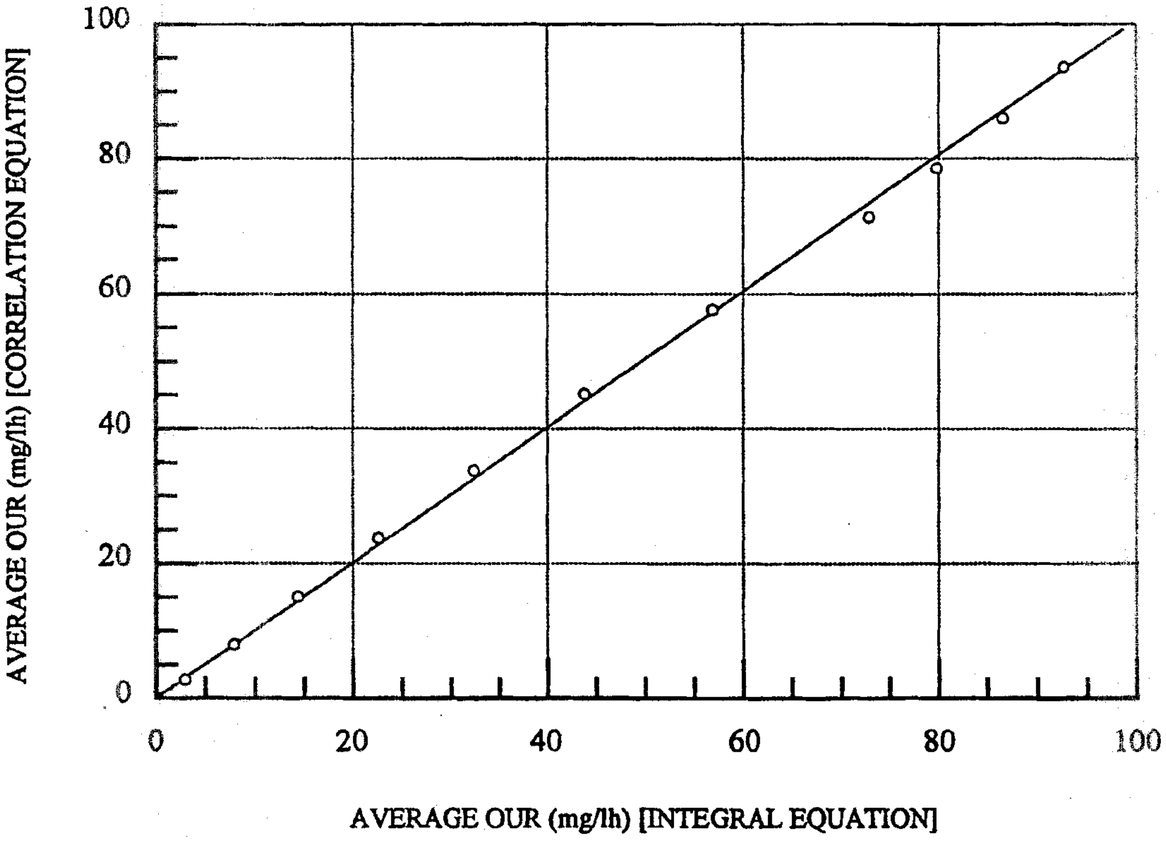
FIGURE AI-5

COMPARISON OF AVERAGE OUR VALUES TAKEN FROM THE CORRELATION EQUATION AND THE INTEGRAL EQUATION



profile curve shifts up and down (compressing and expanding) as the initial OUR (strength of incoming sewage) increases or decreases. As long as the plant operates within the boundaries of the plant design limits, such dynamic behavior will be observed. If circumstances arise which push plant variables beyond the plant design limits, then the general OUR function will no longer describe the situation. For example, if the flow increases beyond a certain threshold, the OUR profile curve will become a horizontal line over the length of the tank. A similar occurrence results if the strength of incoming sewage rises beyond a certain threshold; the OUR profile will again become a horizontal line. A third possibility is if the nature of the sewage matrix changes drastically so that the microbial population is not acclimated to it (or is contaminated by toxic elements) and cannot biodegrade it effectively within the plant design limits. Here again the shape of the OUR profile curve will change. However, when such stress conditions are no longer active, the aeration dynamics will reassert themselves to follow the shape of the general OUR profile function.

APPENDIX II

TEST PROTOCOLS

TEST PROTOCOL FOR REDUCING AIR SUPPLY TO TANK 1, BATTERY A AT THE JAMES C. KIRIE WRP RESPIROMETRY PROJECT
(REVISED MAY 20, 1998)

Objective

The objective of this protocol is to determine the minimum volume of air needed to nitrify the wastewater treated in Tank 1 of Battery A at the James C. Kirie WRP. This objective will be achieved by progressively reducing the air volume of air supplied to Tank 1 of Battery A in 5 percent increments until an effluent NH_4-N concentration of 5 mg/L (NH_4-N bleed-through) occurs from Tank 1 of Battery A.

Test Protocol

STEP 1: DAY 1 THROUGH 5

1. Utilize Tanks 1 and 2 of Battery A during this experiment. Use Tank 1 for generating respirometric information and Tank 2 as "control." It is critical to maintain similar conditions in both experimental Tank 1 and "control" Tank 2. To the best possible extent, maintain similar flows of raw sewage, return activated sludge (RAS), and air supply volume (per pass and total); and HRT, F:M, SVI, MLSS, MLVSS, and RAS SS in both Tanks 1 and 2.

Calibrate raw sewage, RAS, and air flow measuring devices for Tanks 1 and 2. Also calibrate DO probes in Tank 2. Monitor and maintain them periodically until the experiment is over.

Operate Tank 2 of Battery A with a continued aeration control using DO probes as before. In short, neither operational changes nor air reduction in Tank 2 of Battery A is required for this experiment.

However, as explained later, progressive reduction in air supply volume in passes 2 and 3 in Tank 1 will be made with reference to the air volume being supplied to passes 2 and 3 in Tank 2 of Battery A. Therefore, do not control aeration by using DO probes in Tank 1 of Battery A.

2. Record operational and analytical parameters such as raw sewage and RAS flows to Tanks 1 and 2; and HRT, F:M, SVI, MLSS, MLVSS, and RAS SS for Tanks 1 and 2. Also, record the air volume supplied to pass 1 and passes 2 and 3 of Tanks 1 and 2. Good operational and control measures should ensure similarity, including air volumes in both Tanks 1 and 2.

3. Collect influent and effluent samples (from aeration tanks) from both Tanks 1 and 2 for performing standard analytical tests such as total BOD, $CBOD_5$, COD, NH_4-N, NO_2+NO_3-N, TS, TSS, etc. Based on the analytical results of the samples collected, determine the treatment efficiency of Tanks 1 and 2 of Battery A daily with respect to BOD removal and nitrification.

