THE MEASUREMENT AND CONTROL OF FOULING IN FINE PORE DIFFUSER SYSTEMS

by

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Cooperative Agreement No. CR812167

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DISCLAIMER

Development of the information in this report has been funded in part by the U.S. Environmental Protection Agency under Cooperative Agreement No. CR812167 by the American Society of Civil Engineers. The report has been subjected to Agency peer and administrative review and approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Engineering Laboratory is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

As part of these activities, an EPA cooperative agreement was awarded to the American Society of Civil Engineers (ASCE) in 1985 to evaluate the existing data base on fine pore diffused aeration systems in both clean and process waters, conduct field studies at a number of municipal wastewater treatment facilities employing fine pore aeration, and prepare a comprehensive design manual on the subject. This manual, entitled "Design Manual - Fine Pore Aeration Systems," was completed in September 1989 and is available through EPA's Center for Environmental Research Information, Cincinnati, Ohio 45268 (EPA Report No. EPA/625-1-89/023). The field studies, carried out as contracts under the ASCE cooperative agreement, were designed to produce reliable information on the performance and operational requirements of fine pore devices under process conditions. These studies resulted in 16 separate contractor reports and provided critical input to the design manual. This report summarizes the results of one of the 16 field studies.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

PREFACE

In 1985, the U.S. Environmental Protection Agency funded Cooperative Research Agreement CR812167 with the American Society of Civil Engineers to evaluate the existing data base on fine pore diffused aeration systems in both clean and process waters, conduct field studies at a number of municipal wastewater treatment facilities employing fine pore diffused aeration, and prepare a comprehensive design manual on the subject. This manual, entitled "Design Manual - Fine Pore Aeration Systems," was published in September 1989 (EPA Report No. EPA/725/1-89/023) and is available from the EPA Center for Environmental Research Information, Cincinnati, OH 45268.

As part of this project, contracts were awarded under the cooperative research agreement to conduct 16 field studies to provide technical input to the Design Manual. Each of these field studies resulted in a contractor report. In addition to quality assurance/quality control (QA/QC) data that may be included in these reports, comprehensive QA/QC information is contained in the Design Manual. A listing of these reports is presented below. All of the reports are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161 (Telephone: 703-487-4650).

1. "Fine Pore Diffuser System Evaluation for the Green Bay Metropolitan Sewerage District" (EPA/600/R-94/093) by J.J. Marx

2. "Oxygen Transfer Efficiency Surveys at the Jones Island Treatment Plants, 1985-1988" (EPA/600/R-94/094) by R. Warriner

3. "Fine Pore Diffuser Fouling: The Los Angeles Studies" (EPA/600/R-94/095) by M.K. Stenstrom and G. Masutani

4. "Oxygen Transfer Studies at the Madison Metropolitan Sewerage District Facilities" (EPA/600/R-94/096) by W.C. Boyle, A. Craven, W. Danley, and M. Rieth

5. "Long Term Performance Characteristics of Fine Pore Ceramic Diffusers at Monroe, Wisconsin" (EPA/600/R-94/097) by D.T. Redmon, L. Ewing, H. Melcer, and G.V. Ellefson

6. "Case History of Fine Pore Diffuser Retrofit at Ridgewood, New Jersey" (EPA/600/R-94/098) by J.A. Mueller and P.D. Saurer

7. "Oxygen Transfer Efficiency Surveys at the South Shore Wastewater Treatment Plant, 1985-1987" (EPA/600/R-94/099) by R. Warriner

8. "Fine Pore Diffuser Case History for Frankenmuth, Michigan" (EPA/600/R-94/100) by T.A. Allbaugh and S.J. Kang

9. "Off-gas Analysis Results and Fine Pore Retrofit Information for Glastonbury, Connecticut" (EPA/600/R-94/101) by R.G. Gilbert and R.C. Sullivan

10. "Off-Gas Analysis Results and Fine Pore Retrofit Case History for Hartford, Connecticut" (EPA/600/R-94/105) by R.G. Gilbert and R.C. Sullivan

11. "The Measurement and Control of Fouling in Fine Pore Diffuser Systems" (EPA/600/R-94/102) by E.L. Barnhart and M. Collins

12. "Fouling of Fine Pore Diffused Aerators: An Interplant Comparison" (EPA/600/R-94/103) by C.R. Baillod and K. Hopkins

13. "Case History Report on Milwaukee Ceramic Plate Aeration Facilities" (EPA/600/R-94/106) by L.A. Ernest

14. "Survey and Evaluation of Porous Polyethylene Media Fine Bubble Tube and Disk Aerators" (EPA/600/R-94/104) by D.H. Houck

15. "Investigations into Biofouling Phenomena in Fine Pore Aeration Devices" (EPA/600/R-94/107) by W. Jansen, J.W. Costerton, and H. Melcer

16. "Characterization of Clean and Fouled Perforated Membrane Diffusers" (EPA/600/R-94/108) by Ewing Engineering Co.

ABSTRACT

The purpose of the study was two-fold: first, to define the efficiency of various methods of cleaning fine pore diffusers and, second, to develop a methodology that could be used to evaluate the efficiency of the cleaning techniques. Dirty fine pore domes from the North Texas Municipal Water District were cleaned by a variety of techniques, and the improvement in oxygen transfer efficiency was measured. The domes were reinstalled in the aeration tanks and withdrawn at various time intervals thereafter. The deterioration in oxygen transfer efficiency was then noted. The cleaning techniques were repeated, and the improvement in transfer was recorded.

Overall, the domes form the North Texas Plant did not show severe fouling. Low pressure hosing appeared to be as effective as any other method in cleaning the domes. The domes deteriorated promptly after they were reintroduced into the aeration tank, but the deterioration in oxygen transfer was not severe enough to impose an unacceptable aeration cost.

The technique of using an off-line aeration tank for studying the cleaning techniques provided mixed results. The comparison of cleaning techniques appeared to be properly described in this small test tank, but the degree of fouling that had actually occurred in the full-scale plant appeared to be underestimated. This probably resulted from the breakdown of slimes and fouling materials during dome transportation and handling.

The cost of cleaning domes by various techniques is difficult to estimate because of a variety of site specific factors. A method was developed for estimating the cost that would be encountered in a typical case. The cost for simple cleaning was found to vary from approximately $1.20 a dome for small plants to somewhat under $0.80 a dome for large plants.

This report was submitted in partial fulfillment of Cooperative Agreement No. CR812167 by the American Society of Civil Engineers under subcontract to Southern Methodist University under the partial sponsorship of the U.S. Environmental Protection Agency. The work reported herein was conducted over the period of 1985-1987.

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ACKNOWLEDGEMENTS

The work reported herein was supported, in part, by a grant from the U.S. EPA through the American Society of Civil Engineers. Most of the laboratory testing was completed under the supervision of Dr. Michael Collins of Southern Methodist University. Two graduate students, Randall Covington and Ramarao Vuddagiri, performed the actual tests.

The cooperation of the management and staff of the North Texas Municipal Water District is gratefully acknowledged.

INTRODUCTION

Each year the United States spends more than $500 million to transfer oxygen to waste liquor during various wastewater treatment processes (1). The cost of aeration is increasing with the demand for high-level waste treatment. To achieve the most efficient oxygen transfer, many existing treatment plants have installed fine pore diffused aeration systems. Most new municipal plants are also employing this technology. Investigations at some of these plants indicated that diffuser fouling may have a significant impact on the oxygen transfer efficiency (2). The lowering of transfer efficiency by fouled diffusers will add substantially to the wastewater treatment cost.

To better define the conditions contributing to diffuser fouling and to develop methods for evaluating and techniques for controlling this problem, the American Society of Civil Engineers, under a grant from the Environmental Protection Agency has undertaken a study program to develop information and guidelines to improve the design and application of fine pore diffused aeration systems.

Southern Methodist University (SMU), Center for Urban Water Studies, received a grant from the study program, as well as support from several municipal districts interested in promoting developing information on oxygen transfer in fine pore aeration systems. The SMU studies have been directed toward methods of quantifying the degree of deterioration in oxygen transfer and evaluating various cleaning techniques for diffuser systems.

STUDY PURPOSE

The purpose of the study was two-fold: first, to develop a procedure to evaluate diffuser cleaning techniques and second, to investigate the improvement in oxygen transfer efficiency achieved by the various techniques. The advantage of knowing the efficiency of various cleaning methods is clear; however, the information is not totally useful unless the rate of fouling after a dome is cleaned using the various techniques can also be determined. The function of defining the rate of fouling is important for modeling the process or determining an economic optimization of the process.

The first objective of the studies, the development of a procedure to evaluate dome cleaning techniques, is quite important. Existing field data suggest that the optimum method of cleaning may well be different at different plants. If this is the case, a method of evaluating cleaning techniques that can be applied to a particular plant is needed. Because of limited resources, conducting large-scale studies on a wide variety of cleaning methods is impractical for many plants. A more practical technique would be a shop evaluation of the cleaning techniques.

The study program presented in this report involved removing fine pore dome diffusers from the North Texas Municipal Water Treatment Plant in Rowlette. These domes were cleaned by various techniques, and their oxygen transfer efficiency was evaluated in a shop scale tank located at SMU. The cleaned domes were then placed back in service for periods of up to 21 months. Selected domes were removed from the aeration tank at approximately 10 months and 21 months and retested at SMU to evaluate the deterioration of oxygen transfer efficiency.

DESCRIPTION OF SMU TEST TANK

The SMU Test Tank is a steel tank coated with an epoxy lining. The tank is 20 feet long by 3 feet 6 inches wide and has a sidewall depth of 9 feet 6 inches. The operating volume is approximately 17,200 liters. The tank is equipped with glass windows located at several points so that the aeration process can be observed and photographed from outside the tank. The tank is shown schematically in Figure 1 and in a photo in Figure 2.

Air is supplied to the tank from a central compression system that contains a large reservoir so that the air can be fed at a constant temperature and pressure. Air from the compression system flows through a series of metering and control valves and finally through a dual rotameter system that allows precise air flow measurement over a wide range. The rotameters from the air system are tested at regular intervals in the adjacent "Hydraulic Measurements Laboratory", which contains accurate and precise equipment for instrument calibration. The tank is also equipped with a pressure measuring device so that the exact head loss through the aeration equipment can be measured.

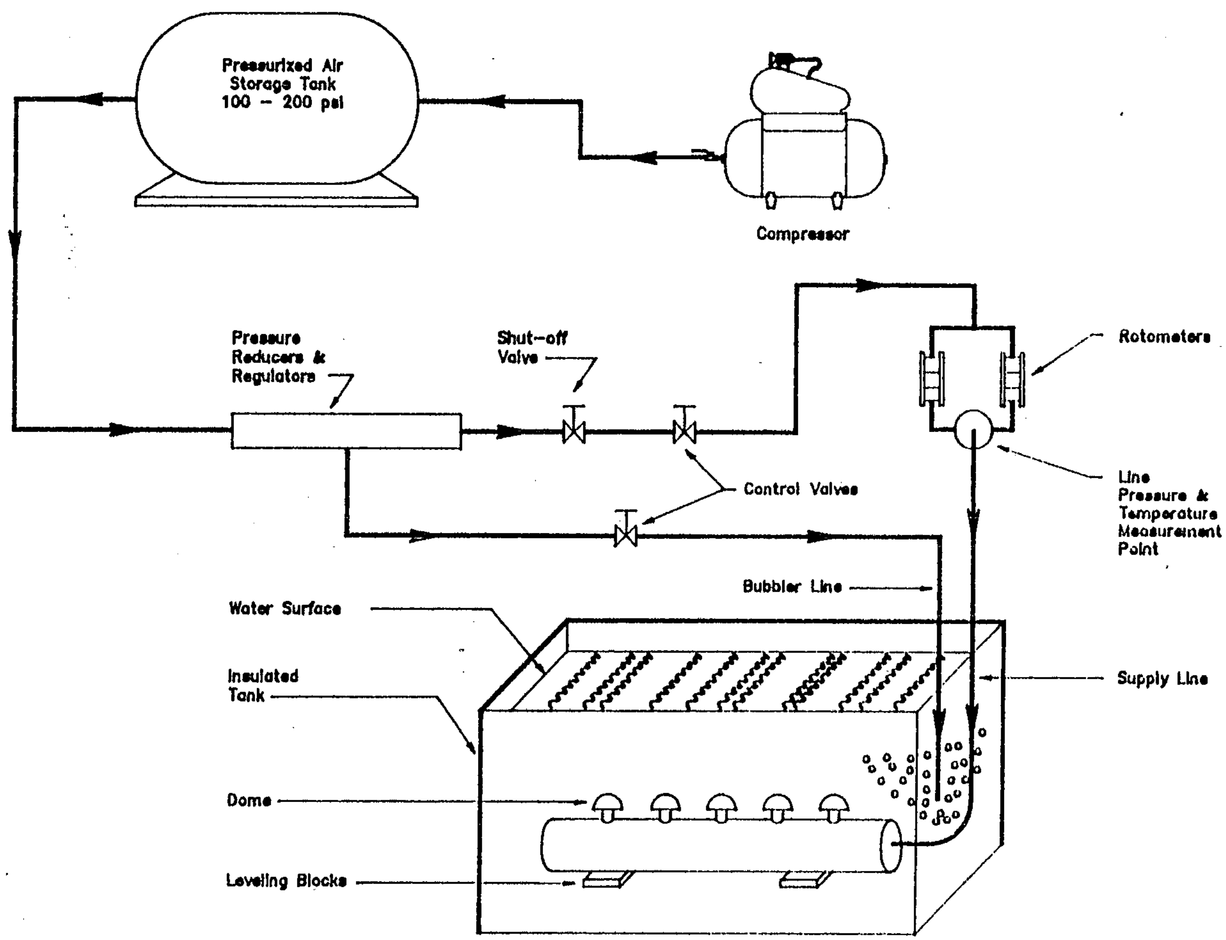


FIGURE 1. SCHEMATIC OF SHOP TEST TANK SYSTEM AT SMU

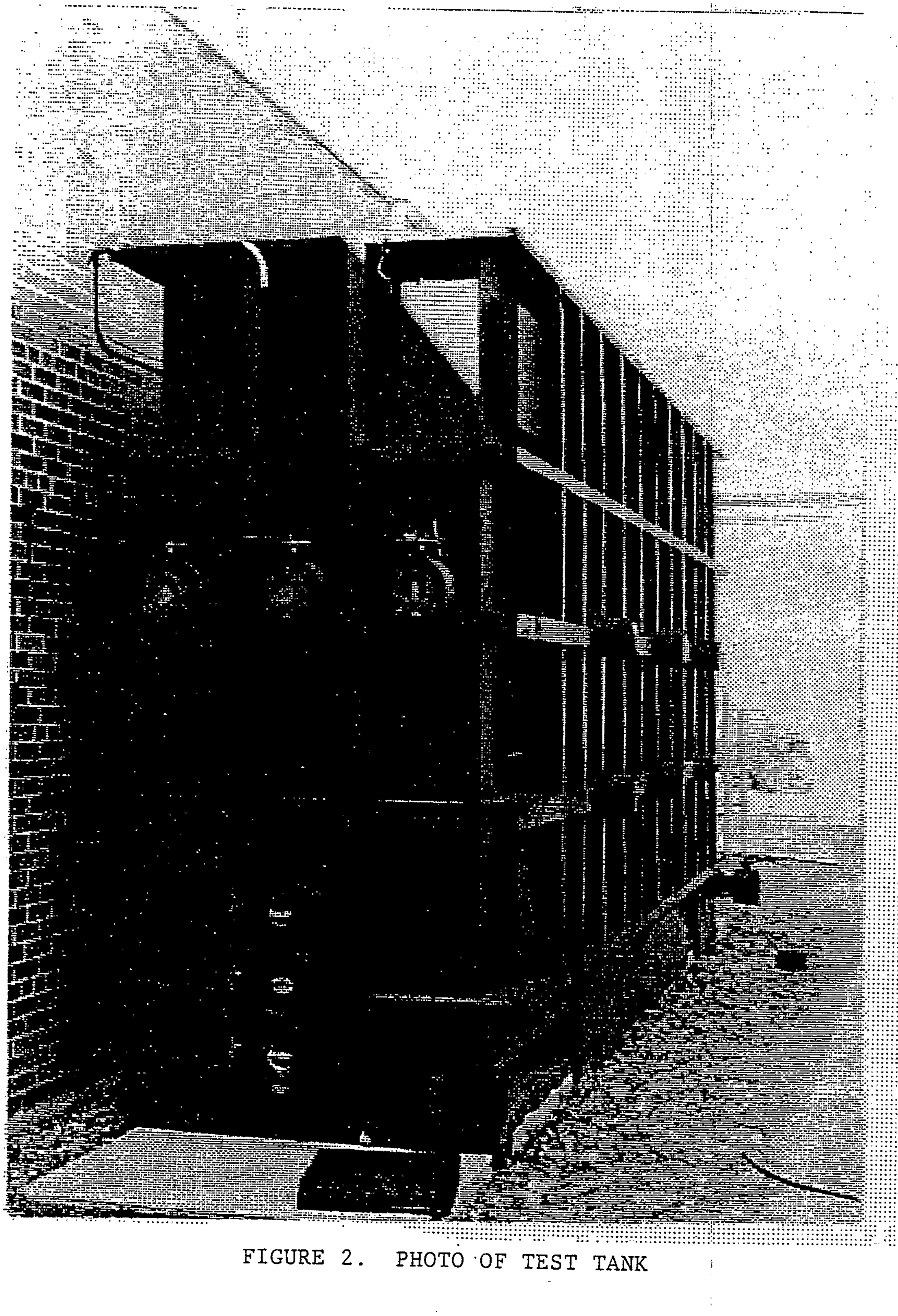


FIGURE 2. PHOTO OF TEST TANK

During oxygen transfer testing, three YSI dissolved oxygen probes are placed to measure representative portions of the total tank volume. Oxygen transfer testing is conducted in accordance with the procedures described in the ASCE "A Standard for the Measurement of Oxygen Transfer in Clean Water." (3)

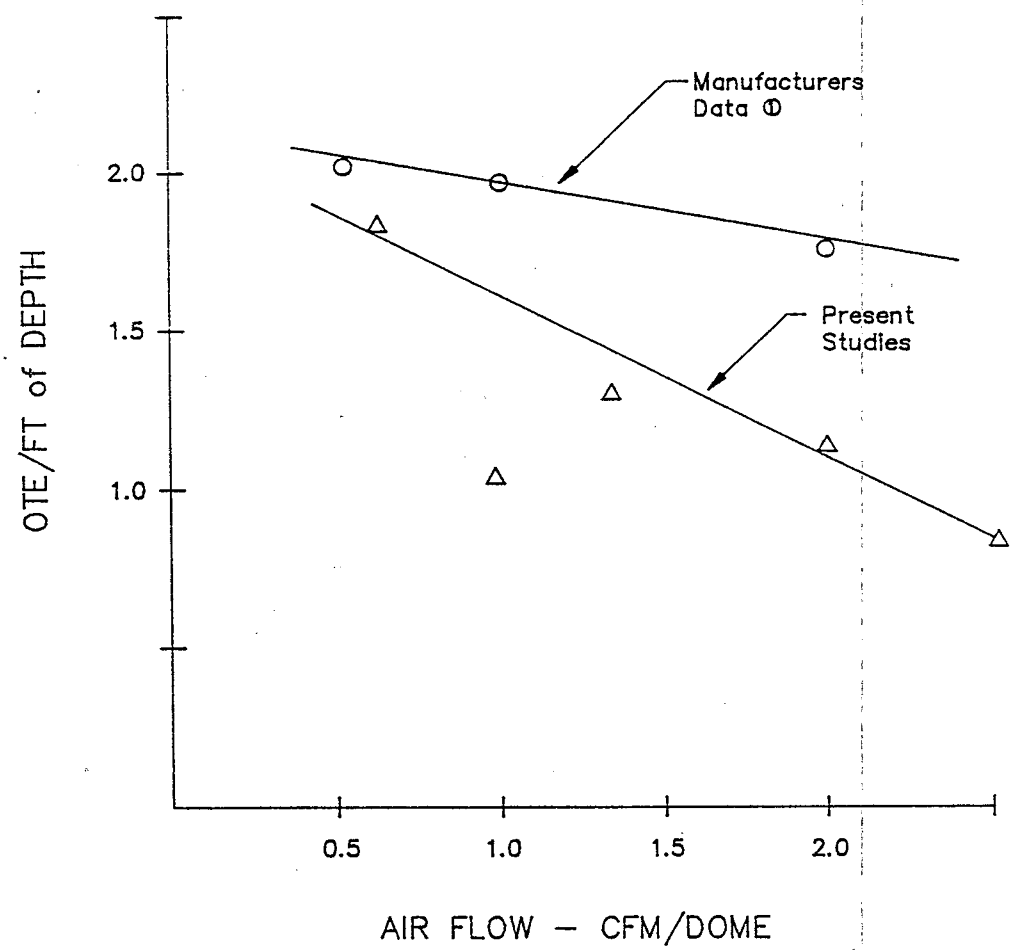
For the purposes of this study the tank was fitted with a four-inch air header containing 10 diffuser assemblies for Norton Domes. Any combination of these assemblies could be used to install domes. The assemblies that were not used were plugged during the tests.

A detailed description of the study procedures is presented as Appendix 1.

