AERATION EQUIPMENT EVALUATION - PHASE II
PROCESS WATER TEST RESULTS

by

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DISCLAIMER

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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 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 the 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 the 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 aeration equipment evaluation was undertaken at the Whittier Narrows Water Reclamation Plant of the Los Angeles County Sanitation Districts using process water test procedures. Systems chosen for evaluation represented the most efficient three systems identified in Phase I of this project. In the first part of Phase II, the three systems were operated in parallel and evaluated. The fine pore ceramic grid system was selected for further evaluation and in the second part of Phase II three fine pore ceramic grid systems were evaluated for an extended period. Information documented herein should be of particular interest to design engineers and municipal officials charged with selecting aeration equipment for new activated sludge treatment plants and/or considering a retrofit to new equipment in existing plants.

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ABSTRACT

This research project was initiated with the principle objective of evaluating the oxygen transfer performance of various generic aeration systems used in activated sludge wastewater treatment. In Phase I of this project the clean water performance of eight types of submerged aeration systems was evaluated. The three most efficient systems (jet, fine pore tube and ceramic dome/disk) were selected for evaluation in process water in Phase II at the Whittier Narrows Water Reclamation Plant.

The project was conducted in two parts. In the first part the three selected aeration systems were operated in parallel aeration basins. Concurrent operation of all three systems began in April 1981. Beginning in January 1982, the tube and jet systems were replaced by ceramic dome systems. During Part 2 of the project, the dome and disk systems were operated in parallel. Concurrent operation of these systems began in May of 1982, with the evaluation period extending through December 1982.

The ceramic domes and disks transferred oxygen more efficiently on an energy basis than the other two systems. The αF factor of the ceramic disk and dome systems was the lowest of all three systems but the aeration efficiency was still greater than the efficiency of the other systems.

This report was submitted in fulfillment of Contract No. 68-03-2906 by the County Sanitation Districts of Los Angeles County under partial sponsorship of the U.S. Environmental Protection Agency. The contract dated November 14, 1979 covers the test period November, 1980 through December, 1982. Data from diffuser cleaning tests which were conducted after December, 1982 are also presented herein.

CONTENTS

FIGURES

Number Page

TABLES

Number Page

TABLES (Continued)

TABLES (Continued)

CONVERSION FACTORS

Measurement	To Convert From U.S. Customary Unit	To SI Unit	Divide By
Aeration Efficiency	lb O_2/wire hp-hr	kg O_2/kWh	1.644
Airflow	cfm	L/sec	2.119
Barometric Pressure	psia	kPa	0.1451
Density	lb/ft^3	kg/m^3	0.06243
Depth	ft	m	3.281
Headloss	in. of H_2O	mm H_2O	0.03937
Headloss	psi	kPa	0.1451
Oxygen Supply Rate	lb O_2/hr	kg O_2/hr	2.205
Oxygen Transfer Rate	lb O_2/hr	kg O_2/hr	2.205
Power	hp	kW	1.341
Power Density	hp/1000 ft^3	W/m^3	0.03797
Temperature	°F	°C	*
Water Volume	ft^3	m^3	35.31

* °C = 5 (°F - 32)/9

PARTIAL LIST OF ABBREVIATIONS AND SYMBOLS

C	dissolved oxygen (DO) concentration
C_i	initial DO concentration corresponding to time t_i
C_t	DO concentration at time t
C_∞	field DO saturation value
C_{h_T}	handbook DO saturation value at temperature T, 14.70 psia, dry air, and 20.9% O_2 by volume
$C_{h_{20}}$	handbook DO saturation value for dry air at 20° C and 14.70 psia (9.17 mg/L)
D	DO deficit (driving force)
D.P.	differential pressure
e	efficiency
e_b	blower efficiency
e_d	drive or coupling efficiency
e_m	motor efficiency
e_p	pump efficiency
f	airflow correction factor
F_a	orifice area correction factor
F_m	manometer fluid temperature correction factor
F_{pe}	pipe expansion correction factor
F_{wv}	relative humidity correction factor
h_L	measured diffuser headloss
h_{Ld}	estimated aeration system piping headloss
h_{Ls}	estimated suction piping headloss
K_La	overall volumetric mass transfer coefficient
K_La_T	overall volumetric mass transfer coefficient at temperature, T
K_La_{20}	overall volumetric mass transfer coefficient at 20°C
N	aeration efficiency
N_{bo}	brake aeration efficiency in clean water at standard conditions of 20°C, 14.70 psia, and 0 mg/L DO
N_{do}	delivered aeration efficiency in clean water at standard conditions of 20°C, 14.70 psia, and 0 mg/L DO
N_{wo}	wire aeration efficiency in clean water at standard conditions of 20°C, 14.70 psia, and 0 mg/L DO
N_o	aeration efficiency in clean water at standard conditions of 20°C, 14.70 psia, and 0 mg/L DO

OSR	oxygen supply rate
OTE	oxygen transfer efficiency
P	aeration power
PD	power density
p	pressure
p_a	barometric pressure
p_{ao}	barometric pressure at standard conditions (14.70 psia)
p_c	aerator air pressure
p_f	flow meter flowing gas pressure
p_i	assumed blower inlet pressure (14.6 psia)
p_{sh}	aerator static head
p_t	Annubar stagnation pressure
p_{vpT}	vapor pressure of water at temperature T
p_{vp20}	vapor pressure of water at 20°C (0.34 psig)
p_w	partial pressure of water vapor
p_1	calculated blower inlet pressure
p_2	calculated blower discharge pressure
q	measured airflow at standard conditions
Q_{scfm}	measured airflow at standard conditions
T	temperature
t	time
V	volume of liquid in aeration tank
z	water depth

SECTION 1

INTRODUCTION

This report describes Phase II of a two Phase project to evaluate high efficiency activated sludge aeration systems. The project was conducted by the County Sanitation Districts of Los Angeles County (Districts) and funded in part by the U.S. Environmental Protection Agency under Contract Number 68-03-2906.

Phase I was conducted at the research facilities at the Districts' Joint Water Pollution Control Plant (JWPCP) in Carson, California. The Phase I findings have been described previously by Yunt and Hancuff (1988). Phase I had as its goal the evaluation of a large variety of aeration systems in clean water. Eight aeration systems representing six generic types were evaluated over a range of water depths and input power levels. The three most efficient aeration system types evaluated in Phase I were selected for evaluation in process water in Phase II. These were the ceramic dome system, porous tube system and jet system. Phase II was comprised of two parts. In Part 1 the three aeration systems selected from Phase I were evaluated in parallel aeration tanks. After a period of concurrent operation, the most efficient aeration system on an energy basis was selected for extensive evaluation in Part 2 of Phase II.

The first part of the Phase II was begun in 1980 with the installation of the first of the three high efficiency aeration systems. Up to this time, the plant had been equipped with a sparged spiral roll aeration system. Over the period of September 1980 through March 1981 the three aeration systems (Sanitaire fine pore ceramic disk in a full floor coverage configuration; Nokia fine pore plastic tubes, in a cross roll configuration; and Aerocleve jet aerators in two configurations) were installed and clean water testing was performed. Clean water testing was necessary because different manufacturers supplied the aeration equipment in Phase II than in Phase I. After clean water testing, each system was evaluated in process water for varying periods of time, ranging from a low of three and a half weeks (first jet system configuration) to a maximum of two years.

Two alternative configurations of the jet system were supplied. The first alternative used a cluster concept, called a "radial aerator unit," with a cluster of jets located in each of three grids. The jets in this configuration were pointed outward from the control unit in a star pattern. This system did not perform as expected and was replaced by a side configuration, called a "unidirectional aerator unit," with jets located along one side of the tank pointing in a direction perpendicular to the tank length.

Beginning in January 1982, the tube and jet systems were replaced by fine pore ceramic dome systems. Porous ceramic diffusers installed in a total floor coverage configuration was deemed more energy efficient than the tube and jet systems. Because of a competitive bidding process, Norton domes, which were originally tested in Phase I, were used to replace the tubes and jets. Table 1 shows the critical periods and events in the project.

A disk diffuser cleaning study was undertaken in 1984. Although the study was not originally planned to be part of the project, the results were considered significant and are included herein.

This report is divided into six sections and various appendices. The six sections contain the introduction, conclusions and recommendations, plant and aeration systems description, clean water test results, process water test results and diffuser cleaning evaluation. The appendices provide plant operation results in the form of tables and figures, and also describe the experimental procedures used during the clean and process water testing.

It should be noted that many of the aeration testing methods, such as the ASCE Clean Water Test Standard (1984) and off-gas analysis procedure (Redmon, et al. 1983) were in development during the lifetime of this project. The methods presented here differ in some ways from the currently accepted procedures. Also, some of the data collected in this project and the experiences gained in testing were used to develop the currently accepted procedure.

Table 1

Project Milestones

Part 1		
Inclusive Dates	Activity	Duration (Months)
9/2/80-3/20/81	Installation of three aeration systems	6.6 months
11/25/80-3/27/81	Clean Water Testing	4.0 months
12/9/80-1/3/81	Operation of Jet System No. 1	0.86
1/28/81-3/12/82	Operation of Jet System No. 2	13.4
12/24/80-present	Operation of Disk System	-
4/7/81-1/15/82	Operation of Tube System	9.3
7/13/81-12/31/81	Operation at reduced wastewater flow rates for the jet system	5.7

Part 2		
Inclusive Dates	Activity	Duration (Months)
1/15/82-5/7/82	Installation/modification of the dome disc/systems	3.7
3/5/82-present	Operation of Dome System A (Tank 2)	-
4/23/82-present	Operation of Dome System B (Tank 3)	-
7/6/82-9/8/82	Conventional operation at 18 MGD	2.1
9/9/82-10/31/82	Step feed operation at 18 MGD	1.7
11/1/82-12/31/82	Conventional operation at 12 MGD	2.0

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

Phase II of the two phase project successfully demonstrated the ability of high efficiency aeration systems to significantly reduce the energy requirements for treating wastewater. The following conclusions and recommendations were reached:

1. The clean water standard aeration efficiencies (SAE's) obtained for the disk and tube systems during the Phase II testing were roughly comparable to the corresponding results obtained during the Phase I testing. This was not the case with the jet system, where a high pump/blower power ratio during the Phase II tests may have reduced the system performance.

2. The fine pore ceramic disk system provided by Sanitaire transferred more oxygen per unit of energy consumption than either the jet system provided by Clevepak or the fine pore tube system provided by Nokia. This occurred even though the disk system had a relatively low αF factor.

3. The tube system suffered atypical mechanical failures. Due to an improper choice of material, many of the schedule 80 PVC nipples which attached the diffusers to the air headers broke. This created uncontrolled air discharge (boils) and allowed mixed liquor to enter the air headers. These high localized air flow rates made aeration efficiency testing very difficult.

4. The analysis of Part 1 operations data, using calculated oxygen demands, estimates that the fine pore ceramic disk system produced an average standard aeration efficiency (αFSAE) of 1.53 lb O_2/wire hp-hr, while the tube and jet systems produced efficiencies of 1.14 and 0.94, respectively. These calculated efficiencies may be lower than actually obtained due to the value of the sludge yields used in the oxygen demand calculations. However, based on this analysis and under comparable oxygen demand conditions, it is estimated that the disk system would require roughly 61% of the energy required by the jet system and 75% of the energy required by the tube system.

5. The analysis of Part 1 off-gas test results obtained under nearly normal plant operating conditions shows that the disk system produced a standard aeration efficiency (αFSAE) of 2.1 lb O_2/wire hp-hr while the jet system produced an efficiency of 1.7 lb O_2/wire hp-hr. Based on these results, under comparable oxygen demand conditions, the disk system would require roughly 81% of the energy required by the jet system. The off-gas test results for the tube system were not included in this report because of the atypical

mechanical problems experienced. The reason for the discrepancies in efficiency obtained by two analytical techniques (an analysis of plant operations data and the off-gas test results) is not clear, but may be related to the sludge yield coefficients determined and used in the operations data analysis as well as to the limited time frame of the off-gas tests.

6. Based on off-gas test results, the flow weighted αF factors for the disk and jet systems were 0.28 and 0.69, respectively. The two αF factors should not be directly compared because the jet system was operated at approximately 75% of the disk system's wastewater flow rate. This reduction was required because of potentially DO limiting conditions in the jet tank.

7. In Phase II, the jet and tube systems were replaced with ceramic dome systems supplied by Norton. Three operating modes were evaluated in this phase: 18 MGD Conventional; 18 MGD Step Feed, and 12 MGD Conventional. Based on an analysis of plant operations data, using calculated oxygen demands, the standard aeration efficiencies (αFSAE's) obtained the for the disk and domes systems during the three modes was not significantly different, and varied between 1.9 and 2.3 lb O_2/wire hp-hr on a period average basis.

8. The analysis of Part 2 off-gas test results obtained during the 18 MGD Conventional Mode shows that the standard aeration efficiencies (αFSAE's) for the disk and dome systems varied from 2.7 to 3.4 lb O_2/wire hp-hr. This contrasts sharply with the corresponding operations data results during this period and is probably due to the limited time frame of the off-gas tests. During the latter two operation modes during Part 2, the standard aeration efficiencies based on off-gas testing varied from 1.8 to 2.3 lb O_2/wire hp-hr. This is in excellent agreement with the aeration efficiencies obtained by analyzing the plant operations data using calculated oxygen demands.

9. Based on off-gas test results, the overall air flow rate weighted αF factor for the disk system during these three periods was 0.343, 0.266, and 0.261, respectively. The αF factor was lowest, for all three systems, at the head end of the aeration tank and gradually increased to a maximum value at the effluent end of the aeration tank. The disk and dome αF factors were as low as 0.15 at the first test point, which was located 25 ft into the 300 ft aeration tank.

10. The data for the disk and dome systems suggests a decline in performance from the time the systems are installed or cleaned. The decline is attributed to diffuser fouling.

11. A number of cleaning methods for the disk diffuser system were evaluated at full and pilot scale. Low pressure hosing from the tank top level was effective in removing biological slimes and partially restored transfer efficiency and reduced media headloss. After approximately three years and one half of operation, the headlosses in the disk diffuser system became excessive. Additional diffuser cleaning methods were needed to restore the proper operation of the system. The "Modified Milwaukee Method," or liquid HCl acid cleaning was used on the disk diffusers and very successfully restored then to near-new condition. The superiority of this technique was also demonstrated at lab scale on a series of single diffuser cleaning tests. A minimum cleaning frequency of low pressure hosing every six months and liquid acid cleaning every two years was recommended.

SECTION 3

PLANT AND AERATION SYSTEMS DESCRIPTION

The Whittier Narrows Water Reclamation Plant (WRP) is a full secondary treatment facility with primary clarification, aeration, secondary clarification, filtration, chlorination and dechlorination. The plant has no sludge processing facilities. The plant is located 38 km inland from the Pacific Ocean. It is operated by the Los Angeles County Sanitation Districts which operate ten other plants in Los Angeles County.

The topology of the Los Angeles Basin is such that long trunk sewers can be operated with very few pump stations from the inland areas to the Districts' large Joint Water Pollution Control Plant (JWPCP) in Carson. Wastewater flows by gravity from the Whittier Narrows area over 32 km to the JWPCP. As growth has occurred the Districts have added treatment capacity at its "upstream" plants such as the Whittier Narrows WRP. This fortuitous situation allows growth without increasing the size of the trunk sewers which operate at near design capacity. The upstream plants generally return primary and secondary sludge to the sewers. These sludges flow to JWPCP and allows the Districts to concentrate its solids processing facilities in one location. The upstream plants also help to meet the water reclamation needs of the various communities. The Whittier Narrows, San Jose Creek, Long Beach, Los Coyotes, and Pomona Water Reclamation Plants all operate in this fashion.

In addition to solids handling facility design, the unique sewer arrangement provides additional operation freedom to these upstream plants. For instance, at the Whittier Narrows WRP, the flow rate is set relatively constant and the plant is less disturbed by the diurnal fluctuations in wastewater flow rate. Furthermore, tank maintenance at the various Districts WRP's can be performed much more easily since a temporary shortfall in capacity at one plant can be treated by another plant. These aspects of the Districts' facilities were one reason that the Whittier Narrows WRP was selected for the Phase II study.

Since the Whittier Narrows WRP provides reclaimed wastewater for reclamation purposes, the plant must produce better than average secondary effluent. To meet Health Department requirements the plant has a turbidity discharge limit of less than 2 NTU, and a total coliform discharge limit of 2.2 MPN or less, which requires the use of effluent filters for compliance.

Both the Districts' and the City of Los Angeles' storm and sanitary sewers are separated. The impacts of stormwater flow on the Whittier Narrows WRP is small compared to plants with combined sewers. Nevertheless there is additional flow during the rainy season (Winter) and for this reason operational flexibility is more limited during these periods.

Figure 1 shows the plan view of the entire treatment plant. There are two primary sedimentation tanks (primary clarifiers), three aeration tanks or basins, six final sedimentation tanks (one tank can be used for filter backwash recovery), six mixed media effluent filters and a chlorine contact chamber. Dechlorination using sulphur dioxide is performed in the channel that collects effluent from the chlorine contact chambers.

Figure 2 shows the process flow with several of the measuring devices. The plant influent flows through the two covered primary clarifiers into a distribution channel for the aeration tanks. Slide gates control the flow rate into each aeration tank. Normally the aeration tanks are operated as separate, single pass units. The gates in each tank can be manually adjusted to assure an even flow split. Wastewater flow can be introduced to each tank along its length in order to provide step feed operation. The tanks can also be operated in serpentine flow to achieve step feed, but this operating mode was not practiced during the project. The effluent of each aeration tank flows into a second distribution channel and the flow is divided among the final clarifiers. Return sludge is pumped from the far end of each clarifier by air lift pumps and then flows by gravity to the head of the aeration tanks. Three propeller meters are located in the return sludge flow line.

Three blowers are located in the basement of the control building. The blower suction is primarily from the headspace under the covers of the primary clarifiers. Air filtration consists of high efficiency "Bio-cel" main filters, preceded by "Amerkleen" prefilters. All filters are of the replaceable cartridge variety and are manufactured by American Air Filter Company. The blowers draw odor containing gases that might be produced in the primary clarifiers and force them into the aeration system. In this way the mixed liquor acts as a gas scrubber. This has been a common odor control technique used by the Districts.

Blower discharge is piped to the head of all three aeration tanks through a single pipeline where it flows into two headers. The first header is located on the east side of Aeration Tank 1 and serves this tank. The second manifold is located between Tanks 2 and 3 and serves both tanks. A separate temporary manifold was provided for the jet aeration system.

Figure 3 shows the location of the aeration systems during Parts 1 and 2 of the project. The disk system was installed in Tank 1 and except for the number of diffusers installed, remained unchanged for the duration of the project. The tube system was installed in Tank 2 and was later replaced by a ceramic dome system. The jet systems (both configurations) were installed in Tank 3 and were later replaced by a dome system.

Tables 2 and 3 show the average operating conditions for the plant during Parts 1 and 2. Monthly summaries are provided in Appendices A and B. The various test periods will be described in more detail in Section 5.

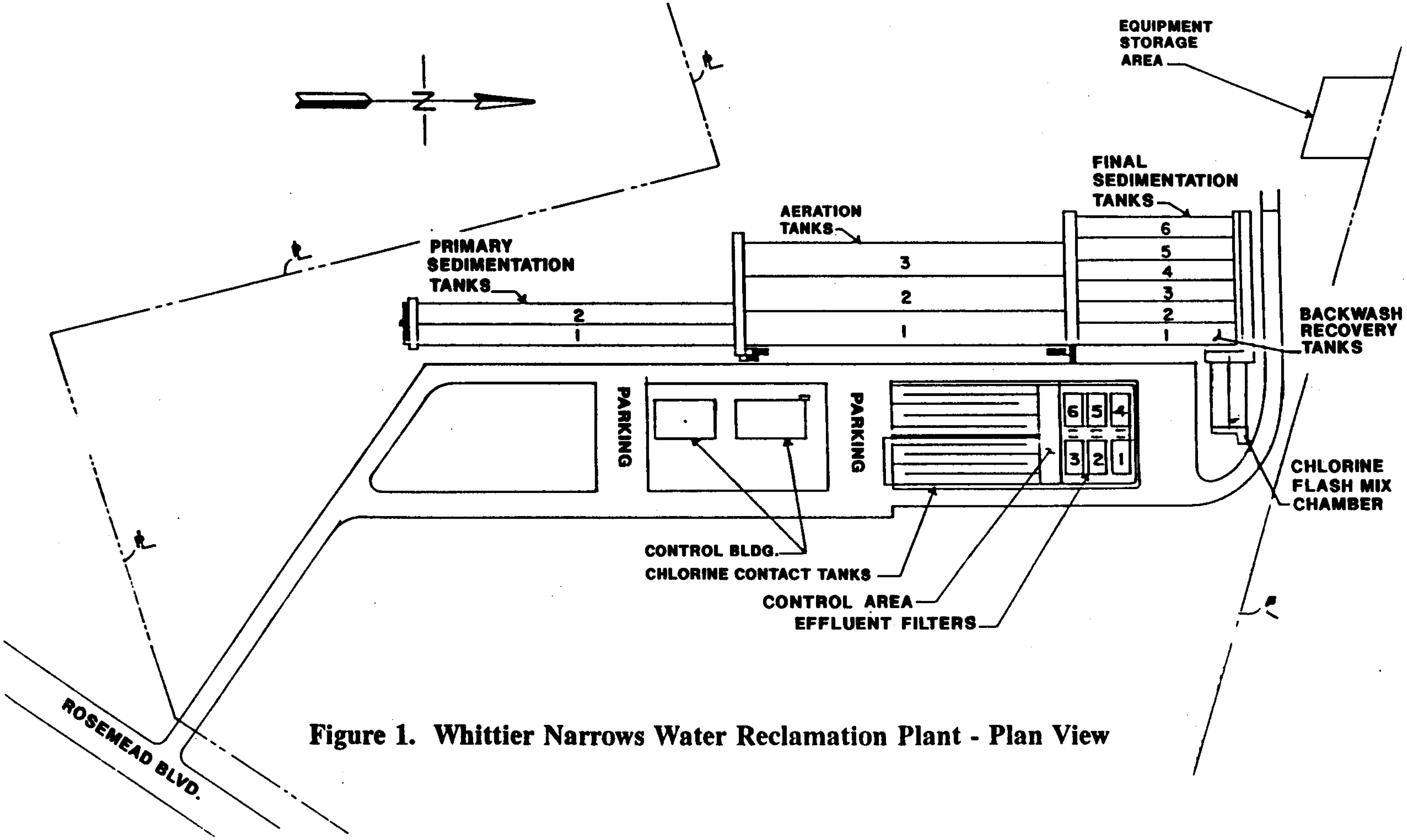


Figure 1. Whittier Narrows Water Reclamation Plant - Plan View

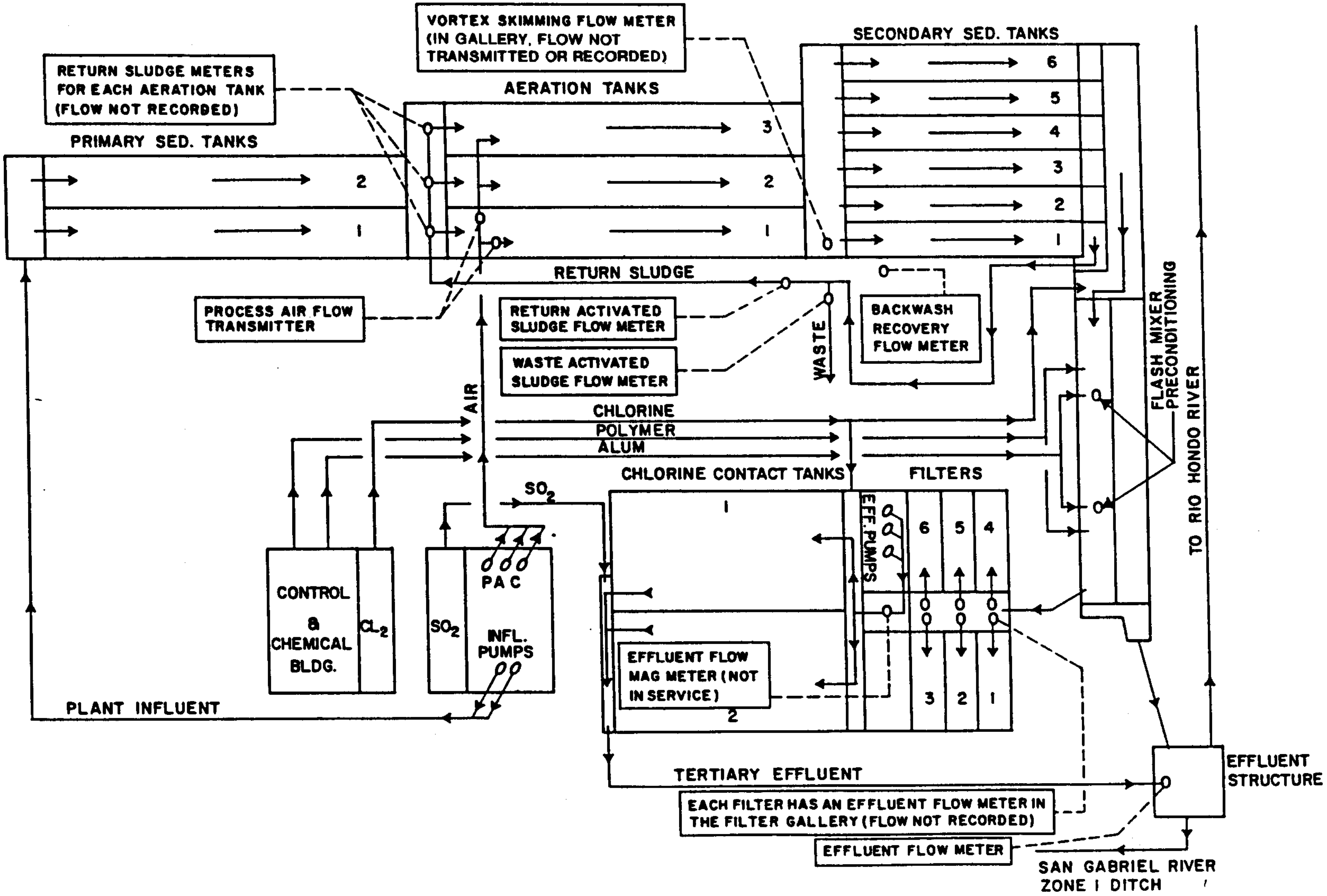
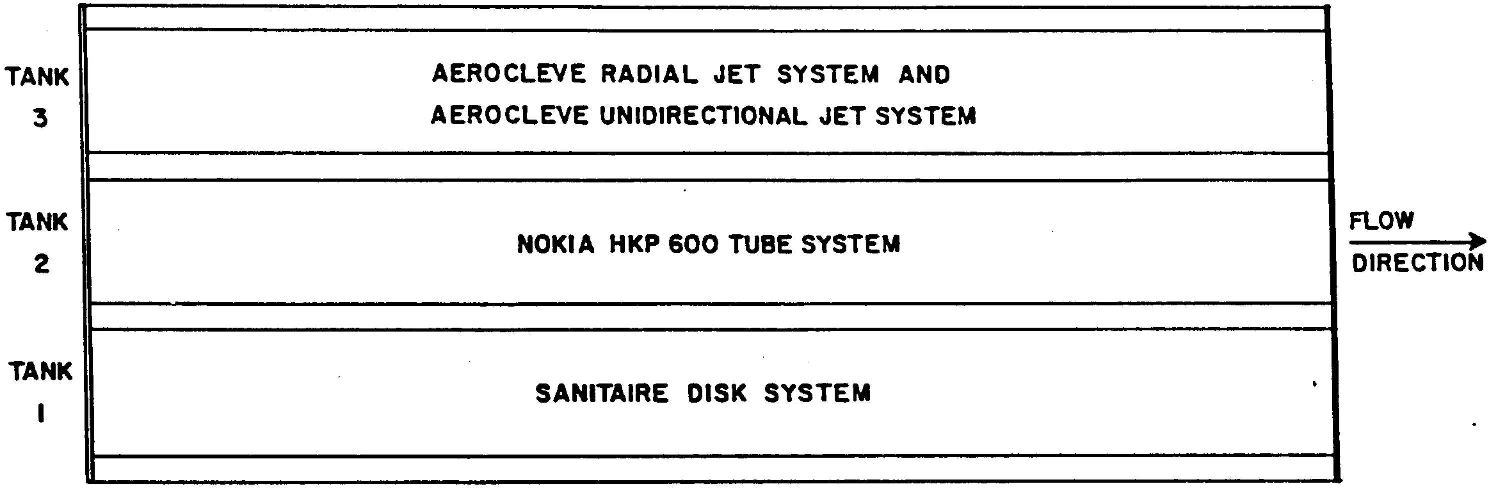
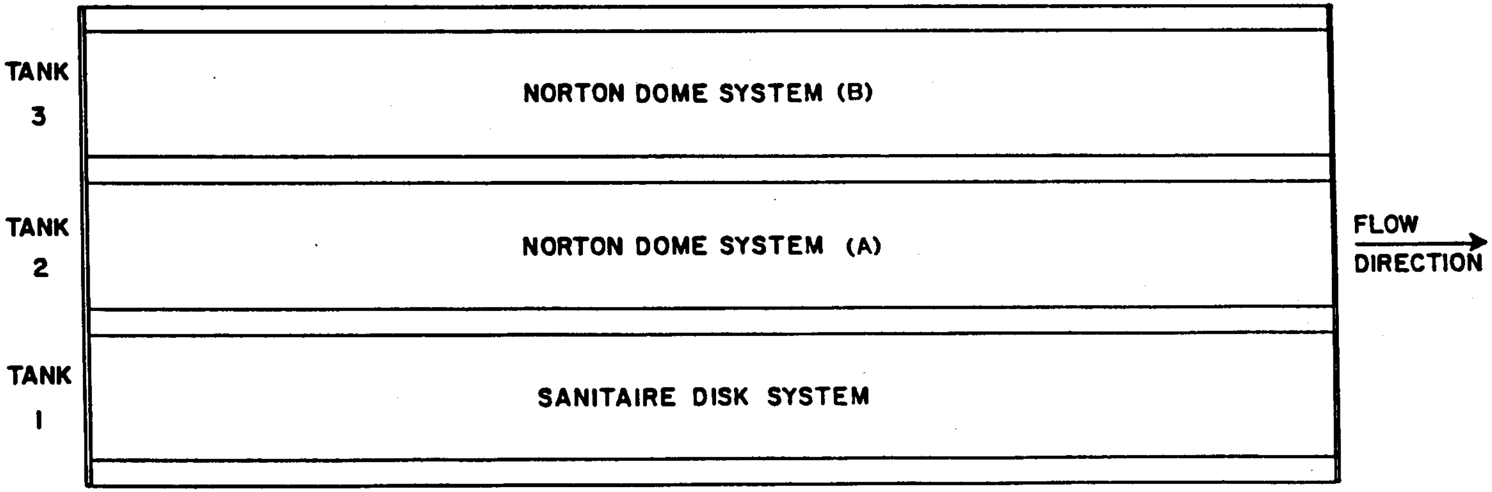


Figure 2. Whittier Narrows WRP Process Flow Sheet



DURING PART I OF THE PROJECT



DURING PART 2 OF THE PROJECT

Figure 3. Systems Tested in Aeration Tanks Nos. 1-3

Table 2

Average Plant Operating Conditions During Part 1*

Parameter	Disk System	Tube System	Jet System	Total Plant
Primary Effluent Flow (MGD)	4.16	4.05	3.10	11.31
Recycle Flow (MGD - %)	1.17 (28.1)	1.01 (25.0)	0.48 (15.5)	2.66 (23.6)
Waste Sludge Flow (MGD)	-	-	-	0.201
Mixed Liquor Aeration Time (V/Q-hrs)	5.46	5.62	7.34	6.03
F/M (lb COD/lb MLVSS)	1.06	0.97	0.95	1.00
MCRT (total system solids basis-days)	-	-	-	3.52
Volumetric Loading (lbs COD/1000 ft^3-day)	66.2	64.4	49.3	60.0
DO (mg/L)**	0.7	0.5	0.7	0.65
Tank Air Flow (scfm)	2147	2624	1754	6525
Air Flow/Diffuser (scfm)	1.29	4.37	27.4	-

* During the test period August through December, 1981.

** Estimates

Table 3

Average Plant Operating Conditions During Part 2*

(continued on next page)

Parameter	Disk System	Dome System A	Dome System B	Total Plant
Primary Effluent Flow (MGD)				
18 MGD Conventional Mode	6.13	5.89	5.89	17.91
18 MGD Step Feed Mode	6.07	5.84	5.84	17.76
12 MGD Conventional Mode	4.28	4.10	4.10	12.48
Recycle Flow (MGD-%)				
18 MGD Conventional Mode	1.74 (28.3)	1.74 (29.5)	1.74 (29.5)	5.21 (29.1)
18 MGD Step Feed Mode	2.13 (35.1)	2.13 (36.4)	2.13 (36.4)	6.39 (35.9)
12 MGD Conventional Mode	1.17 (27.3)	1.17 (28.5)	1.17 (28.5)	3.50 (28.1)
Waste Sludge Flow (MGD)				
18 MGD Conventional Mode	-	-	-	0.245
18 MGD Step Feed Mode	-	-	-	0.320
12 MGD Conventional Mode	-	-	-	0.221
Mixed Liquor Aeration Time (V/Q-hrs)				
18 MGD Conventional Mode	3.74	3.89	3.89	3.84
18 MGD Step Feed Mode	3.04	3.16	3.16	3.12
12 MGD Conventional Mode	5.33	5.56	5.56	5.48
F/M Ratio (lb COD/lb ASVSS)**				
18 MGD Conventional Mode	1.40	1.32	1.33	1.35
18 MGD Step Feed Mode	1.34	1.26	1.27	1.29
12 MGD Conventional Mode	1.43	1.33	1.36	1.37
MCRT (Total System Solids Basis Days)				
18 MGD Conventional Mode	-	-	-	3.53
18 MGD Step Feed Mode	-	-	-	3.89
12 MGD Conventional Mode	-	-	-	3.63

* The test periods were as follows:
18 MGD Conventional Mode - July 6-September 8, 1982
18 MGD Step Feed Mode - September 14-October 31, 1982
12 MGD Conventional Mode - November 6-December 31, 1982

** ASVSS = Aeration System Volatile Suspended Solids

Table 3 (Continued)

Parameter	Disk System	Dome System A	Dome System B	Total Plant
Volumetric Loading Rate (lbs COD/1000 ft^3 day)				
18 MGD Conventional Mode	101.6	97.5	97.5	98.9
18 MGD Step Feed Mode	102.9	98.9	98.9	100.3
12 MGD Conventional Mode	72.9	69.9	69.9	70.9
DO (mg/L)**				
18 MGD Conventional Mode	0.6	0.9	0.5	0.7
18 MGD Step Feed Mode	0.6	0.6	0.7	0.7
12 MGD Conventional Mode	0.8	0.7	0.5	0.6
Air Flow (scfm)				
18 MGD Conventional Mode	3211	3540	3150	9901
18 MGD Step Feed Mode	3372	3138	3076	9586
12 MGD Conventional Mode	2353	2484	2374	7211
Air Flow/Diffuser (scfm)				
18 MGD Conventional Mode	1.58	1.40	1.24	-
18 MGD Step Feed Mode	1.67	1.24	1.22	
12 MGD Conventional Mode	1.16	0.98	0.94	-

** Estimates

DISK AERATION SYSTEM

Figure 4 shows the disk system. The top of the figure shows an exploded view of the diffuser. The unique feature of this system is the fashion of holding and sealing the diffuser stone to the holder. A large o-ring coated with silicon rubber grease provides an airtight seal. The o-ring and stone are held against the holder by a retaining ring nut which screws onto the holder. The thickness of the diffuser stones supplied for this project vary from 0.93 - 1 inch. With this particular system, the stone thickness is intentionally non-uniform; and the disk is slightly compressed in the outer annular space shown on the top portion of Figure 4. The bottom of Figure 4 shows a side view of the diffuser assembly with the diffuser's dimensions. The PVC header pipe is nominally 4" in diameter. The orifices are contained in a screw-in plug and are changeable. Later versions of this diffuser use a thinner stone and a fixed orifice drilled through the pipe wall.

Figure 5 shows the aeration system layout in Tank 1. The diffusers were arranged in three grids with air supplied by a downcomer and control valve for each grid. In Part 1 of the project, the grids had 724, 594, and 352 diffusers for grids 1, 2, and 3, respectively. In Part 2, the number of diffusers was increased to 792, 774, and 460 diffusers. The gates which control influent flow rate are also shown. The step gates were used to introduce primary effluent for step feed operation. Three step gates are provided in each tank.

Figure 6 shows a side view of the grid with a downcomer and the manifold connecting each 4" PVC diffuser header. Note that the tank walls are "wye" shaped. This construction was employed in part to facilitate mixing when the spiral roll aeration system was used, and in part to provide space for air and influent wastewater piping. It is a typical Districts' design. The top of the diffusers were located approximately 2 ft above the tank bottom, which is higher than the manufacturer's normal design recommendations. This was done because of the limited head capabilities of the existing plant blowers, which were sized for the static heads associated with typical coarse bubble equipment.

TUBE AERATION SYSTEM

Figure 7 shows the Nokia tube diffuser used in this project. The diffuser was constructed with a smooth polyethylene plastic disk which on appearance did not seem porous. The diffuser was connected to the pipe manifold with a 3/4" PVC nipple, Schedule 80. A flow control orifice was provided within the diffuser at the end of the PVC nipple. Unfortunately, a number of PVC nipples failed during the study, which complicated aeration testing. Galvanized or stainless steel nipples would have been a better choice.

Figure 8 shows Tank 2 and the aeration system layout. Diffusers were mounted on both tank walls. Diffusers on the west side of the tank (top side in Figure 8) were attached to the swing arms used in the spiral roll aeration system. Diffusers on the east side of the tank were attached to a new fixed header system provided expressly for this project. Figure 9 shows the cross sectional view of the tank with diffusers attached to the swing arm and new header.

Figure 10 shows the locations of the tube diffusers on the swing arms. The diffusers were attached to the 3/4" bosses used previously to attach spargers. The diffuser layouts were

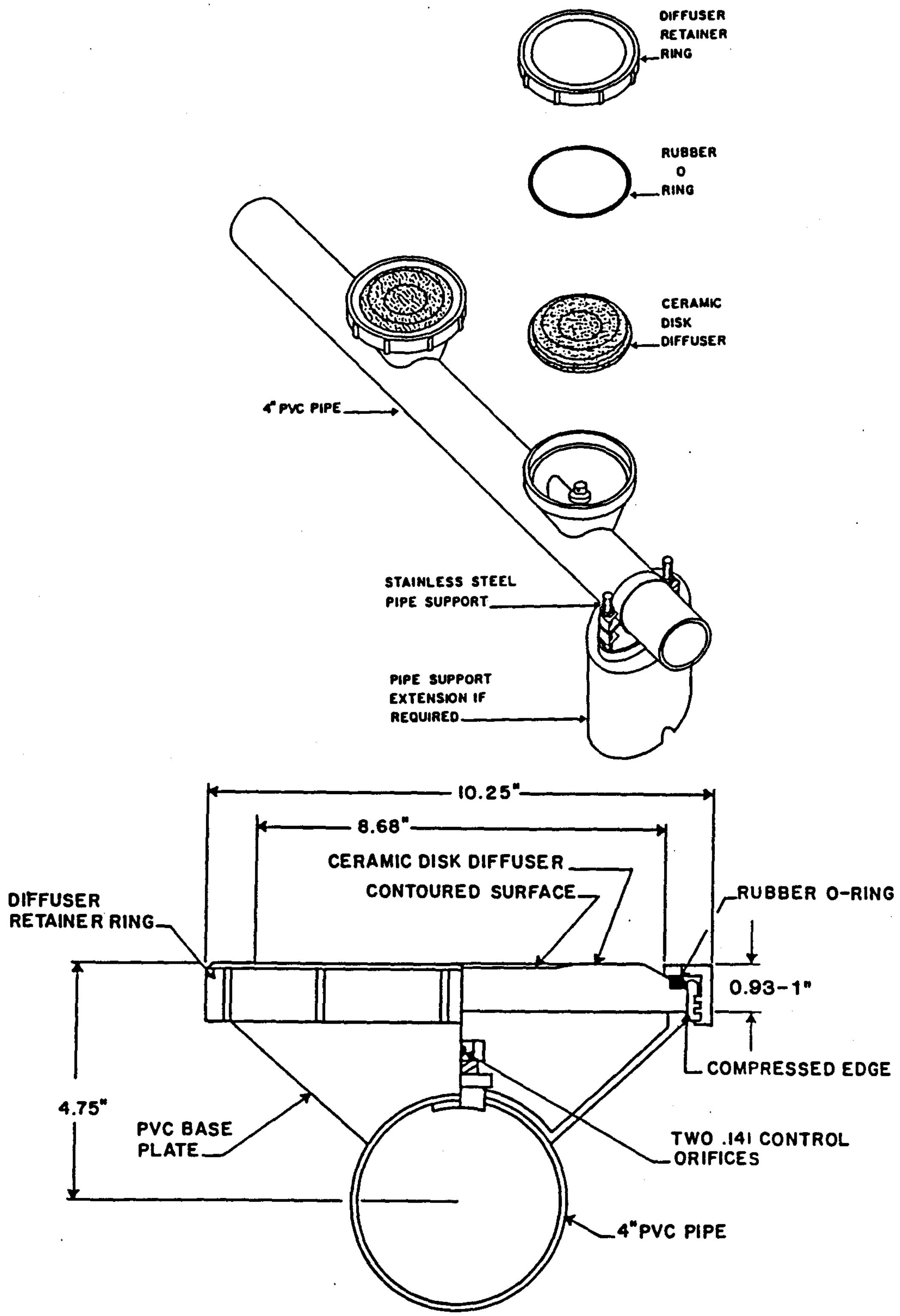


Figure 4. Sanitaire Disk Diffusers

NOTE: THE TANK WAS EQUIPPED WITH SANITAIRE DISK DIFFUSERS IN A TOTAL FLOOR COVERAGE CONFIGURATION.FOR LAYOUT DETAILS, SEE FIGURE 6

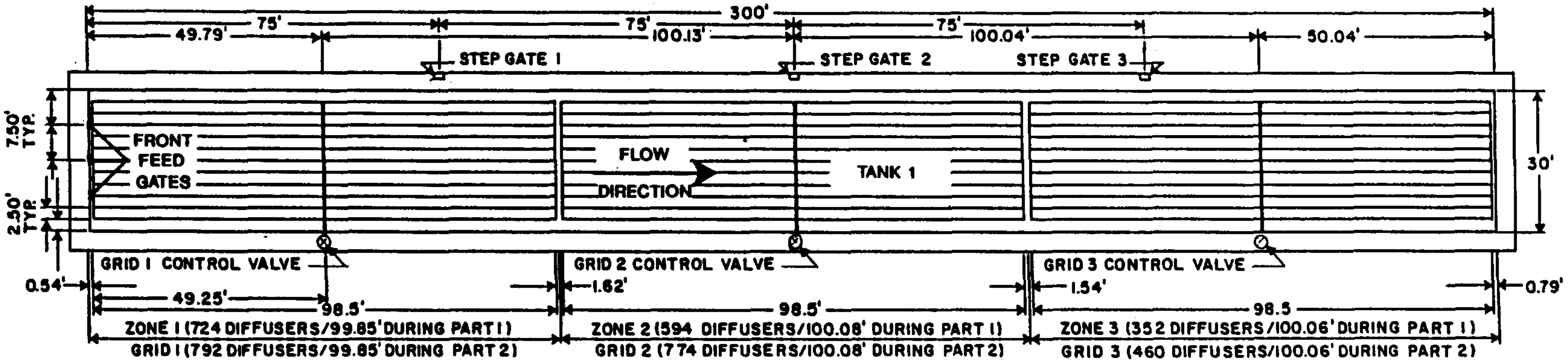


Figure 5. Layout Schematic of the Sanitaire Disk System

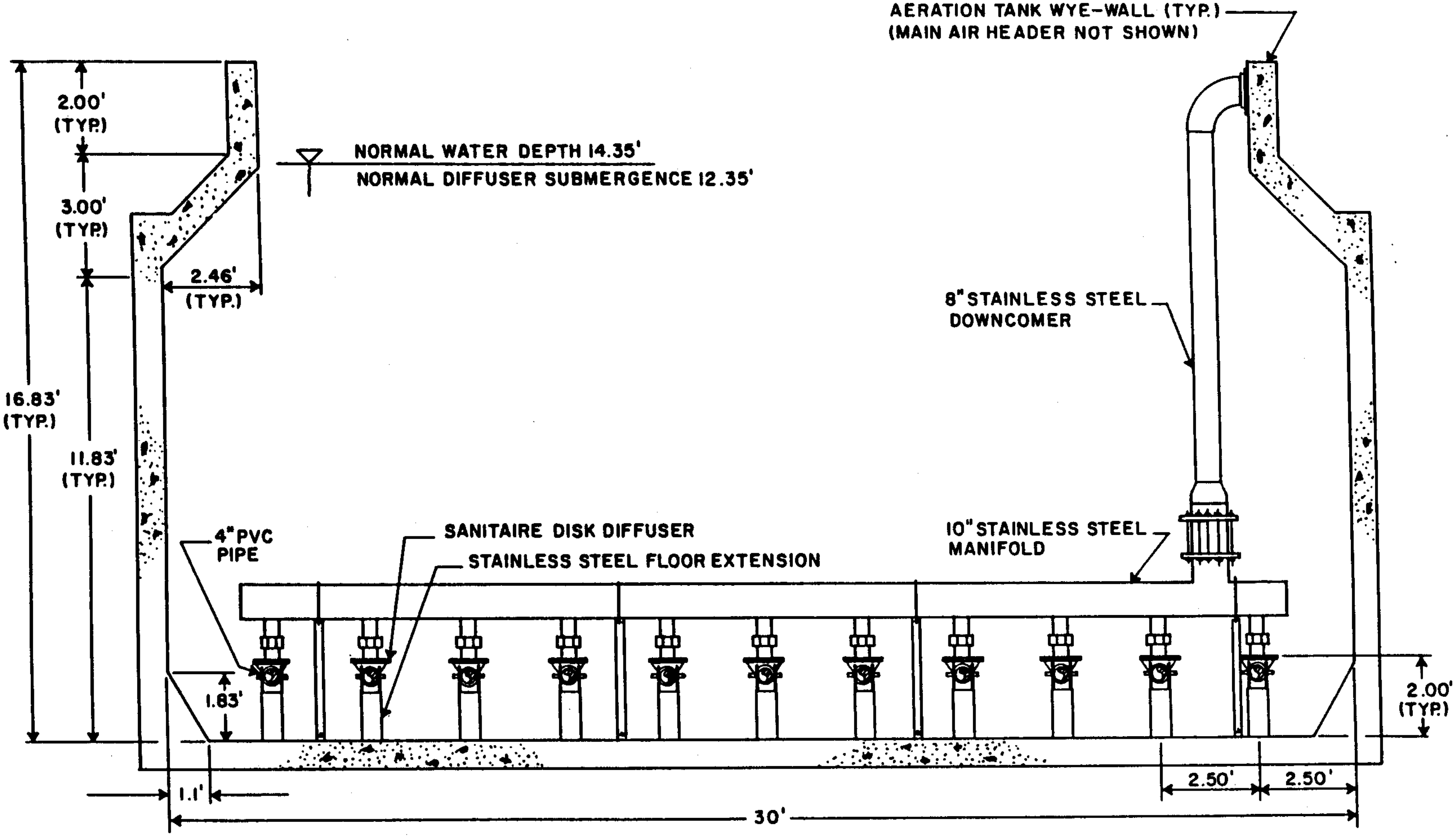


Figure 6. Sanitaire Disk System - Elevation View

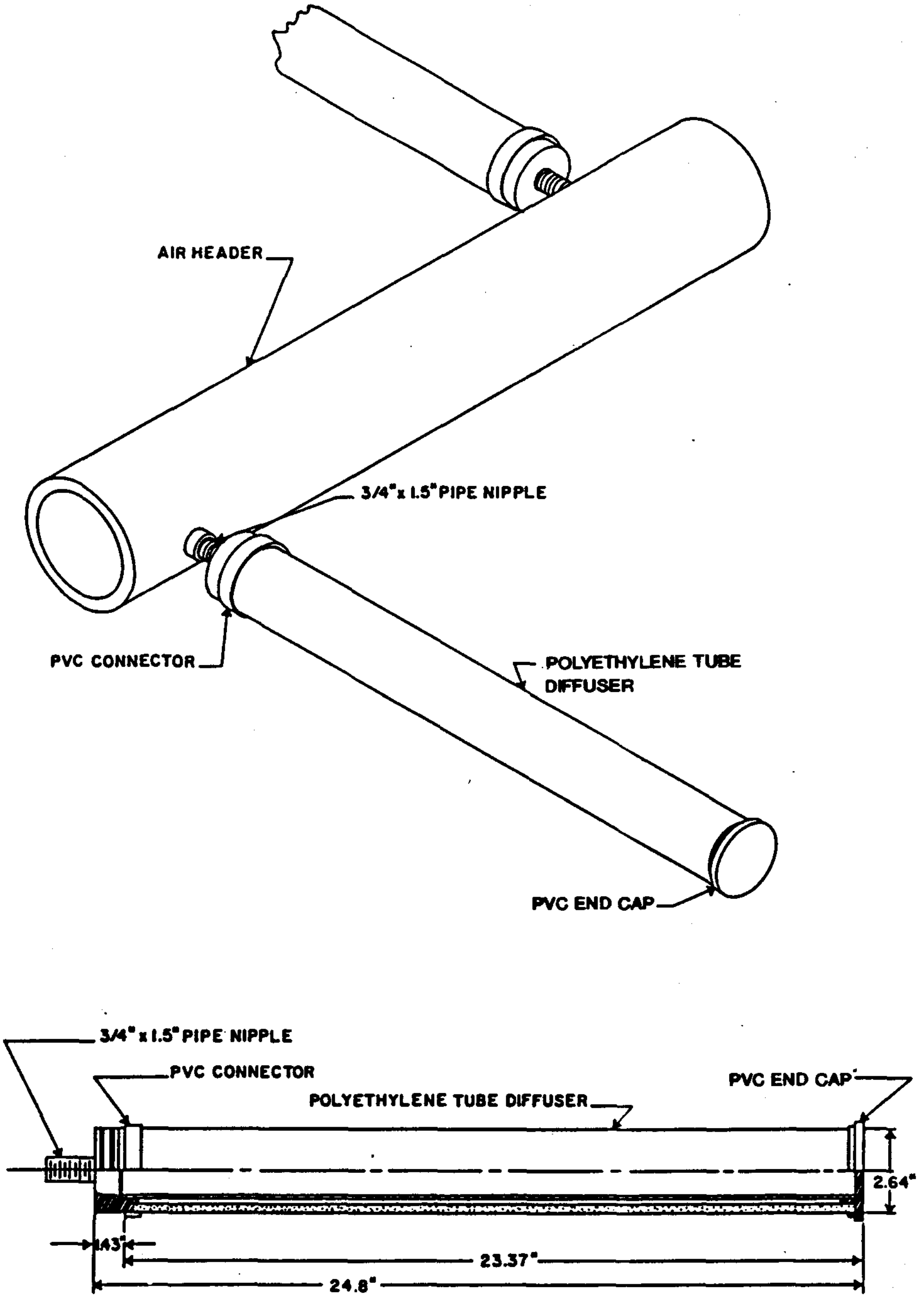
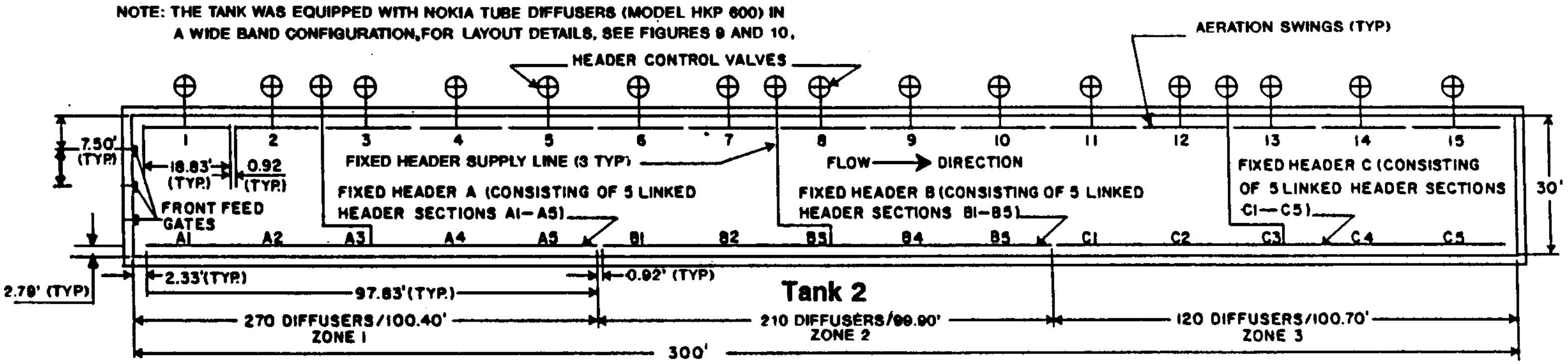


Figure 7. Nokia HKP 600 Tube Diffusers



NOTE: THE TANK WAS EQUIPPED WITH NOKIA TUBE DIFFUSERS (MODEL HKP 600) IN A WIDE BAND CONFIGURATION, FOR LAYOUT DETAILS, SEE FIGURES 9 AND 10.

Figure 8. Layout Schematic of the Nokia HPK 600 Tube System

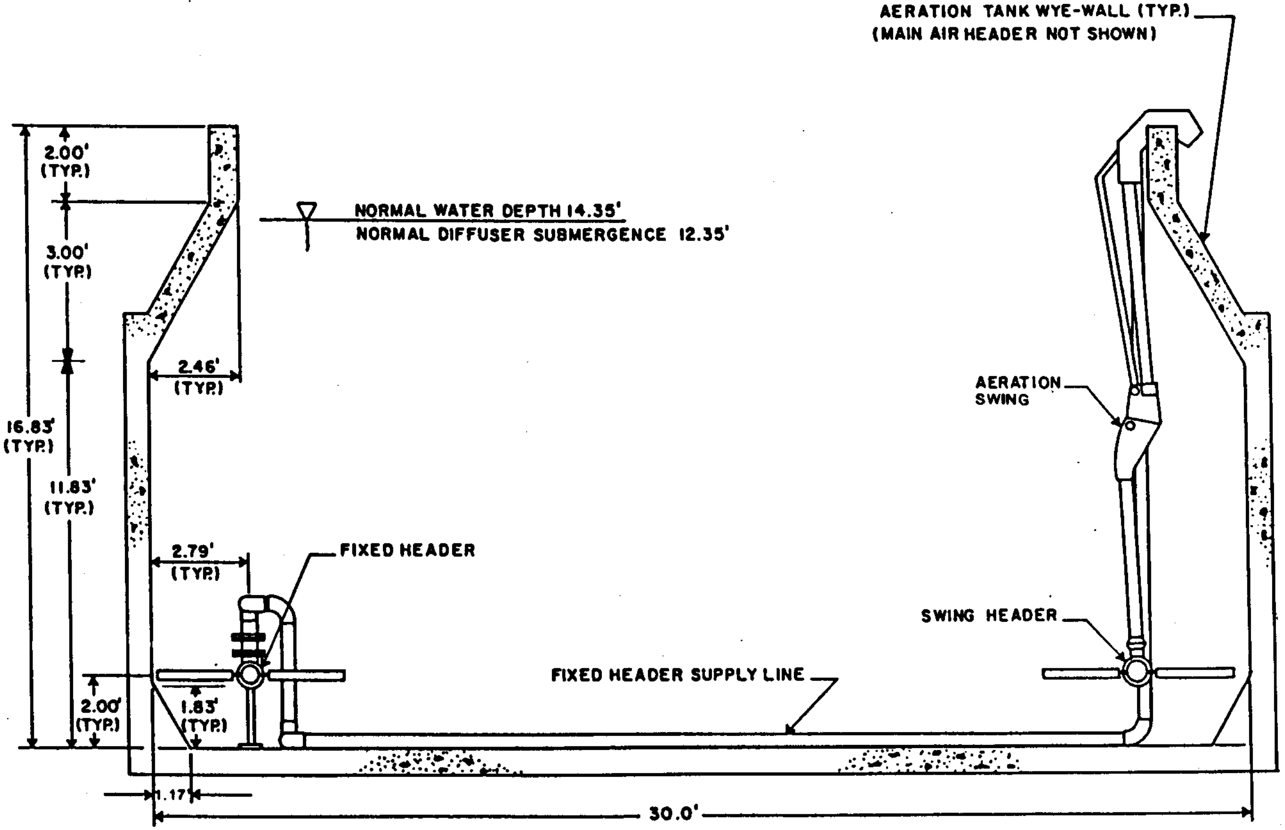


Figure 9. Nokia HKP 600 Tube System–Elevation View

NOTE: THE HEADER SECTIONS WERE LOCATED END TO END,
11" APART ALONG BOTH SIDES OF THE TANK;
SEE FIGURES 8 AND 9.

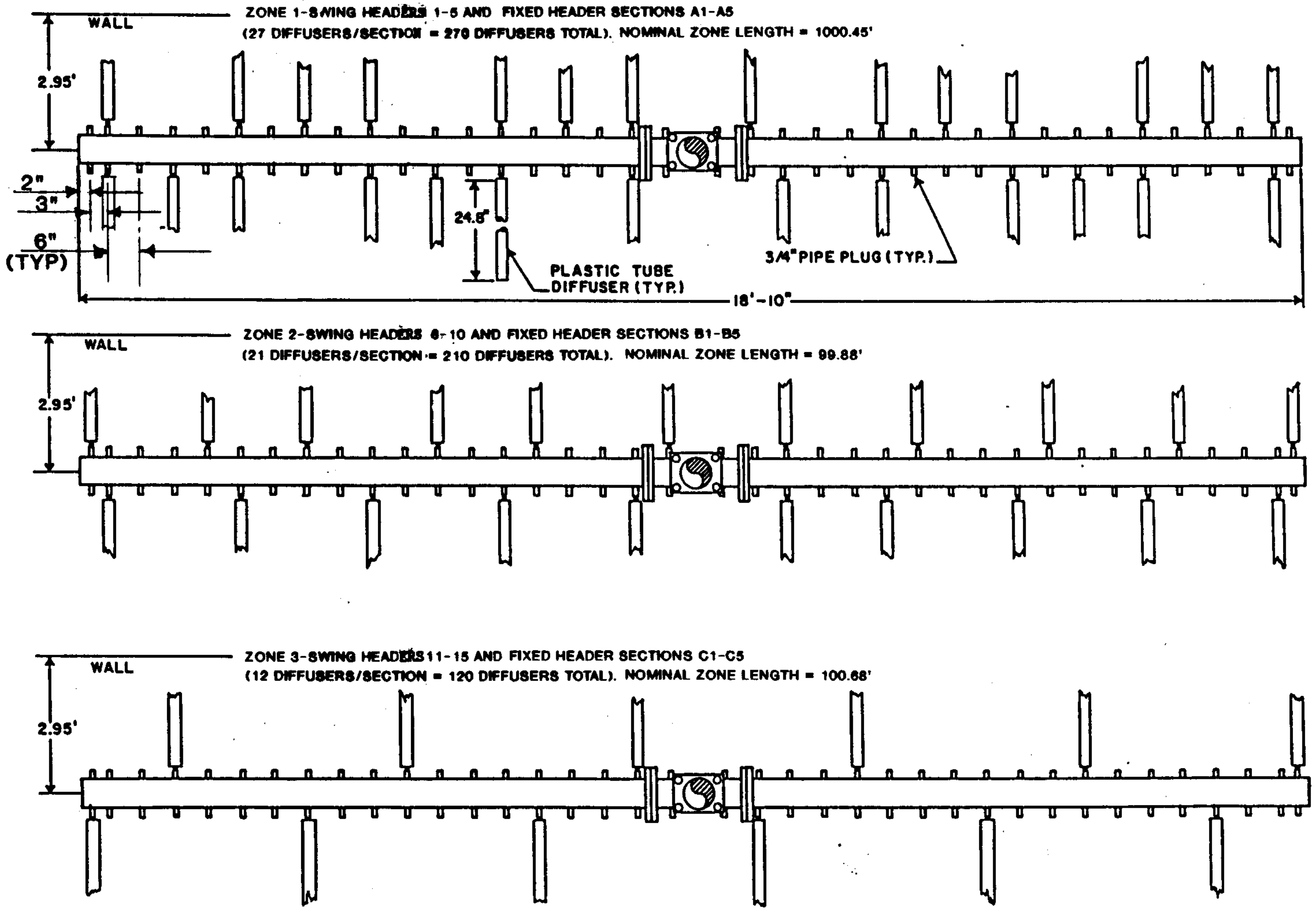


Figure 10. Diffuser Layout for the Nokia HKP 600 Tube System

similar on both sides of the tank.

Tapered aeration was provided by reducing the number of diffusers per swing arm or header, as shown in Figure 10. The tapering was provided in three distinct zones, as in the disk aeration tank. In Zone 1, corresponding to Grid 1 in the disk system, 270 diffusers were located. In Zones 2 and 3, corresponding to Grids 2 and 3 of the disk system, 210 and 120 diffusers were located, respectively.

JET AERATION SYSTEM

Figure 11 shows a jet diffuser and how it functions. Air and water are introduced to the jet and are mixed in a chamber resembling a venturi. This mixing provides a plume of small bubbles which travels horizontally across the tank as the plume rises. The pictorial shown in Figure 11 is for the Pentech diffuser, which was tested in Part 1 of this project at the test tank located at JWPCP. The jets tested in this study were provided by Aerocleve and are slightly different in construction but function on the same principle.

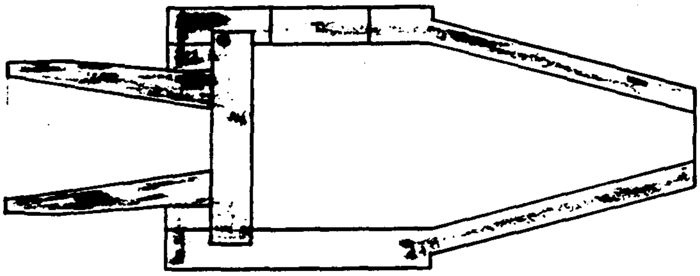
Two jet configurations were tested in this project. The first configuration is shown in Figure 12. Five stationary radial vortex jet aerators were located along the tank length. Tapering was provided by varying the number of jet diffusers in each radial aerator unit. The zones used for tapering do not correspond to the grids or zones used in Tanks 1 and 2 with disks and tubes. A total of 52 jets were used in this first configuration.

Figure 12 also shows the location of the two vertical pumps used to provide the liquid (mixed liquor) flow required by the jets. A vertical view of the pumps and jet aerators are shown in Figure 13. The pumps were mounted on the tank wall and pumped mixed liquor through a 12-inch fiberglass reinforced pipe to the jet aerators. The suction was protected by a large mesh steel screen. Air was supplied from a temporary header located along the west wall of Tank 3 at the walkway level. Steel downcomers were provided which connected to fiberglass reinforced pipe below the water line.

An air back flush line was also provided. When air was supplied through this line with the pump deenergized, liquid flow reversed in order to clean the pump screen and diffuser internals. The aerator shown in Figure 13 shows the mounting of the jet nozzles. The number of nozzles per aerator is adjustable in the field. Diffusers could be removed and the holes filled with PVC plugs. The centerline of each jet nozzle was slightly lower than the disk or tube diffusers, providing approximately 0.4 ft greater submergence.

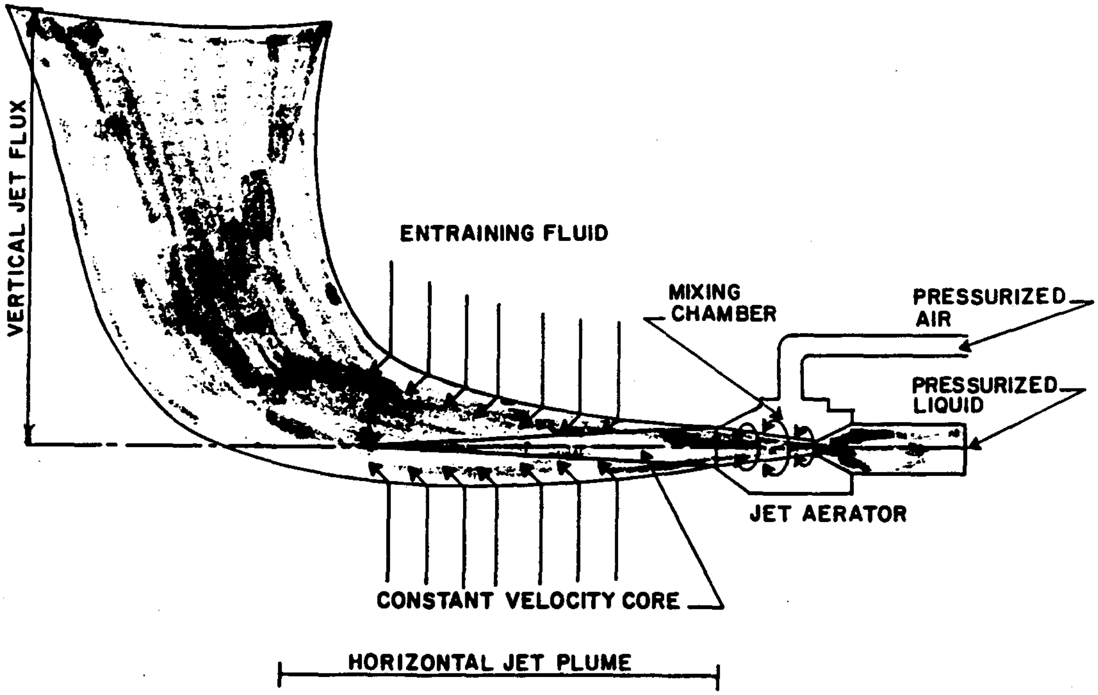
Figure 14 shows view of a typical recirculation station for the jet system. The backflush line and valve are also shown.

The radial aerator configuration was replaced shortly after it was installed with a unidirectional aerator configuration. The jets in this configuration were located along the west wall of Tank 3, which is the top wall shown in Figure 15. In the second configuration the total number of jets was increased from 52 to 64. The jets were located closer to the tank wall in order to provide greater plume travel. Even though the total number of diffusers was increased, the relative taper was maintained the same. Figure 16 shows the plan and section views of the unidirectional aerator unit. This figure also shows the dimensions of the jet diffusers. The



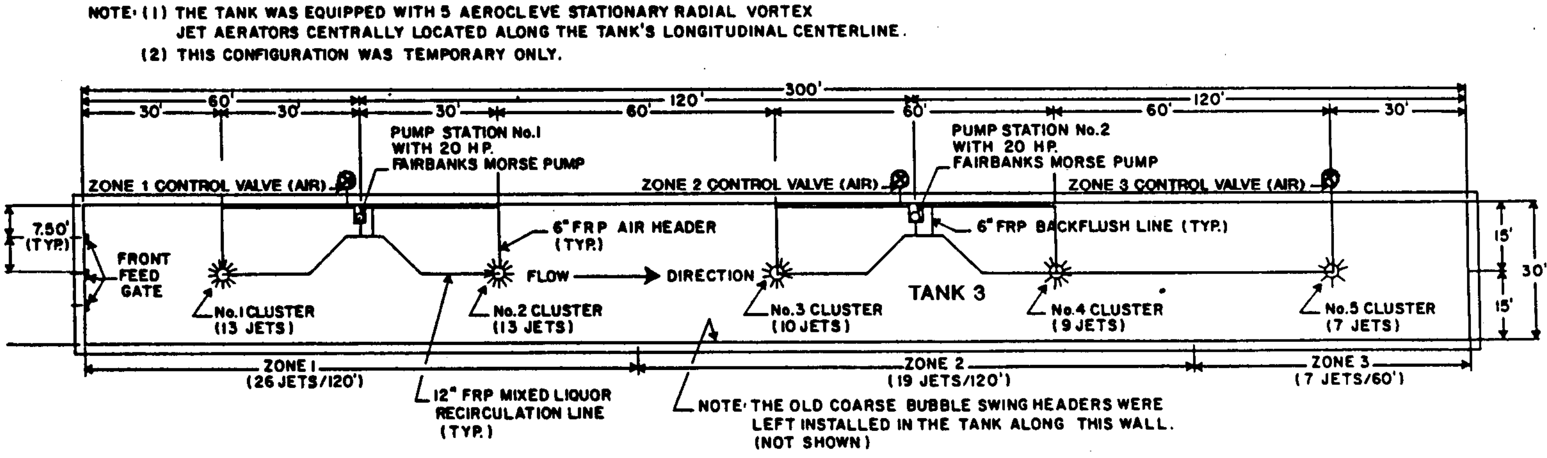
PENTECH 100JA GAS-LIQUID JET MIXER (1")

COURTESY OF PENTECH HOUDAILLE



COURTESY OF PENTECH HOUDAILLE

Figure 11. Jet Aeration Principles of Operation



NOTE: (1) THE TANK WAS EQUIPPED WITH 5 AEROCLEVE STATIONARY RADIAL VORTEX JET AERATORS CENTRALLY LOCATED ALONG THE TANK'S LONGITUDINAL CENTERLINE.
(2) THIS CONFIGURATION WAS TEMPORARY ONLY.

NOTE: THE OLD COARSE BUBBLE SWING HEADERS WERE LEFT INSTALLED IN THE TANK ALONG THIS WALL. (NOT SHOWN)

Figure 12. Layout Schematic of the Aerocleve Radial Jet System

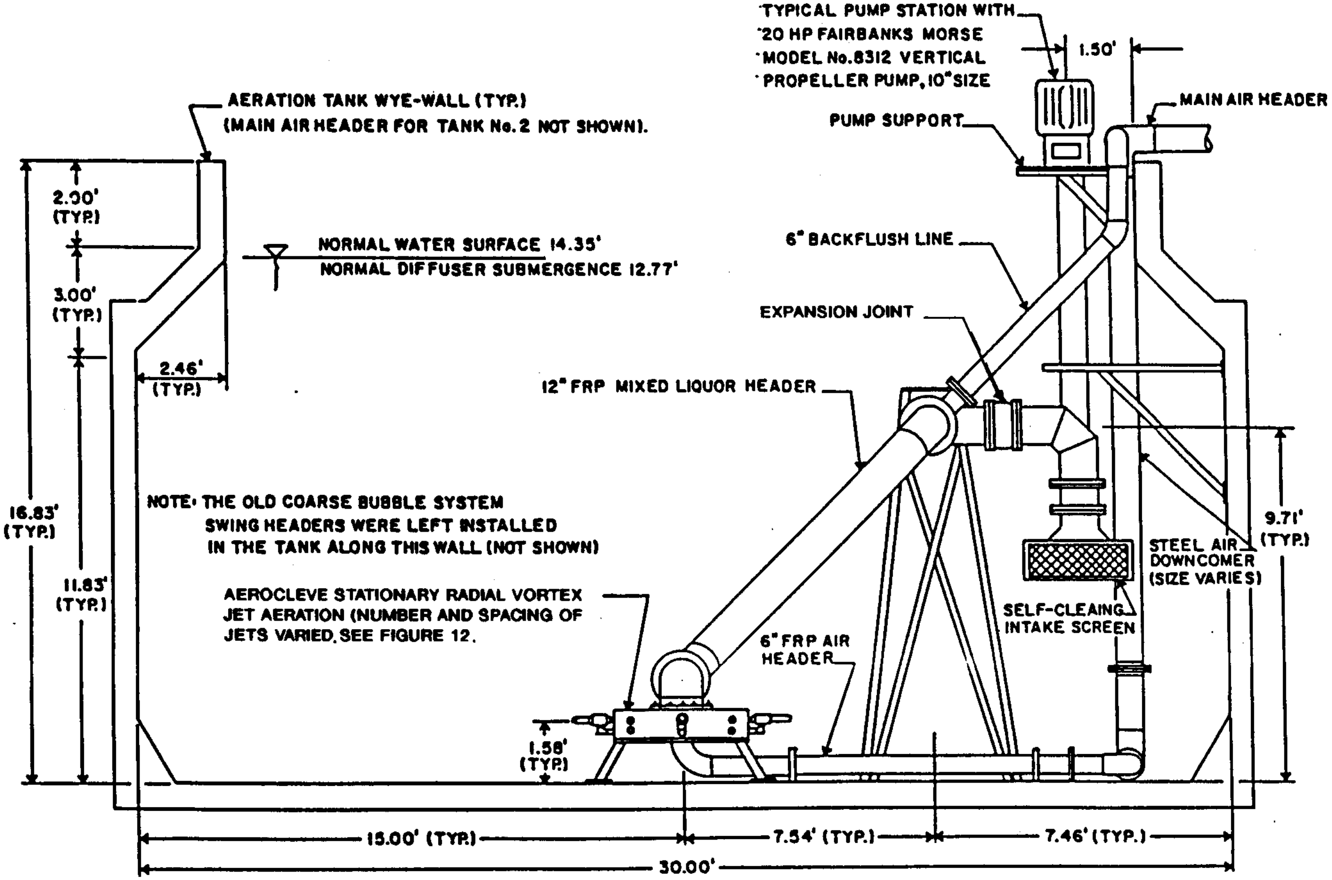
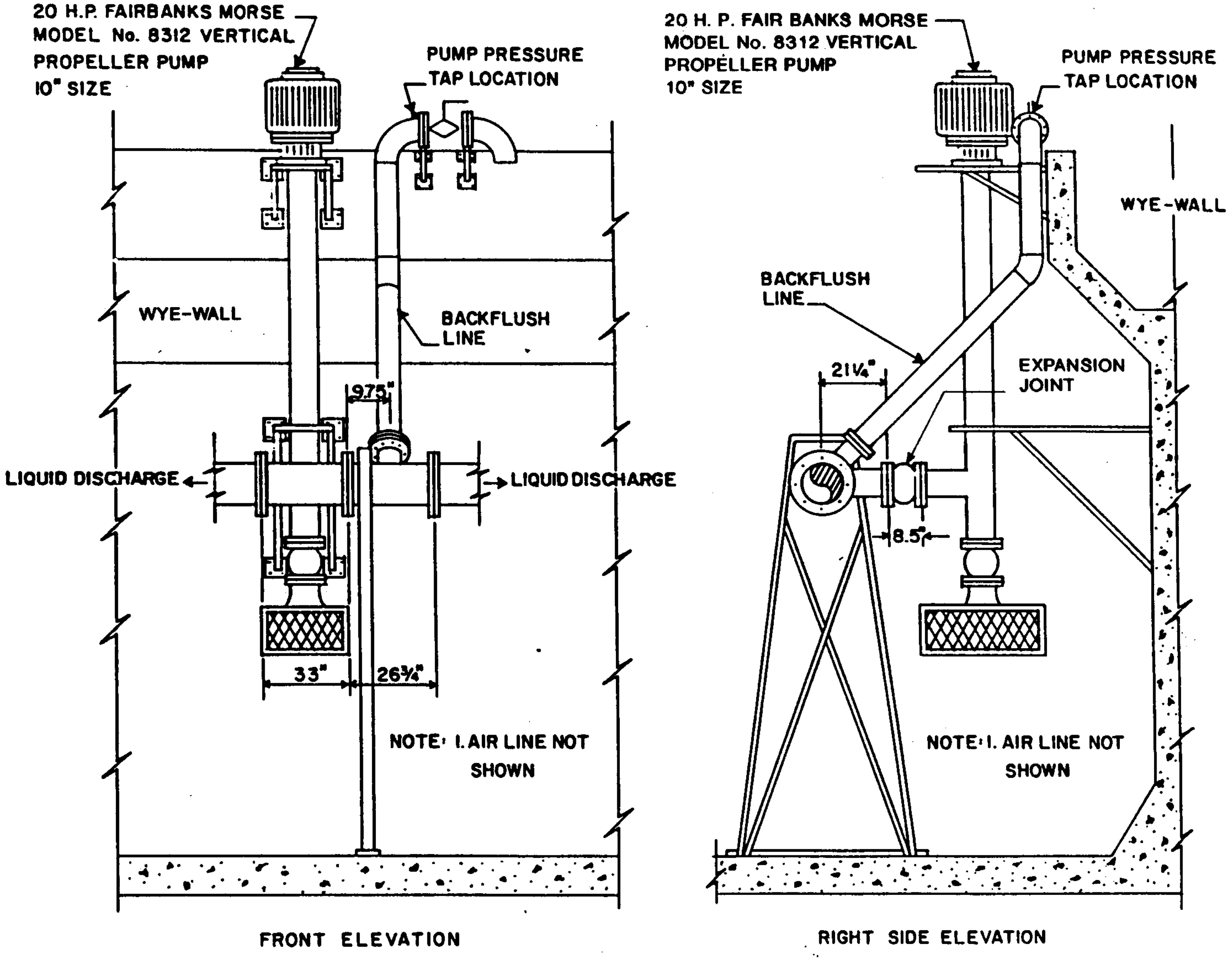


Figure 13. Aerocleve Radial Jet System–Elevation View


FRONT ELEVATION

RIGHT SIDE ELEVATION

Figure 14. Typical Aerocleve Jet System Pump Station

NOTE: (1) THE TANK WAS EQUIPPED WITH 2 AEROCLEVE UNIDIRECTIONAL LONGITUDINAL VORTEX JET AERATORS OPERATING IN THE TRANSVERSE DIRECTION ALONG ONE WALL OF THE TANK.