4. Additionally, collect several samples of Tanks 1 and 2 effluent daily at predetermined intervals for ammonium nitrogen analysis. Split samples for the determination of ammonium nitrogen concentration at the John E. Egan WRP Laboratory and with the specific ion probe and meter.

   Also, obtain a profile of ammonium nitrogen along the length of Tanks 1 and 2 with the aid of a specific ion probe and meter.

5. Record ammonium nitrogen concentration of the combined final effluent of Battery A from the on-line ammonia analyzer. Compare the ammonium nitrogen concentration values recorded by the on-line ammonium nitrogen analyzer and those determined by the specific ion probe and meter

at the John E. Egan WRP Laboratory in samples collected as described in item 4.

STEP 2: DAY 6 THROUGH 10

1. Reduce the air supply in passes 2 and 3 of Tank 1 by 5 percent of the volume of air being supplied in passes 2 and 3 of Tank 2. Continue feeding the same air volume as described in step 1 to pass 1 of both Tanks 1 and 2.

   The 5 percent reduction in the air supply is made with reference to the volume of air being supplied to the passes 2 and 3 of Tank 2. Such reduction in air will not be applicable to pass 1 of Tank 1 of Battery A.

2. Repeat items 2 through 5 of step 1, and determine whether or not ammonia nitrogen concentration in Tank 1 is below the bleed-through concentration of 5 mg/L.

STEP 3: DAY 11 THROUGH 15

1. If the ammonia nitrogen concentration in the effluent of Tank 1 of Battery A does not exceed the bleed-through limit of 5 mg/L, reduce the air supply volume by another 5 percent (i.e., 10 percent of the volume of air being supplied in

passes 2 and 3 of Tank 2) in passes 2 and 3 of Tank 1 with reference to the air volume being supplied to passes 2 and 3 of Tank 2.

2. Repeat items 2 through 5 of step 1, and determine whether or not ammonia nitrogen concentration is below the bleed-through concentration of 5 mg/L.

Conducting the Study Beyond Step 3 and Under Special Conditions

Continue reducing air supply in passes 2 and 3 of Tank 1 in increments of 5 percent (i.e., 15, 20, 25 percent, etc., of the air supplied to passes 2 and 3 of Tank 2) until a bleed-through ammonium nitrogen concentration of 5 mg/L occurs in the effluent of Tank 1 of Battery A. Such stepwise and progressive reduction in air supply will eventually reveal the extent to which the air supply can be reduced without exceeding the bleed-through ammonium nitrogen concentration of 5.0 mg/L in the effluent of Tank 1 of Battery A.

Collect data under steady state conditions to determine whether or not nitrogen ammonia concentration in the effluent of Tank 1 remains below 5 mg/L during each step of progressive air reduction.

Increase the air supply in the second and third passes of Tank 1 if the ammonium nitrogen concentration in the effluent of Tank 1 of Battery A exceeds 5.0 mg/L at any time during progressive reduction of air to these tanks. However, if ammonium nitrogen concentration exceeds 5.0 mg/L in the effluent of Tank 1 due to the effect of an industrial waste discharge, procedure will be suspended until normal plant operations can resume.

Testing conducted during warm weather may exacerbate odors at the return sludge air lifts. If odors reach unacceptable levels, M&O will consult with R&D on suspension of testing. In any case, M&O reserves the right to suspend testing if odors reach unacceptable levels.

Under no circumstances, will the operation of Tank 1 of Battery A be permitted to jeopardize the NPDES ammonium nitrogen or BOD numerical limits.