INITIAL PROBLEMS

Initial studies were conducted using clean water. This was done to establish a baseline for the system and to assure that the test apparatus could duplicate conditions observed by other investigators. Oxygen transfer efficiency was studied over a range of air flows from 0.5 to 2.5 cubic feet per minute (cfm) per dome. Each run was conducted in triplicate. The results of these initial tests are presented in Figure 3.

Previous investigations (4) have shown that although some oxygen is transferred during formation and bursting of the bubbles, this effect is relatively minimal when dealing with fine pore diffusion systems. Over the range of 8 to 16 feet of water depth, the oxygen transfer per foot of depth should be almost constant. As shown in Figure 3, these tests did not match the performance estimates of the manufacturer. A comparison of the initial test data shows that at low air flow rates the observed performance in the SMU aeration system was close to that reported by the equipment manufacturer. However, as the air flow rate increased, deviation from the manufacturer's reported performance



① Norton Domes @ 16' Depth
② Norton Domes @ 8.5' Depth

FIGURE 3: EFFECT OF AIRFLOW RATE ON OTE, PRELIMINARY STUDY

increased. This anomalous behavior was investigated by photographing the submerged domes under conditions of increasing airflow. The pressure drop associated with various airflows was also evaluated. The photographs showed that as the air flow increased so did the percentage of large bubbles. Increased air flow resulted in little increase in pressure loss. These investigations determined that the gasket between the header base plate and the dome was not providing a proper seal. The dome mounting system is shown schematically in Figure 4. As the air flow increased, the air leakage around the gasket also increased.

A dome mounting system was set up outside the test tank to evaluate the mechanics of gasket sealing. The dome was fastened to the mounting apparatus by a brass bolt passing through the center of the dome. This bolt is tightened to compress the gasket between the base plate and the dome until a seal is obtained. Laboratory studies determined that compressing the gasket to effect a tight seal was impossible without cracking the dome. This indicated that the gaskets being employed were much too rigid. The rigid gaskets were replaced with a more ductile gasket that properly sealed the system.

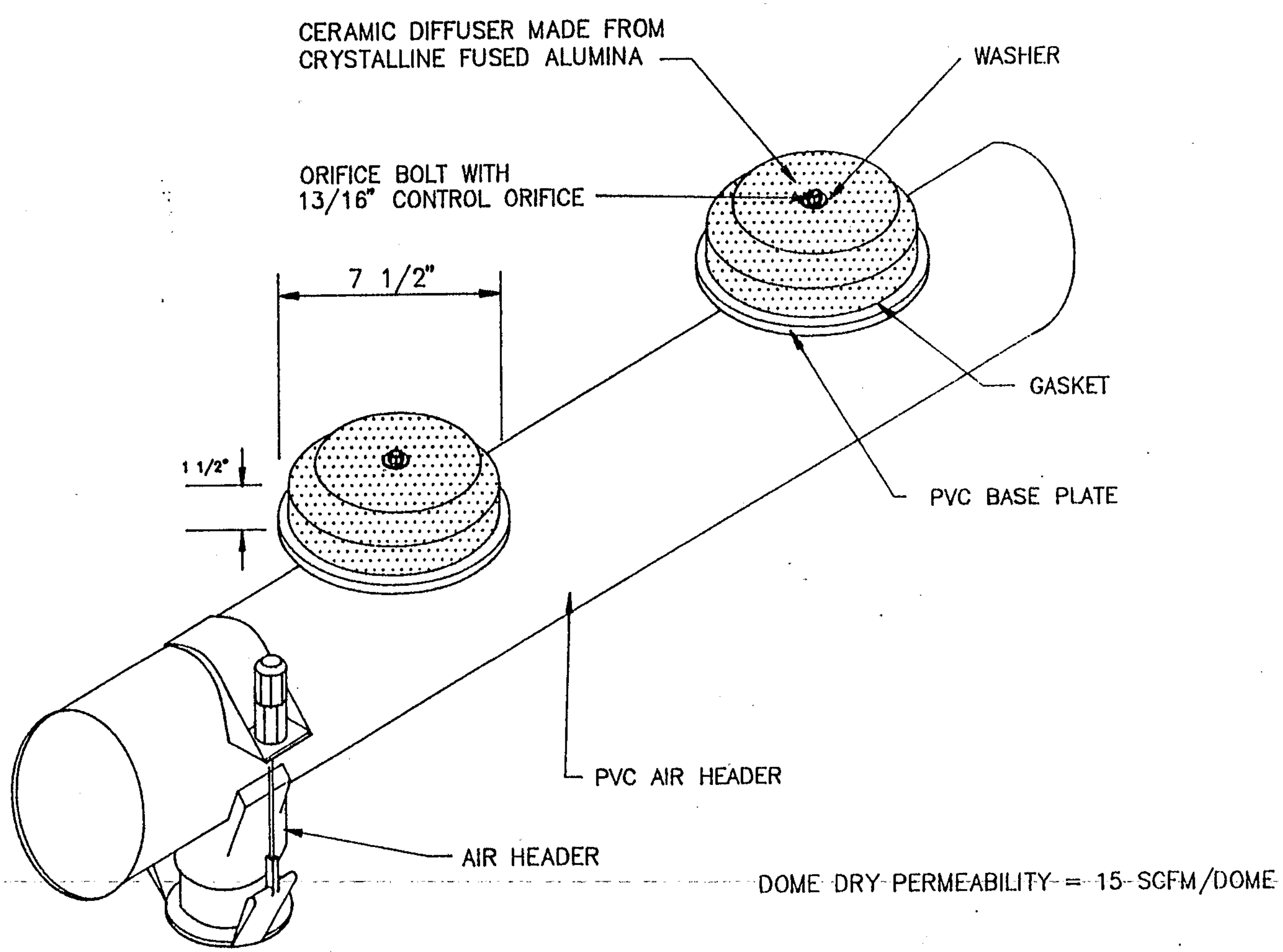


FIGURE 4: NORTON DOME DIFFUSERS ASSEMBLY

The increased ductility of the gasket was needed to compensate for warping of the base plate. The degree of warp was determined using a small micrometer wheel to measure the level of the base plate around its perimeter. By moving the micrometer slowly around the surface, the degree to which the surface was not flat could be determined. Investigation of ten separate units showed a typical unit to be out of flat by approximately 0.05 inches. Individual units showed warping as much as 0.1 inches from the high to the low point on the plane.

The gaskets in the test tank were then replaced with the more ductile gaskets. Care was taken to ensure that no leaking would occur in the system. After the new gaskets were installed and fully checked, a second set of clean water tests (Figure 5). The test study results are also presented in Table 1. When the system is properly sealed, the performance was virtually identical to those reported by the manufacturer.

One other problem worthy of note developed during the initial test program. The City of Highland Park, which

TABLE 1

IMPACT OF AIR FLOW RATE ON OTE

Clean Water Studies @ 8.5' Depth

Air Flow CFM/Dome	K_La 1/hr@20°	OTE	OTE/FT
0.5	1.10	16.0	1.9
1.0	2.40	17.1	2.0
1.5	3.35	16.1	1.9
2.0	4.50	16.0	1.9
2.5	5.30	15.2	1.8

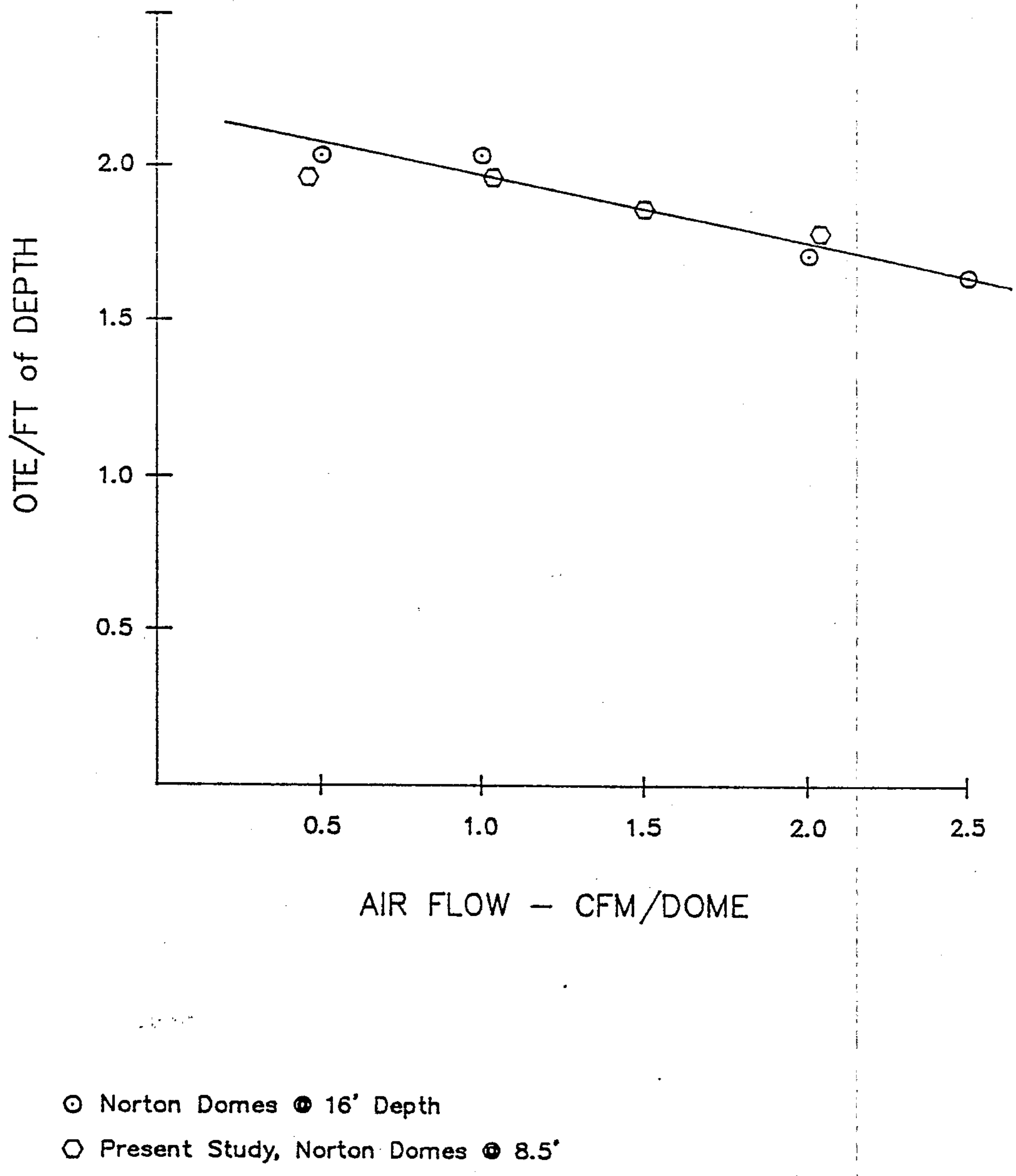


FIGURE 5, EFFECT OF AIRFLOW RATE ON OTE AFTER PROPER SEALING OF THE DOMES provides potable water for Southern Methodist University, utilizes ferrous sulfate as a coagulating chemical. The dosage of this chemical is higher during the warmer months in response to their increased coagulation needs.

As a result, tests conducted in the late spring and early summer were influenced by this change in water chemistry. Observation of the tank indicated that a darkened color was developing when adding the test chemicals. Investigation of the water chemistry revealed that an iron complex was precipitating. This iron complex had a slight absorptive effect on the cobalt, which is a catalyst used during the test. Consequently, if a slight excess of cobalt was not added, the effective cobalt concentration in the tank would drop below the minimum specified for good testing. The problem was resolved by increasing the cobalt concentration by approximately 0.3 mg/l.

The problem of color persisted and made it difficult to provide accurate photographic evidence of transfer during the period when the higher chemical use was in effect at the water plant.

THE PRESSURE MEASUREMENTS

Pressure loss across the diffuser devices were carefully measured during each test run. A bubbler tube was inserted into the tank at an elevation equal to the center of the gas manifold. This pressure reading was subtracted from the pressure drop across the diffuser system to determine the actual pressure loss across the diffusers.

Initial studies of the diffuser pressure loss indicated that a significant time period was required for the diffusers to come to equilibrium. The magnitude of pressure loss increased as dry domes became saturated and decreased as previously wetted domes dried under airflow conditions. Figure 6 shows a summary of pressure loss data after time of aeration.

The investigation concluded that domes must be operated at the intended airflow for approximately 24 hours before a true equilibrium pressure is obtained. Evaluating the impact of changing air pressure relationships on oxygen transfer were not practical. Physical observation of the systems indicated that the air flow from domes changed

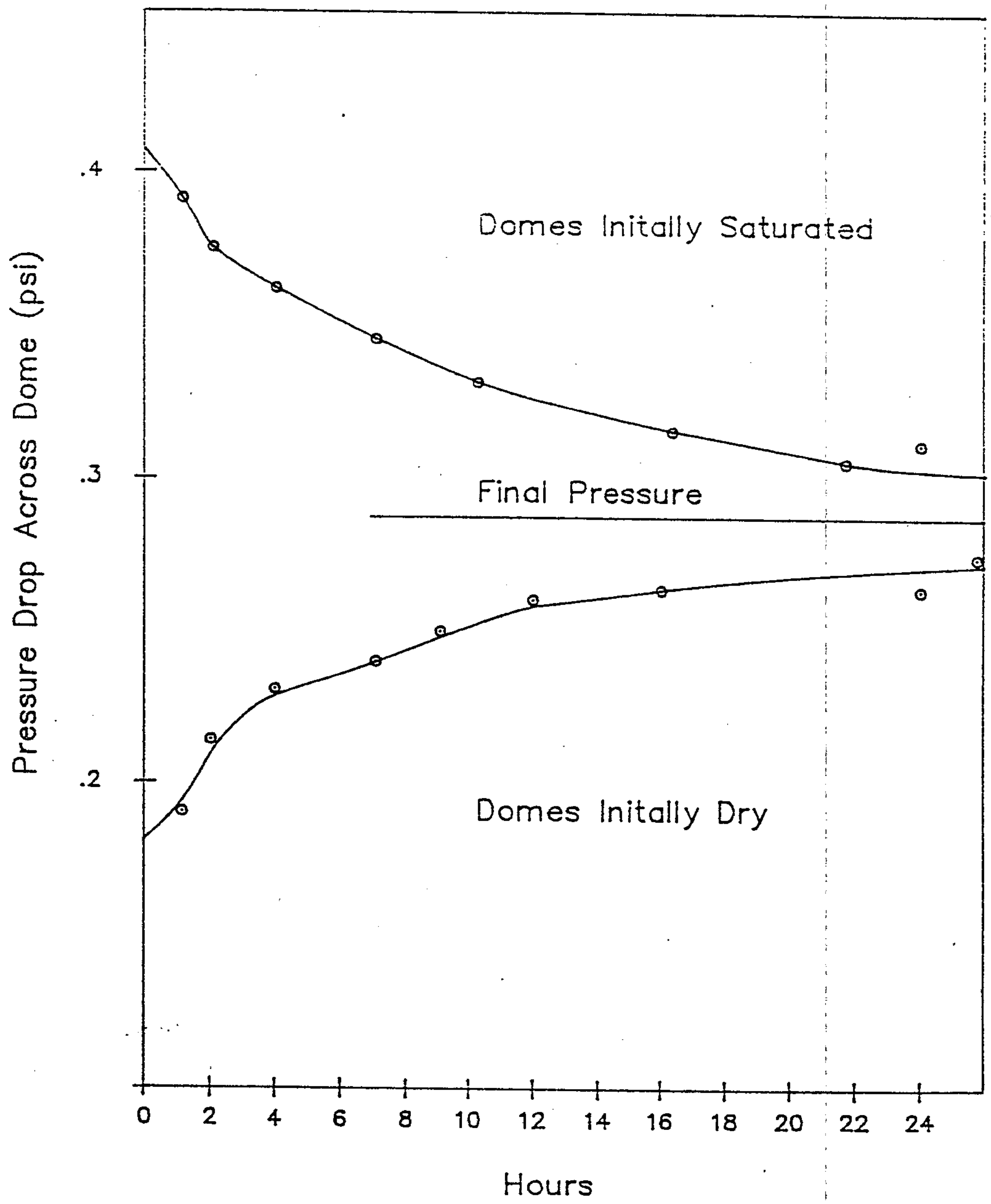


FIGURE 6, PRESSURE LOSS WITH TIME AFTER INSTALLATION somewhat as they reached equilibrium. This observation indicates that the oxygen transfer capability of a dome system is influenced, to some degree, by the dome's condition and the period that it is allowed to operate before testing. In the present investigations, domes to be tested were installed in the tank and allowed to aerate for periods in excess of 12 hours before studies were conducted. In most cases, the domes were aerated at least overnight to allow the equilibrium to be established.

TESTING WITH DETERGENTS ADDED

It was recognized from experience that the most valid comparison of the cleaning efficiency could be obtained by testing in water that simulated, to the degree possible, the conditions that were actually observed in the field. The decision was made to adopt a test fluid that contained approximately 5 mg/l active detergent; essentially similar to that proposed by the British researchers (5). This fluid would be the basis of comparison to be used throughout the study. Parallel studies were also conducted in clean water to provide a basis for comparison to the detergent tests.

A stock detergent solution was prepared using a mixture of household laundry detergent and dishwasher detergent that has low foaming characteristics. Three to 5 mg/l of detergent was found to be of an acceptable range so that a significant impact on the oxygen transfer process with minimum foaming was observed.

Analytical testing by the methylene blue extraction method (6) for the presence of the detergents proved to be erratic. Laboratory concentrations of the detergent taken before testing indicated concentrations generally equal to those calculated from the stock mixture. However, after one or two tests, the concentration of detergent seemed to vary randomly. This variance is likely because of entrainment and the reaction of the materials in the fluid.

Investigations indicated that a much more satisfactory method of tracking the presence of surface active materials in the aeration system is to perform periodic evaluations of the surface tension of the fluid. The intended range of detergent concentration corresponded to a surface tension of approximately 65 dynes per square centimeter as measured by a surface tensiometer. Surface tension was chosen as the preferred method for tracking the condition of the test fluid.

Table 2 presents the studies conducted to determine the impact of the detergent concentration on oxygen transfer efficiency. The study indicated that the alpha of the detergent system was approximately 0.67 at a surface tension of 63 to 65 dynes per square centimeter (dynes/cm^2). Because this level was determined to be an acceptable level that corresponds well with alpha values observed in the

TABLE 2

IMPACT OF DETERGENT LEVEL ON OXYGEN TRANSFER RATE COEFFICIENT

Intended SAA Conc (mg/l)	K_La (1/hr 20°)	Surface Tension (dynes/cm²)	Measured SAA CONC. (mg/l)	α
0	2.36	72	0	
1	1.77	69	1-2	0.75
2	1.8	67	1-2	0.76
4	1.6	64	2-4	0.67
6*	1.4	60	3-6	0.60

* sustained foaming observed.

All runs are the average of duplicate studies.

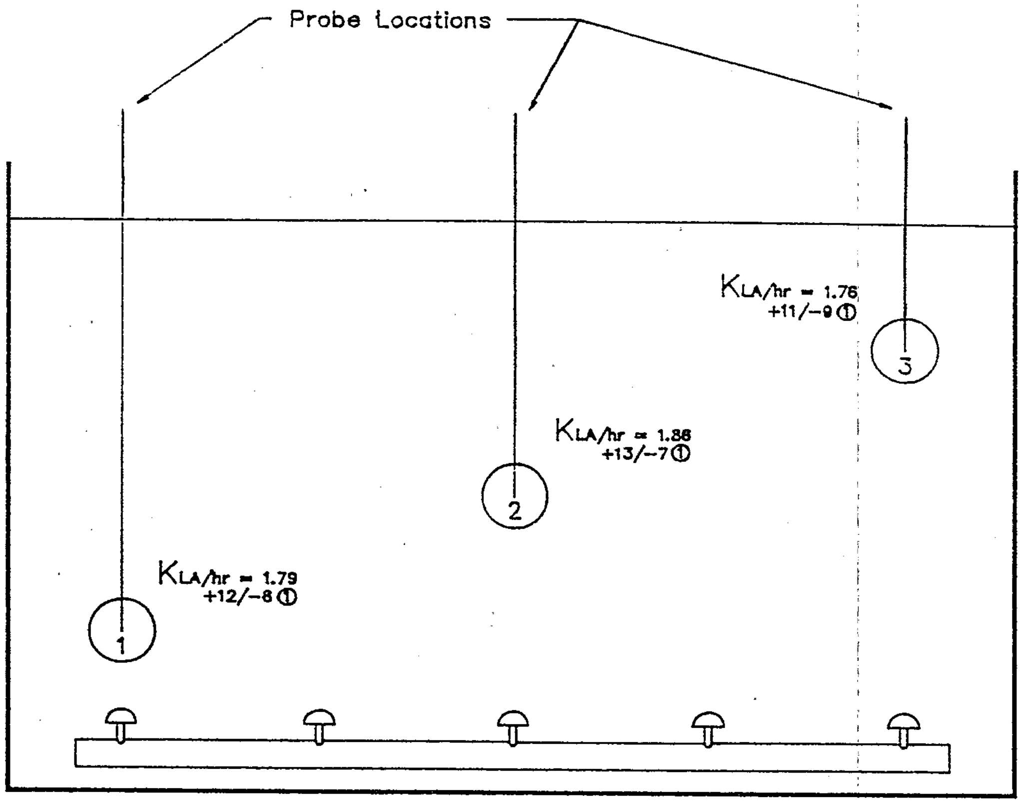
effluent of well performing treatment plants, a surface tension of approximately 65 dynes/cm^2 was used as the basis for comparison during the remainder of this study.