(2) THIS CONFIGURATION WAS USED DURING MOST OF THE JET SYSTEM EVALUATION.

(3) ONLY 30 JETS WERE INSTALLED IN ZONE 1 DURING THE CLEAN WATER TESTS.

(4) THE OLD COARSE BUBBLE SYSTEM SWING HEADERS (NOT SHOWN) WERE LEFT INSTALLED IN THE TANK ALONG THE WALL OPPOSITE THE JET AERATORS.

(5) "FRP" REFERS TO FIBER REINFORCED POLYESTER PIPE.

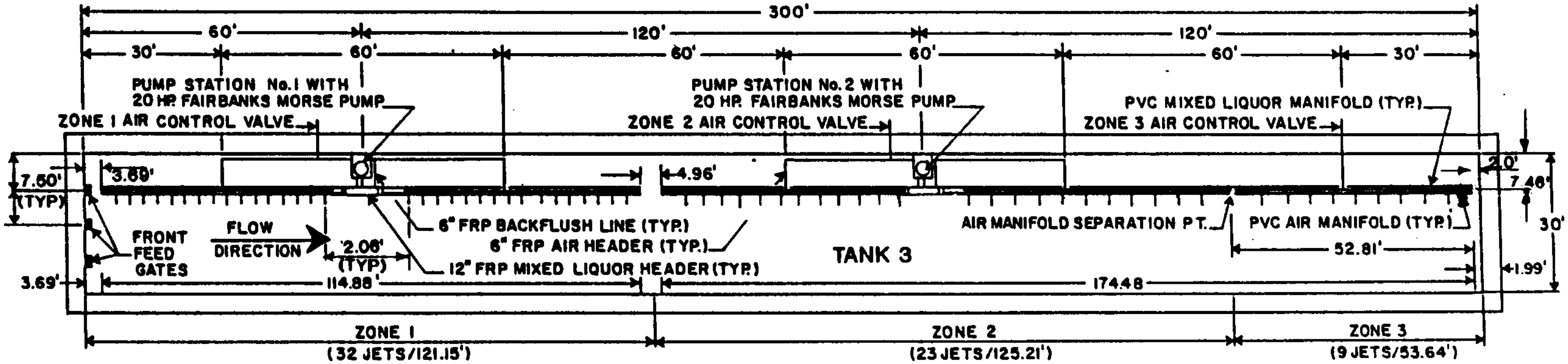
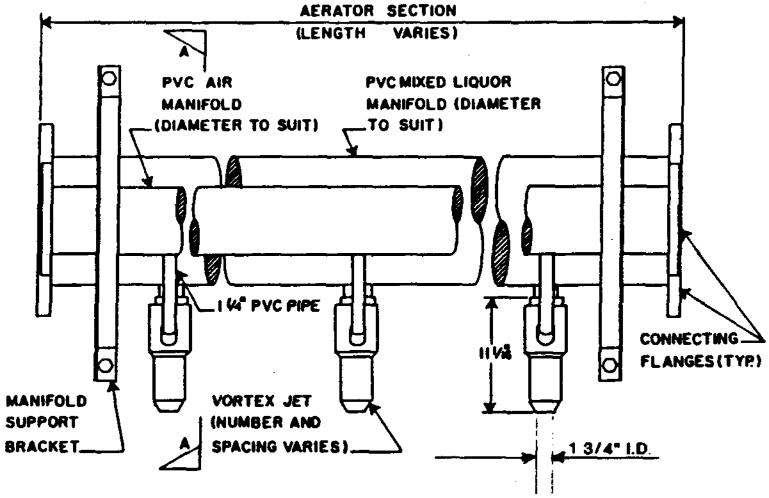
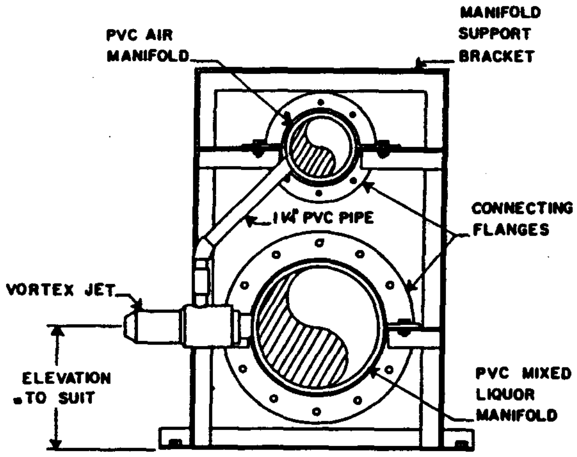


Figure 15. Layout Schematic of the Aerocleve Unidirectional Jet System



PLAN



NOTE: THE AERATOR SHOWN IS AN AEROCLEVE UNIDIRECTIONAL LONGITUDINAL VORTEX JET AERATOR.

SECTION A—A

Figure 16. Aerocleve Unidirectional Vortex Jet Aerator

smaller, upper manifold is used for air. The larger, lower manifold is used for mixed liquor.

Figure 17 shows the elevation view of the unidirectional jet system as it was installed at Whittier Narrows. The pump and most of the previous piping constructed for the first configuration were reused. The center line of the manifold was located approximately 7.5 ft from the tank wall. The diffuser height was reduced to 1.04 ft which provided approximately 1 ft greater submergence than in the disk system.

The swing arms for the coarse bubble diffusers were not removed for the construction of the jet system. They are not shown on the figures, although their presence is noted. The spargers and nipples were removed from the swing arms and the bosses were plugged to prevent air leakage. The old swing arms should have had no impact on the jet aeration system operation.

DOME AERATION SYSTEMS

The tube and jet systems were evaluated in both clean and process water and were inferior to the disk system in terms of oxygen transfer performance. The test results and evaluation are shown later. At the conclusion of the Part 1 testing, both systems were removed and a ceramic dome grid system was installed. Figure 18 shows a diffuser and manifold.

The bottom of the figure shows an exploded view of the diffuser. Each dome is held in place by a single bolt through the center of the diffuser. A small sealing washer is located under the bolt head and plastic washer to provide a top air seal. A large gasket seals the bottom of the dome to the base plate.

Flow control is provided by an orifice in the hold down bolt. The orifice is located in the upper half of the bolt and the bolt is hollow below the orifice. Air is free to travel up the hollow bolt from the 4" PVC header into the space under the dome. The dome thickness is uniform and is 0.75 inches.

A variety of materials are available for the gaskets, washer and bolt. Frequently an acetal bolt is used. In this study fiber reinforced ABS bolts were used because acetal is not highly resistant to attack from HCl acid. It was anticipated that HCl acid gas cleaning would be used at some future date, and HCl resistant materials were specified. Brass, stainless steel, and monel bolts are optional with the design. Metal inserts into the plastic holder can also be provided, but were not used in this study. A "spongy" gasket was used per the diffuser manufacturer's recommendation.

Figure 19 shows a plan view of Tank 3, which is also typical of Tank 2 except that the step gates and downcomers are located on the opposite side of the tank. The grid size and tapering were selected to match the disk system in Tank 1. Grids 1, 2, and 3 contained 985 (Tank 2 = 990), 968 and 574 diffusers, respectively. The number of dome diffusers was selected in direct ratio to the number of disk diffusers. The Districts' previous clean water testing suggested that equal oxygen transfer efficiency (OTE) is achieved with Norton domes and Sanitaire "9-inch" disks when the number of domes is 25% more than the number of disks. Therefore the number of domes for each grid is 25% more than the number of disks in the corresponding grid in Tank 1 (e.g. grid 1 disks = 792, grid 1 domes = 990; 990/792 = 1.25).

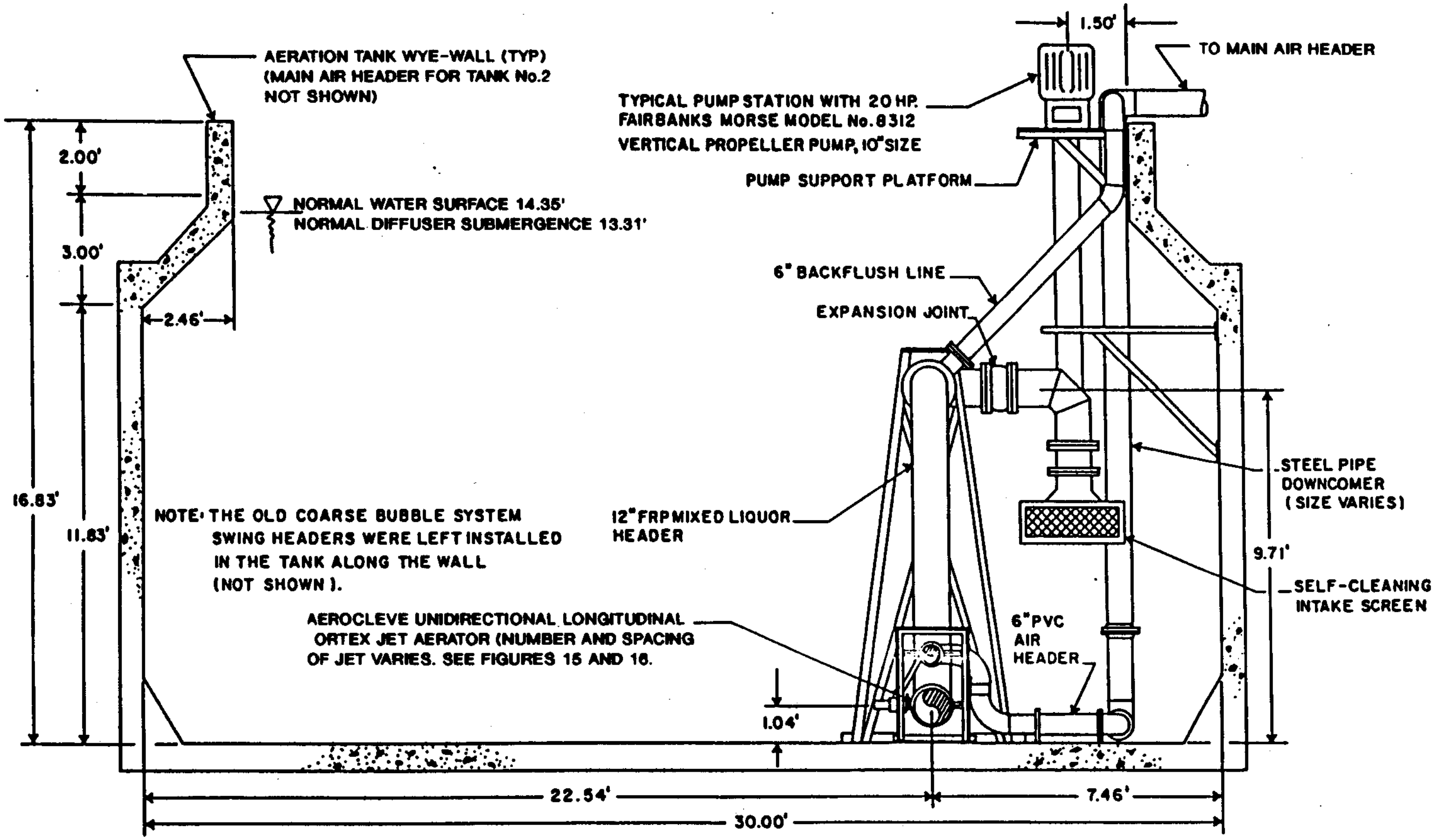
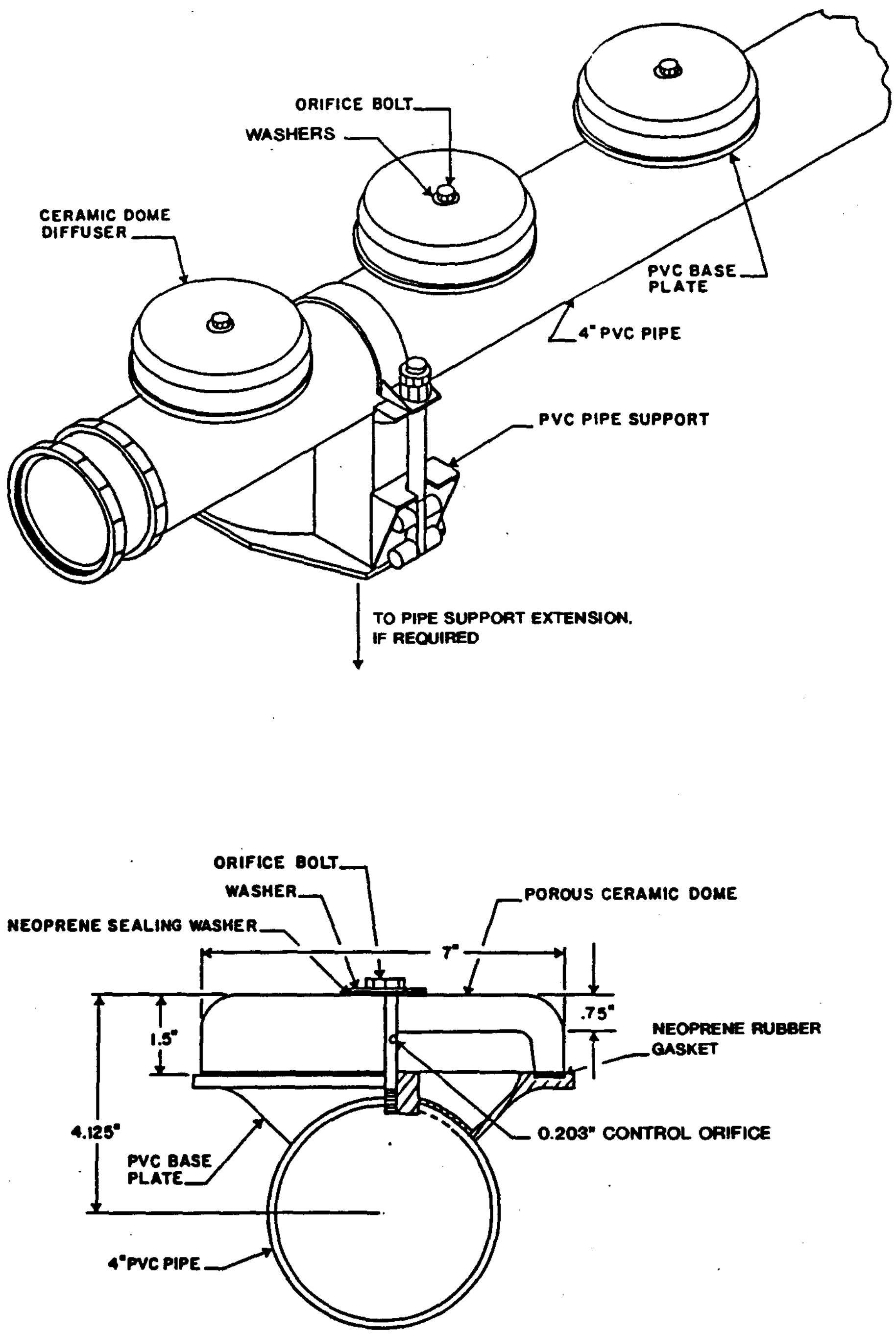


Figure 17. Aerocleve Unidirectional Jet System - Elevation View



COURTESY OF NORTON COMPANY

Figure 18. Norton Dome Diffusers

NOTE: (1) TANK 3 IS SHOWN (TYPICAL OF TANK 2).
(2) BOTH TANKS WERE EQUIPPED WITH NORTON DOME DIFFUSERS IN A TOTAL FLOOR COVERAGE CONFIGURATION. FOR LAYOUT DETAILS, SEE FIGURE 20.

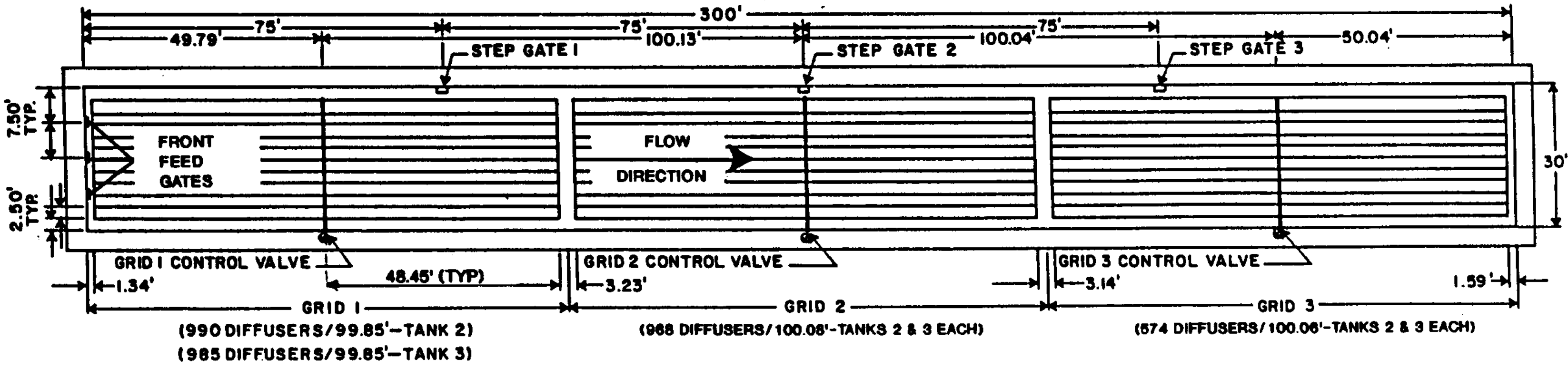


Figure 19. Layout Schematic of the Norton Dome System

Figure 20 shows an elevation view of a typical aeration tank with dome diffusers. The overall aeration system design is virtually identical, relatively speaking, to that for the disk system. Note that the diffuser elevation relative to the tank bottom is 2.0 ft, as in the disk system.

Table 4 shows the number of diffusers in each tank for the various periods of the project.

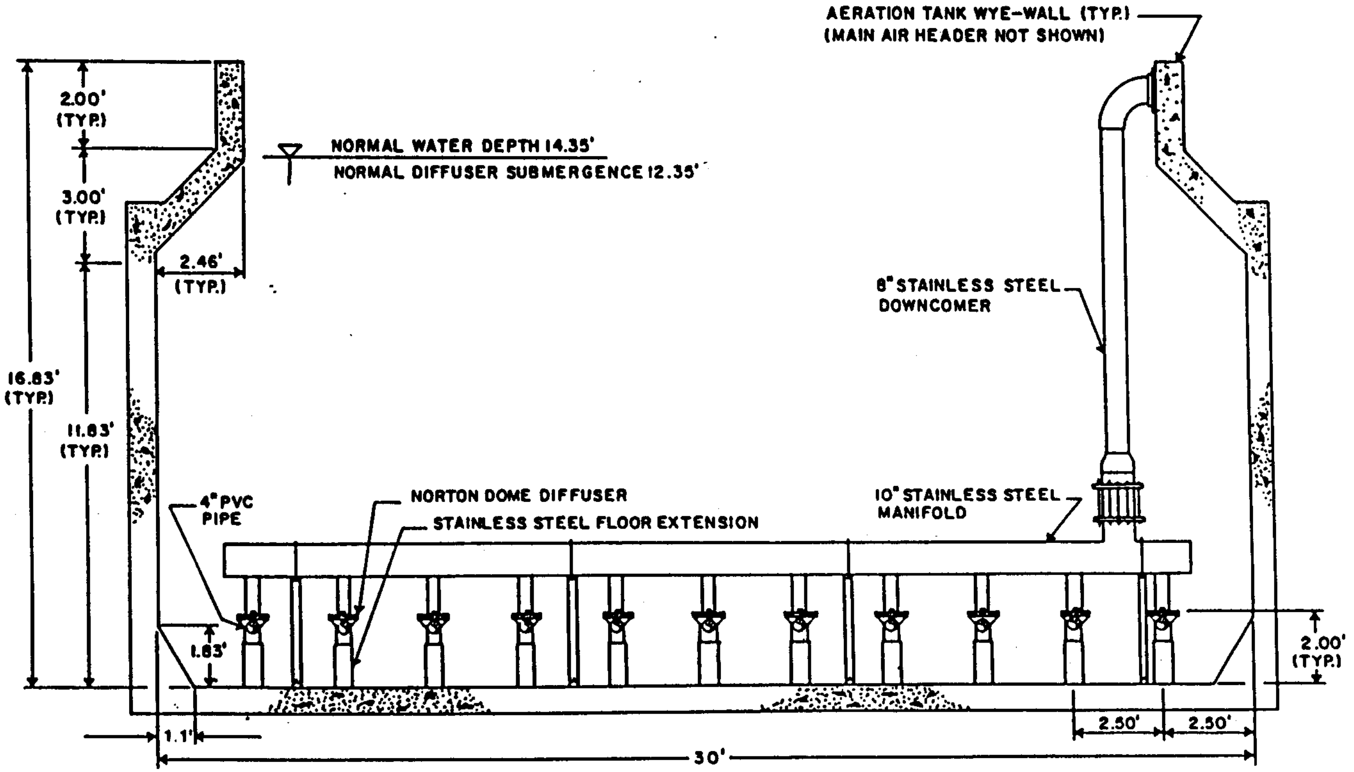


Figure 20. Norton Dome System–Elevation View

Table 4

Diffuser Summary

Period	Tank 1			Tank 2			Tank 3*		
	Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3
Part 1	724 Disks	594 Disks	352 Disks	270 Tubes	210 Tubes	120 Tubes	26 Jets+ 32 Jets++	19 Jets+ 23 Jets++	7 Jets+ 9 Jets++
Part 2	792 Disks	774 Disks	460 Disks	990 Domes	968 Domes	574 Domes	985 Domes	968 Domes	574 Domes

* Tank 3 zones for the jet implementation do not correspond with the zones for the other aeration systems. See Figures 5, 8, 12, 15, and 19.

\+ Configuration 1

++ Configuration 2

SECTION 4

CLEAN WATER TEST RESULTS

Phase I of this project evaluated clean water performance of a number of generic types of aeration systems. The object of the testing was to compare generic types of diffusers as opposed to diffusers provided by different manufacturers. Therefore, not all manufacturers' equipment was tested. The fine pore ceramic, fine pore tube, and jet aeration systems were represented by Norton, FMC and Pentech-Houdaille, respectively. Because of a competitive bidding process, none of these manufacturers were initially utilized for Phase II. In order to obtain the most accurate evaluation in Phase II of this project, additional clean water testing was performed on a full scale at the Whittier Narrows Water Reclamation Plant. The additional testing was necessary because the Districts had not tested the Phase 2 equipment and because full scale data was considered imperative for the tube and jet systems.

All clean water tests were conducted in the first aeration zone in each tank using the procedures in Appendices D and F. Baffles were utilized to isolate the aeration zones.

In Part 2 of Phase II, Norton domes replaced the tube and jet diffusers, and were not tested. It was felt that the Phase I testing, along with the disk tests, was sufficient to quantify the dome performance in the Whittier Narrows configurations.

DISK SYSTEM CLEAN WATER TESTS

The clean water tests of the disk system were performed from December 15 to December 19, 1980. Seven tests were performed on one batch of tap water. Table 5 shows the test conditions. Table 6 shows the results of the tests. As indicated previously, these tests were performed prior to the existence of the ASCE Standard (1984). In general, procedures similar to the Standard were used. Dissolved oxygen concentrations were determined by the Winkler Method on samples collected from four locations in the tank. The sampling frequency recommended by the Standard was followed. The data were analyzed by log deficit and nonlinear regressions.

Table 6 reports the results in terms of K_La_{20}, $C^*_{\infty 20}$, Standard Oxygen Transfer Rate (SOTR), Standard Oxygen Transfer Efficiency (SOTE) and Standard Aeration Efficiency (SAE). The terminology K_La_{20}, $C^*_{\infty 20}$, SOTR, SOTE, and SAE are the same as the nomenclature defined by the ASCE Standard (1984). The term $C^*_{\infty 20}$ refers to the equilibrium DO concentration, with all corrections made to standard conditions (20°C, zero salinity, 760 mm barometric pressure). The terms SOTR, SOTE, and SAE are similarly corrected to standard conditions. The term SAE as used by the Standard is used strictly with wire horsepower, but is reported here with delivered and wire horsepower. Therefore, the power is noted wherever SAE is used. This terminology is used throughout this report.

Table 5

Summary of Clean Water Test Conditions for the Ceramic Disk Aeration System

Date	Run	Water Depth (ft)		Air Flow (scfm)		Water Temp	Ambient Temp	Barometric Pressure	Relative Humidity (%)	Sodium Sulfite Concentration (mg/L)	Water Volume* (gal)		Comments
		With Air	Without Air	Total	Per Diffuser	(°C)	(°F)	(mmHg)			With Air	Without Air	
12/15/80	1	14.84	14.77	914.0	1.26	15.39	80.7	746.9	15.6	370.5	325,007	323,695	major problems with sodium sulfite distribution
12/16/80	1	15.02	14.97	907.6	1.25	15.33	78.5	746.1	27.8	553.6	328,353	327,428	problems with sodium sulfite distribution
12/16/80	2	15.01	14.93	905.6	1.25	15.56	79.2	745.1	27.7	737.1	328,168	326,685	problems with sodium sulfite distribution
12/17/80	1	15.04	14.99	909.6	1.26	15.78	77.0	745.0	31.8	920.0	328,723	327,798	
12/17/80	2	15.04	14.98	916.4	1.27	15.67	71.8	745.0	41.6	1103.0	328,723	327,613	
12/18/80	1	15.04	14.90	1788.6	2.47	15.56	63.4	746.5	61.8	1286.9	328,723	326,127	problems with sodium sulfite distribution
12/19/80	1	14.88	14.78	560.8	0.77	15.89	53.4	748.6	82.1	1472.0	325,754	323,882	

* At the 15.00' water depth, the volume/ft of tank length = 3288.42 gal/ft due to the wye-wall construction of the tank

Table 6

Summary of Clean Water Test Results for the Ceramic Disk Aeration System

Date	Run	Inflated Water Depth (ft)	Air Flow (scfm)		Transfer Rate			Power Requirements				Efficiencies		
			Total	Per Diffuser	K_La_{20} (1/hr)	$C^*_{\infty 20}$ (mg/L)	SOTR (lbs/hr)	Delivered		Wire		SOTE (%)	SAE Delivered (lb O_2/hp-hr)	SAE Wire (lb O_2/hp-hr)
								Power (hp)	Density (hp/1000 ft^3)	(hp)	(kW)			
12/15/80	1	14.84	914.0	1.26	8.89	10.58	253.9	22.65	0.521	36.91	27.54	26.86	11.21	6.88
12/16/80	1	15.02	907.6	1.25	10.14	10.38	287.4	22.68	0.517	36.98	27.58	30.62	12.67	7.77
12/16/80	2	15.01	905.6	1.25	10.10	10.71	294.8	22.66	0.516	36.93	27.55	31.48	13.01	7.98
12/17/80	1	15.04	909.6	1.26	9.93	10.70	290.2	22.79	0.519	37.15	27.71	30.86	12.74	7.81
12/17/80	2	15.04	916.4	1.27	10.17	10.58	294.1	22.93	0.522	37.38	27.88	31.04	12.82	7.87
12/18/80	1	15.04	1788.6	2.47	18.08	10.34	508.4	46.72	1.063	76.15	56.80	27.49	10.88	6.68
12/19/80	1	14.88	560.8	0.77	6.67	10.55	190.0	13.77	0.316	22.45	16.75	32.77	13.79	8.46

Two procedures were used to estimate K_La and C^*_∞. The "measured C^*_∞" procedure and the nonlinear procedure (used by the Standard) were used in all clean water tests. The measured C^*_∞ procedure was possible because the data were collected to well beyond the $4/K_La$ time period. The SOTE, SOTR, and SAE results were calculated using the nonlinear procedure. Table 7 compares the nonlinear and log deficit results for the ceramic disk system. In general, the agreement was fairly good. The results of the disk clean water tests and the other test results are plotted at the end of this section. Table 8 shows the water quality before and after testing.

A particular problem was experienced with the clean water tests on the disk system that was not experienced with the tests on the tube and jet systems. By nature, the total floor coverage disk system tends to be quiescent in appearance, with good, localized top to bottom mixing characteristics. It does not necessarily, however, have good bulk mixing characteristics, as with the tube and jet systems. As a result, it was very difficult to distribute the sodium sulfite required for the clean water tests throughout the large aeration tank volume in a timely fashion. The technique finally utilized to mitigate this problem was to spray the entire surface of the aeration tank with sodium sulfite solution from four technician-manned fire hoses. This method seemed to work reasonably well.

TUBE SYSTEM CLEAN WATER TESTS

Six tests were performed on the tube aeration system between March 25 and March 27, 1981. The testing technique was similar to that described for the disk system and the comments made earlier should apply here as well. Table 9 shows the test conditions and Table 10 shows the results. The nonlinear and log deficit results are compared in Table 11. The agreement between methods is excellent, with the average results differing by less than 0.5%. Table 12 shows the water quality before and after testing.

JET SYSTEM CLEAN WATER TESTS

Two sets of clean water tests were performed on the jet aeration system. The first series of three tests was performed from November 26 to November 29, 1980. Table 13 shows the test conditions and Table 14 shows the results. The repeatability among all three tests was excellent but the results were short of expectations. The jets in this phase transferred oxygen at approximately 2.6 lb O_2 /wire hp-hr. The manufacturer felt that increased efficiency could be obtained with an improved configuration (jets mounted along the wall, as opposed to radial clusters). Therefore the radial configuration was removed and a new configuration with jets located along the tank wall was installed. Also the number of jets was increased from 52 to 64.

Table 15 shows the test conditions for configuration 2 and Table 16 shows the test results. The SAE increased slightly, to approximately 2.7 lb O_2/wire hp–hr. Repeatability among tests was also good.

Tables 17 and 18 compare the results obtained from the measured C^*_∞ and nonlinear procedures. The agreement between methods was very good, with the average results differing by 1.5% in the first series and by only 0.6% in the second series.

Tables 19 and 20 show the water quality results for each test configuration. These two tables show the tap water quality before cobalt addition.

Table 7

Comparison of the Nonlinear and Log Deficit Method Results for the Ceramic Disk Aeration System

Date	Run	Air Flow per Diffuser (scfm)	K_La (1/hr)		C^*_∞ (mg/L)		Log Deficit r^2
			Nonlinear Method	Log Deficit Method	Nonlinear Method	Log Deficit Method	
12/15/80	1	1.26	7.97	8.12	11.48	11.42	0.9954
12/16/80	1	1.25	9.08	7.11	11.26	11.58	0.9910
12/16/80	2	1.25	9.09	8.88	11.57	11.56	0.9988
12/17/80	1	1.26	8.98	8.96	11.49	11.50	0.9991
12/17/80	2	1.27	9.18	9.13	11.40	11.42	0.9993
12/18/80	1	2.47	16.27	14.66	11.18	11.26	0.9949
12/19/80	1	0.77	6.05	6.22	11.35	11.26	0.9993
		Averages	9.52	9.01	11.39	11.43	0.9968

Note:

Average $K_La \times C^*_\infty$ by nonlinear method = 108.43

Average $K_La \times C^*_\infty$ by log deficit method = 102.98

= 5.03% difference

Table 8

Water Batch Laboratory Results for the Ceramic Disc Aeration System

Sample Date	Aeration System	Sample	COD (mg/L)	Suspended Solids (mg/L)	TDS (mg/L)	Sulfate (mg/L SO_4)	pH	Total Alkalinity (mg/L $CaCO_3$)	Total Hardness (mg/L $CaCO_3$)	Total Cobalt (mg/L CO)	Total Iron (mg/L Fe)	Total Manganese (mg/L Mr)	MBAS (mg/L LAS)
12/15/80	Disc (Tank 1)	tank water before testing began	1.6	0.8	215	23	7.98	149	160	0.052*	0.06	<0.005	0.02
12/19/80	Disc (Tank 1)	tank water after testing completed	9.6	6.8	1015	580	8.97	146	160	0.055	0.03	<0.005	0.02

* The sample was collected after cobalt addition.

Table 9

Summary of Clean Water Test Conditions for the Tube Aeration System

Date	Run	Water Depth (ft)		Air Flow (scfm)		Water Temp (°C)	Ambient Temp (°F)	Barometric Pressure mmHg	Relative Humidity (%)	Sodium Sulfite Concentration (mg/L)	Water Volume* (gal)	
		With Air	Without Air	Total	Per Diffuser						With Air	Without Air
3/25/81	Pretest	15.05	15.04	871.6	3.23	17.67	65.0	747.9	86.0	181.1	331,157	330,971
3/25/81	1	14.80	14.79	1086.2	4.02	18.22	68.8	746.6	67.5	364.8	326,475	326,286
3/26/81	1	15.28	15.27	957.1	3.54	18.00	61.6	744.2	64.2	543.6	335,395	335,213
3/26/81	2	15.23	15.22	974.7	3.61	18.22	61.4	742.8	50.2	722.9	334,479	334,296
3/27/81	1	15.20	15.13	1981.3	7.34	17.89	62.6	745.4	56.8	903.1	333,928	332,638
3/27/81	2	15.14	15.11	492.0	1.82	18.28	66.0	744.5	49.2	1083.5	332,823	332,268

* At the 15.00' water depth, the volume/ft of tank length = 3288.42 gal/ft due to the wye-wall construction of the tank.

Table 10

Summary of Clean Water Test
Results for the Tube Aeration System

Date	Run	Inflated Water Depth (ft)	Air Flow (scfm)		Transfer Rate			Power Requirements				Efficiencies		
			Total	Per Diffuser	K_La_{20}	$C^*_{\infty_{20}}$	SOTR	Delivered		Wire		SOTE	SAE Delivered	SAE Wire
					(1/hr)	(mg/L)	(lbs/hr)	Power (hp)	Density (hp/1000 ft^3)	(hp)	(kW)	(%)	(lb O_2/hp-hr)	(lb O_2/hp-hr)
3/25/81	Pretest	15.05	871.6	3.23	5.75	10.41	165.2	22.08	0.499	35.98	26.84	18.33	7.48	4.59
3/25/81	1	14.80	1086.2	4.02	6.91	10.52	197.6	27.74	0.635	45.21	33.72	17.59	7.12	4.37
3/26/81	1	15.28	957.1	3.54	5.90	10.46	172.6	25.27	0.564	41.19	30.72	17.44	6.83	4.19
3/26/81	2	15.23	974.7	3.61	6.01	10.44	174.8	25.60	0.573	41.73	31.13	17.34	6.83	4.19
3/27/87	1	15.20	1981.3	7.34	11.38	10.28	324.4	52.77	1.182	86.01	64.16	15.83	6.15	3.77
3/27/81	2	15.14	492.0	1.82	3.01	10.25	85.5	12.65	0.284	20.62	15.38	16.81	6.76	4.15

Table 11

Comparison of the Nonlinear and Log Deficit Method Results for the Tube Aeration System

Date	Run	Air Flow per Diffuser (scfm)	K_La (1/hr)		C^*_∞ (mg/L)		Log Deficit r^2
			Nonlinear Method	Log Deficit Method	Nonlinear Method	Log Deficit Method	
3/25/81	Pretest	3.23	5.44	5.53	10.77	10.75	0.9985
3/25/81	1	4.02	6.62	6.70	10.73	10.71	0.9994
3/26/81	1	3.54	5.63	5.76	10.69	10.66	0.9992
3/26/81	2	3.61	5.76	5.75	10.60	10.60	0.9998
3/27/81	1	7.34	10.82	10.73	10.54	10.54	0.9984
3/27/81	2	1.82	2.89	2.86	10.42	10.45	0.9994
		Averages	6.19	6.22	10.62	10.62	0.9991

Note:

Average $K_La \times C^*_\infty$ by nonlinear method = 65.74

Average $K_La \times C^*_\infty$ by log deficit method = 66.06

= 0.49% difference

Table 12

Water Batch Laboratory Results for the Tube Aeration System

Sample Date	Aeration System	Sample	COD (mg/L)	Suspended Solids (mg/L)	TDS (mg/L)	Sulfate (mg/L SO_4)	pH	Total Alkalinity (mg/L $CaCO_3$)	Total Hardness (mg/L $CaCO_3$)	Total Cobalt (mg/L CO)	Total Iron (mg/L Fe)	Total Manganese (mg/L Mn)	MBAS (mg/L LAS)
3/24/81	Tube (Tank 2)	tank water before testing	13	6	172	24	9.25	131	143	<0.005	0.02	<0.005	0.02
3/27/81	Tube (Tank 2)	tank water after testing	15	76	841	370	10.5	320	35	0.014	0.03	<0.005	0.04

Table 13

Summary of Clean Water Test Conditions for the Jet Aeration System (Configuration 1)

Date	Run	Water Depth (ft)		Air Flow (scfm)		Pump Rate (gpm)		Water Temp. (°C)	Ambient Temp (°F)	Barometric Pressure (mmHg)	Relative Humidity (%)	Sodium Sulfite Concentration (mg/L)	Water Volume* (gal)	
		With Air	Without Air	Total	Per Jet	Total	Per Jet						With Air	Without Air
11/26/80	1	14.82	14.82	650.3	25.01	2330	89.62	14.83	73.5	750.0	14.0	305.4	392,794	392,794
11/28/80	1	15.02	15.02	644.8	24.80	2330	89.62	15.11	70.5	747.8	23.5	456.3	397,297	397,297
11/29/80	1	14.98	14.98	632.6	24.33	2330	89.62	15.33	67.6	745.2	25.0	607.5	396,401	396,401

* At the 15.00 ft water depth, the volume/ft of tank length = 3288.42 gal/ft due to the wye-wall construction of the tank.

Table 14

Summary of Clean Water Test Results
for the Jet Aeration System (Configuration 1)

Date	Run	Inflated Water Depth (ft)	Air Flow (scfm)		Pump Rate (gpm)		Transfer Rate			Power Requirements					Efficiencies		
			Total	Per Jet	Total	Per Jet	K_La_{20} (1/hr)	$C^*_{\infty 20}$ (mg/L)	SOTR (lbs/hr)	Delivered			Wire		SOTE (%)	SAE Delivered (lb O_2/hp-hr)	SAE Wire (lb O_2/hp-hr)
										Power (hp)	Density (hp/1000 ft^3)	Pump/Blower Split (%)	(hp)	(kW)			
11/26/80	1	14.82	650.3	25.01	2330	89.62	3.24	10.34	109.89	26.80	0.545	44.2/55.8	42.49	31.70	16.34	3.84	2.59
11/28/80	1	15.02	644.8	24.80	2330	89.62	3.11	10.44	107.58	28.63	0.539	44.2/55.8	42.54	31.73	16.14	3.76	2.53
11/29/80	1	14.98	632.6	24.33	2330	89.62	3.06	10.51	106.39	38.28	0.534	44.7/55.3	41.97	31.31	16.27	3.76	2.53

Table 15

Summary of Clean Water Test Conditions for the Jet Aeration System (Configuration 2)

Date	Run	Water Depth (ft)		Air Flow (scfm)		Pump Rate (gpm)		Water Temp. (°C)	Ambient Temp (°F)	Barometric Pressure (mmHg)	Relative Humidity (%)	Sodium Sulfite Concentration (mg/L)	Water Volume* (gal)	
		With Air	Without Air	Total	Per Jet	Total	Per Jet						With Air	Without Air
1/20/81	Pretest	14.95	14.95	616.8	20.56	2548	84.93	15.89	63.6	747.0	60.5	151.5	395,728	395,728
1/21/81	1	15.00	15.00	685.9	22.86	2549	84.97	16.11	69.9	747.2	52.9	302.5	396,849	396,849
1/23/81	1	15.08	15.08	702.6	23.42	2554	85.13	16.39	60.0	750.6	73.0	452.8	398,636	398,636
1/23/81	2	15.02	15.02	702.0	23.40	2554	85.13	16.39	60.2	753.1	73.2	603.7	397,297	397,297
1/23/81	3	14.92	14.92	806.3	26.88	2562	85.40	16.44	63.5	752.4	78.0	755.4	395,053	395,053

* At the 15.00 ft water depth, the volume/ft of tank length = 3288.42 gal/ft due to the wye-wall construction of the tank.

Table 16

Summary of Clean Water Test Results for the Jet Aeration System (Configuration 2)

Date	Run	Inflated Water Depth (ft)	Air Flow (scfm)		Pump Rate (gpm)		Transfer Rate			Power Requirements					Efficiencies		
			Total	Per Jet	Total	Per Jet	K_La_{20}	$C^*_{\infty 20}$	SOTR	Delivered			Wire		SOTE	SAE Delivered	SAE Wire
							(1/hr)	(mg/L)	(lbs/hr)	Power (hp)	Density (hp/1000 ft^3)	Pump/Blower Split (%)	(hp)	(kW)	(%)	(lb O_2/hp-hr)	(lb O_2/hp-hr)
1/20/81	Pretest	14.95	616.8	20.56	2548	84.93	3.13	10.66	110.13	27.29	0.516	42.6/57.4	41.70	31.10	17.27	4.04	2.64
1/21/81	1	15.00	685.9	22.86	2549	84.97	3.47	10.65	122.10	29.00	0.547	40.0/60.0	44.55	33.23	17.22	4.21	2.74
1/23/81	1	15.08	702.6	23.42	2554	85.13	3.49	10.75	124.54	29.65	0.556	39.1/60.9	45.55	33.98	17.14	4.20	2.73
1/23/81	2	15.02	702.0	23.40	2554	85.13	3.54	10.67	125.16	29.46	0.555	39.4/60.6	45.23	33.74	17.24	4.25	2.77
1/23/81	3	14.92	806.3	26.88	2562	85.40	3.74	10.54	129.98	32.07	0.607	36.2/63.8	49.45	36.89	15.59	4.05	2.63

Table 17

Comparison of the Nonlinear and Log Deficit Method Results for the Jet Aeration System (Configuration 1)

Date	Run	Air Flow per Diffuser (scfm)	K_La (1/hr)		C^*_∞ (mg/L)		Log Deficit r^2
			Nonlinear Method	Log Deficit Method	Nonlinear Method	Log Deficit Method	
11/26/80	1	25.01	2.87	2.78	11.40	11.50	0.9989
11/28/80	1	24.80	2.77	2.72	11.41	11.38	0.9992
11/29/80	1	24.33	2.74	2.71	11.40	11.40	0.9991
		Averages	2.79	2.74	11.40	11.43	0.9991

NOTE:

Average $K_La \times C^*_\infty$ by nonlinear method = 31.81

Average $K_La \times C^*_\infty$ by log deficit method = 31.32

= 1.54% difference

Table 18

Comparison of the Nonlinear and Log Deficit Method Results for the Jet Aeration System (Configuration 2)

Date	Run	Air Flow per Diffuser (scfm)	K_La(1/hr)		C^*_∞ (mg/L)		Log Deficit r^2
			Nonlinear Method	Log Deficit Method	Nonlinear Method	Log Deficit Method	
1/20/81	Pretest	20.56	2.84	2.87	11.53	11.43	0.9957
1/21/81	1	22.86	3.16	3.10	11.39	11.39	0.9988
1/23/81	1	23.42	3.20	3.19	11.47	11.39	0.9990
1/23/81	2	23.40	3.25	3.26	11.42	11.39	0.9993
1/23/81	3	26.88	3.44	3.43	11.26	11.28	0.9990
		Averages	3.18	3.17	11.41	11.38	0.9984

NOTE:

Average $K_La \times C^*_\infty$ by nonlinear method = 36.28

Average $K_La \times C^*_\infty$ by log deficit method = 36.07

= 0.58% difference

Table 19

Water Batch Laboratory Results
for the Jet Aeration System (Configuration 1)

Sample Date	Aeration System	Sample	COD (mg/L)	Suspended Solids (mg/L)	TDS (mg/L)	Sulfate (mg/L SO_4)	pH	Total Alkalinity (mg/L $CaCO_3$)	Total Hardness (mg/L $CaCO_3$)	Total Cobalt (mg/L CO)	Total Iron (mg/L Fe)	Total Manganese (mg/L Mn)	MBAS (mg/L LAS)
11/25/80	Jet (#1) (Tank 3)	test tank water before pretest on 11/25/80 (after cobalt addition)	1.4	3.4	209	20	8.10	146	161	0.090	0.19	0.005	0.02
11/26/80	Jet (#1) (Tank 3)	test tank water after Run 1 on 11/26/80 (includes 2nd cobalt addition)	2.8	3.2	459	200	8.29	146	160	0.112	0.12	<0.005	0.02
11/30/80	Jet (#1) (Tank 3)	test tank water after completion of official tests	3.9	1.2	516	220	8.29	147	156	0.055	0.08	<0.005	0.02
11/25/80	Jet (#1) (Tank 3)	tank water on other side of baffle before pretest (after cobalt addition to test side)	4.7	0.8	201	20	8.07	144	160	<0.005	0.06	<0.005	0.02
11/30/80	Jet (#1) (Tank 3)	tank water on other side of baffle after completion of official tests	6.7	1.0	345	120	8.20	145	155	0.045	0.04	0.005	0.02
11/30/80	Jet (#1) (Tank 3)	potable water from tap used to fill tank	4.2	<0.1	197	17	8.06	143	158	<0.005	<0.01	0.010	0.02

Table 20

Water Batch Laboratory Results
for the Jet Aeration System (Configuration 2)

Sample Date	Aeration System	Sample	COD (mg/L)	Suspended Solids (mg/L)	TDS (mg/L)	Sulfate (mg/L SO_4)	pH	Total Alkalinity (mg/L $CaCO_3$)	Total Hardness (mg/L $CaCO_3$)	Total Cobalt (mg/L CO)	Total Iron (mg/L Fe)	Total Manganese (mg/L Mn)	MBAS (mg/L LAS)
1/20/81	Jet (No. 2) (Tank 3)	test tank water before tests (after cobalt addition)	4.6	2	226	37	8.30	143	142	0.080	0.05	<0.005	<0.01
1/24/81	Jet (No. 2) (Tank 3)	test tank water after completion of tests	4.2	2	607	270	8.41	144	145	0.027	0.04	<0.005	<0.01
1/24/81	Jet (No. 2) (Tank 3)	potable water from tap used to fill tank	2.8	1	192	20	8.20	143	145	<0.005	0.01	<0.005	<0.01

CLEAN WATER TESTING SUMMARY

The preceding sections show the results of all the clean water testing performed in Phase II of this project. The Norton dome system was not tested, since identical equipment was tested in Phase I.

The results of all clean water testing are shown in Figures 21 and 22. Pretests results were not included, as well as a point corresponding to the first test of the disk testing sequence, when extreme difficulty was experienced with sodium sulfite distribution. Figure 21 shows the SOTE results. The lower portion of the figure shows the SOTE as a function of energy density while the upper portion shows the SOTE as a function of gas flow rate diffuser. The disk data show a very regular trend with increasing gas flow or energy density.

Figure 22 shows the SAE (wire power) as a function of energy density and gas flow rate per diffuser.

The results of the Phase II clean water tests should be compared to the Phase I test results for the same conditions. The depth of submergence between the two phases was slightly different. The Phase I submergence for the ceramic grid system was 14.1 ft while the Phase II submergence during the clean water tests was 13.0 ft. For the tube system in Phase I, the submergence was 13.0 ft as compared to 13.1 ft during the clean water tests in Phase II. For the Phase I jets, the submergence was 13.6 ft, as compared to 13.4 ft and 14.0 ft for configurations 1 and 2, respectively during the clean water tests for Phase II. The disk and dome systems are roughly comparable, with the dome system in Phase I producing about 7.3 lb O_2/wire hp-hr at the design air flow rate per diffuser and the disk system in Phase II producing 7.9 lb O_2/wire hp-hr (exclusive of the first test where major sodium sulfite distribution problems were experienced). The differences in efficiency may be due to sodium sulfite distribution problems during the full scale Phase II tests and tank geometry differences between the Phase I and II tests.

The tube system during the Phase I tests produced approximately 4.6 lb O_2/wire hp-hr at the design air flow rate per diffuser. In Phase II, the Nokia system produced 4.2 lb O_2/wire hp-hr at a lower diffuser flux rate. Contributing factors to the efficiency discrepancy are the markedly different energy density evaluated during the Phase II tests as compared to the Phase I tests and the geometry differences between the JWPCP test tank and the Whittier Narrows aeration tanks.

The jet systems tested in Phase I and II produced different aeration efficiencies. The Phase I results were approximately 3.2 lb O_2/wire hp-hr at the design flow per nozzle. The Phase II results were 2.6 and 2.7 lb O_2/wire hp-hr for configurations 1 and 2, respectively. The reasons for this discrepancy may be largely due to the different pump/blower power ratios used by the equipment manufacturers during the two sets of tests. The energy density and tank geometry differences between the two sets of tests may also have had an effect, but it is interesting to note that the transfer efficiency results for the Phase I and II tests were very similar.

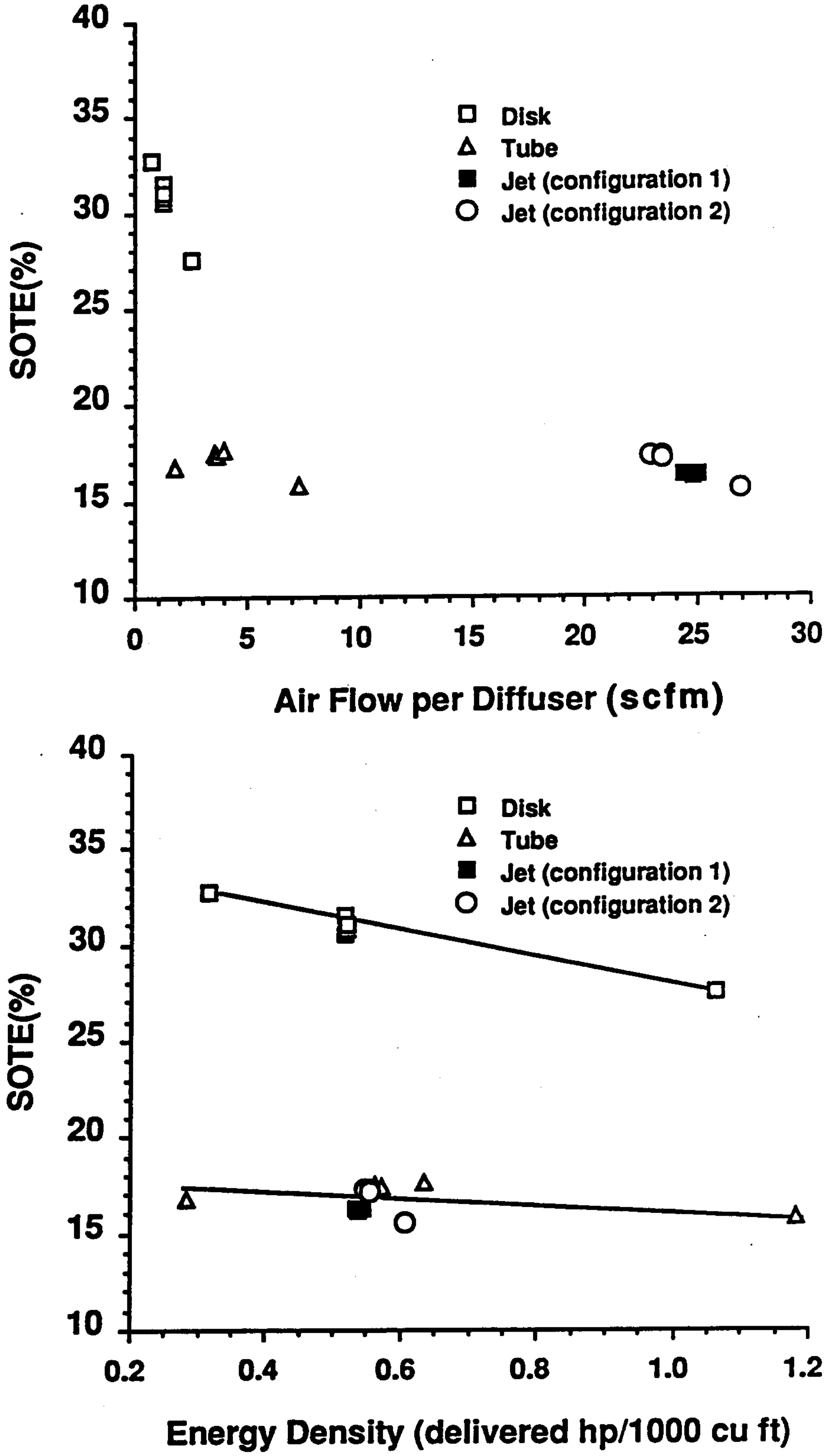
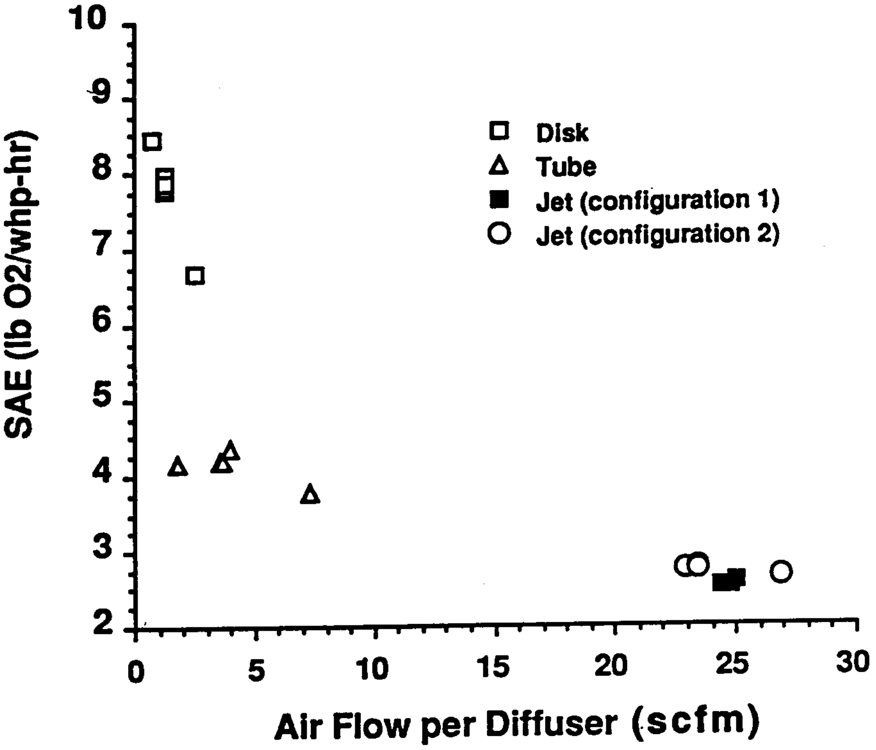


Figure 21. Clean Water SOTEs for All Three Aeration Systems



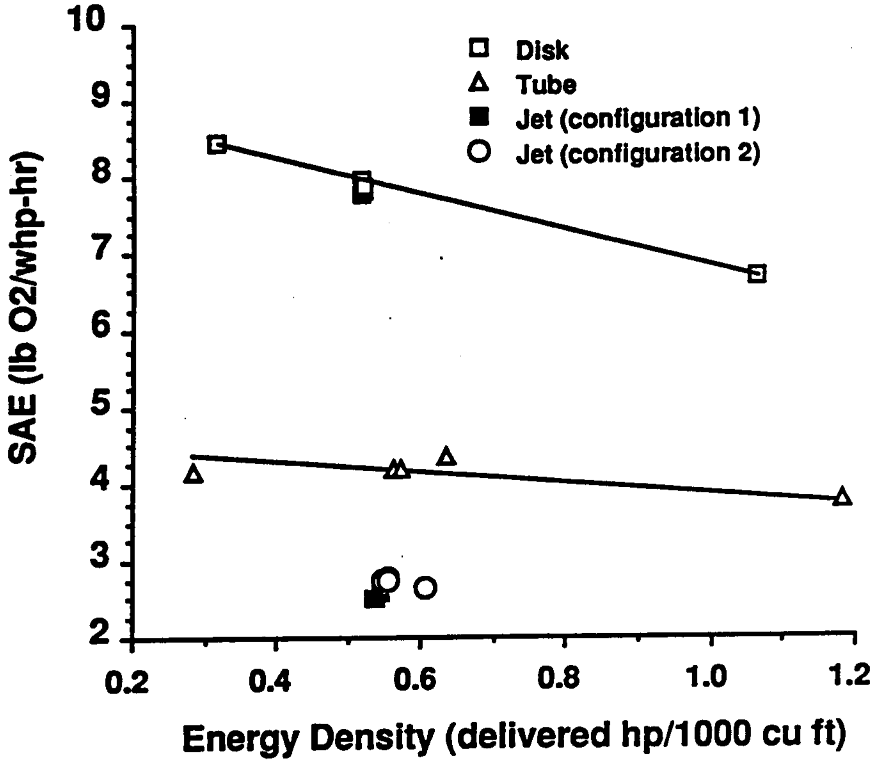


Figure 22. Clean Water SAEs for All Three Aeration Systems

SECTION 5

PROCESS WATER TEST RESULTS

The process water test results in this section should only be discussed with reference to plant operating conditions. Refer to Tables 2 and 3 in Section 3 and to Appendices A and B for the average operating parameters during the various test periods.

OFF-GAS TEST RESULTS

Process water testing was performed on all aeration systems in both parts of Phase II. When this project was first envisioned, the modern off-gas testing procedure, as described by Redmon, Ewing and Boyle (1983) did not exist. A steady-state method of determining oxygen transfer utilizing oxygen uptake rates was available but suffered from certain limitations. A nonsteady-state technique developed by Mueller was also available. Fortunately, the off-gas method of Redmon et al. was developed in time to be of use during the project. The other steady and nonsteady-state methods were evaluated but were abandoned in favor of the off-gas procedure. The results of these other methods have been reported previously by Hwang and Stenstrom (1985) and Mueller (1982).

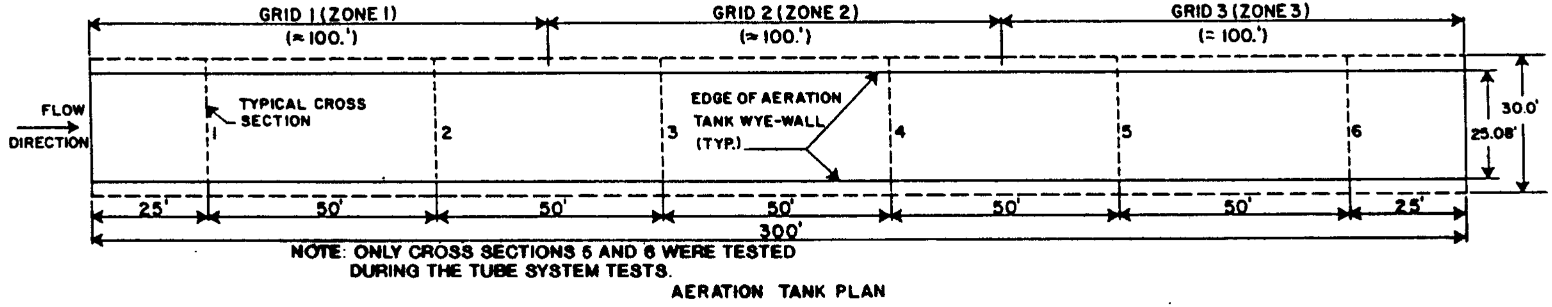
The off-gas analyzer and collection hood used in this investigation was constructed by the Districts, and was patterned after the equipment developed by Redmon, et al. (1983). It was decided to use off-gas testing as the principal measuring technique after an early version of the equipment was demonstrated at the Whittier Narrows WRP on August 12 and 13, 1981. Appendix E describes the equipment and the data reduction procedures. Appendix F describes the flow metering and diffuser headloss equipment utilized.

Figure 23 shows the locations of the off-gas evaluation points. In general, two or three positions were sampled for each cross section. For the disk, tube and dome (Part 2) systems, six cross sections were sampled. For the jet system, only five cross sections were sampled.

During Part 1, five off-gas evaluations were made on the disk system. The first was performed by Dave Redmon of Ewing Engineering on August 12, 1981, using their off-gas analyzer with a collection hood built to their specifications by District and UCLA personnel. This test and a subsequent jet system test performed on August 13 demonstrated the validity of the off-gas testing concept and the Districts decided to construct its own analyzer. The Districts analyzer was used on November 9, 1981 to perform the second test and all subsequent tests.

The tube aeration system was first tested on January 11, 1982. Three more tests were conducted on subsequent days. Unfortunately many of the 3/4" schedule 80 PVC nipples

I. DISK, DOME AND TUBE SYSTEM TESTS



II. JET SYSTEM TESTS

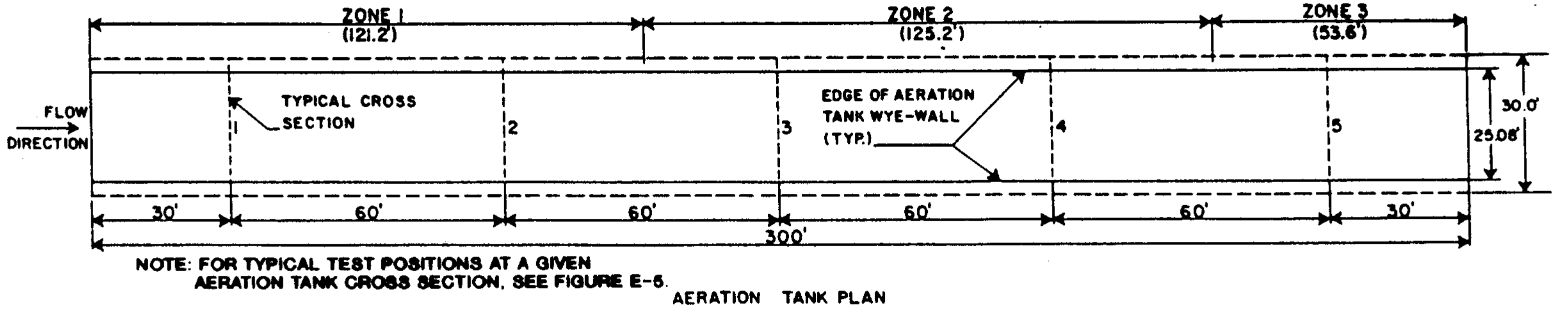


Figure 23. Off-gas Test Cross Sections

connecting the diffusers to the swing arms or manifolds had broken. As a result, the associated diffusers would float to the surface of the tank. The broken diffusers were collected and of these, the diffusers that had been mounted on the swing arms were replaced using 3/4" galvanized nipples. Unfortunately, it was not possible to replace the diffusers on the fixed manifold. Therefore, a large uncontrolled air release (boil) occurred wherever there was a broken nipple. This made it difficult to off-gas test areas in the vicinity of the broken diffusers. In any case, the boils in the tank resulted locally in very low oxygen transfer efficiencies and biased results. After the first two tests, a decision was made not to test the affected portions of the tank. Testing thereafter was essentially limited to the last aeration grid. Therefore, it was not possible to compare the off-gas hood flows with the total tank air flows measured with plant instrumentation. For this reason, the off-gas test results of the tube system are of low precision and accuracy and have not been included in this report.

The jet system was first tested by Dave Redmon of Ewing Engineering with their analyzer on August 13, 1981. An additional six tests were performed by the Districts with the Districts' analyzer. Reasonably good agreement between off-gas flow measurement and tank air flow measurements were obtained. It should be noted that the aeration tank containing the jet aeration system was operated at a reduced wastewater flow rate, which was approximately 75% of the flow rate to each of the other tanks. This was necessary in order to obtain adequate DO concentrations with the available jet system capacity.

Off-gas tests for Part 2 began in September 1982. By this time, much more experience had been obtained using the instrument and developing the testing technique. The tests were performed more rapidly and good agreement between off-gas flow rate and plant instrumentation was obtained. A test was performed on each aeration tank on successive days. Testing in this manner was performed on September 1 to 3, October 27 to 29, and December 14 to 16, 1982.

Table 21 shows the off-gas results. The αFSOTE and αFSAE results are shown for Parts 1 and 2. The αFSOTE and αFSAE results are flow weighted averages over each aeration tank. The terms αFSOTE and αFSAE refer to the process water oxygen transfer efficiency and aeration efficiency with all parameters corrected to standard conditions (68°F, 14.7 psia and 0 mg/L DO). Alpha (α) is the process water K_La of a new diffuser divided by the clean water K_La of a new diffuser. The factor, F, is the process water K_La of a diffuser after a given time in service divided by the K_La of a new diffuser in the same process water.

The average transfer efficiency determined for the disk system on 8/12/81 was 11.2% αFSOTE and 3.0 lb O_2/wire hp-hr αFSAE. For the period 11/9/81 through 11/19/81, the corresponding results were 8.0% αFSOTE and 2.1 lb O_2/wire hp-hr αFSAE, indicating a decline in system performance, possibly due to diffuser fouling. This latter period includes two tests with intentionally high (2.35 scfm/diffuser) and low (0.61 scfm/diffuser) gas flow rates. These flow rates were not typical of normal plant operation. There is reason to believe that the tank was oxygen limited during the low gas flow rate test and that the oxygen limiting conditions might have reduced the α factor. Similarly, it appears that the tank was oxygen enhanced during the high gas flow rate tests and that these conditions improved the α factor. In any case, if only the tests at relatively normal gas flow rates (11/9/81 and 11/21/81) are averaged, the αFSOTE was still 8.0% and the αFSAE was still 2.1 lb O_2/wire hp-hr. Figure 24 shows the average αFSOTE and αFSAE results for Part 1.

Table 21

Off-Gas Test Results

Date	System*	Air Flow per Diffuser (scfm)	αFSOTE	αFSAE**	Months in Operation	Total Hydraulic Flow Rate (MGD)++
Part 1						
8/12/81	Disk	0.94	11.2	3.0	7.6	5.6
11/9/81	Disk	1.22	8.6	2.3	10.5	6.5
11/10/81	Disk	2.35	9.3	2.3	10.6	7.0
11/12/81	Disk	1.23	7.4	2.0	10.6	6.6
11/19/81	Disk	0.61	6.8	1.8	10.9	6.0
8/13/81	Jet	46.6	8.6	1.7	6.5	3.1
11/24-25/81	Jet	26.7	8.2	1.5	9.9	4.0
12/1-2/81	Jet	29.4	10.8	2.1	10.1	3.8
12/7-8/81	Jet	21.2	10.4	1.7	10.3	3.9
12/10/81	Jet	22.8	10.3	1.8	10.4	4.1
12/28/81	Jet	13.6	9.2	1.3	11.0	4.0
12/31/81	Jet	46.5	6.8	1.4	11.1	4.2
Part 2						
9/1/82	Disk	1.09	10.3	2.7	20.3+	7.5
10/29/82	Disk	1.35	7.4	1.9	22.2	9.4
12/14/82	Disk	0.87	7.8	2.1	23.7	5.8
9/2/82	Dome (2)	0.85	11.3	3.0	6.0	6.7
10/28/82	Dome (2)	0.95	7.4	1.9	7.8	9.0
12/15/82	Dome (2)	0.66	6.8	1.8	9.4	5.6
9/3/82	Dome (3)	0.86	12.7	3.4	4.4	8.4
10/27/82	Dome (3)	0.89	7.6	2.0	6.2	9.6
12/16/82	Dome (3)	0.67	8.6	2.3	7.8	6.9

* The jet system tests were conducted on configuration 2. The numbers next to the dome label indicate tank number. Tests performed on 8/12 and 8/13/81 were conducted by Dave Redmon of Ewing Engineering. No tube system results are shown due to the problems with broken diffuser nipples.

\+ The disk system was cleaned by low pressure hosing from the tank surface after 16 months of operation.

** Based on wire power. See Appendix D for power calculation procedures.

++ Primary effluent plus return sludge flows.

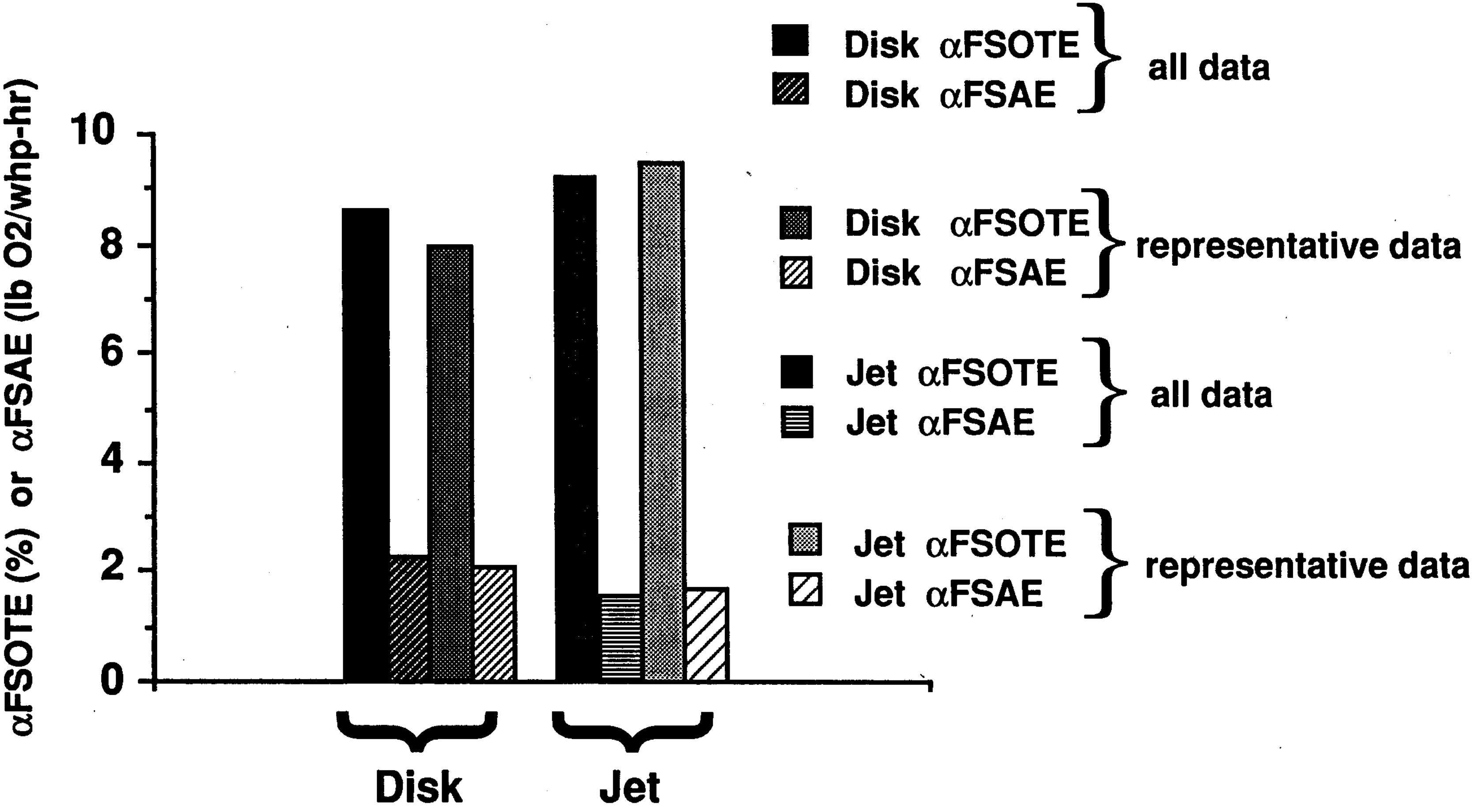


Figure 24. Average Off-gas Test Results for Part 1

The jet system (configuration 2) averaged 9.2% αFSOTE and 1.6 lb O_2/wire hp-hr αFSAE for the period from 8/13/81 through 12/31/81. If only the tests near the normal tank air flow rate per jet are included (i.e. the first 2 jet system tests), the αFSOTE is 9.5% and the αFSAE is 1.7 lb O_2/wire hp-hr. Note that the primary effluent flow rate to the jet tank (Tank 3) was approximately 75% of that to the other tanks during the test period to avoid DO limiting conditions.

Based on the off-gas test results, the αF factors generally showed an increasing trend with increasing levels of treatment. The αF factor at the front of a tank was lowest and gradually increased through the length of the tank. Figure 25 shows this trend for the disk and jet aeration systems, based on test results near the normal tank air flow rates per diffuser. The jet system test had to be performed over two days but good agreement was obtained for the common point at 150 ft of tank distance.

The flow weighted average αF factors are shown in Figure 25 as well. This type of average is influenced more by the data at the head of the tank since the air flow per diffuser or per square unit of tank area is greatest at the head of the tank. The averages for the two aeration systems should not be compared directly since the jet system was operating at a reduced wastewater flow rate relative to that for the disk system. Tables 22 and 23 show the dates, gas flow rates and balance between off-gas flow rates and applied gas flow rates.

The off-gas testing results for Part 2 are shown in Figure 26. Both αFSAE and αFSOTE results are shown for each aeration tank during each of the three operating periods evaluated in Part 2. Each operating period was characterized by one off-gas test for each tank. The air flow rates per diffuser are shown in Figure 26 as well.