APPENDIX III

DISSOLVED OXYGEN CONCENTRATIONS IN CONTROL AND EXPERIMENTAL TANKS

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AIII-1

DO PROFILE DATA OF CONTROL TANK (TANK 2) AT KIRIE WRP

TANK 2 (CONTROL TANK)																									
	DO, mg/L																								
	Distance, ft																								
Date	10	50	100	150	200	250	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700	725	750
7/14/98	1.55	1.28	1.3	1.2	0.98	5.2	5.72	5.26	4.99	4.27	5.37	5.05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
7/15/98	3.30	3.23	3.35	3.33	3.83	4.10	4.36	4.13	3.92	3.41	3.66	3.83	3.86	3.95	4.09	4.22	3.95	4.45	6.77	8.04	5.82	6.07	6.95	7.39	7.23
7/20/98	3.52	3.83	3.54	3.45	3.04	3.51	4.24	3.77	4.84	5.00	5.29	4.10	4.29	4.54	4.43	4.16	5.24	4.17	4.41	4.56	5.98	6.26	6.34	7.12	7.16
7/21/98	N/A																								
7/22/98	0.57	0.41	0.33	0.35	0.38	0.42	1.03	0.84	0.93	0.76	1.35	1.21	1.48	1.25	1.47	1.66	1.55	2.04	1.79	2.18	1.78	2.30	2.19	2.47	2.43
7/23/98	0.60	0.28	0.34	0.43	0.42	0.55	1.04	0.84	0.95	0.74	1.38	1.59	1.75	1.85	1.65	1.66	2.19	1.81	1.89	2.14	1.82	2.49	2.53	2.85	3.16
7/27/98	0.37	0.35	0.30	0.48	0.38	0.65	1.33	0.85	0.97	0.71	1.09	0.80	1.23	1.11	1.35	1.54	1.11	1.65	1.62	1.59	2.18	1.94	2.80	2.98	3.54
7/28/98	0.34	0.31	0.49	0.35	0.36	0.71	1.12	0.73	0.88	0.66	1.02	1.05	1.19	1.39	1.35	1.75	1.45	1.56	1.46	1.74	2.21	2.35	2.95	3.57	3.59
7/29/98	0.50	0.34	0.49	0.39	0.37	0.39	0.69	0.60	0.89	0.94	1.03	1.11	1.07	1.26	1.16	1.60	1.42	1.76	1.99	1.84	1.65	1.43	1.81	2.34	2.72
8/3/98	0.36		0.55		1.07		1.10		1.28		1.55		1.20		1.21	1.48	1.65	1.86	2.31	2.71	3.81	4.40	5.09	5.62	5.77
8/4/98	1.36	0.58	0.56	0.80	0.96	0.81	0.74	0.86	0.88	1.11	1.28	1.14	0.92	1.21	1.02	1.35	2.04	2.42	3.87	4.36	5.43	5.08	6.22	6.46	6.09
8/5/98	0.47	0.34	0.42	0.26	0.41	0.27	0.23	0.37	0.34	0.43	0.68	0.59	0.38	0.71	0.47	0.89	1.04	1.61	2.65	3.55	4.53	4.82	5.66	5.61	5.90
8/6/98	0.89	0.31	0.45	0.86	1.34	0.67	0.52	0.66	0.77	0.90	1.10	1.02	0.88	1.35	1.37	2.69	2.50	3.40	3.88	4.19	4.24	4.89	4.92	5.21	5.32
8/10/98	0.65	0.51	0.56	0.78	1.21	1.1	2.21	1.91	2.72	2.63	3.59	3.83	4.5	4.69	4.97	5.8	6.03	6.02	6.34	6.48	6.5	6.59	6.61	6.48	6.43
8/11/98	0.51	0.26	0.36	0.6	0.91	0.64	0.92	0.46	0.87	0.51	1.22	0.92	0.7	0.85	0.96	1.83	1.55	2.72	3.64	4.54	5.04	5.5	5.89	6.04	6.22
8/12/98	0.9	0.44	0.52	0.92	1.25	0.89	1.01	0.74	1.08	0.8	1.72	1.68	2.12	2.84	3.27	3.97	4.39	5.02	5.48	5.73	6.05	6.04	5.88	6.04	6.08
8/13/98	0.57	0.44	0.63	0.72	1.45	1.44	0.99	0.58	1.08	0.64	1.52	1.33	1.18	1.23	1.69	2.31	2.56	3.04	3.84	3.68	2.95	4.17	3.93	4.01	4.08
8/17/98	0.55	0.28	0.39	0.50	0.99	0.76	0.77	0.39	0.61	0.42	0.90	0.68	0.60	0.63	0.77	1.12	0.81	1.61	1.94	2.94	2.69	4.28	4.51	4.69	4.83
8/18/98	0.55	0.23	0.26	0.32	0.90	0.59	0.79	0.49	0.60	0.33	0.99	0.59	0.50	0.65	0.58	1.07	0.59	0.88	0.87	1.31	1.48	2.10	2.60	3.08	3.56
8/19/98	0.34	0.51	0.39	0.32	0.29	0.39	0.28	0.36	0.46	0.34	0.53	0.37	0.44	0.54	0.36	0.40	0.35	0.57	0.47	0.54	0.72	0.29	0.59	0.32	0.58
8/24/98	1.36	0.62	1.04	1.24	1.54	1.42	0.88	0.51	0.96	0.53	1.32	0.93	1.13	1.28	1.05	2.07	1.34	1.77	1.88	3.67	3.73	5.25	5.40	5.76	5.58
8/25/98	2.50	1.20	1.10	1.22	1.41	1.32	1.13	0.65	1.06	0.87	2.34	2.09	2.08	2.34	2.68	3.23	3.73	3.68	4.29	5.54	5.04	5.33	5.47	5.65	5.33
8/26/98	1.99	0.87	1.04	1.45	1.77	1.63	0.81	0.48	0.68	0.54	0.93	0.49	0.64	0.66	0.65	1.09	0.62	0.88	1.28	1.55	2.13	2.83	3.50	4.35	4.27
8/27/98	0.87	0.41	0.62	0.65	1.23	0.96	0.97	0.64	0.94	0.67	1.13	0.84	0.80	0.90	1.10	1.61	0.87	1.45	1.00	2.06	2.14	3.89	4.06	5.15	5.72
8/31/98	1.01	0.97	0.82	0.86	1.16	1.49	0.97	0.86	0.82	0.60	1.29	0.90	0.99	1.01	1.07	1.51	1.21	1.92	1.30	2.82	3.22	3.89	4.12	4.75	4.87
9/1/98	1.17	0.94	0.62	0.88	1.05	0.91	0.51	1.35	1.08	0.94	0.88	0.57	0.80	0.67	0.49	0.89	0.76	1.17	0.95	1.19	1.20	1.76	2.02	2.86	3.13
9/2/98	0.69	0.43	0.40	0.65	1.09	0.81	0.77	0.58	0.56	0.41	0.89	0.52	0.52	0.73	0.68	0.86	1.02	0.69	1.16	1.14	1.87	2.4	2.9	3.48	3.74
9/3/98	0.74	0.53	0.66	0.54	0.99	0.87	0.89	0.41	0.47	0.37	0.84	0.69	0.59	0.77	0.58	0.82	0.69	0.63	0.99	1.04	1.76	2.07	2.79	3.39	3.78
9/4/98	1.10	0.88	0.74	0.69	0.85	0.93	0.67	0.46	0.63	0.39	0.70	0.52	0.58	0.78	0.62	0.86	0.60	1.01	0.64	1.06	1.31	2.41	2.76	3.37	3.46
9/5/98																									
9/6/98																									
9/7/98																									
9/8/98	1.34	0.76	1.01	1.44	1.82	1.58	0.93	0.69	0.77	0.55	0.99	0.69	0.76	0.89	0.98	1.64	1.84	2.4	3.22	3.92	4.19	4.97	5.64	6.13	5.38
9/9/98	0.57	0.54	0.43	0.66	0.99	0.72	0.7	0.49	0.62	0.5	0.86	0.61	1.21	0.84	0.86	1.45	0.88	1.13	1.25	1.61	2.25	2.62	3.24	4.23	3.7
9/10/98	0.78	0.82	0.51	0.8	0.98	0.99	0.56	0.5	0.5	0.45	0.81	0.57	0.53	0.67	0.72	1.12	0.76	1.39	0.94	1.62	1.86	2.16	2.47	2.67	2.82
9/11/98	0.59	0.46	0.35	0.45	0.89	0.69	0.68	0.46	0.60	0.56	0.88	0.95	0.93	0.89	0.86	1.26	1.42	1.33	1.87	1.94	2.68	2.75	2.88	3.33	3.05
9/12/98																									
9/13/98																									
9/14/98	1.73	1.25	0.87	0.95	1.16	1.31	1.01	0.82	0.75	0.58	1.21	1.04	0.98	0.86	1.21	1.74	1.44	2.21	2.60	3.39	3.98	4.82	4.92	5.32	5.25
9/15/98	1.31	0.78	0.55	0.60	0.85	1.16	0.65	0.82	0.77	0.89	1.19	0.93	1.05	0.71	0.99	1.68	1.70	2.49	2.66	3.08	3.27	3.73	4.03	4.14	4.13
9/16/98	0.69	0.55	0.63	0.86	1.22	0.93	0.48	0.65	0.77	0.84	0.99	1.17	1.14	0.78	0.98	1.20	1.46	1.33	1.71	1.97	2.32	2.41	2.60	2.73	2.68
9/17/98	0.98	0.71	0.74	0.80	1.12	1.06	0.68	0.88	0.72	1.16	1.18	1.34	0.99	0.87	1.22	1.63	1.27	1.77	1.59	2.04	2.09	2.68	2.61	3.16	3.04
9/18/98																									
9/19/98																									
9/20/98																									
9/21/98	0.54	0.46	0.55	1.15	1.65	1.41	0.83	0.61	0.81	0.65	1.42	1.14	1.09	1.05	1.24	1.67	1.88	2.24	2.99	3.31	4.19	4.61	4.97	5.18	4.97
9/22/98	0.61	0.59	0.57	0.85	1.02	0.87	0.74	0.67	0.90	0.76	1.28	1.31	1.17	1.23	1.15	1.48	1.73	1.63	2.12	2.28	2.75	3.15	3.38	3.50	3.56
9/23/98	0.75	0.38	0.42	0.54	0.46	0.62	0.53	0.37	0.58	0.39	0.85	0.65	0.83	0.74	0.76	1.34	1.04	1.22	1.10	1.68	2.23	2.28	2.21	2.59	2.38
9/24/98	0.67	0.45	0.42	0.70	0.71	0.52	0.84	0.35	0.64	0.56	1.01	0.88	0.85	0.81	0.98	1.39	1.34	1.38	1.70	2.09	2.46	2.82	2.75	2.80	2.41