UNIFORMITY OF TEST TANK RESULTS

To evaluate the uniformity of the test tank results, 20 test runs on clear water were performed and analyzed. In each run five domes and flow rates of 1 and 2 cfm/dome were used.

Three probes were located in the test tank as shown in Figure 7, the first probe was located at the left end of the tank, approximately 1/4 depth above the bottom. The second probe was located at the middle of the tank, while the third probe was located at the upper right corner of the tank. The meters and probes themselves were rotated on a random basis so that the same meter and probe were not usually in the same location on consecutive runs. Probes were calibrated at the beginning of each run, and the membrane on probes for all systems were changed at regular intervals.

The results of a comparative study of the mass transfer coefficient calculated at each location are presented as a graphic summary in Figure 7. The average volumetric mass transfer coefficient (K_La) for the tank was 1.80/hr. The variation from point to point was less than 3 percent. The two end locations were slightly less than the average, and



Mean K_{LA}/hr = 1.80

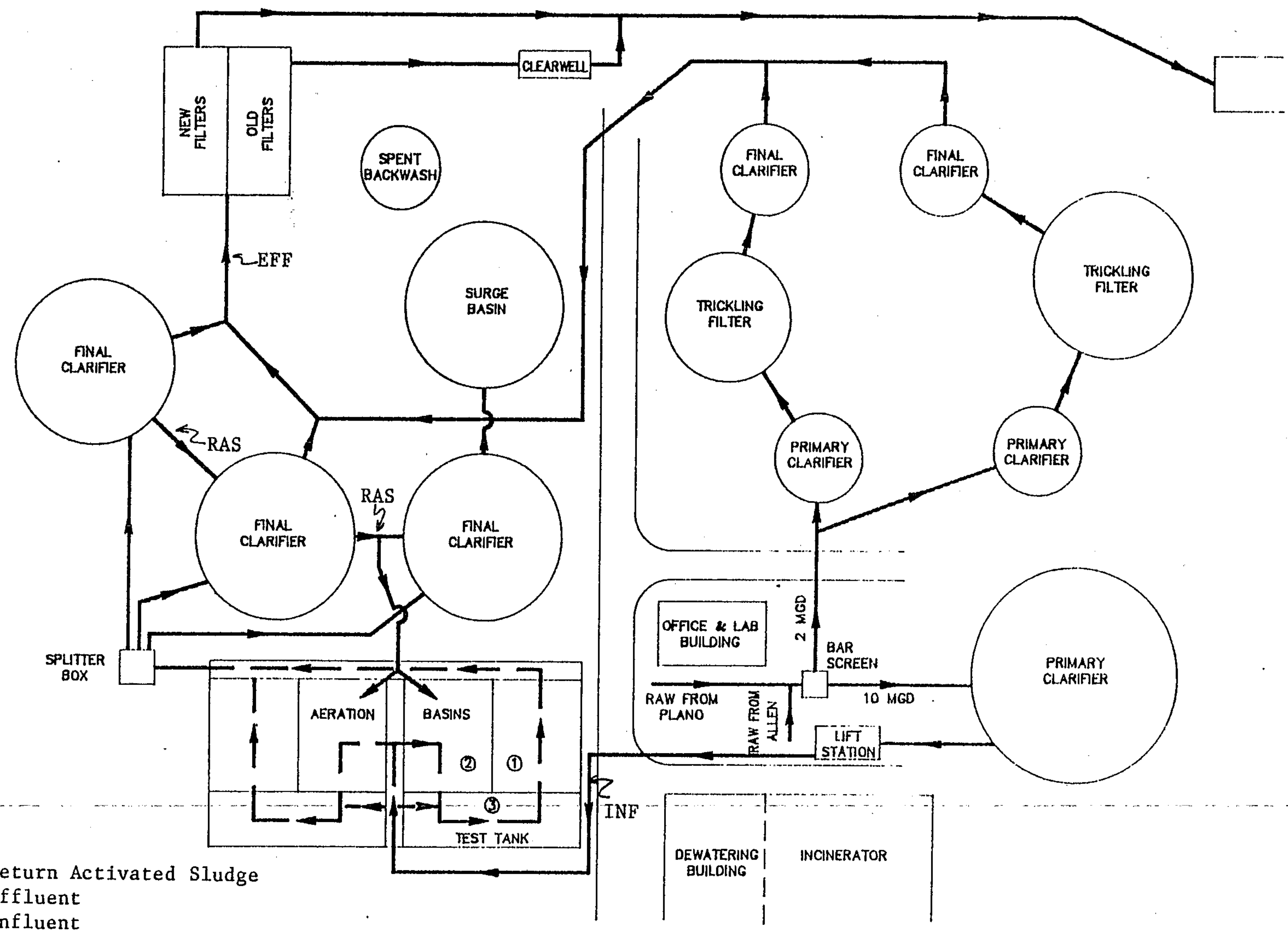
① # of Points Higher Than Average/ # of Points Lower Than Average

FIGURE 7, COMPARISON OF K_{LA} @ LOCATIONS IN TANK the middle location was slightly above average. Examination of the individual data shows that Station 1 was higher than the average 12 times and lower 8 times. Station 2 values were higher 13 times and lower 7, and at Station 3 values were higher 11 times and lower 9. Overall, these data describe a very uniform test tank where each of the points exhibits essentially the same value of K_La.

STUDIES AT NORTH TEXAS MUNICIPAL WATER DISTRICT, ROWLETTE CREEK PLANT

The North Texas Municipal Water District, Rowlette Creek Plant, serves the Cities of Plano and Allen, Texas. A schematic of the waste treatment plant is presented as Figure 8. Figure 9 shows the aeration tank under study. The wastewater receives primary settling and then is pumped to the aeration system. The plant was treating approximately 15 million gallons per day (MGD) during the study period. The aeration system consists of two basins, each with a volume of approximately 2.4 million gallons. The flow pattern to the aeration basin varies depending on the rate of flow entering the treatment plant.

Returned sludge is introduced into the head of the aeration basin. Under average flow conditions, the waste is introduced into aeration Basin 2 where it mixes with the return sludge and proceeds through Basin 3. If the flows become high, because of peak demand or rainfall, the influent is diverted to a second influent point in Tank 1. This had the effect of providing additional detention time for treatment. This process is initiated automatically by the positioning of the inlet structures in the tank.



Legend

RAS = Return Activated Sludge
EFF = Effluent
INF = Influent

FIGURE 8: ROWLETT CREEK REGIONAL WASTEWATER TREATMENT PLANT

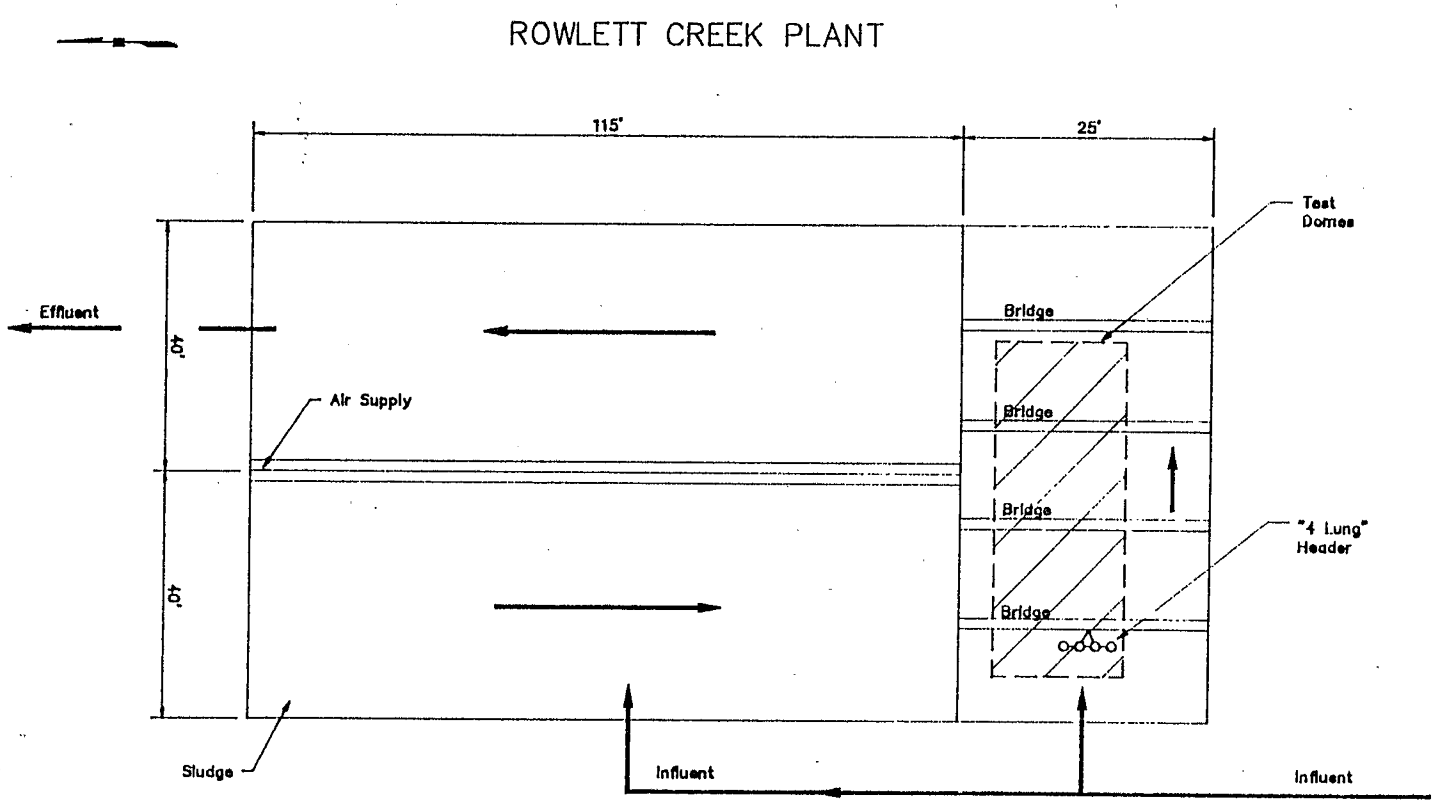


FIGURE 9: AERATION TANK UNDER STUDY

The mixed liquor suspended solids in the aeration basins are normally maintained in the 2,500-mg/l range, and uptakes observed in the test segment are generally in the 25 to 50 mg/l/hr. Table 3 summarizes the operating conditions during the study period. The plant does not keep separate records of activated sludge wastage so sludge age cannot be calculated directly. Indirect calculations indicate that the sludge age during the study period varied from 20 to 14 days.

The Norton Domes located in the aeration basin were installed in 1982 and had never been cleaned except for periodic washdown before the present study. No detailed history of the system is available but discussions with plant personnel indicate that continued problems with breaks in lines were encountered after the original start up. The system was overhauled, and all faulty piping was replaced in the test section in 1983.

The air flow to the plant is supplied by either two or three 2,250-cfm blowers. Depending on oxygen demand, there are no individual air flow meters within the aeration system so

TABLE 3

OPERATING CONDITIONS AT STUDY PLANT: NTMWD

DATE	INF BOD CONC MG/1	F/M	A	% BOD REDUCTION	DATE	INF BOD CONC MG/1	F/M	A	% BOD REDUCTION
NOV 85	156	0.25	10	95%	JAN 87	132	0.20	15	90%
DEC 85	160	0.25	10	93%	FEB 87	140	0.25	10	90%
JAN 86	182	0.23	12	93%	MAR 87	120	0.23	12	92%
FEB 86	148	0.18	17	92%	APR 87	163	0.23	12	93%
MAR 86	188	0.18	17	94%	MAY 87	122	0.18	17	93%
APR 86	138	0.18	17	94%	JUNE 87	110	0.16	19	92%
MAY 86	183	0.27	8	94%	JULY 87	144	0.2	15	95%
JUNE 86	99	0.13	21	87%	AUG 87	146	0.24	11	94%
JULY 86	140	0.17	17	93%					
AUG 86	150	0.21	14	94%					
SEPT 86	134	0.18	13	94%					
OCT 86	153	0.23	12	92%					
NOV 86	150	0.20	15	93%					
DEC 86	132	0.19	16	90%					

A = ESTIMATED SLUDGE AGE (DAYS)

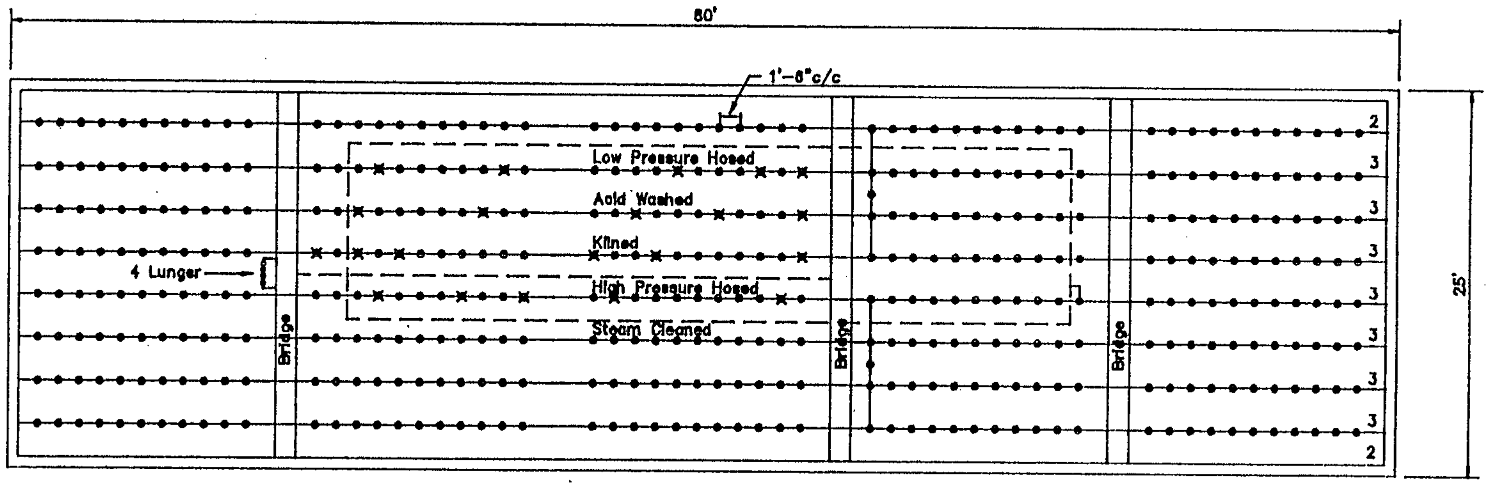
airflow is adjusted by observing the dissolved oxygen level in the tanks and adjusting the airflows until the system balances. With two blowers running, the system provides approximately 1 cfm/dome and with three blowers operating, the air flow is 1.5 cfm/dome. Aeration Basin 2, where the studies are conducted, has a volume of 0.225 million gallons.

DOME CLEANING OPERATIONS

In the summer of 1985 a cleaning program to prepare the domes for testing was undertaken. An area containing a 150 domes in the center of the aeration basin was selected as the test area. A detailed drawing of the test segment is presented as Figure 10. Five methods of cleaning were selected for testing. These included the following: Low pressure hosing, High pressure hosing, Steam cleaning, Acid washing under the Milwaukee Method (7), Kilning. Because sonic cleaning and soaking in bleach had been evaluated in a previous study on similar domes and did not prove particularly effective for the effort involved, they were not chosen for further study during this investigation.

Dome Collection

After the tank was dewatered, the domes to be tested in a contaminated state were carefully removed and placed in plastic Ziplock bags. The domes were stored in an ice chest for transportation and in a refrigerator until they were placed in the test tank. Even with careful handling, much



Section Volume 0.225mg

FIGURE 10: DOME LAYOUT IN THE TEST SECTION

of the growth on the dome surface broke away from the immediate surface of the domes and was lost before testing. The domes to be cleaned were hosed off in the tank and then were cleaned by the various methods.

Low Pressure Hosing

All domes being cleaned received low pressure hosing as the initial step in their cleaning. This was necessary to remove the loose slimes and other materials from the tops of the domes. Low pressuring hosing consisted of washing the domes from the floor of the tank using the standard water pressure, approximately 40 pounds per square inch (psi), available in the plant's main water system. A standard hosing nozzle was used, and each dome as washed for 10 to 30 seconds depending on the time required to clean the surface. Air continued to flow through the domes during the hosing process. No attempt was made to maintain any particular airflow rate through the domes during cleaning.

High Pressure Hosing

A section of domes that were washed at high pressure were cleaned in place in the tank. A water supply system of approximately 85 psi is available at the plant site. This water system was extended into the tank, and an individual washed the surface of each dome at a distance of approximately 1 foot for 1 minute per dome. Attempts to come closer to the dome resulted in splashing and were not continued. Domes were washed until they appeared to be clean.

Milwaukee Method

For the Milwaukee Method of cleaning, the domes were washed with high pressure hosing similar to the procedure described above. Thereafter, the air was turned off and each dome was saturated with a solution of muriatic acid (14% hydrochloric acid solution) and was allowed to set for 30 minutes. No initial reaction appeared to take place, although some small amount of frothing did occur on individual domes. After 30 minutes, no reaction was obvious, and the application of a small amount of additional acid did not appear to cause any additional reaction. The domes were then hosed, using high pressure water, for approximately one minute. The air was then turned back on and hosing of all dome surfaces was carried out for another 10 to 20 seconds.

Steam Cleaning

No steam cleaning apparatus could be gotten into the test bays at Rowlette. The domes were, therefore, removed and taken to SMU where a small steam generator is available in the maintenance area. The units were mounted on a temporary header and exposed to steam for approximately 30 to 40 seconds at a steam pressure of approximately 150 psi. While removing the domes for treatment, it was noted that some domes had a significant amount of material on the inside. The material appeared to be dried activated sludge particles that had somehow entered the chamber under the dome.

Brushing appeared to remove most of this material easily. This material caused concern. Interviews with plant personnel indicated that line damage might have caused similar problems with all the domes in the tank. Because of this possibility, all domes in the test sequence were, thereafter, examined, and all loose material from the interior side of the domes was removed by simple brushing techniques.

Kilning

The domes to be kilned were removed from the test tank and brought to the Art Department at SMU where a large kiln is available. Domes were placed in the kiln, and the temperature was raised gradually to a 980°C over approximately 12 hours. The temperature was then held at 980°C for 4 hours. Then the kiln was allowed to cool, which took approximately 12 hours more. The domes were then removed, brushed free of any obvious accumulated ash or other materials, and returned to the test tank.

MICROSCOPIC PHOTOGRAPHS OF THE DOMES

The entire cleaning operation took about 4 days and required two individuals working most of that time. Six domes cleaned by each method were retained for initial study and investigation in the test tank. The tank was placed back in service on September 19, 1985.

Having some detailed physical method of evaluating the impact of cleaning on the dome materials. After some investigation, electron micrographs of the domes were determined to provide the best insight into examining the surface and the penetration of particles into the dome structure. To achieve effective photography of the dome interior, the domes were held approximately 1 foot above a concrete floor and dropped on their bottom side. This resulted in cracking of the dome without any significant introduction of foreign particles into the dome structure. One dome for each condition was taken to the electron microscope located in the SMU Anthropology and Geology Department, and each dome was photographed. These photographs are shown in Figure 11. Most noteworthy in the photographs is that in both the acid wash and the kilning operations a significant number of particles appear to be remain in the void spaces within the domes. Considerable further investigation of pictures and other information on the domes was conducted.

All that can be said with certainty is that some minor penetration of particles into the domes does occur under conditions of vigorous cleaning. Under uncleaned conditions it is unusual for particles to be more than 2 to 3 grains of aggregate below the surface. After kilning, ash was found 5 to 7 grains deep in the stones. This method of analysis will not likely provide any quantitative method of estimating the efficiency of dome cleaning.