The dome system during the 18 MGD conventional test showed better performance than the disk system. This was most likely due to the newer condition of the domes. In the second and third periods, however, the overall average dome system performance equaled the disk system performance; the average dome systems and the disk system achieved 2.0 lb O_2/wire hp-hr and 7.6% transfer.

The various operating conditions used in Part 2 were designed to ascertain the effect of plant operating conditions on oxygen transfer efficiency. The off-gas test efficiency results obtained for the 18 MGD Conventional Mode, the first test phase during Part 2, are superior to those obtained for the other operational modes. This may be partially due to the better condition of the diffusers (less fouling) during this early test phase.

The implication from Figure 26 is that the step feed mode of operation tended to decrease the performance of the aeration systems. This is not supported, however, by the plant operations data during this time. It should be noted that the number of off-gas tests was very limited and that conclusions drawn from the test results may not necessarily be representative of normal plant operation. The performance of the systems in the 18 MGD Step Feed and 12 MGD Conventional Modes was similar.

Figure 27 shows the αF factor as a function of tank distance. These results are similar to the results obtained in Part 1. The results reported in Figure 27 are for the disk system, but the

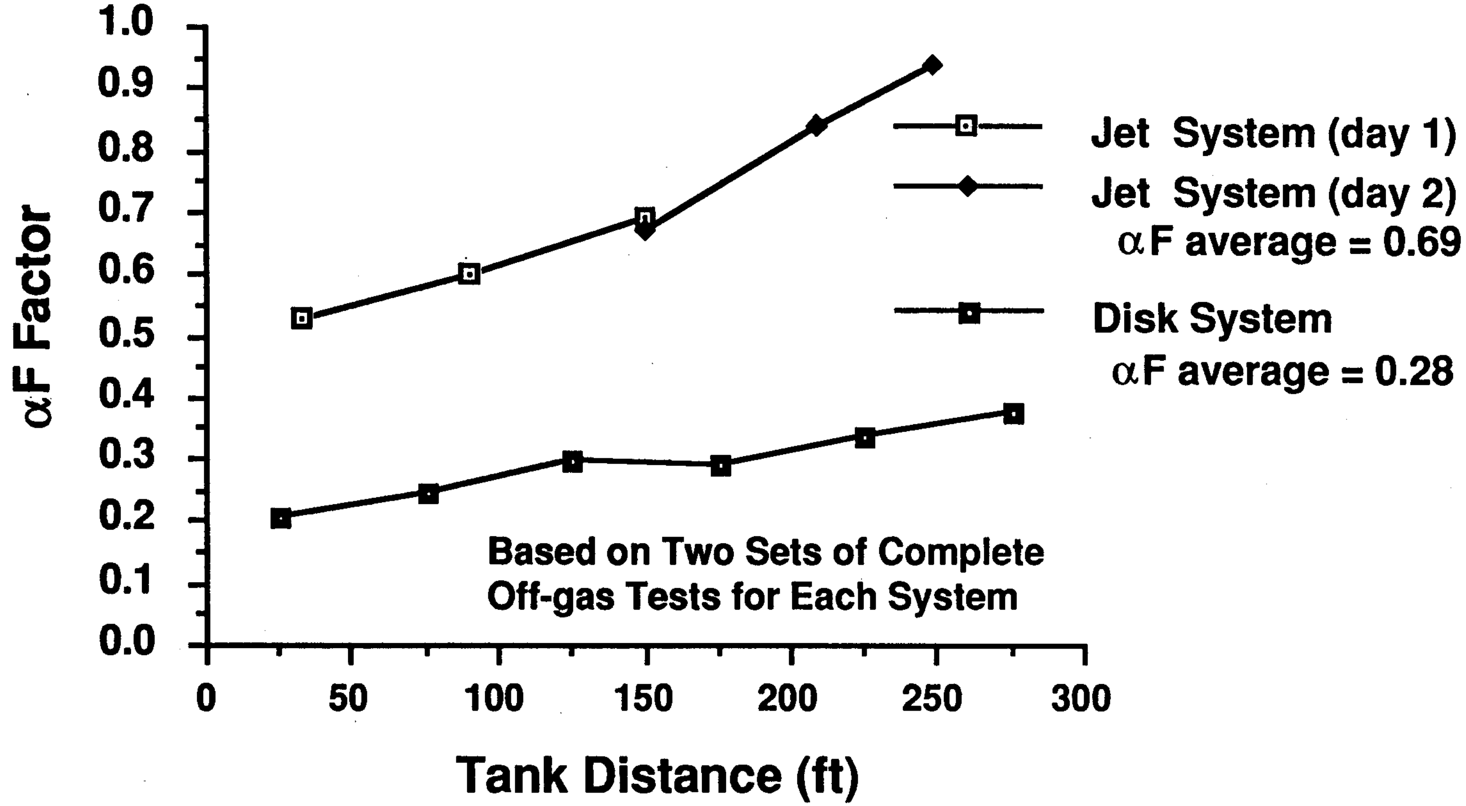


Figure 25. αF Factor Versus Tank Distance for Part 1

Table 22

Comparison of Hood and Applied Gas Flows During Part 1

Aeration System	Test Date	Average Applied Gas Flow/Unit Area[1] (scfm/ft^2)	Average Hood Gas Flow/Unit Area[2] (scfm/ft^2)	Discrepancy (% Applied Gas Flow)
Disk	8/12/81	0.199	0.210	5.53
Disk	11/9/81	0.267	0.288	7.87
Disk[3]	Average	0.233	0.249	6.70
Tube[4]	1/11/82	0.316	0.224	-29.11
Tube[4]	1/12/82	0.321	0.258	-19.63
Tube[5]	1/14/82(1)	0.112	0.095	-15.18
Tube[5]	1/14/82(2)	0.321	0.317	-1.25
Tube[4]	Average	0.268	0.224	-16.29
Jet	8/13/81	0.379	0.363	-4.22
Jet	12/1-2/81	0.240	0.247	2.92
Jet	12/7-8/81	0.166	0.176	6.02
Jet	12/10/81	0.186	0.193	3.76
Jet	12/28/81	0.111	0.132	18.92
Jet	12/31/81	0.383	0.379	-1.04
Jet[6]	Average	0.244	0.248	4.39
Average[7]	8/12/81-1/14/82	0.241	0.248	4.97

Notes:

1. For the purpose of these calculations, the effective width of the aeration tank was assumed to be the same as that covered by the off-gas hood during full coverage sampling = 27.25 ft.
2. The flows used here were hood off-gas flows assuming air composition.
3. Many of the disk system tests were not included in this analysis because of the hood flow measurement problem reported in Appendix E.
4. The agreement between the applied and hood gas flows was poor because of the numerous broken diffusers which resulted in non-uniform off-gas conditions.
5. During this test only Zone 3 (with no broken diffusers) was sampled.
6. One of the jet system tests was not included in this analysis because of the hood flow measurement problem reported in Appendix E.
7. Exclusive of the atypical tube system tests.

Table 23

Comparison of Hood and Applied Gas Flows During Part 2

Aeration System	Test Date	Average Applied Gas Flow/Unit Area[1] (scfm/ft^2)	Average Hood Gas Flow/Unit Area[2] (scfm/ft^2)	Discrepancy % Applied Gas Flow
Disk	9/1/82	0.282	0.287	1.77
Disk	10/29/82	0.334	0.325	-2.69
Disk	12/14/82	0.217	0.231	6.45
Disk	Average	0.278	0.281	1.84
Dome (Tank 2)	9/2/82	0.287	0.280	-2.44
Dome (Tank 2)	10/28/82	0.293	0.280	-4.44
Dome (Tank 2)	12/15/82	0.214	0.212	-0.93
Dome (Tank 2)	Average	0.265	0.257	-2.60
Dome (Tank 3)	9/3/82	0.286	0.266	-6.99
Dome (Tank 3)	10/27/82	0.277	0.266	-3.97
Dome (Tank 3)	12/16/82	0.210	0.201	-4.29
Dome (Tank 3)	Average	0.258	0.244	-5.08
Average	9/1-12/16/82	0.267	0.261	-1.95
Overall Average Parts 1 and 2[3]	8/12/81-12/16/82	0.255	0.255	1.31

Notes:

1. For the purpose of these calculations, the effective width of the aeration tank was assumed to be the same as that covered by the off-gas hood during full coverage sampling = 27.25'

2. The flows used here were hood off-gas flows assuming air composition, with the exception of the October tests, which were hood inlet flows corrected for actual gas composition.

3. Exclusive of the atypical tube system tests.

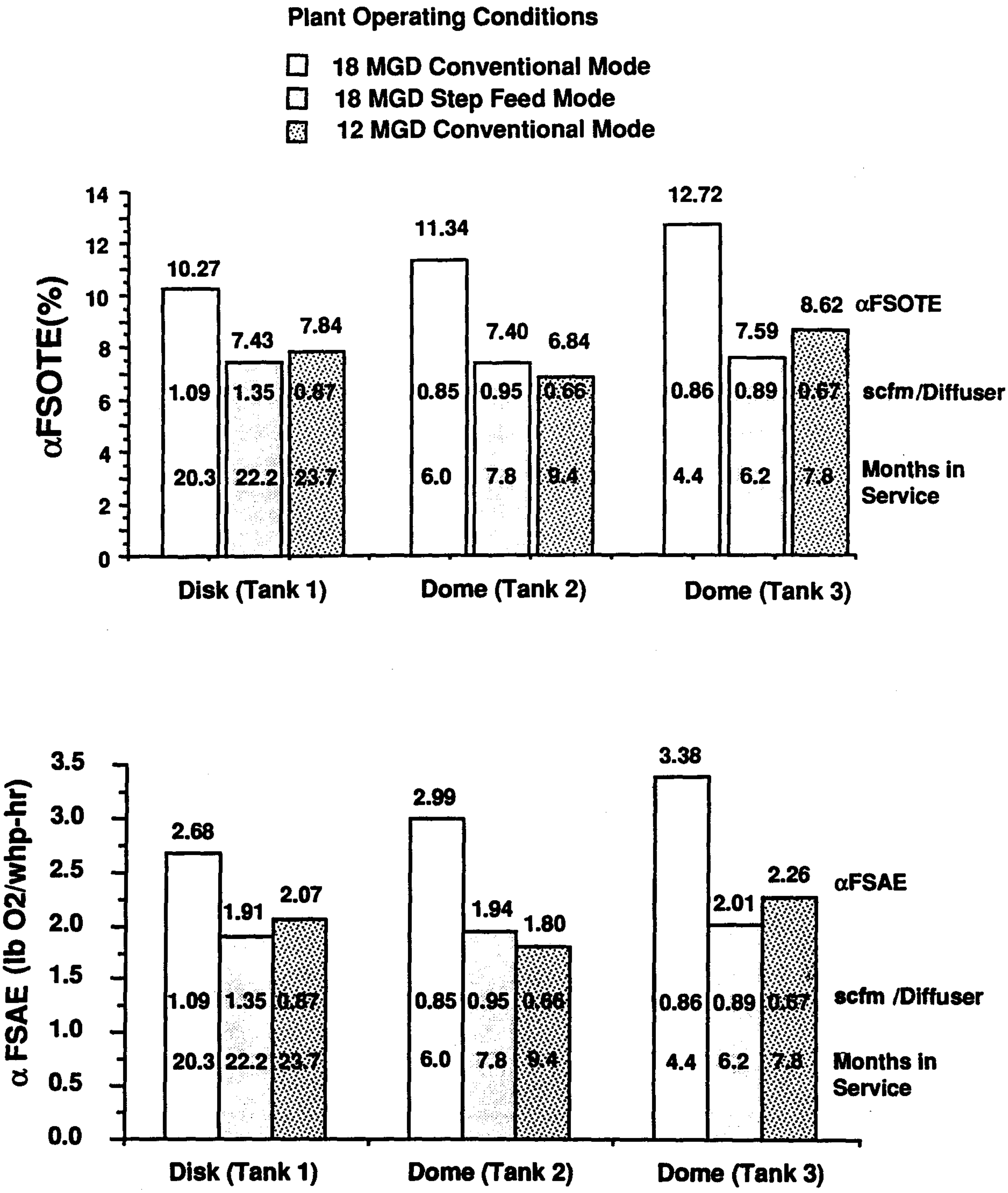
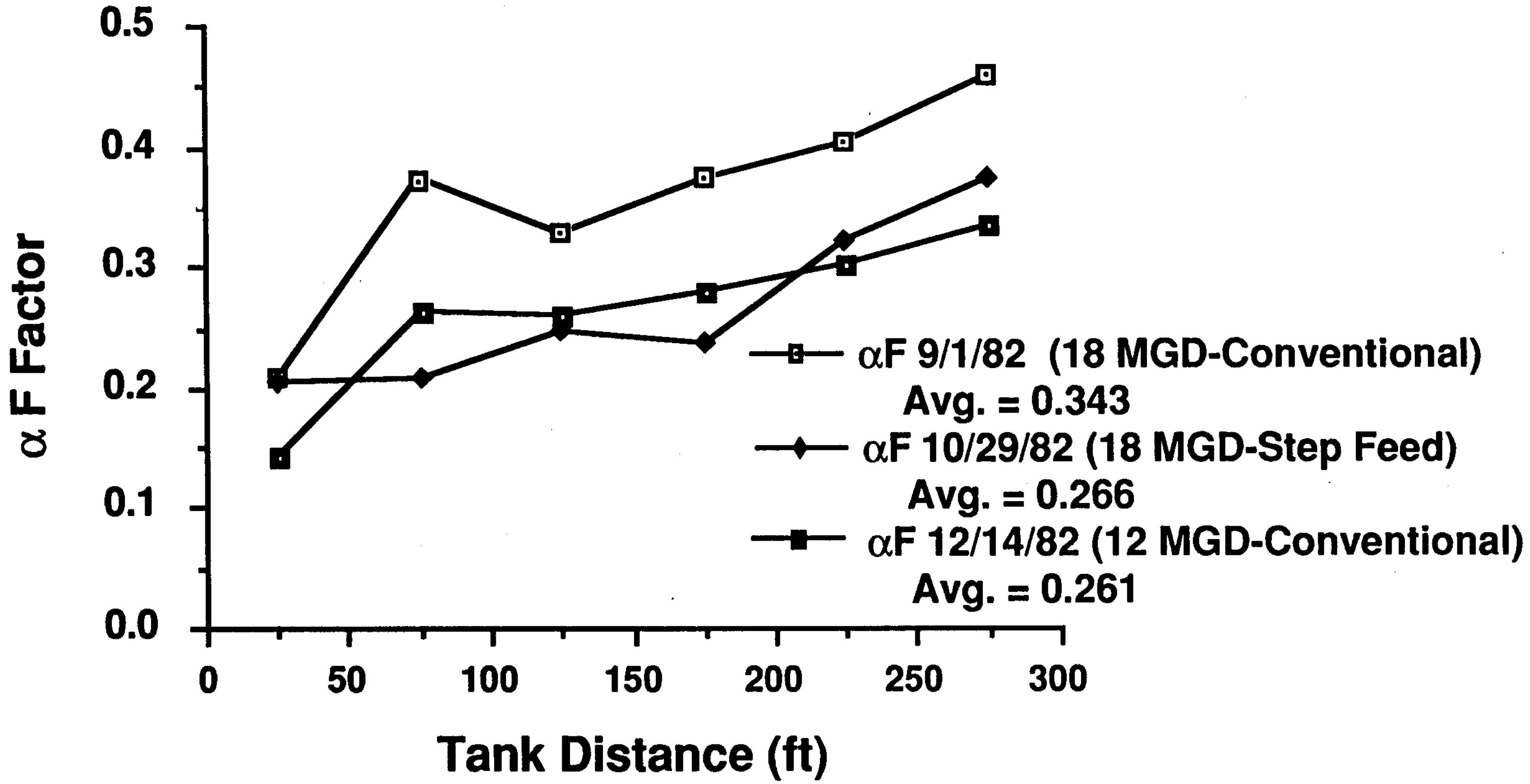


Figure 26. Average Off-gas Test Results for Part 2



Note: System was first put into service in December, 1980. Diffusers were low pressure hosed in April 1982.

Figure 27. αF Factor Versus Tank Distance for the Disk System

dome system showed similar results. The very reduced αF factors at the head end of the tank have important implications for diffuser system design.

PLANT OPERATIONS RESULTS

The plant operations data for Parts 1 and 2 of the project are reported in Appendices A and B, respectively. Included are estimates of oxygen transfer performance based on calculated oxygen demands and measured air flow rates, diffuser headlosses, DO levels and other pertinent parameters. Tables A-21 through A-23 and Figures A-13 and A-14 show the oxygen transfer performance of the three systems tested during Part 1. Tables B-22 through B-25 and Figures B-13 and B-14 show the oxygen transfer performance of the disk and dome systems tested during Part 2. The calculated oxygen demands incorporated COD, sludge production, nitrification, DO and primary effluent flow data. The procedures utilized are reported in Appendix C. The dissolved oxygen sampling locations are as shown in Figure 28. The DO was sampled in the morning and afternoon during Part 1 and in the afternoon during Part 2.

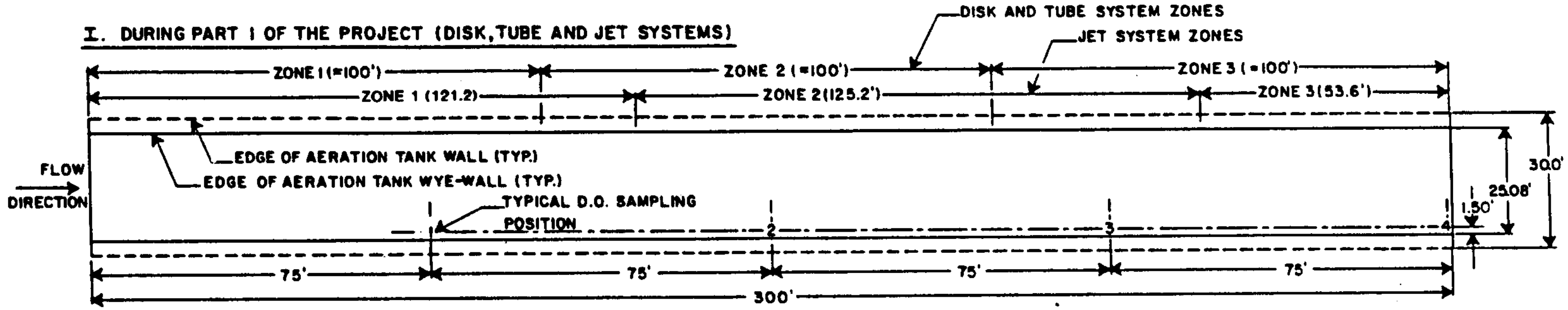
Plots of αFSOTE and αFSAE for Part 1 of the project, based on plant operations results, are shown in Figure 29. It should be noted that the disk system had been in operation since late December 1980 and the tube system had been in operation since early April 1981. Furthermore, the tube system's performance was impacted by the broken nipples discussed previously. The jet system, in order to avoid DO limiting conditions, was operated at approximately 75% of the primary effluent feed rate of the disk and tube systems. It can be seen from Figure 29 that, on the average, the disk system achieved an αFSAE of approximately 1.5 lb O_2/wire hp-hr and an αFSOTE of approximately 5.8%. Comparable numbers are 1.1 and 4.5, respectively, for the tube system and 0.94 and 5.2, respectively, for the jet system. Thus, based on this analysis and under comparable oxygen demand conditions, it is estimated that the disk system would require roughly 61% of the energy required by the jet system and 75% of the energy required by the jet system.

The above efficiency results for Part 1 are markedly lower than the results obtained by off-gas analysis reported in the previous section. One possible explanation for this is the relatively limited number of off-gas tests conducted during the evaluation period, although this is not felt to be the major factor. It is more likely that the discrepancy is due to the gross sludge yield coefficients that were calculated during this period and which affected the oxygen demand calculations.

During Part 1, the average calculated sludge yield was estimated to be relatively high, approximately 0.57 lb VSS/lb COD_R. On the other hand, during Part 2, the average calculated sludge yield was estimated to be significantly lower, approximately 0.43 lb VSS/lb COD_R. According to the oxygen demand calculation procedure in Appendix C, a high sludge yield results in a low oxygen demand, all other factors being equal. It is possible that the calculated sludge yield during Part 1 of the project may have been erroneously high due to problems with plant instrumentation (i.e. waste sludge flow metering), resulting in low estimates of oxygen transfer performance.

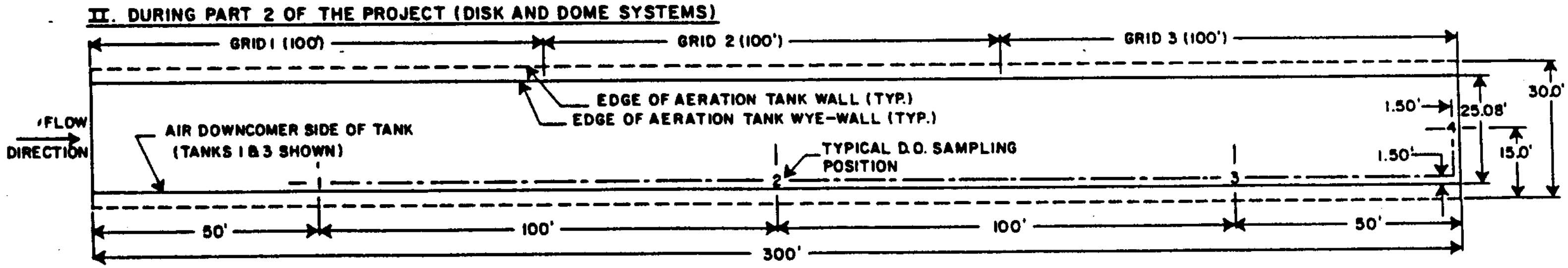
Plots of αFSOTE and αFSAE for Part 2 of the project, based on plant operations results are shown in Figure 30. It can be seen that the αFSAE's for the disk and dome systems during

I. DURING PART 1 OF THE PROJECT (DISK, TUBE AND JET SYSTEMS)



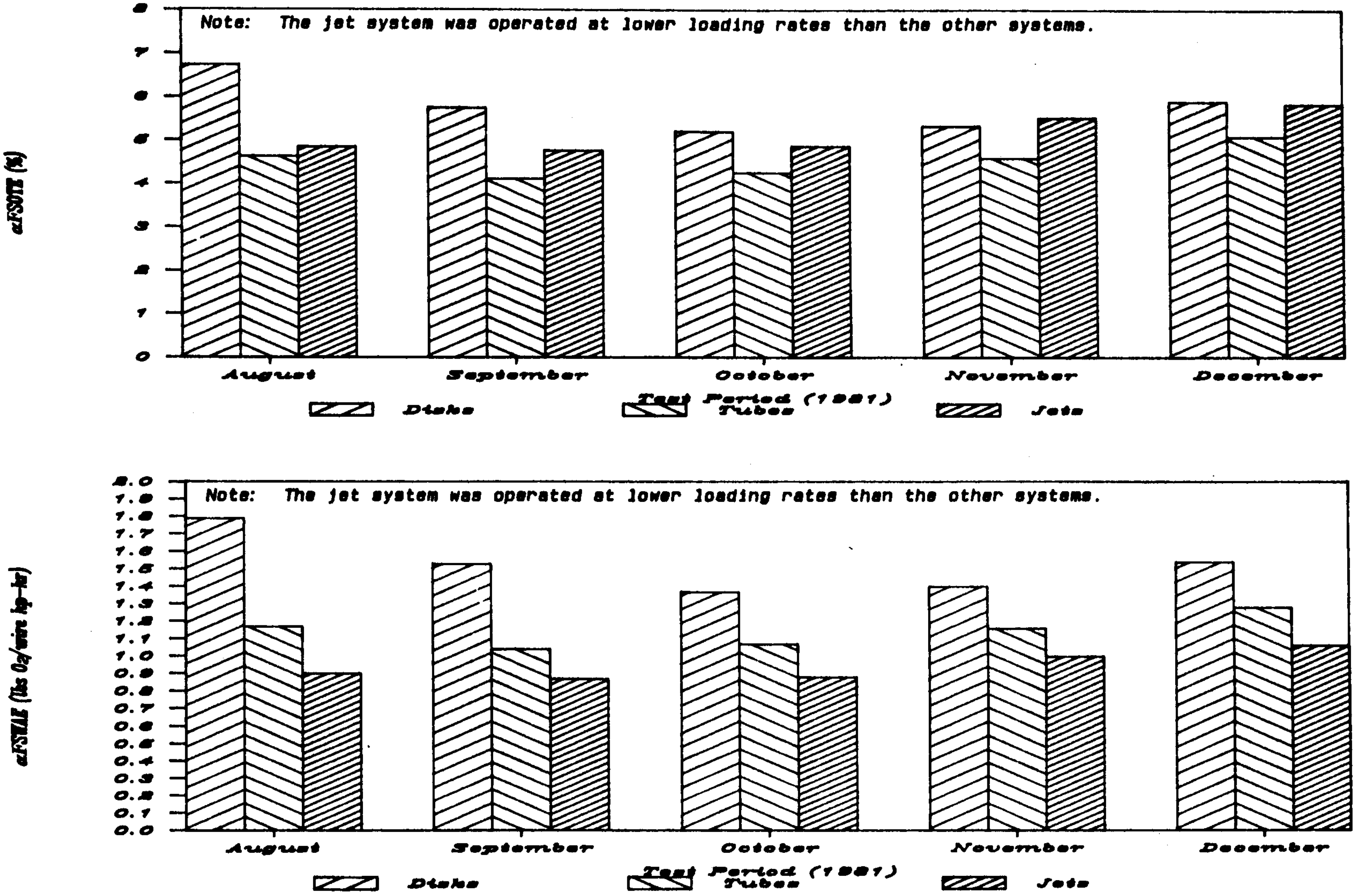
AERATION TANK PLAN

II. DURING PART 2 OF THE PROJECT (DISK AND DOME SYSTEMS)



AERATION TANK PLAN

Figure 28. Dissolved Oxygen Sampling Locations



Note: The jet system was operated at lower loading rates than the other systems.

Note: The jet system was operated at lower loading rates than the other systems.

Figure 29. Standard Oxygen Transfer Efficiency (αFSOTE) and Standard Wire Aeration Efficiency (αFSWAE) During Part 1 Based on Kinetic Calculations of Oxygen Demand

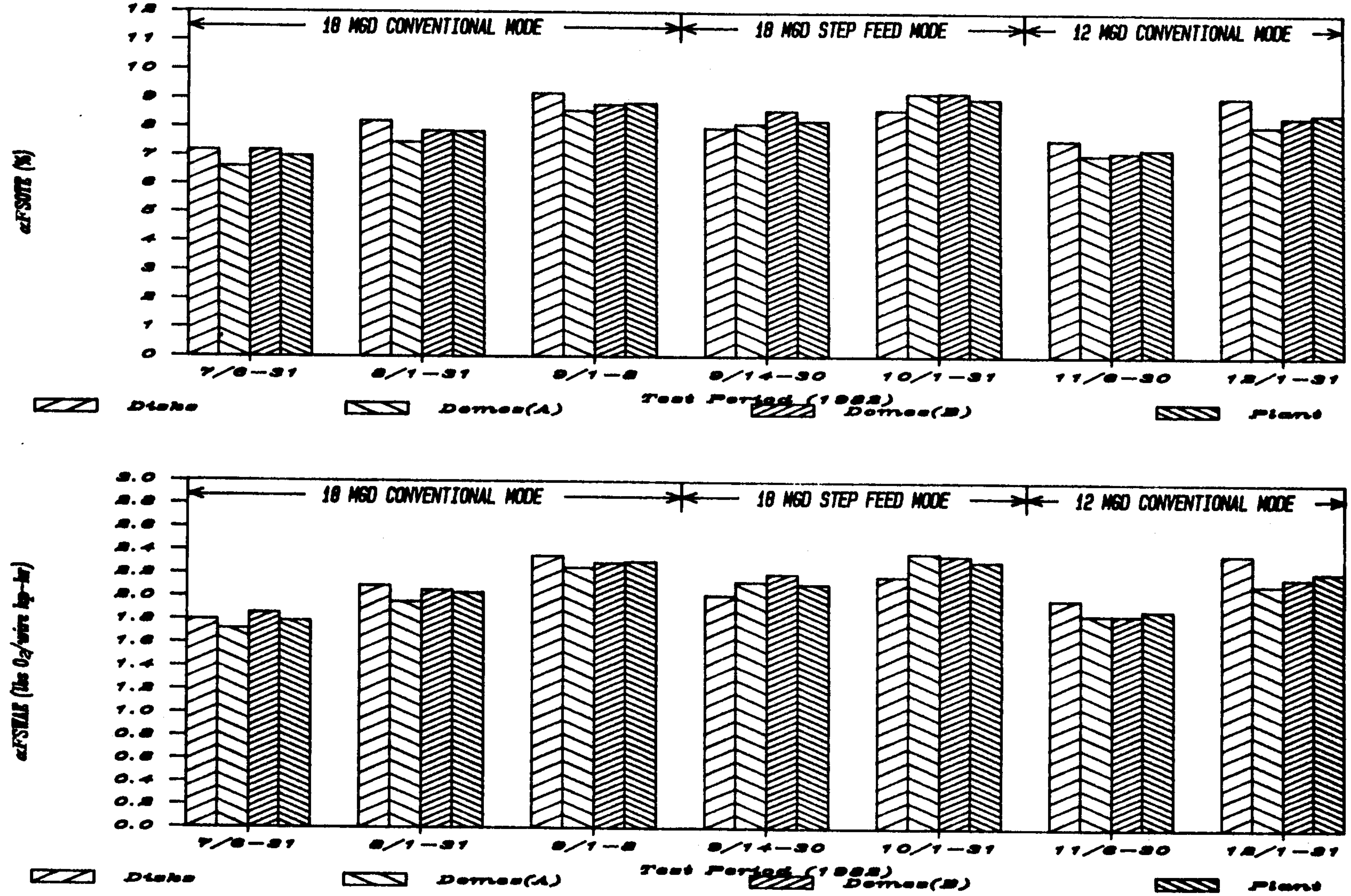


Figure 30. Standard Oxygen Transfer Efficiency (αFSOTE) and Standard Wire Aeration Efficiency (αFSWAE) During Part 2 Based on Kinetic Calculations of Oxygen Demand

the three modes were not significantly different and varied between 1.9 and 2.3 lb O_2/wire hp-hr on a period average basis. αFSOTE's varied between 7.3 and 9.0%.

The average efficiency results obtained from the plant operations data during the 18 MGD Conventional Mode are poorer than the results from the off-gas testing during this same period. This discrepancy is probably due mainly to the limited time frame of the off-gas tests relative to the overall evaluation period. During the latter two operation modes during Part 2, the performance of the disk and dome aeration systems based on plant operations data was in excellent agreement with the performance indicated from the off-gas tests.

SECTION 6

DIFFUSER CLEANING EVALUATION

DIFFUSER FOULING PROBLEM - TANK NO. 1

A. Headloss Onset and Diffuser Cleaning Preparations

As of November 1983, the Sanitaire disk aeration equipment installed in Tank 1 at the Whittier Narrows Water Reclamation Plant had been in operation for almost three years. During this period, the headloss had risen at a very slow and predictable rate (approximately 0.1 psi/yr) and was within original expectations. In November 1983, however, the headloss began to increase at a more rapid rate, particularly in Grids 1 and 3.

No specific occurrence could be established as the cause of the plugging. In particular, the aeration system power failures that occurred did not result in any long-term headloss increases. Also, a mechanical problem with the process air filtration system, which originally had been suspected, was later shown to be only a minor contributing factor. Furthermore, it could not be established that reduced air flows per diffuser, which resulted due to reduced plant flows in the past year, had any effect on the diffuser headloss buildup.

By December 1983, the headloss situation in Tank 1 had worsened to the extent that the operators had to make a substantial air header valve change to obtain the required air flow distribution between tanks. This was followed by further changes in February 1984. By March 1984, a decision was made to drain Tank 1 so that the Sanitaire diffusers could be inspected and hosed off. The previous hosing had been done a year earlier in March 1983.

Prior to draining the tank on March 13, 1984, extreme course bubbling could be observed in Grid 1. Furthermore, due to the high Grid 1 headloss, much of the air that had originally flowed to Grid 1 was now flowing to Grids 2 and 3.

After completely draining the tank, the diffuser slime growth appeared no worse than usual. In fact, the last grid appeared to have less slime than usual, with much of the disk surface readily visible. After low pressure hosing the diffusers from the top of the aeration tank (approximately 3 hours for 2 maintenance personnel), it was discovered that there was a hard, white, somewhat powdery substance adhering to the surface of many diffusers. A Districts' laboratory analysis showed that the surface scrapings after hosing were 21.6% $CaCO_3$ and 4% grease, with the remainder of undetermined origin. Later tests by Sanitaire on diffusers removed from Tank 1 showed the presence of aluminum in the foulant material as well.

Upon partially filling the tank, the distribution of air between diffusers and across a given diffuser was very poor. Some diffusers were totally plugged. One diffuser orifice was plugged with a white, grease-like material.

After making necessary observations and minor repairs, the tank was put back into operation on March 15, 1984. It was clear that the diffuser headloss conditions were improved, particularly in Grid 1, as higher air flows were obtained. Furthermore, the system air pressure was observed to drop slightly. Nevertheless, the diffuser headloss was still excessive (29 inches of H_2O at 1.02 scfm/diffuser in Grid 1). It was clear that further steps would be needed to restore the diffuser headloss to satisfactory operating levels.

At this time a continuing effort was begun to obtain as much information as possible on diffuser plugging as well as various cleaning options. A literature review and phone conversations with various fine bubble diffuser users provided considerable insight.

It was learned, for instance, that it is characteristic of fine bubble diffuser systems to have a relatively slow headloss buildup for years, followed by a relatively rapid buildup thereafter. This can be explained by the following theory. When a diffuser is new, there are thousands of media passageways available to the air stream. At normal air rates, almost all of the media headloss is due to the work required to form air bubbles against the surface tension of water; very little of the headloss is due to losses within the passageways themselves. Since it takes less energy to form large bubbles than small bubbles, only those passageways are used which exit at the diffuser surface with relatively large openings. As these openings become reduced in size due to plugging (most probably from the liquid side), the media headloss increases very slowly. This slow rate of increase is due to the relatively large pore diameter of the openings relative to the amount of plugging material available and the availability of other unused passageways within the diffuser. As diffuser fouling continues, the size of the diffuser openings decrease relative to the amount of plugging material available. Furthermore, the number of alternative passageways becomes fewer. The result is a much greater rate of increase in media headloss.

Another theory helped explain a rather unexpected headloss phenomenon observed with the Tank 1 aeration system. It seems that Grids 1 and 3 were relatively more plugged than Grid 2. A readily apparent common denominator for Grids 1 and 3 that was not common to Grid 2 was the operation at relatively high air flows per diffuser. A conversation with Jerry Wren of Sanitaire revealed another theory. It postulated that scaling occurs to a greater extent at active diffuser pore sites. At higher air flows/diffuser more of the diffuser pores are active, ultimately resulting in higher diffuser headlosses over a long period of time. This might be the explanation for the observed conditions at Whittier Narrows.

Two diffuser cleaning options were initially considered: "firing" and acid gas cleaning. Firing is a historical approach which requires removing the diffusers from the aeration tank, heating them to a high temperature in a furnace, and rinsing with an acid. The procedure is reportedly effective, but costly and time consuming, and was considered to be a last resort. Acid gas cleaning could be performed in-situ, but its effectiveness had not been conclusively demonstrated. It is being marketed presently by Sanitaire Co., who, along with Ewing Engineering Co., have improved the process and have obtained a process patent. Of the two options, gas cleaning seemed to be far less involved and less costly over a long period of time.

Negotiations were begun in December 1983 with Sanitaire to provide a demonstration of their patented gas cleaning process at the Whittier Narrows plant. Because of the legal and practical ramifications involved, considerable time was required to work out an acceptable agreement. In the meantime, discussions were held with other companies involved with a gas cleaning process. A signed agreement was finally reached with Sanitaire in June 1984. It called for cleaning all three grids in aeration Tank 1 on a one-time basis, with any future cleanings to be negotiated. The Districts would pay for the HCl gas, some minor distribution equipment, and the labor to conduct the gas cleaning. Sanitaire would waive their gas cleaning license fee, provide the necessary gas regulation equipment, and provide on-site consultation services.

In April 1984, Tanks 2 and 3 at Whittier Narrows were drained for routine low pressure hosing of the fine bubble diffusers. No serious headloss problems had been experienced in these two tanks. After hosing, there was no visible evidence of any calcium carbonate deposits on the diffuser media. This observation suggests that the calcium carbonate deposits on the diffusers in Tank 1 were more a result, as opposed to a cause of the diffuser plugging. If the deposits had been a cause, it is almost certain that similar deposits would have shown up in Tanks 2 and 3.

Six of the dirty diffusers from Tank 2 were removed for special testing at Professor W.C. Boyle's laboratory at the University of Wisconsin. Even though the Tank 2 diffusers were not plugged to any great extent, it was hoped that something could be learned about the nature of diffuser plugging and about the viability of various cleaning options.

In May 1984, Professor Boyle communicated the results of his special laboratory tests. The slight plugging that had taken place in Tank 2 appeared to be limited to the top surface of the diffuser stones. Furthermore, the results of tests with various cleaning methods indicated that a high pressure hosing, followed by muriatic acid addition, followed by high pressure hosing (referred to as the "Milwaukee Method" by its developers, the Milwaukee Metropolitan Sewage District) provided the best results. Limited testing with steam cleaning and acid gas cleaning provided slightly less effective results.

Since these cleaning methods were performed on the relatively clean diffusers from Tank 2, there was no assurance that they would be as effective on the relatively plugged diffusers in Tank 1. This was a particular concern with the acid gas cleaning method. It was felt that more than one method might be required to regain the full diffuser effectiveness. For this reason, a decision was made to clean the Tank 1 diffusers by the Milwaukee Method first, followed by the acid gas cleaning process.

In May and June 1984, the necessary preparations were made for the cleaning processes to be used at Whittier Narrows. Muriatic acid and several hand held liquid acid sprayers were purchased for use with the Milwaukee Method. Six hundred pounds of anhydrous hydrogen chloride (technical grade), 20 pounds of nitrogen purge gas, and the necessary distribution tubing and valves were purchased for the acid gas cleaning method. In addition, acid gas injection nozzles were sent by Sanitaire for installation in the downcomers for each aeration grid in Tank 1 at Whittier Narrows.

By the time the diffuser cleaning preparations were complete, the diffuser headloss in Tank 1 had risen significantly. Figure 31 shows the headloss increase as a function of time for Grid 1. The other grids were similar. On March 20, 1984, after low pressure hosing, the total diffuser headloss for Grid 1 was 29 inches of water at 1.02 scfm/diffuser. By April 27, 1984, the headloss was 35.3 inches of water at the same air flow per diffuser and was nonconservatively

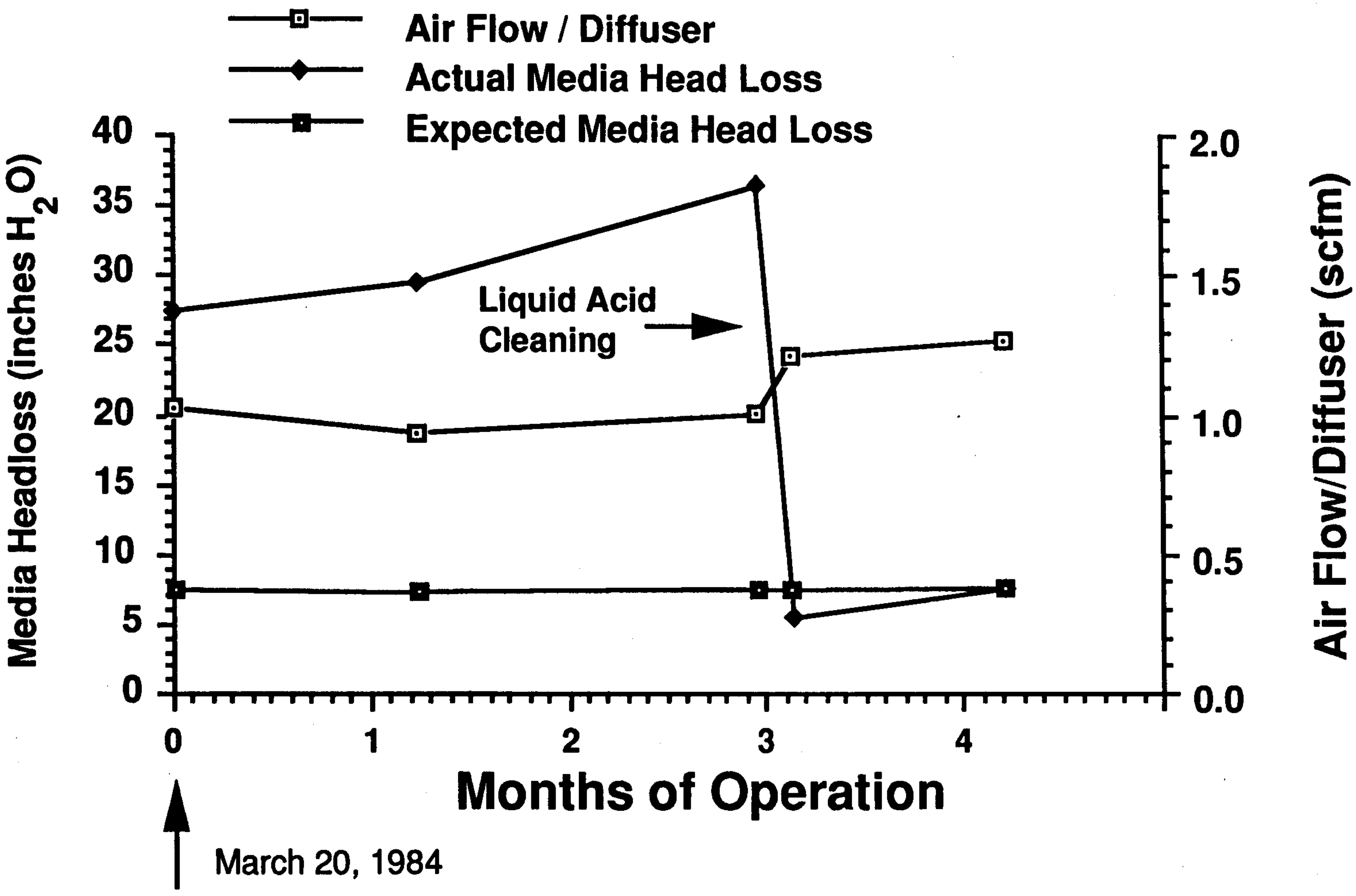


Figure 31. Grid 1 Disk Diffuser Media Headloss Versus Months of Operation

estimated to be 45.7 inches of water at the design air flow/diffuser (1.25 scfm). The total diffuser headloss for a clean diffuser at the design air flow per diffuser in clean water is approximately 10 to 11 inches of water (depending on the orifice headloss). Figure 32 shows the headloss versus air flow rate for Grid 1 as of April 27, 1984. By June 17, 1984, the total diffuser headloss for Grid 1 had risen to 37.4 inches of water at 1.00 scfm/diffuser.

The headlosses for Grids 2 and 3 also increased between March 20 and June 17. The increase for Grid 3 was particularly large, so that just before cleaning, the Grid 3 headlosses were nearly equal to those of Grid 1.

B. Diffuser Cleaning Using a Modified Milwaukee Method

By June 19, 1984, Tank 1 had been drained for diffuser cleaning by the Milwaukee Method. The diffusers in Grid 1 appeared to be fairly heavily slimed, as usual, while those in Grids 2 and 3 were only slightly slimed due to the recent low pressure hosing in March.

Prior to low pressure hosing, a total of 25 diffusers were removed from Grids 1, 2 and 3 for special testing. Some of these diffusers were sent to Professor Boyle for analysis and cleaning by various methods. Some diffusers were sent to Sanitaire for analysis and cleaning by the acid gas procedure. The remaining diffusers were kept by the Districts for "in-house" analysis to be discussed later.

The first step in the cleaning process was to remove the diffuser slime on all three grids by low pressure hosing. This was accomplished with the air on. Over 2,000 diffusers were hosed by 2 to 3 maintenance personnel form the top of the aeration tank within a 2 to 3 hour period using low pressure nozzles operating at approximately 57 psi and 20.7 gpm. It is estimated that the actual hosing time for each diffuser was approximately 7.5 seconds. After hosing, the deposits of calcium carbonate and grease were readily apparent as before.

The second step in the cleaning process was high pressure hosing of the diffusers at close range (approximately 8 inches form the diffuser surface). This was accomplished with the air on, using high pressure nozzles operating at 80 psi and approximately 9.3 gpm. It is estimated that each diffuser was hosed for approximately 7.5 seconds. Considerable time was expended trying to move the 1 inch hose around the thousands of diffuser baseplates within the tank. After hosing, the diffusers seemed cleaner than before, although the white deposits appeared to be completely unaffected.

The acid addition step was performed only after the necessary safety precautions were made. Full rubber raingear (pants, jacket and boots) was worn with rubber gloves and full face shields. Oxygen readings were taken every 15 minutes. Hydrogen sulfide and explosimeter readings were taken because of residual sludge in the bottom of the aeration tank. A respirometer was on standby. In addition, a rescue team was available on top of the tank, if needed. In hindsight, HCl gas canister filters for each maintenance man in the tank would have been appropriate as well.

The protection of the concrete aeration tank and the metal components of the aeration system was also considered. At least 3-4 inches of water was left in the bottom of the aeration

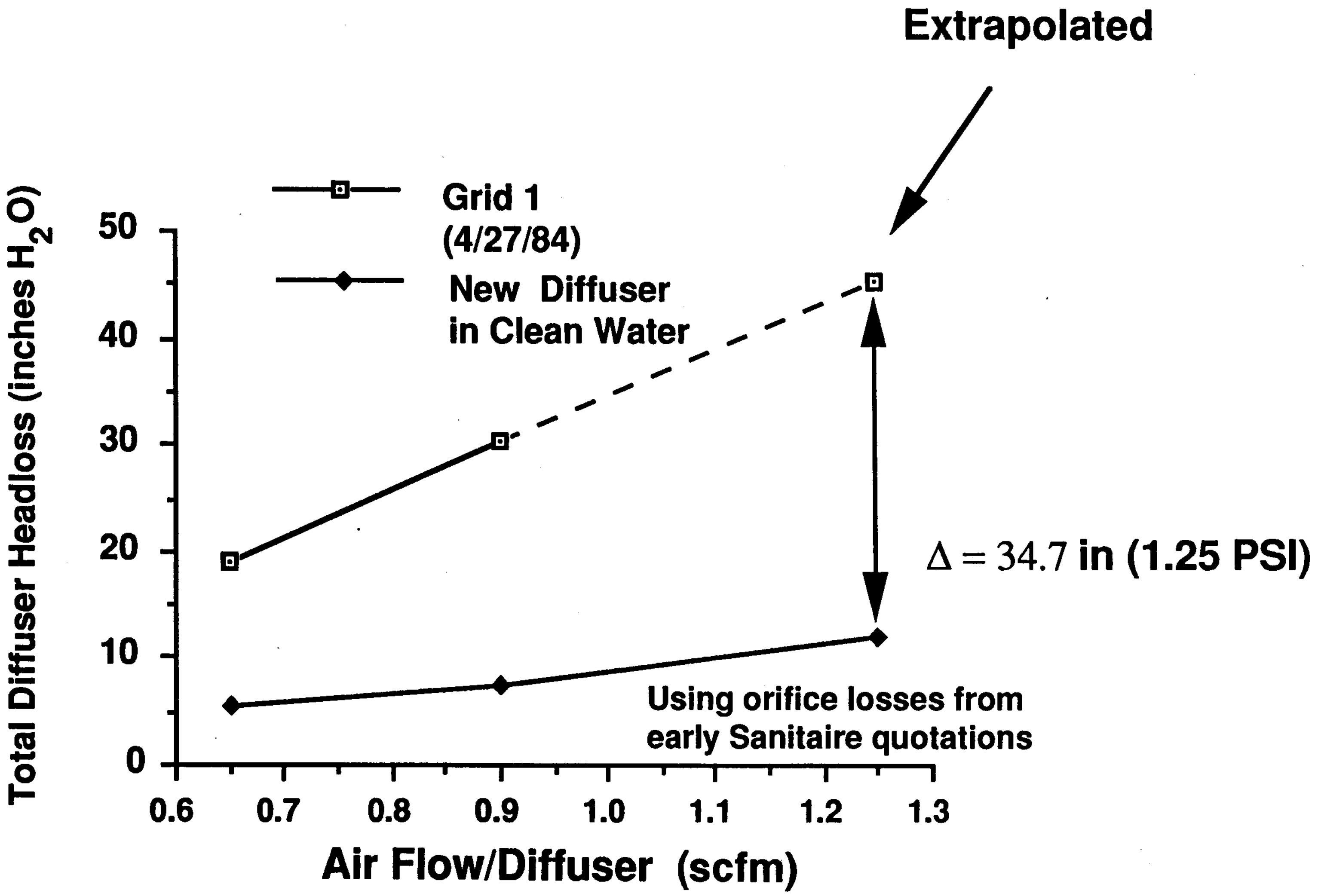


Figure 32. Tank 1, Grid 1 Headloss Profile (4/27/84)

tank to dilute the acid solution before contact with the concrete floor. Every attempt was made to avoid contact of the acid solution with the metal components of the aeration system.

The acid addition step required 2 hand-operated compressed air acid sprayers. Each sprayer was of 2-gallon capacity. A 50 percent solution of industrial grade muriatic acid was used. The acid was readily available from a local pool supply store and was approximately 31.4 percent HCl prior to dilution. This acid differed slightly from the 18° Baume' inhibited muriatic acid generally recommended, but harder to obtain. With the air off, approximately 50 mls of acid solution was added to each diffuser through an adjustable fan spray nozzle on the acid sprayers. The approximate acid volume was supplied to each diffuser by timing the acid delivery after first calibrating the acid sprayers. In our case, acid was sprayed on each diffuser for approximately 7 seconds.

The acid addition step was performed by grid. It required 1 to 2 hours to acidify the diffusers in each grid (the number of grid diffusers varied from 460 to 792. The acid was left standing on all diffusers until the last diffuser had been acidified for at least 30 minutes. It is estimated that on the average, acid was left standing on the diffusers for over one hour.

After evacuating all personnel from the aeration tank, the air was turned on to near the design air rate per diffuser. The air flow forced the acid, which had soaked into the diffuser stone, back to the surface of the diffuser. There, the intense bubbling action promoted further cleaning of the diffuser (air/acid agitation). This was allowed to continue for approximately 10 minutes. During this time, the acid solution was observed to be dark brown in color, indicating the effectiveness of the cleaning process.

Following this bubbling action, the diffusers were hosed from the top of the tank using the low pressure nozzles. This was done for safety reasons to ensure that the diffusers would be relatively free of acid during the close range high pressure hosing step which followed. It is estimated that several seconds were spent with the low pressure rinse on each diffuser. Afterwards the diffusers appeared very clean, almost like new in appearance.

The final step in the cleaning procedure was the high pressure rinse. This was accomplished in identical fashion to the high pressure hosing prior to the acid addition step. Afterwards the diffusers looked like new diffusers.

The aeration tank was put back into service on June 22, 1984. The distribution between diffusers and across any given diffuser appeared to be excellent. The total diffuser headloss readings taken on the same day at the design air rate per diffuser (1.25 scfm) were 10.2, 10.0, and 9.1 inches of water, for Grids 1, 2 and 3, respectively, as compared to approximately 10 inches of water for a new diffuser in clean water. The results of the liquid acid cleaning method far exceeded expectations.

It was clear from these results that the acid gas cleaning process would not be required at that time. Since there was still interest in the potential of the gas cleaning process, a decision was made to postpone Sanitaire's demonstration until the diffuser media headlosses had risen approximately 50 percent higher than those of a clean diffuser.

Headloss readings were repeated on July 26, 1984, for Grid 1 at the design air rate per diffuser. The total diffuser headloss was shown to have increased approximately 1.2 inches of water over the 34 day period (see Figure 32). This is a very normal phenomenon and was certainly no cause for alarm. All indications to this date are that the liquid acid cleaning process has been very effective in reducing headloss.

A major increase in oxygen transfer performance was also observed as a result of the diffuser cleaning. It was estimated that the air usage for Tank 1 dropped by nearly 48% after the cleaning.

DIFFUSER CLEANING PILOT STUDY

A. Cleaning and Evaluation Methods

After the successful cleaning of the diffusers in Tank 1, a decision was made to evaluate other cleaning methods. This was done to determine the most cost effective cleaning option, and would supplement information supplied by Professor Boyle on the subject. A small diffuser cleaning pilot unit was built to evaluate different cleaning techniques and to test their effectiveness by media headloss measurements.

Media headloss was determined by manometric measurement of diffuser plenum pressure, followed by subtraction of the diffuser static head (2 inches of H_2O for all tests in this study). Diffuser orifice headlosses were also measured, using plenum and total diffuser pressure taps.

All the cleaning methods tested during this study were in-place techniques requiring drainage of an aeration tank. The following methods were evaluated:

1. "Bumping"
2. Low pressure hosing
3. High pressure hosing
4. Steam cleaning (with soap and brushing)
5. Liquid acid addition
6. Various combinations and variations on the above.

The gas cleaning technique was not evaluated because of the specialized equipment and expertise involved, the plans for future full scale testing, and because other researchers were conducting studies in this area.

Descriptions of the various cleaning methods are shown in Table 24. "Bumping" is a technique where the air flow to the diffuser is increased to a high rate (i.e. 3 scfm) for a period of time, forcing some solids to be broken loose from the diffuser stone. Low pressure hosing, as used here, refers to hosing with a low pressure nozzle from a distance (approximately 18 feet for our study, as from the top of an aeration tank) at a nozzle pressure of less than 60 psi (57 psi and

Table 24

Cleaning Techniques as Used During the Diffuser Cleaning Pilot Study

Technique	Methodology
Bumping	Operated at 3.1 SCFM/diffuser for as long as 1 hour.
Low Pressure Hosing	Hosed at a distance (approximately 18 feet) using a low pressure nozzle at 57 psi and 20.7 gpm. Hosing time varied from short (7.5 seconds) to long (1 minute).
High Pressure Hosing	Hosed at close range (approximately 8 inches) using a high pressure nozzle at 80 psi and 9.3 gpm. Hosing times varied from short (7.5 seconds) to long (1 minute).
Steam Cleaning (with soap and brushing)	Fairly standard cleaning technique. For these tests the steaming operation was preceded by short low pressure hosing. The diffuser top surface was then steamed for 3 minutes 10 seconds, including 20 seconds of soap and brushing. The bottom surface of the diffuser was steamed for 30 seconds.
Liquid Acid Addition[1]	
A. Milwaukee Method	Utilized 50 mls of a 50 percent solution of muriatic acid directly on the diffuser surface for 30 minutes. The acid addition was preceded and followed by high pressure hosing at close range for approximately 1 minute.
B. Modified Milwaukee Method	Refers to any variation on the above method including: (1) low pressure hosing at a distance; (2) relatively short hosing times (i.e., 7.5 seconds); (3) different acid soaking times; (4) air/acid agitation of the diffuser surface (i.e., 2.5 minutes with acid and air at the low air rate, followed by 7.5 minutes with acid and air at the design air rate, both preceded by the acid soaking procedure).

1. 18° Baume inhibited muriatic acid is generally recommended. Uninhibited muriatic acid at 31.4% HCl (undiluted) was used during this study, however.

20.7 gpm/nozzle for our tests). High pressure hosing, as used here, refers to close range (approximately 8 inches for our study) with a high pressure nozzle at a pressure of 80 to 120 psi (80 psi and 9.3 gpm/nozzle for our tests). Steam cleaning (with soap and brushing) is a fairly standard cleaning technique. Finally, liquid acid cleaning is accomplished by adding a 50 percent solution of muriatic acid to the diffuser surface for a period of time. This is initiated and followed by a hosing operation.

The liquid acid cleaning methodology deserves special discussion because of the steps involved. The techniques used during this study were the Milwaukee Method and various forms of the Modified Milwaukee Method. As mentioned previously, the Milwaukee Method consists of high pressure hosing, followed by acid addition, followed by high pressure hosing. The high pressure hosing is usually performed as above, for times as long as 1 minute per diffuser. The acid is generally left on the diffuser for 30 minutes or more. The Modified Milwaukee Method refers to variations on the basic Milwaukee Method. These variations can include:

1. Low pressure hosing at a distance (i.e., 57 psi at approximately 18 feet).
2. Relatively short hosing times (i.e., 7.5 seconds).
3. Both shorter and longer acid soaking times (15 minutes to several hours).
4. Air/acid agitation of the diffuser surface.

B. Diffuser Characterization Tests

Prior to performing the cleaning evaluations, several diffuser characterization test were run. The tests were conducted to determine the following:

1. The effect of varying amounts of retained water on media headloss (both clean and dirty diffusers).
2. The effect of solids blowoff on dirty diffuser media headloss due to testing at high air rates.
3. The effect of time and drying on dirty diffuser media headloss.

It was considered imperative that these effects be known before meaningful headloss tests could be run during the cleaning evaluation.

In the discussions which follow the "low" or "minimum" air rate refers to 0.62 scfm/Sanitaire diffuser. The "design" air rate refers to 1.25 scfm/Sanitaire diffuser and the "high" air rate refers to 3.1 scfm/Sanitaire diffuser.

Figure 33 shows the headloss versus flow relationships for a new Sanitaire diffuser. The orifice, media, and total diffuser headlosses are shown. It is clear that at low air rates the media is the controlling headloss while the orifice is the controlling headloss at higher air rates.

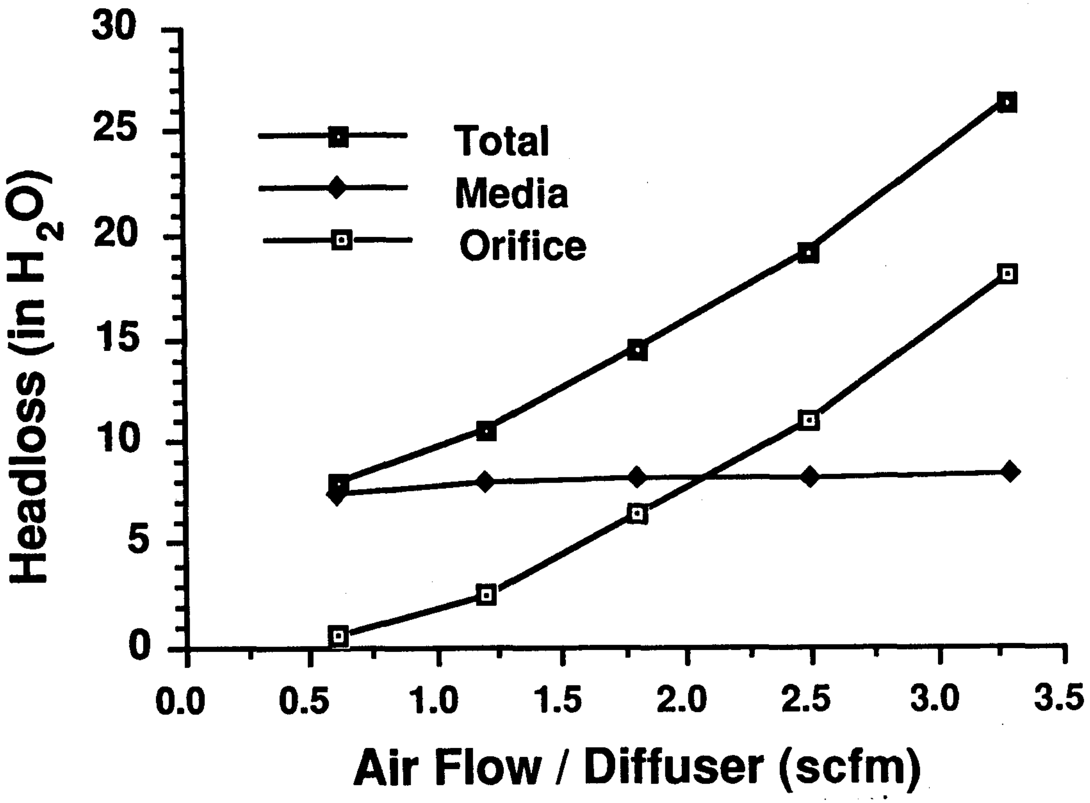


Figure 33. New Disk Diffuser Headloss Profile

For the tests on both the clean and fouled diffusers, the following procedure was developed. Prior to testing, the diffuser was soaked for 10 minutes and then blown out at the minimum air rate for 8 minutes. The tests were performed from low air rate to high air rate, since it was learned that the media headloss after operation at abnormally high air flow rates was substantially reduced. This was due to the displacement of retained water in the stone. Approximately 4 to 5 minutes were spent at each air rate.

It was felt that running the tests in this fashion would provide relatively consistent results, even though they might not be entirely comparable to results obtained in the field. It was expected that the pilot unit's low air rate tests would have slightly higher headloss results than comparable results in the field due to the greater level of retained water in the pilot unit diffusers. The field diffusers would be expected to have less retained water due to their relatively long periods of operation at the test air rate (essentially steady-state conditions).

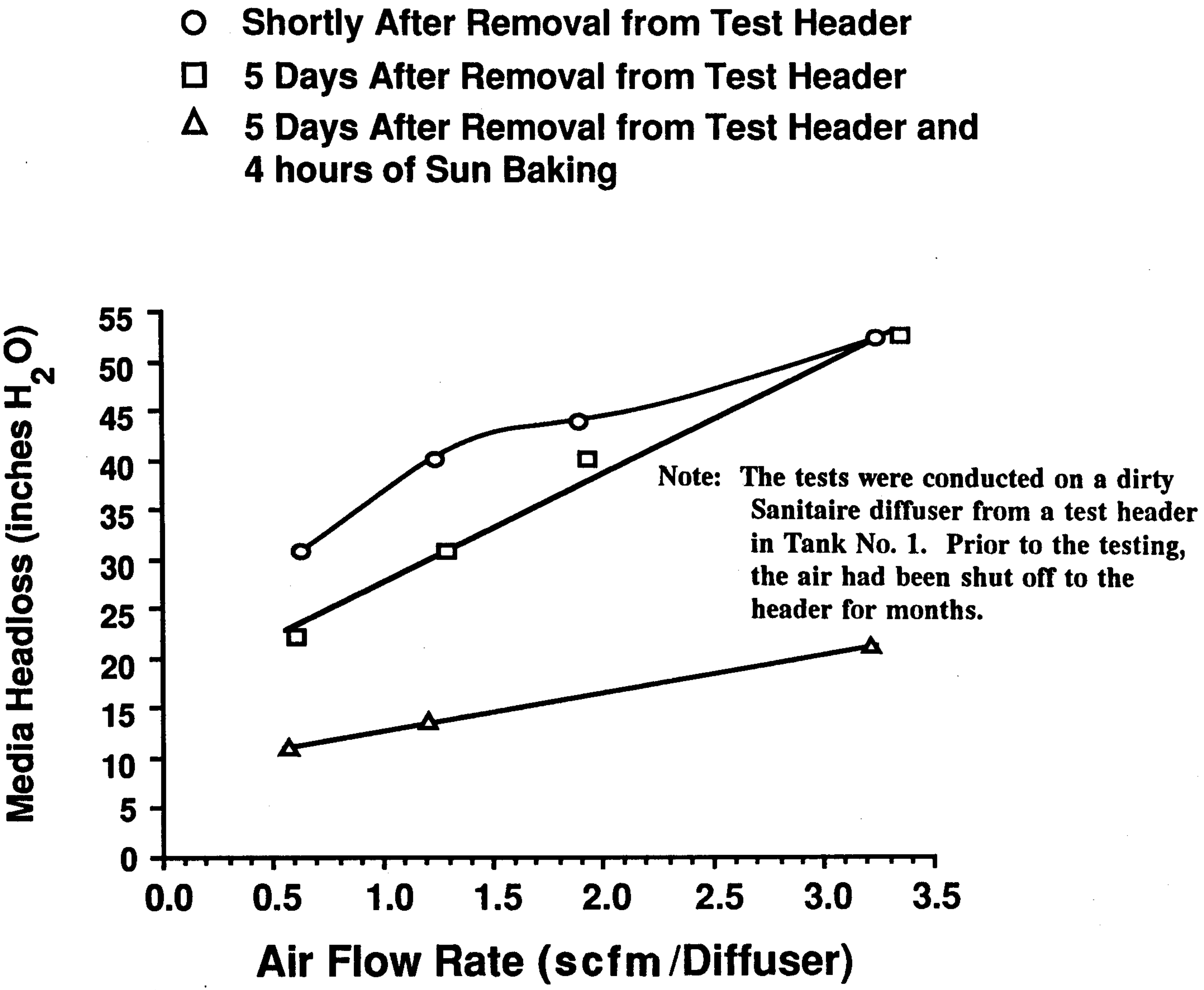
After conducting all tests and after discussions with experts in the field, it was felt that a better procedure would have been to blow out all diffusers at a high air rate after soaking and before any headloss tests. The ensuing headloss results would probably have been more typical of field conditions. The procedure used for this study has almost certainly led to "high" headloss results at the low and design air rates per diffuser.

It was not possible to run the cleaning evaluation headloss tests immediately after the dirty diffusers were removed from Tank 1. Even though the diffusers were stored in moist plastic bags and sealed, there was much concern that the diffuser slime and other contaminants would change (i.e., decompose, compact, dry out, etc.). Visual observations tended to confirm this.

Figure 34 shows the effect of time and drying on dirty diffuser media headloss. "Time" refers to the time interval between the diffuser's removal from active service and its testing in the pilot unit. "Drying" refers to the drying of the diffuser slime and other contaminants. The tests in Figure 34 were conducted on a diffuser removed from a special test header in Tank 1. The first set of tests was conducted shortly after the diffuser was removed from the header; the second set of tests was conducted after 5 days storage in a moist plastic bag; and the third set of tests was conducted after an additional 4 hours of sun baking.

The results in Figure 34 show that additional time and drying resulted in lower headlosses at the same air flow rate. This was particularly true of drying, as evidenced by the curve obtained after 4 hours of sun baking. Drying caused cracking and shrinking of the diffuser slime, with the result that some of the material was blown off once the diffuser was put back into operation. The effect of time, without appreciable drying, had less of an effect on headloss.

As before, the effect of retained water and/or solids removal by bumping had a significant effect on headloss. This is evidenced in Figure 34 by the two repeat headlosses at the low air rate obtained after operation at the high air rates. The absolute results for this test header diffuser should not be extrapolated to other results shown later, since the test header had been shut down for a period of time prior to the testing. The results are shown only to indicate the impact of diffuser drying on the headloss measurements.



Note: The tests were conducted on a dirty Sanitaire diffuser from a test header in Tank No. 1. Prior to the testing, the air had been shut off to the header for months.

Figure 34. Effect of Time and Drying on Diffuser Media Headloss

Before discussing the results of the diffuser cleaning pilot tests, it should be noted that the headloss results obtained for the dirty diffusers in the pilot unit were significantly higher, in general, than results obtained in the field prior to the draining of Tank 1. Tests conducted by Professor Boyle and by Sanitaire have also confirmed this observation. At the present time, it would appear that the discrepancy is due largely to:

1. The greater level of retained water in the diffusers during the pilot unit tests, as compared to the full scale tests.
2. The diffusers tested in the pilot unit perhaps being non-representative of the full scale diffusers.
3. Some effect due to the "time and drying" of the diffusers that was not evident from the special time and drying tests performed.

In any case, because of the discrepancy between the pilot and full scale diffuser headloss tests, the cleaning evaluation results which follow should be considered more qualitative than quantitative.

C. DIFFUSER CLEANING TESTS

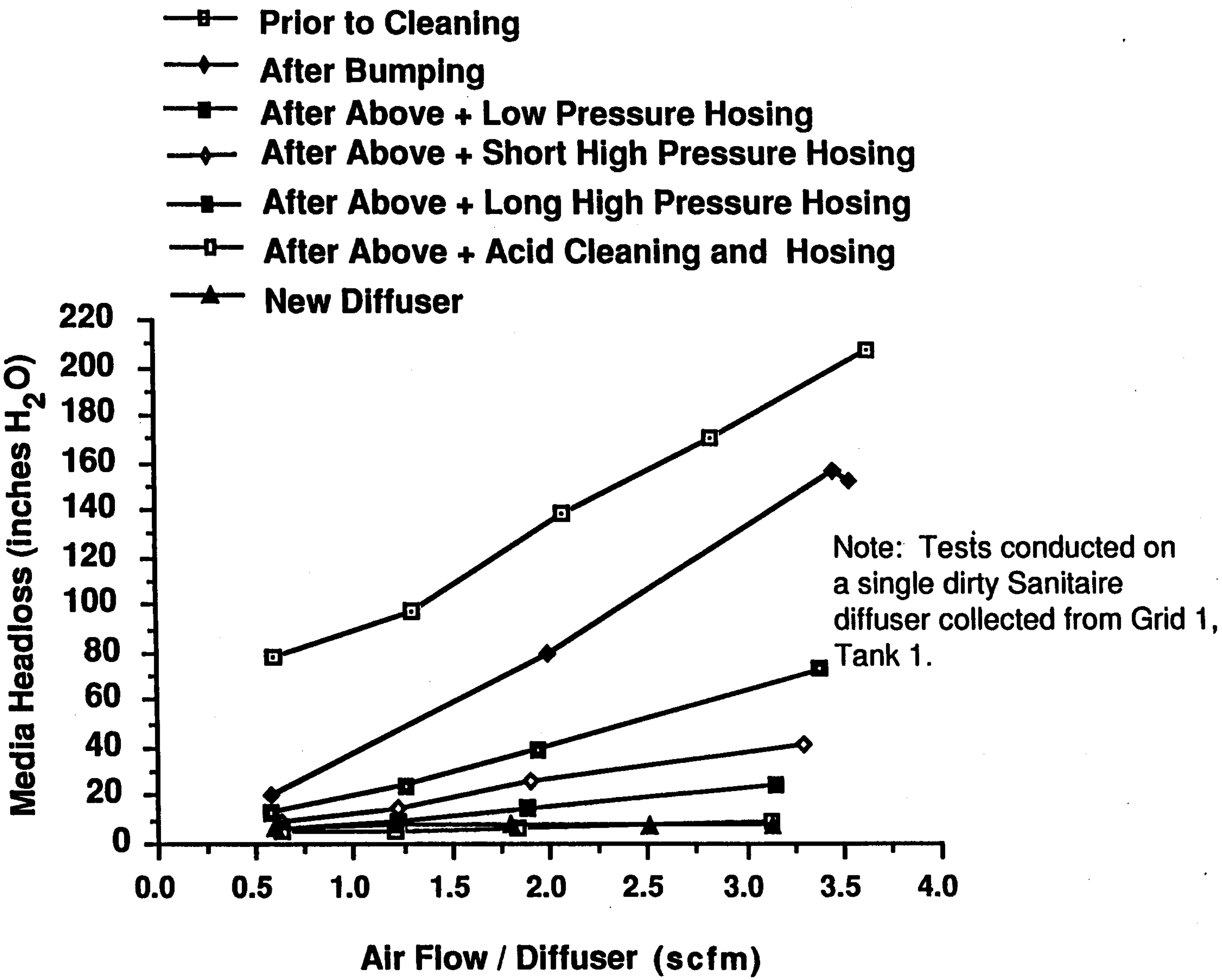
Figure 35 shows results of a series of cleaning method tests on a diffuser removed from Grid 1 in Tank 1. It is clear that "bumping" (at the high air rate for over 1 hour) reduced the media headloss somewhat. Short low pressure hosing further reduced the media headloss, as did short high pressure hosing. Additional high pressure hosing and liquid acid addition followed by short high pressure hosing, each reduced the headlosses further. After the acid addition step, the media headlosses were at new diffuser levels.

Figure 36 shows the relative effect of steam cleaning with soap and brushing, after short low pressure hosing. The steam cleaning operation was performed by steaming the top of the diffuser for 3 minutes 10 seconds, including 20 seconds with soap and brushing. To determine the maximum effect of steam cleaning, the bottom of the diffuser was steamed for 30 seconds as well. The overall procedure was considered to be much more extensive than would ever be practical in the field.

It can be seen from the results in Figure 36 that short low pressure hosing prior to steam cleaning had a very significant effect on media headloss. It is also clear that steam cleaning reduced the headloss levels further, but not to those of a new diffuser. During the cleaning process the hard white deposits on the diffuser stone were resistant to the steam, and were only removed after heaving brushing. The acid addition step which followed, however, did restore the headloss to clean diffuser levels.

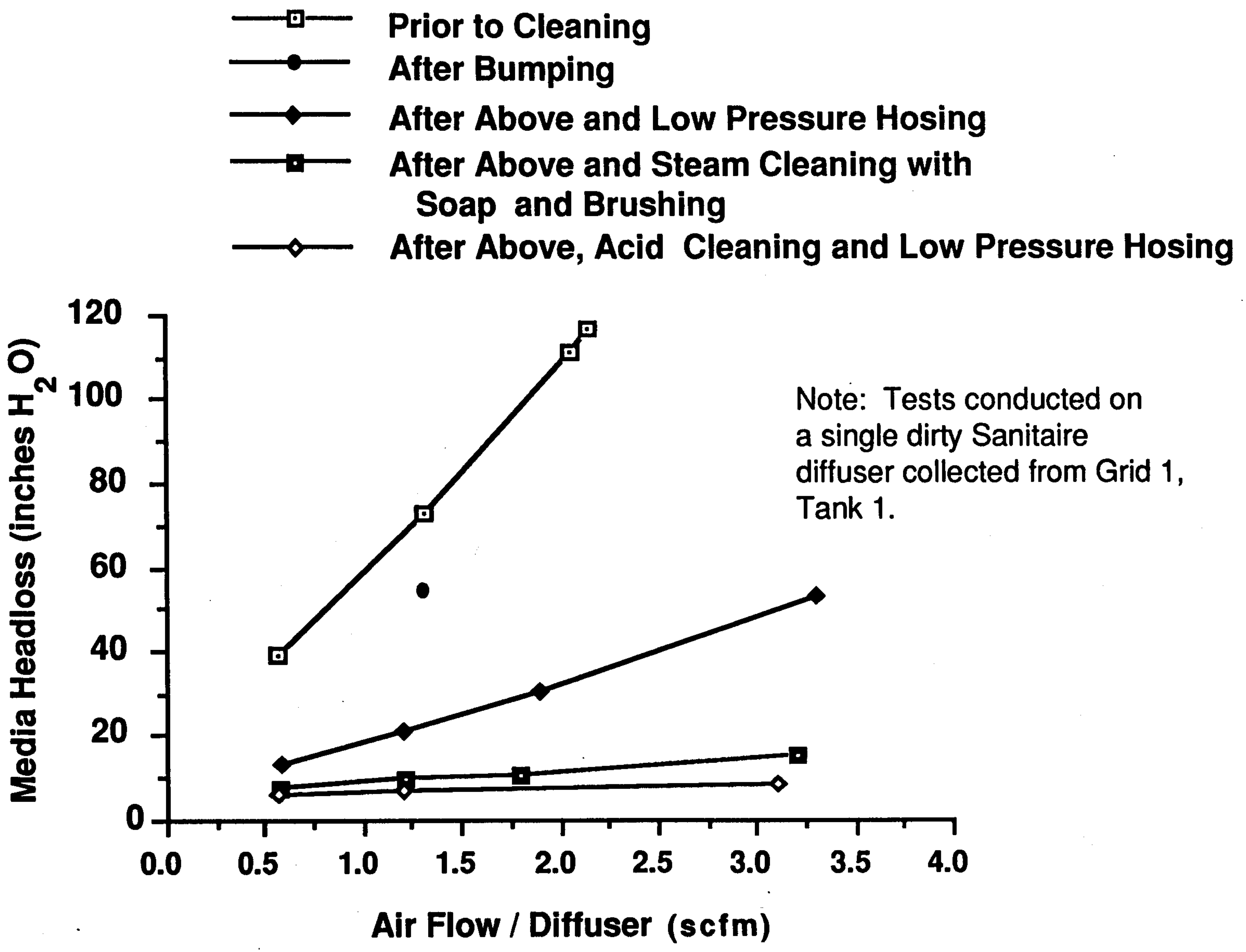
It is interesting to note that the steam cleaning worked very well on the bottom of the diffuser. Evidently the fouling material there, most likely grease from the air under the primary tank covers, was amenable to breakdown by the steam cleaning operation.