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TABLE AIII-2

DO PROFILE DATA OF EXPERIMENTAL TANK (TANK 1) AT KIRIE WRP

TANK 1 (EXPERIMENTAL TANK)																									
	DO, mg/L																								
	Distance, ft																								
Date	10	50	100	150	200	250	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700	725	750
7/14/98	1.18	1.11	1.53	1.45	1.48	1.4	1.87	1.52	1.74	2.01	2.18	2.02	1.77	1.95	1.79	2.36	2.4	2.5	2.6	2.68	2.69	3.06	3.66	4.1	5.06
7/15/98	4.90	4.21	3.70	3.40	3.43	3.50	3.58	3.62	3.34	4.01	3.76	3.75	4.00	3.54	3.73	4.12	3.88	4.10	4.15	4.37	4.45	4.72	5.42	5.83	6.11
7/20/98	5.01	5.08	5.24	5.04	4.74	4.59	4.93	5.27	6.04	6.18	6.22	6.31	6.72	7.05	7.00	7.56	7.87	8.07	8.25	8.52	8.43	8.20	9.65	9.04	9.09
7/21/98	5.28	5.50	5.63	4.59	4.70	4.51	6.85	5.72	3.28	6.52	6.28	6.19	7.12	3.77	3.85	6.00	5.95	4.10	7.35	7.16	6.85	7.05	7.31	7.52	7.58
7/22/98	0.40	0.55	0.35	0.53	0.35	0.41	0.95	1.22	1.23	2.14	1.85	2.18	2.26	2.38	2.22	2.83	3.16	3.97	4.30	4.86	5.17	5.38	5.84	5.97	6.23
7/23/98	0.74	0.61	0.41	0.56	0.71	0.72	1.45	1.34	1.99	1.89	2.23	2.07	2.64	2.71	2.83	2.99	3.24	3.64	4.10	4.08	4.06	4.28	4.78	4.85	5.29
7/27/98	0.85	0.64	0.47	0.63	0.75	0.90	0.89	0.70	1.11	1.13	1.01	1.22	1.03	1.41	1.25	1.88	1.77	2.54	3.00	3.62	3.89	4.30	4.68	5.00	5.30
7/28/98	0.60	0.41	0.64	0.71	0.82	0.83	0.85	0.82	1.27	1.09	1.33	1.17	1.39	1.50	1.42	1.83	1.45	1.84	1.99	2.01	1.94	2.08	2.60	3.06	3.59
7/29/98	0.40	0.37	0.31	0.35	0.59	0.61	0.75	0.60	0.92	0.51	1.11	0.81	1.17	1.18	1.26	1.57	1.32	1.77	1.30	1.86	1.75	2.52	3.06	3.39	3.34
8/3/98	0.37		0.46		0.72		1.00		1.37		1.26		1.17		1.37	1.52	1.32	1.51	1.55	1.84	1.90	2.31	2.81	3.38	3.81
8/4/98	0.67	0.55	0.75	1.05	0.84	0.87	0.56	0.58	0.74	0.85	0.63	0.67	0.69	0.97	0.71	1.21	0.88	0.83	1.04	1.03	0.79	0.71	0.78	0.80	1.19
8/5/98	0.49	0.38	0.34	0.30	0.28	0.32	0.29	0.29	0.45	0.27	0.54	0.31	0.47	0.68	0.65	0.76	0.54	0.81	0.81	1.10	0.74	0.85	0.70	0.66	0.88
8/6/98	0.69	0.77	0.81	0.88	0.96	0.90	0.62	0.59	0.56	0.63	0.70	0.41	0.53	0.58	0.60	0.93	0.57	0.70	0.58	0.82	0.67	0.81	0.45	0.72	0.50
8/10/98	0.57	0.69	0.72	0.95	0.83	1	0.8	0.83	0.8	0.88	1.09	1.05	0.88	1.16	0.92	1.31	0.88	1.22	1.35	1.42	1.16	0.85	0.88	0.95	1.05
8/11/98	0.49	0.69	0.56	0.8	0.6	0.65	0.52	0.5	0.59	0.65	0.63	0.56	0.81	0.74	0.69	1.02	0.58	0.79	0.88	0.96	0.65	0.63	0.66	0.5	0.77
8/12/98	0.77	0.55	0.88	1.12	1.05	0.9	0.46	0.5	0.7	0.55	0.76	0.54	0.63	0.84	0.65	0.99	0.64	1.04	1.05	1.46	1.51	1.84	1.99	2.21	2.77
8/13/98	0.67	0.55	0.61	0.78	0.71	0.82	0.46	0.35	0.63	0.55	0.50	0.58	0.43	0.61	0.38	0.71	0.35	0.82	0.77	0.88	0.49	0.53	0.31	0.51	0.55
8/17/98	0.51	0.45	0.65	0.79	0.55	0.74	0.46	0.43	0.70	0.77	0.73	0.54	0.57	0.87	0.60	1.11	0.74	0.73	0.92	0.74	0.86	0.46	0.68	0.49	0.80
8/18/98	0.35	0.40	0.36	0.42	0.50	0.57	0.48	0.39	0.57	0.49	0.65	0.42	0.51	0.63	0.52	0.73	0.43	0.53	0.60	0.56	0.47	0.44	0.41	0.52	0.54
8/19/98	0.28	0.18	0.22	0.31	0.84	0.51	0.53	0.32	0.44	0.36	0.76	0.40	0.48	0.50	0.48	0.99	0.54	0.62	0.98	1.11	1.62	1.93	2.56	2.99	3.08
8/24/98	0.90	1.30	1.01	0.85	0.96	1.33	0.65	0.74	0.88	0.95	1.20	0.99	1.07	1.20	1.15	1.22	0.94	1.27	1.20	1.51	1.55	1.31	1.22	1.13	1.63
8/25/98	0.89	0.76	0.83	0.81	0.86	1.20	0.62	0.69	0.85	0.96	1.26	1.31	1.48	1.60	1.58	2.70	2.61	2.92	3.05	5.22	5.20	4.74	4.82	4.70	4.71
8/26/98	1.19	1.41	1.52	1.49	1.13	1.07	0.79	0.65	0.75	0.81	0.55	0.64	0.60	0.77	0.84	0.76	0.57	0.72	0.56	0.67	0.82	0.52	0.77	0.59	0.97
8/27/98	0.72	0.78	0.84	0.73	0.84	0.93	0.98	0.82	0.96	1.14	0.74	1.15	0.71	1.08	1.13	1.42	0.94	1.26	1.27	1.38	1.51	0.84	1.06	0.91	1.52
8/31/98	0.95	0.86	0.84	0.79	1.05	1.12	0.60	0.72	0.60	0.94	0.79	0.68	0.72	1.00	0.80	1.03	0.67	0.68	0.81	0.56	0.64	0.61	0.92	0.45	0.64
9/1/98	0.44	0.51	0.42	0.37	0.36	0.54	0.43	0.38	0.63	0.89	0.78	0.53	0.59	0.60	0.41	0.55	0.31	0.49	0.95	0.89	0.75	0.53	0.90	0.80	0.76
9/2/98	0.69	0.32	0.31	0.43	0.30	0.67	0.30	0.42	0.55	0.34	0.44	0.49	0.33	0.57	0.50	0.70	0.35	0.50	0.54	0.29	0.49	0.37	0.49	0.46	0.67
9/3/98	0.42	0.31	0.27	0.20	0.38	0.48	0.35	0.37	0.49	0.45	0.39	0.40	0.33	0.43	0.46	0.56	0.40	0.47	0.54	0.40	0.61	0.36	0.37	0.49	0.43
9/4/98	0.50	0.48	0.40	0.37	0.42	0.62	0.41	0.36	0.62	0.43	0.50	0.53	0.56	0.65	0.57	0.73	0.51	0.64	0.85	0.77	1.00	0.52	0.71	0.40	0.70
9/5/98																									
9/6/98																									
9/7/98																									
9/8/98	0.86	0.91	1.05	1	1.04	1.55	0.88	0.69	1.02	1.13	1.13	1.14	1.79	1.35	1.13	1.23	0.69	0.97	1.3	1.51	1.47	1.24	1.07	1.79	1.85
9/9/98	0.35	0.22	0.33	0.31	0.24	0.43	0.28	0.38	0.61	0.59	0.57	0.53	0.72	0.72	0.67	0.68	0.57	0.73	0.87	0.66	0.53	0.54	0.58	0.5	0.67
9/10/98	0.21	0.32	0.25	0.29	0.41	0.46	0.31	0.3	0.44	0.46	0.5	0.47	0.3	0.52	0.45	0.67	0.43	0.78	0.75	0.66	0.8	0.45	0.72	0.56	0.62
9/11/98	0.34	0.42	0.30	0.31	0.34	0.38	0.29	0.31	0.35	0.41	0.38	0.40	0.23	0.66	0.54	0.66	0.63	0.78	0.83	0.69	0.58	0.46	0.49	0.65	0.39
9/12/98																									
9/13/98																									
9/14/98	0.84	0.88	0.70	0.66	0.73	0.97	0.66	0.65	0.63	0.74	0.60	0.69	0.86	0.91	0.97	0.61	0.92	1.08	0.99	1.12	0.89	0.63	0.54	0.80	0.72
9/15/98	0.88	0.93	0.67	0.80	0.76	0.94	0.96	0.58	0.73	0.69	0.90	0.69	0.86	0.78	0.83	0.99	0.92	1.03	1.00	1.25	1.46	1.16	1.54	1.35	1.32
9/16/98	0.28	0.26	0.34	0.53	0.40	0.96	0.49	0.45	0.79	0.86	0.93	1.03	0.92	1.21	1.08	1.85	0.70	1.03	0.81	1.09	1.16	0.69	0.79	0.84	0.82
9/17/98	0.43	0.53	0.64	0.49	0.52	0.77	0.55	0.49	0.74	0.77	0.88	0.64	0.65	0.84	0.95	0.93	0.65	0.89	0.93	0.84	1.11	0.65	0.60	0.82	0.79
9/18/98																									
9/19/98																									
9/20/98																									
9/21/98	0.42	0.32	0.28	0.56	0.41	0.65	0.46	0.40	0.81	0.83	1.02	0.84	1.08	1.09	1.37	1.43	1.26	1.53	1.44	1.55	1.83	1.11	1.16	1.09	1.10
9/22/98	0.39	0.45	0.39	0.32	0.40	0.58	0.50	0.48	0.65	0.45	0.68	0.46	0.69	0.58	0.75	0.84	0.68	0.89	1.03	0.84	0.86	0.81	0.47	0.73	0.71
9/23/98	0.34	0.27	0.29	0.39	0.38	0.41	0.38	0.33	0.49	0.54	0.57	0.53	0.49	0.71	0.69	0.74	0.46	0.75	0.97	0.88	0.96	0.62	0.61	0.71	0.53
9/24/98	0.83	0.62	0.68	0.85	0.65	0.97	1.10	0.94	1.68	1.57	1.56	1.50	1.53	1.69	1.89	1.79	1.35	1.88	1.71	1.57	1.80	1.49	1.51	1.06	1.56