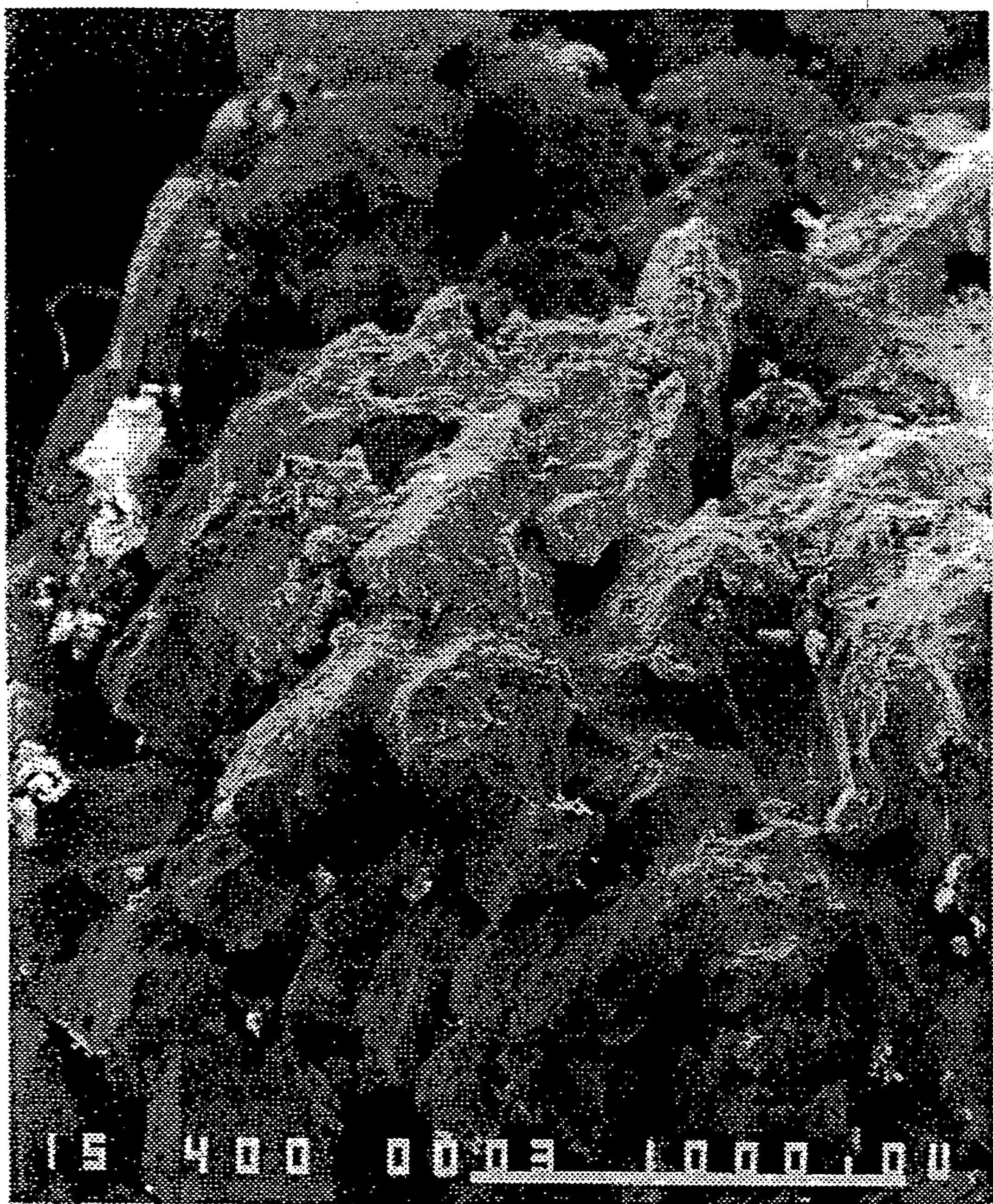


FIGURE 11a: ELECTRON MICROGRAPH OF A DIRTY DOME

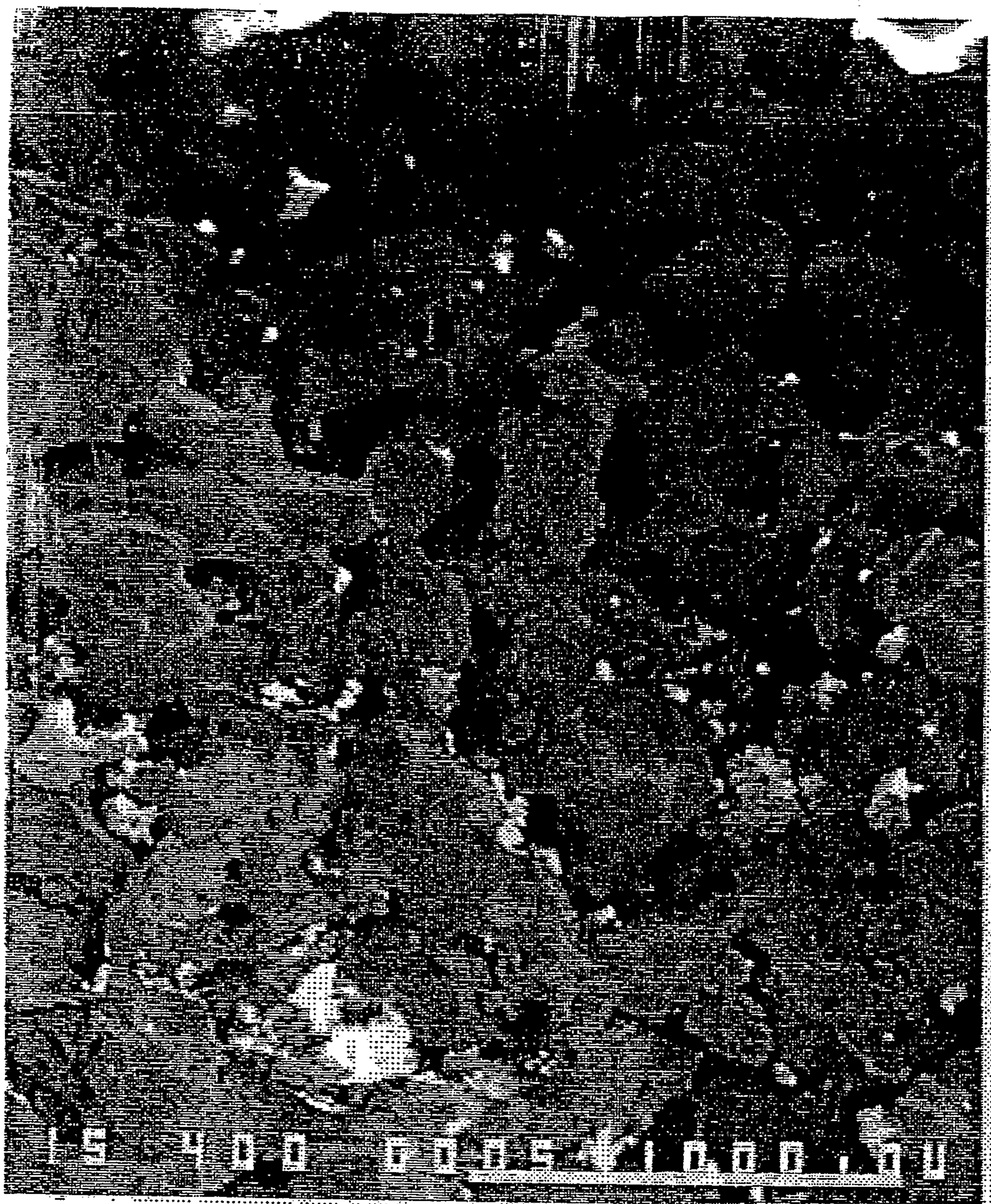


FIGURE 11b: ELECTRON MICROGRAPH OF A DOME AFTER LOW PRESSURE HOSING

FIGURE 11c: ELECTRON MICROGRAPH OF A DOME
AFTER ACID WASHING

FIGURE 11d: ELECTRON MICROGRAPH OF A DOME AFTER KILNING

STUDY RESULTS OF CLEANING INVESTIGATIONS

Table 4 presents the results of the oxygen transfer studies conducted on new domes, the dirty domes removed from the North Texas aeration chambers, and the domes after cleaning by the five selected test methods. The data are presented for airflows of 1 and 2 cfm per dome. The test water for all tests contained detergent in a sufficient concentration to lower the surface tension to approximately 65 dynes/cm^2.

The test shows that the dirty domes are transferring approximately 75 percent of the oxygen of the new units. Cleaning appears to restore the domes to between 80 and 90 percent of their original performance level. There does not appear to be any significant difference between the cleaning efficiency that is achieved by the various methods.

The oxygen transfer efficiency of clean domes was improved to about 85 percent of the value of new domes, which is a 10 percent improvement over the 75 percent transfer observed for dirty domes. Tables 5 and 6 show the results of similar testing after 9 months and 21 months of exposure of the

TABLE 4

"αSOTE" OF DOMES[1] BEFORE AND AFTER INTERNAL CLEANING AS TESTED IN DETERGENT SOLUTION*

DOME CONDITION	AIR FLOW CFM/DOME	αSOTE	OTE/FT	% OF NEW DOMES
NEW	1.0	12.75	1.5	
	2.0	9.78	1.15	
DIRTY	1.0	9.35	1.1	73
	2.0	7.65	0.9	78
KILNED	1.0	11.5	1.35	90
	2.0	8.5	1.0	87
LOW PRESSURE	1.0	11.9	1.4	93
HOSED	2.0	7.9	0.93	82
HIGH PRESSURE	1.0	11.0	1.3	87
HOSED	2.0	7.8	0.92	81
STEAM CLEANED	1.0	10.2	1.2	80
	2.0	8.6	1.03	90
ACID WASHED	1.0	10.2	1.2	80
	2.0	7.9	0.93	80

*All test conducted in a solution with a surface tension = 65 dynes/cm². (measured average 3.5 mg/l SAA). All runs were conducted in duplicate.

1 Domes were on service for 3 years before testing.

TABLE 5

αSOTE OF CLEANED DOMES AFTER 9 MONTHS OF USE

DOME CLEANING METHOD	AIR FLOW CFM	SURFACE TENSION DYNE/CM[2]	αSOTE	αSOTE/FT OF WATER DEPTH
LOW PRESSURE	1	65	8.05	0.95
HOSING	2	64	6.5	0.77
HIGH PRESSURE	1	64	7.15	.84
HOSING	2	65	6.23	.73
ACID	1	63	9.65	1.13
WASHED	2	65	6.7	0.79
KILNED[1]	DATA ON KILNED DOMES WERE NOT INCLUDED DUE TO ANALYTICAL PROBLEMS.			

TABLE 6

αSOTE OF DOMES AFTER 21 MONTHS

JUNE 1987

DOMES	AIR FLOW	SURFACE TENSION DYNE/CM^2	αSOTE	αSOTE/FT OF WATER DEPTH
DIRTY	1.0	63	8.2	0.96
	1.0	63	7.7	0.905
LOW PRESSURE	1.0	62	7.6	0.9
HOSING	1.0	62	8.4	0.99
HIGH PRESSURE	1.0	63	7.9	0.93
HOSING	1.0	63	8.5	1.00
ACID	1.0	62	8.0	0.94
WASHED	1.0	62	8.5	1.0
KILNED	1.0	64	6.0	0.71
	1.0	64	6.0	0.71

domes to the tank conditions. The data for steam cleaned domes are not available in the latter periods. During the test program the header that contained the steam cleaned domes was broken loose, and this unit had to be replaced. In view of the data that had been collected to date, a decision was made not to reinstall the steam cleaned units.

Table 7 summarizes the data for the 1 cfm dome testing study. The data suggest that the newly cleaned domes returned to their former condition within the 9 months after cleaning. Thereafter, little deterioration in the systems were noted. Visual inspection of the domes tended to support this conclusion. No difference was observed in the pressure required to pass air through the individual domes at the desired flow rate.

Concern must be expressed regarding the efficacy of the test method. When the dirty domes were placed in the aeration tank for study, the activity of handling the domes resulted in a disturbance of the films. Under aeration in the detergent solution, particles of growth broke off the domes in a random manner. This had the impact of changing the appearance of the aeration pattern in the tank somewhat

TABLE 7

SUMMARY OF DIFFUSER CLEANING DATA

DETERGENT TESTING

DOME TYPE	OCT 85[1]	αSOTE @ 1.0 CFM/DOME JULY 86 9 MONTHS	JUNE 87 21 MONTHS
NEW	12.75		11.9
DIRTY	9.35		8.0
LOW PRESSURE HOSING	11.9	8.05	8.0
HIGH PRESSURE HOSING	11.0	7.15	8.2
ACID WASHED	10.2	9.65	8.2
KILNED	11.5		6.0
STEAM CLEANED	10.2	--	--

1 Newly cleaned domes; these domes were 3 years old at time of cleaning.

during the studies.

Close observation of the domes indicates that even with careful handling, some degree of anaerobiosis develops under thick films. This anaerobic process most likely results in a condition where the bond between the slimes and the stone is broken. When these units are placed in the aeration tank, a cleaning process begins. The degree to which sluffing and cleaning occurs appears to be random. This occurs in spite of vigorous efforts to maintain the units in proper condition. This changing condition on the surface of the domes leads to the conclusion that this test method is not particularly suitable for evaluating dirty domes.

OFF-GAS TESTING

A field study was conducted to evaluate the oxygen transfer in the tank under study. The three tanks in the study portion of plant were evaluated using "off-gas" techniques to determine the system efficiency. The data are presented in detail in Table 8. In the test section, the air flow/dome is 1.19 cfm/unit and the oxygen transfer efficiency, as αSOTE, averages 6.75 percent or 0.45 percent per foot (ft) of depth based on 15 feet of depth. This is substantially below the value of approximately 1.0 percent/ft observed in the SMU shop testing of the domes.

The lower transfer efficiency is most likely the result of a lower α in the waste and the generally dirtier condition of most of the domes in the tank. The fact that the αSOTE is much lower in the actual tank, compared to that in the shop tests, raised concerns regarding the efficacy of using the shop test data except in a comparative mode.

TABLE 8
ROWLETTE CREEK AERATION STUDY

DATE: 02/02/87 TIME: 02:31 PM

ROWLETTE CREEK AERATION STUDY: OFF GAS AND OUR ANALYSIS OF OXYGEN TRANSFER EFFICIENCIES

1-29-30/8 STATION	OUR MG/L/H	ROTO NO	ROTO RDG	HOOD FLOW SCFM	AREA FT2	FLOW SCFM	REF MV	OFFGAS MV	DO MG/L	CO2 %	Yog	MRogi	MRoi	OTEf %	OTE 20C,0 DO % (10.1)	OTE 20C,2 DO % (19.5)	FLOW WEIGHTED OTE AVERAGES: FIELD OTE*SCFM	OTE 20/0 OTE*SCFM	OTE 20/2 OTE*SCFM
I-1	66	2	129	13.4	751	314	1.001	0.934	0.5	0.0070	0.1955	0.2451	0.2650	0.075	0.079	0.064	1.007	1.059	0.860
I-2	63	2	142	14.6	507	231	1.006	0.949	0.4	0.0060	0.1976	0.2482	0.2650	0.054	0.066	0.053	0.929	0.967	0.785
I-3	63	2	86	9.5	507	151	1.002	0.934	0.7	0.0090	0.1953	0.2454	0.2650	0.074	0.080	0.064	0.703	0.754	0.612
I-4	63	2	92	10	507	158	1.005	0.930	0.4	0.0100	0.1939	0.2426	0.2650	0.085	0.088	0.071	0.846	0.881	0.716
I-5	76	2	85	9.4	507	149	1.005	0.936	0.5	0.0120	0.1951	0.2445	0.2650	0.077	0.081	0.065	0.726	0.764	0.620
I-6	76	2	83	9.2	507	146	1.008	0.943	0.5	0.0110	0.1960	0.2459	0.2650	0.072	0.076	0.061	0.664	0.698	0.567
I-7	76	2	99	10.5	507	166	1.012	0.944	0.6	0.0140	0.1954	0.2450	0.2650	0.075	0.080	0.064	0.792	0.841	0.683
I-8	51	2	107	11.3	573	202	0.996	0.937	0.5	0.0090	0.1971	0.2476	0.2650	0.066	0.069	0.055	0.742	0.780	0.633
						1518											0.073	0.077	0.062
FIRST RUN																			
II-1	64	2	75	8.5	227	60	1.001	0.928	0.6	0.0100	0.1942	0.2431	0.2650	0.083	0.088	0.070	0.702	0.745	0.605
II-2	64	2	67	7.8	227	55	1.001	0.936	0.3	0.0090	0.1959	0.2458	0.2650	0.073	0.075	0.060	0.567	0.585	0.475
II-3	51	2	79	8.8	227	62	1.003	0.942	0.6	0.0060	0.1968	0.2471	0.2650	0.068	0.072	0.058	0.595	0.632	0.513
II-4	51	2	80	8.9	227	63	1.004	0.941	0.8	0.0060	0.1964	0.2465	0.2650	0.070	0.076	0.061	0.623	0.675	0.548
II-5	60	2	78	8.8	227	62	1.002	0.944	0.4	0.0040	0.1974	0.2481	0.2650	0.064	0.067	0.053	0.563	0.586	0.476
II-6	60	2	111	11.7	227	83	1.006	0.956	0.2	0.0060	0.1991	0.2508	0.2650	0.054	0.055	0.044	0.629	0.643	0.522
II-7	63	2	77	8.7	454	123	0.999	0.948	0.3	0.0070	0.1988	0.2503	0.2650	0.055	0.057	0.046	0.483	0.498	0.404
						510											0.066	0.069	0.056
2ND RUN																			
II-1	64	2	70	8	227	57	0.996	0.927	0.4	0.0080	0.1950	0.2443	0.2650	0.078	0.081	0.065	0.624	0.650	0.528
II-2	64	2	70	8	227	57	0.997	0.934	0.3	0.0060	0.1963	0.2463	0.2650	0.071	0.073	0.058	0.564	0.582	0.472
II-3	51	2	85	9.4	227	67	1.005	0.945	0.6	0.0070	0.1970	0.2475	0.2650	0.066	0.070	0.057	0.622	0.661	0.537
II-4	51	2	83	9.3	227	66	1.003	0.946	0.5	0.0060	0.1976	0.2484	0.2650	0.063	0.066	0.053	0.583	0.613	0.497
II-5	60	2	80	8.9	227	63	1.006	0.951	0.4	0.0080	0.1980	0.2491	0.2650	0.060	0.063	0.050	0.534	0.556	0.451
II-6	60	2	107	11.3	227	80	1.009	0.959	0.2	0.0070	0.1991	0.2508	0.2650	0.054	0.055	0.044	0.606	0.619	0.502
II-7	63	2	87	9.5	454	135	1.002	0.951	0.2	0.0050	0.1988	0.2504	0.2650	0.055	0.056	0.045	0.525	0.536	0.436
						524											0.063	0.065	0.053
III-1	30	2	156	15.8	751	371	1.006	0.926	2.4	0.0070	0.1928	0.2410	0.2650	0.091	0.119	0.095	1.432	2.112	1.501
III-2	30	2	153	15.6	507	247	1.003	0.934	2.1	0.0050	0.1951	0.2445	0.2650	0.077	0.098	0.078	1.208	1.712	1.223
III-3	30	2	141	14.5	507	230	1.006	0.934	1.8	0.0050	0.1945	0.2436	0.2650	0.081	0.098	0.079	1.173	1.598	1.147
III-4	30	2	140	14.4	507	228	1.006	0.941	2.4	0.0060	0.1960	0.2459	0.2650	0.072	0.095	0.076	1.041	1.535	1.091
III-5	25	2	135	14	507	222	1.001	0.936	2.8	0.0070	0.1959	0.2458	0.2650	0.073	0.100	0.081	1.018	1.588	1.120
III-6	25	2	114	11.9	507	189	0.997	0.931	2.7	0.008	0.1956	0.2453	0.2650	0.074	0.101	0.081	0.883	1.359	0.961
III-7	25	2	121	12.6	507	200	0.994	0.933	2.4	0.009	0.1966	0.2469	0.2650	0.068	0.089	0.072	0.860	1.269	0.902
III-8	24	2	103	10.9	573	195	0.995	0.936	1.6	0.007	0.1971	0.2476	0.2650	0.066	0.078	0.063	0.716	0.952	0.685
						1881											0.076	0.111	0.079
						--------					5.890								
						4433													
																RUN (II)	0.072	0.069	0.068

CLEAN WATER STUDIES

At the end of the plant scale studies, a set of domes was removed from the tank, and the domes were recleaned by low pressure hosing, high pressure hosing, acid wash and kilning. These domes were tested in clean water and compared with unclean domes from the respective sections. The results of these studies are presented in Table 9.

Old domes that had not been cleaned at any time during the program were also tested as part of this evaluation. The results of the study were erratic.

In general, the domes after cleaning returned to within 10 percent of the original test level. Variability in the data makes it difficult to draw detailed conclusions concerning any of the individual cleaning methods. As a general observation, all the methods worked well.

TABLE 9

RECLEANING AFTER 21 MONTHS SERVICE

CLEAN WATER

DOME TYPE	BEFORE RECLEANING			AFTER RECLEANING
		DETERGENT αSOTE	CLEAN WATER αSOTE	CLEAN WATER αSOTE
OLD DOMES NOT CLEANED	1.0 cfm/d	8.0	9.25	
LOW PRESSURE	1.0 cfm/d	8.0	11.7	10.65
HOSING	2.0 cfm/d			12.65
HIGH PRESSURE	1.0 cfm/d	8.2	8.5	12.65
HOSING	2.0 cfm/d			12.4
ACID	1.0 cfm/d	8.2	8.4	11.5
WASHED	2.0 cfm/d			10.6
KILNED	1.0 cfm/d	6.0	11.5	9.3
	2.0 cfm/d			10.3

NEW DOMES 12.6% @ 1 cfm/dome

OBSERVATIONS ON DIFFUSER CLEANING

Overall observations suggest that, in the test plant, fouling of the diffusers was not a major problem. The major diffuser problems appear to have been caused by failures in the system that allowed broad-based contamination. The growths that developed on the exterior of the domes did not appear to dramatically reduce the OTE over the study period. Over a substantial period fouling does develop on the domes and periodic cleaning is recommended. Field investigations suggest that conscientious low pressure hosing is an acceptable routine technique for diffuser cleaning. High pressure hosing could be helpful periodically to improve cleaning of the systems. In the study system it is probably not justified each time the tank is taken down.