The results in Figure 35 and 36 give an indication of the effectiveness of the various cleaning methods in reducing media headloss. The results do not indicate the length of field



Note: Tests conducted on a single dirty Sanitaire diffuser collected from Grid 1, Tank 1.

Figure 35. Cumulative Effect of Various Cleaning Methods on Diffuser Media Headloss



Note: Tests conducted on a single dirty Sanitaire diffuser collected from Grid 1, Tank 1.

Figure 36. Effect of Steam Cleaning on Diffuser Media Headloss

operation time required after each method before the diffuser headlosses would return to high levels. There is considerable reason to believe that diffusers cleaned by techniques which are only partially effective, may return to high headloss operation within a relatively short period of time. This concern may warrant the selection of more effective techniques, even though they may be more costly.

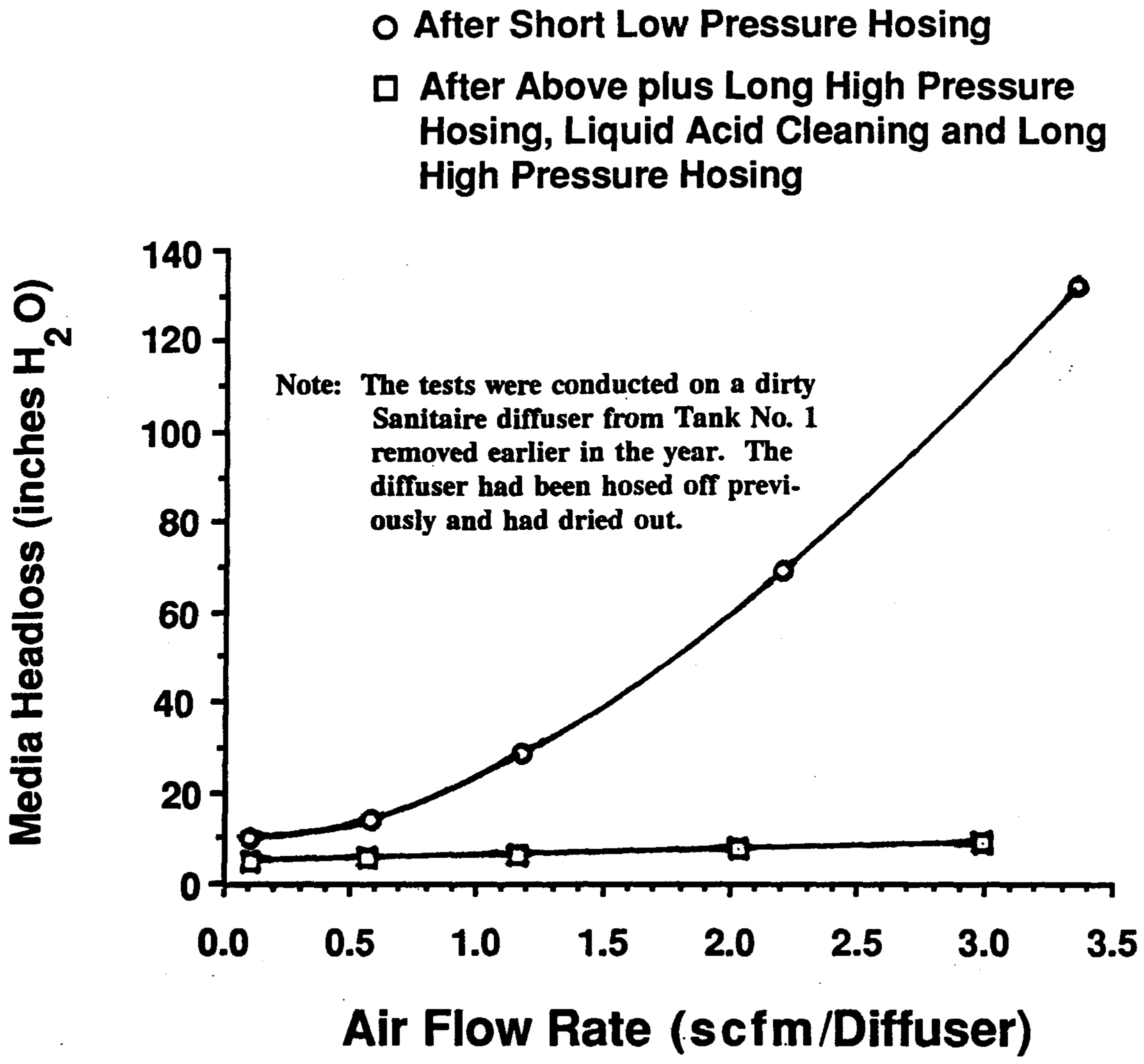
It is interesting to note the apparent effectiveness of short low pressure hosing during this study. The Districts have had previous experience with this technique on heavily slimed diffusers that were not really plugged in the sense of high headloss operation. In these cases, the hosing removed the thick slime buildup completely, but made only a small change in the diffuser headloss (several inches of H_2O or so). All this leads to the conclusion that it is not the thick slime itself that causes a headloss problem. The plugging is more likely due to material embedded in the upper pores of the diffuser media. This material is possibly some byproduct of the slime. In any case, when it is present, short low pressure hosing can be effective in reducing media headloss.

Figure 37 shows the results of testing with the liquid acid cleaning procedure in conjunction with long high pressure hosing (Milwaukee Method). These tests were conducted on a diffuser which had been removed from Tank 1 earlier in the year. The diffuser had been hosed off at low pressure at the time and was inadvertently allowed to dry out fully. The test results show, as would be expected from the other acid cleaning tests, that the diffuser was restored to new diffuser headloss levels.

To further understand the nature of the plugging at Whittier Narrows, a test was conducted to determine the proportion of total media headloss that was due to top surface and bottom surface fouling, respectively. To accomplish this, a diffuser stone removed from Grid 3 in Tank 1 was set upside down in a plate of acid solution to a depth approximately 1/2 the thickness of the stone. After 15 minutes, the stone's top surface was rinsed in a bucket of water, followed by long low pressure hosing.

The ensuing tests on the cleaned diffuser showed that the media headloss was restored to almost new diffuser levels. Since the premise of this test was that only the top portion of the diffuser stone was exposed to the acid, the results indicate that the great majority of the fouling took place near the diffuser's top surface. This has been corroborated by visual observation after cracking a dirty diffuser stone, which indicated plugging in the top 1/16-inch of the diffuser media.

The liquid acid cleaning procedure, in all its variations (hosing pressure and duration, acid contact time, air acid surface agitation, etc.) cleaned the diffusers to headloss levels nearly equivalent to those of a new diffuser, even though some diffusers were much more fouled than others. It appears to be a very effective cleaning procedure if aeration tanks can be removed from service and drained. Table 25 shows the economics of the procedure as modified by the Districts.



Note: The tests were conducted on a dirty Sanitaire diffuser from Tank No. 1 removed earlier in the year. The diffuser had been hosed off previously and had dried out.

Figure 37. Effect of Liquid Acid Cleaning on Diffuser Media Headloss

Table 25
Economics of the Liquid Acid Cleaning Procedure Using the Modified Milwaukee Method[1]

Item	Description	Cost($)
Labor	3.5 men required for 1.5 days = 42 man-hrs. at $20/man-hr	840
Acid	Muriatic Acid	25
Air	For grids during hosing and air/acid agitation	50
Water (Effluent)	For hosing	10
Acid Spray Equipment	Portable, hand operated compressed air type	25
Additional Equipment	Nozzles, safety equipment, etc.	35
	Total cost for 2026 diffusers	985
	Unit cost (per diffuser)	0.49

1. The Modified Milwaukee Method as used here refers to:

   a. Short low pressure hosing for approximately 7.5 seconds per diffuser, both preceding and following the acid addition step.

   b. 50 mls of 50% muriatic acid solution applied for an average time of approximately 1 hour, followed by air/acid agitation for approximately 10 minutes.

   The economics apply to 2026 Sanitaire diffusers. The costs of acid spray and additional equipment have been capitalized to obtain approximate costs per cleaning.

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APPENDICES

These Appendices summarize the plant performance during the evaluation periods and describe the experimental and calculation procedures. Appendices A & B summarize the plant performance during the first and second phase of the tests, respectively. Appendix C describes the procedures for calculating oxygen demand and other parameters. Appendix D describes the clean water oxygen transfer test protocol. The clean water tests conducted during this project predate the ASCE standard (1984); consequently there are small differences in procedures. Appendix E describes the off-gas testing methodology. The gas analyzer used was patterned after the Redmon/Ewing analyzer but differed in several ways. The experimental procedures and data reduction techniques were slightly different than used in the more recent EPA/ASCE sponsored investigations. Appendix F describes other test procedures.

A. MONTHLY OPERATIONS RESULTS FOR PART 1.

This appendix summarizes the plant operating data during Part 1 of the project (August to December, 1981).

Table A-1 and Figure A-1 show the hydraulic flow rates through the plant. The average daily primary effluent flow rate, reported in MGD, was based upon the totalized propeller meter measurements of the plant's total final effluent flow. Additions were made to correct for waste sludge flow, skimmings flow, and waste backwash flow. The flow split among tanks was equalized by inlet gate flow calibration and the hydraulic profile.

The plant's average daily return sludge flow rate was based upon the totalized measurements of the propeller meter located in the main return sludge flow line. During Part 1 of the project, the return sludge flow to each tank was based on the plant return sludge flow and the relative indications of return sludge flow from the propeller meters for each tank.

The average daily waste sludge flow rate and skimmings flow rate was based upon totalized propeller flow meter readings. The average waste backwash flow rate was determined from estimates of the waste backwash flow from the backwash recovery tank. During other times it was based upon totalized propeller flow meter measurements of the entire filter backwash flow.

Table A-2 and Figure A-2 show the "centroidal mixed liquor aeration time." The centroid of loading concept is a District parameter used to determine an effective aeration time during step feed operation. The centroid of loading was assumed to be the average, flow-weighted inlet point of primary effluent flow into the aeration tank. The centroidal mixed liquor aeration time (V/Q basis) was calculated by dividing the aeration tank volume downstream of the centroid by the total primary effluent flow. During Part 1 of the project, the plant was operated in a conventional mode, so that the centroid of loading was at the front of each aeration tank. Recycle flow rate was included in the aeration time calculations on a V/(Q+R) basis.

Table A-3 and Figure A-3 show the biological loading parameters on a plant basis. In general these parameters were calculated according to standard engineering practice, but the following additional points are relevant. Mean cell residence time was calculated using total system solids. The solids mass in the secondary clarifiers was calculated from the product of the mixed-liquor suspended solids concentration entering the clarifiers and the clarifier volume. Daily net growth took into account the storage of solids in the plant in an effort to more accurately determine actual microbial growth. F/M was calculated using applied COD on both an aeration system and total system solids basis.

Table A-4 and Figure A-4 show the F/M ratio and volumetric loading rate for each aeration system. The volumetric loading rate was calculated using the applied COD and the entire aeration tank volume.

Table A-5 and Figure A-5 show the daily average air flows to each aeration system. During Part 1 of the project, direct measurement of daily average air flows was not possible for each aeration system. Instead these flows were estimated as follows: Instantaneous air flow readings were taken on each aeration system usually twice each day. Totalized air flow readings were taken on the disk system once each day. The ratio of totalized to instantaneous flow for the disk system was used to determine the totalized flows for the other systems based on their instantaneous readings. Daily average zone flows were determined from the daily average system flows in the same proportion as occurred during the instantaneous readings.

The instantaneous system air flows for the disk system were determined from the sum of the three downcomer flows. The instantaneous system air flows for the tube and jet systems were determined from their respective air header flows. It should be mentioned that the totalized readings for the disk system were taken on the air header meter. These readings were adjusted slightly before use to compensate for the differences in flow between the header meter and the sum of the three tank downcomer meters.

Table A-6 and Figure A-6 show the air flow per diffuser. These were calculated from the daily average flow rates and the total number of diffusers. In a similar fashion the daily average flow rate per unit of tank surface area, shown in Table A-7 and Figure A-7, were calculated. Table A-8 and Figure A-8 show the daily average air usage per unit of flow and per unit of COD removed.

Tables A-9 through A-11 show the average morning DO and air flow profiles along the tank length for each aeration system, respectively. The air flow-weighted average DO for each system profile is also shown. The air flow-weighted DO was calculated by multiplying each DO by its respective air flow rate and dividing by the tank air flow rate. Figure A-9 shows the morning air flow weighted DO results for each system. Similarly, the average afternoon DO profile results are shown in Tables A-12 through A-14 and Figure A-10.

It was not possible to measure the average tank DO concentrations over a 24 hour basis. Table A-15 shows the estimates of the daily average DO in each system along with the minimum and maximum in each tank. The daily average DO was estimated from the relative DO concentrations in each tank, and assuming that the overall plant DO for all three tanks was approximately 0.65 mg/L. The minimum and maximum DO concentrations were read from the plant's strip chart recordings of DO concentrations.

Tables A-16 through A-18 show the power utilization for each aeration system. The power consumption was estimated according to the procedures described in Appendix D. Table A-19 and Figure A-11; and Table A-20 and Figure A-12 show the delivered and wire power by zone, respectively.

Tables A-21 through A-23 and Figures A-13 and A-14 show the aeration efficiency results for each aeration system. These were calculated using the oxygen uptake procedures shown in Appendix C. The actual oxygen transfer efficiency (AOTE) was determined by dividing the oxygen transfer rate (calculated uptake rate plus measured DO requirement) by the oxygen supply rate (1.034 times the average air flow rate, in scfm) and multiplying by 100.

Table A-24 and Figure A-15 show the secondary clarifier operating parameters. The parameters were determined in accordance with standard engineering practice.

Table A-25 shows the plant's performance over Part 1. The results are for the entire plant and are not reported by aeration system. The parameters were determined in accordance with standard engineering practice and the following comments. The COD conversion efficiency is obtained by subtracting the effluent soluble COD from the primary effluent total COD, then dividing by the primary effluent COD, with the result expressed as a percent. The nitrification efficiency was calculated by dividing the total keldjal nitrogen (TKN) converted by nitrification by the TKN available for conversion (less the synthesis requirements of the heterotrophs).

Tables A-26 through A-31 and Figures A-16 through A-22 show plant performance and miscellaneous laboratory results. The laboratory data collection and analysis techniques were in accordance with *Standard Methods* (1980).

Table A-32 and Figure A-23 and A-24 show the instances of polymer addition to the final tanks, alum addition to the filters, and blower shutdowns.

TABLE A-1. HYDRAULIC FLOWS

Test Period	Average Daily Primary Effluent Flow (MGD)				Average Daily Return Sludge Flow (MGD) (% Recycle In Parentheses)				Average Daily Waste Sludge Flow	Average Daily Skimmings Flow	Average Waste Backwash Flow*
(1981)	Disk System	Tube System	Jet System	Total Plant	Disk System	Tube System	Jet System	Total Plant	(MGD)	(MGD)	(MGD)
August	4.10	3.99	3.05	11.14	1.23(30.0)	0.92(23.1)	0.51(16.7)	2.66(23.9)	0.204	0.184	0.116
September	4.11	4.00	3.06	11.17	1.23(29.9)	0.79(19.8)	0.48(15.7)	2.50(22.4)	0.203	0.294	0.116
October	4.21	4.09	3.13	11.43	1.09(25.9)	1.04(25.4)	0.45(14.4)	2.58(22.6)	0.198	0.402	0.116
November	4.27	4.15	3.18	11.59	1.11(26.0)	1.10(26.5)	0.44(13.8)	2.65(22.8)	0.200	0.394	0.116
December	4.13	4.01	3.07	11.21	1.19(28.8)	1.20(29.9)	0.52(16.9)	2.90(26.0)	0.199	0.419	0.116
Period Average	4.16	4.05	3.10	11.31	1.17(28.1)	1.01(25.0)	0.48(15.5)	2.66(23.6)	0.201	0.339	0.116

* Estimated backwash flow going to the sewer.

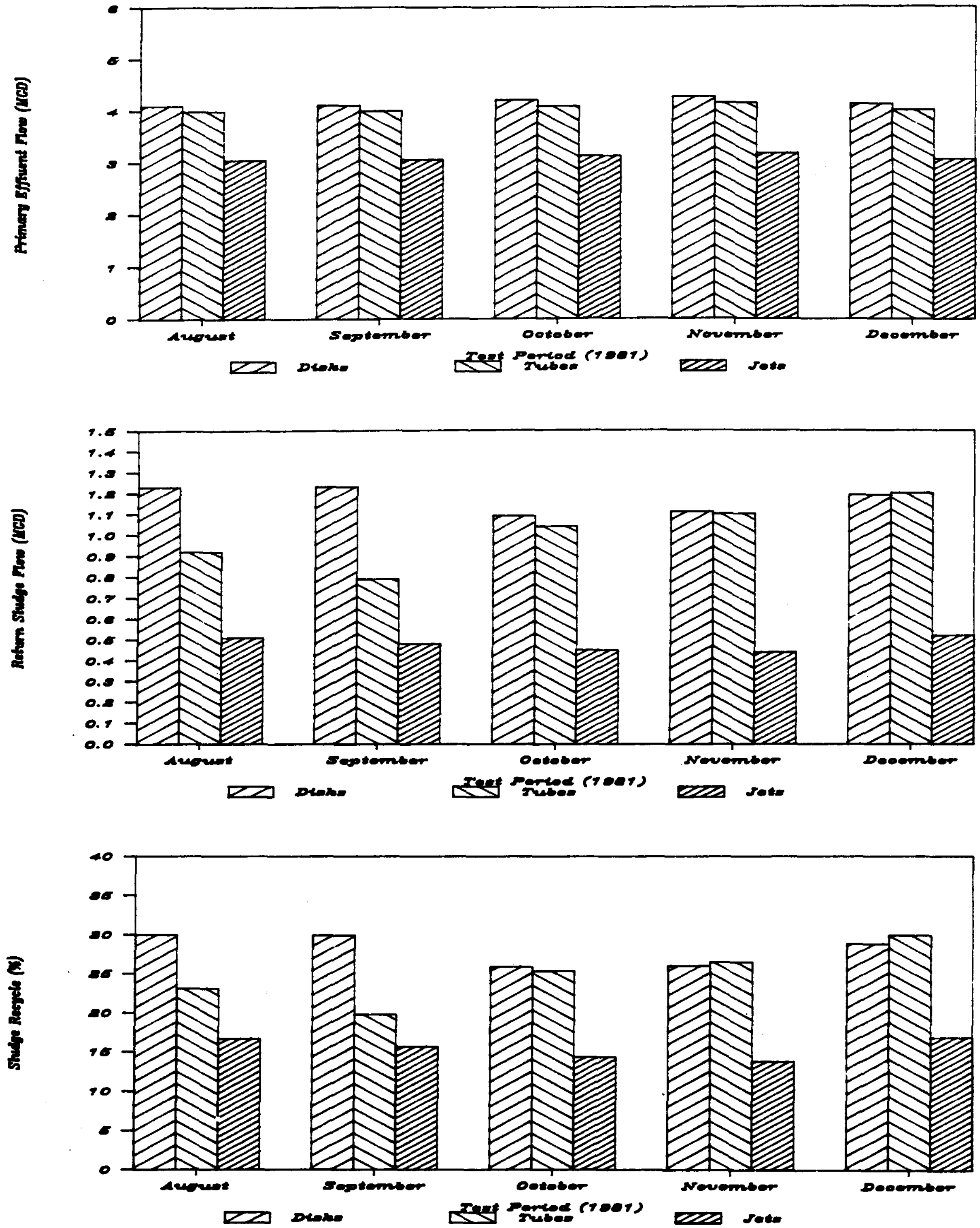


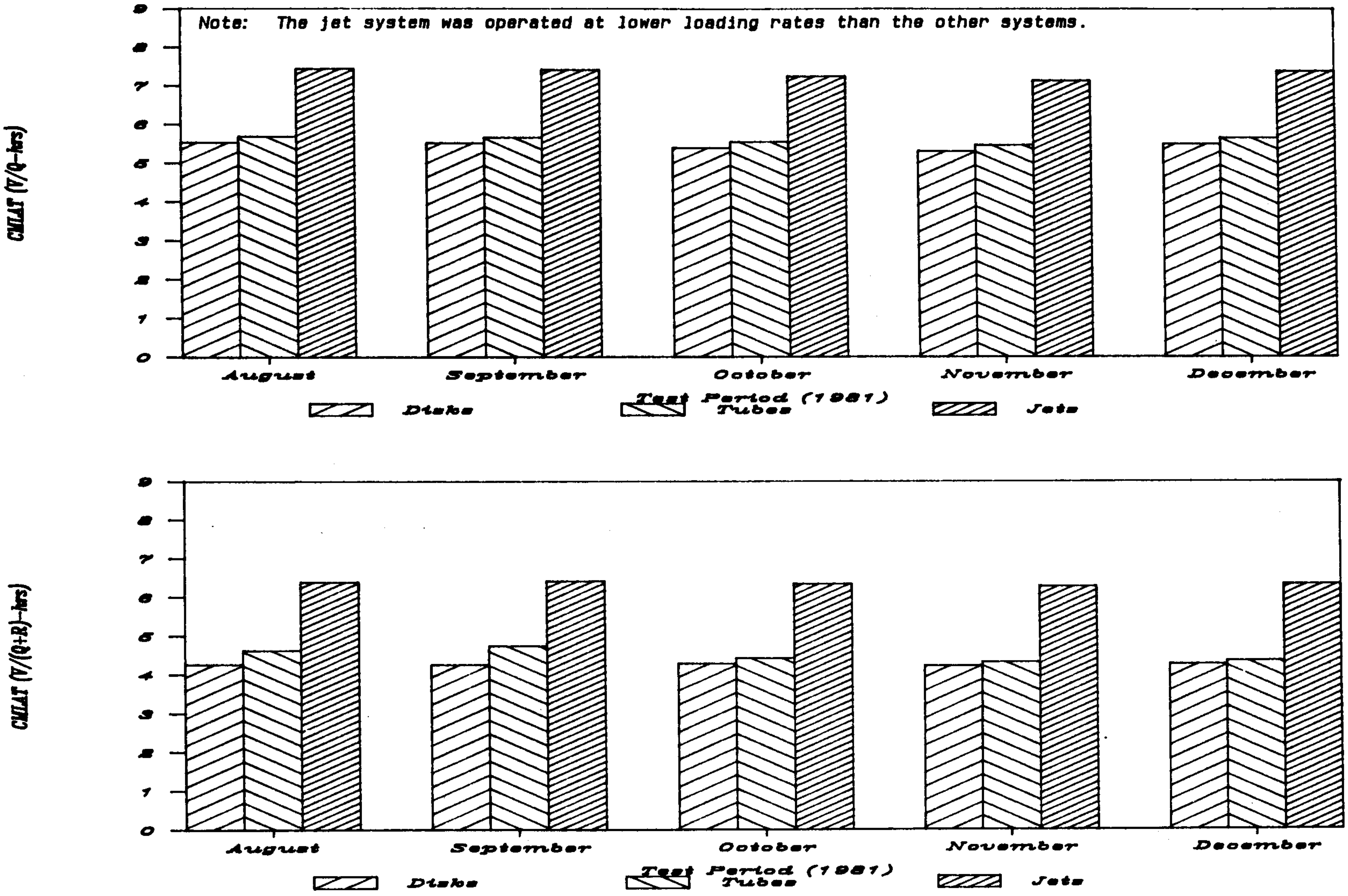
Figure A-1. Daily Average Hydraulic Flows

TABLE A-2. CENTROIDAL MIXED LIQUOR AERATION TIME

Test Period	Centroidal Mixed Liquor Aeration Time (V/Q-hrs)*				Centroidal Mixed Liquor Aeration Time (V/(Q+R)-hrs)+			
(1981)	Disk System	Tube System	Jet System	Total Plant	Disk System	Tube System	Jet System	Total Plant
August	5.54	5.70	7.45	6.12	4.27	4.63	6.39	4.94
September	5.53	5.68	7.43	6.11	4.26	4.75	6.42	4.99
October	5.40	5.56	7.26	5.97	4.29	4.43	6.35	4.87
November	5.32	5.48	7.15	5.88	4.23	4.33	6.28	4.79
December	5.50	5.67	7.40	6.08	4.27	4.36	6.33	4.83
Period Average	5.46	5.62	7.34	6.03	4.26	4.50	6.35	4.88

* The aeration time calculated with the primary effluent flow and the centroid of loading.

+ The aeration time calculated with the primary effluent and return sludge flows and the centroid of loading.



Note: The jet system was operated at lower loading rates than the other systems.

Figure A-2. Centroidal Mixed Liquor Aeration Time (CMLAT) Based on V/Q and V/(Q+R)

TABLE A-3. BIOLOGICAL LOADING PARAMETERS - PLANT BASIS

Test Period (1981)	Total Aeration System Volatile Suspended Solids (lbs)	Total Secondary Clarifier Volatile Suspended Solids# (lbs)	Total Plant Volatile Suspended Solids+ (lbs)	Waste Flow Volatile Suspended Solids (lbs)	Skimmings Flow Volatile Suspended Solids (lbs)	Secondary Flow Volatile Suspended Solids (lbs)	Daily Net Growth		Food To Microorganism Ratio (F/M)*		Mean Cell Residence Time (MCRT)^ (days)
							$\left(\frac{\text{lbs VSS}}{\text{day}}\right)$	$\left(\frac{\text{lbs VSS}}{\text{lb COD}}\right)$	$\left(\frac{\text{lbs COD}}{\text{lb TPVSS-day}}\right)$	$\left(\frac{\text{lbs COD}}{\text{lb ASVSS-day}}\right)$	
August	22523	8773	31295	7797	208	263	8193	0.426	0.68	0.94	3.79
September	21268	8278	29547	8239	331	260	8572	0.436	0.73	1.02	3.35
October	23880	9367	33247	9018	465	339	10272	0.479	0.71	0.99	3.38
November	22478	8839	31317	8454	452	409	9399	0.440	0.75	1.05	3.36
December	24336	9534	33870	8173	485	465	8924	0.413	0.70	0.98	3.71
Period Average	22910	8963	31874	8336	388	347	9073	0.439	0.72	0.99	3.52

Estimated.
+ Aeration system plus secondary clarifiers.
* Ratios on a BOD basis can be approximated by multiplying the COD basis numbers by 0.54.
^ On a total system solids basis.

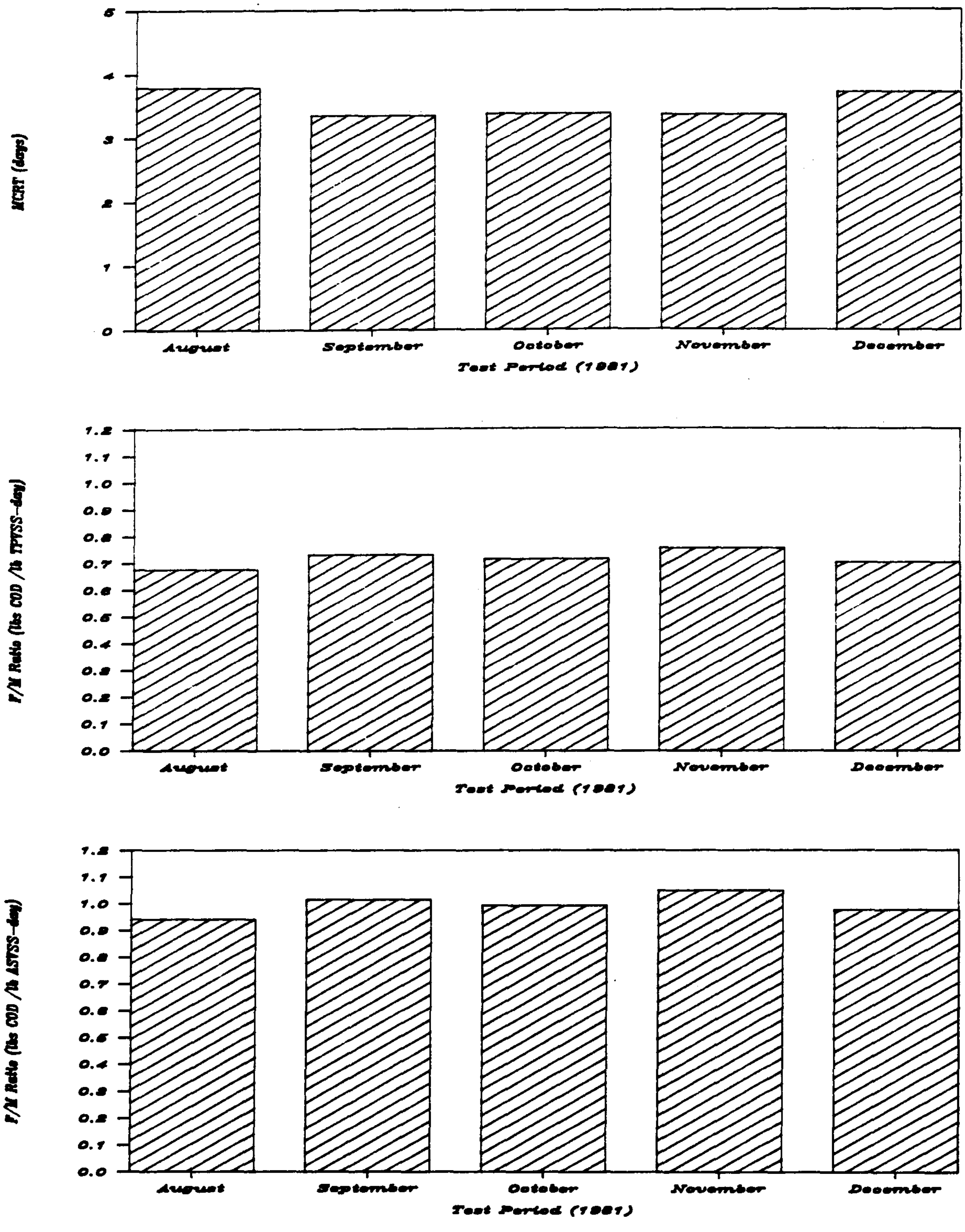
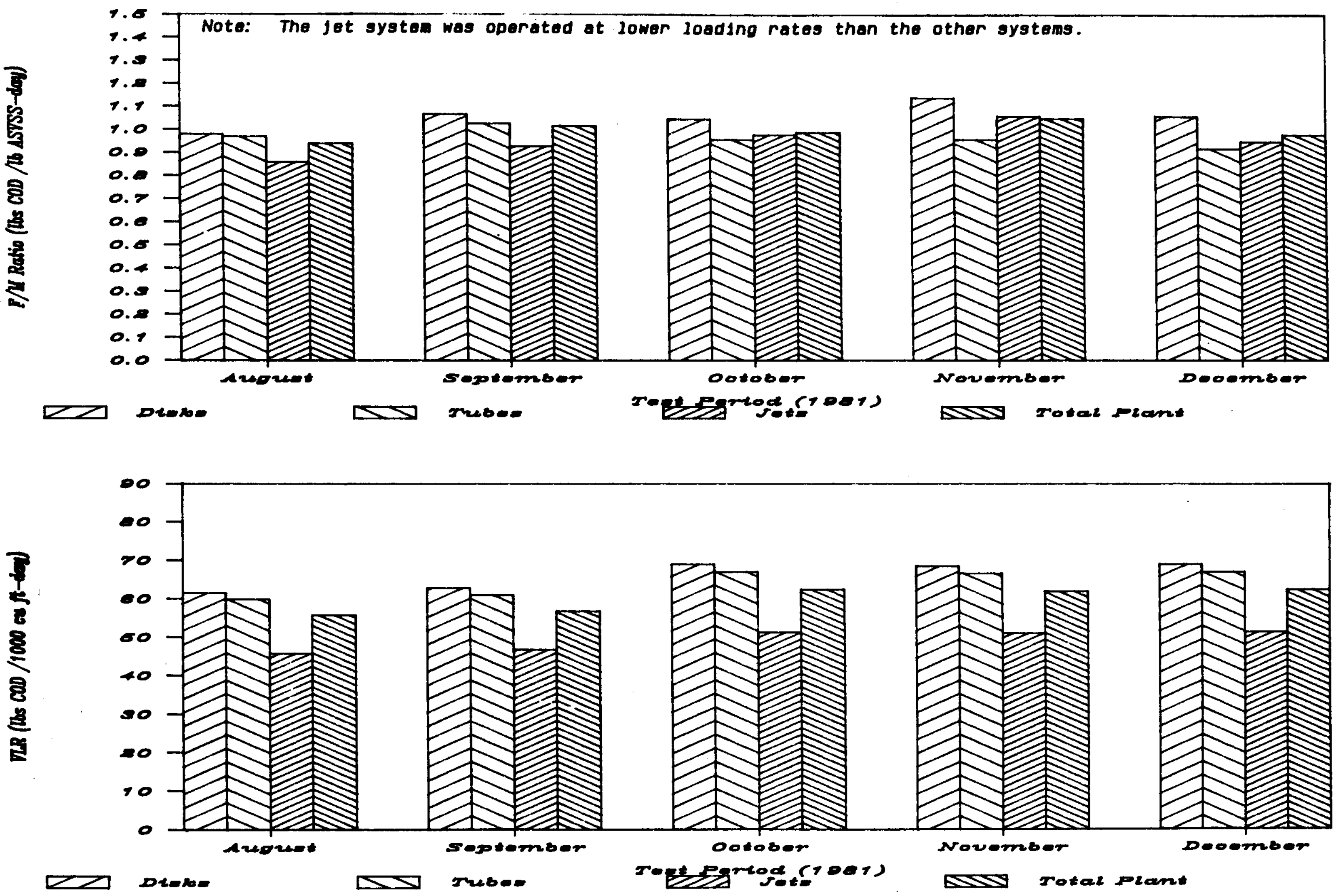


Figure A-3. Mean Cell Residence Time (MCRT) And Food To Microorganism Ratio (F/M) Based On Total Plant (TP) And Total Aeration System (AS) Solids

TABLE A-4. BIOLOGICAL AND VOLUMETRIC LOADING PARAMETERS - SYSTEM BASIS*

Test Period	Food To Microorganism Ratio (F/M) (lbs COD /lb ASVSS-day)				Volumetric Loading Rate (lbs COD /1000 cu ft-day)			
(1981)	Disk System	Tube System	Jet System	Total Plant	Disk System	Tube System	Jet System	Total Plant
August	0.98	0.97	0.86	0.94	61.6	59.9	45.8	55.8
September	1.07	1.03	0.93	1.02	62.8	61.1	46.8	56.9
October	1.05	0.96	0.98	0.99	69.0	67.1	51.3	62.5
November	1.14	0.96	1.06	1.05	68.6	66.7	51.1	62.1
December	1.06	0.92	0.95	0.98	69.1	67.1	51.4	62.5
Period Average	1.06	0.97	0.95	1.00	66.2	64.4	49.3	60.0

* The results on a BOD basis can be approximated by multiplying the COD basis numbers by 0.54.



Note: The jet system was operated at lower loading rates than the other systems.

Figure A-4. Food to Microorganism Ratio (F/M) Based on Aeration System Solids (AS) And Volumetric Loading Rate (VLR)

TABLE A-5. DAILY AVERAGE AIR FLOW

Test Period	Daily Average Air Flow (scfm)											
	Disk System				Tube System				Jet System*			
(1981)	Zone 1	Zone 2	Zone 3	Total Tank	Zone 1	Zone 2	Zone 3	Total Tank	Zone 1	Zone 2	Zone 3	Total Tank
August	714	617	455	1786	918	990	566	2474	897	651	306	1854
September	772	694	482	1948	981	1012	578	2570	851	631	279	1761
October	857	782	543	2181	1032	1018	582	2632	833	625	260	1719
November	928	866	599	2393	1104	1034	591	2729	817	616	280	1712
December	950	866	613	2428	1178	979	559	2715	829	630	265	1724
Period Average	844	765	538	2147	1042	1006	575	2624	846	630	278	1754

* The jet system loading rates and aeration zones were different than those for the other systems.

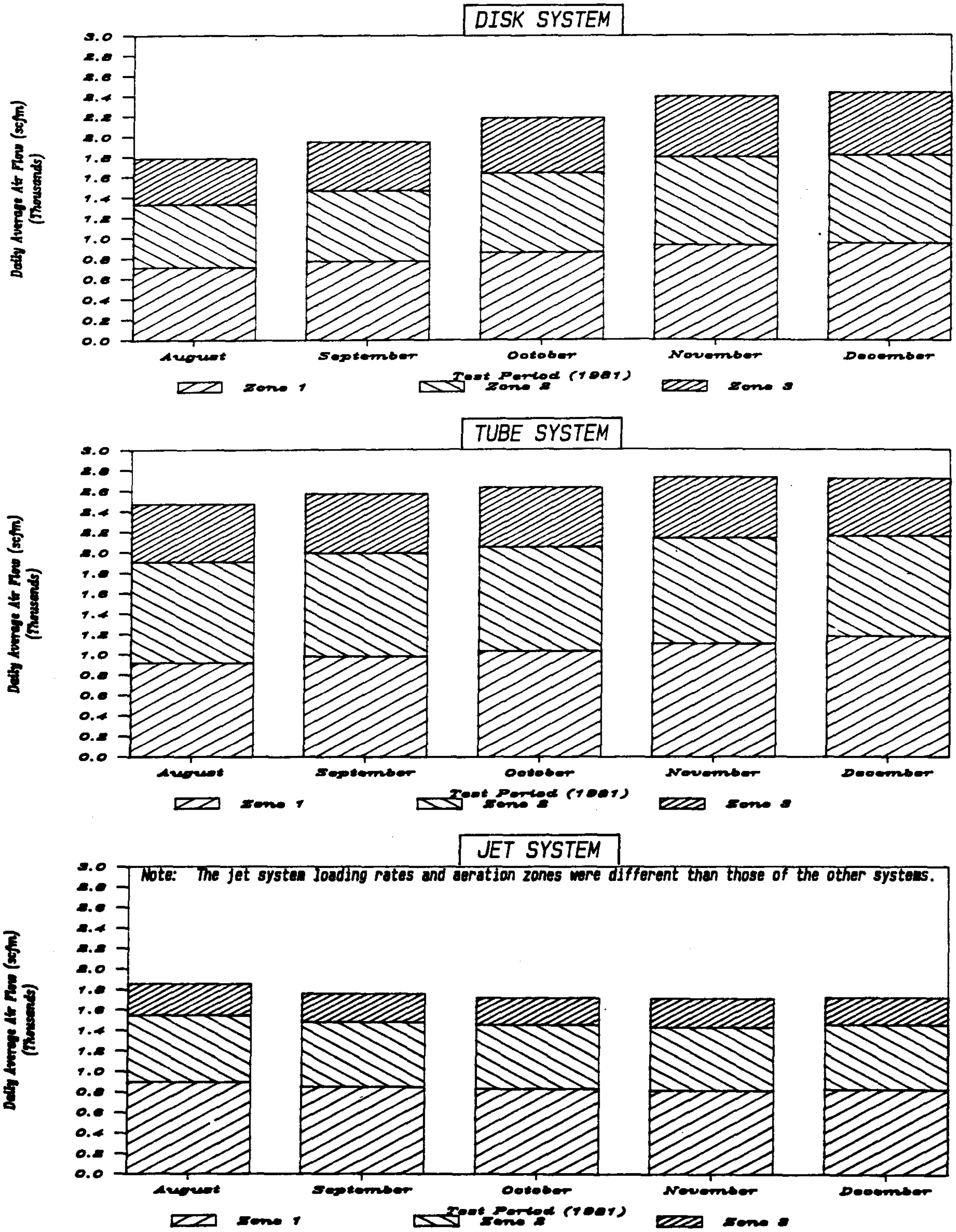
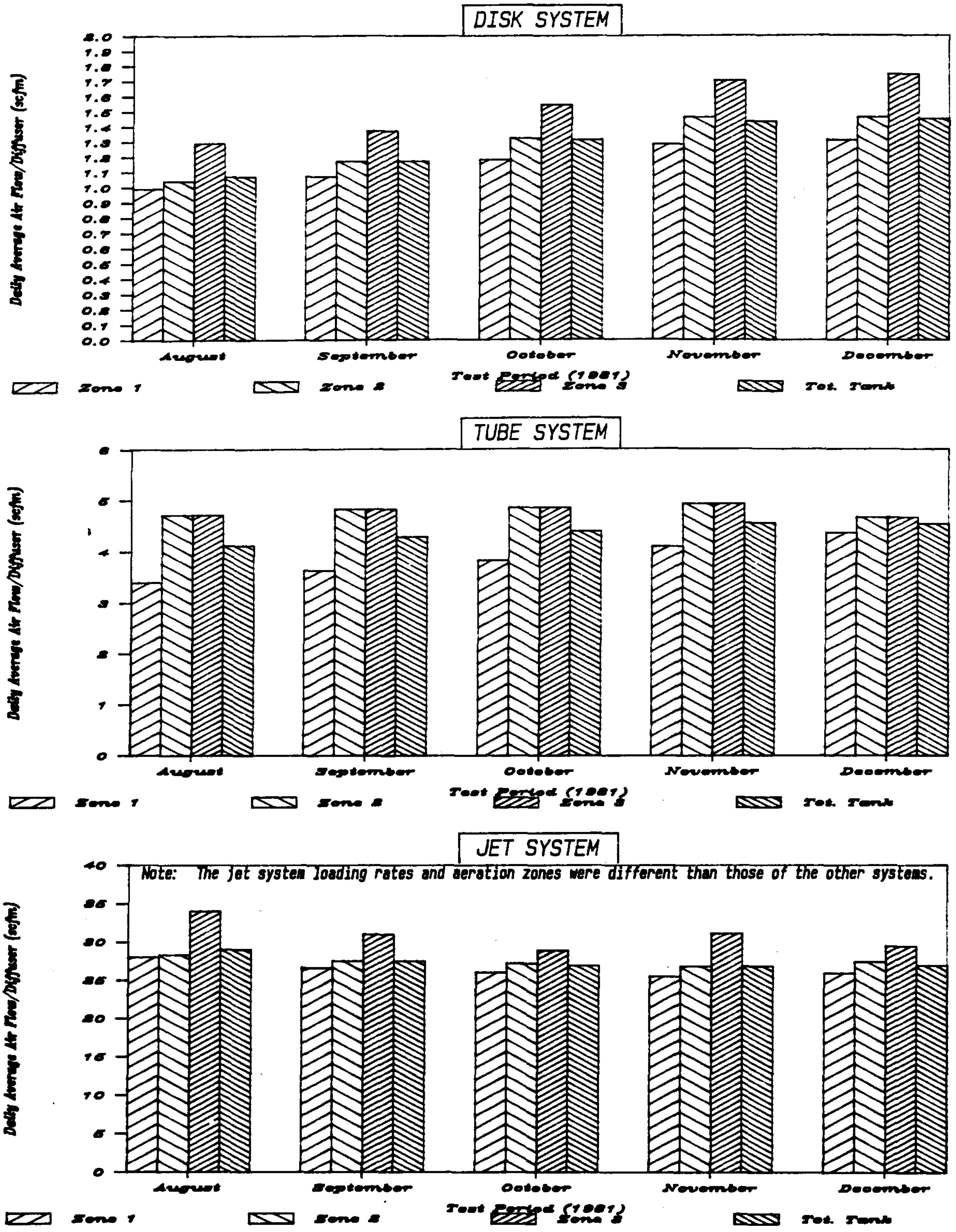


Figure A-5. Daily Average Air Flow

TABLE A-6. DAILY AVERAGE AIR FLOW/DIFFUSER

Test Period	Daily Average Air Flow/Diffuser (scfm)											
	Disk System				Tube System				Jet System*			
(1981)	Zone 1	Zone 2	Zone 3	Total Tank	Zone 1	Zone 2	Zone 3	Total Tank	Zone 1	Zone 2	Zone 3	Total Tank
August	0.99	1.04	1.29	1.07	3.40	4.72	4.72	4.12	28.00	28.30	34.00	29.00
September	1.07	1.17	1.37	1.17	3.63	4.82	4.82	4.28	26.60	27.50	31.00	27.50
October	1.18	1.32	1.54	1.31	3.82	4.85	4.85	4.39	26.00	27.20	28.90	26.90
November	1.28	1.46	1.70	1.43	4.09	4.92	4.92	4.55	25.50	26.80	31.10	26.80
December	1.31	1.46	1.74	1.45	4.36	4.66	4.66	4.53	25.90	27.40	29.40	26.90
Period Average	1.17	1.29	1.53	1.29	3.86	4.79	4.79	4.37	26.40	27.44	30.88	27.42

* The jet system loading rates and aeration zones were different than those for the other systems.



Note: The jet system loading rates and aeration zones were different than those of the other systems.

Figure A-6. Daily Average Air Flow/Diffuser

TABLE A-7. DAILY AVERAGE AIR FLOW/TANK SURFACE AREA

Test Period	Daily Average Air Flow/Tank Surface Area (scfm/sq ft)											
	Disk System				Tube System				Jet System*			
(1981)	Zone 1	Zone 2	Zone 3	Total Tank	Zone 1	Zone 2	Zone 3	Total Tank	Zone 1	Zone 2	Zone 3	Total Tank
August	0.238	0.206	0.152	0.198	0.306	0.330	0.189	0.275	0.247	0.173	0.190	0.206
September	0.257	0.231	0.161	0.216	0.327	0.337	0.193	0.286	0.234	0.168	0.173	0.196
October	0.286	0.261	0.181	0.242	0.344	0.339	0.194	0.292	0.229	0.166	0.162	0.191
November	0.309	0.289	0.200	0.266	0.368	0.345	0.197	0.303	0.225	0.164	0.174	0.190
December	0.317	0.289	0.204	0.270	0.393	0.326	0.186	0.302	0.228	0.168	0.165	0.192
Period Average	0.281	0.255	0.180	0.238	0.348	0.335	0.192	0.292	0.233	0.168	0.173	0.195

* The jet system loading rates and aeration zones were different than those for the other systems.

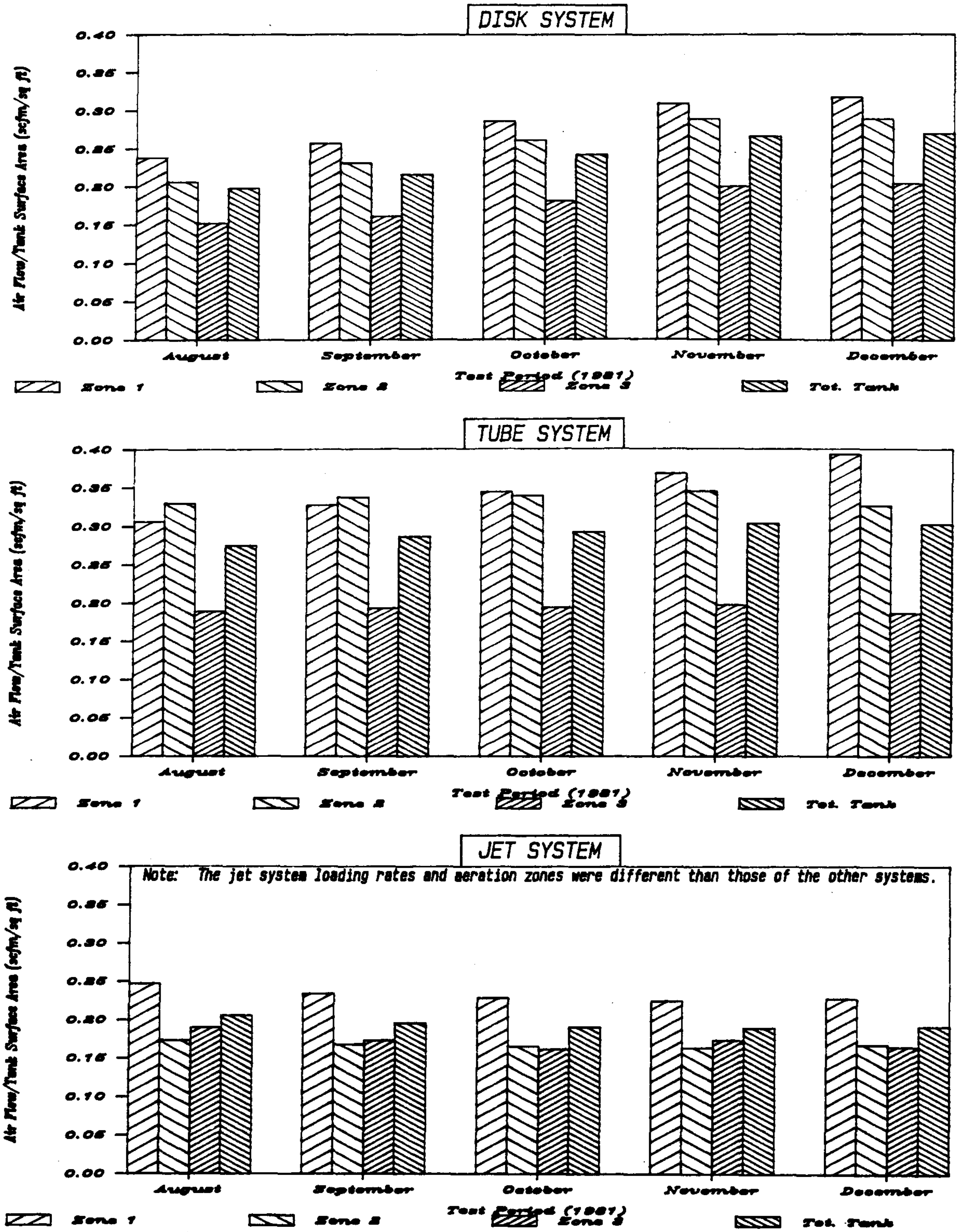


Figure A-7. Daily Average Air Flow/Tank Surface Area

TABLE A-8. DAILY AVERAGE AIR USAGE

Test Period (1981)	Daily Average Air Usage Per Feed Volume (scf/gal)			Daily Average Air Usage Per COD Removed (scf/lb)		
	Disk System	Tube System	Jet System*	Disk System	Tube System	Jet System*
August	0.627	0.893	0.875	363	517	507
September	0.682	0.925	0.829	388	526	471
October	0.746	0.927	0.791	398	494	421
November	0.807	0.947	0.775	438	514	421
December	0.847	0.975	0.809	440	506	420
Period Average	0.742	0.933	0.816	405	511	448

* The jet aeration system was operated at lower loading rates than the disk and tube systems.

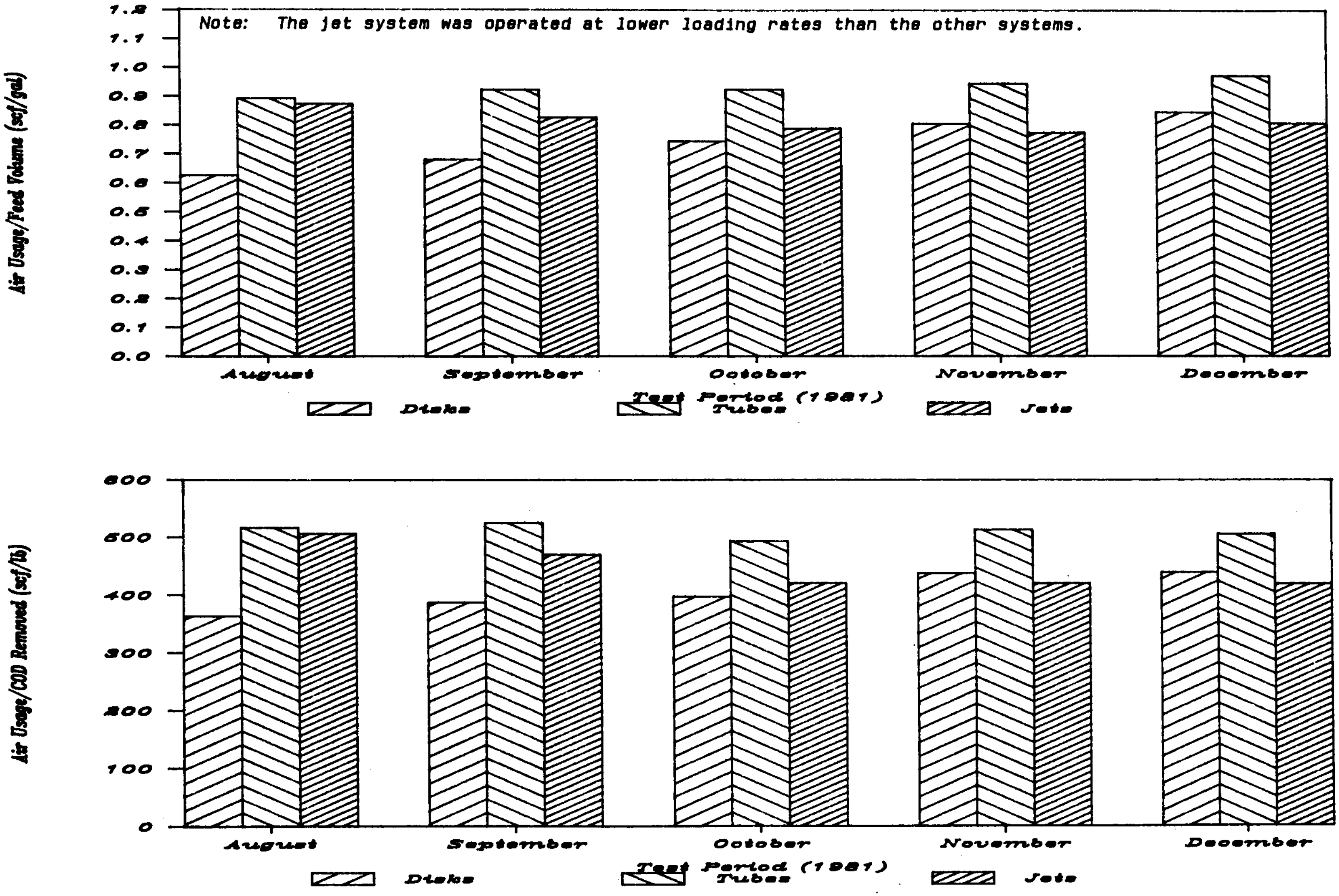

Note: The jet system was operated at lower loading rates than the other systems.

Figure A-8. Daily Average Air Usage

TABLE A-9. MORNING DO PROFILE RESULTS - DISK SYSTEM

Test Period (1981)	Number of Profiles	DO Concentration (mg/l)						Air Flow (scfm)			
		Position 1#	Position 2+	Position 3*	Position 4^	Position 5!	Weighted Average<	Zone 1	Zone 2	Zone 3	Total Tank
August	10	0.30	1.24	2.28	1.83	1.32	1.59	772	687	492	1951
September	8	0.29	1.00	1.44	1.13	0.85	1.07	766	693	490	1949
October	12	0.17	0.96	2.11	1.99	1.76	1.50	919	840	582	2340
November	5	0.36	0.98	2.14	1.92	1.78	1.53	925	864	600	2388
December	5	0.23	1.43	2.54	2.56	2.36	1.93	963	884	626	2473
Period Average	40(Tot.)	0.27	1.12	2.11	1.89	1.62	1.53	869	794	558	2221

Front of aeration tank (Grid 1).
+ 75 ft from front of aeration tank (Grid 1).
* 150 ft from front of aeration tank (Grid 2).
^ 225 ft from front of aeration tank (Grid 3).
! End of aeration tank (Grid 3).
< Air flow weighted average.

TABLE A-10. MORNING DO PROFILE RESULTS - TUBE SYSTEM

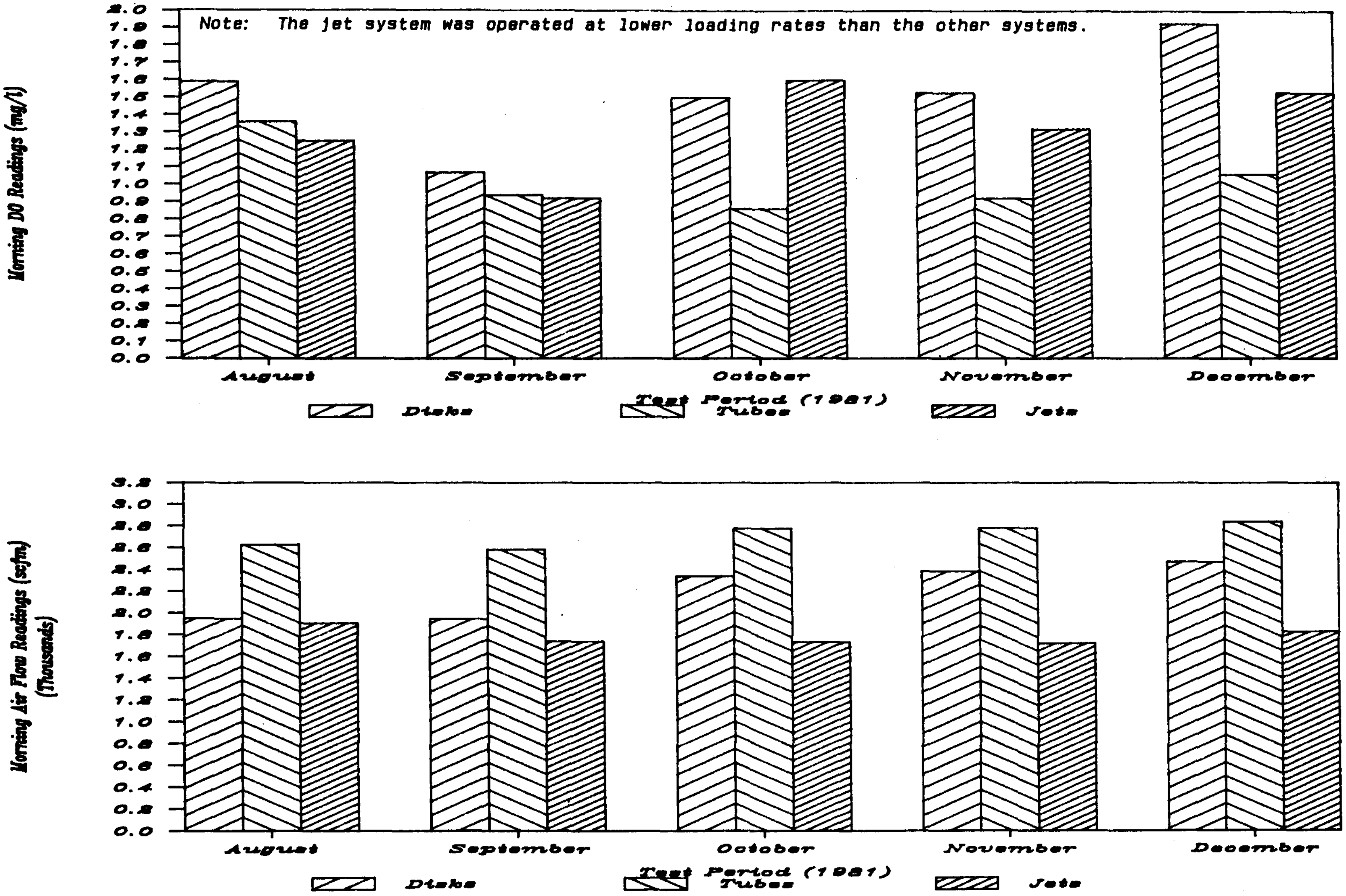
Test Period (1981)	Number of Profiles	DO Concentration (mg/l) Position 1#	Position 2+	Position 3~	Position 4^	Position 5!	Weighted Average<	Air Flow (scfm) Zone 1	Zone 2	Zone 3	Total Tank
August	10	0.14	1.10	1.96	1.41	1.04	1.36	992	1042	595	2628
September	8	0.08	0.90	1.23	1.00	0.85	0.94	942	1046	597	2585
October	12	0.07	0.27	0.94	1.74	2.05	0.86	1070	1088	622	2779
November	5	0.06	0.32	1.08	1.86	2.12	0.92	1099	1073	613	2784
December	5	0.57	0.42	1.10	2.26	2.37	1.06	1259	1007	575	2841
Period Average	40 (Tot.)	0.19	0.60	1.26	1.66	1.69	1.03	1073	1051	600	2724

\# Front of aeration tank (Grid 1).
\+ 75 ft from front of aeration tank (Grid 1).
~ 150 ft from front of aeration tank (Grid 2).
^ 225 ft from front of aeration tank (Grid 3).
! End of aeration tank (Grid 3).
< Air flow weighted average.

TABLE A-11. MORNING DO PROFILE RESULTS - JET SYSTEM

Test Period (1981)	Number of Profiles	DO Concentration (mg/l)						Air Flow (scfm) >			
		Position 1#	Position 2+	Position 3~	Position 4^	Position 5!	Weighted Average<	Zone 1	Zone 2	Zone 3	Total Tank
August	10	0.36	1.01	1.97	1.32	1.39	1.25	929	667	313	1908
September	8	0.32	0.79	1.45	0.92	0.92	0.92	838	628	276	1742
October	12	0.21	1.07	2.48	2.09	2.05	1.60	822	639	275	1736
November	5	0.16	0.81	2.10	1.81	1.81	1.32	822	619	283	1724
December	5	0.27	1.10	2.31	1.91	2.02	1.53	869	691	268	1828
Period Average	40 (Tot.)	0.26	0.96	2.07	1.61	1.64	1.33	856	649	283	1788

Front of aeration tank (Grid 1).
+ 75 ft from front of aeration tank (Grid 1).
~ 150 ft from front of aeration tank (Grid 2).
^ 225 ft from front of aeration tank (Grid 3).
! End of aeration tank (Grid 3).
< Air flow weighted average.
> The jet system loading rates and aeration zones were different than those for the other systems.



Note: The jet system was operated at lower loading rates than the other systems.

Figure A-9. Morning DO Profile Results

TABLE A-12. AFTERNOON DO PROFILE RESULTS - DISK SYSTEM

Test Period (1981)	Number of Profiles	DO Concentration (mg/l) Position 1#	DO Concentration (mg/l) Position 2+	DO Concentration (mg/l) Position 3~	DO Concentration (mg/l) Position 4^	DO Concentration (mg/l) Position 5!	DO Concentration (mg/l) Weighted Average<	Air Flow (scfm) Zone 1	Air Flow (scfm) Zone 2	Air Flow (scfm) Zone 3	Air Flow (scfm) Total Tank
August	8	0.26	0.33	0.40	0.45	0.59	0.38	725	639	462	1826
September	4	0.08	0.06	0.20	0.30	0.51	0.19	746	681	479	1906
October	12	0.11	0.10	0.32	0.97	1.54	0.44	909	837	577	2323
November	4	0.27	0.41	0.68	0.86	1.94	0.69	912	847	600	2359
December	6	0.21	0.52	0.95	1.55	2.13	0.94	934	854	605	2393
Period Average	34(Tot.)	0.19	0.28	0.51	0.83	1.34	0.53	845	772	545	2162

Front of aeration tank (Grid 1).
+ 75 ft from front of aeration tank (Grid 1).
~ 150 ft from front of aeration tank (Grid 2).
^ 225 ft from front of aeration tank (Grid 3).
! End of aeration tank (Grid 3).
< Air flow weighted average.

TABLE A-13. AFTERNOON DO PROFILE RESULTS - TUBE SYSTEM

Test Period (1981)	Number of Profiles	DO Concentration (mg/l) Position 1#	Position 2+	Position 3*	Position 4^	Position 5!	Weighted Average<	Air Flow (scfm) Zone 1	Zone 2	Zone 3	Total Tank
August	8	0.14	0.28	0.37	0.48	0.42	0.34	909	963	550	2422
September	4	0.03	0.12	0.22	0.29	0.34	0.19	936	960	548	2444
October	12	0.03	0.06	0.13	0.61	1.22	0.25	1035	1063	608	2706
November	4	0.05	0.10	0.38	0.85	1.02	0.37	1123	975	557	2656
December	6	0.12	0.15	0.35	1.09	1.24	0.41	1236	962	550	2748
Period Average	34 (Tot.)	0.07	0.14	0.29	0.67	0.85	0.31	1048	985	563	2596

Front of aeration tank (Grid 1).
+ 75 ft from front of aeration tank (Grid 1).
* 150 ft from front of aeration tank (Grid 2).
^ 225 ft from front of aeration tank (Grid 3).
! End of aeration tank (Grid 3).
< Air flow weighted average.

TABLE A-14. AFTERNOON DO PROFILE RESULTS - JET SYSTEM

Test Period (1981)	Number of Profiles	DO Concentration (mg/l)						Air Flow (scfm)>			
		Position 1#	Position 2+	Position 3*	Position 4^	Position 5!	Weighted Average<	Zone 1	Zone 2	Zone 3	Total Tank
August	8	0.19	0.30	0.70	0.74	0.90	0.52	867	638	290	1795
September	4	0.05	0.18	0.63	0.67	0.86	0.43	803	611	272	1686
October	12	0.08	0.16	0.65	1.18	1.58	0.61	798	613	274	1685
November	4	0.09	0.27	0.67	1.11	1.36	0.61	840	622	253	1715
December	6	0.08	0.24	0.97	1.19	1.58	0.69	885	664	255	1804
Period Average	34 (Tot.)	0.10	0.23	0.72	0.98	1.26	0.57	839	630	269	1738

Front of aeration tank (Grid 1).
+ 75 ft from front of aeration tank (Grid 1).
* 150 ft from front of aeration tank (Grid 2).
^ 225 ft from front of aeration tank (Grid 3).
! End of aeration tank (Grid 3).
< Air flow weighted average.
> The jet system loading rates and aeration zones were different than those for the other systems.

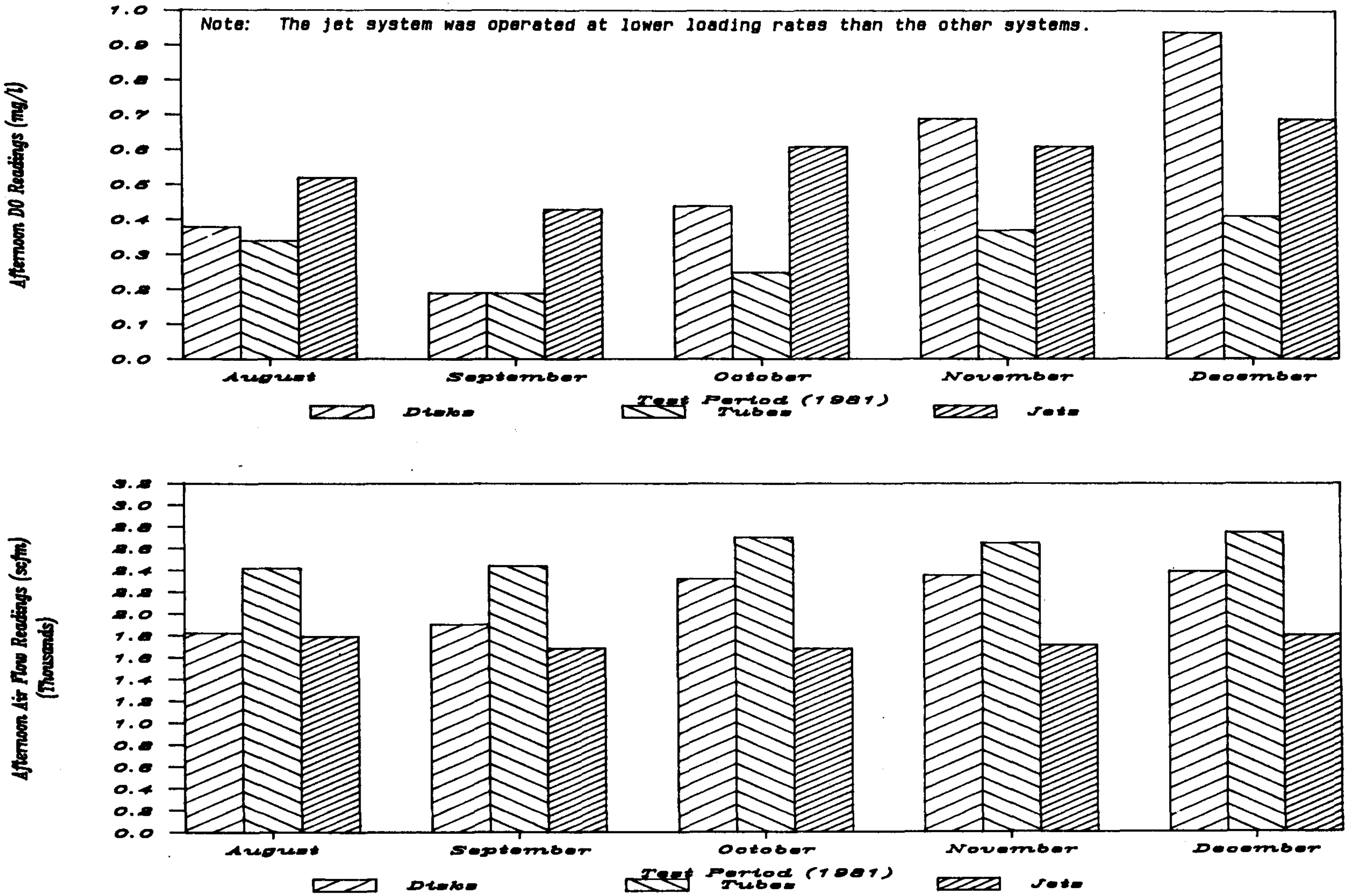


Figure A-10. Afternoon DO Profile Results

TABLE A-15. ESTIMATED DAILY AVERAGE DO LEVELS AND MIN/MAX EXIT DO LEVELS

Test Period	Estimated Daily Average DO Level[*] (mg/l)			Minimum Exit DO Level[+] (mg/l)			Maximum Exit DO Level[+] (mg/l)		
(1981)	Disk System	Tube System	Jet System	Disk System	Tube System	Jet System	Disk System	Tube System	Jet System
August	0.7	0.6	0.7	0.2	0.1	0.6	1.7	1.4	2.1
September	0.4	0.4	0.5	0.2	0.2	0.5	1.8	2.1	1.9
October	0.7	0.4	0.8	0.2	0.2	0.6	2.6	2.6	2.4
November	0.9	0.5	0.8	0.2	0.2	0.6	2.9	3.5	2.3
December	1.1	0.6	0.9	0.5	0.2	0.8	3.3	2.8	2.5
Period Average	0.7	0.5	0.7	0.3	0.2	0.6	2.5	2.5	2.2

[*] It was not possible to make 24 hr average measurements of total tank DO concentration. The rough estimates shown are based on an assumed total plant mode average DO of 0.65 mg/l. The relative DO levels by tank and month were estimated from existing DO profile information.

[+] From chart recordings of DO concentration at the effluent end of the aeration tanks.

TABLE A-16. OVERALL POWER UTILIZATION - DISK SYSTEM

Test Period (1981)	Total Tank Air Flow (scfm)	Average Air Flow Per Diffuser (scfm)	Estimated Total Diffuser Headloss (in. wc)	Blower Delivered Power* (hp)	Blower Wire Power+ (hp)
August	1786	1.07	8.3	42.6	69.6
September	1948	1.17	8.8	46.6	76.1
October	2181	1.31	9.9	52.4	85.7
November	2393	1.43	11.4	58.0	94.7
December	2428	1.45	11.6	58.9	96.2
Period Average	2147	1.29	10.0	51.7	84.4

* Using the adiabatic compression formula.

\+ Using the adiabatic compression formula and an overall blower/coupling /motor efficiency of 0.612.

TABLE A-17. OVERALL POWER UTILIZATION - TUBE SYSTEM

Test Period (1981)	Total Tank Air Flow (scfm)	Average Air Flow Per Diffuser (scfm)	Estimated Total Diffuser Headloss (in. wc)	Blower Delivered Power* (hp)	Blower Wire Power+ (hp)
August	2474	4.12	18.3	62.0	101.4
September	2570	4.28	18.7	64.6	105.5
October	2632	4.39	18.9	66.2	108.1
November	2729	4.55	19.0	68.7	112.2
December	2715	4.53	19.0	68.3	111.6
Period Average	2624	4.37	18.8	66.0	107.7

* Using the adiabatic compression formula.

+ Using the adiabatic compression formula and an overall blower/coupling /motor efficiency of 0.612.

TABLE A-18. OVERALL POWER UTILIZATION - JET SYSTEM#

	Blower Power					Pump Power					Total Power	
Test Period (1981)	Total Tank Air Flow (scfm)	Average Air Flow Per Diffuser (scfm)	Estimated Total Diffuser Headloss (in. wc)	Blower Delivered Power+ (hp)	Blower Wire Power* (hp)	Total Mixed Liquor Recirculation Flow^ (gpm)	Average Mixed Liquor Flow Per Nozzle^ (gpm)	Pump Total Dynamic Head! (ft)	Pump Delivered Power< (hp)	Pump Wire Power^ (hp)	Total Delivered Power> (hp)	Total Wire Power (hp)
August	1854	29.00	1.7	44.5	72.8	5168	80.8	17.2	22.4	31.2	67.0 (0.664)	104.0
September	1761	27.50	1.3	42.2	69.0	5170	80.8	17.2	22.4	31.2	64.7 (0.652)	100.2
October	1719	26.90	1.1	41.2	67.3	5170	80.8	17.2	22.4	31.2	63.6 (0.648)	98.4
November	1712	26.80	1.1	41.0	67.0	5171	80.8	17.2	22.4	31.2	63.4 (0.647)	98.2
December	1724	26.90	1.2	41.3	67.5	5170	80.8	17.2	22.4	31.2	63.7 (0.648)	98.7
Period Average	1754	27.42	1.3	42.0	68.7	5170	80.8	17.2	22.4	31.2	64.5 (0.651)	99.9

The jet system loading rates and aeration zones were different than those of the other systems.
+ Using the adiabatic compression formula.
* Using the adiabatic compression formula and an overall blower/coupling/motor efficiency of 0.612.
^ Based on certified pump performance curves and TDH measurements.
! Based on measurements.
< Using the theoretical pump power draw formula.
> The ratio of blower delivered power to total delivered power is shown in parentheses.