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AIII-3

EXPERIMENTAL AND CONTROL TANKS DO PROFILE DATA SORTED BY PERCENT AIR REDUCTION

													DO, mg/L												
													Distance, ft												
Date	% Air Reduction	10	50	100	150	200	250	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700	725	750
7/28/98	3.43	0.60	0.41	0.64	0.71	0.82	0.83	0.85	0.82	1.27	1.09	1.33	1.17	1.39	1.50	1.42	1.83	1.45	1.84	1.99	2.01	1.94	2.08	2.60	3.06	3.59
9/15/98	5.05	0.88	0.93	0.67	0.80	0.78	0.94	0.96	0.58	0.73	0.69	0.90	0.69	0.86	0.78	0.83	0.99	0.92	1.03	1.00	1.25	1.46	1.16	1.54	1.35	1.32
9/17/98	5.15	0.43	0.53	0.64	0.49	0.52	0.77	0.55	0.49	0.74	0.77	0.88	0.64	0.65	0.84	0.95	0.93	0.65	0.88	0.93	0.84	1.11	0.65	0.60	0.82	0.79
AVG	4.54	0.64	0.62	0.65	0.67	0.70	0.85	0.79	0.63	0.91	0.85	1.04	0.83	0.97	1.04	1.07	1.25	1.01	1.25	1.31	1.37	1.50	1.30	1.58	1.74	1.90