Although the data are not conclusive, we believe that the use of acid washing system, such as the Milwaukee Method, should be used at the North Texas plant, at intervals of possibly 3 to 5 years. A note of caution: this technique should be used with care to avoid possible harm to employees.

More elaborate cleaning techniques such as kilning require removing the domes from the mounts and should be avoided. The problems associated with removing domes, handling them, and replacing them outweigh the benefits that appear to be associated with these types of techniques. The effort involved in such a program does not appear to be justified, based on the observed results at North Texas.

GENERAL DISCUSSION OF RESULTS

The proposed test method, based on removing specific devices from an aeration tank and performing shop tests, seems to be limited in value. Even if the method can be carried out in a vigorous, controlled atmosphere, the changes in conditions and the variations introduced by handling the devices appear to significantly influence results.

There is a significant variation in test data, which is magnified when a relatively shallow tank is employed. Variations appear to occur among individual aeration devices, which suggests that a large number of samples would be required to develop a statistically significant evaluation of the transfer capacity. This does not appear to be very practical in a small test tank.

Using detergent in the test solution allows the fluid to more closely represent the actual field conditions under which transfer occurs; however, including detergent appears to cause some degree of cleaning of the domes. This inter-reaction changes the concentration of surface active materials and causes some sluffing of slimes from the dirty units. The importance of this phenomenon is hard to quantify, but observation indicates that it is significant.

The clean water testing shows the efficiency of domes. Although the methods very imprecise it does not overwhelm the data interpretation. Overall, using a test tank of small size, and evaluating a limited number of domes, does not appear to provide an efficient, effective means of estimating the need for diffuser cleaning. On the other hand, using such a tank appears to be appropriate in comparing the relative degree of cleaning that can be achieved by various methods. Such a comparison is helpful in determining the appropriate cleaning techniques that should be used for diffuser maintenance.

EVALUATION OF DOME AIR FLOW CHARACTERISTICS

At the end of the study, five domes from each cleaning group were removed from the Rowlette Creek treatment system and were sent to the University of Wisconsin for evaluation. The detailed data collected from this survey are included as Appendix 2. Evaluation of these data suggests that the domes vary widely in all measurable characteristics. No discernible pattern or correlation between the physical variables and the transfer characteristics was apparent. Further investigation of the meaning of the data and the relationships between diffuser fouling and oxygen transfer will be required before this information can be meaningfully related to plant performance.

Figure 12 shows the Dynamic Wet Pressure (DWP) variation from clean units to the average of each fouled unit. Figure 13 shows the variation of DWP from unit to unit for the cleaned domes.

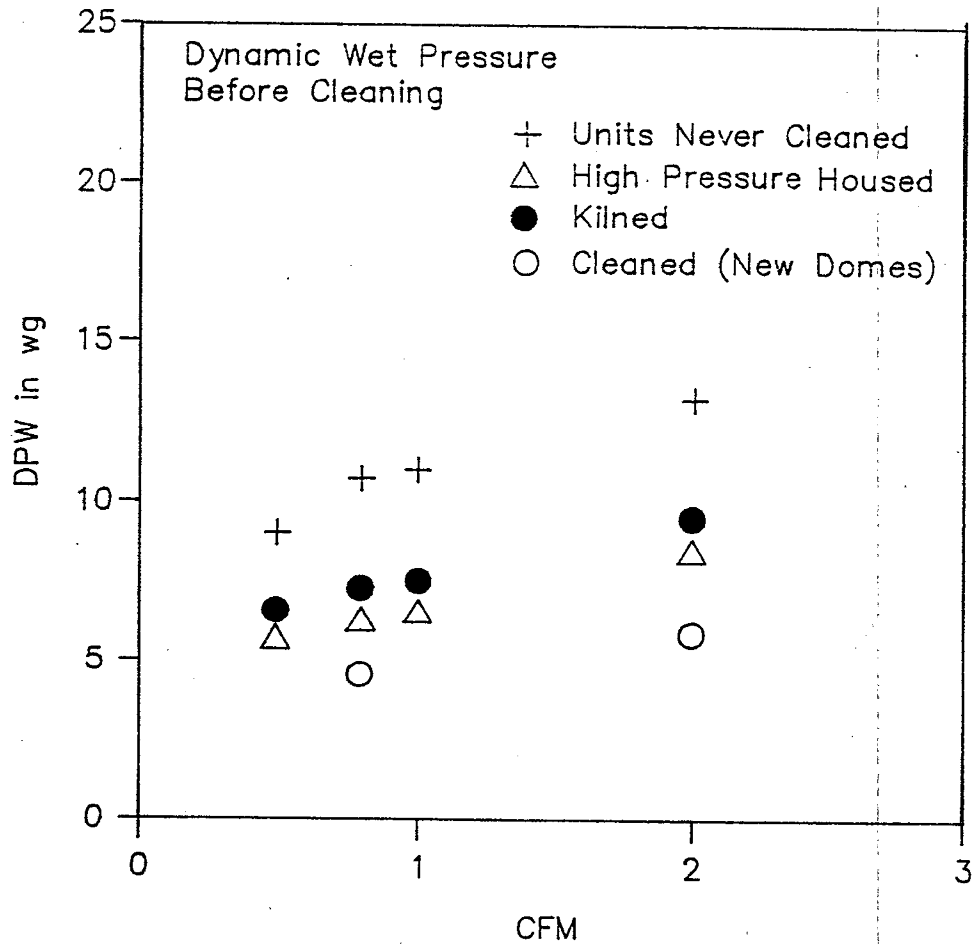


FIGURE 12: DYNAMIC WET PRESSURE OF CONTAMINATED DOMES

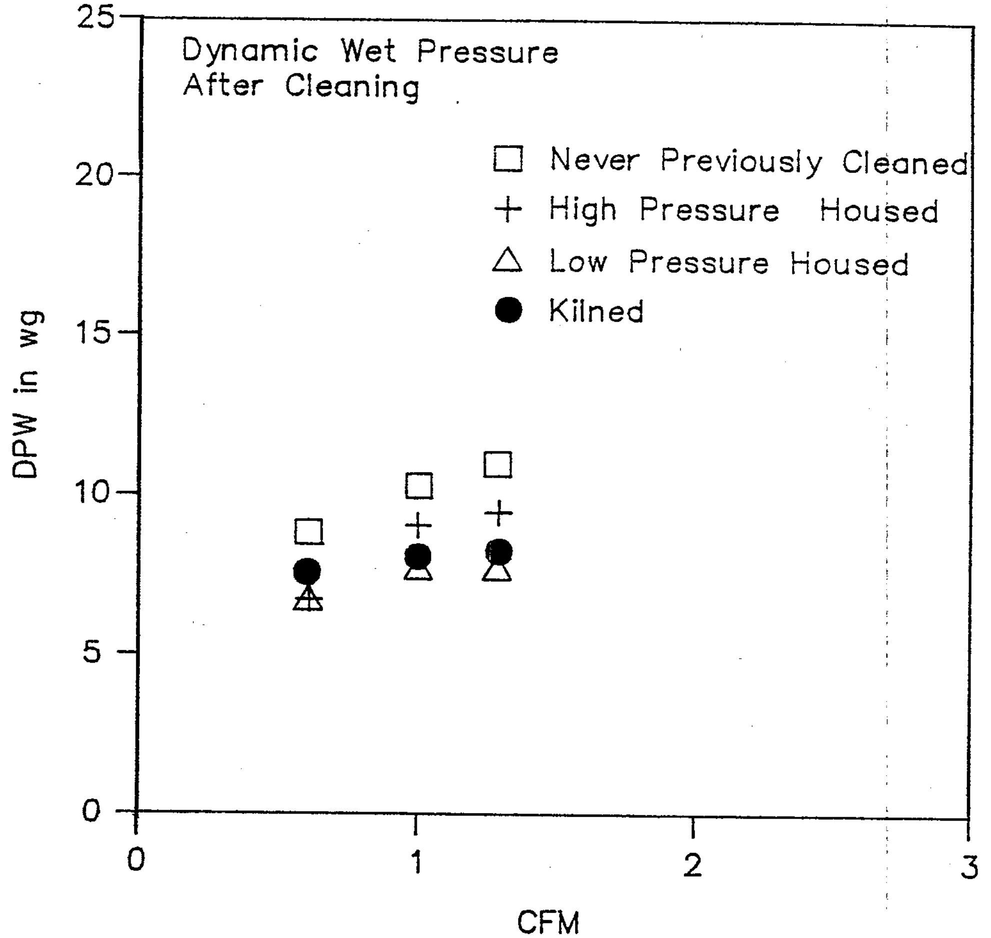


FIGURE 13: DYNAMIC WET PRESSURE OF CLEANED DOMES

SPECIAL STUDIES - NEW DOMES

A special study was conducted to examine the variations that would occur by virtue of the cleaning techniques on new domes. To accomplish this study, 24 new domes were selected from a lot available at Fort Worth Village Creek Treatment Plant. These domes were divided into four groups. Each group of domes were installed in the test tank and was tested at 1 and 2 cfm. Each test was carried out in triplicate. In the first set of tests, the domes were evaluated as received. After that, the tank water level was lowered, and the domes were washed according to the low pressure hosing procedure. The run was then repeated. The domes were also high pressure washed, acid washed and kilned, and then retested.

Only two sets of kilned domes were studied because the Art Department had to shut down the kiln during the latter portions of the study.

The detailed analytical data from this investigation are presented in Appendix 3. Table 10 summarizes the run for the K_La and the standard oxygen transfer efficiency (SOTE)

TABLE 10
CLEAN DOME STUDY

ASCE/EPA Research Project
Clean Dome Study
student "T" Test
Data is Kla/min and SOTE from the test tank

New Domes 1 cfm		2 cfm		Low Press Hosed 1 cfm		2 cfm		High Pres Hosed 1 cfm		2 cfm		Acid Washed 1 cfm		2 cfm		Kilned 1 cfs		2 cfs	
Kla/min	SOTE	Kla/min	SOTE	Kla/min	SOTE	Kla/min	SOTE	Kla/min	SOTE	Kla/min	SOTE	Kla/min	SOTE	Kla/min	SOTE	Kla/min	SOTE	Kla/min	SOTE
0.0152	6.688	0.0399	8.778	0.03	13.2	0.051	11.22	0.0314	13.816	0.0685	15.07	0.03	13.2	0.0615	13.53	0.0244	10.736	0.0421	9.262
0.0108	4.752	0.0375	8.25	0.032	14.08	0.0477	10.494	0.0277	12.188	0.0613	13.486	0.03	13.2	0.058	12.76	0.0214	9.416	0.0483	10.626
0.0112	4.928	0.0358	7.876	0.0315	13.86	0.056	12.32	0.0316	13.904	0.057	12.54	0.0298	13.112	0.056	12.32	0.024	10.56	0.0497	10.934
0.0266	11.704	0.048	10.56	0.024	10.56	0.05	11	0.032	14.08	0.06	13.2	0.037	16.28	0.0625	13.75	0.025	11	0.0414	9.108
0.0321	14.124	0.047	10.34	0.025	11	0.046	10.12	0.029	12.76	0.054	11.88	0.032	14.08	0.058	12.76	0.0252	11.088	0.0447	9.834
0.027	11.88	0.042	9.24	0.026	11.44	0.049	10.78	0.03	13.2	0.048	10.56	0.029	12.76	0.066	14.52	0.0245	10.78	0.0484	10.648
0.022	9.68	0.045	9.9	0.035	15.4	0.048	10.56	0.034	14.96	0.061	13.42	0.039	17.16	0.065	14.3				
0.024	10.56	0.045	9.9	0.032	14.08	0.064	14.08	0.029	12.76	0.064	14.08	0.031	13.64	0.055	12.1				
0.021	9.24	0.047	10.34	0.034	14.96	0.0403	8.866	0.028	12.32	0.058	12.76	0.025	11	0.046	10.12				
0.02	8.8	0.046	10.12	0.023	10.12	0.053	11.66	0.0305	13.42	0.059	12.98	0.033	14.52	0.057	12.54				
0.019	8.36	0.069	15.18	0.0265	11.66	0.051	11.22	0.035	15.4	0.076	16.72	0.027	11.88	0.042	9.24				
0.013	5.72	0.073	16.06	0.036	15.84	0.053	11.66	0.03	13.2	0.073	16.06	0.025	11	0.054	11.88				
0.022744	8.869666	0.051333	10.54533	0.029055	12.78444	0.050477	11.10511	0.030833	13.56666	0.061444	13.51777	0.030888	13.59111	0.056166	12.35666	0.0249	10.956	0.044833	9.863333
0.006421	2.825349	0.010994	2.418671	0.004314	1.898540	0.005519	1.214375	0.002149	0.945886	0.007512	1.652772	0.004071	1.791661	0.006811	1.498518	0.001262	0.555642	0.003226	0.709895
	10.00755		11.29333																

Test	Mean Kla/min	(x-M)^2	# Of Points	"T" stst			
new 1cfm	0.022744	0.00078	9				
new 2cfm	0.051333	0.00145	9	n/l 1	-0.57528	l/h 1	-0.19443
lph 1cfm	0.029055	0.01098	12	n/h 1	-2.76709	l/aw 1	-0.19134
lph 2 cfm	0.050477	0.00294	12	n/aw 1	-1.83829	l/h 2	-2.09704
				n/k 1	-0.20228		
hph 1 cfs	0.030833	0.000055	12	n/l 2	0.127642	l/a 2	-1.05543
hph 2 cfs	0.061444	0.00067	12	n/h 2	-2.17075	l/k 1	0.359783
aw 1 cfs	0.030888	0.001138	12	n/a 2	-0.66065	l/k 2	0.478940
aw 2 cfs	0.056166	0.00378	12	n/k 2	0.554966		
Kil 1cfs	0.02408	0.00126	6				
Kil 2cfs	0.04576	0.00327	6				

for each study condition. The mean and standard deviations of each set of studies are presented in that table. The data from the initial run on clean domes are inconsistent with all other observations. The reason for this change is believed to be related to system problems in airflow. Field observations, as well as the values obtained, suggest that these values are not representative. The average for the new dome set is calculated by deleting the initial triplicate set of data.

Table 11 compares the new domes with the various cleaning methods. The data present a curious picture. The new domes in this test showed an oxygen transfer efficiency less than observed in all previous testing. The new domes would be expected to transfer approximately 12.8 percent at 1 cfm and 12.2 percent at 2 cfm. The first run with new domes is suspect because of erratic air flow; all other runs should be considered valid. The lower than expected values for clean domes may have resulted from a film or coating on the dome surface.

The values obtained for the low pressure, high pressure, and acid testing are statistically significantly higher than the

TABLE 11

NEW DOME STUDY - TRIPLICATE RUNS IN CLEAN WATER

	SCFM/UNIT	MEAN	SOTE STANDARD DEVIATION
NEW DOMES	1	10.0	2.8
	2	11.3	2.4
LOW PRESSURE	1	12.8	1.9
HOSING	2	11.1	1.2
HIGH PRESSURE	1	13.5	0.9
HOSING	2	13.5	1.6
ACID	1	13.6	1.8
WASHED	2	12.3	1.5
KILNED	1	10.96	0.55
	2	9.86	0.71

values obtained for new domes. They are statistically equal to the values that would have been expected for the new domes based on previous testing. The kilned values are lower than would have been expected.

Examination of the new domes showed no physical reason why the lower performance was observed. Examination of the data and study techniques did not indicate any problem. The fact that these runs were run at the end of the study is also an important consideration. Techniques had been refined, the personnel were well trained, and the test conditions were ideal. The only possible problem was that the temperatures were somewhat lower than desirable for testing, but the clean water runs were all above 9°C. This problem is not believed to have interfered significantly with test data gathering. We do not know the reason for this seeming anomaly in the information.

COST OF DOME CLEANING

To collect significant information on the cost of dome cleaning, the data available from several treatment plants were reviewed. Examination of the information showed a wide range of costs associated with this process. Further examination of the data revealed that each plant tabulates costs in a unique fashion; grouping together both cost of dome cleaning and a wide variety of related activities. Activities such as draining tanks, cleaning tanks, inspecting and repairing dome systems, and carrying out other required maintenance are usually reported as an integral part of the total cost of a dome cleaning operation. This procedure makes it very difficult to provide any specific information on the individual unit operations associated with this process.

The cost of dome cleaning is also significantly influenced by the work rules and procedures employed at a particular plant. The impact of work rules on the total time required for a project can be exemplified in the following example, Case 1.

CASE 1 - TYPICAL WORK DAY FOR DOME CLEANING AT ONE PLANT

7:00 a.m.	Arrive, dress for days work, review work assignment with the supervisor, walk to tank.
7:35 a.m.	Enter tank and begin work.
9:15 a.m.	Out of tank and coffee break.
9:40 a.m.	Reenter tank and work.
11:00 a.m.	Leave tank, walk to lunch room, wash-up, half-hour for lunch, redress, walk back to tank.
12:00 p.m.	Reenter tank.
1:20 p.m.	Leave tank, 10-minute break.
1:30 p.m.	Reenter tank.
2:30 p.m.	Leave tank, walk to locker room, wash-up, fill out sheets on daily activities.
3:00 p.m.	End of shift.

The actual time spent in the tank washing domes during the 8-hour day in Case 1 came to approximately 5.3 hours. In a second case, a contractor was able to have 7.2 hours of actual work during a day. Although these cases are well within standard operating efficiency expectations, they represent a significantly different effort in the given period, which impacts the cost information obtained.

Another major factor that must be considered when evaluating time estimates is the availability of mechanical equipment to assist in the cleaning process. For example, in one case, the plant is able to lower a small front-end loader into the aeration tank to assist with removing grit and other debris; however, in another case, the removal of debris is manual with shovels and buckets. The difference in man-hours associated with these two operations is obviously very significant.

FACTORS THAT INFLUENCE TANK CLEANING COSTS

A wide variety of factors influence the cost of dome cleaning. These factors relate to the design and operating load at the treatment system.

To carry out any cleaning operation, the tank must be first dewatered. The relative ease of dewatering depends on the plant's design. In many instances, the tanks can be drained by gravity with a minimum of inconvenience. In other cases, complicated rerouting of the sewage and or return sludge flow is required to dewater a tank. In other instances, the tanks must actually be pumped to achieve effective drainage. The time required for dewatering a tank can vary from 1 to 2 man-hours up to 8 to 10 man-hours depending on the considerations of the individual plant.

After the tank is dewatered, the condition of the floor is the next factor of major concern. In most plants, grit and other heavy materials will precipitate in the zone below the diffusers. If the diffusers are placed more than 1 foot above the floor, significant deposits of material will normally be observed at least in the front end of the system. The relative ease or difficulty of removing these materials will depend on the forethought of the engineering design. If the system has been designed to allow easy operation and cleaning, this material can be hosed down or bucketed out. If the units have been placed too close to each other and if the piping is complicated, removing this material can be a long and tedious task. In some plants mechanical equipment must be brought in to effectively handle the removal of grit and other solids. Other plants have used vacuum type pumps to facilitate cleaning.

Before a tank can be returned to service, the aeration system should be inspected and repaired as necessary. The age and condition of the aeration system will obviously impact this particular activity in a significant manner.

THE UNIT OPERATIONS OF TANK CLEANING

To come up with some effective and reasonable cost estimates for cleaning and operations, a study was performed on the unit operations associated with the process. This was done by observing, in the field and in a laboratory, the work-time required for each process associated with dome cleaning. The data presented in this report are generalizations and not intended to be precise. They are presented to allow the engineer to make a reasonable estimate of the costs associated with various cleaning operations.

UNIT OPERATION	DESCRIPTION
(1) Tank Dewatering	Depends on Design--Withdrawal or pumping will influence time. Normal needs, 4 to 6 man-hours.
(2) Tank Cleaning	Depends on location of the diffusers, the height off the floor, and whether or not the plant has primary treatment. Twenty man-hours per 1,000 diffusers.

(3) Cleaning--Low Pressure Hosing

The initial unit operation in any cleaning system must be low pressure hosing to remove the loose growths from the system. Ten man-hours for setup and ten man-hours per 1,000 domes, including pipes and supports.

(4) Inspection and Repair

Any obvious system breaks will be observed and noted while a small amount of water still covers the diffusers. Inspection of the system and repair of it depends on the system's age. Ten man-hours per 1,000 domes.

(5) High Pressure Hosing

Can be accomplished after low pressure hosing. Twenty-five man-hours per 1,000 domes.

(6) Steam Cleaning

Should be accomplished after low

pressure hosing. Assume that mechanical equipment is available to lower equipment into tanks; forty man-hours per 1,000 domes.

(7) Acid Washing — This process requires approximately 60 man-hours per 1000 domes.

(8) Dome Removal and Replacement — Removing domes from the system for any cleaning and operation and subsequently replacing them will require significant time and some degree of equipment replacement. Eighty-five man-hours per 1,000 domes, plus replacement of 5 percent of equipment.

(9) Kilning — If kilning is to take place, estimate $5 per dome above the cost of removal and replacement.