TABLE A-19. DELIVERED AERATION POWER DENSITY BY ZONE

Test Period	Delivered Aeration Power Density (hp/1000 cu ft)*											
	Disk System				Tube System				Jet System+			
(1981)	Zone 1	Zone 2	Zone 3	Total Tank	Zone 1	Zone 2	Zone 3	Total Tank	Zone 1	Zone 2	Zone 3	Total Tank
August	0.401	0.349	0.259	0.336	0.541	0.591	0.338	0.490	0.645	0.547	0.423	0.531
September	0.434	0.394	0.275	0.368	0.581	0.604	0.345	0.510	0.622	0.536	0.406	0.512
October	0.482	0.449	0.311	0.414	0.613	0.608	0.347	0.523	0.613	0.532	0.396	0.504
November	0.525	0.503	0.346	0.458	0.656	0.617	0.353	0.542	0.605	0.527	0.403	0.503
December	0.538	0.502	0.354	0.465	0.701	0.584	0.333	0.539	0.611	0.535	0.400	0.505
Period Average	0.476	0.439	0.309	0.408	0.618	0.601	0.343	0.521	0.619	0.535	0.406	0.511

* Based on power determinations using the adiabatic compression formula.

\+ The jet system loading rates and aeration zones were different than those of the disk and tube systems.

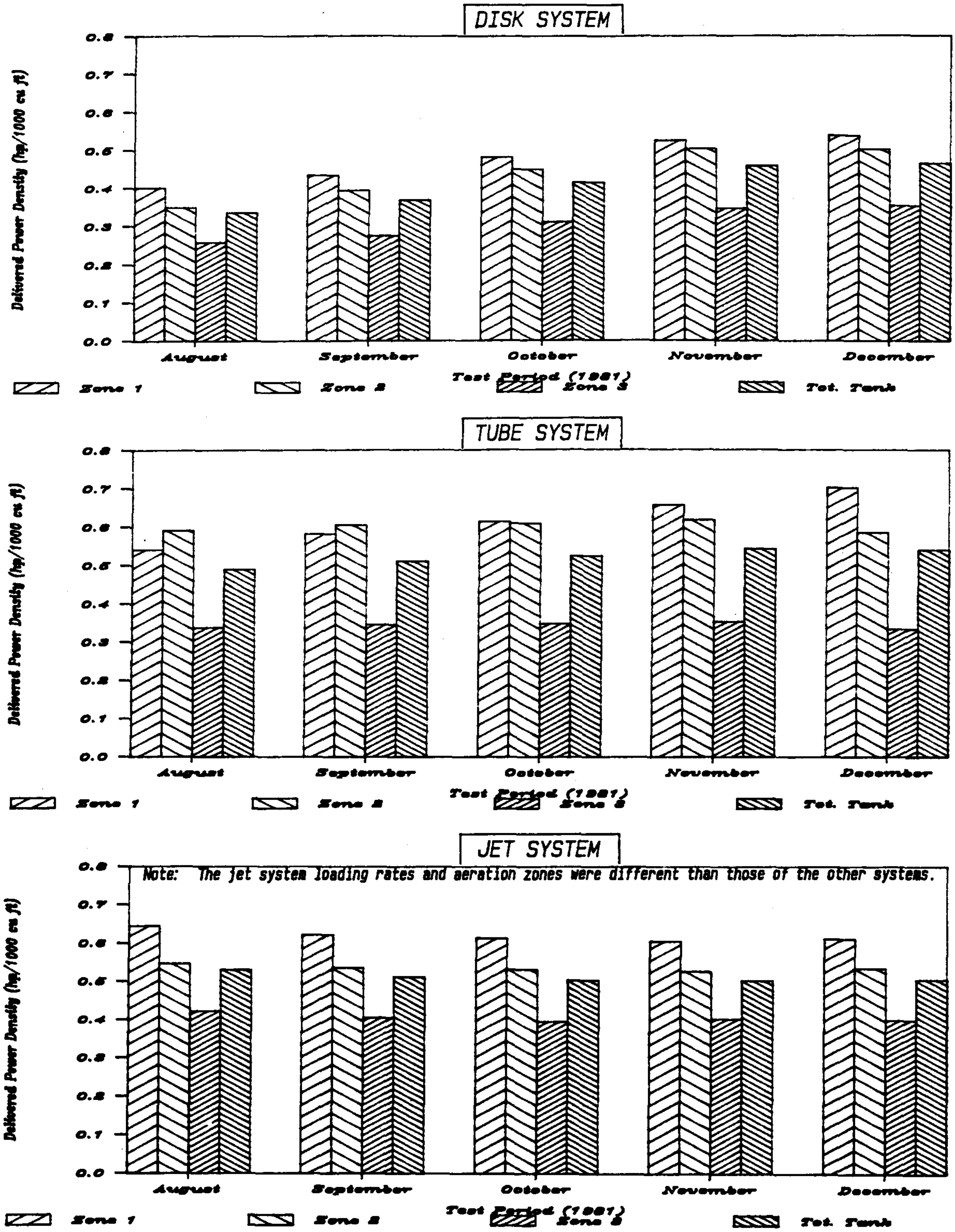


Figure A-11. Delivered Aeration Power Density

TABLE A-20. WIRE POWER UTILIZATION BY ZONE

Test Period	Wire Power Utilization (hp)*											
	Disk System				Tube System				Jet System+			
(1981)	Zone 1	Zone 2	Zone 3	Total Tank	Zone 1	Zone 2	Zone 3	Total Tank	Zone 1	Zone 2	Zone 3	Total Tank
August	27.6	24.1	17.9	69.6	37.3	40.8	23.3	101.4	51.2	15.8	36.9	104.0
September	29.9	27.2	18.9	76.1	40.1	41.7	23.8	105.5	49.3	15.5	35.4	100.2
October	33.2	30.9	21.5	85.7	42.3	41.9	24.0	108.1	48.6	15.4	34.5	98.4
November	36.2	34.7	23.9	94.7	45.3	42.6	24.3	112.2	47.9	15.2	35.0	98.2
December	37.1	34.6	24.4	96.2	48.4	40.3	23.0	111.6	48.4	15.5	34.8	98.7
Period Average	32.8	30.3	21.3	84.4	42.7	41.5	23.7	107.7	49.1	15.5	35.3	99.9

* Based on blower power determinations using the adiabatic compression formula and an overall efficiency of 0.612.
+ The jet system loading rates and aeration zones were different than those of the disk and tube systems.

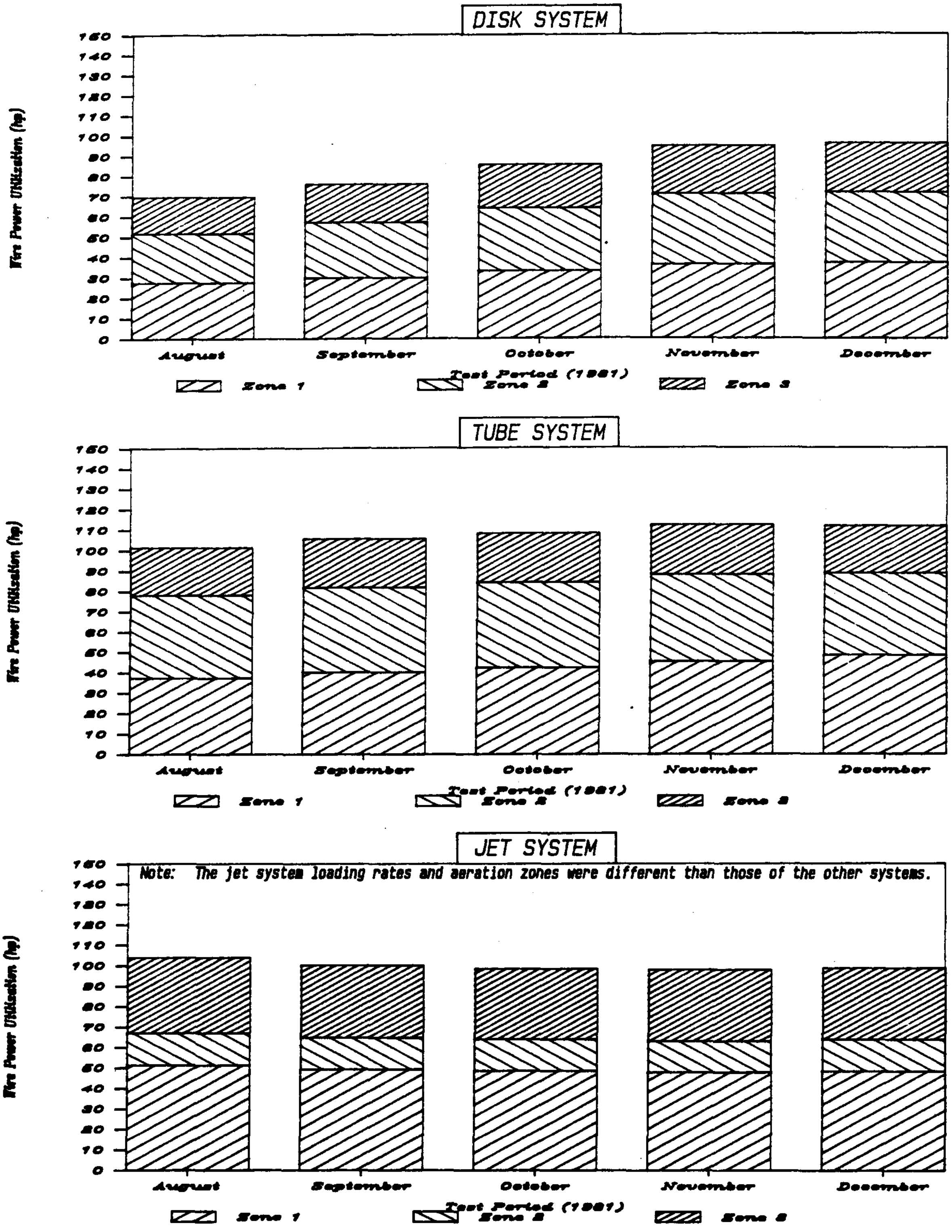


Figure A-12. Aeration System Wire Power Utilization

TABLE A-21. AERATION EFFICIENCY RESULTS - DISK SYSTEM*

Test Period (1981)	Estimated Oxygen Uptake Rate+ (lbs/day)	Estimated Mixed Liquor Temperature~ (deg. F)	Daily Average Air Flow Per Diffuser (scfm)	Total Delivered Power Density^ $\left(\frac{\text{hp}}{\text{1000 cu ft}}\right)$	Estimated Daily Average DO Level! (mg/l)	Oxygen Transfer Efficiency (%)		Delivered Aeration Efficiency^ (lbs O_2/hp-hr)		Wire Aeration Efficiency> (lbs O_2/hp-hr)	
						Actual (AOTE)	Standard< (αFSOTE)	Actual (ADAE)	Standard< (αFSDAE)	Actual (AWAE)	Standard< (αFSWAE)
August	2837	80	1.07	0.336	0.7	6.39	6.74	2.78	2.93	1.70	1.79
September	2731	81	1.17	0.368	0.4	5.64	5.76	2.44	2.50	1.50	1.53
October	2670	78	1.31	0.414	0.7	4.92	5.21	2.12	2.25	1.30	1.37
November	2930	75	1.43	0.458	0.9	4.92	5.34	2.11	2.28	1.29	1.40
December	3170	72	1.45	0.465	1.1	5.25	5.90	2.24	2.52	1.37	1.54
Period Average	2868	77	1.29	0.408	0.7	5.43	5.79	2.34	2.50	1.43	1.53

* The oxygen transfer rates on which these efficiencies were based were determined from kinetic calculations, rather than by direct measurement. As a result, the efficiencies shown should only be considered approximate.

\+ From kinetic calculations.

~ Approximated by morning final effluent temperature readings.

^ Based on power determinations using the adiabatic compression formula.

! Rough estimates only. See Table A-14.

< Based on standard conditions of 68 degrees F, 14.70 psia and 0 mg/l DO.

\> Based on power determinations using the adiabatic compression formula and an overall blower/coupling/motor efficiency of 0.612.

TABLE A-22. AERATION EFFICIENCY RESULTS - TUBE SYSTEM#

Test Period	Estimated Oxygen Uptake Rate+	Estimated Mixed Liquor Temperature*	Daily Average Air Flow Per Diffuser	Total Delivered Power Density^	Estimated Daily Average DO Level!	Oxygen Transfer Efficiency (%)		Delivered Aeration Efficiency^ (lbs O_2/hp-hr)		Wire Aeration Efficiency> (lbs O_2/hp-hr)	
(1981)	(lbs/day)	(deg. F)	(scfm)	$\left(\frac{\text{hp}}{\text{1000 cu ft}}\right)$	(mg/l)	Actual (AOTE)	Standard< (αFSOTE)	Actual (ADAE)	Standard< (αFSDAE)	Actual (AWAE)	Standard< (αFSWAE)
August	2728	80	4	0.49	0.580	4.4	4.64	1.83	1.92	1.12	1.17
September	2580	81	4	0.51	0.370	4.0	4.11	1.66	1.70	1.02	1.04
October	2712	78	4	0.52	0.390	4.1	4.25	1.71	1.75	1.04	1.07
November	2996	75	5	0.54	0.490	4.4	4.60	1.82	1.89	1.11	1.16
December	3249	72	5	0.54	0.550	4.8	5.08	1.98	2.09	1.21	1.28
Period Average	2854	77	4	0.52	0.477	4.4	4.54	1.80	1.87	1.10	1.14

The oxygen transfer rates on which these efficiencies were based were determined from kinetic calculations, rather than by direct measurement. As a result, the efficiencies shown should only be considered approximate.

+ From kinetic calculations.

* Approximated by morning final effluent temperature readings.

^ Based on power determinations using the adiabatic compression formula.

! Rough estimates only. See Table A-14.

< Based on standard conditions of 68 degrees F, 14.70 psia and 0 mg/l DO.

> Based on power determinations using the adiabatic compression formula and an overall blower/coupling/motor efficiency of 0.612.

TABLE A-23. AERATION EFFICIENCY RESULTS - JET SYSTEM#

Test Period	Estimated Oxygen Uptake Rate+	Estimated Mixed Liquor Temperature*	Daily Average Air Flow Per Diffuser	Daily Average Mixed Liquor Flow Per Nozzle^	Total Delivered Power Density!	Estimated Daily Average DO Level<	Oxygen Transfer Efficiency (%)		Delivered Aeration Efficiency! (lbs O_2/hp-hr)		Wire Aeration Efficiency@ (lbs O_2/hp-hr)	
(1981)	(lbs/day)	(deg. F)	(scfm)	(gpm)	$\left(\frac{hp}{1000\ cu\ ft}\right)$	(mg/l)	Actual (AOTE)	Standard> (αFSOTE)	Actual (ADAE)	Standard> (αFSDAE)	Actual (AWAE)	Standard> (αFSWAE)
August	2120	80	29.00	80.8	0.531	0.7	4.60	4.85	1.32	1.39	0.85	0.90
September	2017	81	27.50	80.8	0.512	0.5	4.61	4.77	1.30	1.35	0.84	0.87
October	1937	78	26.90	80.8	0.504	0.8	4.53	4.87	1.27	1.36	0.82	0.88
November	2199	75	26.80	80.8	0.503	0.8	5.17	5.53	1.44	1.55	0.93	1.00
December	2299	72	26.90	80.8	0.505	0.9	5.36	5.84	1.50	1.64	0.97	1.06
Period Average	2114	77	27.42	80.8	0.511	0.7	4.85	5.17	1.37	1.46	0.88	0.94

The transfer rates on which these efficiencies were based were determined from kinetic calculations, rather than by direct measurement. As a result, the efficiencies shown should only be considered approximate. It should also be noted that the jet system was operated at lower loading rates than the other systems.

+ From kinetic calculations.

* Approximated by morning final effluent temperature readings.

^ Based on certified pump performance curves and TDH measurements.

! Based on power determinations using the adiabatic compression formula.

< Rough estimates only. See Table A-14.

> Based on standard conditions of 68 degrees F, 14.70 psia and 0 mg/l DO.

@ Based on power determinations using the adiabatic compression formula and an overall blower/coupling/motor efficiency of 0.612, and pump power determinations from certified performance curves.

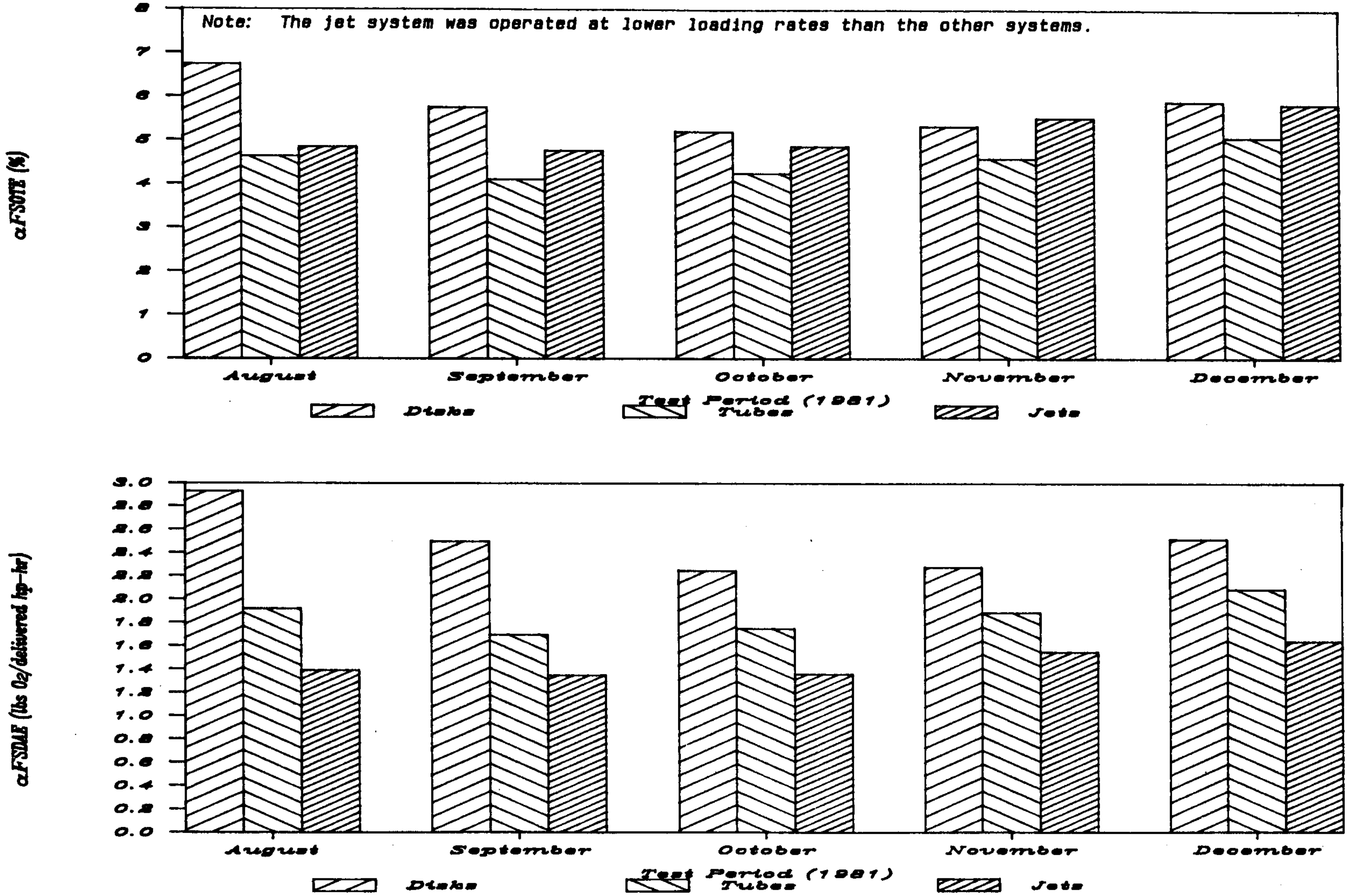


Figure A-13. Standard Oxygen Transfer Efficiency (αFSOTE) And Standard Delivered Aeration Efficiency (αFSDAE) Based On Kinetic Calculations of Oxygen Demand

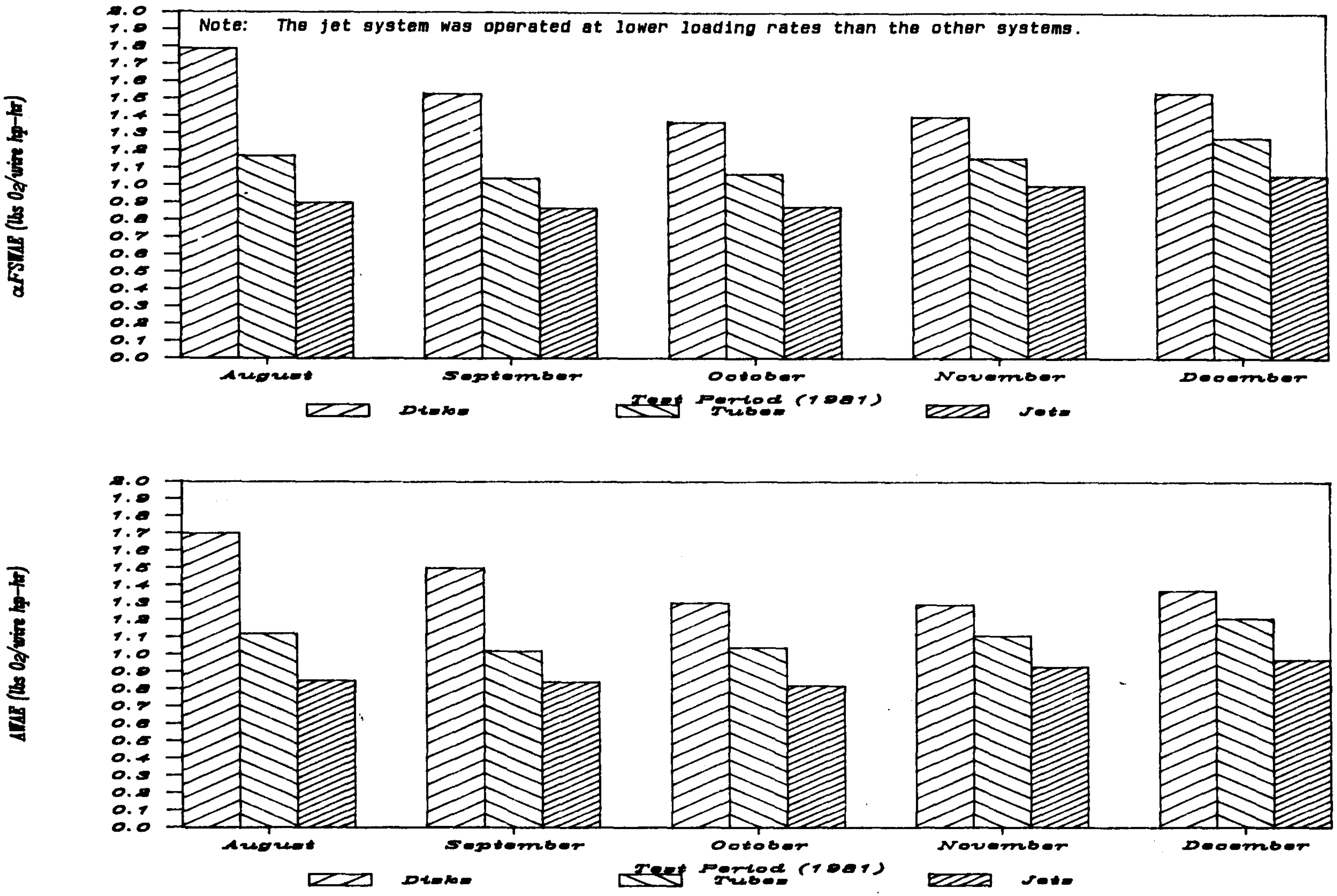

Note: The jet system was operated at lower loading rates than the other systems.

Figure A-14. Standard Wire Aeration Efficiency (αFSWAE) And Actual Wire Aeration Efficiency (AWAE) Based On Kinetic Calculations of Oxygen Demand

TABLE A-24. SECONDARY CLARIFIER PARAMETERS

Test Period (1981)	Clarifiers In Service (#)	Overflow Rate (gal/day / sq ft)	Detention Time (hrs)	Solids Loading Rate (lbs/day / sq ft)	Weir Overflow Rate (gal/day / ft)
August	5	717	1.93	10.3	11204
September	5	711	1.96	9.7	11121
October	5	722	1.93	11.0	11285
November	5	733	1.89	10.6	11468
December	5	706	1.92	11.2	11037
Period Average	5	718	1.93	10.6	11222

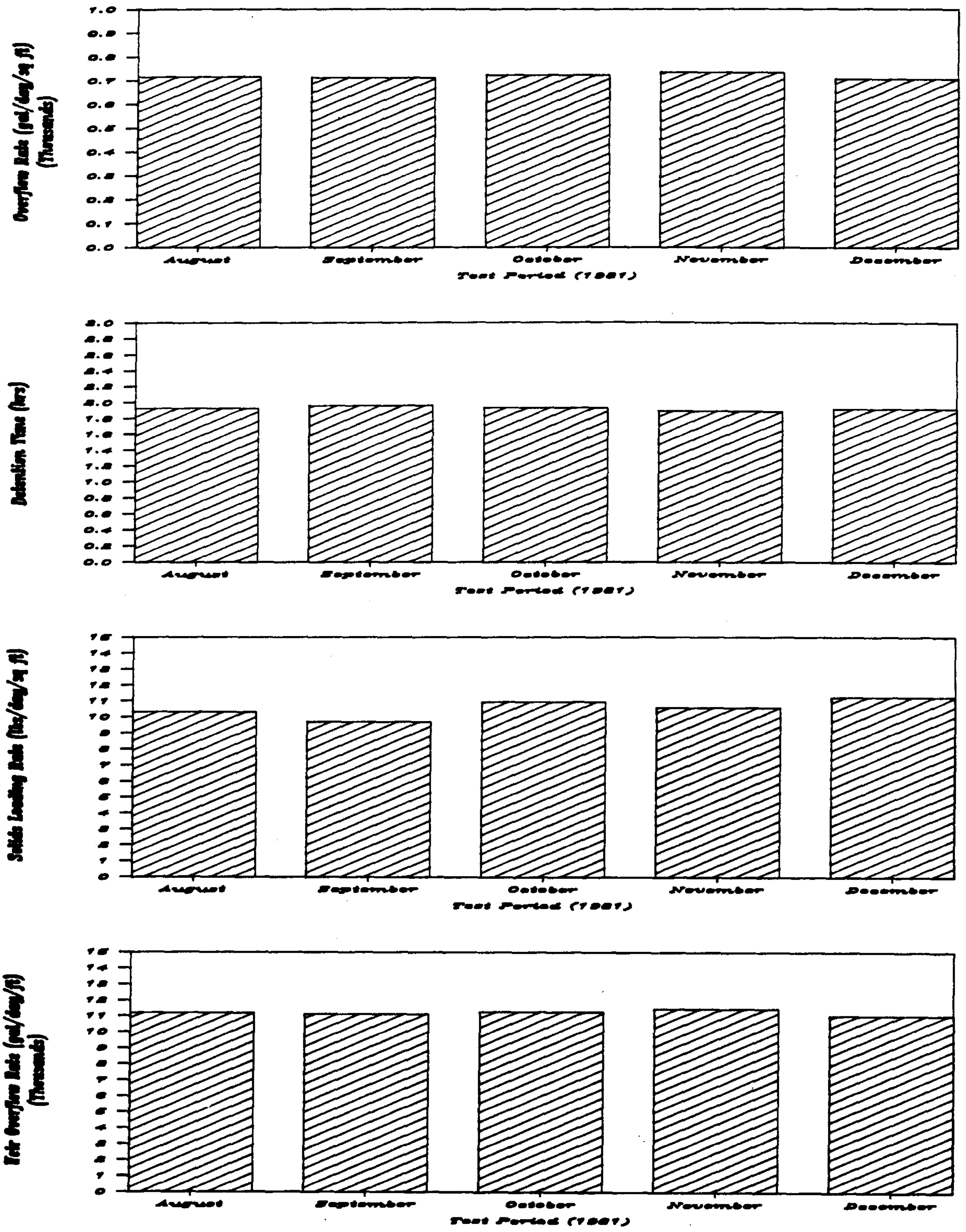


Figure A-15. Secondary Clarifier Parameters

TABLE A-25. PLANT PERFORMANCE‡

Test Period	Total Plant Basis+				Secondary System Basis*							
	Total COD Removal	Effluent Total COD	Effluent Turbidity	Effluent Suspended Solids	Total COD Removal	COD Conversion Efficiency^	Effluent Total COD	Effluent Turbidity	Suspended Solids Removal	Effluent Suspended Solids	Effluent Ammonia	Nitrification Efficiency!
(1981)	(%)	(mg/l)	(JTU)	(mg/l)	(%)	(%)	(mg/l)	(JTU)	(%)	(mg/l)	(mg/l)	(%)
August	96.2	22	1.4	<1	88.6	90.7	26	2.2	95.7	4	10.6	3.7
September	96.2	23	1.0	<1	88.8	90.8	26	1.8	95.8	4	11.4	2.3
October	95.2	26	1.0	<1	88.0	90.4	30	1.9	94.4	5	14.9	0.0
November	95.2	26	1.2	<1	86.9	90.3	32	2.7	93.6	6	15.7	0.0
December	95.9	25	1.1	<1	87.8	90.8	31	2.7	93.7	7	13.8	0.0
Period Average	95.7	24	1.1	<1	88.0	90.6	29	2.3	94.6	5	13.3	1.2

‡ See later tables for additional waste stream laboratory results.

+ Plant influent to chlorine contact chamber effluent.

* Primary effluent to secondary clarifier effluent.

^ (Primary effluent total COD minus secondary effluent soluble COD) divided by primary effluent total COD, times 100.

! TKN converted by nitrifiers divided by TKN available for conversion (less synthesis requirements of heterotrophs).

TABLE A-26. COD AND BOD RESULTS

Test Period	COD (mg/l)						BOD (mg/l)		
	Raw	Primary	Secondary		Final*		Raw	Primary	Final*
(1981)	(Total)	(Total)	(Total)	(Soluble)	(Total)	(Soluble)	(Total)	(Total)	(Total)
August	582	228	26	21	22	20	209	95	4
September	606	232	26	21	23	20	214	114	4
October	540	249	30	24	26	22	191	92	2
November	543	244	32	23	26	23	145	74	3
December	603	254	31	23	25	23	216	117	3
Period Average	575	241	29	22	24	22	195	98	3

* After all treatment, including filtration and chlorination.

TABLE A-27. SUSPENDED SOLIDS RESULTS

Test Period	Suspended Solids Results (mg/l)							
	Flow Streams					Mixed Liquor		
(1981)	Raw	Primary	Secondary	Final*	Return Sludge	Disk System	Tube System	Jet System+
August	389	94	4	<1	6452	1395	1399	1202
September	408	96	4	<1	6887	1321	1334	1137
October	331	89	5	<1	7527	1450	1538	1153
November	322	94	6	<1	7060	1341	1517	1073
December	346	111	7	<1	6811	1424	1604	1192
Period Average	359	97	5	<1	6947	1387	1479	1152

* After all treatment, including filtration and chlorination.

\+ The jet system was operated at lower loading rates than the disk and tube systems.

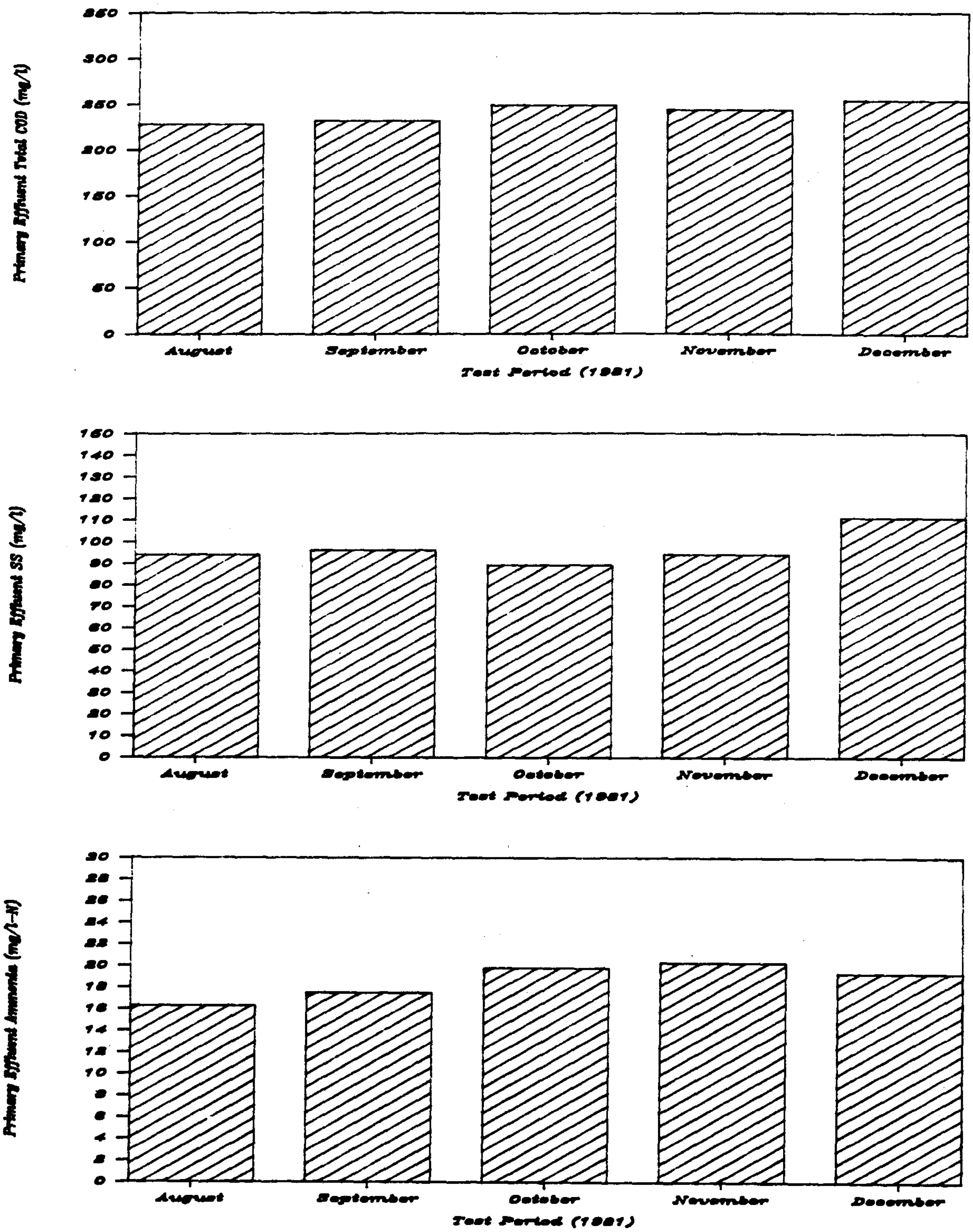


Figure A-16. Primary Effluent Total COD, Suspended Solids (SS) And Ammonia

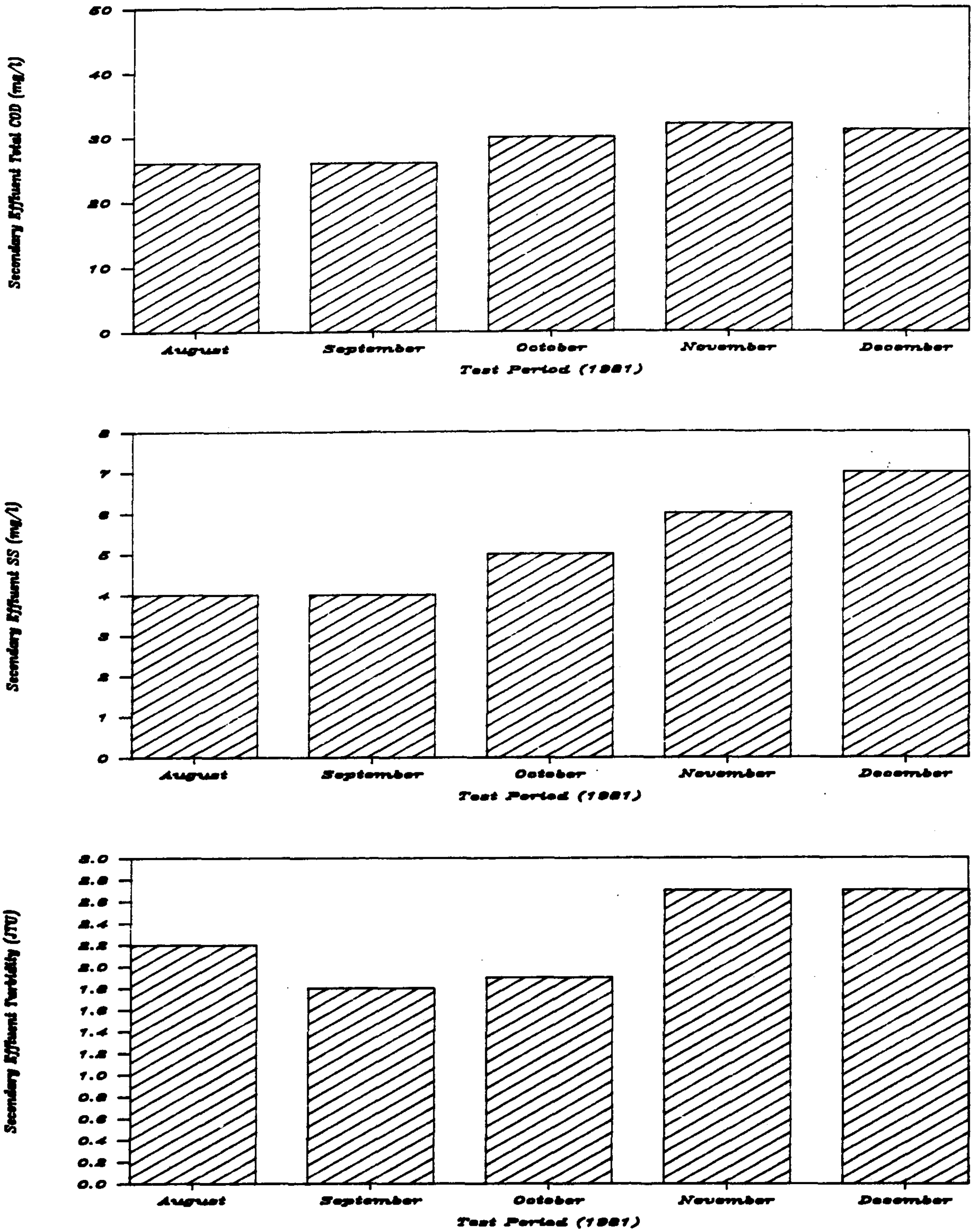


Figure A-17. Secondary Effluent Total COD, Suspended Solids (SS) And Turbidity

TABLE A-28. NITROGEN RESULTS

Test Period (1981)	Primary Effluent Ammonia (mg/l-N)	Secondary Effluent Ammonia (mg/l-N)	Secondary Effluent Nitrite (mg/l-N)	Secondary Effluent Nitrate (mg/l-N)	Secondary System Ammonia Removal (%)
August	16.3	10.6	1.162	2.8	34.8
September	17.5	11.4	1.101	2.6	35.5
October	19.8	14.9	1.141	1.9	26.0
November	20.3	15.7	1.089	1.3	24.2
December	19.3	13.8	1.627	1.6	27.8
Period Average	18.6	13.3	1.226	2.0	29.7

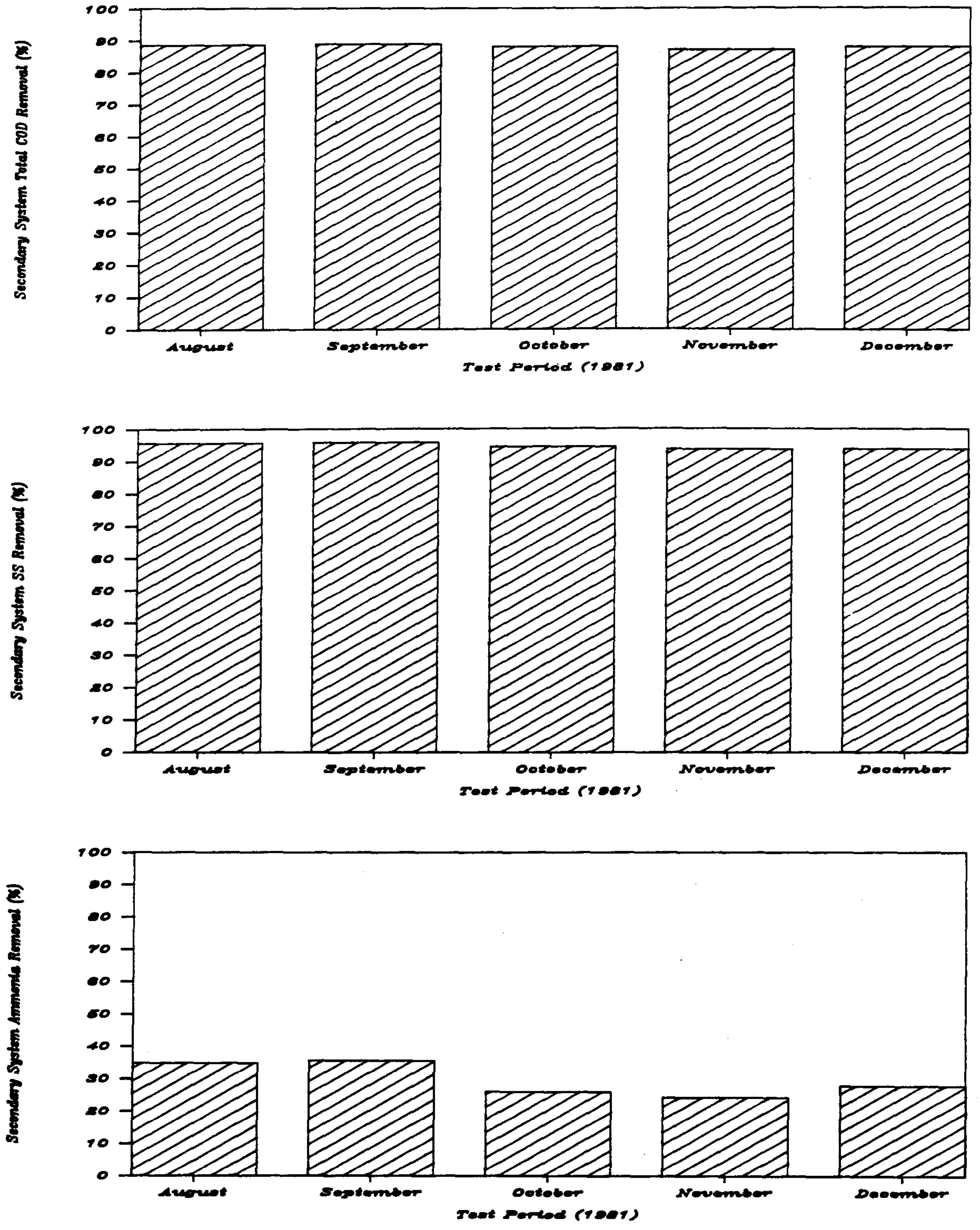
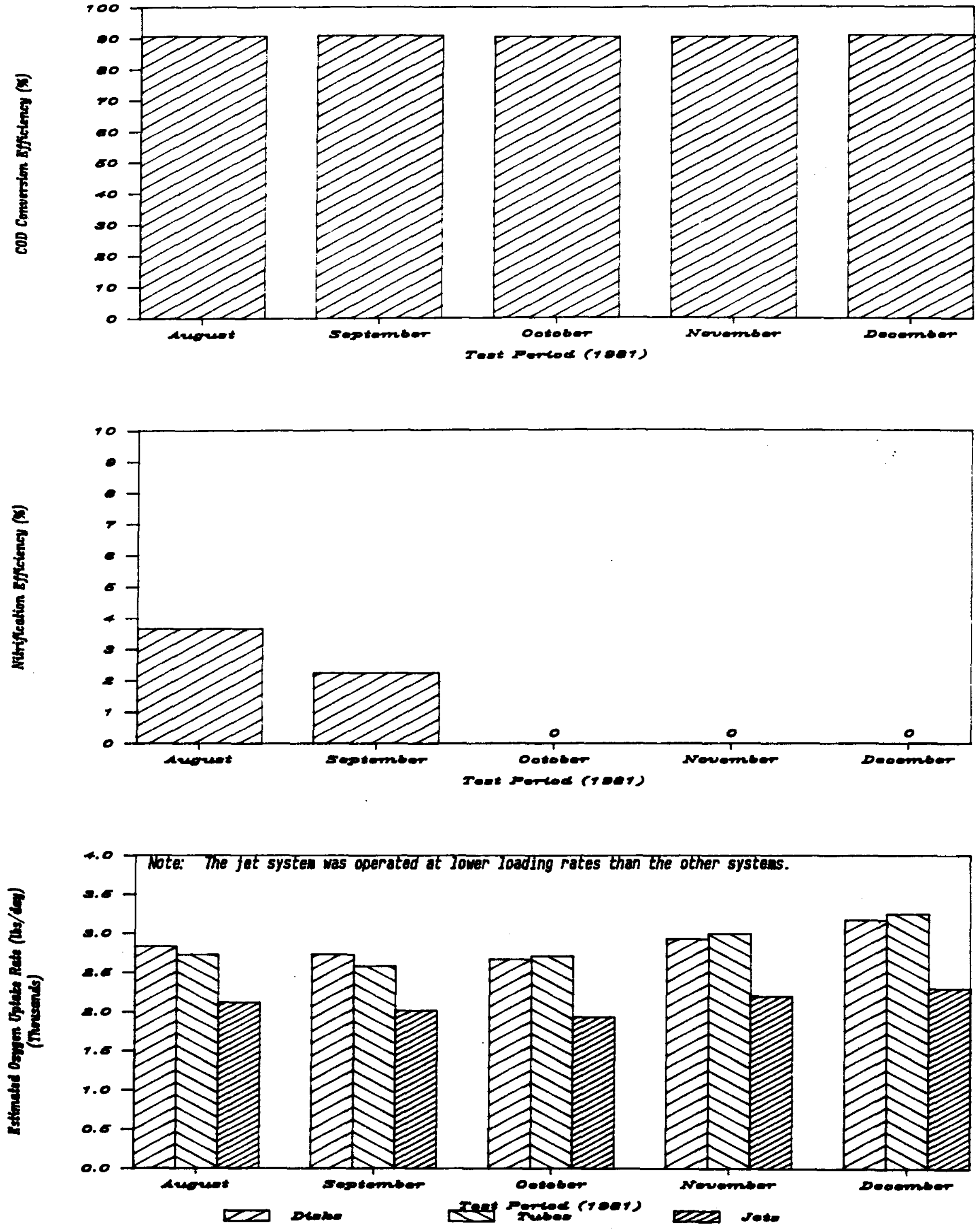


Figure A-18. Secondary System Removal Efficiencies - COD, Suspended Solids (SS) And Ammonia



Note: The jet system was operated at lower loading rates than the other systems.

Figure A-19. Secondary System COD Conversion Efficiency, Nitrification Efficiency and Estimated Oxygen Uptake Rates

TABLE A-29. NITRITE AND NITRATE RESULTS ON MIXED LIQUOR GRAB SAMPLES*

Test Period	Nitrites (mg/l-N)						Nitrates (mg/l-N)					
	Low Flow Case			High Flow Case			Low Flow Case			High Flow Case		
(1981)	Disk System	Tube System	Jet System+	Disk System	Tube System	Jet System+	Disk System	Tube System	Jet System+	Disk System	Tube System	Jet System+
August	1.241	1.566	2.141	3.279	2.729	3.891	1.20	1.47	2.07	3.29	2.95	4.30
September	1.949	1.888	2.231	3.923	3.477	4.379	1.05	1.18	1.23	2.10	2.19	2.96
October	2.033	1.885	2.564	3.552	3.050	4.372	0.85	<0.84	0.85	1.08	1.03	<1.35
November	1.476	1.640	1.871	3.020	3.343	3.921	<0.18	<0.16	<0.21	<0.42	<0.50	<0.66
December	2.323	2.413	2.396	4.701	4.315	4.935	0.59	<0.22	<0.30	<0.43	<0.32	<0.38
Period Average	1.806	1.880	2.243	3.698	3.382	4.302	<0.78	<0.78	<0.93	<1.47	<1.40	<1.93

* Tests conducted at high flow and low flow on alternate days.
+ The jet system was operated at lower loading rates than the disk and tube systems.

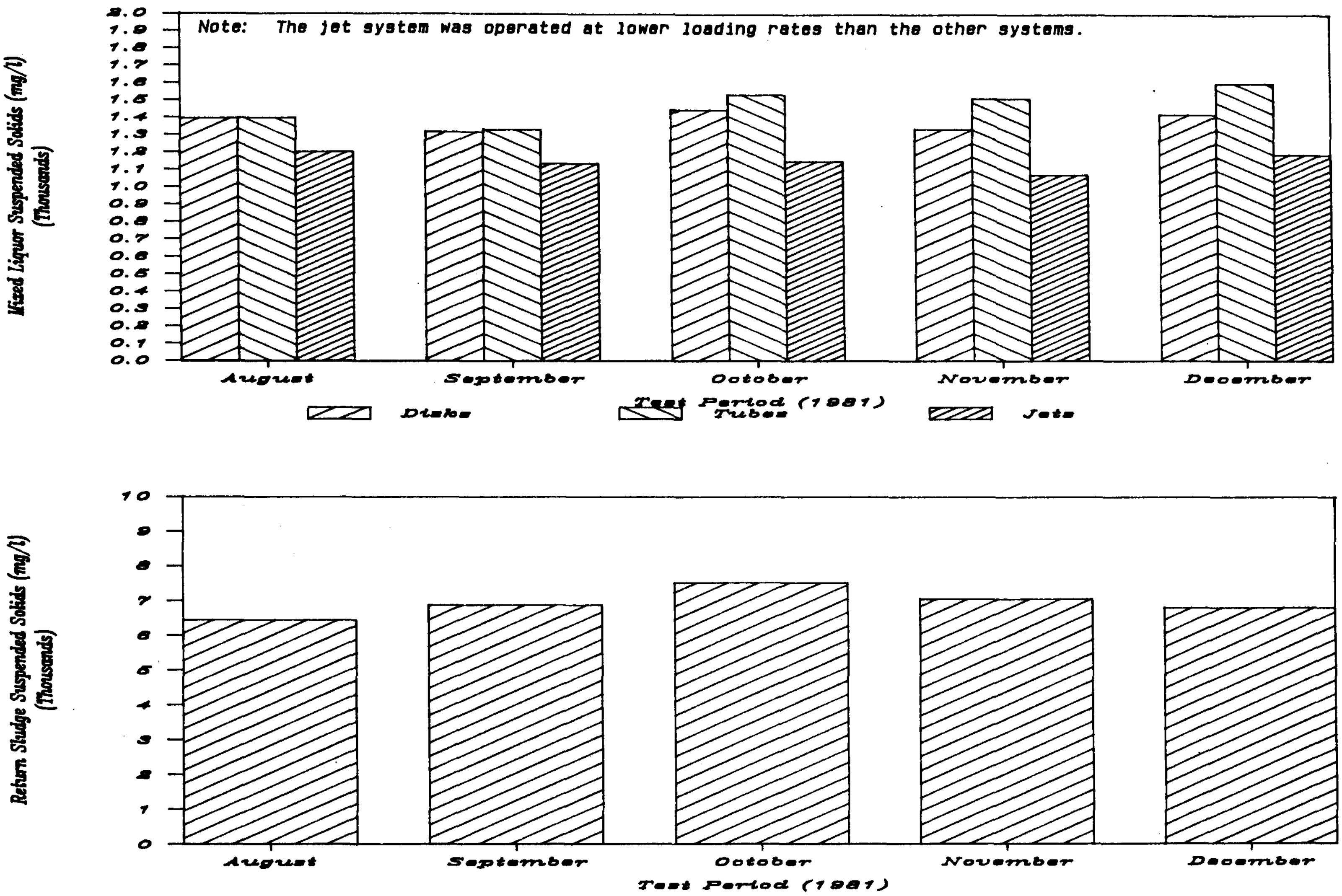

Note: The jet system was operated at lower loading rates than the other systems.

Figure A-20. Mixed Liquor and Return Sludge Suspended Solids

TABLE A-30. SLUDGE VOLUME INDEX AND MIXED LIQUOR VOLATILE SUSPENDED SOLIDS RESULTS*

Test Period (1981)	Sludge Volume Index (SVI-ml/gm)			ML Volatile Suspended Solids (%)		
	Disk System	Tube System	Jet System+	Disk System	Tube System	Jet System
August	135	132	138	72	71	71
September	154	152	161	71	71	71
October	144	145	145	73	73	73
November	148	142	143	72	73	72
December	132	131	133	73	73	73
Period Average	142	140	144	72	72	72

* Based on grab sample tests.

\+ The jet system was operated at lower loading rates than the disk and tube systems.

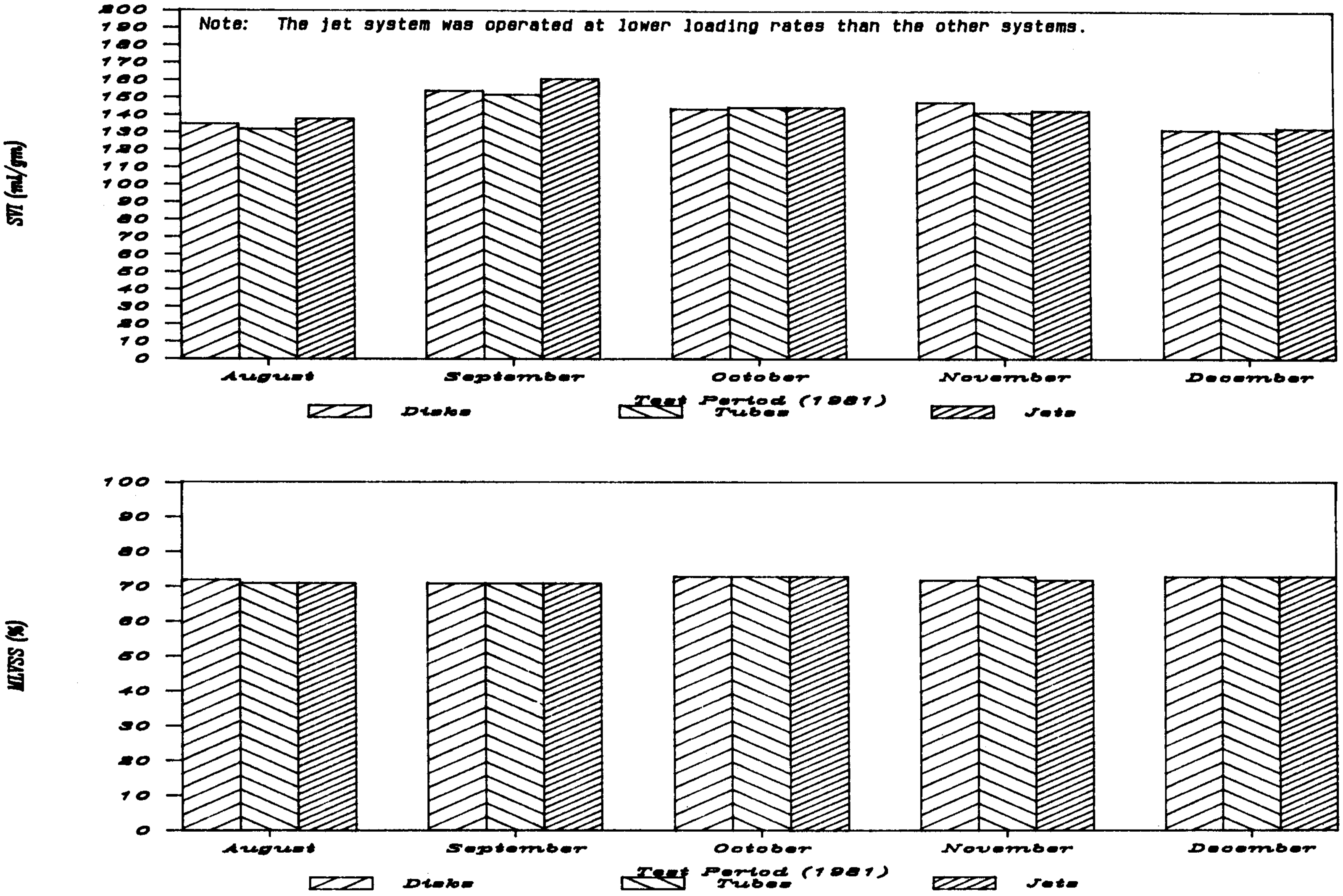

Note: The jet system was operated at lower loading rates than the other systems.

Figure A-21. Sludge Volume Index (SVI) And Mixed Liquor Volatile Suspended Solids (MLVSS)

TABLE A-31. MISCELLANEOUS LABORATORY RESULTS

Test Period (1981)	Secondary Clarifier Secchi Disk Reading (ft)	Final Effluent Settleable Solids (ml/l)	Final Effluent Total Dissolved Solids (mg/l)	Final Effluent Oil And Grease (mg/l)	Final Effluent ph
August	11.5	<0.1	497	<1.0	7.03
September	11.8	<0.1	494	----	7.07
October	10.5	<0.1	482	<1.1	7.06
November	9.4	<0.1	451	<1.0	7.08
December	9.4	<0.1	459	<1.0	6.96
Period Average	10.5	<0.1	477	<1.0	7.04

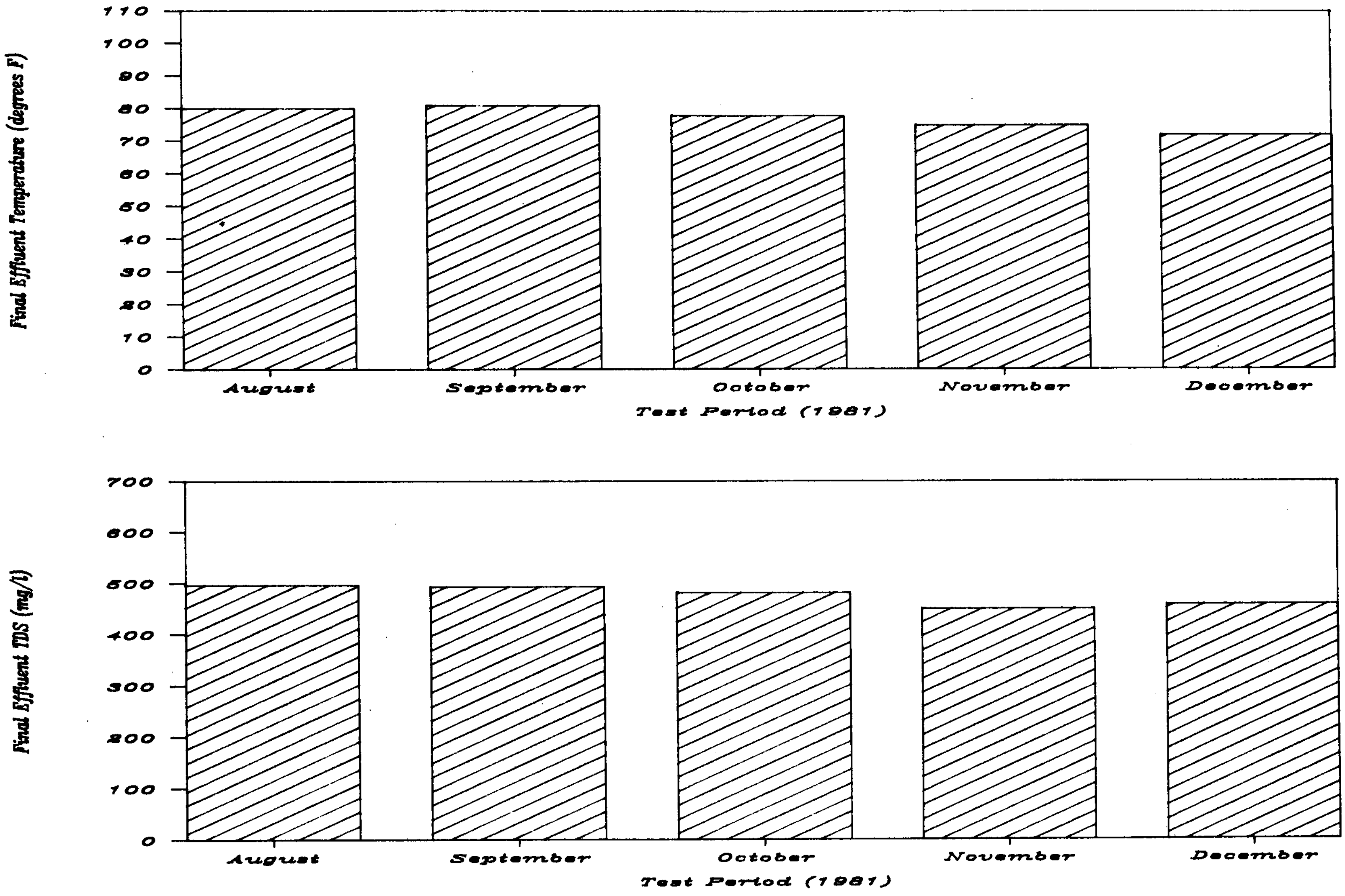


Figure A-22. Final Effluent Temperature and Total Dissolved Solids (TDS)

TABLE A-32. CHEMICAL ADDITION AND BLOWER SHUTDOWN RECORDS

Test Period	Chemical Addition		Blower Shutdowns	
	Polymer To Finals*	High Alum To Filters	Shutdowns	Average Duration
(1981)	(# days)	(# days)	(#)	(hrs)
August	1	4	0	0.00
September	0	3	3	1.21
October	1	1	1	4.82
November	3	10	0	0.00
December	0	2	0	0.00
Period Total	5	20	4	2.12 (Avg)

* The number of days requiring alum addition above normal operating levels.

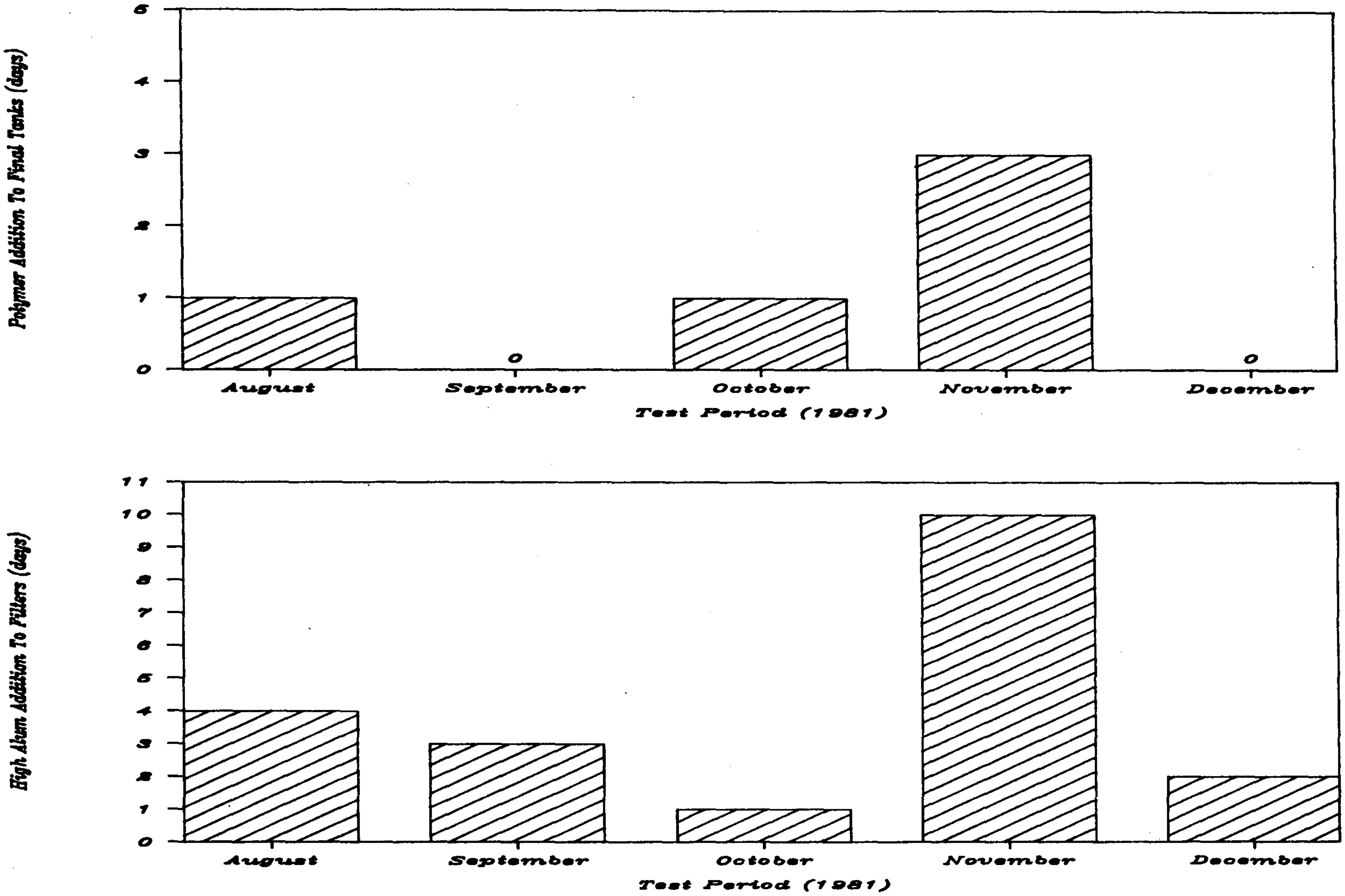


Figure A-23. Polymer And Alum Addition

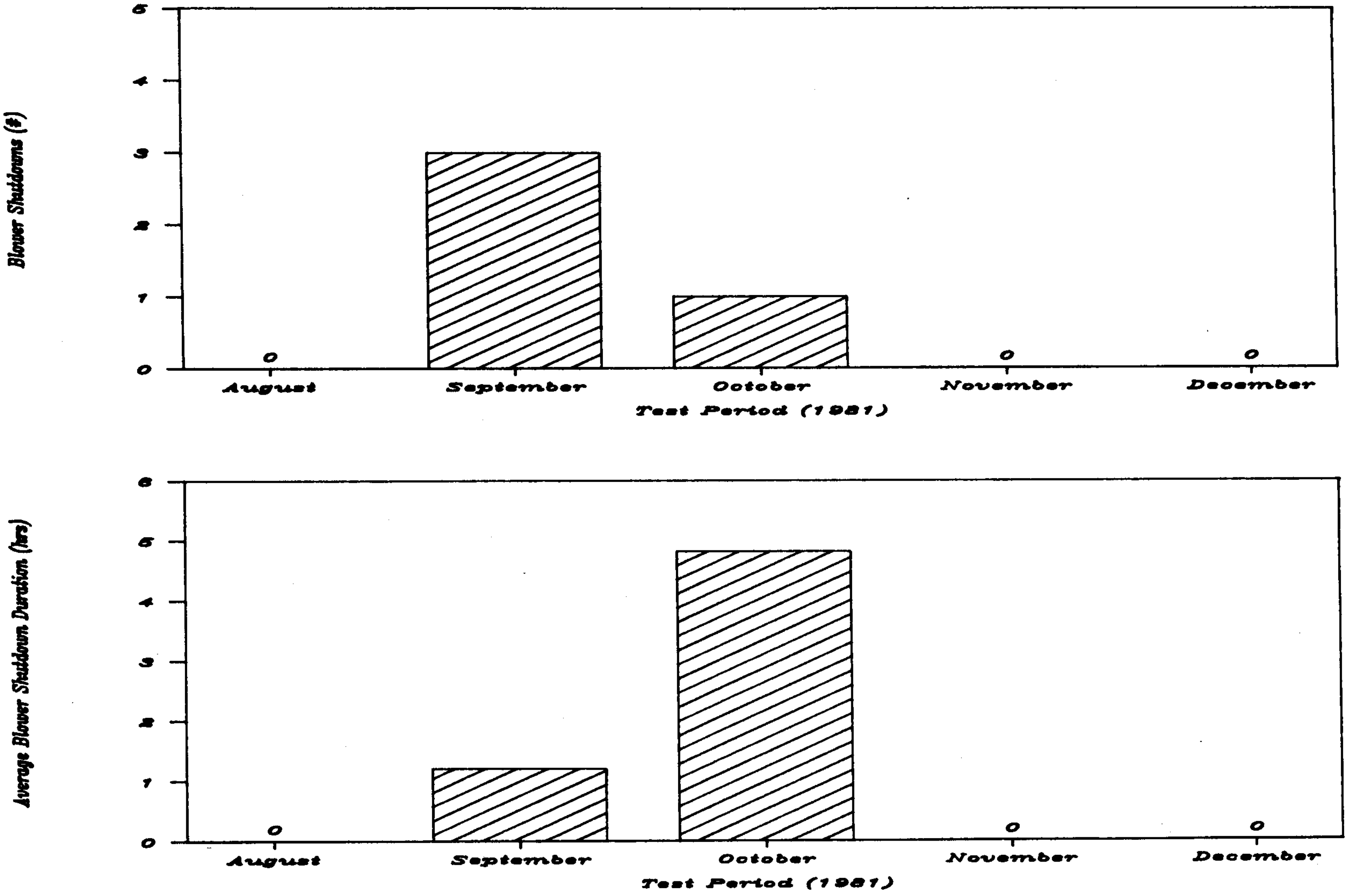


Figure A-24. Blower Shutdown Incidents

B. MONTHLY OPERATIONS RESULTS FOR PART 2.

This appendix show the operational results and flow rates for Part 2 of the study, from July to December, 1982. The procedures for calculations and data presentation are the same as in Part 1, except for the following:

1. In Part 2 the return sludge flow split among tanks was assumed equal.

2. The plant was operated in the step feed mode during a portion of Part 2. During this period, the flow rates to each portion of the tank were based on the individual feed gate flow calibrations. Table B-2 shows the aeration step feed pattern.

3. The centroidal return sludge aeration time in Table B-4 was calculated using the return sludge flow and the volume of the aeration tank upstream of the centroid of loading.

4. In Part 2, instantaneous air flow rates and DO profiles were measured once per day.

5. Direct measurement of daily average air flows was not possible for each aeration system. Instead these flows were estimated as follows:

   Instantaneous air flow readings were taken on each aeration system once each day. These readings were summed to obtain the instantaneous total plant aeration system flows. Totalized (daily average) air flow readings were taken on the total plant once each day. The ratio of totalized to instantaneous air flows for the total plant was used to determine the totalized flows for each system based on their instantaneous readings. Daily average grid glows were determined from the daily average system flows in the same proportion as occurred during the instantaneous readings. The instantaneous air flows for each system were determined from the sum of the three downcomer flows. It should be mentioned that the totalized readings for the total plant were taken from the air header meters. These readings were adjusted slightly before use to compensate for the differences in flow between the header meters and the sum of the plant downcomer meters.

TABLE B-1. HYDRAULIC FLOWS

Test Period	Average Daily Primary Effluent Flow (MGD)				Average Daily Return Sludge Flow (MGD) (% Recycle in Parentheses)				Average Daily Waste Sludge Flow	Average Daily Skimmings Flow	Average Waste Backwash Flow*
(1982)	Disk System	Dome System A	Dome System B	Total Plant	Disk System	Dome System A	Dome System B	Total Plant	(MGD)	(MGD)	(MGD)
"18 MGD" CONVENTIONAL MODE											
July 6-31	6.29	6.04	6.04	18.38	1.75(27.8)	1.75(29.0)	1.75(29.0)	5.25(28.6)	0.239	0.098	0.614
August 1-31	6.12	5.88	5.88	17.87	1.74(28.4)	1.74(29.6)	1.74(29.6)	5.21(29.2)	0.262	0.111	0.614
September 1-8	5.67	5.45	5.45	16.57	1.68(29.6)	1.68(30.8)	1.68(30.8)	5.04(30.4)	0.196	0.082	0.522
Period Average	6.13	5.89	5.89	17.91	1.74(28.3)	1.74(29.5)	1.74(29.5)	5.21(29.1)	0.245	0.102	0.603
"18 MGD" STEP FEED MODE											
September 14-30	6.46	6.21	6.21	18.89	2.39(37.0)	2.39(38.5)	2.39(38.5)	7.17(38.0)	0.281	0.034	0.519
October 1-31	5.86	5.64	5.64	17.14	1.99(34.0)	1.99(35.3)	1.99(35.3)	5.96(34.8)	0.341	0.047	0.521
Period Average	6.07	5.84	5.84	17.76	2.13(35.1)	2.13(36.4)	2.13(36.4)	6.39(35.9)	0.320	0.042	0.520
"12 MGD" CONVENTIONAL MODE											
November 6-30	4.28	4.11	4.11	12.49	1.17(27.3)	1.17(28.5)	1.17(28.5)	3.51(28.1)	0.253	0.049	0.135
December 1-31	4.28	4.10	4.10	12.48	1.17(27.3)	1.17(28.5)	1.17(28.5)	3.50(28.1)	0.195	0.051	0.116
Period Average	4.28	4.10	4.10	12.48	1.17(27.3)	1.17(28.5)	1.17(28.5)	3.50(28.1)	0.221	0.050	0.124

* Estimated backwash flow going to the sewer.