													DO, mg/L												
													Distance, ft												
Date	% Air Reduction	10	50	100	150	200	250	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700	725	750
7/28/98	0.00	0.34	0.31	0.49	0.35	0.38	0.71	1.12	0.73	0.88	0.66	1.02	1.05	1.19	1.39	1.35	1.75	1.45	1.56	1.46	1.74	2.21	2.35	2.95	3.57	3.59
9/15/98	0.00	1.31	0.76	0.55	0.60	0.85	1.16	0.65	0.82	0.77	0.89	1.19	0.93	1.05	0.71	0.99	1.68	1.70	2.49	2.66	3.08	3.27	3.73	4.03	4.14	4.13
9/17/98	0.00	0.98	0.71	0.74	0.80	1.12	1.06	0.68	0.88	0.72	1.16	1.18	1.34	0.99	0.87	1.22	1.63	1.27	1.77	1.59	2.04	2.09	2.68	2.61	3.16	3.04
AVG	0.00	0.88	0.60	0.59	0.58	0.78	0.98	0.82	0.81	0.79	0.90	1.13	1.11	1.08	0.99	1.19	1.69	1.47	1.94	1.90	2.29	2.52	2.92	3.20	3.62	3.59

													DO, mg/L												
													Distance, ft												
Date	% Air Reduction	10	50	100	150	200	250	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700	725	750
9/21/98	6.65	0.42	0.32	0.28	0.56	0.41	0.85	0.46	0.40	0.81	0.83	1.02	0.84	1.06	1.09	1.37	1.43	1.26	1.53	1.44	1.55	1.83	1.11	1.16	1.09	1.10
8/24/98	7.59	0.90	1.30	1.01	0.85	0.96	1.33	0.65	0.74	0.88	0.95	1.20	0.99	1.07	1.20	1.15	1.22	0.94	1.27	1.20	1.51	1.55	1.31	1.22	1.13	1.83
8/17/98	7.67	0.51	0.45	0.65	0.79	0.55	0.74	0.46	0.43	0.70	0.77	0.73	0.54	0.57	0.87	0.60	1.11	0.74	0.73	0.92	0.74	0.86	0.46	0.68	0.49	0.80
9/22/98	7.69	0.39	0.45	0.39	0.32	0.40	0.58	0.50	0.48	0.65	0.45	0.66	0.48	0.69	0.58	0.75	0.84	0.68	0.89	1.03	0.84	0.86	0.81	0.47	0.73	0.71
8/19/98	10.12	0.28	0.18	0.22	0.31	0.84	0.51	0.53	0.32	0.44	0.36	0.76	0.40	0.48	0.50	0.48	0.99	0.54	0.62	0.98	1.11	1.62	1.93	2.56	2.99	3.08
8/18/98	10.14	0.35	0.40	0.36	0.42	0.50	0.57	0.48	0.39	0.57	0.49	0.65	0.42	0.51	0.63	0.52	0.73	0.43	0.53	0.60	0.56	0.47	0.44	0.41	0.52	0.54
AVG	8.31	0.48	0.52	0.49	0.54	0.61	0.73	0.51	0.46	0.68	0.64	0.84	0.61	0.73	0.81	0.81	1.05	0.77	0.93	1.03	1.05	1.20	1.01	1.08	1.16	1.31

													DO, mg/L												
													Distance, ft												
Date	% Air Reduction	10	50	100	150	200	250	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700	725	750
9/21/98	0.00	0.54	0.46	0.55	1.15	1.65	1.41	0.83	0.61	0.81	0.65	1.42	1.14	1.09	1.05	1.24	1.67	1.88	2.24	2.99	3.31	4.19	4.61	4.97	5.18	4.97
8/24/98	0.00	1.38	0.62	1.04	1.24	1.54	1.42	0.88	0.51	0.98	0.53	1.32	0.93	1.13	1.28	1.05	2.07	1.34	1.77	1.88	3.67	3.73	5.25	5.40	5.76	5.58
8/17/98	0.00	0.55	0.28	0.39	0.50	0.99	0.76	0.77	0.39	0.61	0.42	0.90	0.68	0.80	0.63	0.77	1.12	0.81	1.61	1.94	2.94	2.69	4.28	4.51	4.69	4.83
9/22/98	0.00	0.61	0.59	0.57	0.85	1.02	0.87	0.74	0.67	0.90	0.76	1.28	1.31	1.17	1.23	1.15	1.48	1.73	1.63	2.12	2.28	2.75	3.15	3.38	3.50	3.56
8/19/98	0.00	0.34	0.51	0.39	0.32	0.29	0.39	0.28	0.36	0.46	0.34	0.53	0.37	0.44	0.54	0.36	0.40	0.35	0.57	0.47	0.54	0.72	0.29	0.59	0.32	0.58
8/18/98	0.00	0.55	0.23	0.26	0.32	0.90	0.59	0.79	0.49	0.60	0.33	0.99	0.59	0.50	0.65	0.56	1.07	0.59	0.88	0.87	1.31	1.48	2.10	2.60	3.08	3.56
AVG	0.00	0.66	0.45	0.53	0.73	1.07	0.91	0.72	0.51	0.72	0.51	1.07	0.84	0.82	0.90	0.86	1.30	1.12	1.45	1.71	2.34	2.59	3.28	3.58	3.76	3.85

													DO, mg/L												
													Distance, ft												
Date	% Air Reduction	10	50	100	150	200	250	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700	725	750
9/16/98	12.26	0.26	0.26	0.34	0.53	0.40	0.96	0.49	0.45	0.79	0.86	0.93	1.03	0.92	1.21	1.08	1.85	0.70	1.03	0.81	1.09	1.16	0.69	0.79	0.84	0.82
9/3/98	12.80	0.42	0.31	0.27	0.20	0.38	0.48	0.35	0.37	0.49	0.45	0.39	0.40	0.33	0.43	0.46	0.56	0.40	0.47	0.54	0.40	0.61	0.36	0.37	0.49	0.43
8/4/98	13.96	0.67	0.55	0.75	1.05	0.84	0.87	0.56	0.58	0.74	0.85	0.63	0.67	0.69	0.97	0.71	1.21	0.88	0.83	1.04	1.03	0.79	0.71	0.78	0.60	1.19
AVG	13.01	0.45	0.37	0.45	0.59	0.54	0.77	0.47	0.47	0.67	0.72	0.65	0.70	0.65	0.87	0.75	1.21	0.66	0.78	0.80	0.84	0.85	0.59	0.65	0.71	0.81

METROPOLITAN WATER RECLAMATION DISTRICT OF GREATER CHICAGO

TABLE AIII-3 (Continued)