Using these data to estimate the cost of cleaning is demonstrated in the following example:

EXAMPLE 1:

TYPICAL CASE--LOW PRESSURE HOSING

1,000 DOMES/5,000 DOMES

(1) 1,000 domes would treat approximately 1.5 million gallons of sewage per day.

		1,000 DOMES	5,000 DOMES
(1)	Dewater Tank	4 mh	4 mh
(2)	Clean Tank	20 mh	100 mh
(3)	Low Pressure Hosing	20 mh	60 mh
(4)	Inspect and Repair	10 mh	50 mh
(5)	Refill Tank	4 mh	4 mh
	TOTAL	58 mh	218 mh

For 1,000 Domes:

58 man-hours x $7.50/hr pay x 2.1 (indirect costs including benefits) = $913.50 x efficiency factor of 1.3 = $1,187.55, or approximately $1.19 per dome.

For 5,000 Domes:

The cost per dome is $0.89 per dome.

The 2.1 (indirect cost including benefits factor) used in the above example accounts for the in-direct manpower costs including supervision, administrative, payroll, and benefit costs.

The efficiency factor of 1.3 is used to relate the time spent cleaning domes to the total hours worked by the individual. This considers such time as preparation time, breaks, and washup.

If two men are employed the total estimated time for cleaning a tank of 1,000 domes is approximately 1 week. Experience suggests that such operations usually occupy the full time allotted for the task. Adding a third man to the staff, for example, is unlikely to result in the tank's being cleaned any faster. It will most likely result in a more thorough job of cleaning and inspection.

EXAMPLE 2:

If the 1,000 domes from Example 1 are to be acid washed, in addition to previous cleaning, an additional sixty man-hours would be required. This would result in a total cost of one hundred-eighteen man-hours or $2.40 per dome.

Although these formulations are not considered to be precise or scientific, they do provide a reasonable estimate of the costs associated with cleaning. These numbers have been checked against the actual data available from field studies and correlate realistically.

GENERAL OBSERVATIONS

The following observations have been made concerning the cleaning process and may be helpful in actual plant operations:

(1) Domes should be regularly cleaned; once a year appears to be desirable. The operations are likely to be more smooth if they are planned in advance rather than being undertaken when the occasion presents itself.

(2) When dewatering the tank, leave the air on until the water level reaches the domes. This policy may require adjusting other tank conditions to maintain airflow throughout the system. If possible, stop the dewatering when the water is about 1 to 2 feet above the domes. At this point, inspect the system from the tank edge to identify any discontinuity or breaks in the aeration system. Carefully map the location of any problems so that they can be corrected later when the tank is completely dewatered.

(3) If possible, do the low pressure washing from within the tank and close to the domes. Water, particularly from fire hoses, cascading on domes from the top of the tank, has an adverse affect on the units and in some cases causes cracking in the housings.

(4) Do not loosen or move domes unless it is absolutely necessary. Reseating domes in a proper manner is a difficult and time-consuming operation.

(5) Acid washing of the domes every several years is probably desirable. There is, however, no absolute

evidence to reenforce this belief under the operating conditions observed at the North Texas plant.

OVERALL DISCUSSION OF RESULTS

The studies conducted on the cleaning of domes suggest that the costs vary significantly from plant to plant. The cost differences are usually associated with the ancillary operations attendant to dome cleaning rather than the cleaning itself. These variations are caused both by design features and work rules. In case, the cost of cleaning the domes are relatively modest. For domes operated in the range of 1 cfm/unit, the cost of providing air for a year is estimated at $18.50 per unit. If the efficiency can be improved by 10 percent each year by cleaning, the costs savings would be about $1.85, which is roughly equivalent to the cleaning costs of the unit. Improving the efficiency by 20 percent would certainly be a good investment.

Keeping an aeration system in top condition will lead to better overall operation of the treatment plant and better effluent quality. This consideration alone is sufficient to justify the investment in maintenance and upkeep of aeration equipment.

REFERENCES:

(1) BARNHART, E.L. "An Overview of Oxygen Transfer Systems" Proc. Workshop on Aeration System Designs, Operation, Testing and Control, U.S.EPA, EPA 600/9-85-005, Cincinnati, Ohio (January, 1985).

(2) BOYLE, W.C. and REDMON, D.T. "Biological Fouling of Fine Bubble Diffusers: State-of-Art" ASCE Journal of the Environmental Engineering 109,5,991-1005 (1983).

(3) "A Standard for the Measurement of Oxygen Transfer in Clean Water" American Society of Civil Engineers, Oxygen Transfer Standards Committee, New York, New York (1984).

(4) BARNHART, E.L. "Transfer of Oxygen in Aqueous Solutions" ASCE Journal of the Sanitary Engineering Division, 95, 3, 645-661 (1969).

(5) DOWLING, A.L. and BOON, A.G. "Oxygen Transfer in the Activated Sludge Process", In Advances In Biological Waste Treatment, Ed W.W. Eckenfelder, Jr. and B.J. McCabe Pergammon Press, New York, New York (1963).

(6) Standard Methods for the Examination of Water and Wastewater, 16th Edition (1985).

(7) Quality Assurance Program Plan ASCE/EPA "Design Information On Fine Bubble Diffused Aeration": C. Robert Baillod, Section A12.0, 1985.

APPENDIX 1

DETAILED TEST TANK PROCEDURES

SMU TEST TANK STUDIES

Measurement of Oxygen Transfer Rate in Clean Water and Detergent Tests. This method of procedure was employed for all testing.

1. Scope

This method covers the measurement of the oxygen transfer rate, OTR, as a mass of oxygen per unit time is dissolved in a volume of water by an oxygen transfer system operating at a given gas flow rate. It is intended to measure the rate of oxygen transfer from diffused gas oxygenation devices to relatively large volumes of water. Although the method is intended primarily for clean water, it applies to water containing surface active agents and low concentration of salts.

The study results are expressed as the Standardized Oxygen Transfer Rate, (SOTR), a hypothetical mass of oxygen transferred per unit time at zero dissolved oxygen concentration, a water temperature of 20°C, and a barometric pressure of 1.00 atm, under specified gas rate and power conditions. The results can be used to estimate oxygen transfer rates at process conditions.

2. Summary of Method

The Test method is based on removing dissolved oxygen (DO) from the water volume by sodium sulfite followed by reoxygenation to near the saturation level. The DO inventory of the water volume is monitored during the reaeration period by measuring DO concentrations at several determination points selected so that each point senses an equal tank volume. These DO concentrations may be sensed <u>in situ</u> using membrane probes. The method specifies a minimum number, distribution, and range of DO measurements at each determination point.

The data obtained at each determination point are then analyzed by a simplified mass transfer model to estimate the apparent volumetric mass transfer coefficient, K_La, and the saturation concentration, C^*_∞. The basic model is defined as follows:

$$C = C^*_\infty - (C^*_\infty - C_O) \exp(-K_La\ t) \qquad 1$$

where:

C = DO concentration, $m\ L^{-3}$

C^*_∞ = DO concentration attained as time approached infinity, $m\ L^{-3}$

C_o = DO concentration at time zero, $m\ L^{-3}$

K_La = Apparent volumetric mass transfer coefficient t^{-1}, defined so that

$$K_La = \frac{\text{rate of mass transfer per unit volume}}{C^*_\infty - C}$$

Nonlinear regression is employed to fit Equation 1 to the DO profile measured at each determination point during reoxygenation. In this way, estimates of K_La and C^*_∞ as are obtained at each determination point. These estimates are adjusted to standard conditions, and the standardized oxygen transfer rate (mass of oxygen dissolved per unit time at an hypothetical concentration of zero DO) is obtained as the product of the average adjusted K_La value, the average adjusted C^*_∞ value, and the tank volume.

3. Significance and Limitations

Oxygen transfer rate measurements are useful for comparing the performance and energy efficiency of oxygenation devices operating in clean water. Performance of these devices in process water may significantly differ from the performance in clean water, and the amount of difference will depend on the device and on the nature of the process water.

4. Definitions and Nomenclature

4.1 Mass Transfer Terms

4.1.1 Oxygen Transfer Rate (OTR). Mass of oxygen per unit time dissolved in a volume of water by an oxygen transfer system operating under given conditions of temperature, barometric pressure, power, gas rate and dissolved oxygen concentration.

4.1.2 Oxygen Transfer Rate at Zero DO (OTR_o). OTR when the DO concentration is equal to zero at all points in the water volume.

4.1.3 Oxygen Transfer Rate in Process Water (OTR_f). OTR for the oxygenation system operating at a specified average DO concentration and temperature in wastewater.

4.1.4 Standardized Oxygen Transfer Rate (SOTR). OTR in clean water when the DO concentration is zero at all points in the water volume, the water temperature is 20°C, and the barometric pressure is 1.00 atm.

4.1.5 Aeration Efficiency (AE). OTR per unit total power input. Power input may be used either on delivered power or wire power.

4.1.6 Standardized Aeration Efficiency (SAE). SOTR per unit standard power input; may be based on Total Delivered Standard Power or Wire Standard Power.

4.1.7 Oxygen Transfer Efficiency (OTE). Fraction of oxygen in an injected gas steam dissolved under given conditions of temperature, barometric pressure, gas rate, and DO concentration.

4.1.8 Oxygen Transfer Efficiency at Zero DO (OTE_o). OTE when the DO concentration is equal to zero at all points in the water volume.

4.1.9 Standardized Oxygen Transfer Efficiency (SOTE). OTE_o when the water temperature is 20°C and the barometric pressure is 1.00 atm.

5. Apparatus and Methods

5.1 Tank. The SMU test tank is 20 feet long, 3.5 feet wide and 9.5 feet. deep. Allowing for 1 foot of free board, the system contains 17,800 liters of water.

5.2 Water. For determination of a standardized OTR, the water to which oxygen was transferred was potable public water from the City of Highland Park, Texas.

5.3 Oxygenation Device. This method was applied to a variety of oxygenation devices installed in the tank including Norton Domes, WYSS tubes, and flat plate diffusers.

5.4 Dissolved Oxygen Measurement

5.4.1 *In situ* Membrane Electrode Measurement of DO was employed with Section 421F of Standard Methods (6).

5.5 Temperature Measurement. Water temperature measurement was in accordance with Section 212 of Standard Methods (6).

5.6 Deoxygenation Chemicals

5.6.1 Sodium Sulfite. Technical Grade sodium sulfite (Na_2SO_3) was used for deoxygenation in accordance with Section 6.8

5.6.2 Cobalt Catalyst. Either reagent grade cobalt chloride, $CoCl_2$, was used to catalyze the deoxygenation reaction in accordance with Section 6.8.

5.7 Electronic Computer. A digital computer was used for running the nonlinear regression method of parameter estimation described in Section 7.2.1.

5.8 Gas Flow Measurement Apparatus. Rotameters, calibrated at regular intervals, were used for all air flow measurements.

6.0 Procedure

6.1 Water Quality

6.1.1 General and Total Dissolved Solids. The water supplied for the tests was a potable public water supply. Repetitive testing was conducted in the water only twice so that the TDS did not exceed 1,500 mg/l in any case.

6.1.2 Temperature. The water temperature should be between 5° and 30°C. Low temperatures were recognized to slow the deoxygenation reaction, which may introduce some error. A standard Θ value of 1.024 was employed to adjust for temperature. Appreciable error can be introduced when the actual Θ value differs from this and the temperature difference is more than 5°C. The water temperature did not change by more than 2°C during a single unsteady state test.

6.1.3 Water Quality Analyses. Initial Analyses: Before beginning the testing program, a representative sample of the water was tested and analyzed for TDS, alkalinity, sulfite, iron, manganese, residual chlorine, pH, total organic carbon or chemical oxygen demand, cobalt, surfactant (MBAS), and temperature.

6.2 System Stability. The aeration system was operated to achieve-steady state hydraulic conditions before starting the oxygen transfer evaluation. The hydraulic mixing regime was established in the test tank for each test condition before deoxygenation.

6.3 Deoxygenation Chemicals. Technical grade sodium sulfite (Na_2SO_3) was used for deoxygenation. The sulfite was essentially cobalt free and contained no impurities that would alter the OTR analysis. Sodium sulfite was added in solution by dissolving the sulfite in a separate mixing tank before adding it to the test tank.

The sulfite deoxygenation reaction is catalyzed by cobalt. The cobalt source utilized was technical grade cobalt chloride, $CoCl_2$. The cobalt was dissolved before adding it to the test tank. Care was taken to ensure that the cobalt salt was completely dissolved.

6.4 Addition of Deoxygenation Chemicals

6.4.1 Cobalt Addition. A solution of cobalt salt was added to the test tank to achieve a soluble cobalt concentration between 0.3 and 0.5 mg/l in the test water.

The cobalt solution was added before the beginning of the oxygen transfer testing with the aeration system operating. The solution was uniformly distributed into the test tank. The cobalt solution was dispersed throughout the tank by operating the aeration system for longer than 30 minutes. The cobalt catalyst was normally added once for each test water.

6.4.2 <u>Sulfite Addition.</u> The theoretical sodium sulfite requirement for deoxygenation is 7.88 mg/l per 1.0 mg/l DO concentration. Sulfite additions were made in 130 percent excess of stoichiometric amounts.

Sufficient sulfite solution was added to depress the DO level below 0.50 mg/l at all points in the test water. In most cases, the DO concentration reached zero at all sample points and remained at zero at least several minutes prior to beginning the run.

Sodium sulfite was dissolved in a small mixing tank outside the test tank and distributed uniformly and rapidly into the test tank. Care was exercised to assure adequate dispersion and dissolution in the test tank.

6.5 Determination of Dissolved Oxygen at Various Points in the Tank During the Unsteady State Test. The DO concentration was determined at various points in the tank and at various times during the unsteady state test. This determination shall be carried out by in situ measurement of dissolved oxygen in the tank by membrane probes.

6.5.1 Location of Dissolved Oxygen Determination Points. Three determination points were used: One at a shallow depth, one at a deep location< and one at mid-depth. The points were mid-tank.

The determination points were located so that each senses an equal portion of the tank volume and were distributed vertically and horizontally to best represent the tank contents.

6.5.2 <u>Times of Dissolved Oxygen Determination.</u> A minimum of 20 DO values were measured at prescribed times at each determination point during the unsteady state test. In most cases, 30 points were obtained.

6.5.3 <u>Run Duration and DO Saturation.</u> DO data were obtained over as wide a range as possible. Data at DO levels of less than 10 percent of C^*_∞ were truncated to avoid lingering effects of the deoxygenation technique.

All test runs were continued for a period approximately equal to 4 divided by the anticipated value of K_La. This is equivalent to continuing the run until the DO concentration is 98 percent of the saturation concentration, C^*_∞; the system was allowed to run overnight to obtain data on C^*_∞.

Measured values and tabulated values of DO surface saturation concentrations were used for comparative information only and were not used as model parameters for calculation of oxygen transfer rates.

6.6 Dissolved Oxygen Measurements

6.6.1 Measurement by In Situ and Sample Line DO Probes. The in situ DO probes were fast response probes with 1.0-mil membranes, and care was taken to ensure that the water velocity was sufficient past the probe. The probes were calibrated using the Winkler procedure with test tank water and checked for linearity against Winkler procedure titrated samples. The calibration and linearity were established before every two runs. Probe calibration and linearity check can be conveniently accomplished by comparing probe readings with Winkler measurements on discrete samples taken at the probe locations.

7.0 Data Analysis

7.1 Nonlinear Regression Method. This method is based on nonlinear regression of the model (Equation 1) through the DO versus time data as prepared for analysis in Section 7.1. The best estimates of the parameters K_La, C^*_∞ and C_0 are selected as the values that drive the model equation through the prepared DO concentration versus time data points with a minimum residual sum of squares. The parameter estimates are selected so that the sum of the squares of the residuals is minimized. A "residual" refers to the difference in concentration between a measured DO value at a given time and the DO value predicted by the model at the same time.

The data were calculated employing the computer program attached as Attachment 1 to this section.

8.0 Interpretation and Reporting of Results

8.1 <u>Standardized Oxygen Transfer Rate (SOTR).</u> By convention, the oxygen transfer capacity of an oxygenation system is expressed as the rate of oxygen transfer predicted by the model at zero dissolved oxygen under standard conditions of temperature and pressure, usually 1.00 atmosphere and 20°C. This is termed the Standardized Oxygen Transfer Rate (SOTR). It should be noted that the SOTR is a hypothetical value based on zero dissolved oxygen in the oxygenation zone that is not usually desirable in real oxygenation systems operating in process water. The SOTR value shall be determined by correcting the values of K_La and C^*_∞ estimated for each determination point to standard conditions by:

$$K_La_{20} = K_La \, \Theta^{(20-T)} \qquad (2)$$

$$C^*_{\infty 20} = C^*_\infty \left(\frac{1}{\tau \, \Omega}\right) \qquad (3)$$

where:

K_La = determination point value of K_La estimated according to Section 7.2.1 or Section 7.2.2.

K_La_{20} = determination point value of K_La corrected to 20°C.

Θ = empirical temperature correction factor, defined by Equation 16; shall be taken equal to 1.024 unless proven to have a different value for the aeration system and tank tested

C^*_∞ = determination point value of C^*

$C^*_{\infty 20}$ = determination point value of C^*_∞ corrected to 20°C and a standard pressure of 1.00 atm.

τ = temperature correction factor = $\dfrac{C^*_{st}}{C^*_{s20}}$

C^*_{st} = tabular value of dissolved oxygen surface saturation concentration, mg/l, at the test temperature and a standard total pressure of 1.00 atm, (5)

C^*_{s20} = tabular value of dissolved oxygen surface saturation concentration, mg/l, at 20°C and a standard total pressure of 1.00 atm, shall be taken as 9.07 mg/l (5)

Ω = Pressure correction factor =

$$\frac{P_b + Y_{wt}d_e - P_{v20}}{P_s + Y_{ws}d_e - P_{v20}}$$

P_b = Barometric pressure during test, f/l^2.

P_{v20} = saturated vapor pressure of water at 20°C.

P_s = standard barometric pressure of 1.00 atm, f/l^2.

Y_{wt} = weight density of water at test conditions, f/l^3.

Y_{ws} = weight density of water at 20.0°C f/L^3.

P_{vt} = saturated vapor pressure of water at the test temperature, f/l^2.

d_e = effective saturation depth at infinite time, defined by:

$$d_e = \frac{1}{Y_{wt}} \frac{C^*_\infty}{C^*_{sT}} (P_s \quad P_{vt}) - P_b + P_{vt}$$

The average values of K_La_{20} and C^*_{20} shall be calculated by averaging the values at each of the n determination points by:

$$\text{Average } K_La = \overline{K_La_{20}} = \frac{1}{n} \sum_{1}^{n} K_La_{20} \qquad 4$$

$$\text{Average } C^*_{\infty 20} = \overline{C^*_{\infty 20}} = \frac{1}{n} \sum_{1}^{n} C^*_{\infty 20} \qquad 5$$

The Standard Oxygen Transfer Rate (SOTR) shall be computed by:

$$SOTR = \overline{K_La_{20}} \cdot \overline{C^*_{\infty 20}} \cdot V \qquad 6$$

where: V = volume of water in the test tank

The individual and average values of K_La_{20}, $C^*_{\infty 20}$, d_e, and the actual test temperature and tank volume shall be reported along with the SOTR. For subsurface gas injection systems, the value of SOTE should also be reported (See Section 8.4). If possible, the standard deviations of the K_La, C^*_{∞}, parameter estimates should also be reported.

8.2 <u>Spatial Uniformity and Reproducibility of K_La, $C^*_{\infty 20}$, Values.</u> Replicate tests, conducted sequentially under the same conditions of temperature and pressure and the replicate K_La, $C_{\infty 20}$ values can be compared directly without temperature and pressure adjustments.