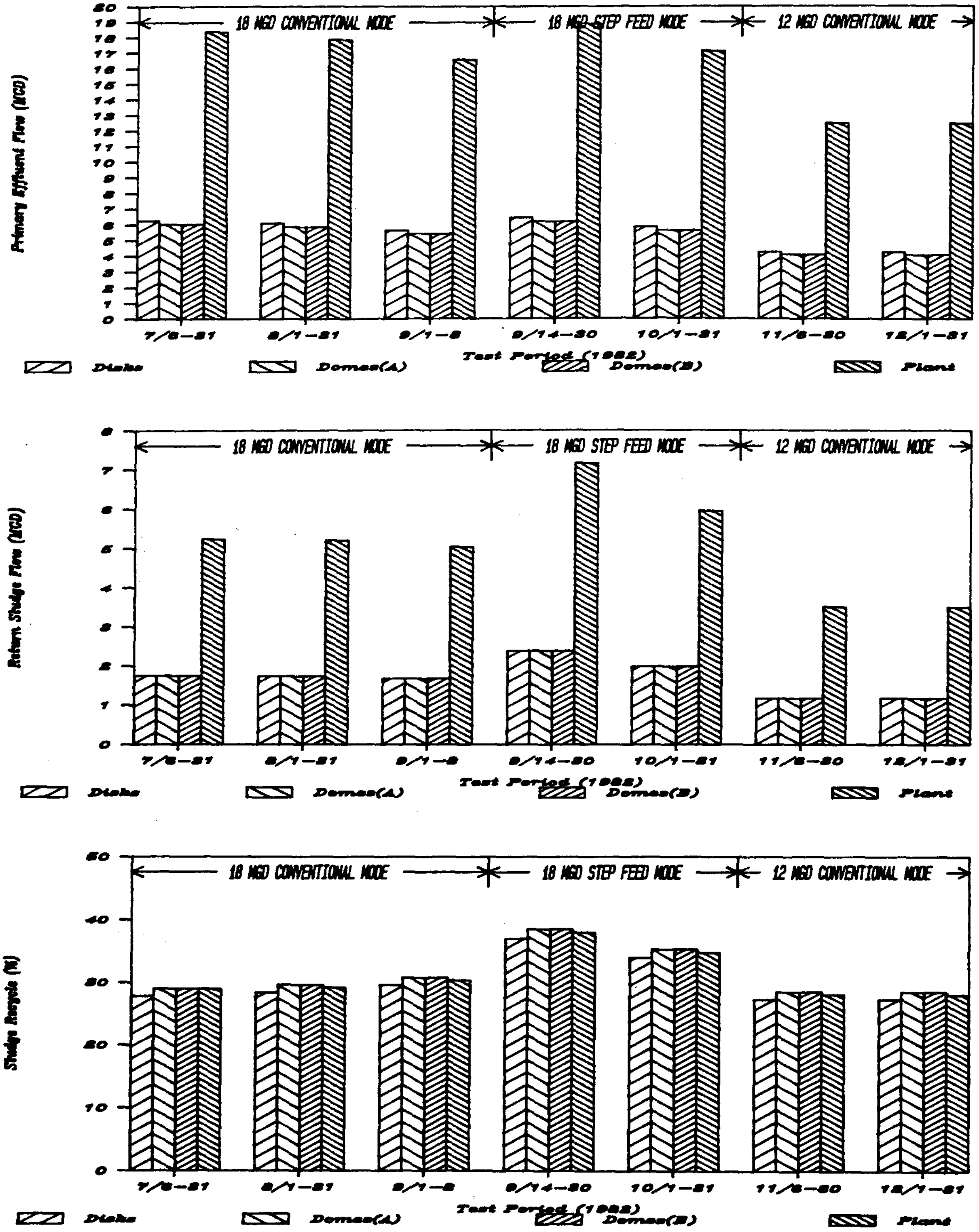


Figure B-1. Daily Average Hydraulic Flows

TABLE B-2. AERATION SYSTEM STEP FEED PATTERN

Test Period	Step Feed Pattern (% of Total Tank Flow)								
	Disk System			Dome System A			Dome System B		
(1982)	Front Gates#	Step Gate 1+	Step Gate 2^	Front Gates#	Step Gate 1+	Step Gate 2^	Front Gates#	Step Gate 1+	Step Gate 2^
"18 MGD" CONVENTIONAL MODE									
July 6-31	100.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0
August 1-31	100.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0
September 1-8	100.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0
Period Average	100.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0
"18 MGD" STEP FEED MODE									
September 14-30	42.4	38.9	18.7	42.4	38.9	18.7	42.4	38.9	18.7
October 1-31	41.6	39.1	19.3	41.6	39.1	19.3	41.6	39.1	19.3
Period Average	41.9	39.0	19.1	41.9	39.0	19.1	41.9	39.0	19.1
"12 MGD" CONVENTIONAL MODE									
November 6-30	100.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0
December 1-31	100.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0
Period Average	100.0	0.0	0.0	100.0	0.0	0.0	100.0	0.0	0.0

Located at the front of the aeration tank.
\+ Located 75 ft from the front of the aeration tank.
^ Located 150 ft from the front of the aeration tank.

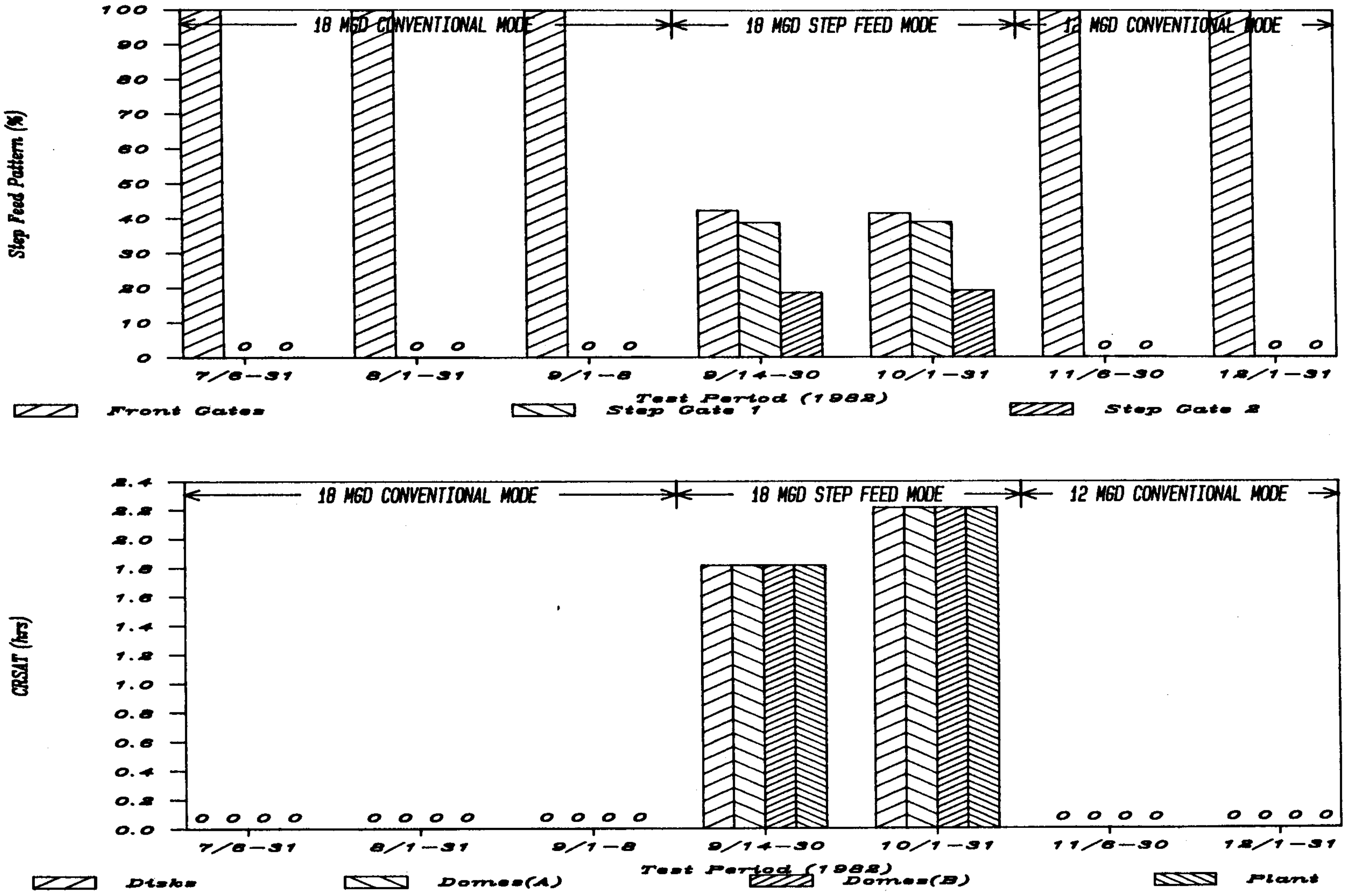


Figure B-2. Aeration System Step Feed Pattern And Centroidal Return Sludge Aeration Time (CRSAT)

TABLE B-3. CENTROIDAL MIXED LIQUOR AERATION TIME

Test Period	Centroidal Mixed Liquor Aeration Time (V/Q-hrs)*				Centroidal Mixed Liquor Aeration Time (V/(Q+R)-hrs)+			
(1982)	Disk System	Dome System A	Dome System B	Total Plant	Disk System	Dome System A	Dome System B	Total Plant
"18 MGD" CONVENTIONAL MODE								
July 6-31	3.64	3.79	3.79	3.74	2.85	2.94	2.94	2.91
August 1-31	3.74	3.89	3.89	3.84	2.91	3.00	3.00	2.97
September 1-8	4.04	4.20	4.20	4.14	3.11	3.21	3.21	3.18
Period Average	3.74	3.89	3.89	3.84	2.91	3.00	3.00	2.97
"18 MGD" STEP FEED MODE								
September 14-30	2.86	2.98	2.98	2.94	2.09	2.15	2.15	2.13
October 1-31	3.14	3.26	3.26	3.22	2.34	2.41	2.41	2.39
Period Average	3.04	3.16	3.16	3.12	2.25	2.32	2.32	2.30
"12 MGD" CONVENTIONAL MODE								
November 6-30	5.33	5.55	5.55	5.48	4.19	4.32	4.32	4.28
December 1-31	5.33	5.57	5.57	5.48	4.19	4.33	4.33	4.28
Period Average	5.33	5.56	5.56	5.48	4.19	4.33	4.33	4.28

* The aeration time calculated with the primary effluent flow and the centroid of loading.

\+ The aeration time calculated with the primary effluent and return sludge flows and the centroid of loading.

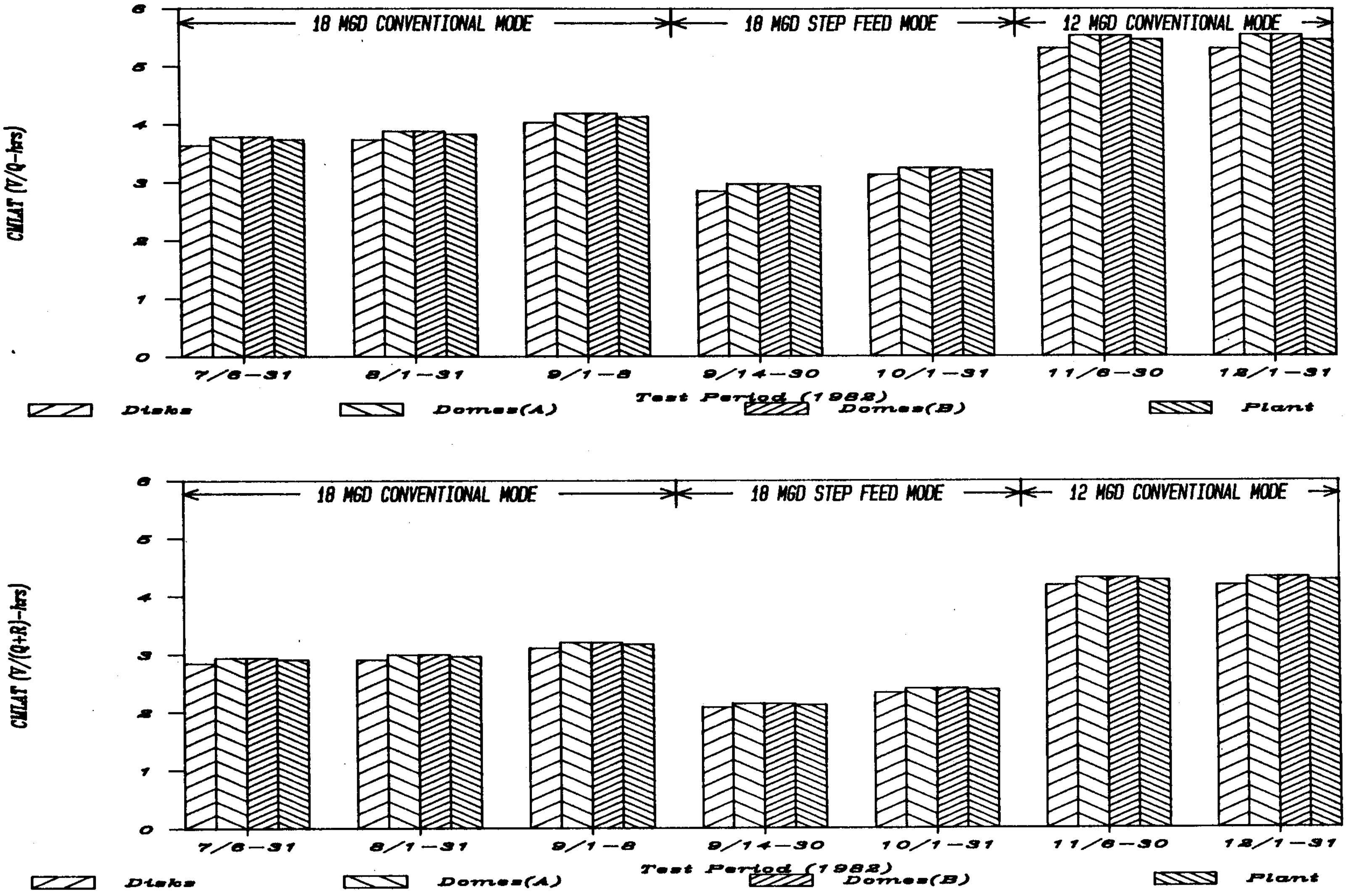


Figure B-3. Centroidal Mixed Liquor Aeration Time (CMLAT) Based on V/Q and V/(Q+R)

TABLE B-4. CENTROIDAL RETURN SLUDGE AERATION TIME

Test Period (1982)	Centroidal Return Sludge Aeration Time (hrs)*			
	Disk System	Dome System A	Dome System B	Total Plant
"18 MGD" CONVENTIONAL MODE				
July 6-31	0.0	0.0	0.0	0.0
August 1-31	0.0	0.0	0.0	0.0
September 1-8	0.0	0.0	0.0	0.0
Period Average	0.0	0.0	0.0	0.0
"18 MGD" STEP FEED MODE				
September 14-30	1.82	1.82	1.82	1.82
October 1-31	2.22	2.22	2.22	2.22
Period Average	2.08	2.08	2.08	2.08
"12 MGD" CONVENTIONAL MODE				
November 6-30	0.0	0.0	0.0	0.0
December 1-31	0.0	0.0	0.0	0.0
Period Average	0.0	0.0	0.0	0.0

* The aeration time calculated with the return sludge flow and the centroid of loading.

TABLE B-5. BIOLOGICAL LOADING PARAMETERS - PLANT BASIS

Test Period (1982)	Total Aeration System Volatile Suspended Solids (lbs)	Total Secondary Clarifier Volatile Suspended Solids# (lbs)	Total Plant Volatile Suspended Solids+ (lbs)	Waste Flow Volatile Suspended Solids (lbs)	Skimmings Flow Volatile Suspended Solids (lbs)	Secondary Flow Volatile Suspended Solids (lbs)	Daily Net Growth (lbs VSS / day)	Daily Net Growth (lbs VSS / lb COD)	Food To Microorganism Ratio (F/M)* (lbs COD / lb TPVSS-day)	Food To Microorganism Ratio (F/M)* (lbs COD / lb ASVSS-day)	Mean Cell Residence Time (MCRT)^ (days)
"18 MGD" CONVENTIONAL MODE											
July 6-31	28665	13151	41816	11554	112	650	12392	.353	.94	1.37	3.40
August 1-31	27812	12762	40574	11033	127	525	11460	.342	.92	1.34	3.47
September 1-8	26454	12135	38589	8388	96	704	9889	.311	.90	1.32	4.20
Period Average	27986	12840	40826	10916	117	597	11639	.342	.93	1.35	3.53
"18 MGD" STEP FEED MODE											
September 14-30	37198	13365	50562	11297	40	685	11376	.321	.78	1.05	4.48
October 1-31	26630	9825	36454	10230	56	634	9768	.292	1.04	1.42	3.56
Period Average	30373	11079	41451	10608	50	652	10338	.302	.94	1.29	3.89
"12 MGD" CONVENTIONAL MODE											
November 6-30	18622	7202	25824	7660	58	464	7997	.335	1.05	1.45	3.16
December 1-31	20681	7929	28610	6530	60	543	7568	.309	.95	1.31	4.01
Period Average	19762	7604	27366	7034	59	508	7760	.321	.99	1.37	3.63

Estimated.
+ Aeration system plus secondary clarifiers.
* Ratios on a BOD basis can be approximated by multiplying the COD basis numbers by 0.54
^ On a total system solids basis.

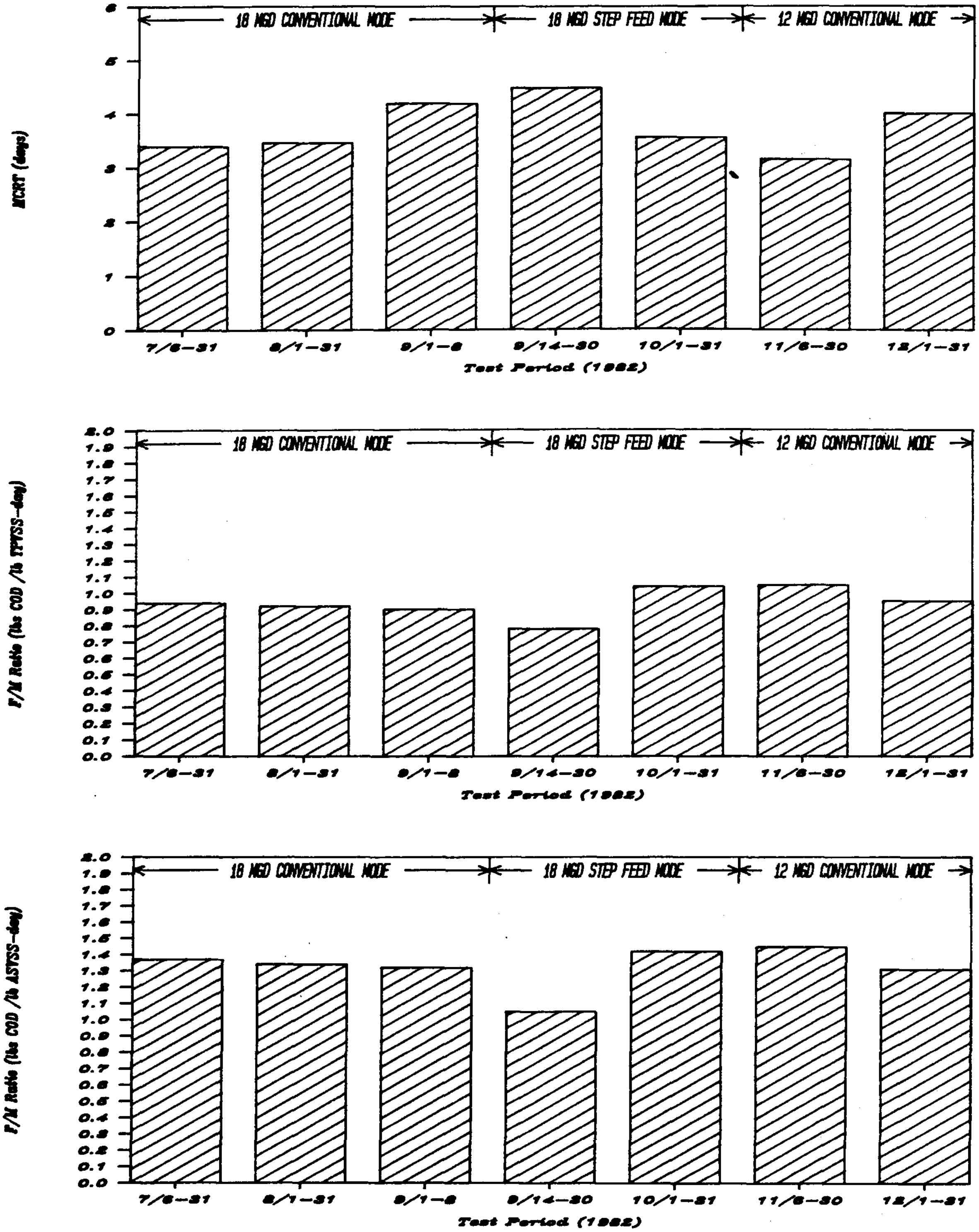


Figure B-4. Mean Cell Residence Time (MCRT) And Food To Microorganism Ratio (F/M) Based On Total Plant (TP) And Total Aeration System (AS) Solids

TABLE B-6. BIOLOGICAL AND VOLUMETRIC LOADING PARAMETERS - SYSTEM BASIS*

Test Period	Food To Microorganism Ratio (F/M) (lbs COD /lb ASVSS-day)				Volumetric Loading Rate (lbs COD /1000 cu ft-day)			
(1982)	Disk System	Dome System A	Dome System B	Total Plant	Disk System	Dome System A	Dome System B	Total Plant
"18 MGD" CONVENTIONAL MODE								
July 6-31	1.44	1.33	1.36	1.37	105.8	101.5	101.5	102.9
August 1-31	1.37	1.33	1.32	1.34	100.1	96.2	96.2	97.5
September 1-8	1.40	1.27	1.29	1.32	93.5	89.8	89.8	91.1
Period Average	1.40	1.32	1.33	1.35	101.6	97.5	97.5	98.9
"18 MGD" STEP FEED MODE								
September 14-30	1.11	1.03	1.03	1.05	105.5	101.4	101.4	102.8
October 1-31	1.47	1.38	1.4	1.42	101.4	97.6	97.6	98.9
Period Average	1.34	1.26	1.27	1.29	102.9	98.9	98.9	100.3
"12 MGD" CONVENTIONAL MODE								
November 6-30	1.45	1.44	1.45	1.45	72.7	69.8	69.8	70.8
December 1-31	1.41	1.24	1.28	1.31	73.0	69.9	69.9	71.0
Period Average	1.43	1.33	1.36	1.37	72.9	69.9	69.9	70.9

* The results on a BOD basis can be approximated by multiplying the COD basis numbers by 0.54.

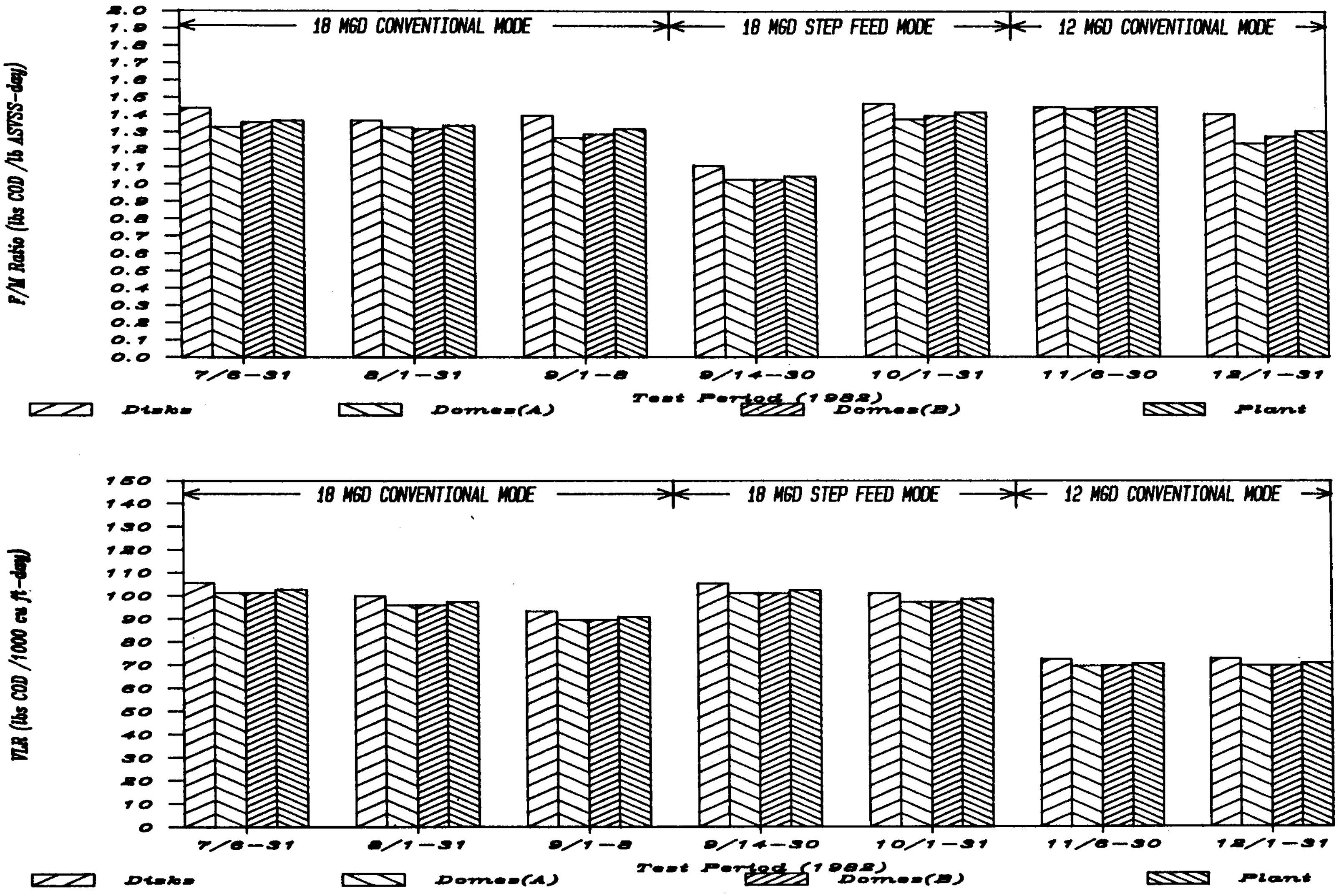


Figure B-5. Food to Microorganism Ratio (F/M) Based on Aeration System Solids (AS) And Volumetric Loading Rate (VLR)

TABLE B-7. DAILY AVERAGE AIR FLOW

Test Period	Daily Average Air Flow (scfm)											
	Disk System				Dome System A				Dome System B			
(1982)	Grid 1	Grid 2	Grid 3	Total Tank	Grid 1	Grid 2	Grid 3	Total Tank	Grid 1	Grid 2	Grid 3	Total Tank
"18 MGD" CONVENTIONAL MODE												
July 6-31	1548	1215	768	3530	1796	1331	831	3958	1547	1161	664	3371
August 1-31	1312	1046	684	3042	1560	1084	675	3318	1452	1003	589	3044
September 1-8	1197	988	649	2833	1439	985	620	3043	1431	882	530	2842
Period Average	1392	1106	713	3211	1639	1170	731	3540	1487	1051	612	3150
"18 MGD" STEP FEED MODE												
September 14-30	1404	1170	785	3358	1545	1038	698	3280	1480	943	659	3082
October 1-31	1419	1120	840	3379	1404	945	711	3059	1422	890	761	3073
Period Average	1414	1138	820	3372	1453	978	706	3138	1443	908	725	3076
"12 MGD" CONVENTIONAL MODE												
November 6-30	990	723	604	2317	971	800	581	2352	983	788	557	2327
December 1-31	1014	769	599	2382	1052	914	625	2591	1011	831	571	2412
Period Average	1003	748	601	2353	1016	863	605	2484	998	812	564	2374

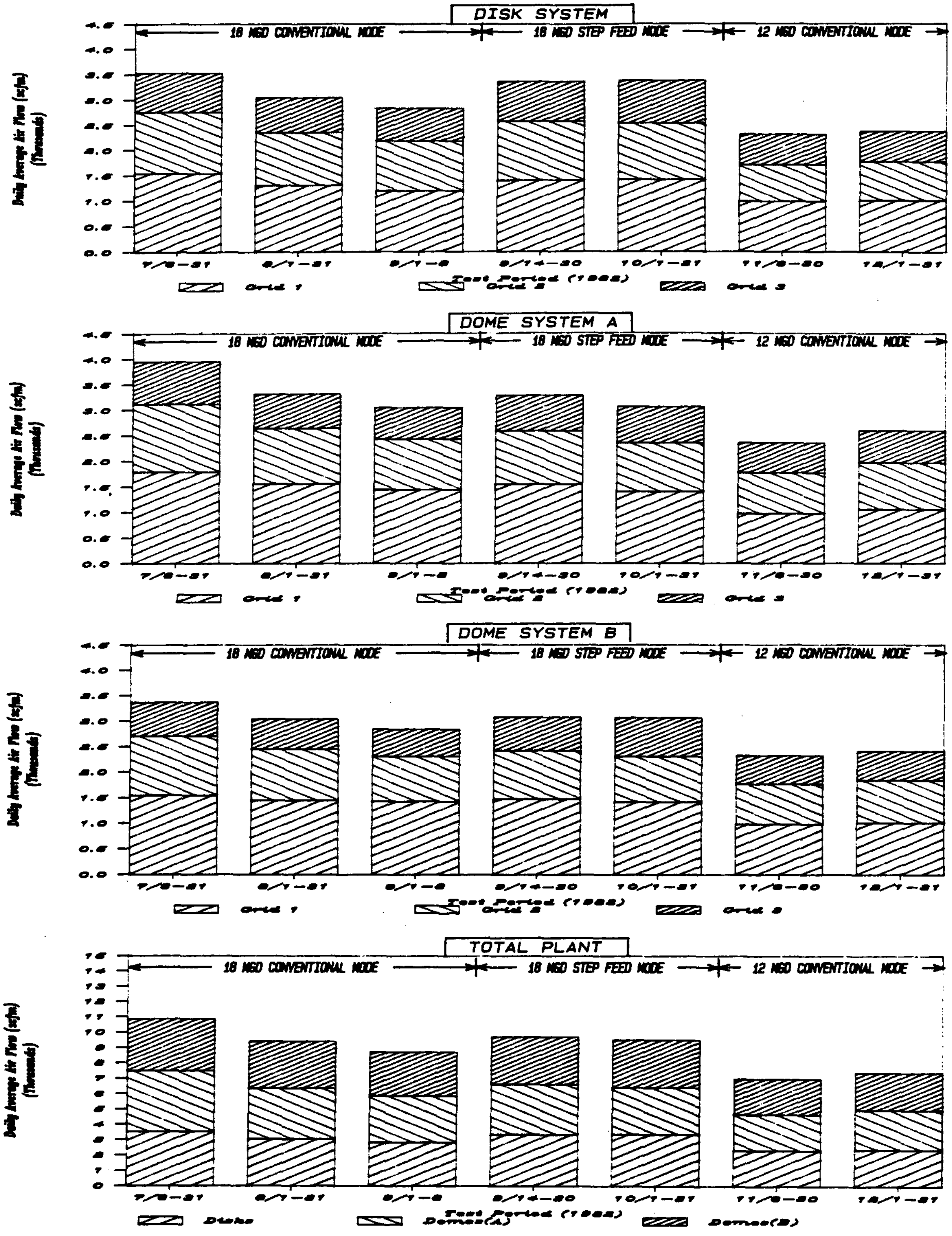


Figure B-6. Daily Average Air Flow

TABLE B-8. DAILY AVERAGE AIR FLOW/DIFFUSER

Test Period	Daily Average Air Flow/Diffuser (scfm)*											
	Disk System				Dome System A				Dome System B			
(1982)	Grid 1	Grid 2	Grid 3	Total Tank	Grid 1	Grid 2	Grid 3	Total Tank	Grid 1	Grid 2	Grid 3	Total Tank
"18 MGD" CONVENTIONAL MODE												
July 6-31	1.95	1.57	1.67	1.74	1.81	1.38	1.45	1.56	1.57	1.20	1.16	1.33
August 1-31	1.66	1.35	1.49	1.50	1.58	1.12	1.18	1.31	1.47	1.04	1.03	1.20
September 1-8	1.51	1.28	1.41	1.40	1.45	1.02	1.08	1.20	1.45	0.91	0.92	1.12
Period Average	1.76	1.43	1.55	1.58	1.66	1.21	1.28	1.40	1.51	1.09	1.07	1.24
"18 MGD" STEP FEED MODE												
September 14-30	1.77	1.51	1.71	1.66	1.56	1.07	1.22	1.30	1.50	0.97	1.15	1.22
October 1-31	1.79	1.45	1.83	1.67	1.42	0.98	1.24	1.21	1.44	0.92	1.33	1.22
Period Average	1.78	1.47	1.79	1.67	1.47	1.01	1.23	1.24	1.46	0.94	1.27	1.22
"12 MGD" CONVENTIONAL MODE												
November 6-30	1.25	0.93	1.31	1.14	0.98	0.83	1.01	0.93	1.00	0.81	0.97	0.92
December 1-31	1.28	0.99	1.30	1.18	1.06	0.94	1.09	1.02	1.03	0.86	0.99	0.95
Period Average	1.27	0.96	1.30	1.16	1.02	0.89	1.05	0.98	1.02	0.84	0.98	0.94

* The differences in air flow per diffuser shown for the disk and dome systems are partially due to the difference in size between the two diffuser types.

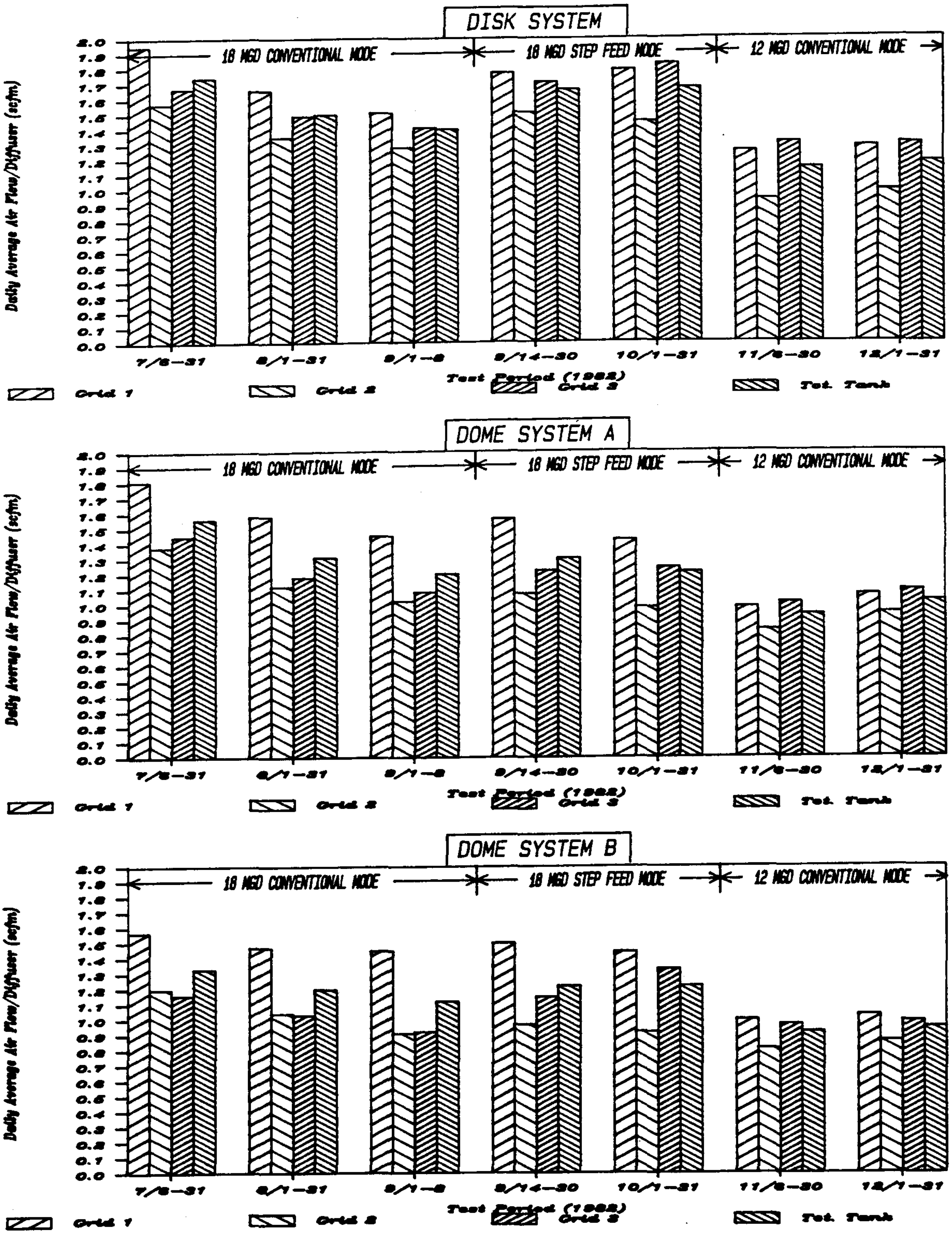


Figure B-7. Daily Average Air Flow/Diffuser

TABLE B-9. DAILY AVERAGE AIR FLOW/TANK SURFACE AREA

Test Period	Daily Average Air Flow/Tank Surface Area (scfm/sq ft)											
	Disk System				Dome System A				Dome System B			
(1982)	Grid 1	Grid 2	Grid 3	Total Tank	Grid 1	Grid 2	Grid 3	Total Tank	Grid 1	Grid 2	Grid 3	Total Tank
"18 MGD" CONVENTIONAL MODE												
July 6-31	0.516	0.405	0.256	0.392	0.599	0.444	0.277	0.440	0.516	0.387	0.221	0.375
August 1-31	0.437	0.349	0.228	0.338	0.520	0.361	0.225	0.369	0.484	0.334	0.196	0.338
September 1-8	0.399	0.329	0.216	0.315	0.480	0.328	0.207	0.338	0.477	0.294	0.177	0.316
Period Average	0.464	0.369	0.238	0.357	0.547	0.390	0.244	0.394	0.496	0.350	0.204	0.350
"18 MGD" STEP FEED MODE												
September 14-30	0.468	0.390	0.262	0.373	0.515	0.346	0.233	0.364	0.493	0.314	0.220	0.342
October 1-31	0.473	0.373	0.280	0.375	0.468	0.315	0.237	0.340	0.474	0.296	0.254	0.341
Period Average	0.471	0.379	0.274	0.374	0.485	0.326	0.236	0.348	0.481	0.302	0.242	0.341
"12 MGD" CONVENTIONAL MODE												
November 6-30	0.330	0.241	0.201	0.257	0.324	0.267	0.194	0.261	0.328	0.263	0.186	0.259
December 1-31	0.338	0.256	0.200	0.265	0.351	0.305	0.208	0.288	0.337	0.277	0.190	0.268
Period Average	0.334	0.249	0.200	0.261	0.339	0.288	0.202	0.276	0.333	0.271	0.188	0.264

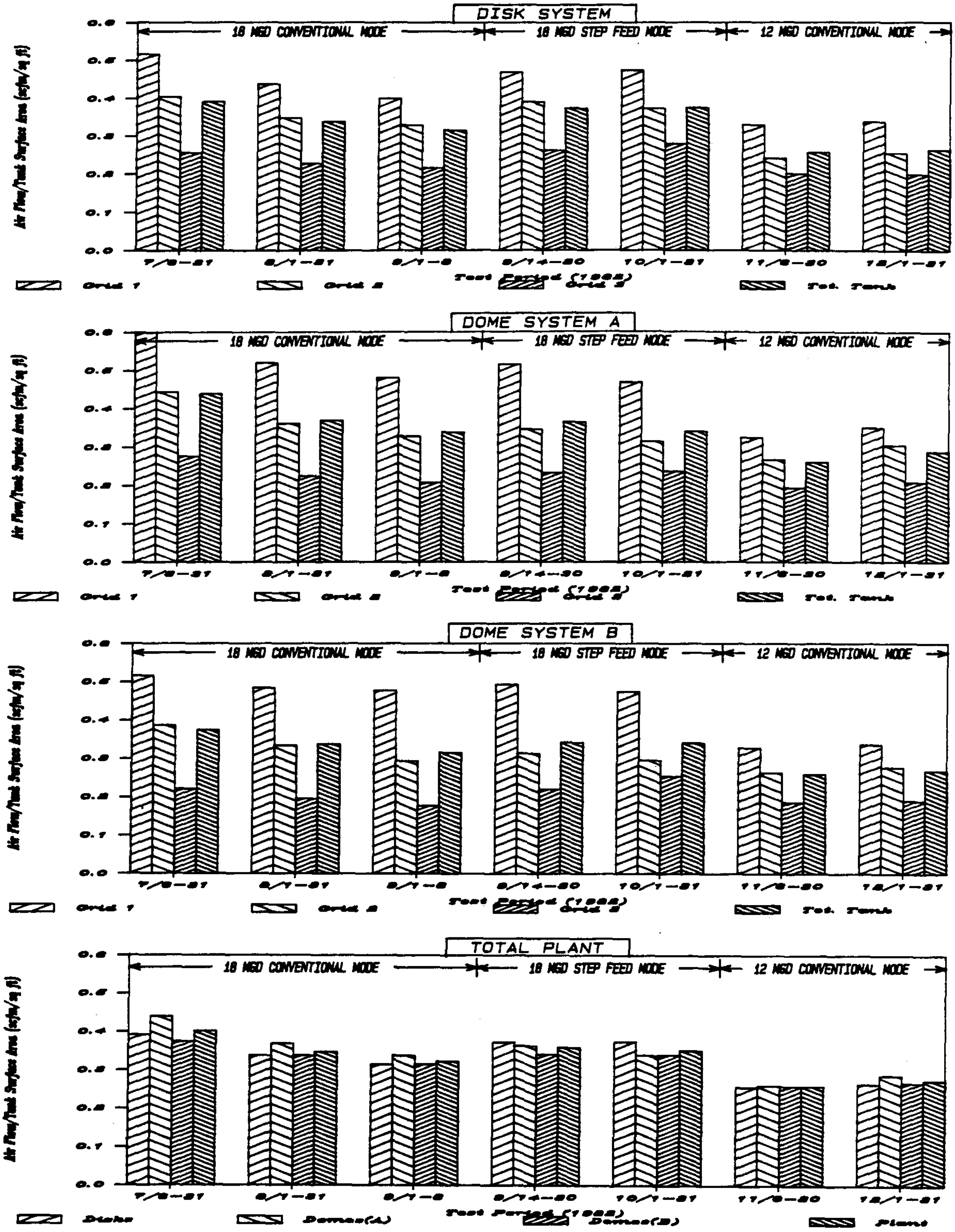


Figure B-8. Daily Average Air Flow/Tank Surface Area

TABLE B-10. DAILY AVERAGE AIR USAGE

Test Period	Daily Average Air Usage/Feed Volume (scf/gal)				Daily Average Air Usage/COD Removed (scf/lb)			
(1982)	Disk System	Dome System A	Dome System B	Total Plant	Disk System	Dome System A	Dome System B	Total Plant
"18 MGD" CONVENTIONAL MODE								
July 6-31	0.808	0.944	0.804	0.851	423	494	421	446
August 1-31	0.716	0.813	0.745	0.758	381	433	397	404
September 1-8	0.720	0.804	0.751	0.758	375	419	392	395
Period Average	0.753	0.864	0.769	0.795	397	456	406	419
"18 MGD" STEP FEED MODE								
September 14-30	0.749	0.761	0.715	0.741	399	405	381	395
October 1-31	0.830	0.781	0.785	0.799	425	400	402	409
Period Average	0.801	0.774	0.760	0.778	416	402	394	404
"12 MGD" CONVENTIONAL MODE								
November 6-30	0.779	0.824	0.815	0.807	408	431	427	422
December 1-31	0.801	0.910	0.847	0.852	409	464	432	435
Period Average	0.791	0.872	0.833	0.832	409	450	430	429

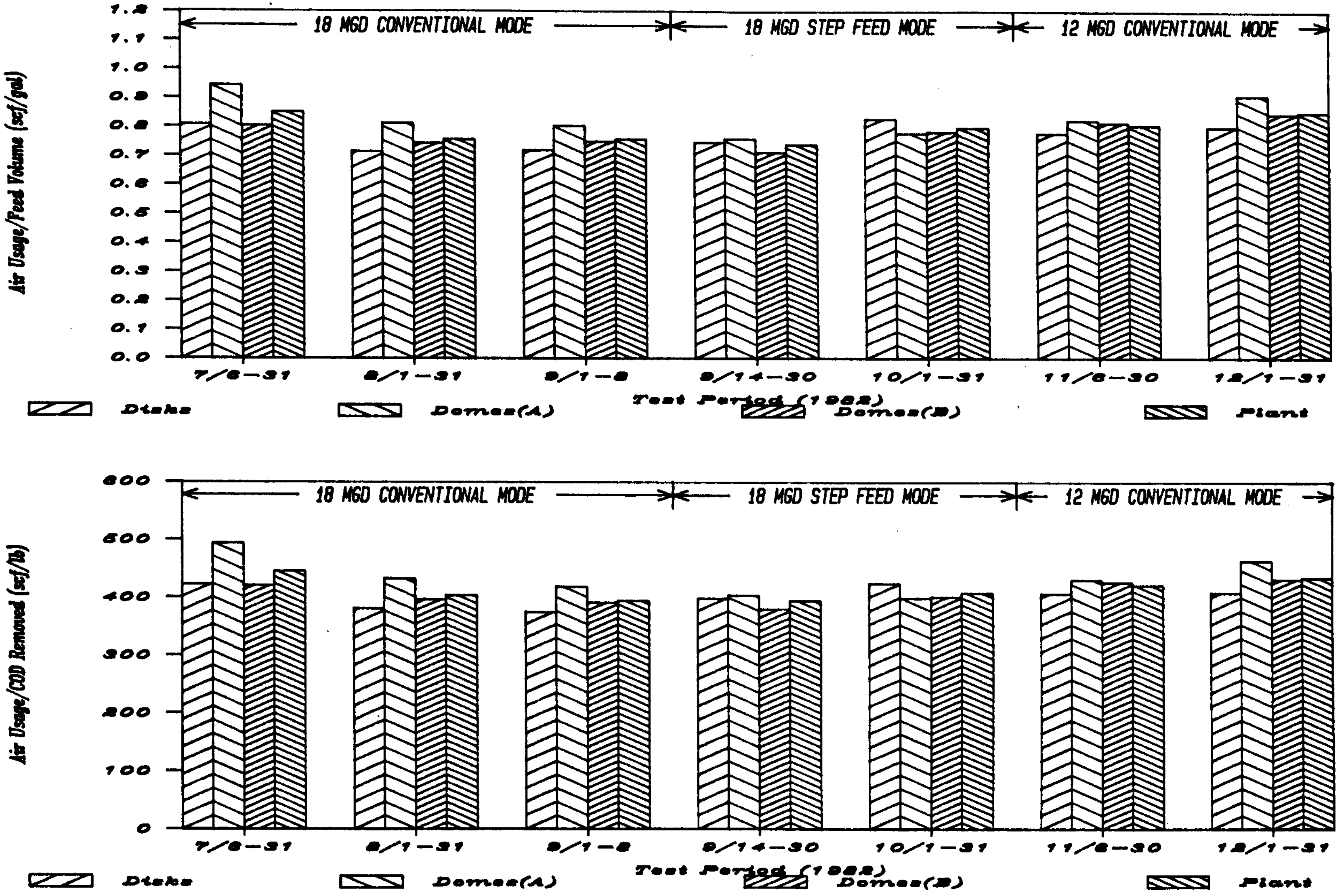


Figure B-9. Daily Average Air Usage

TABLE B-11. AFTERNOON DO PROFILE RESULTS - DISK SYSTEM

Test Period (1982)	Number of Profiles	DO Concentration (mg/l) Position 1#	Position 2+	Position 3*	Position 4^	Weighted Average!	Air Flow (scfm) Grid 1	Grid 2	Grid 3	Total Tank
"18 MGD" CONVENTIONAL MODE										
July 6-31	23	0.15	0.51	0.66	0.66	0.39	1533	1208	761	3502
August 1-31	22	0.15	0.43	0.46	0.45	0.31	1244	984	646	2874
September 1-8	1	0.20	0.40	0.40	0.60	0.33	1282	1075	691	3047
Period Average	46 (Tot.)	0.16	0.46	0.53	0.55	0.34	1364	1085	698	3147
"18 MGD" STEP FEED MODE										
September 14-30	14	0.18	0.22	0.31	0.49	0.23	1472	1233	823	3528
October 1-31	23	0.69	0.32	0.86	1.56	0.64	1427	1111	826	3364
Period Average	37 (Tot.)	0.51	0.28	0.67	1.18	0.49	1443	1154	825	3422
"12 MGD" CONVENTIONAL MODE										
November 6-30	24	0.17	0.32	0.59	1.60	0.39	929	679	567	2174
December 1-31	13	0.16	1.04	1.65	2.38	0.86	969	732	565	2266
Period Average	37 (Tot.)	0.16	0.72	1.18	2.03	0.65	951	708	566	2225

50 ft from front of aeration tank (Grid 1).
+ 150 ft from front of aeration tank (Grid 2).
* 250 ft from front of aeration tank (Grid 3).
^ 300 ft from front of aeration tank (effluent end).
! Air flow weighted average.

TABLE B-12. AFTERNOON DO PROFILE RESULTS - DOME SYSTEM A

Test Period (1982)	Number of Profiles	DO Concentration (mg/l) Position 1#	Position 2+	Position 3*	Position 4^	Weighted Average!	Air Flow (scfm) Grid 1	Grid 2	Grid 3	Total Tank
"18 MGD" CONVENTIONAL MODE										
July 6-31	23	0.19	0.95	0.95	1.11	0.61	1781	1323	827	3931
August 1-31	22	0.14	0.60	0.58	0.70	0.39	1470	1046	646	3161
September 1-8	1	0.20	0.50	0.60	0.70	0.38	1576	1029	647	3252
Period Average	46 (Tot.)	0.17	0.73	0.73	0.86	0.48	1607	1155	718	3480
"18 MGD" STEP FEED MODE										
September 14-30	14	0.23	0.29	0.43	0.71	0.31	1629	1092	732	3453
October 1-31	23	0.73	0.25	0.60	1.09	0.58	1395	934	701	3030
Period Average	37 (Tot.)	0.55	0.26	0.54	0.96	0.48	1478	990	712	3180
"12 MGD" CONVENTIONAL MODE										
November 6-30	24	0.15	0.35	0.43	0.68	0.31	912	749	544	2204
December 1-31	13	0.18	1.10	1.03	1.22	0.71	1010	857	588	2455
Period Average	37 (Tot.)	0.17	0.77	0.76	0.98	0.53	966	809	568	2343

50 ft from front of aeration tank (Grid 1).
+ 150 ft from front of aeration tank (Grid 2).
* 250 ft from front of aeration tank (Grid 3).
^ 300 ft from front of aeration tank (effluent end).
! Air flow weighted average.

TABLE B-13. AFTERNOON DO PROFILE RESULTS - DOME SYSTEM B

Test Period	Number of Profiles	DO Concentration (mg/l)					Air Flow (scfm)			
(1982)		Position 1#	Position 2+	Position 3~	Position 4^	Weighted Average!	Grid 1	Grid 2	Grid 3	Total Tank
"18 MGD" CONVENTIONAL MODE										
July 6-31	23	0.14	0.39	0.37	0.47	0.28	1535	1153	659	3346
August 1-31	22	0.13	0.33	0.33	0.41	0.24	1367	965	567	2898
September 1-8	1	0.20	0.30	0.30	0.40	0.25	1509	933	563	3005
Period Average	46 (Tot.)	0.14	0.35	0.34	0.43	0.26	1451	1036	603	3091
"18 MGD" STEP FEED MODE										
September 14-30	14	0.23	0.25	0.54	0.93	0.32	1556	991	683	3230
October 1-31	23	0.57	0.46	0.73	1.43	0.62	1412	878	754	3044
Period Average	37 (Tot.)	0.45	0.39	0.66	1.25	0.51	1463	918	729	3110
"12 MGD" CONVENTIONAL MODE										
November 6-30	24	0.15	0.31	0.40	0.65	0.28	923	740	522	2185
December 1-31	13	0.15	0.63	0.93	1.06	0.50	968	786	543	2296
Period Average	37 (Tot.)	0.15	0.49	0.69	0.88	0.40	948	766	533	2247

50 ft from front of aeration tank (Grid 1).
+ 150 ft from front of aeration tank (Grid 2).
~ 250 ft from front of aeration tank (Grid 3).
^ 300 ft from front of aeration tank (effluent end).
! Air flow weighted average.

TABLE B-14. AFTERNOON DO PROFILE RESULTS - AVERAGE SYSTEM

Test Period (1982)	Number of Profiles	DO Concentration (mg/l) Position 1#	Position 2+	Position 3*	Position 4^	Weighted Average!	Air Flow (scfm) Grid 1	Grid 2	Grid 3	Total Tank
"18 MGD" CONVENTIONAL MODE										
July 6-31	23	0.16	0.62	0.66	0.75	0.43	1616	1228	749	3593
August 1-31	22	0.14	0.45	0.46	0.52	0.31	1360	998	620	2978
September 1-8	1	0.20	0.40	0.43	0.57	0.32	1456	1012	634	3101
Period Average	46 (Tot.)	0.16	0.51	0.54	0.62	0.36	1474	1092	673	3239
"18 MGD" STEP FEED MODE										
September 14-30	14	0.21	0.25	0.43	0.71	0.29	1552	1105	746	3404
October 1-31	23	0.66	0.34	0.73	1.36	0.61	1411	974	761	3146
Period Average	37 (Tot.)	0.50	0.31	0.62	1.13	0.50	1461	1021	755	3237
"12 MGD" CONVENTIONAL MODE										
November 6-30	24	0.16	0.33	0.47	0.98	0.33	921	723	544	2188
December 1-31	13	0.16	0.92	1.20	1.55	0.69	982	792	565	2339
Period Average	37 (Tot.)	0.16	0.66	0.87	1.30	0.53	955	761	556	2272

\# 50 ft from front of aeration tank (Grid 1).
\+ 150 ft from front of aeration tank (Grid 2).
* 250 ft from front of aeration tank (Grid 3).
^ 300 ft from front of aeration tank (effluent end).
! Air flow weighted average.

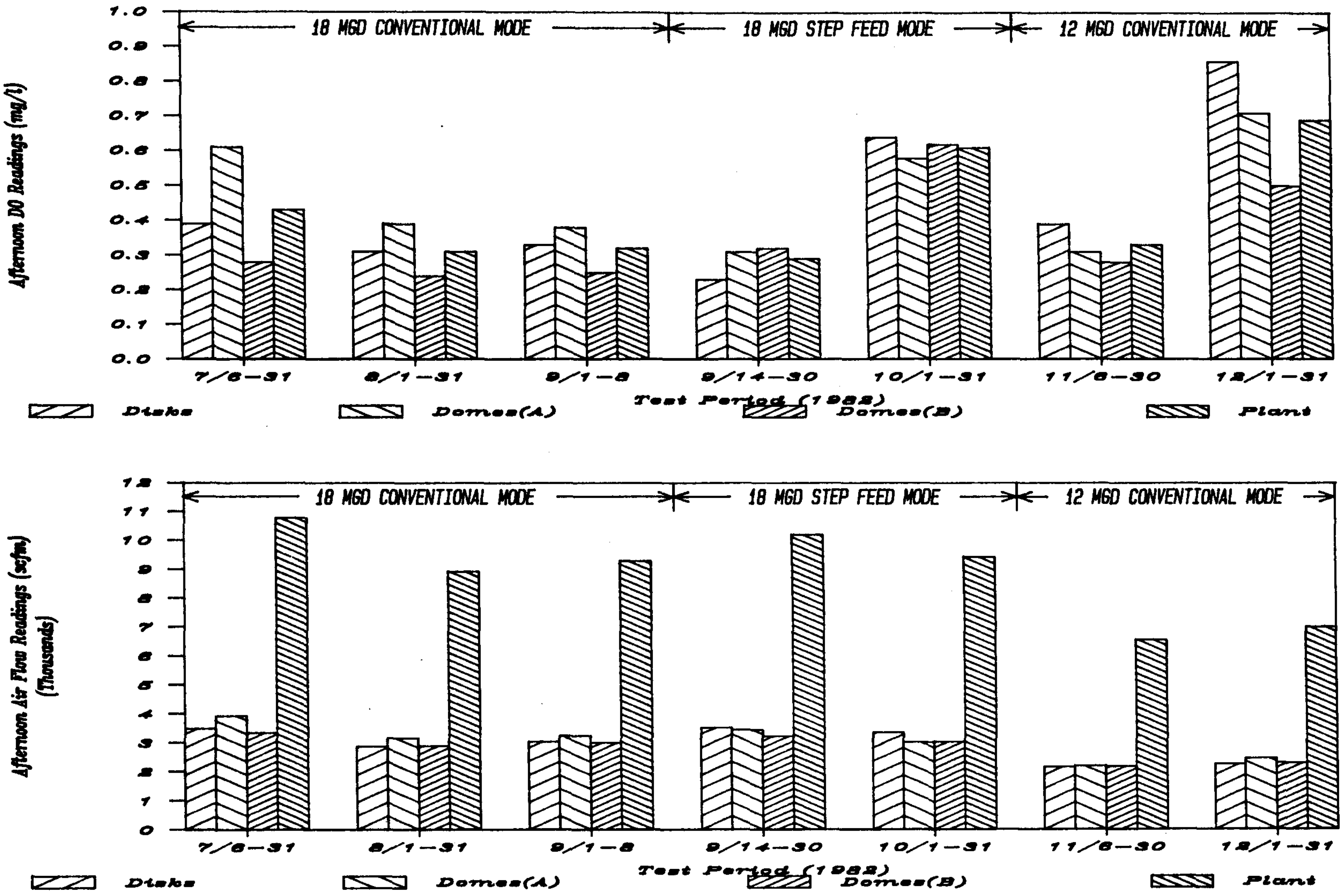


Figure B-10. Afternoon DO Profile Results

TABLE B-15. ESTIMATED DAILY AVERAGE DO LEVELS AND MIN/MAX EXIT DO LEVELS

Test Period	Estimated Daily Average DO Level* (mg/l)				Minimum Exit DO Level+ (mg/l)				Maximum Exit DO Level+ (mg/l)			
(1982)	Disk System	Dome System A	Dome System B	Total Plant	Disk System	Dome System A	Dome System B	Total Plant	Disk System	Dome System A	Dome System B	Total Plant
"18 MGD" CONVENTIONAL MODE												
July 6-31	0.7	1.1	0.5	0.8	0.5	0.7	0.6	0.6	2.6	3.9	3.3	3.3
August 1-31	0.6	0.7	0.4	0.6	0.3	0.4	0.5	0.4	1.9	2.6	2.4	2.3
September 1-8	0.6	0.7	0.5	0.6	0.2	0.3	0.4	0.3	1.6	2.0	2.1	1.9
Period Average	0.6	0.9	0.5	0.7	0.4	0.5	0.5	0.5	2.1	3.0	2.7	2.7
"18 MGD" STEP FEED MODE												
September 14-30	0.3	0.4	0.4	0.4	0.2	0.3	0.5	0.3	2.2	3.4	3.4	3.0
October 1-31	0.8	0.8	0.8	0.8	0.8	0.9	1.0	0.9	3.2	6.9	5.2	5.1
Period Average	0.6	0.6	0.7	0.7	0.6	0.7	0.8	0.7	2.8	5.7	4.6	4.4
"12 MGD" CONVENTIONAL MODE												
November 6-30	0.5	0.4	.3	.4	0.4	0.4	0.8	0.5	2.2	5.7	5.4	4.4
December 1-31	1.1	0.9	.6	.9	0.4	0.4	0.5	0.4	1.6	5.4	3.8	3.6
Period Average	0.8	0.7	.5	.6	0.4	0.4	0.6	0.4	1.9	5.5	4.5	4.0

* It was not possible to make 24 hr average measurements of total tank DO concentration. The rough estimates shown are based on an assumed total plant mode average DO of 0.65 mg/l. The relative DO levels by tank and month were estimated from existing DO profile information.

+ From chart recordings of DO concentration at the effluent end of the aeration tanks.

TABLE B-16. OVERALL POWER UTILIZATION - DISK SYSTEM

Test Period (1982)	Total Tank Air Flow (scfm)	Average Air Flow Per Diffuser (scfm)	Estimated Total Diffuser Headloss (in. wc)	Blower Delivered Power* (hp)	Blower Wire Power+ (hp)
"18 MGD" CONVENTIONAL MODE					
July 6-31	3530	1.74	19.2	89.5	146.2
August 1-31	3042	1.50	15.3	75.7	123.6
September 1-8	2833	1.40	13.7	69.9	114.2
Period Average	3211	1.58	16.7	80.5	131.5
"18 MGD" STEP FEED MODE					
September 14-30	3358	1.66	17.5	84.2	137.6
October 1-31	3379	1.67	17.6	84.8	138.5
Period Average	3372	1.67	17.6	84.6	138.2
"12 MGD" CONVENTIONAL MODE					
November 6-30	2317	1.14	10.3	56.0	91.5
December 1-31	2382	1.18	10.5	57.7	94.2
Period Average	2353	1.16	10.4	56.9	93.0

* Using the adiabatic compression formula.

\+ Using the adiabatic compression formula and an overall blower/coupling /motor efficiency of 0.612.

TABLE B-17. OVERALL POWER UTILIZATION - DOME SYSTEM A

Test Period (1982)	Total Tank Air Flow (scfm)	Average Air Flow Per Diffuser (scfm)	Estimated Total Diffuser Headloss (in. wc)	Blower Delivered Power* (hp)	Blower Wire Power+ (hp)
"18 MGD" CONVENTIONAL MODE					
July 6-31	3958	1.56	12.0	96.8	158.2
August 1-31	3318	1.31	10.4	80.5	131.6
September 1-8	3043	1.20	9.7	73.6	120.2
Period Average	3540	1.40	11.0	86.2	140.8
"18 MGD" STEP FEED MODE					
September 14-30	3280	1.30	10.3	79.4	129.7
October 1-31	3059	1.21	12.1	74.7	122.1
Period Average	3138	1.24	11.5	76.4	124.8
"12 MGD" CONVENTIONAL MODE					
November 6-30	2352	0.93	9.7	56.7	92.6
December 1-31	2591	1.02	10.4	62.7	102.4
Period Average	2484	0.98	10.1	60.0	98.0

* Using the adiabatic compression formula.

\+ Using the adiabatic compression formula and an overall blower/coupling /motor efficiency of 0.612.

TABLE B-18. OVERALL POWER UTILIZATION - DOME SYSTEM B

Test Period (1982)	Total Tank Air Flow (scfm)	Average Air Flow Per Diffuser (scfm)	Estimated Total Diffuser Headloss (in. wc)	Blower Delivered Power* (hp)	Blower Wire Power+ (hp)
"18 MGD" CONVENTIONAL MODE					
July 6-31	3371	1.33	12.1	82.5	134.8
August 1-31	3044	1.20	10.7	74.0	120.9
September 1-8	2842	1.12	10.4	69.0	112.7
Period Average	3150	1.24	11.2	76.8	125.5
"18 MGD" STEP FEED MODE					
September 14-30	3082	1.22	14.5	76.2	124.4
October 1-31	3073	1.22	14.9	76.1	124.3
Period Average	3076	1.22	14.8	76.1	124.3
"12 MGD" CONVENTIONAL MODE					
November 6-30	2327	0.92	12.4	56.9	92.9
December 1-31	2412	0.95	12.7	59.0	96.5
Period Average	2374	0.94	12.6	58.1	94.9

* Using the adiabatic compression formula.
\+ Using the adiabatic compression formula and an overall blower/coupling motor efficiency of 0.612.

TABLE B-19. OVERALL POWER UTILIZATION - TOTAL PLANT

Test Period (1982)	Total Tank Air Flow (scfm)	Average Air Flow Per Diffuser (scfm)	Estimated Total Diffuser Headloss (in. wc)	Blower Delivered Power* (hp)	Blower Wire Power+ (hp)
"18 MGD" CONVENTIONAL MODE					
July 6-31	10860	1.74(S) 1.44(N)	14.4	268.8	439.2
August 1-31	9403	1.50(S) 1.26(N)	12.1	230.2	376.1
September 1-8	8719	1.40(S) 1.16(N)	11.3	212.5	347.1
Period Average	9902	1.58(S) 1.32(N)	12.9	243.5	397.8
"18 MGD" STEP FEED MODE					
September 14-30	9721	1.66(S) 1.26(N)	14.1	239.8	391.7
October 1-31	9511	1.67(S) 1.22(N)	14.9	235.6	384.9
Period Average	9585	1.67(S) 1.23(N)	14.6	237.1	387.3
"12 MGD" CONVENTIONAL MODE					
November 6-30	6996	1.14(S) 0.92(N)	10.8	169.6	277.0
December 1-31	7385	1.18(S) 0.98(N)	11.2	179.4	293.1
Period Average	7211	1.16(S) 0.95(N)	11.0	175.0	285.9

* Using the adiabatic compression formula.
+ Using the adiabatic compression formula and an overall blower/coupling /motor efficiency of 0.612.

TABLE B-20. DELIVERED AERATION POWER DENSITY BY GRID

Test Period	Delivered Aeration Power Density (hp/1000 cu ft)*											
	Disk System				Dome System A				Dome System B			
(1982)	Grid 1	Grid 2	Grid 3	Total Tank	Grid 1	Grid 2	Grid 3	Total Tank	Grid 1	Grid 2	Grid 3	Total Tank
"18 MGD" CONVENTIONAL MODE												
July 6-31	0.937	0.720	0.449	0.702	1.029	0.767	0.483	0.759	0.897	0.667	0.378	0.647
August 1-31	0.773	0.611	0.396	0.593	0.890	0.617	0.387	0.631	0.838	0.569	0.334	0.580
September 1-8	0.696	0.575	0.374	0.548	0.819	0.559	0.353	0.577	0.828	0.496	0.299	0.541
Period Average	0.829	0.650	0.414	0.631	0.937	0.670	0.421	0.676	0.860	0.599	0.347	0.602
"18 MGD" STEP FEED MODE												
September 14-30	0.836	0.691	0.459	0.662	0.881	0.590	0.401	0.624	0.859	0.546	0.391	0.599
October 1-31	0.846	0.659	0.495	0.667	0.813	0.541	0.408	0.587	0.823	0.514	0.457	0.598
Period Average	0.842	0.670	0.482	0.665	0.837	0.558	0.406	0.600	0.836	0.525	0.434	0.598
"12 MGD" CONVENTIONAL MODE												
November 6-30	0.564	0.411	0.346	0.441	0.551	0.456	0.331	0.446	0.562	0.454	0.327	0.448
December 1-31	0.579	0.439	0.343	0.454	0.599	0.523	0.357	0.493	0.579	0.479	0.335	0.464
Period Average	0.572	0.427	0.344	0.448	0.578	0.493	0.345	0.472	0.571	0.468	0.331	0.457

* Based on blower power determinations using the adiabatic compression formula.

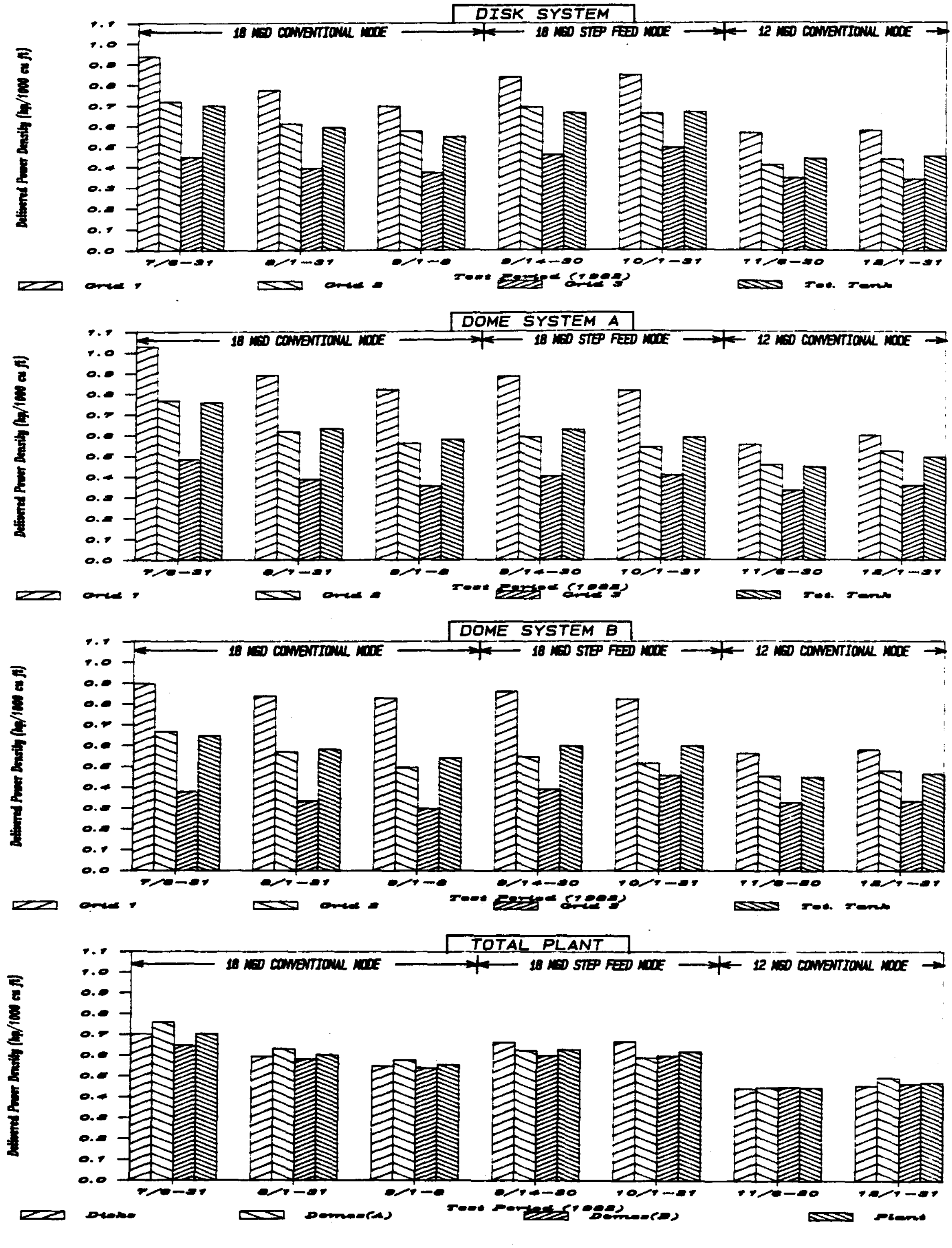


Figure B-11. Delivered Aeration Power Density

TABLE B-21. WIRE POWER UTILIZATION BY GRID

Test Period	Wire Power Utilization (hp)*											
	Disk System				Dome System A				Dome System B			
(1982)	Grid 1	Grid 2	Grid 3	Total Tank	Grid 1	Grid 2	Grid 3	Total Tank	Grid 1	Grid 2	Grid 3	Total Tank
"18 MGD" CONVENTIONAL MODE												
July 6-31	65.0	50.0	31.2	146.2	71.4	53.2	33.5	158.2	62.3	46.3	26.3	134.8
August 1-31	53.7	42.4	27.5	123.6	61.8	42.9	26.9	131.6	58.2	39.5	23.2	120.9
September 1-8	48.3	39.9	26.0	114.2	56.9	38.8	24.5	120.2	57.5	34.4	20.8	112.7
Period Average	57.6	45.1	28.8	131.5	65.0	46.5	29.2	140.8	59.8	41.6	24.1	125.5
"18 MGD" STEP FEED MODE												
September 14-30	57.9	47.9	31.8	137.6	61.0	40.9	27.8	129.7	59.5	37.8	27.1	124.4
October 1-31	58.6	45.6	34.3	138.5	56.3	37.5	28.3	122.1	57.0	35.6	31.7	124.3
Period Average	58.4	46.4	33.4	138.2	58.0	38.7	28.1	124.8	57.9	36.4	30.1	124.3
"12 MGD" CONVENTIONAL MODE												
November 6-30	39.1	28.5	24.0	91.5	38.2	31.6	22.9	92.6	38.9	31.4	22.6	92.9
December 1-31	40.1	30.4	23.8	94.2	41.5	36.2	24.7	102.4	40.1	33.2	23.2	96.5
Period Average	39.7	29.6	23.9	93.0	40.0	34.1	23.9	98.0	39.6	32.4	22.9	94.9

* Based on blower power determinations using the adiabatic compression formula and an overall efficiency of 0.612.

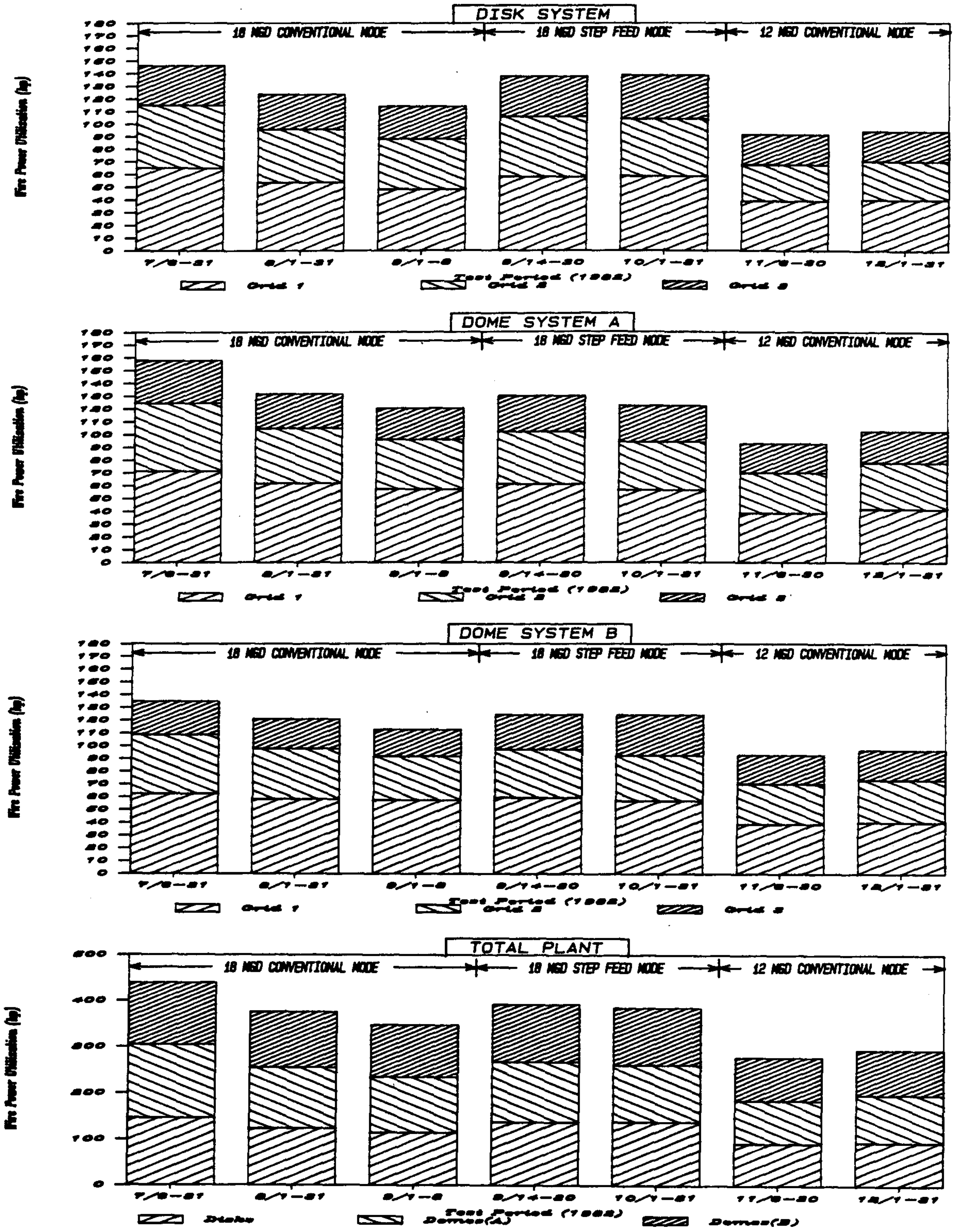


Figure B-12. Aeration System Wire Power Utilization

TABLE B-22. AERATION EFFICIENCY RESULTS - DISK SYSTEM*

Test Period	Estimated Oxygen Uptake Rate+	Estimated Mixed Liquor Temperature~	Daily Average Air Flow Per Diffuser	Total Delivered Power Density^	Estimated Daily Average DO Level!	Oxygen Transfer Efficiency (%)		Delivered Aeration Efficiency^ (lbs O_2/hp-hr)		Wire Aeration Efficiency> (lbs O_2/hp-hr)	
(1982)	(lbs/day)	(deg. F)	(scfm)	$\left(\frac{\text{hp}}{\text{1000 cu ft}}\right)$	(mg/l)	Actual (AOTE)	Standard< (αFSOTE)	Actual (ADAE)	Standard< (αFSDAE)	Actual (AWAE)	Standard< (αFSWAE)
"18 MGD" CONVENTIONAL MODE											
July 6-31	5955	79	1.74	0.702	0.7	6.78	7.19	2.77	2.94	1.70	1.80
August 1-31	5982	81	1.50	0.593	0.6	7.91	8.22	3.29	3.43	2.02	2.10
September 1-8	6199	82	1.40	0.548	0.6	8.80	9.20	3.70	3.86	2.26	2.36
Period Average	5998	80	1.58	0.631	0.6	7.57	7.93	3.13	3.29	1.92	2.01
"18 MGD" STEP FEED MODE											
September 14-30	6616	80	1.66	0.662	0.3	7.92	8.00	3.27	3.31	2.00	2.02
October 1-31	6749	79	1.67	0.667	0.8	8.03	8.65	3.32	3.57	2.03	2.19
Period Average	6702	79	1.67	0.665	0.6	7.99	8.42	3.30	3.48	2.02	2.13
"12 MGD" CONVENTIONAL MODE											
November 6-30	4221	76	1.14	0.441	0.5	7.33	7.60	3.14	3.26	1.92	1.99
December 1-31	4859	73	1.18	0.454	1.1	8.21	9.12	3.51	3.90	2.15	2.39
Period Average	4574	74	1.16	0.448	0.8	7.82	8.44	3.34	3.61	2.05	2.21

* The oxygen transfer rates on which these efficiencies were based were determined from kinetic calculations, rather than by direct measurement. As a result, the efficiencies shown should only be considered approximate.
+ From kinetic calculations.
~ Approximated by morning final effluent temperature readings.
^ Based on power determinations using the adiabatic compression formula.
! Rough estimates only. See Table A-14.
< Based on standard conditions of 68 degrees F, 14.70 psia and 0 mg/l DO.
> Based on power determinations using the adiabatic compression formula and an overall blower/coupling/motor efficiency of 0.612.