EXPERIMENTAL AND CONTROL TANKS DO PROFILE DATA SORTED BY PERCENT AIR REDUCTION

														DO, mg/L Distance, ft												
Date	% Air Reduction	10	50	100	150	200	250	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700	725	750
9/16/98	0.00	0.69	0.55	0.63	0.86	1.22	0.93	0.48	0.65	0.77	0.84	0.99	1.17	1.14	0.78	0.98	1.20	1.46	1.33	1.71	1.97	2.32	2.41	2.60	2.73	2.68
9/3/98	0.00	0.74	0.53	0.66	0.54	0.99	0.87	0.89	0.41	0.47	0.37	0.84	0.89	0.59	0.77	0.58	0.82	0.69	0.63	0.99	1.04	1.76	2.07	2.79	3.39	3.78
8/4/98	0.00	1.36	0.58	0.56	0.80	0.96	0.81	0.74	0.86	0.88	1.11	1.28	1.14	0.92	1.21	1.02	1.35	2.04	2.42	3.87	4.36	5.43	5.08	6.22	6.46	6.09
AVG	0.00	0.93	0.55	0.62	0.73	1.06	0.87	0.70	0.64	0.71	0.77	1.04	1.00	0.88	0.92	0.86	1.12	1.40	1.46	2.19	2.46	3.17	3.19	3.87	4.19	4.16

														DO, mg/L Distance, ft												
Date	% Air Reduction	10	50	100	150	200	250	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700	725	750
8/25/98	17.31	0.69	0.76	0.83	0.81	0.86	1.20	0.62	0.69	0.85	0.96	1.26	1.31	1.48	1.60	1.58	2.70	2.61	2.92	3.05	5.22	5.20	4.74	4.62	4.70	4.71
9/14/98	18.65	0.84	0.88	0.70	0.66	0.73	0.97	0.66	0.65	0.63	0.74	0.60	0.69	0.86	0.91	0.97	0.61	0.92	1.08	0.99	1.12	0.89	0.63	0.54	0.80	0.72
9/11/98	18.93	0.34	0.42	0.30	0.31	0.34	0.38	0.29	0.31	0.35	0.41	0.38	0.40	0.23	0.66	0.54	0.66	0.63	0.78	0.83	0.69	0.58	0.46	0.49	0.65	0.39
9/10/98	19.11	0.21	0.32	0.25	0.29	0.41	0.46	0.31	0.3	0.44	0.46	0.5	0.47	0.3	0.52	0.45	0.67	0.43	0.78	0.75	0.66	0.8	0.45	0.72	0.56	0.62
9/9/98	19.13	0.35	0.22	0.33	0.31	0.24	0.43	0.26	0.38	0.61	0.59	0.57	0.53	0.72	0.72	0.67	0.68	0.57	0.73	0.87	0.66	0.53	0.54	0.58	0.5	0.67
AVG	18.63	0.53	0.52	0.48	0.48	0.52	0.69	0.43	0.47	0.58	0.63	0.66	0.68	0.72	0.88	0.84	1.06	1.03	1.26	1.30	1.67	1.60	1.36	1.43	1.44	1.42

														DO, mg/L Distance, ft												
Date	% Air Reduction	10	50	100	150	200	250	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700	725	750
8/25/98	0.00	2.50	1.20	1.10	1.22	1.41	1.32	1.13	0.65	1.06	0.87	2.34	2.09	2.08	2.34	2.68	3.23	3.73	3.68	4.29	5.54	5.04	5.33	5.47	5.65	5.33
9/14/98	0.00	1.73	1.25	0.67	0.95	1.16	1.31	1.01	0.62	0.75	0.58	1.21	1.04	0.98	0.86	1.21	1.74	1.44	2.21	2.60	3.39	3.98	4.82	4.92	5.32	5.25
9/11/98	0.00	0.59	0.46	0.35	0.45	0.89	0.69	0.68	0.46	0.60	0.56	0.88	0.95	0.93	0.89	0.86	1.26	1.42	1.33	1.67	1.94	2.68	2.75	2.88	3.33	3.05
9/10/98	0.00	0.76	0.82	0.51	0.8	0.98	0.99	0.56	0.5	0.5	0.45	0.81	0.57	0.53	0.67	0.72	1.12	0.76	1.39	0.94	1.62	1.86	2.16	2.47	2.67	2.82
9/9/98	0.00	0.57	0.54	0.43	0.66	0.99	0.72	0.7	0.49	0.62	0.5	0.86	0.61	1.21	0.84	0.86	1.45	0.88	1.13	1.25	1.61	2.25	2.62	3.24	4.23	3.7
AVG	0.00	1.23	0.85	0.65	0.82	1.09	1.01	0.82	0.54	0.71	0.59	1.22	1.05	1.15	1.12	1.27	1.76	1.65	1.95	2.19	2.82	3.16	3.54	3.80	4.24	4.03

														DO, mg/L Distance, ft												
Date	% Air Reduction	10	50	100	150	200	250	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700	725	750
8/27/98	23.63	0.72	0.78	0.84	0.73	0.64	0.93	0.98	0.82	0.96	1.14	0.74	1.15	0.71	1.08	1.13	1.42	0.94	1.26	1.27	1.38	1.51	0.84	1.06	0.91	1.52
8/31/98	24.76	0.95	0.86	0.84	0.79	1.05	1.12	0.60	0.72	0.60	0.94	0.79	0.68	0.72	1.00	0.80	1.03	0.67	0.68	0.81	0.56	0.64	0.61	0.92	0.45	0.64
9/1/98	25.00	0.44	0.51	0.42	0.37	0.36	0.54	0.43	0.38	0.63	0.89	0.78	0.53	0.59	0.60	0.41	0.55	0.31	0.49	0.95	0.89	0.75	0.53	0.90	0.80	0.76
AVG	24.46	0.70	0.72	0.70	0.63	0.75	0.86	0.67	0.64	0.73	0.99	0.77	0.79	0.67	0.89	0.78	1.00	0.64	0.81	1.01	0.94	0.97	0.66	0.96	0.72	0.97

														DO, mg/L Distance, ft												
Date	% Air Reduction	10	50	100	150	200	250	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700	725	750
8/27/98	0.00	0.87	0.41	0.62	0.65	1.23	0.96	0.97	0.64	0.94	0.67	1.13	0.84	0.80	0.90	1.10	1.61	0.87	1.45	1.00	2.06	2.14	3.89	4.06	5.15	5.72
8/31/98	0.00	1.01	0.97	0.82	0.86	1.16	1.49	0.97	0.86	0.82	0.60	1.29	0.90	0.99	1.01	1.07	1.51	1.21	1.92	1.30	2.82	3.22	3.89	4.12	4.75	4.87
9/1/98	0.00	1.17	0.94	0.62	0.88	1.05	0.91	0.51	1.35	1.08	0.94	0.88	0.57	0.80	0.67	0.49	0.89	0.76	1.17	0.95	1.19	1.20	1.76	2.02	2.86	3.13
AVG	0.00	1.02	0.77	0.69	0.80	1.15	1.12	0.82	0.95	0.95	0.74	1.10	0.77	0.86	0.86	0.89	1.34	0.95	1.51	1.08	2.02	2.19	3.18	3.40	4.25	4.57