8.3 <u>Oxygen Transfer Efficiency (OTE).</u> Oxygen transfer efficiency (OTE) refers to the fraction of oxygen in an injected gas stream, dissolved under given conditions. The Standardized Oxygen Transfer Efficiency (SOTE), which refers to the OTE at a given gas rate, a water temperature of 20°C, a DO of zero, and a barometric pressure of 1.00 atm, is calculated. For a given flow rate of air, this is given by:

$$SOTE = \frac{SOTR\ lb/hr}{1.034\ Q_s} \qquad 7$$

where: Q_s = volumetric air flow rate, scfm

ATTACHMENT 1

Basic Program for Non Linear Regression

This Attachment gives the BASIC computer language adaptation of the FORTRAN non linear estimation program.

```
10  DS =  CHRS (4)
20   REM
30   REM  NON-LINEAR LEAST SQUARES PROGRAM IN APPLE II BASIC
40   REM  FOR OXYGEN TRANSFER PARAMETERS
50   REM  OUTPUT SETUP FOR 40 POSITION CRT/MONITOR
60   TEXT : CALL  - 936: REM  CLEARS SCREEN
70   REM
80   REM  ::::::::::::::::::::::
90   REM  STEP 1
100   REM  WRITE TITLES
110   REM  ::::::::::::::::::::::
120   REM
130   PRINT "****************************************"
140   PRINT "         NON-LINEAR ESTIMATION FOR"
150   PRINT "      UNSTEADY-STATE OXYGEN TRANSFER"
160   PRINT "****************************************"
170   PRINT "                    BY"
180   PRINT "LINFIELD C. BROWN & GEORGE R. FISETTE"
190   PRINT "VERSION  1.0-NOVEMBER 11, 1979"
200   PRINT
210   INVERSE : PRINT "THE VALUES ARE TRUNCATED": PRINT "AND NOT ROUNDED OFF." :P
RINT  : NORMAL
220   REM
230   REM  PROGRAM HAS MAXIMUM LIMIT OF 30 DATA POINTS
240   REM
250   DIM C(30),T(30),F(30),R(30)
260   INPUT "IS DATA IN DISK FILE;Y/N?";A$
270   INPUT "INPUT NAME OF DATE FILL?";N$
280   IF A$ = " " GOTO 650: REM  GET DATA FROM DISK FILL
290   INPUT "DO YOU WANT INPUT DATA SAVED ON DISK,Y/N?";A$
300   PRINT "INPUT DATA IN TIME,DO DATA PAIRS"
310   PRINT "INPUT 999,999 AS LAST DATA PAIR"
320   FOR I = 1 TO 30
330   INPUT T(I),C(I)
340   IF T(I) = 999.0 GOTO 360
350   NEXT I
360  ND = I - 1.0
370   INPUT "BEST ESTIMATE FOR C-STAR OR USE 10.0 MG/L?";CS
380   INPUT "BEST ESTIMATE FOR C-ZERO OR USE 0.0 MG/L?";CO
390   INPUT "BEST ESTIMATE FOR KLA-PRIME OR USE 4.0 1/HR?";XK
400  XK = XK / 60.0
410   IF A$ = "N" GOTO 790
420   REM
430   REM  WRITE DATA TO DISK FILE
440   REM  SPECIFIC FOR APPLE/MICROSOFT BASIC
450   REM
460   PRINT D$;"OPEN "N$;",VO,L15"
470   FOR I = 1 to ND
480   PRINT D$;"WRITE "N$;",BO,R";I
490   PRINT T(I): PRINT C(I)
500   NEXT I
510   PRINT D$;"WRITE "N$;",BO,RO"
520   PRINT ND
530   PRINT D$;"WRITE "N$;",BO,R";ND + 1.
540   PRINT CS
```

```
550   PRINT DS:"WRITE "NS;",B0,R";ND + 2.
560   PRINT CO
570   PRINT DS;"WRITE "NS;",B0,R";ND + 3.
580   PRINT XK
590   PRINT DS;"CLOSE "NS
600   GOTO 790
610   REM
620   REM  READ DISK FILE FOR DATA
630   REM  SPECIFIC FOR APPLE/MICROSOFT BASIC
640   REM
650   PRINT DS;"OPEN "NS;",V0,L15"
660   PRINT DS;"READ "NS:",B0,R0"
670   INPUT ND
680   FOR I = 1 TO ND
690   PRINT DS;"READ "NS;",B0,R";I
700   INPUT T(I),C(I)
710   NEXT I
720   PRINT DS:"READ "NS;",B0,R";ND + 1.
730   INPUT CS
740   PRINT D$;"READ "NS;",B0,R";ND + 2.
750   INPUT CO
760   PRINT D$;"READ "NS;",B0,R";ND + 3.
770   INPUT XK
780   PRINT D$;"CLOSE "N$
790   PRINT : FLASH : INPUT "HIT RETURN FOR ITERATIONS.";I$: NORMAL
800   CALL    936: PRINT : PRINT "          DATA SET ";NS: PRINT
810   PRINT "ITERATION" TAB( 11)"C-STAR" TAB( 18)"C-ZERO" TAB( 26)"KLA" TAB ( 33)"
SUM OF"
820   PRINT TAB( 2)"NUMBER" TAB( 26)"PRIME" TAB( 33)"SQUARES"
830   PRINT TAB ( 11)"(MG/L)" TAB( 18)"(MG/L)" TAB ( 26)"(1/HR)"
840   PRINT
850   REM
860   REM  :::::::::::::::::::::
870   REM  STEP 2
880   REM  INITIALIZATION OF VARIABLES
890   REM  DO ITERATION CALCULATIONS
900   REM  :::::::::::::::::::::
910   REM
920  K% = 0
930  OS = 0.0
940   FOR I = 1 TO ND
950  F(I) = CS - (CS - CO) * EXP ( - XK * T(I))
960  R(I) = C(I) - F(I)
970  OS = OS + R(I) * R(I)
980   NEXT I
990  ZZ$ = STR$ (CS) :VA = 5.: GOSUB 2900
1000  CS$ = ZZ$:ZZ$ = STR$ (CO): GOSUB 2900
1010  CO$ = ZZ$:ZZ$ = STR$ (XK * 60.): GOSUB 2900
1020  XK$ = ZZ$:ZZ$ = STR$ (OS): GOSUB 2900
1030  OS$ = ZZ$
1040   PRINT TAB( 4)K% TAB( 10)CS$ TAB( 18)CO$ TAB( 26)XK$ TAB( 33)OS$
1050   GOTO 1070
1060   REM
1070   REM  CALCULATION LOOP - INITILIZE VARIABLES
```

```
1080  REM
1090  K% = K% ÷ 1
1100  A1 = 0.0
1110  A2 = 0.0
1120  A3 = 0.0
1130  A4 = 0.0
1140  A5 = 0.0
1150  A6 = 0.0
1160  C1 = 0.0
1170  C2 = 0.0
1180  C3 = 0.0
1190  SQ = 0.0
1200  REM
1210  REM  ::::::::::::::::::::::
1220  REM  STEP 3
1230  REM  SETUP NORMAL EQUATIONS FOR LINEARIZED MODEL
1240  REM  USING CURRENT LEAST SQUARE ESTIMATES
1250  REM  ::::::::::::::::::::::
1260  REM
1270  FOR I = 1 TO ND
1280  Z2 = EXP ( - XK * T(I))
1290  Z1 = 1.0 - Z2
1300  Z3 = T(I) * Z2 * (CS - CO)
1310  A1 = A1 + Z1 * Z1
1320  A2 = A2 + Z1 * Z2
1330  A3 = A3 + Z1 * Z3
1340  A4 = A4 + Z2 * Z2
1350  A5 = A5 + Z2 * Z3
1360  A6 = A6 + Z3 * Z3
1370  F(I) = CS - (CS - CO) * Z2
1380  R(I) = C(I) - F(I)
1390  C1 = C1 + R(I) * Z1
1400  C2 = C2 + R(I) * Z2
1410  C3 = C3 + R(I) * Z3
1420  NEXT I
1430  REM
1440  REM  ::::::::::::::::::::::
1450  REM  STEP 4
1460  REM  SOLUTION OF NORMAL EQUATIONS FOR CORRECTIONS
1470  REM  TO THE PRIOR LEAST SQUARES ESTIMATES
1480  REM  ::::::::::::::::::::::
1490  REM
1500  D1 = A1 * A4 - A2 * A2
1510  D2 = A1 * C3 - A3 * C1
1520  D3 = A1 * A5 - A3 * A2
1530  D4 = A6 * A1 - A3 * A3
1540  D5 = A1 * C2 - A2 * C1
1550  XN = D1 * D2 - D3 * D5
1560  XD = D1 * D4 - D3 * D3
1570  X3 = XN / XD
1580  YN = D5 - D3 * X3
1590  X2 = YN / D1
1600  X1 = (C1 - A2 * X2 - A3 * X3) / A1
1610  REM
```

```
1620  REM  ::::::::::::::::::::::
1630  REM  STEP 5
1640  REM  UPDATE ESTIMATES, SUM OF SQUARES
1650  REM  ::::::::::::::::::::::
1660  REM
1670  T1 = X1 + CS
1680  T2 = X2 + CO
1690  T3 = X3 + XK
1700  FOR I = 1 TO ND
1710  F(I) = T1 - (T1 - T2) * EXP ( - T3 * T(I))
1720  R(I) = C(I) - F(I)
1730  SQ = SQ + R(I) * R(I)
1740  NEXT I
1750  REM
1760  REM  ::::::::::::::::::::::
1770  REM  STEP 6
1780  REM  TEST FOR CONVERGENCE - PARAMETERS   1 PART IN 100,000
1790  REM  :::::::::::::::::::::
1800  REM
1810  IF (X1 / T1 ≥ 0.00001) AND (X2 / T2 ≥ 0.00001) AND (X3 / T3 ≥ 0.00001) GOT
0 2160
1820  REM
1830  REM  PARAMETERS NOT CONVERGED,
1840  REM  TEST SUM OF SQUARES - 1 PART IN 1,000,000
1850  REM
1860  IF ABS ((OS - SQ)/SQ)≤0.000001 GOTO 2160
1870  REM
1880  REM  SUM OF SQUARES NOT CONVERGED,
1890  REM  TEST NO. OF ITERATIONS
1900  REM
1910  IF (K%   10) GOTO 2090
1920  ZZ$ = STR$ (T1) : GOSUB 2900
1930  T1$ = ZZ$:ZZ$ =  STR$ (T2) : GOSUB 2900
1940  T2$ = ZZ$:ZZ$ =  STR$ (T3  * 60.): GOSUB 2900
1950  T3$ = ZZ$:ZZ$ =  STR$ (SQ) : GOSUB 2900
1960  SQ$ = ZZ$
1970  PRINT TAB( 4)K% TAB( 10)T1$ TAB( 18)T2$ TAB( 26)T3$ TAB( 33)SQ$
1980  REM
1990  REM  NEW ESTIMATES
2000  REM
2010  CS = T1
2020  CO = T2
2030  XK = T3
2040  OS = SQ
2050  GOTO 1090
2060  REM
2070  REM  OUTPUTS
2080  REM
2090  PRINT
2100  PRINT "SOLUTION NOT CONVERGED IN 10 ITERATIONS'"
2110  PRINT  "CHANGE VALUE IN LINE 2670 TO TRY MORE  ITERATIONS."
2120  END
2130  REM
2140  REM  OUTPUT PARAMETER ESTIMATES
```

```
2150  REM
2160 ZZ$ =  STR$ (T1): GOSUB 2900
2170 T1$ = ZZ$:ZZ$ = STR$ (T2): GOSUB 2900
2180 T2$ = ZZ$:ZZ$ = STR$ (T3 * 60.): SOSUB 2900
2190 T3$ = ZZ$:ZZ$ = STR$ (SQ): GOSUB 2900
2200 SQ$ = ZZ$
2210  PRINT TAB( 4)K% TAB( 10)T1$ TAB( 18)T2$ TAB( 26)T3$ TAB( 33)SQ$
2220  PRINT
2230  REM
2240  REM  ::::::::::::::::::::::
2250  REM  STEP 7
2260  REM   COMPUTE STANDARD DEVIATIONS OF PARAMETER ESTIMATES
2270  REM  ::::::::::::::::::::::
2280  REM
2290 XF = ND - 3.0
2300 RS = SQ / XF
2310 ER = SQR (RS)
2320  PRINT "STD DEVIATIONS OF PARAMETER ESTIMATES"
2330  PRINT
2340 DP = A1 * A4 * A6 + 2.0 * A2 * A3 * A5
2350 DN = A1 * A5 * A5 + A4 * A3 * A3 + A6 * A2 * A2
2360 DT = DP - DN
2370 F1 = A4 * A6 - A5 * A5
2380 F2 = A1 * A6 - A3 * A3
2390 F3 = A1 * A4 - A2 * A2
2400 V1 = (F1 / DT) * RS
2410 V2 = (F2 / DT) * RS
2420 V3 = (F3 / DT) * RS
2430 S1 = SQR (V1)
2440 S2 = SQR (V2)
2450 S3 = SQR (V3)
2460 ZZ$ = STR$ (S1):VA = 5.: GOSUB 2900
2470 S1$ = ZZ$:ZZ$ = STR$ (S2): GOSUB 2900
2480 S2$ = ZZ$:ZZ$ = STR$ (S3 * 60.): GOSUB 2900
2490 S3$ = ZZ$
2500  PRINT " UNITS" TAB( 10)S1$ TAB( 18)S2$ TAB( 26)S3$
2510 S1 = S1 / CS * 100.0
2520 S2 = S2 / CO * 100.0
2530 S3 = S3 / XK * 100.0
2540 ZZ$ = STR$ (S1):VA = 3.: GOSUB 2900
2550 S1$ = ZZ$:ZZ$ = STR$ (S2): GOSUB 2900
2560 S2$ = ZZ$:ZZ$ = STR$ (s3): GOSUB 2900
2570 S3$ = ZZ$
2580  PRINT "% OF LSE" TAB( 10)S1$ TAB( 18)S2$ TAB( 26)S3$
2590  PRINT
2600 ZZ$ = STR$ (ER):VA = 4.: GOSUB 2900
2610 ER$ = ZZ$
2620  PRINT "ESTIMATE OF ERROR = ";ER$
2630  REM
2640  REM  ::::::::::::::::::::::
2650  REM  STEP 8
2660  REM  WRITE SUMMARY
2670  REM  ::::::::::::::::::::::
```

```
2680  REM
2690  PRINT
2700  FLASH : INPUT "HIT RETURN FOR SUMMARY OF DATA.";I$: NORMAL
2710  CALL - 936: PRINT : PRINT : REM  CLEARS SCREEN
2720  PRINT TAB( 13)"SUMMARY OF DATA"
2730  PRINT : PRINT
2740  PRINT TAB( 8)"TIME" TAB( 16)"CONC" TAB( 22)"FIT VALUE" TAB( 32)"RESIDUAL"
2750  PRINT TAB( 8)"(MIN)" TAB( 15)"(MG/L)" TAB( 23)"MG/L"
2760  PRINT
2770  FOR I = 1 TO ND
2780 ZZ$ = STR$ (F(I)):VA = 4.: GOSUB 2900
2790 H1$ = ZZ$:ZZ$ = STR$ (R(I)): GOSUB 2900
2800 H2$ = ZZ$
2810  PRINT TAB( 2)I TAB( 8)T(I) TAB( 16)C(I) TAB( 25)H1$ TAB( 33)H2$
2820  NEXT I
2830  PRINT : PRINT
2840  PRINT "****************************************"
2850  END
2860  REM
2870  REM  OUTPUT FORMATTING ROUTINES
2880  REM  SPECIFIC FOR APPLE/MICROSOFT BASIC
2890  REM
2900 LL = LEN (ZZ$)
2910  IF LL < 12 THEN ZZ$ = LEFT$ (ZZ$,VA): RETURN
2920  IF  MID$ (ZZ$,LL - 2,1) = "+" THEN ZZ$ = LEFT$ (ZZ$,VA - 3) + RIGHT$ (ZZ
$ 3):  RETURN
2930 CC = 2.: IF LEFT$ (ZZ$,1)   =   "-" THEN CC = 1.
2940  IF MID$ (ZZ$,LL - 3,1) = "E" THEN EE = VAL (RIGHT$ (ZZ$,2)):NN$ = MID$
 (ZZ$,CC,1): FOR J = 1 TO EE:NN$ = "0" + NN$:: NEXT J:ZZ$ = "." NN$ + MID$ (Z
Z$,CC + 2,LL - 4): IF CC = 2. THEN ZZ$ = "-" + ZZ$
2950 ZZ$ = LEFT$ (ZZ$,VA): RETURN
2960  REM
2970  REM  NON-LINEAR LEAST SQUARES PROGRAM FOR
2980  REM  UNSTEADY-STATE OXYGEN TRANSFER
2990  REM  LY LINFIELD C. BROWN & GEORGE R. FISETTE
3000  REM  VERSION  1.0-NOVEMBER 11, 1979
3010  REM  COPYRIGHT BY ASCE
```

APPENDIX 2

FOULANT SUMMARY SHEET FOR FINE BUBBLE DIFFUSERS

Diffusers Recieved From: SMU CME Dept.

Date Received: 4/21/87

Date Tested	Diffuser Type	Total Solids (g/sq in)	Volatile solids (g/sq in)	Percent Volatiles	Fixed Solids (g/sq in)
4/22/87	Sanitaire * Dirty #1	0.015	0.007	48.7%	0.008
4/22/87	Sanitaire * Dirty #2	0.821	0.007	34.3%	0.014
4/26/87	Sanitaire * Dirty #3	0.038	0.012	30.2%	0.027
4/30/87	Sanitaire * Dirty #4	0.028	0.010	35.9%	0.018
4/30/87	Sanitaire * Dirty #5	0.032	0.010	30.6%	0.022

Acid Insoluble

Diffuser Type	Total Solids (g/sq in)	Volatile solids (g/sq in)	Percent Volatiles	Fixed Solids (g/sq in)
* Sanitaire Dirty #1	ERR	ERR	ERR	ERR
* Sanitaire Dirty #2	0.004	0.00025	6.3%	0.004
* Sanitaire Dirty #3	0.010	0.00044	4.2%	0.010
* Sanitaire Dirty #4	0.008	0.00017	2.2%	0.008
* Sanitaire Dirty #5	0.005	0.00113	22.9%	0.004

* indicates acid testing

SUMMARY OF DIFFUSER CHARACTERIZATION DATA

Diffusers Received From: SMU CME Dept.
Date Received: 4/21/87

Date Tested	Diffuser Type	Diffuser Condition and Identification	Avg. BRV	S / x
4/22/87	Norton	Dirty #1	17.902	0.258
4/22/87	Norton	Dirty #2	18.054	0.294
4/26/87	Norton	Dirty #3	19.331	0.363
4/30/87	Norton	Dirty #4	12.656	0.206
4/30/87	Norton	Dirty #5	10.512	0.234

	DWP (in wg.) .5 cfm	.75 cfm	1.0 cfm	2.0 cfm	Ratio DWP@.75 BRV
Dirty #1	9.2	10.0	10.5	14.1	0.559
Dirty #2	9.4	11.2	11.5	13.3	0.620
Dirty #3	10.9	11.2	11.3	12.5	0.579
Dirty #4	6.1	7.7	8.6	12.0	0.608
Dirty #5	7.9	8.4	8.7	11.7	0.799

Air Flow Profile	Flux Rate Inner (cfm/sqft)	Flux Rate Middle (cfm/sqft)	Flux Rate Outer (cfm/sqft)
Dirty #1	2.11	1.63	4.51
Dirty #2	2.81	1.54	4.27
Dirty #3	2.6	1.47	4.5
Dirty #4	3.1	2.02	3.85
Dirty #5	2.18	1.96	4.31

SUMMARY OF DIFFUSER CHARACTERIZATION DATA

Diffusers Received From: SMU CME Dept.
Date Received: 4/21/87

Date Tested	Diffuser Type	Diffuser Condition and Identification	Avg. BRV	S / x
4/22/87	Norton	LPH #1	9.256	0.122
4/22/87	Norton	LPH #2	12.825	0.186
4/26/87	Norton	LPH #3	12.654	0.223
4/30/87	Norton	LPH #4	22.224	0.406
4/30/87	Norton	LPH #5	13.701	0.223

	DWP (in wg.) .5 cfm	.75 cfm	1.0 cfm	2.0 cfm	Ratio DWP@.75 BRV
LPH #1	6.9	7.3	7.7	10.1	0.789
LPH #2	7.2	8.0	8.7	11.3	0.624
LPH #3	6.1	6.4	6.8	8.0	0.506
LPH #4	8.1	8.8	9.3	13.3	0.396
LPH #5	7.1	8.6	8.9	10.6	0.628

Air Flow Profile

	Flux Rate Inner (cfm/sqft)	Flux Rate Middle (cfm/sqft)	Flux Rate Outer (cfm/sqft)
LPH #1	2.64	1.86	4.24
LPH #2	4.53	1.59	3.64
LPH #3	2.21	2.04	4.11
LPH #4	1.96	1.33	4.95
LPH #5	3.18	1.50	4.25

FOULANT SUMMARY SHEET FOR FINE BUBBLE DIFFUSERS

Diffusers Recieved From: SMU CME Dept.

Date Received: 4/21/87

Date Tested	Diffuser Type	Total Solids (g/sq in)	Volatile solids (g/sq in)	Percent Volatiles	Fixed Solids (g/sq in)
4/22/87	Sanitaire * LPH #1	0.029	0.012	40.1%	0.017
4/22/87	Sanitaire * LPH #2	0.024	0.003	13.1%	0.021
4/26/87	Sanitaire * LPH #3	0.039	0.011	27.6%	0.029
4/30/87	Sanitaire * LPH #4	0.061	0.012	19.8%	0.049
4/30/87	Sanitaire * LPH #5	0.009	0.002	28.8%	0.006

Acid Insoluble

Diffuser Type	Total Solids (g/sq in)	Volatile solids (g/sq in)	Percent Volatiles	Fixed Solids (g/sq in)
* Sanitaire LPH #1	0.010	0.00068	6.9%	0.009
* Sanitaire LPH #2	ERR	ERR	ERR	ERR
* Sanitaire LPH #3	0.013	0.00023	1.7%	0.013
* Sanitaire LPH #4	0.029	0.00041	1.4%	0.029
* Sanitaire LPH #5	0.002	0.00013	7.4%	0.002

* indicates acid testing

FOULANT SUMMARY SHEET FOR FINE BUBBLE DIFFUSERS

Diffusers Recieved From: SMU CME Dept.