TABLE B-23. AERATION EFFICIENCY RESULTS - DOME SYSTEM A*

Test Period	Estimated Oxygen Uptake Rate+	Estimated Mixed Liquor Temperature~	Daily Average Air Flow Per Diffuser	Total Delivered Power Density^	Estimated Daily Average DO Level!	Oxygen Transfer Efficiency (%)		Delivered Aeration Efficiency^ (lbs O_2/hp-hr)		Wire Aeration Efficiency> (lbs O_2/hp-hr)	
(1982)	(lbs/day)	(deg. F)	(scfm)	$\left(\frac{hp}{1000 \text{ cu ft}}\right)$	(mg/l)	Actual (AOTE)	Standard< (αFSOTE)	Actual (ADAE)	Standard< (αFSDAE)	Actual (AWAE)	Standard< (αFSWAE)
"18 MGD" CONVENTIONAL MODE											
July 6-31	5860	79	1.56	0.759	1.1	5.95	6.62	2.52	2.80	1.54	1.72
August 1-31	5833	81	1.31	0.631	0.7	7.07	7.48	3.02	3.20	1.85	1.96
September 1-8	6157	82	1.20	0.577	0.7	8.14	8.60	3.49	3.69	2.13	2.26
Period Average	5884	80	1.40	0.676	0.9	6.75	7.27	2.88	3.10	1.76	1.90
"18 MGD" STEP FEED MODE											
September 14-30	6501	80	1.30	0.624	0.4	7.97	8.15	3.41	3.49	2.09	2.14
October 1-31	6576	79	1.21	0.587	0.8	8.65	9.22	3.67	3.91	2.24	2.39
Period Average	6549	79	1.24	0.600	0.6	8.41	8.84	3.58	3.76	2.19	2.30
"12 MGD" CONVENTIONAL MODE											
November 6-30	4042	76	0.93	0.446	0.4	6.91	7.09	2.97	3.05	1.82	1.86
December 1-31	4816	73	1.02	0.493	0.9	7.48	8.13	3.20	3.48	1.96	2.13
Period Average	4470	74	0.98	0.472	0.7	7.23	7.67	3.10	3.29	1.90	2.01

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* The oxygen transfer rates on which these efficiencies were based were determined from kinetic calculations, rather than by direct measurement. As a result, the efficiencies shown should only be considered approximate.

\+ From kinetic calculations.

~ Approximated by morning final effluent temperature readings.

^ Based on power determinations using the adiabatic compression formula.

! Rough estimates only. See Table A-14.

< Based on standard conditions of 68 degrees F, 14.70 psia and 0 mg/l DO.

\> Based on power determinations using the adiabatic compression formula and an overall blower/coupling/motor efficiency of 0.612.

TABLE B-24. AERATION EFFICIENCY RESULTS - DOME SYSTEM B#

Test Period	Estimated Oxygen Uptake Rate+	Estimated Mixed Liquor Temperature*	Daily Average Air Flow Per Diffuser	Total Delivered Power Density^	Estimated Daily Average DO Level!	Oxygen Transfer Efficiency (%)		Delivered Aeration Efficiency^ (lbs O_2/hp-hr)		Wire Aeration Efficiency> (lbs O_2/hp-hr)	
(1982)	(lbs/day)	(deg. F)	(scfm)	$\left(\frac{hp}{1000\ cu\ ft}\right)$	(mg/l)	Actual (AOTE)	Standard< (αFSOTE)	Actual (ADAE)	Standard< (αFSDAE)	Actual (AWAE)	Standard< (αFSWAE)
"18 MGD" CONVENTIONAL MODE											
July 6-31	5818	79	1.33	0.647	0.5	6.94	7.19	2.94	3.04	1.80	1.86
August 1-31	5822	81	1.20	0.580	0.4	7.69	7.88	3.28	3.36	2.01	2.06
September 1-8	6070	82	1.12	0.541	0.5	8.59	8.82	3.67	3.77	2.24	2.30
Period Average	5851	80	1.24	0.602	0.5	7.50	7.72	3.19	3.28	1.95	2.01
"18 MGD" STEP FEED MODE											
September 14-30	6448	80	1.22	0.599	0.4	8.42	8.62	3.53	3.61	2.16	2.21
October 1-31	6577	79	1.22	0.598	0.8	8.61	9.24	3.60	3.86	2.20	2.37
Period Average	6531	79	1.22	0.598	0.7	8.54	9.02	3.58	3.77	2.19	2.31
"12 MGD" CONVENTIONAL MODE											
November 6-30	4066	76	0.92	0.448	0.3	7.03	7.18	2.98	3.04	1.82	1.86
December 1-31	4791	73	0.95	0.464	0.6	7.99	8.44	3.38	3.57	2.07	2.19
Period Average	4467	74	0.94	0.457	0.5	7.56	7.88	3.20	3.33	1.96	2.04

The oxygen transfer rates on which these efficiencies were based were determined from kinetic calculations, rather than by direct measurement. As a result, the efficiencies shown should only be considered approximate.
+ From kinetic calculations.
* Approximated by morning final effluent temperature readings.
^ Based on power determinations using the adiabatic compression formula.
! Rough estimates only. See Table A-14.
< Based on standard conditions of 68 degrees F, 14.70 psia and 0 mg/l DO.
> Based on power determinations using the adiabatic compression formula and an overall blower/coupling/motor efficiency of 0.612.

TABLE B-25. AERATION EFFICIENCY RESULTS - TOTAL PLANT#

Test Period	Estimated Oxygen Uptake Rate+	Estimated Mixed Liquor Temperature*	Daily Average Air Flow Per Diffuser	Total Delivered Power Density^	Estimated Daily Average DO Level!	Oxygen Transfer Efficiency (%)		Delivered Aeration Efficiency^ (lbs O_2/hp-hr)		Wire Aeration Efficiency> (lbs O_2/hp-hr)	
(1982)	(lbs/day)	(deg. F)	(scfm)	$\left(\frac{hp}{1000\ cu\ ft}\right)$	(mg/l)	Actual (AOTE)	Standard< (αFSOTE)	Actual (ADAE)	Standard< (αFSDAE)	Actual (AWAE)	Standard< (αFSWAE)
"18 MGD" CONVENTIONAL MODE											
July 6-31	17633	79	1.74(S) 1.44(N)	.703	0.8	6.56	7.00	2.74	2.93	1.68	1.79
August 1-31	17638	81	1.50(S) 1.26(N)	.601	0.6	7.56	7.86	3.20	3.33	1.96	2.04
September 1-8	18425	82	1.40(S) 1.16(N)	.555	0.6	8.51	8.87	3.62	3.77	2.21	2.31
Period Average	17733	80	1.58(S) 1.32(N)	.636	0.7	7.28	7.64	3.07	3.22	1.88	1.97
"18 MGD" STEP FEED MODE											
September 14-30	19565	80	1.66(S) 1.26(N)	.628	0.4	8.10	8.26	3.40	3.47	2.08	2.12
October 1-31	19902	79	1.67(S) 1.22(N)	.617	0.8	8.43	9.04	3.53	3.78	2.16	2.32
Period Average	19783	79	1.67(S) 1.23(N)	.621	0.7	8.31	8.76	3.48	3.67	2.13	2.25
"12 MGD" CONVENTIONAL MODE											
November 6-30	12329	76	1.14(S) 0.92(N)	.445	0.4	7.09	7.29	3.03	3.12	1.85	1.90
December 1-31	14467	73	1.18(S) 0.98(N)	.470	0.9	7.89	8.56	3.36	3.65	2.06	2.24
Period Average	13513	74	1.16(S) 0.95(N)	.459	0.6	7.53	7.99	3.21	3.41	1.97	2.09

The oxygen transfer rates on which these efficiencies were based were determined from kinetic calculations, rather than by direct measurement. As a result, the efficiencies shown should only be considered approximate.
+ From kinetic calculations.
* Approximated by morning final effluent temperature readings.
^ Based on power determinations using the adiabatic compression formula.
! Rough estimates only. See Table A-14.
< Based on standard conditions of 68 degrees F, 14.70 psia and 0 mg/l DO.
> Based on power determinations using the adiabatic compression formula and an overall blower/coupling/motor efficiency of 0.612.

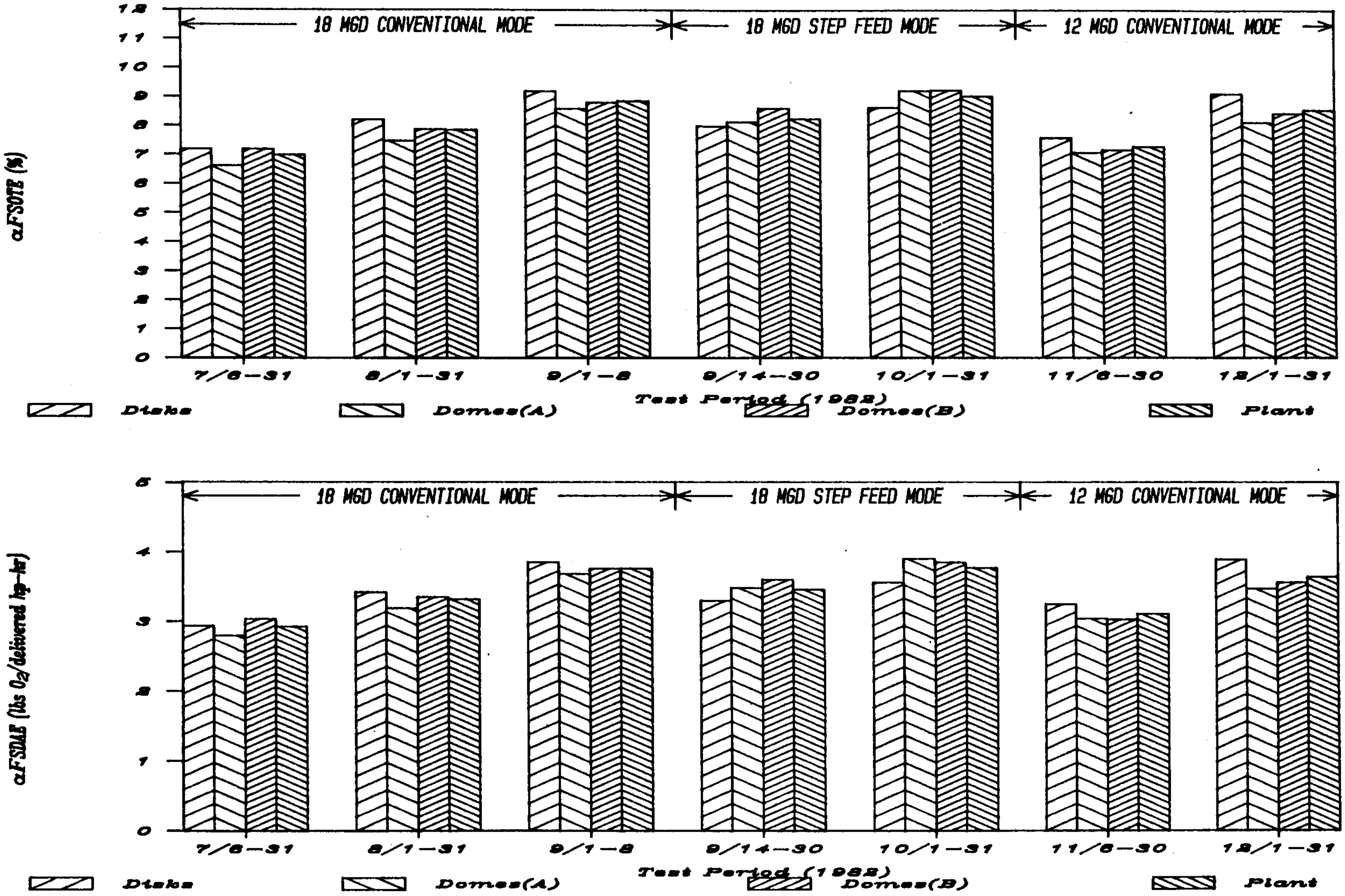

Figure B-13. Standard Oxygen Transfer Efficiency (αFSOTE) And Standard Delivered Aeration Efficiency (αFSDAE) Based On Kinetic Calculations of Oxygen Demand

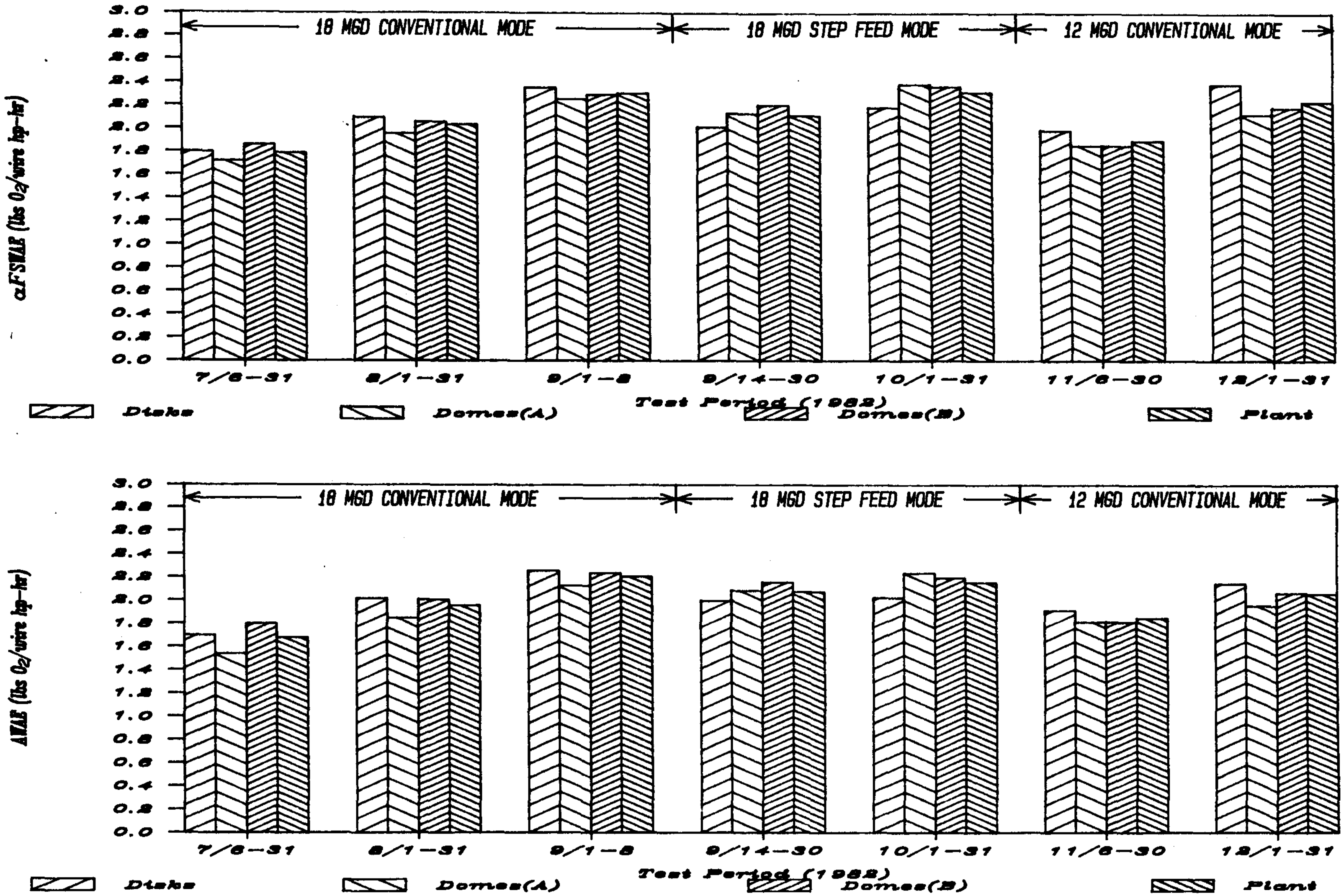

Figure B-14. Standard Wire Aeration Efficiency (αFSWAE) And Actual Wire Aeration Efficiency (AWAE) Based On Kinetic Calculations of Oxygen Demand

TABLE B-26. SECONDARY CLARIFIER PARAMETERS

Test Period (1982)	Clarifiers In Service (#)	Overflow Rate (gal/day / sq ft)	Detention Time (hrs)	Solids Loading Rate (lbs/day / sq ft)	Weir Overflow Rate (gal/day / ft)
"18 MGD" CONVENTIONAL MODE					
July 6-31	6.00	1002	1.34	18.3	15660
August 1-31	6.00	972	1.37	17.3	15203
September 1-8	6.00	905	1.46	15.0	14148
Period Average	6.00	976	1.37	17.4	15256
"18 MGD" STEP FEED MODE					
September 14-30	5.65	1095	1.14	22.6	17120
October 1-31	5.84	956	1.33	13.4	14946
Period Average	5.77	1005	1.26	16.6	15716
"12 MGD" CONVENTIONAL MODE					
November 6-30	5.04	806	1.66	9.3	12610
December 1-31	5.00	815	1.65	10.5	12748
Period Average	5.02	811	1.65	10.0	12686

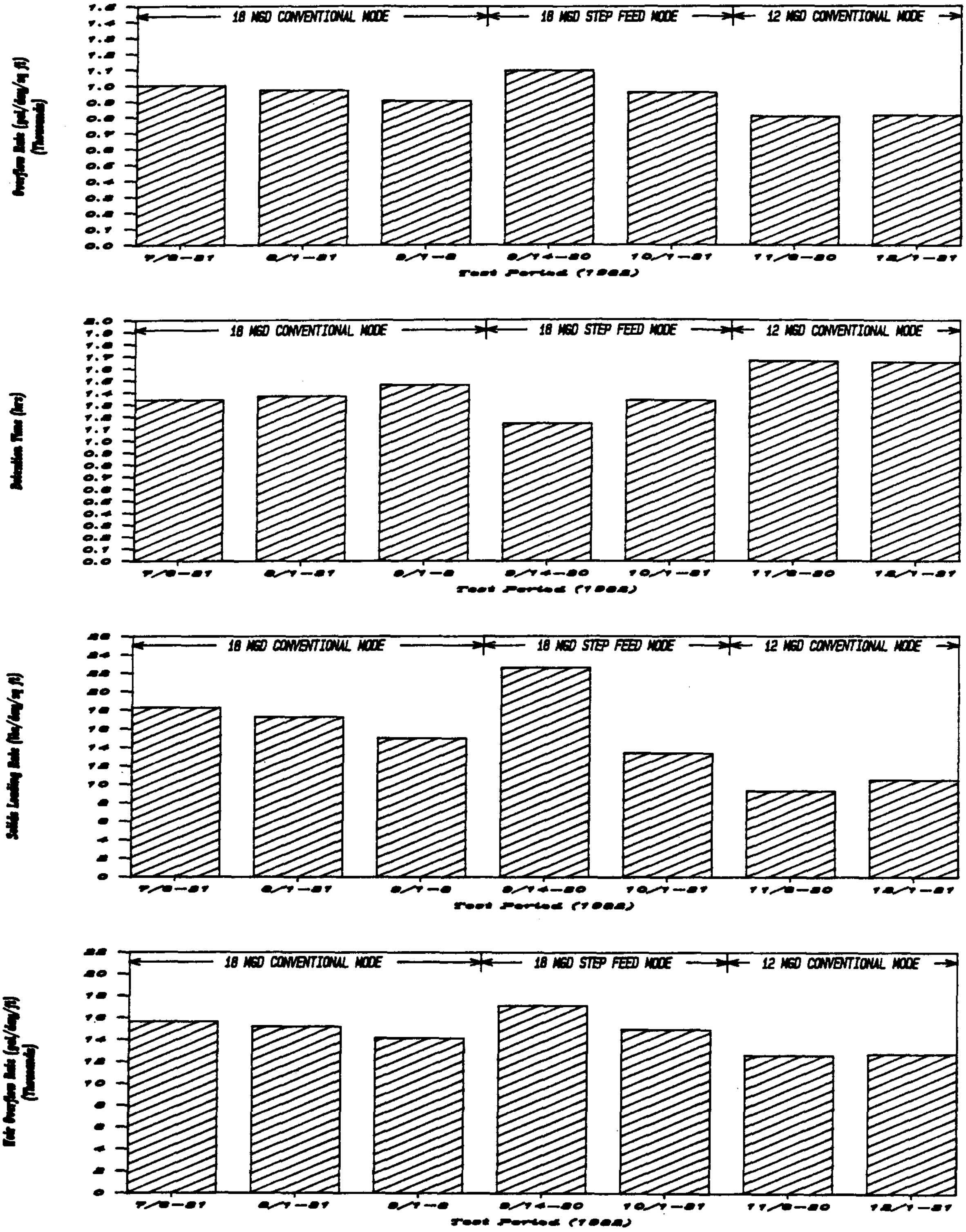

Figure B-15. Secondary Clarifier Parameters

TABLE B-27. PLANT PERFORMANCE#

Test Period	Total Plant Basis+				Secondary System Basis*							
(1982)	Total COD Removal * (%)	Effluent Total COD (mg/l)	Effluent Turbidity (JTU)	Effluent Suspended Solids (mg/l)	Total COD Removal (%)	COD Conversion Efficiency^ (%)	Effluent Total COD (mg/l)	Effluent Turbidity (JTU)	Suspended Solids Removal (%)	Effluent Suspended Solids (mg/l)	Effluent Ammonia (mg/l)	Nitrification Efficiency! (%)
"18 MGD" CONVENTIONAL MODE												
July 6-31	94.2	31	1.5	<2	86.0	87.4	36	2.5	93.9	6	14.4	0.7
August 1-31	94.5	29	1.5	<2	87.2	89.9	32	2.5	95.5	5	13.8	6.0
September 1-8	95.7	25	1.4	<2	88.1	91.3	30	3.2	93.5	7	14.6	0.0
Period Average	94.5	29	1.5	<2	86.8	89.1	33	2.6	94.6	6	14.1	3.1
"18 MGD" STEP FEED MODE												
September 14-30	95.1	28	1.3	2	87.6	90.2	31	2.2	94.0	6	17.4	0.8
October 1-31	94.0	34	1.3	<2	86.0	88.4	37	2.7	93.9	6	17.1	7.4
Period Average	94.4	32	1.3	<2	86.6	89.0	35	2.5	93.9	6	17.2	5.1
"12 MGD" CONVENTIONAL MODE												
November 6-30	93.9	36	1.2	<2	85.3	87.8	38	2.5	93.7	6	19.2	0.0
December 1-31	94.7	29	1.5	<2	86.9	90.3	34	3.3	92.9	7	17.1	3.8
Period Average	94.3	32	1.4	<2	86.2	89.2	36	2.9	93.3	7	18.0	2.1

See later tables for additional waste stream laboratory results.
+ Plant influent to chlorine contact chamber effluent.
* Primary effluent to secondary clarifier effluent.
^ (Primary effluent total COD minus secondary effluent soluble COD) divided by primary effluent total COD, times 100.
! TKN converted by nitrifiers divided by TKN available for conversion (less synthesis requirements of heterotrophs).

TABLE B-28. COD AND BOD RESULTS

Test Period	COD (mg/l)						BOD (mg/l)		
	Raw	Primary	Secondary		Final*		Raw	Primary	Final*
(1982)	(Total)	(Total)	(Total)	(Soluble)	(Total)	(Soluble)	(Total)	(Total)	(Total)
"10 MGD" CONVENTIONAL MODE									
July 6-31	532	257	36	28	31	28	184	96	4
August 1-31	524	250	32	25	29	25	276	147	3
September 1-8	580	252	30	22	25	23	262	120	4
Period Average	534	253	33	26	29	26	237	123	4
"10 MGD" STEP FEED MODE									
September 14-30	567	249	31	24	28	25	172	80	4
October 1-31	565	264	37	30	34	30	271	148	4
Period Average	566	259	35	28	32	28	236	124	4
"12 MGD" CONVENTIONAL MODE									
November 6-30	590	259	38	30	36	31	272	162	4
December 1-31	546	260	34	25	29	26	376	187	3
Period Average	566	260	36	27	32	28	330	176	3

* After all treatment, including filtration and chlorination.

TABLE B-29. SUSPENDED SOLIDS RESULTS

Test Period (1982)	Suspended Solids Results (mg/l)								
	Flow Streams					Mixed Liquor			
	Raw	Primary	Secondary	Final*	Return Sludge	Disk System	Dome System A	Dome System B	Total Plant
"18 MGD" CONVENTIONAL MODE									
July 6-31	324	98	6	<2	8051	1638	1701	1667	1669
August 1-31	359	110	5	<2	7013	1622	1612	1623	1619
September 1-8	365	108	7	<2	6934	1450	1532	1513	1498
Period Average	346	105	6	<2	7418	1607	1638	1627	1624
"18 MGD" STEP FEED MODE									
September 14-30	393	100	6	2	6129	2088+	2138+	2138+	2121
October 1-31	344	99	6	<2	4433	1456+	1490+	1490+	1479
Period Average	361	99	6	<2	5034	1680+	1720+	1720+	1707
"12 MGD" CONVENTIONAL MODE									
November 6-30	334	95	6	<2	4922	1084	1049	1027	1053
December 1-31	353	98	7	<2	5516	1123	1219	1199	1180
Period Average	345	97	7	<2	5251	1106	1143	1122	1124

* After all treatment, including filtration and chlorination.
+ Estimated from a mass balance of the primary effluent and return sludge flow streams.

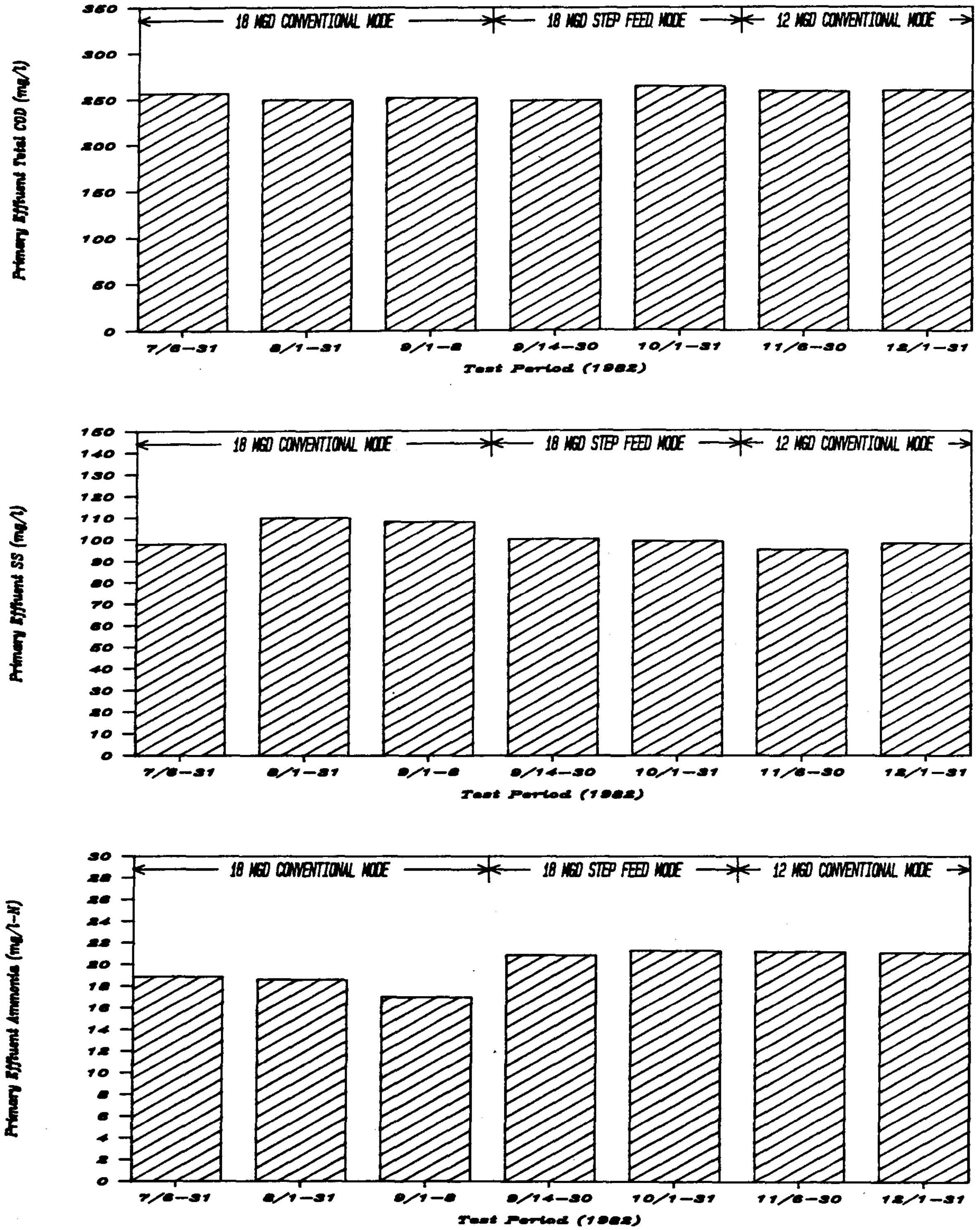

Figure B-16. Primary Effluent Total COD, Suspended Solids (SS) And Ammonia

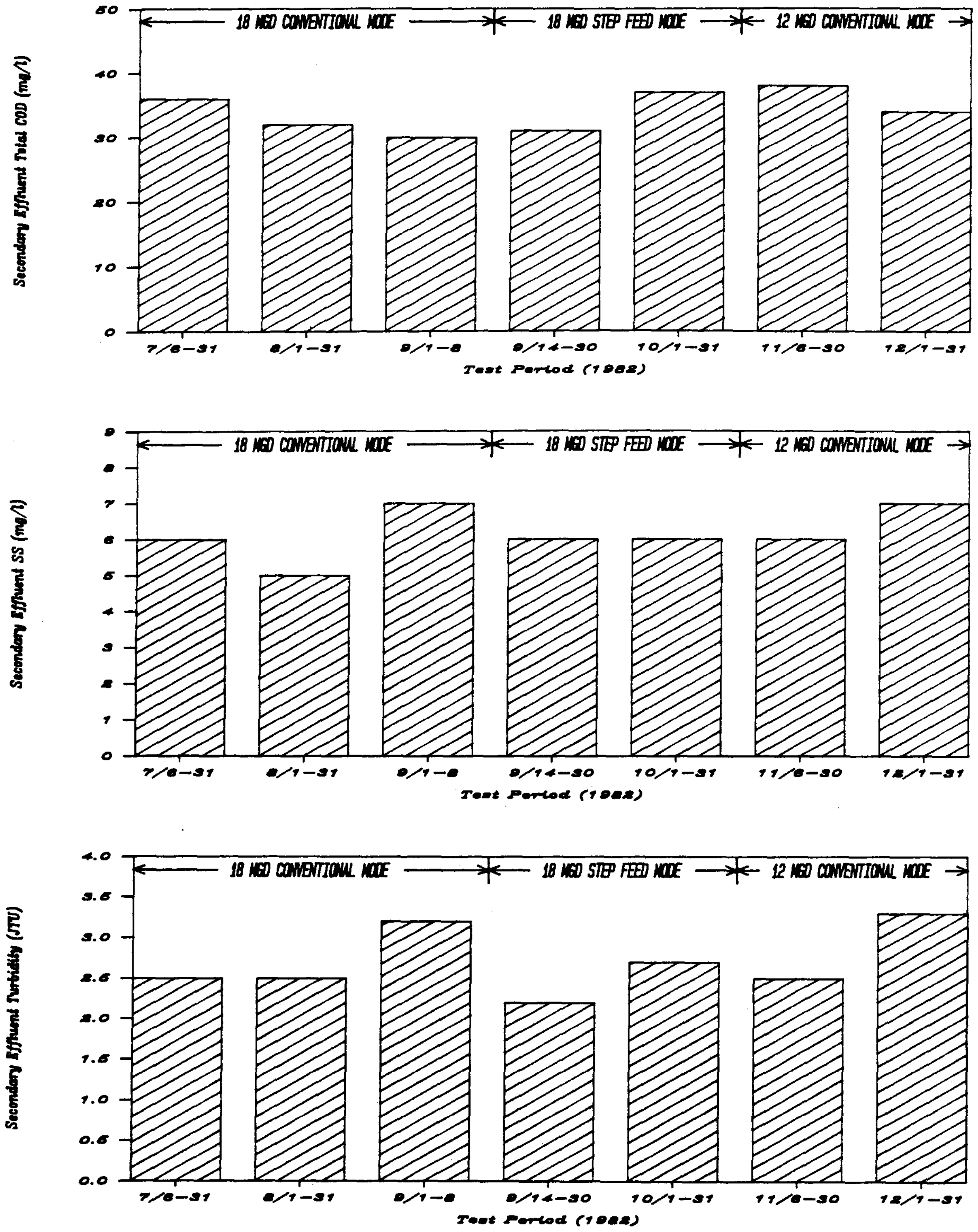

Figure B-17. Secondary Effluent Total COD, Suspended Solids (SS) And Turbidity

TABLE B-30. NITROGEN RESULTS

Test Period (1982)	Primary Effluent Ammonia (mg/l-N)	Secondary Effluent Ammonia (mg/l-N)	Secondary Effluent Nitrite (mg/l-N)	Secondary Effluent Nitrate (mg/l-N)	Secondary System Ammonia Removal (%)
"18 MGD" CONVENTIONAL MODE					
July 6-31	18.9	14.4	1.157	1.4	23.8
August 1-31	18.6	13.8	0.996	1.7	25.9
September 1-8	17.0	14.6	0.850	1.3	13.8
Period Average	18.5	14.1	1.042	1.5	23.6
"18 MGD" STEP FEED MODE					
September 14-30	20.9	17.4	0.224	1.1	17.3
October 1-31	21.3	17.1	0.680	1.5	19.0
Period Average	21.2	17.2	0.519	1.4	18.4
"12 MGD" CONVENTIONAL MODE					
November 6-30	21.2	19.2	0.328	0.7	9.7
December 1-31	21.1	17.1	0.826	1.3	18.9
Period Average	21.1	18.0	0.604	1.0	14.8

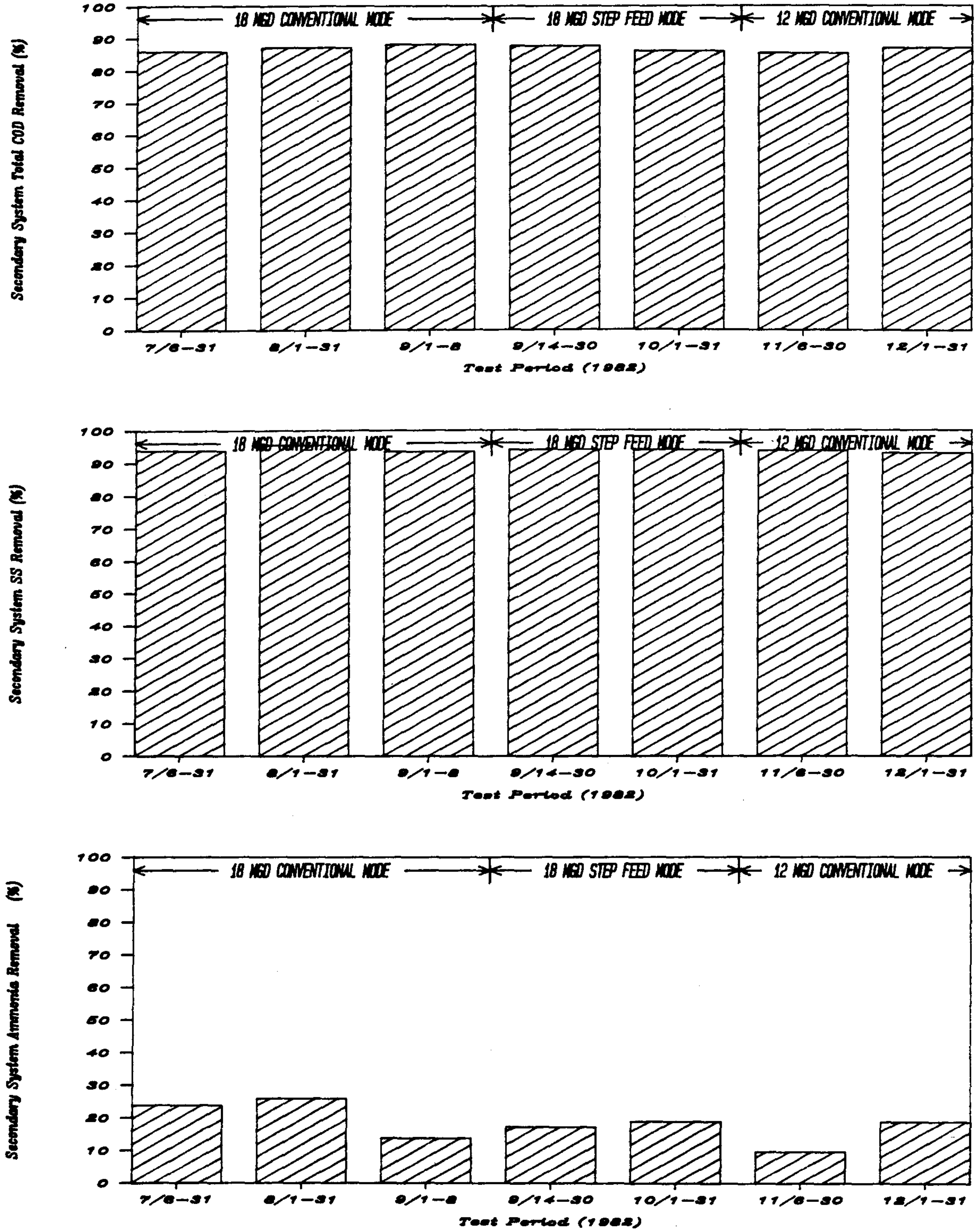

Figure B-18. Secondary System Removal Efficiencies - COD, Suspended Solids (SS) And Ammonia

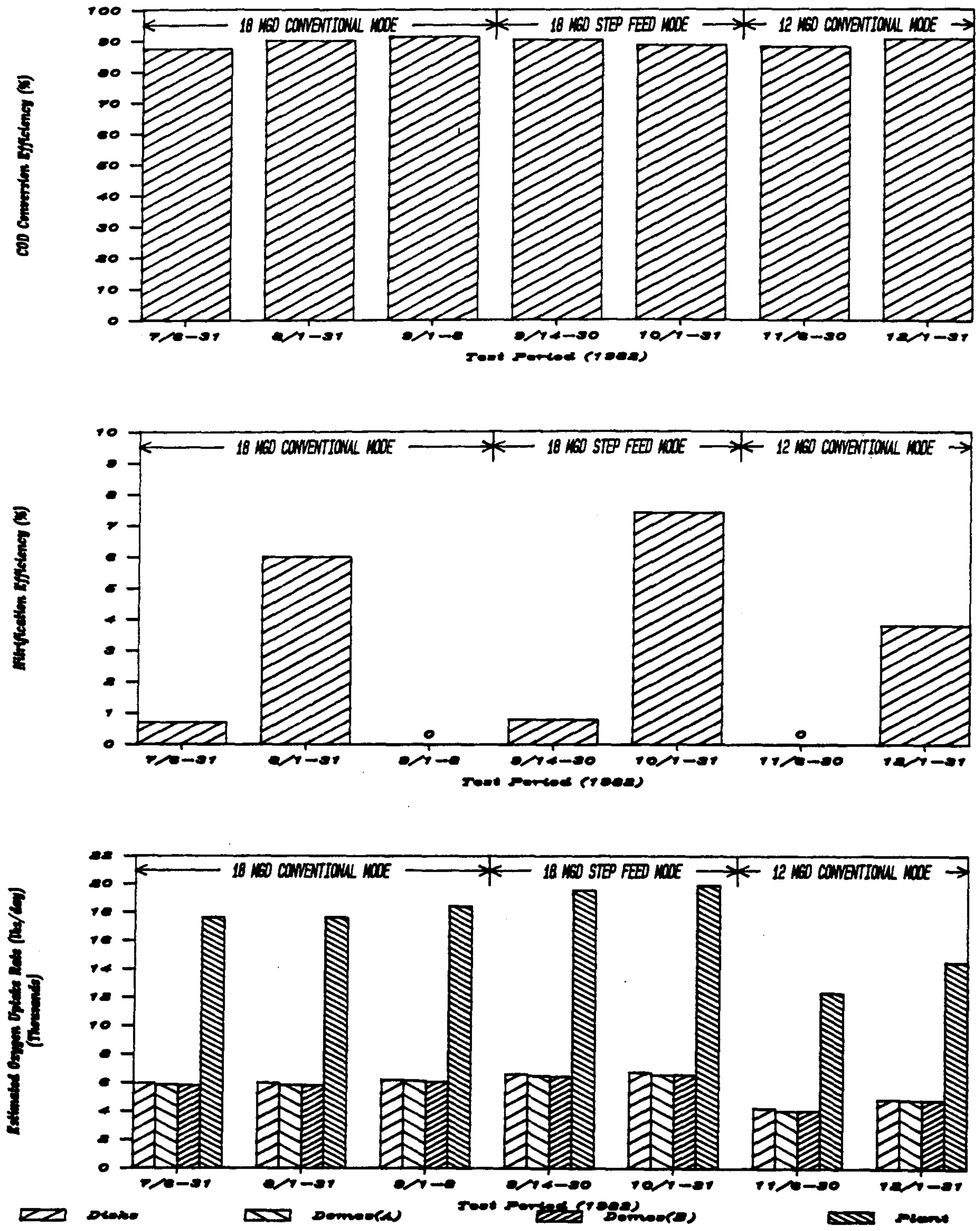

Figure B-19. Secondary System COD Conversion Efficiency, Nitrification Efficiency and Estimated Oxygen Uptake Rates

TABLE B-31. NITRITE AND NITRATE RESULTS ON MIXED LIQUOR GRAB SAMPLES*

Test Period	Nitrites (mg/l-N)						Nitrates (mg/l-N)					
	Low Flow Case			High Flow Case			Low Flow Case			High Flow Case		
(1982)	Disk System	Dome System A	Dome System B	Disk System	Dome System A	Dome System B	Disk System	Dome System A	Dome System B	Disk System	Dome System A	Dome System B
"18 MGD" CONVENTIONAL MODE												
July 6-31	3.364	3.955	3.472	1.553	1.811	1.199	0.88	0.80	0.58	0.38	0.46	0.29
August 1-31	2.811	4.115	3.587	1.254	2.239	1.669	<0.88	1.45	1.31	<0.49	0.57	<0.42
September 1-8	2.632	3.232	2.920	1.602	2.102	2.958	0.84	0.98	0.90	0.41	0.72	0.60
Period Average	3.010	3.942	3.459	1.416	2.051	1.640	<0.88	1.13	0.97	<0.44	0.54	<0.39
"18 MGD" STEP FEED MODE												
September 14-30	1.160	1.584	1.669	<0.296	<0.281	0.306	0.53	0.66	0.60	0.14	0.13	0.09
October 1-31	2.145	2.176	1.837	0.969	0.861	0.718	0.72	0.70	<0.62	<0.20	<0.37	<0.83
Period Average	1.796	1.966	1.778	<0.731	<0.656	0.572	0.65	0.69	<0.61	<0.18	<0.29	<0.57
"12 MGD" CONVENTIONAL MODE												
November 6-30	0.074	0.092	0.096	<0.125	<0.146	0.149	<0.06	<0.06	<0.07	0.13	0.16	0.17
December 1-31	2.149	2.356	2.240	1.281	1.205	0.905	<0.62	<0.52	0.47	0.49	<0.32	<0.25
Period Average	1.223	1.345	1.283	<0.765	<0.732	0.568	<0.37	<0.31	<0.29	0.33	<0.25	<0.21

* Tests conducted at high flow and low flow on alternate days.

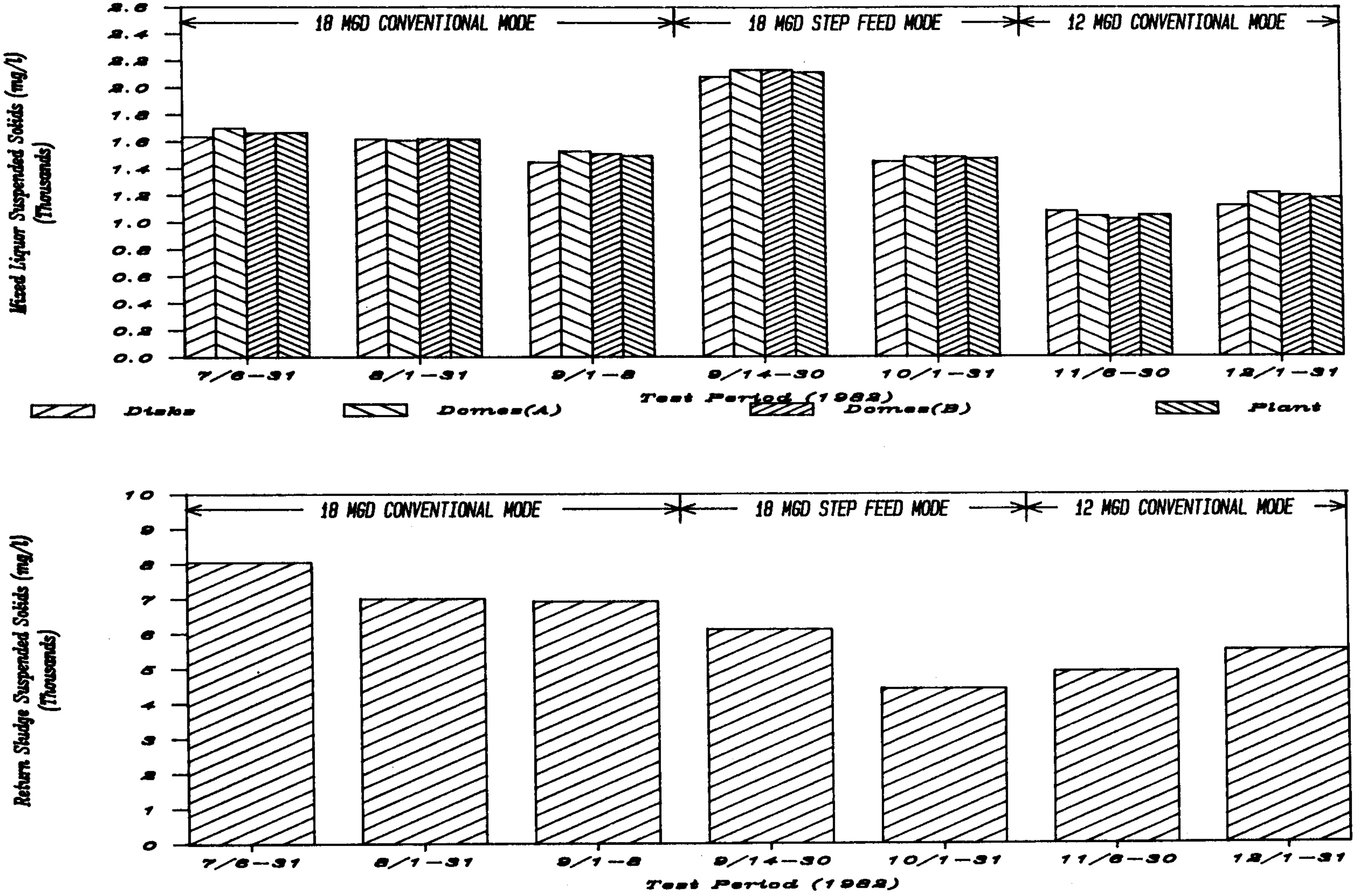

Figure B-20. Mixed Liquor and Return Sludge Suspended Solids

TABLE B-32. SLUDGE VOLUME INDEX AND MIXED LIQUOR VOLATILE SUSPENDED SOLIDS RESULTS*

Test Period (1982)	Sludge Volume Index (SVI-ml/gm)				Mixed Liquor Volatile Suspended Solids (%)			
	Disk System	Dome System A	Dome System B	Total Plant	Disk System	Dome System A	Dome System B	Total Plant
"18 MGD" CONVENTIONAL MODE								
July 6-31	93	90	94	92	72	72	72	72
August 1-31	115	112	118	115	72	72	72	72
September 1-8	119	117	122	119	74	74	74	74
Period Average	107	104	109	107	72	72	72	72
"18 MGD" STEP FEED MODE								
September 14-30	118	118	125	120	73	74	74	74
October 1-31	172	160	169	167	76	76	75	76
Period Average	153	145	153	150	75	75	75	75
"12 MGD" CONVENTIONAL MODE								
November 6-30	126	123	136	128	74	74	75	74
December 1-31	110	107	118	112	74	74	73	74
Period Average	117	114	126	119	74	74	74	74

* Based on grab sample tests.

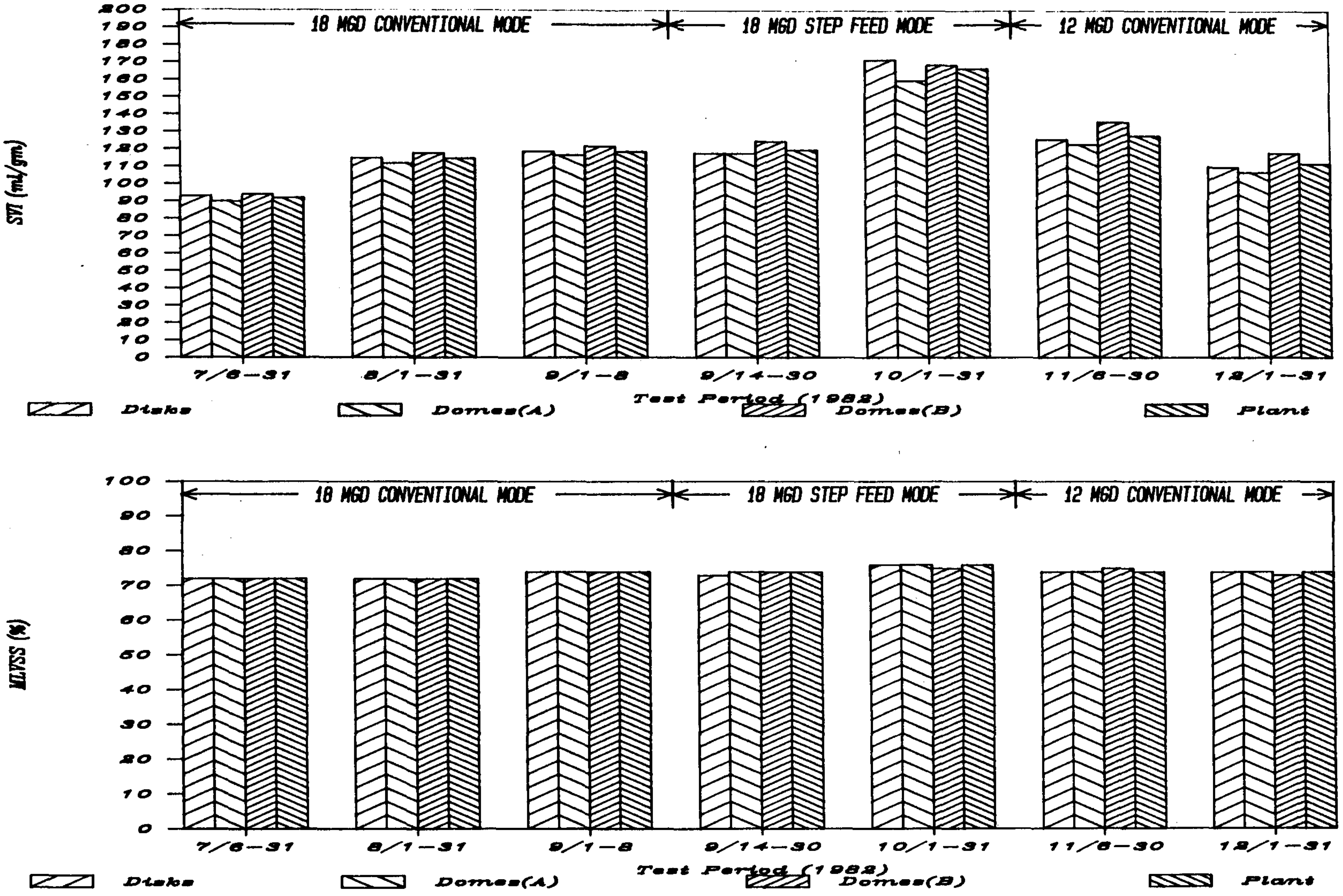

Figure B-21. Sludge Volume Index (SVI) And Mixed Liquor Volatile Suspended Solids (MLVSS)

TABLE B-33. MISCELLANEOUS LABORATORY RESULTS

Test Period (1982)	Secondary Clarifier Secchi Disk Reading (ft)	Final Effluent Settleable Solids (ml/l)	Final Effluent Total Dissolved Solids (mg/l)	Final Effluent Oil And Grease (mg/l)	Final Effluent ph
"18 MGD" CONVENTIONAL MODE					
July 6-31	10.5	<0.1	511	<1.0	7.12
August 1-31	11.5	<0.1	520	1.0	7.09
September 1-8	11.4	<0.1	514	<1.0	7.08
Period Average	11.1	<0.1	516	<1.0	7.10
"18 MGD" STEP FEED MODE					
September 14-30	10.8	<0.1	503	----	7.22
October 1-31	11.6	<0.1	462	<1.0	7.20
Period Average	11.3	<0.1	477	<1.0	7.21
"12 MGD" CONVENTIONAL MODE					
November 6-30	6.0	<0.1	450	----	7.25
December 1-31	5.2	<0.1	434	2.2	7.16
Period Average	5.6	<0.1	441	2.2	7.20

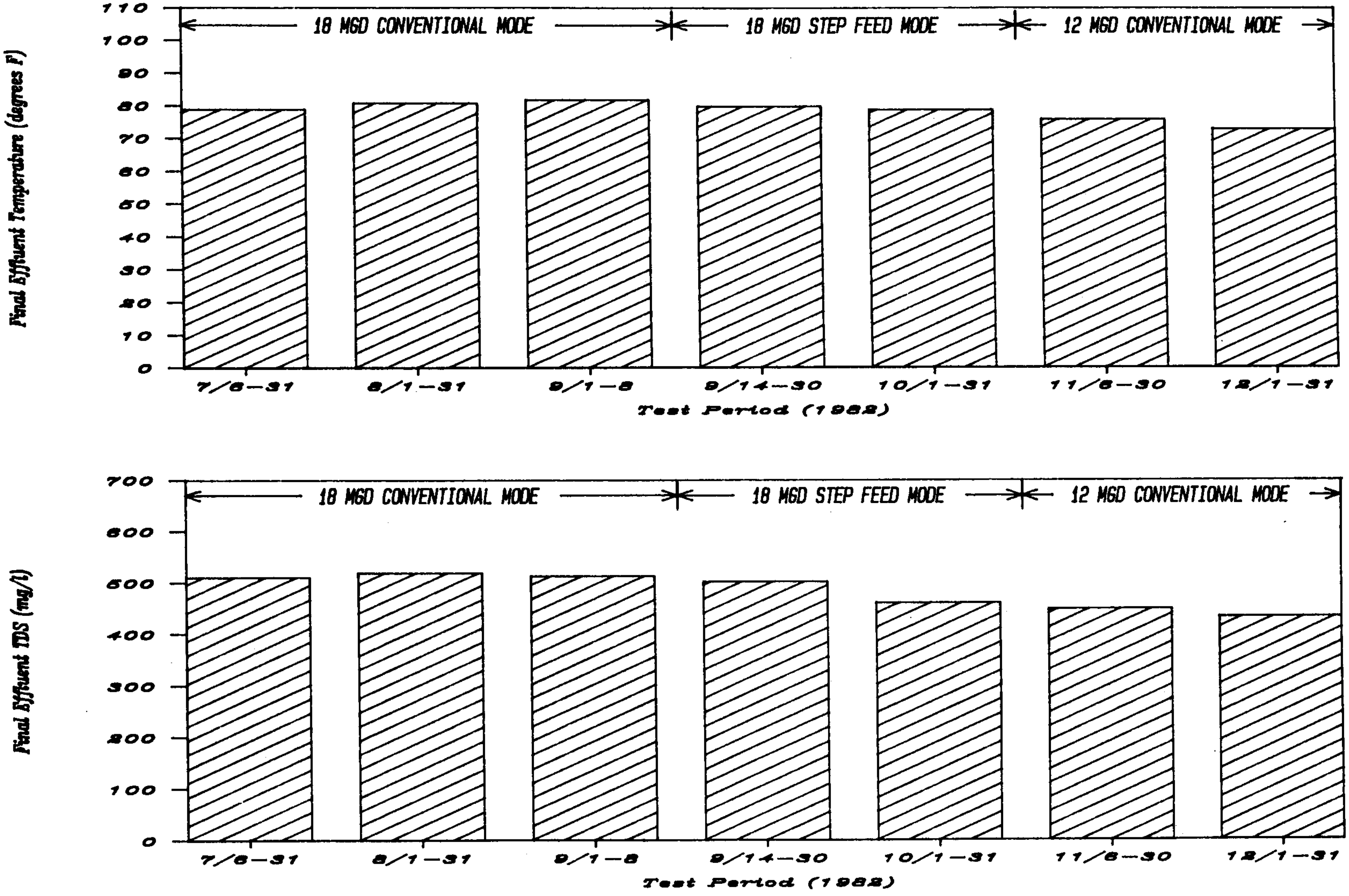

Figure B-22. Final Effluent Temperature and Total Dissolved Solids (TDS)

TABLE B-34. CHEMICAL ADDITION AND BLOWER SHUTDOWN RECORDS

Test Period	Chemical Addition		Blower Shutdowns	
	Polymer To Finals*	High Alum To Filters	Shutdowns	Average Duration
(1982)	(# days)	(# days)	(#)	(hrs)
"18 MGD" CONVENTIONAL MODE				
July 6-31	10	3	1+	0.25
August 1-31	6	3	0	0.00
September 1-8	1	1	0	0.00
Period Total	17	7	1	0.25 (Avg)
"18 MGD" STEP FEED MODE				
September 14-30	1	0	1	0.08
October 1-31	11	3	6	0.75
Period Total	12	3	7	0.65 (Avg)
"12 MGD" CONVENTIONAL MODE				
November 6-30	7	4	1	0.09
December 1-31	22	13	0	0.00
Period Total	29	17	1	0.09 (Avg)

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* The number of days requiring alum addition above normal operating levels.

+ A blower shutdown occurred on July 2, 1982, prior to the start of this test mode.

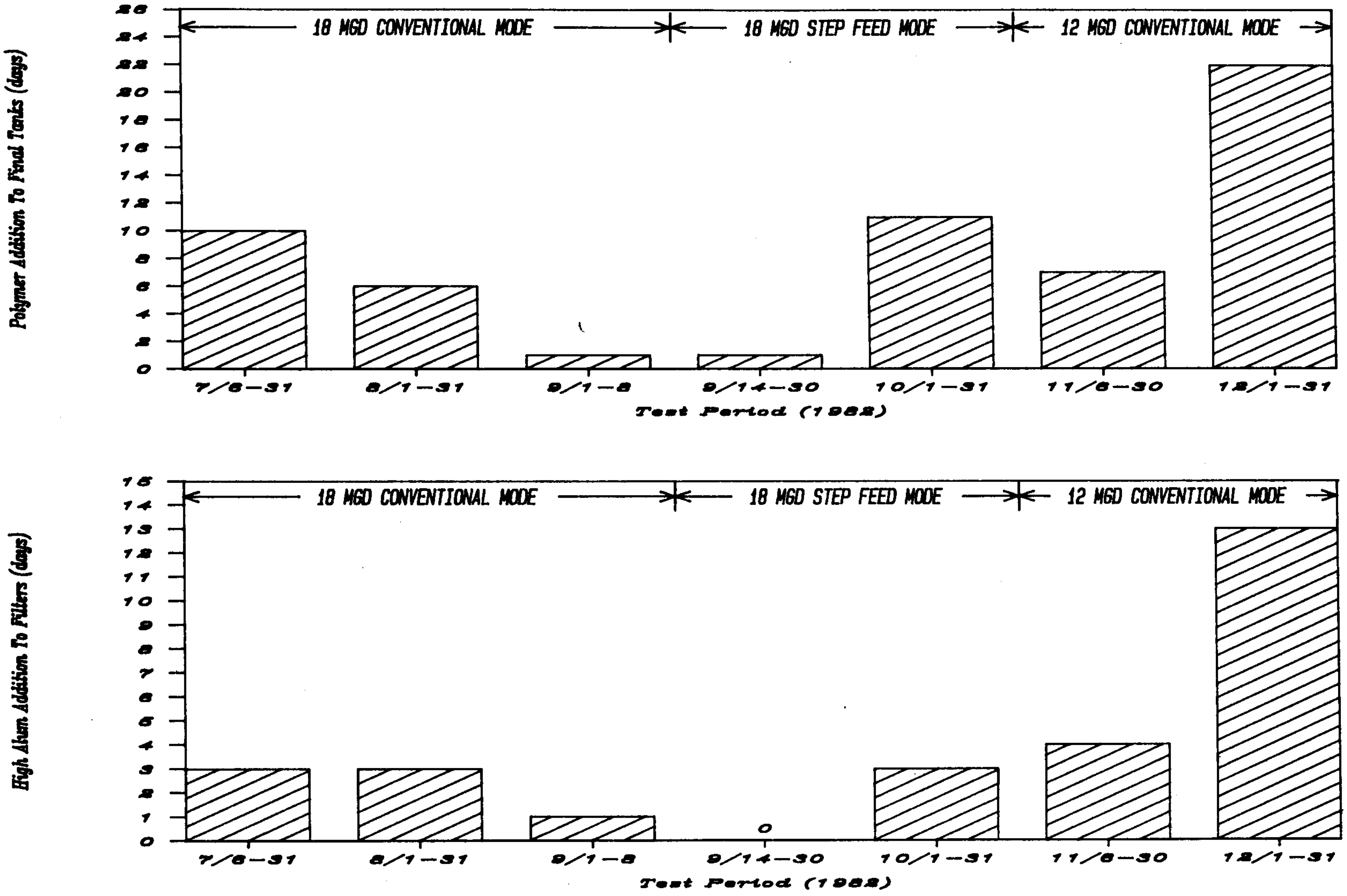


Figure B-23. Polymer And Alum Addition

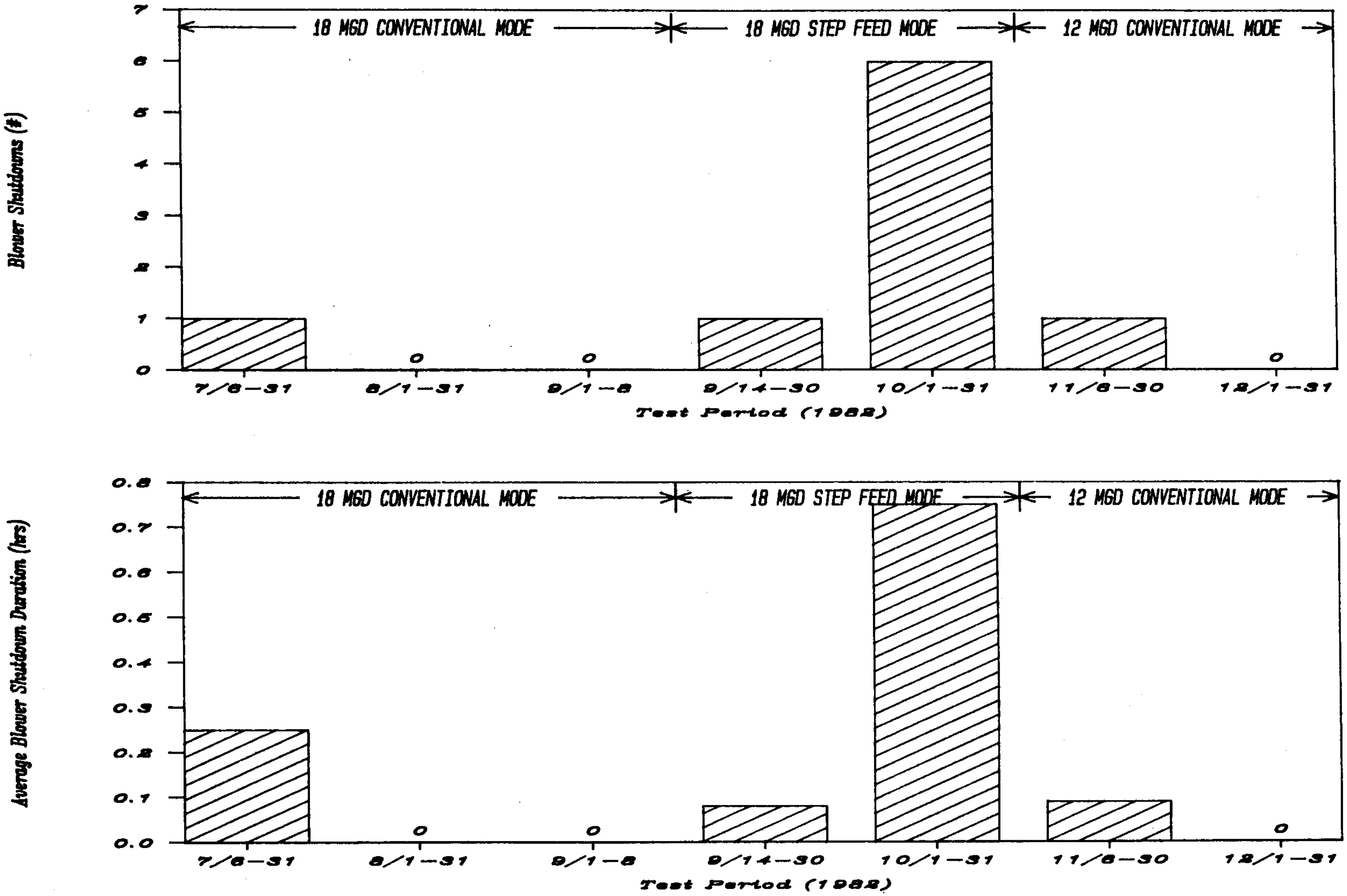


Figure B-24. Blower Shutdown Incidents

C. OXYGEN DEMAND DETERMINATIONS

During this project estimates were made of the theoretical oxygen demand occurring in each aeration tank. This and other information was used to obtain a rough estimate of daily average oxygen transfer performance, independent of the test results by the off-gas method. Obviously, calculations of theoretical oxygen demand are subject to error, but if performed properly with good data, the results can be meaningful.

The basic calculation procedure for oxygen demand involved the determination of two parameters as follows:

$$TOD_i = COD_i + NOD_i \tag{C.1}$$

where

TOD_i = the total oxygen demand in aeration tank i, lbs.

COD_i = the carbonaceous oxygen demand in aeration tank i, lbs.

NOD_i = the nitrogenous oxygen demand in aeration tank i, lbs.

In an actual system, the carbonaceous and nitrogenous oxygen demands are largely satisfied by heterotrophic and autotrophic organisms, respectively. Each type of demand consists of two components:

1. the oxygen required to convert the constituents to stable end products and to produce a gross amount of microbial mass, and
2. the oxygen required to convert a portion of the microbial mass to stable end products (e.g. endogenous respiration).

The daily laboratory COD results and primary effluent flow rates provided a convenient estimate of the total carbonaceous oxygen demand that would have occurred in a tank if all the microbial mass (heterotrophic organisms in this case) had been converted to stable end products. In reality, some of the microbial mass was wasted from a tank before it was oxidized during endogenous respiration so that oxygen demand estimates from COD results alone were high. A correction was made by subtracting out the oxygen equivalent of the wasted cells (waste sludge).

Because there were no direct laboratory or field determinations of nitrogenous oxygen demand, estimates were made for this parameter using an empirical relationship describing the oxygen requirements of the nitrification process in terms of the nitrification achieved. The oxygen demand calculation was performed for the entire plant. From this total, estimates were made of the demand in each individual tank in direct proportion to the primary effluent flow rates. Use of the empirical relationship and the difficulty in obtaining representative plant nitrogen samples probably make the NOD results less accurate than the COD results. Because of the very low nitrification levels encountered, this inaccuracy is not of major consequence.

There were several factors which either complicated or reduced the credibility of these procedures, particularly during Part 1 of the project. The first factor was that most effluent laboratory parameters were determined from secondary effluent samples for the total plant, rather than aeration tank effluent samples for each aeration tank. Thus, assumptions were made that the degree of carbonaceous and nitrogenous treatment in each aeration tank was equal to the degree of treatment for the total plant as a whole. This may not have been a particularly good assumption during Part 1 of the project when the jet system was operated at different hydraulic loading rates than the other systems.

Another factor complicated the demand calculations considerably. Because the hydraulic loading rates were different for the jet system during Part 1, an effort was made to account for the effective heterotrophic wasting rates from each aeration tank in order to obtain more comparable estimates of carbonaceous oxygen demand (the actual wasting was performed from the plant return sludge line). In order to do this, an estimate of the net heterotrophic sludge production in each tank was made based on gross yield coefficients and the estimated endogenous levels.

The above procedure was not employed in the nitrogenous case primarily because of the inherent limitations of the empirical relationship used to determine oxygen demand. It was also felt however, that the wasting of autotrophic organisms from each tank was relatively insignificant due to the low levels of nitrification encountered and the relatively small autotrophic growth yields.

Another factor which complicated these calculations was an attempt to take into account an additional oxygen demand in each aeration tank due to endogenous respiration that would have taken place in the clarifier if adequate DO had been present. This additional oxygen demand was only accounted for in the carbonaceous case, as it was considered relatively insignificant in the nitrogenous case.

It should also be noted that the empirical relationship used to describe the oxygen requirements of the nitrification process was based on an assumed net yield of autotrophic organisms of 0.09 mg VSS/mg NH_4^+–N. This assumed yield, while believed to be fairly typical of many nitrification applications may not been entirely appropriate for the Whittier Narrows testing. This could be the case if the assumed yield was derived from tests at different mean cell residence times. The degree of error in the overall oxygen demand associated with this uncertainty is felt to be very small, because of the low autotrophic yield coefficients and the low levels of nitrification encountered during this study.

Finally, the procedures used to determine the oxygen demand in each tank either assumed that no reaeration occurred in the clarifier (carbonaceous case) or that no oxygen demand occurred in the clarifier (nitrogenous case). These assumptions may not have been entirely valid but their effect on oxygen demand was probably relatively minor.

With this information as background, the detailed procedures for the determination of COD_i and NOD_i are presented below. The total oxygen demand for each system (TOD_i) was calculated from Equation C.1. It should be noted that TOD_i was also referred to as the "estimated oxygen uptake rate," during this study. It should not be confused with the "estimated oxygen transfer rate" which includes an additional oxygen quantity due to the elevation of the process water DO from the influent to effluent end of the aeration tank.

C.1 CARBONACEOUS OXYGEN DEMAND

The net carbonaceous oxygen demand in aeration tank i was determined as follows:

$$COD_i = COD_{ri} - EODN_{hi} \qquad (C.2)$$

where

COD_{ri} = the chemical oxygen demand removed in aeration tank i, lbs/day

$EODN_{hi}$ = the heterotrophic endogenous oxygen demand not exerted in the process, approximately equal to the oxygen equivalent of the waste cells, lbs/day

The chemical oxygen demand removed in aeration tank i was based on COD laboratory analyses and the primary effluent flow as follows:

$$COD_{ri} = 8.34\ Q_{PE_i} \left[TCOD_{PE_i} - SCOD_{SE_i}\right] \qquad (C.3)$$

where

Q_{PE_i} = the primary effluent flow for aeration tank i, MGD

$TCOD_{PE_i}$ = the total chemical oxygen demand of the primary effluent for aeration tank i, mg/L

$SCOD_{SE_i}$ = the soluble chemical oxygen demand of the secondary effluent for aeration tank i, mg/L

The COD laboratory analyses represent the complete oxygen stabilization of the carbonaceous portion of a sample.

For purposes of this study, an assumption was made that the same degree of treatment occurred in each aeration tank. During the first part of the project, it is possible that this assumption was not entirely valid. No other analytical alternatives were available, however. With this assumption, the influent and effluent COD's for the total plant were used when calculating the COD_{ri} for each aeration tank. The determination of $EODN_{hi}$ was considerably more involved because it was necessary to estimate the effective wasting rates from each aeration tank (refer to a previous discussion).

The theoretical heterotrophic endogenous respiration that actually occurs in a system can be expressed as follows:

$$EOD_{hi} = 1.42\, k_d\, X_{hi} \tag{C.4}$$

where

EOD_{hi} = the theoretical heterotrophic endogenous oxygen demand in aeration tank i, lbs/day

1.42 = the theoretical oxygen demand required to stabilize a unit mass of biological cells, lb/lb

k_d = the heterotrophic organism decay coefficient, (assumed to be 0.1 day^{-1} for this study)

X_{hi} = the heterotrophic organism mass in aeration tank i, lbs VSS

By similar reasoning it follows that the endogenous respiration that did not occur in aeration tank i is related to the mass of organisms wasted from aeration tank i as follows:

$$EODN_{hi} = 1.42\, k_d\, W_{hi} \tag{C.5}$$

where

W_{hi} = the heterotrophic organism mass wasted from aeration tank i in one day, lbs VSS

For each tank, W_{hi} was determined as follows:

$$W_{hi} = (NSP_{hi} - S_{hi})(1\ \text{day}) \tag{C.6}$$

where

NSP_{hi} = the net sludge production of the heterotrophic organisms in aeration tank i, lbs VSS/day

S_{hi} = the storage of heterotrophic organisms in aeration tank i, lbs VSS/day

The S_{hi} was determined easily based on the average daily difference in mixed liquor volatile suspended solids results.