														DO, mg/L Distance, ft												
Date	% Air Reduction	10	50	100	150	200	250	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700	725	750
8/26/98	26.07	1.19	1.41	1.52	1.49	1.13	1.07	0.79	0.65	0.75	0.81	0.55	0.64	0.60	0.77	0.84	0.76	0.57	0.72	0.56	0.67	0.82	0.52	0.77	0.59	0.97
9/2/98	26.52	0.69	0.32	0.31	0.43	0.30	0.67	0.30	0.42	0.55	0.34	0.44	0.49	0.33	0.57	0.50	0.70	0.35	0.50	0.54	0.29	0.49	0.37	0.49	0.46	0.67
AVG	26.30	0.94	0.87	0.92	0.96	0.72	0.87	0.55	0.54	0.65	0.58	0.50	0.57	0.47	0.67	0.67	0.73	0.46	0.61	0.55	0.48	0.66	0.45	0.63	0.53	0.62

TABLE AIII-3 (Continued)

EXPERIMENTAL AND CONTROL TANKS DO PROFILE DATA SORTED BY PERCENT AIR REDUCTION

		DO, mg/L Distance, ft																								
Date	% Air Reduction	10	50	100	150	200	250	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700	725	750
8/26/98	0.00	1.99	0.87	1.04	1.45	1.77	1.63	0.81	0.48	0.68	0.54	0.93	0.49	0.64	0.66	0.65	1.09	0.62	0.88	1.28	1.55	2.13	2.83	3.50	4.35	4.27
9/2/98	0.00	0.69	0.43	0.40	0.65	1.09	0.81	0.77	0.58	0.56	0.41	0.89	0.52	0.52	0.73	0.68	0.86	1.02	0.69	1.16	1.14	1.87	2.4	2.9	3.48	3.74
AVG	0.00	1.34	0.65	0.72	1.05	1.43	1.22	0.79	0.53	0.62	0.48	0.91	0.51	0.58	0.70	0.67	0.98	0.82	0.79	1.22	1.35	2.00	2.62	3.20	3.92	4.01

		DO, mg/L Distance, ft																								
Date	% Air Reduction	10	50	100	150	200	250	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700	725	750
8/5/98	31.63	0.49	0.38	0.34	0.30	0.28	0.32	0.29	0.29	0.45	0.27	0.54	0.31	0.47	0.68	0.65	0.76	0.54	0.81	0.81	1.10	0.74	0.85	0.70	0.66	0.88
8/10/98	35.14	0.57	0.69	0.72	0.96	0.83	1	0.8	0.83	0.8	0.88	1.09	1.06	0.88	1.16	0.92	1.31	0.88	1.22	1.35	1.42	1.16	0.85	0.88	0.95	1.05
AVG	33.39	0.53	0.54	0.53	0.63	0.56	0.66	0.55	0.56	0.63	0.58	0.82	0.68	0.68	0.92	0.79	1.04	0.71	1.02	1.08	1.26	0.95	0.85	0.79	0.81	0.97

		DO, mg/L Distance, ft																								
Date	% Air Reduction	10	50	100	150	200	250	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700	725	750
8/5/98	0.00	0.47	0.34	0.42	0.26	0.41	0.27	0.23	0.37	0.34	0.43	0.68	0.59	0.38	0.71	0.47	0.89	1.04	1.61	2.65	3.55	4.53	4.82	5.66	5.61	5.90
8/10/98	0.00	0.65	0.51	0.58	0.78	1.21	1.1	2.21	1.91	2.72	2.63	3.59	3.83	4.5	4.69	4.97	5.8	6.03	6.02	6.34	6.48	6.5	6.59	6.61	6.48	6.43
AVG	0.00	0.56	0.43	0.50	0.52	0.81	0.69	1.22	1.14	1.53	1.53	2.14	2.21	2.44	2.70	2.72	3.35	3.54	3.82	4.50	5.02	5.52	5.71	6.14	6.05	6.17

		DO, mg/L Distance, ft																								
Date	% Air Reduction	10	50	100	150	200	250	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700	725	750
8/11/98	36.17	0.49	0.69	0.56	0.8	0.6	0.65	0.52	0.5	0.59	0.65	0.63	0.56	0.81	0.74	0.69	1.02	0.58	0.79	0.88	0.96	0.65	0.83	0.66	0.5	0.77
8/12/98	36.63	0.77	0.55	0.88	1.12	1.05	0.9	0.46	0.5	0.7	0.55	0.76	0.54	0.63	0.84	0.65	0.99	0.64	1.04	1.05	1.46	1.51	1.84	1.99	2.21	2.77
8/13/98	37.65	0.67	0.55	0.61	0.78	0.71	0.82	0.46	0.35	0.63	0.55	0.50	0.58	0.43	0.61	0.38	0.71	0.35	0.82	0.77	0.88	0.49	0.53	0.31	0.51	0.55
8/6/98	37.87	0.69	0.77	0.81	0.88	0.96	0.90	0.62	0.59	0.56	0.63	0.70	0.41	0.53	0.58	0.60	0.93	0.57	0.70	0.58	0.82	0.67	0.61	0.45	0.72	0.50
AVG	37.08	0.66	0.64	0.72	0.90	0.83	0.82	0.52	0.49	0.62	0.60	0.65	0.52	0.60	0.69	0.58	0.91	0.54	0.84	0.82	1.03	0.83	0.95	0.85	0.99	1.15

		DO, mg/L Distance, ft																								
Date	% Air Reduction	10	50	100	150	200	250	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700	725	750
8/11/98	0.00	0.51	0.26	0.36	0.6	0.91	0.64	0.92	0.46	0.87	0.51	1.22	0.92	0.7	0.85	0.96	1.83	1.55	2.72	3.64	4.54	5.04	5.5	5.89	6.04	6.22
8/12/98	0.00	0.9	0.44	0.52	0.92	1.25	0.89	1.01	0.74	1.08	0.8	1.72	1.68	2.12	2.84	3.27	3.97	4.39	5.02	5.48	5.73	6.05	6.04	5.88	6.04	6.08
8/13/98	0.00	0.57	0.44	0.63	0.72	1.45	1.44	0.99	0.58	1.08	0.64	1.52	1.33	1.16	1.23	1.69	2.31	2.56	3.04	3.84	3.68	2.95	4.17	3.93	4.01	4.08
8/6/98	0.00	0.89	0.31	0.45	0.86	1.34	0.67	0.52	0.66	0.77	0.90	1.10	1.02	0.88	1.35	1.37	2.69	2.50	3.40	3.88	4.19	4.24	4.89	4.92	5.21	5.32
AVG	0.00	0.72	0.36	0.49	0.78	1.24	0.91	0.86	0.61	0.95	0.71	1.39	1.24	1.22	1.57	1.82	2.70	2.75	3.55	4.21	4.54	4.57	5.15	5.16	5.33	5.43