Date Received: 4/21/87

Date Tested	Diffuser Type	Total Solids (g/sq in)	Volatile solids (g/sq in)	Percent Volatiles	Fixed Solids (g/sq in)
4/22/87	Sanitaire * HPH #1	0.024	0.004	14.9%	0.020
4/22/87	Sanitaire * HPH #2	0.018	0.007	38.9%	0.011
4/26/87	Sanitaire * HPH #3	0.017	0.005	27.9%	0.012
4/30/87	Sanitaire * HPH #4	0.020	0.004	21.8%	0.015
4/30/87	Sanitaire * HPH #5	0.034	0.010	30.5%	0.024

Acid Insoluble

Diffuser Type	Total Solids (g/sq in)	Volatile solids (g/sq in)	Percent Volatiles	Fixed Solids (g/sq in)
* Sanitaire HPH #1	ERR	ERR	ERR	ERR
* Sanitaire HPH #2	0.005	0.00058	12.2%	0.004
* Sanitaire HPH #3	0.004	0.00034	8.3%	0.004
* Sanitaire HPH #4	0.004	0.00027	6.8%	0.004
* Sanitaire HPH #5	0.009	0.00079	8.6%	0.008

* indicates acid testing

SUMMARY OF DIFFUSER CHARACTERIZATION DATA

Diffusers Received From: SMU CME Dept.
Date Received: 4/21/87

Date Tested	Diffuser Type	Diffuser Condition and Identification	Avg. BRV	S / x
4/22/87	Norton	HPH #1	23.589	0.495
4/22/87	Norton	HPH #2	16.858	0.341
4/26/87	Norton	HPH #3	12.919	0.264
4/30/87	Norton	HPH #4	11.766	0.392
4/30/87	Norton	HPH #5	13.672	0.37

	DWP (in wg.) .5 cfm	.75 cfm	1.0 cfm	2.0 cfm	Ratio DWP@.75 BRV
HPH #1	6.8	14.0	14.2	15.8	0.593
HPH #2	6.9	7.4	7.7	9.1	0.439
HPH #3	6.5	6.8	7.9	10.2	0.526
HPH #4	6.2	6.6	6.8	8.7	0.561
HPH #5	7.6	8.2	8.7	12.9	0.600

Air Flow Profile

	Flux Rate Inner (cfm/sqft)	Flux Rate Middle (cfm/sqft)	Flux Rate Outer (cfm/sqft)
HPH #1	4.65	3.34	1.72
HPH #2	4.23	2.36	2.86
HPH #3	2.71	2.07	3.94
HPH #4	4.77	1.62	3.34
HPH #5	4.43	2.14	3.1

SUMMARY OF DIFFUSER CHARACTERIZATION DATA

Diffusers Received From: SMU CME Dept.
Date Received: 4/21/87

Date Tested	Diffuser Type	Diffuser Condition and Identification	Avg. BRV	S / x
4/22/87	Norton	Acid Washed #1	11.146	0.234
4/22/87	Norton	Acid Washed #2	18.734	0.227
4/26/87	Norton	Acid Washed #3	8.831	0.16
4/26/87	Norton	Acid Washed #4	11.005	0.45
4/26/87	Norton	Acid Washed #5	9.635	0.231

	DWP (in wg.) .5 cfm	.75 cfm	1.0 cfm	2.0 cfm	Ratio DWP@.75 BRV
Acid Washed #1	5.4	5.7	6.0	6.9	0.511
Acid Washed #2	8.2	9.0	9.6	16.5	0.480
Acid Washed #3	4.8	5.2	5.4	6.4	0.589
Acid Washed #4	Cracked				
Acid Washed #5	5.4	6.1	6.5	10.0	0.633

Air Flow Profile

	Flux Rate Inner (cfm/sqft)	Flux Rate Middle (cfm/sqft)	Flux Rate Outer (cfm/sqft
Acid Washed #1	2.07	2.70	3.41
Acid Washed #2	3.87	2.83	2.61
Acid Washed #3	3.00	1.93	3.79
Acid Washed #4	Cracked		
Acid Washed #5	2.20	1.75	4.52

FOULANT SUMMARY SHEET FOR FINE BUBBLE DIFFUSERS

Diffusers Recieved From: SMU CME Dept.

Date Received: 4/21/87

Date Tested	Diffuser Type	Total Solids (g/sq in)	Volatile solids (g/sq in)	Percent Volatiles	Fixed Solids (g/sq in)
4/22/87	Sanitaire * Acid Washed #1	0.007	0.002	33.5%	0.005
4/22/87	Sanitaire * Acid Washed #2	0.046	0.018	38.5%	0.028
4/26/87	Sanitaire * Acid Washed #3	0.024	0.008	33.3%	0.016
4/26/87	Sanitaire * Acid Washed #4	0.092	0.021	22.7%	0.071
4/26/87	Sanitaire * Acid Washed #5	0.035	0.012	35.4%	0.023

Acid Insoluble

Diffuser Type	Total Solids (g/sq in)	Volatile solids (g/sq in)	Percent Volatiles	Fixed Solids (g/sq in)
* Sanitaire Acid Washed #1	0.002	0.00057	30.4%	0.001
* Sanitaire Acid Washed #2	0.017	0.00077	4.5%	0.016
* Sanitaire Acid Washed #3	0.006	0.00032	5.0%	0.006
* Sanitaire Acid Washed #4	0.034	0.00046	1.3%	0.034
* Sanitaire Acid Washed #5	0.010	0.00026	2.7%	0.009

* indicates acid testing

FOULANT SUMMARY SHEET FOR FINE BUBBLE DIFFUSERS

Diffusers Recieved From: SMU CME Dept.

Date Received: 4/21/87

Date Tested	Diffuser Type	Total Solids (g/sq in)	Volatile solids (g/sq in)	Percent Volatiles	Fixed Solids (g/sq in)
4/22/87	Sanitaire * Kilned #1	0.021	0.006	27.7%	0.015
4/22/87	Sanitaire * Kilned #2	0.021	0.007	30.9%	0.015
4/26/87	Sanitaire * Kilned #3	Broken in two			
4/30/87	Sanitaire * Kilned #4	0.031	0.011	35.5%	0.020
4/30/87	Sanitaire * Kilned #5	0.039	0.006	14.7%	0.033

Acid Insoluble

Diffuser Type	Total Solids (g/sq in)	Volatile solids (g/sq in)	Percent Volatiles	Fixed Solids (g/sq in)
* Sanitaire Kilned #1	0.007	0.00042	5.9%	0.007
* Sanitaire Kilned #2	0.009	0.00044	5.0%	0.008
* Sanitaire Kilned #3	Broken in two			
* Sanitaire Kilned #4	0.008	0.00055	6.6%	0.008
* Sanitaire Kilned #5	0.020	0.00091	4.6%	0.019

* indicates acid testing

SUMMARY OF DIFFUSER CHARACTERIZATION DATA

Diffusers Received From: SMU CME Dept.
Date Received: 4/21/87

Date Tested	Diffuser Type	Diffuser Condition and Identification	Avg. BRV	S / x
4/22/87	Norton	Kilned #1	16.213	0.215
4/22/87	Norton	Kilned #2	11.472	0.258
4/26/87	Norton	Kilned #3	Broke in two	
4/26/87	Norton	Kilned #4	11.895	0.345
4/26/87	Norton	Kilned #5	12.482	0.294

	DWP (in wg.) .5 cfm	.75 cfm	1.0 cfm	2.0 cfm	Ratio DWP@.75 BRV
Kilned #1	7.2	8.6	9.0	12.0	0.530
Kilned #2	7.2	7.6	7.8	9.6	0.662
Kilned #3	Broke in two				
Kilned #4	7.3	7.7	7.9	9.2	0.647
Kilned #5	8.6	9.8	10.2	17.9	0.785

Air Flow Profile

	Flux Rate Inner (cfm/sqft)	Flux Rate Middle (cfm/sqft)	Flux Rate Outer (cfm/sqft)
Kilned #1	2.50	2.47	3.53
Kilned #2	3.93	2.71	2.84
Kilned #3	Broke in two		
Kilned #4	2.99	1.86	4.02
Kilned #5	4.13	2.82	2.58

APPENDIX 3

NEW DOMES CLEANED
BY NOTED METHODS

ASCE/EPA
DATA SUMMARY

	AIR FLOW	T (°C)	C^*	K_La_t	K_La_{20}
CLEAN	1.0	14	10.67	0.0107	0.0152
CLEAN	1.0	14	12.55	0.0075	0.0108
CLEAN	1.0	14	12.85	0.0083	0.0112
CLEAN	2.0	10	10.46	0.0276	0.0399
CLEAN	2.0	10	11.20	0.0263	0.0375
CLEAN	2.0	10	11.74	0.0250	0.0358
LPH[1]	1.0	10	10.61	0.0369	0.0300
LPH	1.0	10	10.50	0.0240	0.0320
LPH	1.0	10	11.10	0.0230	0.0315
LPH	2.0	10	10.50	0.0370	0.0510
LPH	2.0	10	11.17	0.0350	0.0477
LPH	2.0	10	10.75	0.0410	0.0560
HPH[2]	1.0	5	12.40	0.0220	0.0314
HPH	1.0	5	12.50	0.0194	0.0277
HPH	1.0	5	11.77	0.0220	0.0316
HPH	2.0	5	11.84	0.0480	0.0685
HPH	2.0	5	12.16	0.0430	0.0613
HPH	2.0	5	12.30	0.0400	0.0570
AW[3]	1.0	4	13.20	0.0206	0.0300
AW	1.0	4	13.36	0.0206	0.0300
AW	1.0	4	13.90	0.0204	0.0298
AW	2.0	4	13.20	0.0421	0.0615
AW	2.0	4	13.70	0.0396	0.0580
AW	2.0	4	13.70	0.0380	0.0560

LPH[1] - LOW PRESSURE HOSING

HPH[2] - HIGH PRESSURE HOSING

AW[3] - ACID WASHED

NEW DOMES CLEANED
BY NOTED METHODS

ASCE/EPA
DATA SUMMARY

	AIR FLOW	T (°C)	C^*	K_La_t	K_La_{20}
CLEAN	1.0	11	10.66	0.0196	0.0266
CLEAN	1.0	11	10.20	0.0236	0.0321
CLEAN	1.0	11	11.00	0.0197	0.0270
CLEAN	2.0	11	11.01	0.0350	0.0480
CLEAN	2.0	11	10.83	0.0360	0.0490
CLEAN	2.0	11	11.08	0.0306	0.0420
LPH[1]	1.0	9	10.88	0.0190	0.0240
LPH	1.0	9	11.07	0.0195	0.0250
LPH	1.0	9	10.77	0.0200	0.0260
LPH	2.0	9	10.82	0.0384	0.0500
LPH	2.0	9	10.96	0.0360	0.0460
LPH	2.0	9	10.95	0.0380	0.0490
HPH[2]	1.0	6	12.79	0.0230	0.0320
HPH	1.0	6	13.00	0.0210	0.0290
HPH	1.0	6	12.87	0.0210	0.0300
HPH	2.0	6	12.67	0.0430	0.0600
HPH	2.0	6	12.74	0.0380	0.0540
HPH	2.0	6	13.20	0.0350	0.0480
AW[3]	1.0	4.5	13.40	0.0260	0.0370
AW	1.0	4.5	14.00	0.0220	0.0320
AW	1.0	4.5	14.30	0.0205	0.0296
AW	2.0	4.5	13.76	0.0430	0.0625
AW	2.0	4.5	14.40	0.0400	0.0580
AW	2.0	4.5	13.30	0.0460	0.0660

LPH[1] - LOW PRESSURE HOSING

HPH[2] - HIGH PRESSURE HOSING

AW[3] - ACID WASHED

NEW DOMES CLEANED
BY NOTED METHODS

ASCE/EPA
DATA SUMMARY

	AIR FLOW	T (°C)	C^*	$K_L at$	$K_L a_{20}$
CLEAN	1.0	9	11.58	0.0150	0.0200
CLEAN	1.0	9	12.15	0.0150	0.0190
CLEAN	1.0	9	14.30	0.0100	0.0130
CLEAN	2.0	9	11.32	0.0360	0.0460
CLEAN	2.0	9	10.30	0.0530	0.0690
CLEAN	2.0	9	10.04	0.0560	0.0730
LPH[1]	1.0	4	12.60	0.0150	0.0230
LPH	1.0	4	12.10	0.0180	0.0265
LPH	1.0	4	10.88	0.0240	0.0360
LPH	2.0	4	11.90	0.0360	0.0530
LPH	2.0	4	12.02	0.0350	0.0510
LPH	2.0	4	11.85	0.0360	0.0530
HPH[2]	1.0	5	12.80	0.0210	0.0305
HPH	1.0	5	12.50	0.0240	0.0350
HPH	1.0	5	13.20	0.0210	0.0300
HPH	2.0	5	12.77	0.0420	0.0590
HPH	2.0	5	12.49	0.0530	0.0760
HPH	2.0	5	12.24	0.0510	0.0730
AW[3]	1.0	7	13.10	0.0240	0.0330
AW	1.0	7	13.96	0.0199	0.0270
AW	1.0	7	14.00	0.0190	0.0250
AW	2.0	7	13.26	0.0420	0.0570
AW	2.0	7	14.50	0.0310	0.0420
AW	2.0	7	13.93	0.0400	0.0540

LPH[1] - LOW PRESSURE HOSING

HPH[2] - HIGH PRESSURE HOSING

AW[3] - ACID WASHED

NEW DOMES CLEANED
BY NOTED METHODS

ASCE/EPA
DATA SUMMARY

	AIR FLOW	T (°C)	C*	K_La_t	K_La_{20}
CLEAN	1.0	14	10.23	0.0162	0.0220
CLEAN	1.0	14	10.50	0.0175	0.0240
CLEAN	1.0	14	11.30	0.0150	0.0210
CLEAN	2.0	14	10.19	0.0330	0.0450
CLEAN	2.0	14	10.79	0.0330	0.0450
CLEAN	2.0	14	10.65	0.0340	0.0470
LPH[1]	1.0	10	10.25	0.0260	0.0350
LPH	1.0	10	10.39	0.2480	0.0324
LPH	1.0	10	10.29	0.0260	0.0340
LPH	2.0	10	11.34	0.0370	0.0480
LPH	2.0	10	10.88	0.0480	0.0640
LPH	2.0	10	11.73	0.0303	0.0403
HPH[2]	1.0	7	12.50	0.0250	0.0343
HPH	1.0	7	13.36	0.0214	0.0290
HPH	1.0	7	13.34	0.0210	0.0280
HPH	2.0	7	12.76	0.0450	0.0610
HPH	2.0	7	12.53	0.0470	0.0640
HPH	2.0	7	13.15	0.0420	0.0580
AW[3]	1.0	4	13.15	0.0270	0.0390
AW	1.0	4	13.97	0.0210	0.0310
AW	1.0	4	14.60	0.0170	0.0250
AW	2.0	4	13.50	0.0450	0.0650
AW	2.0	4	14.30	0.0380	0.0550
AW	2.0	4	14.70	0.0310	0.0460

LPH[1] - LOW PRESSURE HOSING

HPH[2] - HIGH PRESSURE HOSING

AW[3] - ACID WASHED

TABLE 8

ROWLETTE CREEK AERATION STUDY

DATE: 02/02/87 TIME: 02:31 PM

ROWLETTE CREEK AERATION STUDY: OFF GAS AND OUR ANALYSIS OF OXYGEN TRANSFER EFFICIENCIES

															10.1	19.5	FLOW WEIGHTED OTE AVERAGES		
																	************************		
1/29-30/8 STATION	OUR MG/L/H	ROTO NO	ROTO RDG	HOOD FLOW SCFM	AREA FT2	FLOW SCFM	REF MV	OFFGAS MV	DO MG/L	CO2 %	Yog	MRogl	MRoi	OTEf %	OTE 20C,0 DO %	OTE 20C,2 DO %	FIELD OTE*SCFM	OTE 20/0 OTE*SCFM	OTE 20/2 OTE*SCFM
I-1	66	2	129	13.4	751	314	1.001	0.934	0.5	0.0070	0.1955	0.2451	0.2650	0.075	0.079	0.064	1.007	1.059	0.860
I-2	63	2	142	14.6	507	231	1.006	0.949	0.4	0.0060	0.1976	0.2482	0.2650	0.064	0.066	0.053	0.929	0.967	0.785
I-3	63	2	86	9.5	507	151	1.002	0.934	0.7	0.0090	0.1953	0.2454	0.2650	0.074	0.080	0.064	0.703	0.754	0.612
I-4	63	2	92	10	507	158	1.005	0.930	0.4	0.0100	0.1939	0.2426	0.2650	0.085	0.088	0.071	0.846	0.881	0.715
I-5	76	2	85	9.4	507	149	1.005	0.936	0.5	0.0120	0.1951	0.2445	0.2650	0.077	0.081	0.065	0.726	0.764	0.620
I-6	76	2	83	9.2	507	146	1.008	0.943	0.5	0.0110	0.1960	0.2459	0.2650	0.072	0.076	0.061	0.664	0.698	0.567
I-7	76	2	99	10.5	507	166	1.012	0.944	0.6	0.0140	0.1954	0.2450	0.2650	0.075	0.080	0.064	0.792	0.841	0.683
I-8	51	2	107	11.3	573	202	0.996	0.937	0.5	0.0090	0.1971	0.2476	0.2650	0.066	0.069	0.055	0.742	0.780	0.633
						1518											0.073	0.077	0.062
FIRST RUN																			
II-1	64	2	75	8.5	227	60	1.001	0.928	0.6	0.0100	0.1942	0.2431	0.2650	0.083	0.088	0.070	0.702	0.745	0.605
II-2	64	2	67	7.8	227	55	1.001	0.936	0.3	0.0090	0.1959	0.2458	0.2650	0.073	0.075	0.060	0.567	0.585	0.475
II-3	51	2	79	8.8	227	62	1.003	0.942	0.6	0.0060	0.1968	0.2471	0.2650	0.068	0.072	0.058	0.595	0.632	0.513
II-4	51	2	80	8.9	227	63	1.004	0.941	0.8	0.0060	0.1964	0.2465	0.2650	0.070	0.076	0.061	0.623	0.675	0.548
II-5	60	2	78	8.8	227	62	1.002	0.944	0.4	0.0040	0.1974	0.2481	0.2650	0.064	0.067	0.053	0.563	0.586	0.476
II-6	60	2	111	11.7	227	83	1.006	0.956	0.2	0.0060	0.1991	0.2508	0.2650	0.054	0.055	0.044	0.629	0.643	0.522
II-7	63	2	77	8.7	454	123	0.999	0.948	0.3	0.0070	0.1988	0.2503	0.2650	0.055	0.057	0.046	0.483	0.498	0.404
						510											0.066	0.069	0.056
2ND RUN																			
II-1	64	2	70	8	227	57	0.996	0.927	0.4	0.0080	0.1950	0.2443	0.2650	0.078	0.081	0.065	0.624	0.650	0.528
II-2	64	2	70	8	227	57	0.997	0.934	0.3	0.0060	0.1963	0.2463	0.2650	0.071	0.073	0.058	0.564	0.582	0.472
II-3	51	2	85	9.4	227	67	1.005	0.945	0.6	0.0070	0.1970	0.2475	0.2650	0.066	0.070	0.057	0.622	0.661	0.537
II-4	51	2	83	9.3	227	66	1.003	0.946	0.5	0.0060	0.1976	0.2484	0.2650	0.063	0.066	0.053	0.583	0.613	0.497
II-5	60	2	80	8.9	227	63	1.006	0.951	0.4	0.0080	0.1980	0.2491	0.2650	0.060	0.063	0.050	0.534	0.556	0.451
II-6	60	2	107	11.3	227	80	1.009	0.959	0.2	0.0070	0.1991	0.2508	0.2650	0.054	0.055	0.044	0.606	0.619	0.502
II-7	63	2	87	9.5	454	135	1.002	0.951	0.2	0.0050	0.1988	0.2504	0.2650	0.055	0.056	0.045	0.525	0.536	0.436
						524											0.063	0.065	0.053
III-1	30	2	156	15.8	751	371	1.006	0.926	2.4	0.0070	0.1928	0.2410	0.2650	0.091	0.119	0.095	1.432	2.112	1.501
III-2	30	2	153	15.6	507	247	1.003	0.934	2.1	0.0050	0.1951	0.2445	0.2650	0.077	0.098	0.078	1.208	1.712	1.223
III-3	30	2	141	14.5	507	230	1.006	0.934	1.8	0.0050	0.1945	0.2436	0.2650	0.081	0.098	0.079	1.173	1.598	1.147
III-4	30	2	140	14.4	507	228	1.006	0.941	2.4	0.0060	0.1960	0.2459	0.2650	0.072	0.095	0.076	1.041	1.535	1.091
III-5	25	2	135	14	507	222	1.001	0.936	2.8	0.0070	0.1959	0.2458	0.2650	0.073	0.100	0.081	1.018	1.588	1.120
III-6	25	2	114	11.9	507	189	0.997	0.931	2.7	0.008	0.1956	0.2453	0.2650	0.074	0.101	0.081	0.883	1.359	0.961
III-7	25	2	121	12.6	507	200	0.994	0.933	2.4	0.009	0.1966	0.2469	0.2650	0.068	0.089	0.072	0.860	1.269	0.902
III-8	24	2	103	10.9	573	195	0.995	0.936	1.6	0.007	0.1971	0.2476	0.2650	0.066	0.078	0.063	0.716	0.952	0.685
						1881											0.076	0.111	0.079
						--------					5.890								
						4433													
																RUN III	0.072	0.089	0.045