The net sludge production of the heterotrophic organisms in tank i was determined as follows

$$NSP_{hi} = GSP_{hi} - ESD_{hi} \tag{C.7}$$

where

GSP_{hi} = the gross sludge production of the heterotrophic organisms in aeration tank i, lbs VSS/day

ESD_{hi} = the endogeneous sludge destruction of the heterotrophic organisms in aeration tank i, lbs VSS/day

From basic principles it follows that

$$GSP_{hi} = 8.34\ Y_h \left[TCOD_{PE_i} - SCOD_{PE_i}\right] Q_{PE_i} \tag{C.8}$$

$$= Y_h\ COD_{ri}$$

where

Y_h = the gross yield of heterotrophic organisms/lb of COD removed

The yield coefficient Y_h was assumed to be the same for all three systems and was approximated from actual operations data in a method to be discussed later.

The parameter ESD_{hi} in equation C.7 was assumed equal to the following

$$ESD_{hi} = ESD_{hati} + ESD_{hpci} \tag{C.9}$$

where

ESD_{hati} = the endogenous heterotrophic sludge destruction that would theoretically occur in aeration tank i based on the systems composite sample of mixed liquor volatile suspended solids, lbs VSS/day

ESD_{hpci} = the portion of the remaining endogenous heterotrophic sludge destruction that would theoretically have occurred in the clarifier with adequate DO that actually occurred in the aeration tank upon initial reentry, lbs VSS/day

From basic principles it follows that

$$ESD_{hati} = k_d X_{hati} \tag{C.10}$$

where

X_{hati} = the heterotrophic organism mass in aeration tank i, lbs VSS

The parameter X_{hati} was determined from mixed liquor volatile suspended solids results knowing the fraction of heterotrophic to total organism mass. This fraction was determined from the production of all microbial mass for the entire plant and the estimate for the net production of autotrophic mass in accordance with Part C.2 of this Appendix.

The parameter ESD_{hpci} was determined as follows:

1. An estimate was made of the maximum endogenous heterotrophic sludge destruction that could occur in the clarifiers with adequate DO

$$ESD_{hcm} = k_d X_{hc} \tag{C.11}$$

where

ESD_{hcm} = the maximum endogenous heterotrophic sludge destruction that could occur in the clarifiers, lbs VSS/day

X_{hc} = the total heterotrophic organism mass in the clarifiers, lbs VSS

The parameter X_{hc} was determined from a rough estimate of the volatile suspended solids in the clarifiers (assumed equal to the million lbs of liquid in the clarifiers times the liquor volatile suspended solids concentration leaving the aeration tanks), knowing the fraction of heterotrophic to total organism mass.

2. An estimate was made of the actual heterotrophic endogenous sludge destruction that occurred in the clarifiers based on the available DO levels:

$$ESD_{hca} = \frac{O_{hc}}{1.42} \tag{C.12}$$

where

ESD_{hca} = the actual endogenous heterotrophic sludge destruction in the clarifiers, lbs/day

O_{hc} = the oxygen available to the heterotrophic organisms in the clarifiers

The parameter O_{hc} was determined from the DO levels and flows leaving the aeration tanks, knowing the fraction of heterotrophic to total organisms mass. An assumption was made that no reaeration occurred at the clarifier water surface.

3. An estimate was made of the portion of the remaining endogenous sludge destruction in the clarifier that was satisfied upon initial reentry in the aeration tanks.

$$ESD_{hpc} = K\left[ESD_{hcm} - ESD_{hca}\right] \tag{C.13}$$

where

K = an assumed fraction (O.5 was used for this study).

4. Finally, the fraction of the ESD_{hpc} associated with each aeration tank was calculated as follows:

$$ESD_{hpci} = \frac{Q_{RSi}}{Q_{RSt}} ESD_{hpc} \tag{C.14}$$

where

Q_{RSi} = the return sludge flow for aeration tank i
Q_{RSt} = the return sludge flow for the total plant

The development thus far makes it possible to estimate the net carbonaceous oxygen demand COD_i from Equation C.1 as long as an appropriate value of Y_h is used in Equation C.8. For this study, Y_h was estimated from an analysis of the actual plant data for each month. From Equation C.7 it follows that

$$NSP_{ht} = GSP_{ht} - ESD_{ht} \tag{C.15}$$

where

NSP_{ht} = the net sludge production of the heterotrophic organisms in the total secondary system (aeration tanks and secondary clarifiers)

GSP_{ht} = the gross sludge production of the heterotrophic organisms in the total secondary system

ESD_{ht} = the endogenous sludge destruction of the heterotrophic organisms in the total secondary system

The parameter NSP_{ht} was determined from a mass balance of volatile suspended solids around the total secondary system, knowing the fraction of heterotrophic to total organism mass. The parameter ESD_{ht} was determined as follows:

$$ESD_{ht} = \sum_{i=1}^{3} ESD_{hi} + ESD_{hca} \tag{C.16}$$

From Equation C.8 it follows that

$$GSP_{ht} = Y_h \, COD_{rt} \tag{C.17}$$

where

COD_{rt} = the total chemical oxygen demand for the total secondary system, lbs/day

Substituting Equation C.15 into Equation C.17 and rearranging, the following expression is obtained for Y_h:

$$Y_h = \frac{NSP_{ht} + ESD_{ht}}{COD_{rt}} \tag{C.18}$$

It should be mentioned that the calculated values for Y_h obtained during this study were based on assumed k_d values of 0.1/day.

C.2 NITRIFICATION OXYGEN DEMAND

Since there were no direct measurements of nitrification oxygen demand, the following empirical equation was used to relate the conversion of ammonia to autotrophic cells and nitrate.

$$\begin{aligned} NH_4^+ + 1.83\, O_2 + 1.98\, HCO_3^- &\longrightarrow 0.021\, C_5H_7NO_2 + 1.041\, H_2O \\ &+ 0.98\, NO_3^- + 1.88\, H_2CO_3 \end{aligned} \tag{C.19}$$

For the purposes of this study, the conversion to nitrate was assumed to be complete, that is no nitrite or nitrogen gas end products were produced. Based on Equation C.19, 4.18 lbs of oxygen are required per lb of nitrogen converted.

An assumption was then made that the total system nitrification oxygen demand occurred entirely within the aeration system itself. Furthermore, the nitrification oxygen demand in a given tank was determined from the total system nitrification oxygen demand in the same proportion as the ratio of the tank primary effluent flow to the total primary effluent flow. Strictly speaking, this procedure was not entirely correct, but it provided estimates that were fairly close.

As mentioned previously, the empirical relationship shown in Equation C.19 assumes a net microbial yield of 0.09 mg VSS/mg $NH_4^+ - N$. To be technically correct, this applies to a given get of conditions with particular regard to mean cell residence time. An assumption was made for this project that Equation C.19 applied under all circumstances incurred. The resulting error in the total system oxygen demand is felt to be small.

In order to determine the nitrification oxygen demand, it was necessary to determine the mass of nitrogen converted to nitrate and autotrophic cells. Since Equation C.19 applies to a total system, the ammonium ion converted was approximated from a balance around the entire secondary system (aeration tanks and final clarifiers). A theoretical oxygen demand for the system was then determined using the ratio of 4.18 lbs/lb $NH_4^+ - N$.

The following discussion clarifies the procedures, utilized to determine the nitrification oxygen demand. The mass balance of ammonium ion around the total secondary system can be expressed as follows:

$$\left(NH_4^+ - N\right)_{\text{IN}} + \left(NH_4^+ - N\right)_{\text{PRODUCED}} = \left(NH_4^+ - N\right)_{\text{OUT}} + \left(NH_4^+ - N\right)_{\text{STORED}} \tag{C.20}$$

The -N designations above indicate that the parameters are expressed on a nitrogen (rather than ammonium ion) basis. The $NH_4^+ - N$ produced was calculated as follows:

$$\underset{\substack{\text{PRODUCED}}}{\left(NH_4^+-N\right)}=\underset{\substack{\text{IN CONVERTED}\\ \text{TO } NH_4^+}}{(ORG\,N-N)}-\underset{\substack{\text{CONVERTED TO}\\ \text{HETEROTROPHIC}\\ \text{CELLS}}}{\left(NH_4^+-N\right)}-\underset{\substack{\text{CONVERTED TO } NO_3^-\\ \text{AND}\\ \text{AUTOTROPHIC CELLS}}}{\left(NH_4^+-N\right)} \qquad (C.21)$$

The NH_4^+-N converted to NO_2^-, NO_3^- and autotrophic cells is stoichiometricly related to the NH_4^+ term in Equation C.19. Inserting Equation C.21 in Equation C.20 and rearranging, the following equation results:

$$\underset{\substack{\text{CONVERTED}\\ \text{TO } NO_3^- \text{ AND}\\ \text{AUTOTROPHIC CELLS}}}{\left(NH_4^+-N\right)}=\underset{\substack{\text{IN}}}{\left(NH_4^+-N\right)}+\underset{\substack{\text{IN CONVERTED}\\ \text{TO } NH_4^+}}{(ORG\,N-N)}-\underset{\substack{\text{CONVERTED}\\ \text{TO HETEROTROPHIC}\\ \text{CELLS}}}{\left(NH_4^+-N\right)}-\underset{\substack{\text{OUT}}}{\left(NH_4^+-N\right)}-\underset{\substack{\text{STORED}}}{\left(NH_4^+-N\right)} \qquad (C.22)$$

If it is assumed that all the incoming organic nitrogen is converted to ammonium ion, then the first two terms in Equation C.22 are equivalent to the incoming total kjedahl nitrogen (TKN-N). Furthermore, the ammonium nitrogen converted to heterotrophic cells can be expressed as follows:

$$\underset{\substack{\text{CONVERTED TO}\\ \text{HETEROTROPHIC}\\ \text{CELLS}}}{\left(NH_4^+-N\right)}=\left(NSP_{ct}-N\right)-\left(NSP_{at}-N\right) \qquad (C.23)$$

where

$NSP_{ct}-N$ = the combined net sludge production of the heterotrophic and autotrophic organisms in the total secondary system on a nitrogen basis.

$NSP_{at}-N$ = the net sludge production of the autotrophic organisms in the total secondary system on a nitrogen basis.

Making this substitution in Equation C.22, the following expression results:

$$\underset{\substack{\text{CONVERTED TO}\\ NO_3^- \text{ AND}\\ \text{AUTOTROPHIC CELLS}}}{\left(NH_4^+-N\right)}=(TKN-N)-\left(NSP_{ct}-N\right)+\left(NSP_{at}-N\right)-\underset{\substack{\text{OUT}}}{\left(NH_4^+-N\right)}-\underset{\substack{\text{STORED}}}{\left(NH_4^+-N\right)} \qquad (C.24)$$

The TKN-N IN, NH_4^+–N OUT, and NH_4^+–N STORED were calculated from daily average nitrogen concentrations for the pertinent flow streams. The "IN" flow stream was the primary effluent; the "OUT" flow streams were the secondary effluent, waste sludge, final clarifier skimmings and the backwash recovery effluent (during the periods of backwash recovery operation only). The volume associated with the "STORED" ammonium ion was assumed to be the entire secondary system (aeration tanks and final clarifiers).

The total net sludge production, NSP_{ct} -N in Equation C.24 was determined from a mass balance of volatile suspended solids around the secondary system, assuming the average bacterial cell composition was approximately 12.39% nitrogen by weight. Thus

$$(NSP_{ct}-N) = 0.1239\ NSP_{ct} \tag{C.25}$$

where

NSP_{ct} = the combined net sludge production of the heterotrophic and autotrophic organisms in the total secondary system on a volatile suspended solids basis.

From Equation C.19, the net sludge production of the nitrifying organisms, NSP_{at} –N, is related to the ammonium ion coverted to NO_2^-, NO_3^-, and autotrophic cells as follows:

$$\left(NSP_{at}-N\right) = 0.021 \underset{\substack{\text{CONVERTED TO} \\ NO_3^- \text{ AND} \\ \text{AUTOTROPHIC CELLS}}}{\left(NH_4^+-N\right)} \tag{C.26}$$

Making this substitution in Equation C.24 and rearranging the following equation results

$$0.979\times\underset{\substack{\text{CONVERTED TO} \\ NO_3^- \text{ AND} \\ \text{AUTOTROPHIC CELLS}}}{\left(NH_4^+-N\right)} = \underset{\text{IN}}{(TKN-N)} - \left(NSP_{ct}-N\right) - \underset{\text{OUT}}{\left(NH_4^+-N\right)} - \underset{\text{STORED}}{\left(NH_4^+-N\right)} \tag{C.27}$$

Thus, with the available plant data, it was possible to estimate the NH_4^+-N that was converted to nitrate and autotrophic cells. With this information, the nitrification oxygen demand was calculated from Equation C.19, using the ratio of 4.18 lbs of oxygen per lb of nitrogen converted. The proportion of the total nitrification oxygen demand that occurred in each aeration tank was then determined on the basis of the primary effluent flow split.

It should be mentioned that the inlet total kjedahl nitrogen was not measured directly. Instead, inlet ammonia nitrogen levels were measured and assumptions were made as to the inlet organic nitrogen levels based on prior testing. It was also assumed that the soluble organic nitrogen levels were essentially zero in all flow streams.

D. CLEAN WATER TEST PROCEDURES

D.1 GENERAL

All mass transfer tests used as a basis for verification of the systems performance were performed by the non-steady state reaeration or reoxygenation technique. The tests described here are similar to the ASCE Standard (1984) procedure but were performed before the procedure was finalized. For this reason some of the procedures are different from the Standard.

During the testing, sodium sulfite catalyzed by cobalt chloride was used to strip residual dissolved oxygen between reaeration test runs. During the test runs, samples were withdrawn from the tank and collected in BOD bottles for later dissolved oxygen (DO) concentration measurement by the Winkler Method.

In general, all readings other than DO concentration were taken twice during the run: once just prior to the addition of the deoxygenation chemicals and once again near the end of the main sampling period, at a time given approximately by $4/K_La$. The arithmetic average of the two sets of readings was used for data analysis purposes. No corrections were made to the measured values of any parameter for possible errors due to instrument calibration, method of measurement, data observation, reduction of data, or measurement accuracy.

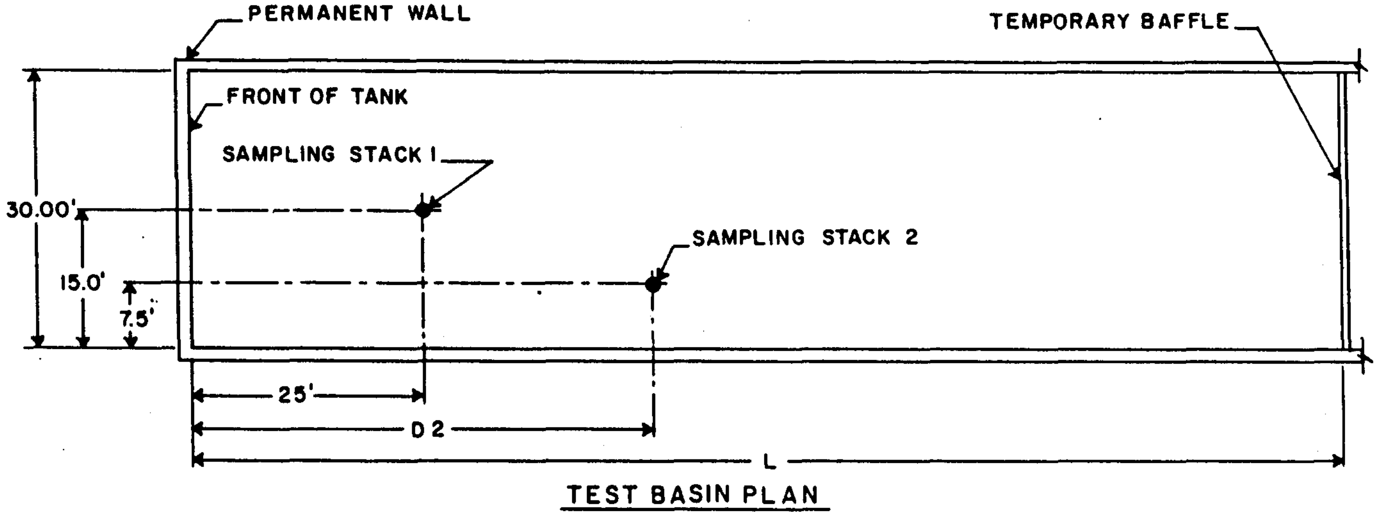
D.2 AIR FLOW MEASUREMENT

Air flow measurements were made with acceptable flow measurement devices, installed with due consideration for the straight lengths of pipe required. In no case was the uncertainty in flow measurement greater than ±1.5% of the actual air flows, with the exception of the tests on the tube system, which were slightly less accurate. Air line temperature and pressure and ambient temperature, pressure, and relative humidity were measured. These readings were used to convert the air flow measurements to standard conditions of 68°F, 14.70 psia and 36% relative humidity.

D.3 SAMPLING

D.3.a Sampling Locations

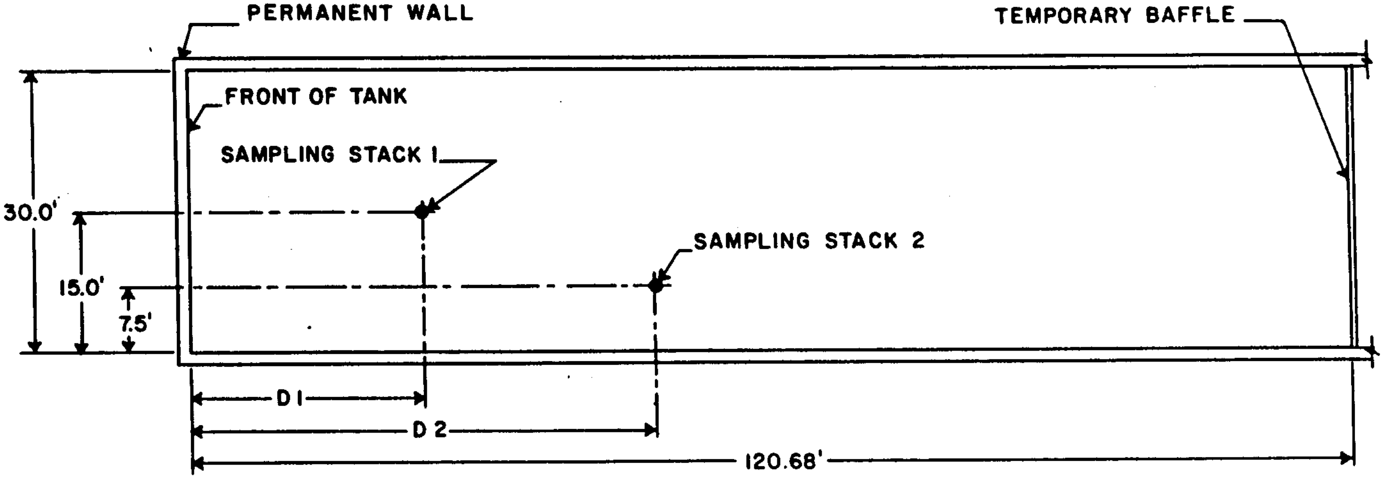
Water samples analyzed by the Winkler Method were collected from four locations in the aeration tank. There were two vertical sampling "stacks" with two sampling locations each, positioned as shown in Figure D-1 for the tube and disk systems, and in Figure D-2 for the jet



NOTES:

1. THE TEST BASIN WAS LOCATED IN ZONE 1 OF TANK 1 FOR THE DISK SYSTEM TESTS AND IN ZONE 1 OF TANK 2 FOR THE TUBE SYSTEM TESTS.
2. FOR THE TEST BASIN DIFFUSER LATOUTS, SEE FIGURES 5 AND 8-10 FOR THE DISK AND TUBE SYSTEMS, RESPECTIVELY.
3. D2 WAS 54.74 FT. AND 50.42 FT. FOR THE DISK AND TUBE SYSTEM TESTS, RESPECTIVELY.
4. L WAS 99.74 FT. AND 100.42 FT. FOR THE DISK AND TUBE SYSTEM TESTS, RESPECTIVELY.
5. THE NOMINAL WATER DEPTH FOR ALL TESTS WAS 15.0 FT.
6. SAMPLING STACK 1 HAD SAMPLING LOCATIONS AT 2 FT. BELOW THE WATER SURFACE AND AT MID-DEPTH.
7. SAMPLING STACK 2 HAD SAMPLING LOCATIONS AT 2 FT. ABOVE THE TANK BOTTOM AND AT MID-DEPTH.

Figure D-1. Clean Water Test Tank Plan for the Disk and Tube Systems



TEST BASIN PLAN

NOTES:
1. THE TEST BASIN WAS LOCATED IN ZONE 1 OF TANK 3.
2. FOR THE TEST BASIN JET LAYOUTS, SEE FIGURES 12-17 FOR THE RADIAL AND UNIDIRECTIONAL JET SYSTEMS, RESPECTIVELY.
3. D1 WAS 28 FT. AND 30 FT. FOR THE RADIAL AND UNIDIRECTIONAL JET SYSTEM TESTS, RESPECTIVELY.
4. D2 WAS 60.68 FT. AND 67.50 FT. FOR THE RADIAL AND UNIDIRECTIONAL JET SYSTEM TESTS, RESPECTIVELY.
5. THE NOMINAL WATER DEPTH FOR ALL TESTS WAS 15.0 FT.
6. SAMPLING STACK 1 HAD SAMPLING LOCATIONS AT 2 FT. BELOW THE WATER SURFACE AND AT MID-DEPTH.
7. SAMPLING STACK 2 HAD SAMPLING LOCATIONS AT 2 FT. ABOVE THE TANK BOTTOM AND AT MID-DEPTH.

Figure D-2. Clean Water Test Tank Plan for the Jet Systems system. Sampling Stack No. 1 had sample locations at 2 feet below the water surface and at mid-depth; Sampling Stack No. 2 had sample locations at 2 feet off of the bottom of the tank and at mid-depth.

D.3.b Sampling Equipment

Submersible pumps were used to withdraw the water samples from the tank. They were sized so that they could fill a BOD bottle approximately 3-5 times in 15 seconds. This insured adequate displacement of the water in the BOD bottle and minimized the detention time in the sample lines. The pump rates from the various sample locations were set as close to each other as possible.

An anti-air entrainment device was installed on each pump to avoid introducing air bubbles in the samples. These devices consisted of a 6" length of 1-1/2" pipe pointed vertically upward on the suction side of the pump. Theoretically, the velocity in the suction line was less than the rise velocity of the air bubbles in the tank and helped to avoid introducing air bubbles in the water samples.

The submersible pumps discharged the sample water through flexible tubing to an external sampling station. The tubing diameter was selected so that it was small enough to fit easily into the neck of a BOD bottle, but large enough to keep the liquid velocity below 5 ft/sec, in order to avoid air entrainment upon insertion or withdrawal of the tubes in the bottles. Furthermore, the length of the sample tubes was kept as short as possible. In no case, did the detention time in the sample lines exceed 20 seconds. The diameters and lengths of the tubing from the four sample locations was the same.

An in-tank probe was installed at a readily accessible location near the tank wall at the mid-depth position. The function of this probe was to signal the start and finish of the oxygen transfer test; probe data were not used to calculate K_La's or to determine dissolved oxygen saturations.

D.3.c Sampling Procedure

During each run, an attempt was made to collect approximately 13 samples from each location as follows:

1. Approximately 8 samples evenly distributed over the period of time from 0 to $2/K_La$.
2. An additional 4 samples evenly distributed over the period of time from $2/K_La$ to $4/K_La$.
3. A final "equilibrium" sample after a period of time of at least $6/K_La$.

The submersible sample pumps withdrew the tank water continuously during the test period. Time was monitored with a stop-watch. During the BOD bottle fill operation, the end of the sample tubing was inserted to within one inch of the bottom of the bottles. Water was allowed to overflow the BOD bottles until the desired time, t, at which time the sampling tubes were withdrawn and the BOD bottles stoppered. The overflow water from the BOD bottles was collected in a 50-gallon tank and was continuously pumped back to the aeration tank.

D.4 DO MEASUREMENT

The official DO measurements were made on captured samples by the Azide Modification of the Winkler Method. All laboratory procedures were in accordance with *Standard Methods*. All reagents used were fresh (less than 2 weeks old). The sodium thiosulfate used for the tests was standardized at least once each day.

The DO determinations were made as close to the time the samples were taken as possible, but in no case was the interval between the time a sample was collected and analyzed allowed to exceed 1 hour. The DO concentration, sample time, and sample location was recorded for each sample.

A blank was run on the aeration tank water. The blank was obtained by omitting the manganous sulfate addition step in the normal Winkler procedure. Any DO reading obtained was subtracted from all the DO readings obtained during the clean water test in order to obtain the official results.

The in-tank probe was calibrated by a suitable calibration technique.

D.5 POWER DETERMINATION

Power determinations were made for both the blower and pump portions of the aeration system. The total wire horsepower consumption for the test tank was the sum of the blower and pump wire horsepower consumptions as follows:

$$P_{ttw} = P_{ttbw} + P_{ttpw} \tag{D.1}$$

where

P_{ttw} = total wire power consumption for the test tank, hp

P_{ttbw} = blower standard wire power consumption for the test tank, hp

P_{ttpw} = pump wire power consumption for the test tank, hp

The methods used for the blower and pump power determinations are discussed in the sections which follow:

D.5.a Blower Power

The following modification of the adiabatic compression formula was used to estimate the blower standard wire power consumption for the test tank:

$$P_{ttbw} = \left[\frac{0.227}{e_b}\right] Q_{tt} \left[\left(\frac{p_2}{p_1}\right)^{0.283} - 1\right] \tag{D.2}$$

where

Q_{tt} = total test tank air flow at standard conditions of 20°C, 14.70 psia, and 36% relative humidity, scfm

e_b = estimated overall adiabatic efficiency, fraction

p_2 = estimated blower discharge pressure, psia

p_1 = estimated blower inlet pressure, psia

The estimated blower discharge pressure, p_2, was calculated according to the following equation:

$$p_2 = 14.70 + p_{sh} + h_{La} + h_{Lp} \tag{D.3}$$

where

p_{sh} = measured aerator static head, psig

h_{La} = measured aerator headloss, psia

h_{Lp} = estimated full scale discharge piping headloss, psia

The values of the parameters used in these equations were 0.612 for e_b (e_b = 0.70 for blower x 0.95 for coupling x 0.92 for motor), 14.5 psia for p_1, and 0.3 psia for h_{Lp}. The parameters p_{sh} and h_{La} were determined by measurement using a bubbler system and a pressure tap in the air piping immediately upstream of the aerator. Care was taken to clear all pressure tubing of water prior to taking any readings.

Upon substitution of the known quantities in Equations D.2 and D.3, and simplifying, the following form of the blower wire power consumption equation was obtained:

$$P_{ttb} = 0.37\, Q_b \left[\left(\frac{15.0 + p_{sh} + h_{La}}{14.5} \right)^{0.283} - 1 \right] \tag{D.4}$$

D.5.b Pump Power

The recirculation pump wire power determinations were made from certified pump and motor performance curves and total dynamic head measurements.

D.6 CHEMICAL ADDITION

Cobalt chloride was used as a catalyst for the deoxygenation reactions. It was added once at a dosage of 0.1 mg/L as cobalt ion to each batch of test water. The chemical was added to the test tank in water solution and was allowed to mix for at least thirty minutes prior to the start of the first test for each water batch.

Anhydrous sodium sulfite (technical grade) was used to deoxygenate the water prior to the start of each test and was added in sufficient quantity to maintain the tank at zero DO for at least two minutes. The sodium sulfite was added to the tank in solution form at a minimum of 4 points. This ensured that distribution was as rapid and complete as possible. The chemical lines were flushed with tap water to get rid of any residual sodium sulfite.

An attempt was made to keep the accumulated sodium sulfite concentration in the tank below 1,000 mg/L. This level was exceeded during three of the tests however.

D.7 WATER QUALITY

The test water was supplied from a local well. Laboratory analyses were conducted on water samples from the tank collected prior to and following the testing with a given batch of water. The tests included pH, alkalinity, hardness, sulfate, total dissolved solids, cobalt, iron and manganese.

D.8 PRE-TEST

Prior to the first official test on a batch of water, a pre-test was made. This was done in order to condition the water for the official tests. The pre-test consisted of de-oxygenating the water with sodium sulfite and aerating it back to saturation. No official data were generated during this run.

D.9 CLEAN WATER TESTS - STEP-BY-STEP PROCEDURE

a. A water sample was collected for laboratory analysis prior to the first test on a batch of water.

b. The mixed liquor recirculation pumps were turned on (jet system only).

c. Prior to the first test on any given day, the aeration system was "blown out" by operating at a high air rate for at least one hour.

d. The aeration tank water level was set to the approximate depth.

e. The air flow rate was set to the approximate rate.

f. The water level was set to the exact depth (15.0 depth).

g. The air flow was set to the desired value and maintained at those conditions for a minimum of thirty minutes prior to the start of the test.

h. Cobalt chloride was added (if necessary) in solution form at 0.1 mg/L dosage as cobalt ion. Additional cobalt was added as necessary to account for diffusion across the aeration tank baffle.

i. The required amount of sodium sulfite was mixed in the mix tank.

j. A pre-test was run prior to the first official test.

k. The BOD bottle fill rates were adjusted so that the bottles were filled in approximately 3-5 seconds.

l. The sodium thiosulfate was standardized for the Winkler Method (at least once each day).

m. The DO probe was checked to make sure it was in good operating condition and then calibrated by a suitable calibration technique.

n. The DO probe was installed in its proper position in the tank and set to the proper scale.

o. The recording watt meter was turned on and adjusted as necessary (jet system only - not used in any official manner).

p. After a minimum of thirty minutes of steady state operation and just prior to the start of the test, the following readings were taken:

   1. ambient temperature, barometric pressure, and relative humidity
   2. flow meter differential pressure or air flow, line temperature, and line pressure
   3. aerator air temperature
   4. aerator static head
   5. aerator headloss
   6. recirculation pump wire power consumption (jet system only)
   7. aeration tank water temperature
   8. aeration tank water level

q. The sodium sulfite solution was added and chemical lines flushed with tap water.

r. The DO concentration in the tank was monitored with the in-tank probe. The DO concentration was to remain at zero for a minimum of two minutes.

s. The start of the test was signaled when the DO concentration began to rise.

t. Samples were collected at preselected time intervals.

u. The first two Winkler reagents (manganous sulfate and alkali-iodide azide) were added to the samples as soon as possible. The samples were shaken, allowed to settle half-way down in the bottle, and then shaken again.

v. A second complete set of readings were taken at the end of the primary sampling period (at a time given approximately by $4/K_La$, prior to the collection of the equilibrium samples).

w. All the Winkler samples were acidified, shaken, and titrated as soon as possible (not more than 1 hour after collection).

x. A blank was run to determine if there was a chemical interference in the Winkler Method.

y. After the tank reached equilibrium (i.e. at least 20 minutes at a steady DO concentration, indicated either by sampling or by the in-tank DO probe), a set of 4 equilibrium samples was collected (one for each location).

z. A Winkler analysis was performed on the equilibrium samples.

aa. The equilibrium results from the four sampling locations and the DO probe were compared.

ab. In some cases, if the equilibrium results seemed satisfactory, the blowers and recirculation pumps were shut off. After all the air had left the tank, the aeration tank water level was measured.

ac. After the last test run on a given water batch, a water sample was collected for laboratory analysis.

D.10 CLEAN WATER TESTS - DATA ANALYSIS METHOD

The "exponential method" was used for the oxygen transfer data analysis. The pertinent equation can be derived from the basic oxygen transfer relationship:

$$\frac{dC}{dt} = K_L a\,(C^*_\infty - C) \tag{D.5}$$

where

$\frac{dC}{dt}$ = the volumetric oxygen transfer rate (mg/L-hr)

$K_L a$ = overall volumetric mass transfer coefficient, 1/hr

C^*_∞ = dissolved oxygen saturation at temperature, T, mg/L

C = dissolved oxygen concentration at time, t, mg/L

Integration of Equation D.5 yields the following expression:

$$\ln(C^*_\infty - C) = -K_L a(t) + \ln(C^*_\infty - C_i) \tag{D.6}$$

where

t = time, hrs

C_i = initial dissolved oxygen concentration corresponding to time, t = 0, mg/L

Equation D.6 can be transformed to obtain the exponential form of the basic oxygen transfer relationship. From Equation D.6 it follows that

$$C = C^*_\infty - (C^*_\infty - C_i)e^{-K_La(t)} \tag{D.7}$$

Equation D.7 is the basis of the exponential method, which has now become the standard method as adopted by ASCE.

D.10.a Regression Analysis

A nonlinear least squares regression analysis was used to fit the (C,T) data to Equation D.7. The regression analysis determined the best estimate of the parameters K_La, C^*_∞ and C_i. The parameters K_La, and C^*_∞ were of prime importance. While a number of different nonlinear least squares regression analyses exist, the method to be used for this analysis was the "Complex Method of Box" (Stenstrom, et al. 1981).

The oxygen transfer data were analyzed for each sample location. Arithmetic averages were then taken of K_La and C^*_∞. The exponential method was not used on location average (C,T) data. The (C,T) data used for analysis were truncated below 20% of the measured C^*_∞ for a given sample location. No "upper end" data truncation was required or allowed for the exponential method. The parameters K_La, C^*_∞, and C_i were reported for each sample location, as well as the tank average.

D.11 TEST LIMITATIONS

The use of the oxygen transfer equations developed so far depends upon the fact that the tank is completely mixed. Significant gradients in DO concentration at any point in time were taken as a sign that this condition was not satisfied. Modest DO concentration gradients were allowed. The test was considered void if any DO concentration at the start of the run (20% C^*_∞) differed by more than 1.5 mg/L from the average DO concentration at that time. The test was also considered void if, at the end of the test (equilibrium) any DO concentration differed by more than 0.2 mg/L from the average DO at that time.

D.12 CONVERSION TO STANDARD CONDITIONS

The values of K_La and C^*_∞ determined from the regression analysis were for a specific water temperature, T, and barometric pressure, p_a. Both of these parameters were converted to standard conditions of 20°C and 14.70 psia. The parameter, K_La was converted as follows:

$$K_La_{20} = \frac{K_La}{1.024^{T-20}} \tag{D.8}$$

where

K_La_{20} = projected overall volumetric mass transfer coefficient at 20°C, 1/hr

T = water temperature, °C

The parameter C_∞^* was converted to standard conditions based upon the concept of "equivalent depth." The equivalent depth is that depth which corresponds to the derived dissolved oxygen saturation value, when the appropriate pressure correction is applied to the textbook value of C_∞^* at temperature, T. The following equation shows the relationship of equivalent depth to the other pertinent variables:

$$C_\infty^* = \left[\frac{p_a + 0.4335 z_e - p_{vpT}}{14.70}\right] C_{hT}^* \qquad \text{(D.9)}$$

or

$$z_e = 33.9\left[\frac{C_\infty^*}{C_{hT}^*}\right] + 2.31\,[p_{vpT} - p_a] \qquad \text{(D.10)}$$

where

C_{hT}^* = handbook dissolved oxygen saturation at temperature, T, and 14.70 psia (dry air, 20.9% O_2 by volume), mg/L

p_a = barometric pressure, psia

z_e = equivalent depth corresponding to the derived oxygen saturation value, ft

p_{vpT} = vapor pressure of water at temperature, T, psi

The factor in equation (D.9) relating C_∞^* and C_{hT}^* is known as a pressure correction factor. The numerator of this factor represents the total pressure of dry air at the equivalent depth in the field. Dividing by 14.70 is necessary since C_{hT}^* is for 14.70 psia (760 mm Hg).

In order to determine the saturation at 20°C and 14.70 psia, it is assumed that the equivalent depth calculated at temperature, T, and barometric pressure, p_a, is equal to the equivalent depth at 20°C and 14.70 psia. Thus, from Equation D.9 at standard conditions,

$$C_{\infty 20}^* = [\frac{14.70 + 0.4335\, z_e - p_{vp20}}{14.70}] C_{h20}^* \qquad \text{(D.11)}$$

where

$C_{\infty 20}^*$ = projected field dissolved oxygen saturation at standard conditions of 20°C and 14.70 psia

C_{h20}^* = handbook dissolved oxygen saturation at 20°C and 14.70 psia (dry air, 20.9% O_2 by volume, 9.17 mg/L)

z_e = equivalent depth as calculated by Equation D.10, ft

p_{vp20} = vapor pressure of water at 20°C (0.34 psi)

Upon substitution of the handbook values, the equation reduces to the following:

$$C^*_{\infty 20} = 0.624\ (14.36 + 0.4335\ z_e) \qquad \text{(D.12)}$$

For the clean water tests, the standard dissolved oxygen saturation $C^*_{\infty 20}$ was determined by Equations D.10 and D.12.

D.13 STANDARD TEST TANK TRANSFER RATE ($SOTR_{tt}$)

The standard oxygen transfer rate for the test tank ($SOTR_{tt}$, lbs O_2/hr dissolved in tap water at standard conditions of 20°C, 14.70 psia (water saturated air), and 0 mg/L dissolved oxygen concentration) was computed as follows:

$$SOTR_{tt} = (K_La_{20})(C^*_{\infty 20})W \qquad \text{(D.13)}$$

where

$SOTR_{tt}$ = standard oxygen transfer rate for the test tank, lbs/hr

K_La_{20} = projected overall volumetric mass transfer coefficient at 20°C, 1/hr

$C^*_{\infty 20}$ = projected field dissolved oxygen saturation at standard conditions of 20°C and 14.70 psia, mg/L

W = weight of water, 10^6 lbs

E. OFF-GAS TEST METHODOLOGY

E.1 BASIC TECHNIQUE

The off-gas method was the primary process water oxygen transfer technique used during this study. An early form of this method has been used previously by other researchers, but was limited in applicability and effectiveness. The historical method used an off-gas hood to collect gas eminating from the surface of the aeration tank. The composition and volume of this gas were then determined precisely. Many stations were sampled in this manner to obtain an overall estimate of the volume and composition of gas leaving various zones in the aeration tank. The volume and composition of gas entering these various aeration zones were also determined. A mass balance was then used to determine the amount of oxygen that had been dissolved in each process water zone.

This historical method was limited in that it required very accurate measurements of the inlet and off-gas flow rates for an accurate mass balance. This meant that extensive sampling was necessary in each aeration zone. The method was best applied to tanks that were entirely covered, facilitating the collection and flow measurement of the off-gas stream. In any case, it was often difficult to obtain accurate assessments of inlet or off-gas volumes, because of insufficient and/or inaccurate plant flow meters. These were serious limitations with the use of the historical off-gas method.

The off-gas technique utilized during this project was conceived by Lloyd Ewing of Ewing Engineering and was a novel variation of the historical method. Instead of using the inlet and off-gas flow streams to provide an oxygen mass balance, the new technique made the transfer efficiency at any sampling station a function of off-gas composition alone. This is possible with several assumptions. The first is that the inert components in the inlet gas stream (primarily nitrogen and argon) are conservative during the aeration process; that is, they are not absorbed into or stripped from the process water. The second assumption is that the mole ratio of oxygen to inerts in the inlet gas is the same as that for standard air. The inert components can then be used like a tracer. With these assumptions, the mole ratios of oxygen to inerts in the off-gas and standard air can be used to calculate oxygen transfer efficiency. The assumption that all inert gas components are conservative is generally a good one except perhaps at the front of an aeration system where some nitrogen stripping may occur. The second assumption is also very reasonable in most cases.

Using this form of the off-gas technique overcomes the gas flow rate measuring problems mentioned previously. With the new approach, gas flow rates only affect transfer efficiency in that they are used to flow weight the individual station results. They are used, however, to determine aeration system operating conditions and to compare the collected gas flow rate with the associated inlet gas flow rate.

Since small changes in off-gas oxygen purity can have major effects on the oxygen transfer efficiency calculation, it is necessary that the calibration of the oxygen analyzer be known at all times during the testing. The new approach uses the known composition of a reference gas (i.e. standard ambient air except for water vapor content) to calibrate the oxygen analyzer between each off-gas determination. This procedure compensates for analyzer drift.

E.2 EQUIPMENT

E.2.a Equipment Setup

The equipment setup for a typical off-gas test is shown in Figure E-1. As mentioned previously, the equipment consists of a floating hood connected to an off-gas analyzer by means of a 1.5" vacuum hose. An ordinary canister vacuum is used to draw the off-gas through the analyzer, where measurements of O_2, CO_2, and gas flow are made. A separate line is used to monitor hood pressure.

A one-inch reference gas line is connected between the main air header and a special inlet throttling manifold. Downstream of this manifold another one inch gas line is connected to the off-gas analyzer. This portion of the reference gas line is allowed to float in the aeration tank to achieve thermal equilibrium at the mixed liquor temperature.

E.2.b Off–Gas hood

Detailed drawings of the hood are shown in Figure E-2. This design and drawings are courtesy of Ewing Engineering Co. The hood used during our study was made by Sanitation Districts' and UCLA personnel from 24" diameter fiberglass reinforced polyester (FRP) pipe with 8" diameter FRP pontoons, PVC bulkheads and stainless steel hardware. The hood bulkheads were sloped so that the hood could extend into the wye-wall portion of the aeration tank. Some of the pertinent hood related specifications are as follows:

Hood length = 10.06 ft
Hood width = 1.98 ft
Estimated hood extension under wye wall = 1.08 ft
Estimated hood overlap = 1.47 ft
Hood surface area = 19.93 sq ft
Total independent hood surface area across
width of tank at each cross section = 54.01 sq ft

E.2.c Off–Gas Analyzer

The off-gas analyzer used during this project is shown in Figure E-3. The basic concept was modeled after the Ewing Engineering Co. design. The analyzer was built by Sanitation Districts' personnel and is certainly less sophisticated than even the earliest Ewing Engineering design. It represents the project engineer's attempt at simplification and economy in light of

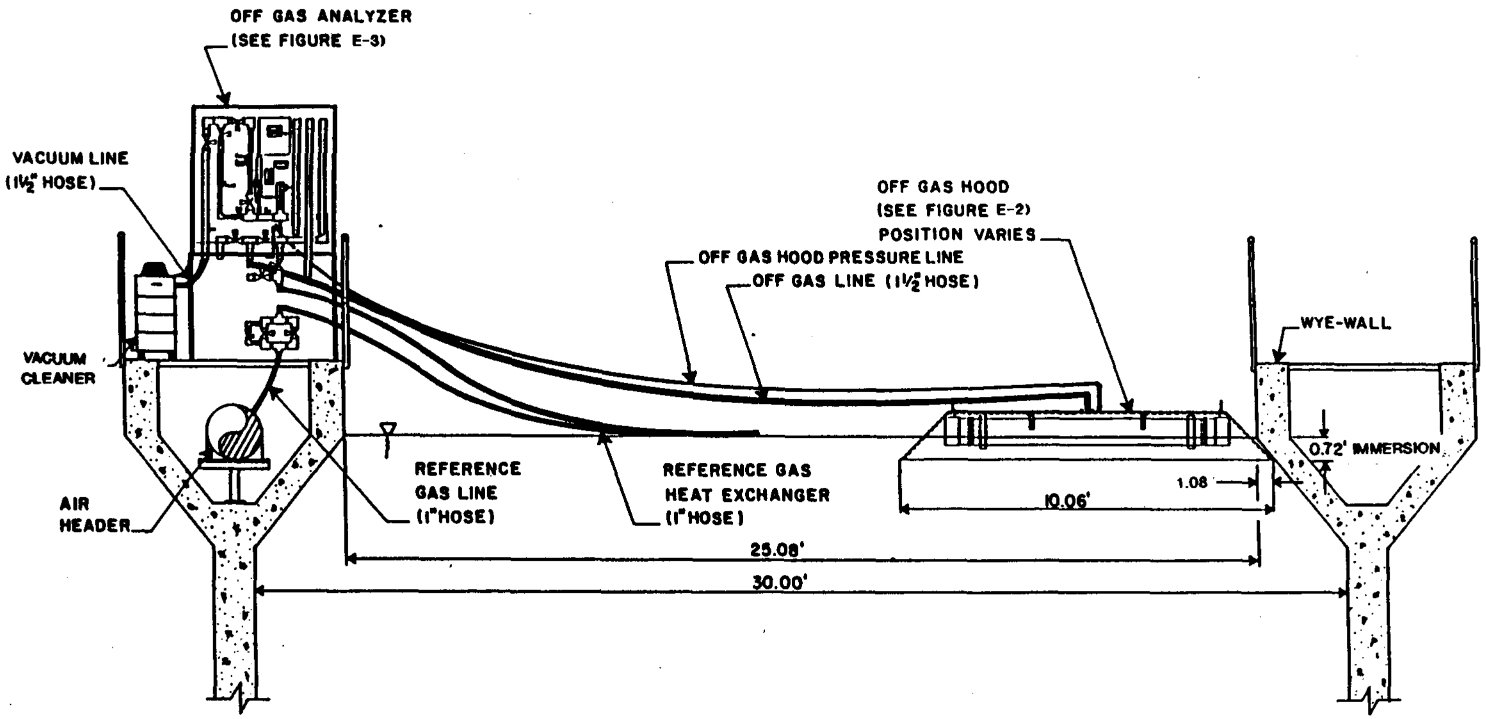
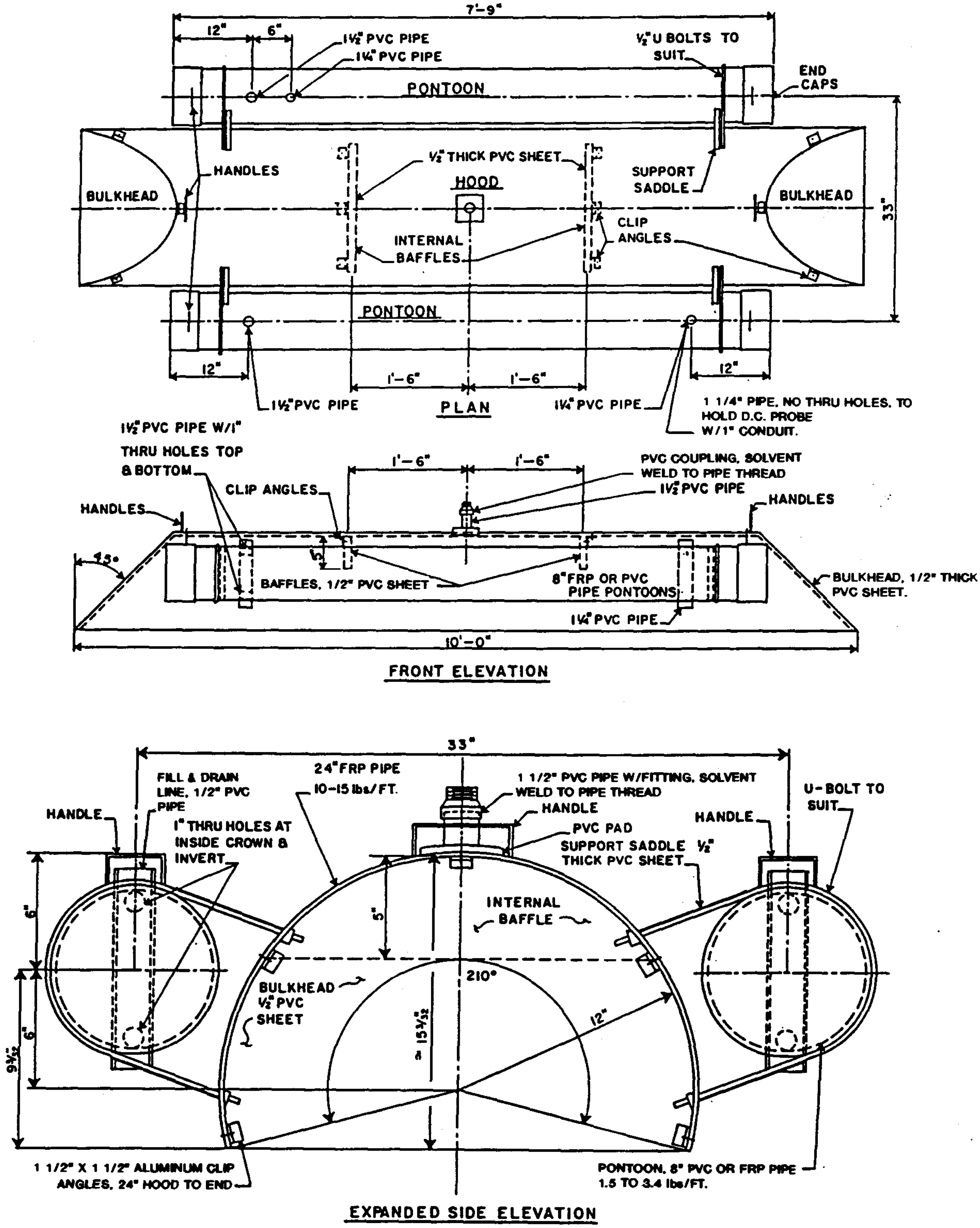


Figure E-1. Off-gas Analyzer and Hood with Hoses

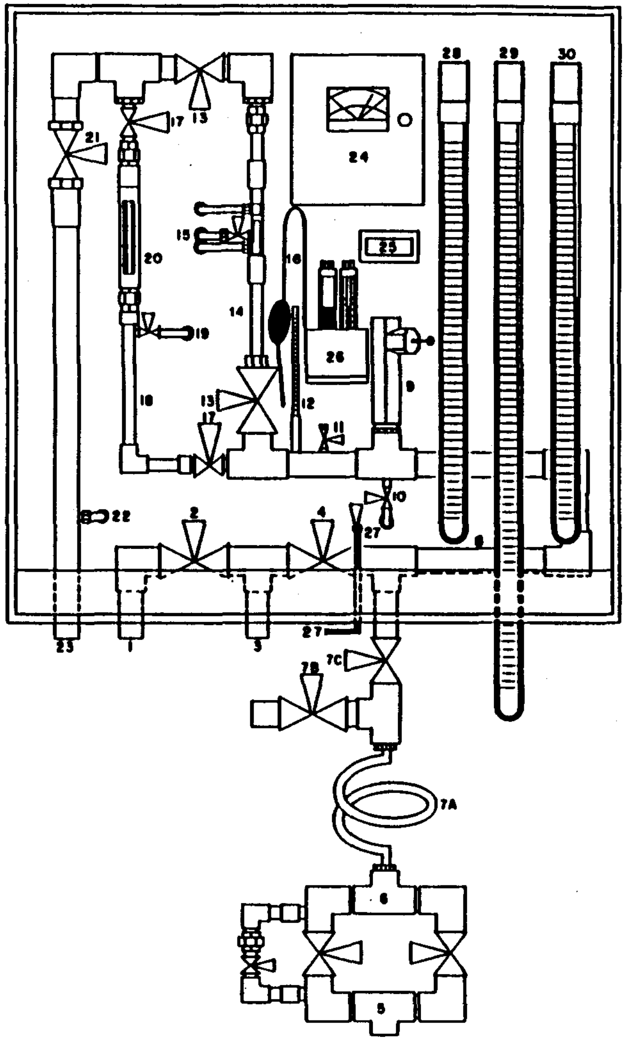
 PLAN

FRONT ELEVATION

EXPANDED SIDE ELEVATION

DESIGN AND DRAWING COURTESY OF EWING ENGINEERING CO.

Figure E-2. Off-gas Hood



CONCEPT COURTESY OF EWING ENGINEERING CO.

1. OFF GAS BYPASS OUTLET
2. OFF GAS BYPASS VALVE
3. OFF GAS INLET
4. OFF GAS ISOLATION VALVE
5. REFERENCE GAS INLET
6. REFERENCE GAS INLET THROTTLING MANIFOLD

7A. REFERENCE GAS HEAT EXCHANGER

7B. REFERENCE GAS BYPASS VALVE

7C. REFERENCE GAS ISOLATION VALVE

8. PVC GAS LINE
9. OXYGEN PROBE
10. OXYGEN PROBE PRESSURE TAP
11. CO_2 SAMPLING TAP
12. THERMOMETER (FOR LINE TEMPERATURE AND HUMIDITY)
13. HIGH FLOW METERING LINE SHUT OFF VALVE
14. HIGH FLOW METERING LINE
15. ANNUBAR LINE PRESSURE TAP
16. ANNUBAR WITH DIFFERENTIAL PRESSURE TAPS
17. LOW FLOW METERING LINE SHUT OFF VALVE
18. LOW FLOW METERING LINE
19. ROTAMETER LINE PRESSURE TAP
20. ROTAMETER
21. OFF GAS ANALYZER DISCHARGE THROTTLING VALVE
22. OFF GAS ANALYZER DISCHARGE PRESSURE TAP
23. OFF GAS ANALYZER DISCHARGE OUTLET
24. OXYGEN ANALYZER
25. OXYGEN ANALYZER MILLIVOLT METER
26. CO_2 ANALYZER WITH SAMPLING BULB
27. OFF GAS HOOD PRESSURE TAP
28. "PRESSURE" MANOMETER (24" H_2O)
29. "FLOW" MANOMETER (36" H_2O)
30. "VACUUM" MANOMETER (24"Hg)

Figure E-3. Off-gas Analyzer

existing budget constraints. The main deviation in design between this unit and a typical Ewing Engineering unit of the time was the fact that the entire off-gas stream was analyzed, as opposed to a small sidestream. This fact and others resulted in certain technical drawbacks, which will be discussed fully in a later section of this report.

The off-gas analyzer consisted of the following basic equipment:

1. an oxygen analyzer
2. a CO_2 analyzer
3. wet and dry bulb thermometers
4. two separate flow rate measuring devices: an Annubar line for high flow rates and a rotameter for low flow rates
5. a 24" water filled "pressure" manometer
6. a 36" water filled "flow" manometer
7. a 24" mercury filled "vacuum" manometer

At any given station, an off-gas analysis was performed, followed immediately by a reference gas analysis.

E.2.d Considerations and Concerns

Theoretically the off-gas method can be a very valuable technique in evaluating oxygen transfer performance. Unless proper attention is paid to the design, construction and operation of the off-gas analyzer, however, serious errors can result. This is particularly true of the oxygen analyzer and probe.

E.2.d.1 Oxygen Analyzer and Probe--

At the time the off-gas analyzer was designed considerable thought went into the selection of the oxygen analyzer and probe. One of the main concerns was the use of a dissolved oxygen probe in the very wet off-gas environment. Many probes are sensitive to the presence of water droplets on the probe membrane. This can affect the probe's response and result in significant errors in oxygen purity measurement. The analyzer and probe selected for the project, the Leeds and Northrup Model 7931, was reported to be completely insensitive to water droplets.

The Leeds and Northrup probe is unusual in that it is a passive probe (i.e., there is no diffusion or transport of oxygen at equilibrium, and no net reaction at the electrodes). This type of probe was reported to have the following advantages over other types: insensitivity to sample flow; insensitivity to degree of probe fouling; a permanent probe membrane, electrodes, and electrolyte, and insensitivity to moisture on the membrane.

The Leeds and Northrup unit worked well during the project, although there were problems experienced with probe drift. To minimize this, the analyzer and probe was allowed to warm up for a minimum of 48 hours prior to testing. Normally the warm up period was several weeks or longer.

In order to accurately monitor the analyzer output, a 200 millivolt digital voltmeter was used instead of the less readable analyzer meter. During normal operation, the calibration of the oxygen analyzer in reference air was set high (to 190 mv) in order to improve the measurement accuracy.

E.2.d.2 Temperature Equivalence of the Reference and Off-Gas Streams--

A disadvantage of the particular off-gas design used during this project was that if did not ensure that the reference gas (ambient air except for water vapor content) and off-gas streams were at exactly the same temperature. This is desirable in order to minimize errors in the probe's temperature compensation circuitry. The earliest Ewing analyzer design incorporated a heat exchanger which guaranteed the temperature equivalence of the two gas streams. It was soon discovered, however that because the sample flow was small in comparison to the surface area of the analyzer piping, the heat exchanger was not actually necessary.

In the case of the Districts' off-gas analyzer, the temperature of the two gas streams was not always equal. This was due primarily to the fact that the entire hood off-gas flow was passed through the analyzer, rather than just a small sidestream as with the Ewing analyzers. This flow was large relative to the surface area of the analyzer piping and the resulting heat exchange to ambient was less than it would have been with the Ewing analyzers.

During Part 1 of the project the reference gas temperature averaged approximately 2° F cooler than the off-gas temperature. An attempt was made to warm the reference gas flow by inserting a long length of reference gas hose into the aeration tank mixed liquor. Another attempt was the maintenance of continuous gas flow through the reference gas line at all times. This was discontinued during Part 2 of the project, however, because of rather limited success. During Part 2, the length of the off-gas vacuum hose was shortened in a further attempt to equilibrate the temperature of the reference and off-gas streams. This was largely successful, in that the reference gas temperature was now only 0.5° F cooler than the off-gas temperature. The magnitude of error due to the temperature differences between the reference and off-gas streams is difficult to ascertain.

E.2.d.3 CO_2 Determinations--

Another concern experienced during the project involved the measurement of CO_2 concentration. At the start of the off-gas testing, an Orsat CO_2 indicator was used. Perhaps due to the excessively high range of the instrument, difficulty was experienced in obtaining consistent readings. This problem was resolved by using CO_2 gas color tubes, which change color and indicate the purity of CO_2 gas present. The accuracy and precision of this technique is felt to be very good.

E.2.d.4 Gas Composition Assumptions--

For the purposes of this study, the following assumptions were made regarding reference gas, inlet gas and off-gas composition:

1. The reference gas and inlet gas was assumed to be standard air except for the water vapor content. No measurements of nitrogen, oxygen or CO_2 concentrations were made on these gas streams. Humidity was determined using wet and dry bulb thermometers. The reference gas was used to calibrate the oxygen analyzer.

2. The off-gas oxygen and CO_2 concentrations were measured directly. The off-gas relative humidity was assumed to be 100% at the temperature of the process water. Nitrogen was considered to be the remaining component of the off-gas stream.

It was learned after the project completion that the assumption of 100% relative humidity in the off-gas stream is not necessarily valid. It would be more appropriate in future tests to measure this parameter directly or to dry the gas stream prior to analysis. Furthermore, because of the time required to take wet bulb and dry bulb readings, it might be more appropriate to use water vapor color tubes for both the reference and off-gas humidity determinations.

It should also be noted that the reference gas used during this study was not ambient air in the strictest sense, in that the gas was withdrawn primarily from under the primary clarifier covers. This was the same gas used to supply the aeration system. An attempt was made to verify that this gas was essentially of the same composition as ambient air, except for water vapor content. Results obtained from analytical measurements on both gas streams supported this hypothesis. For the purposes of this study, the reference gas was assumed to be standard ambient air, except for water vapor content.

E.3 TEST PLAN

This section deals with the overall off-gas test plan used to analyze the aeration systems during Parts 1 and 2 of the project. Many of the differences between the Part 1 and 2 test plans is a result of the experience gained over the course of the mixed liquor testing.

All tests during the study were conducted under normal primary effluent and return sludge flow conditions. No attempt was made to alter these flows for a particular test. A slight diurnal flow variation was experienced during the course of a day's testing, however.

During Part 1 of the project, an attempt was made to obtain mixed liquor transfer results at various air flow rates per diffuser for each system. It was hoped that curves relating oxygen transfer efficiency and air flow per diffuser could then be developed. On a given day's test during Part 1 of the Project, an attempt was made to set the air flow per diffuser to the same rate throughout the entire tank. On another day, the air flow per diffuser would be changed and the test rerun. This procedure was followed for the dome and jet systems, but was not followed for the tube system due to the poor mechanical condition of the aeration system.

After analysis of the data from Part 1 of the project, it was clear that running tests at various air flows per diffuser had one very serious limitation. Running tests at very low air flows per diffuser produced DO limiting conditions in the aeration tank. These conditions forced the biostabilization to occur further down the length of the aeration tank or perhaps even reduced the degree of stabilization. The net effect was to markedly reduce the α factor.

In similar fashion, running at high air flows per diffuser seemed to improve the oxygen transfer results. The normal Districts operation tends to be at relatively low DO concentrations. When the air flow rates are increased above normal levels the biostabilization tends to occur closer to the front of the aeration tank. This results in an improved α factor for the aeration process. The best way to counter these effects would have been to reduce the primary effluent and return sludge flows in proportion to the air flow. This was not done because of the need to treat the total plant flow.

During Part 2 of the project, a decision was made to limit testing to normal operating conditions. No attempt was made to obtain profiles over a range of air flow rates per diffuser. It was felt that the α factors obtained at unusually low or high air flows per diffuser would not be typical of normal operation. Furthermore, on a given day's test, no attempt was made to make the air flows per diffuser uniform throughout the entire tank or to make them constant during the entire test.

All off-gas tests during this study were conducted at numerous points on the surface of the aeration tank. Each aeration system was sampled at 5 or 6 cross sections along the length of the aeration tank as shown in Figure E-4. At each cross section, anywhere from 1 to 3 hood positions were monitored as shown in Figure E-5. Table E-1 shows the off-gas test dates. An attempt was made to select sampling positions for each aeration system that were representative of the tank as a whole. Because of generic differences in the aeration systems, the sampling positions were different from one system to the next.

In all cases, the off-gas testing began at the front of the aeration tank and proceeded towards the effluent end. The time required from the start of off-gas testing at the first station to the completion of testing at the last station, averaged a little over 6 1/2 hours. Thus the evaluation of a system's oxygen transfer performance was not instantaneous but required a finite period of time. Ideally, more meaningful results would have been obtained if the testing could have been performed more rapidly. This was a serious disadvantage of the "economized" off-gas analyzer used during the study.

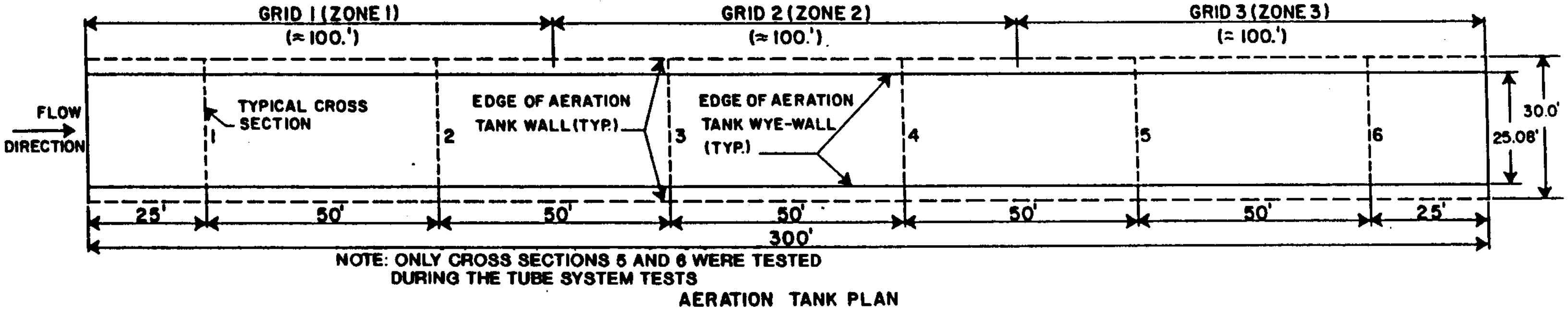
The time required for testing was particularly problematic with the early tests performed on the jet aeration system. The jet system, because of its nonuniform mixing pattern, required more extensive sampling at first to obtain reliable transfer results. As a result, it was necessary to split the testing over a 2-day period. This procedure was utilized on the first three of six test runs conducted on the jet system. On the last three runs, it was possible to use fewer sampling positions because of information learned during the earlier tests.

E.4 OFF-GAS FIELD TEST PROCEDURES

E.4.a Overall Test Plan

In general, each test series conformed to the following conditions:

I. DISK, DOME AND TUBE SYSTEM TESTS



II. JET SYSTEM TESTS

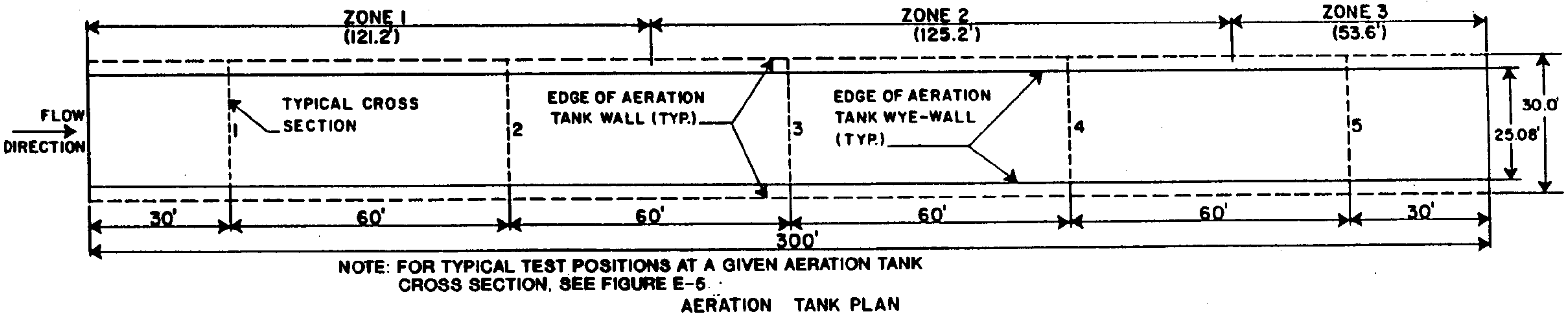
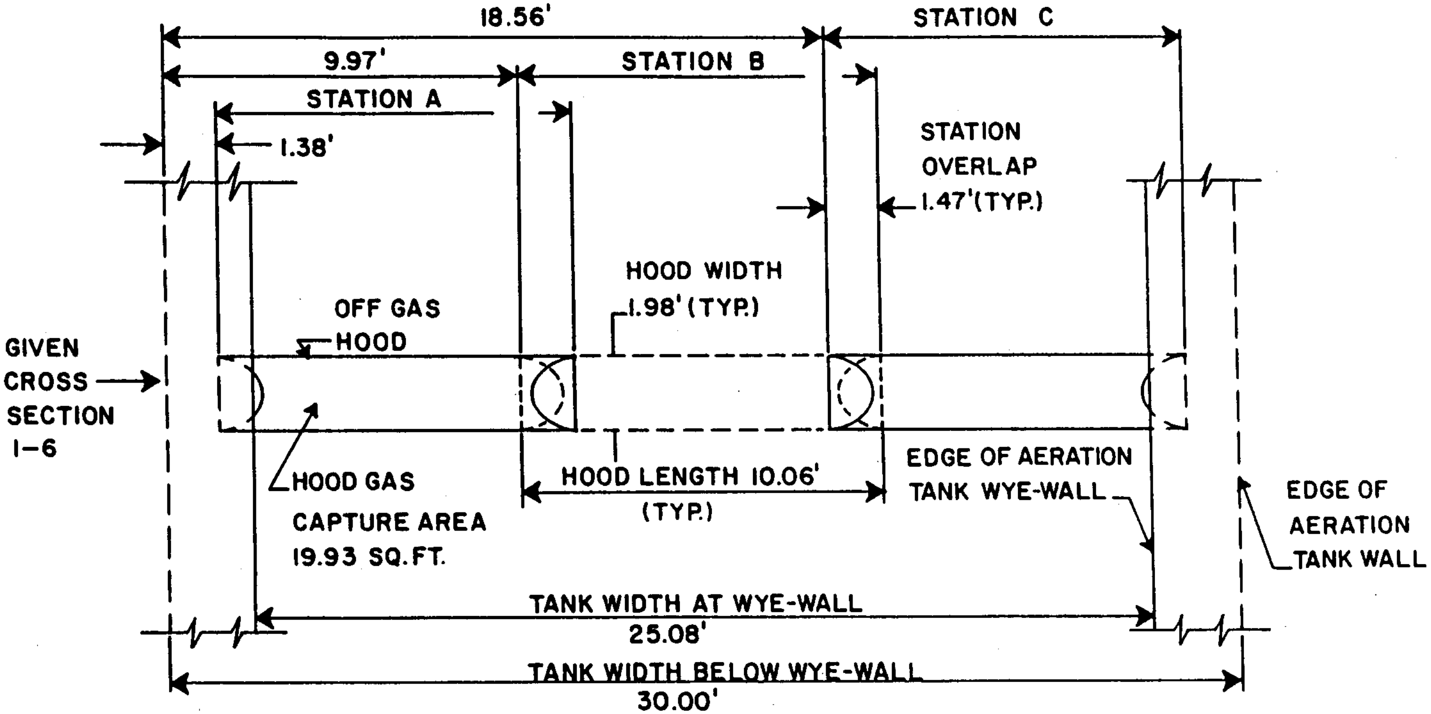


Figure E-4. Off-gas Test Cross Sections



NOTES: (1) ONE OR MORE OF THE ABOVE POSITIONS WAS TESTED AT EACH TEST CROSS SECTION (SEE TABLE E-1).
(2) FOR THE VARIOUS TEST CROSS SECTIONS, SEE FIGURE E-4.

AERATION TANK PLAN

Figure E-5. Typical Off-gas Hood Locations at a Given Tank Cross Section

Table E-1. Off-Gas Test Sampling Stations

Project Part	Aeration System	Test Date	Plant Operation Mode	Average Tank Air Flow per Diffuser (scfm)	Sampling Stations*	Test Duration+ (hrs:min)
1	Disk	8/12/81	12 MGD Conventional	0.94	3 hood positions at each of 5 different cross sections**	5:23
1	Disk	11/9/81	"	1.22	1B,A;1C;2B;3B;4B;5B;6B	6:38
1	Disk	11/10/81	"	2.35	1A,B;2A,B;3B;4B;5B;6B	6:24
1	Disk	11/12/81	"	1.23	1A,B;2B,A;3B,C;4A,B;5A,B;6B,C	7:07
1	Disk	11/19/81	"	0.61	1B,C;2A,B;3B,C;4A,B;5A,B;6B,C	7:25
1	Tube	1/11/82	"		1C;2C;3C,B,A;6A,B,C	6:24
1	Tube	1/12/82	"		1C;2C;3C,B,A;4A,B,C;5C,B,A;6AB,C	8:44
1	Tube	1/14/82(1)	"		5A,B,C;6C,B,A	3:40
1	Tube	1/14/82(2)	"		5A,B,C;6C,B,A	2:54
1	Jet	8/13/81	"	46.60	3 hood positions at each of 5 different cross sections**	3:02
1	Jet	11/24/81	"	26.70	1A,B,C;2A,B,C;3A,B,C	5:36
1	Jet	11/25/81	"	26.70	3C,B,A;4A,B,C;5C,B,A	5:55
1	Jet	12/1/81	"	29.43	1A,B,C;2C,B,A;3A,B,C	5:45
1	Jet	12/2/81	"	29.43	3C,B,A;4A,B,C;5C,B,A;3B	6:10
1	Jet	12/7/81	"	21.20	1A,B,C;2C,B,A;3A,B,C	5:58
1	Jet	12/8/81	"	21.20	3C,B,A;4A,B,C;5C,B,A;3A,B,C	7:05
1	Jet	12/10/81	"	22.75	1A,B,C;2C,B,A;3A,B,C;4C,B;5B,C	7:34
1	Jet	12/28/81	"	13.60	1B,C,A;2B,C;3C,B;4B,C;5C,B	5:52
1	Jet	12/31/81	"	46.48	1A,B,C;2C,B;3B,C;4C,B;5B,C,A	6:50
2	Disk	9/1/82	18 MGD Conventional	1.09	1A,B;2B,C;3B,A;4B,C;5B,A;6B,C	7:03
2	Disk	10/29/82	"	1.35	1B,C;2B,A;3B,C;4B,A;5B,A;6B,C	6:38
2	Disk	12/14/82	"	0.87	1B,C;2A,B;3B,C;4B,C;5B,A;6B,C	6:47
2	Dome(A)	9/2/82	18 MGD Step Feed	0.85	1A,B;2B,C;3B,A;4B,C;5B,C;6B,A	6:22
2	Dome(A)	10/28/82	"	0.95	1C,B;2B,A;3A,B;4B,C;5B,C;6B,A	6:12
2	Dome(A)	12/15/82	"	0.66	1B,A;2B,C;3B,A;4B,A;5B,C;6A,B	6:45
2	Dome(B)	9/3/82	12 MGD Conventional	0.86	1B,A;2B,C;3B,A;4B,C;5B,A;6B,C	6:12
2	Dome(B)	10/27/82	"	0.89	1C,B;2B,A;3B,C;4B,A;5B,C;6B,A	6:50
2	Dome(B)	12/16/82	"	0.67	1B,C;2B,A;3B,C;4C,B;5B,A;6C,B	7:00

* See Figure E-5. Note the different sampling positions for the jet system tests.

\+ From the start of testing at the first station to the completion at the last station.

** Tests conducted by Dave Redmon of Ewing Engineering Co.

1. A test was run on a single aeration system during the day shift under normal primary effluent and return sludge flow conditions. Some diurnal variation in flow and wastewater strength were experienced.

2. During Part 1 of the project a desired air flow per diffuser was set and maintained throughout the entire aeration tank. During Part 2 of the project, only the plant's normal operating air flows per diffuser were evaluated; no attempt was made to make the air flows per diffuser uniform throughout the entire tank or to make them constant throughout the entire test.

3. Off-gas and reference gas analyses were conducted at numerous stations on the surface of the aeration tank.

4. All off-gas testing proceeded from the front to the rear of the aeration tank.

5. Mixed liquor DO readings were taken at each sampling position at mid-depth. Additional DO readings were sometimes taken upstream and downstream of the sampling position to show local DO variations.

6. The following readings were taken on an hourly basis:

    a. primary effluent flow (based on head gate measurements)

    b. return sludge flow (based on totalizer readings)

    c. zone or grid air flows, including line temperatures and pressures

    d. ambient barometric pressure

    e. ambient relative humidity

    f. mixed liquor depth

    g. mixed liquor temperature

7. During the jet system tests, pump total dynamic head (TDH) readings were taken at each pump station at the start and conclusion of each test.

8. When DO concentrations were adequate and time permitted, a steady state oxygen transfer test was performed.

E.4.b Off–Gas Analyzer Operating Procedure

Each day off-gas testing conducted during this study consisted of an initialization step at the first station, followed by a series of off-gas/reference gas analyses at the various stations throughout the tank. The steps which follow describe the methodology used to perform the off-gas/reference gas analyses.

E.4.b.1 Equipment Setup and Initialization--

The off-gas test equipment was set up in accordance with Figure E-1. In addition, the following steps were taken:

1. The probe and analyzer were left on for a minimum of 48 hours prior to the start of any testing. Usually the stabilization period was much longer (i.e., several weeks or months).
2. The probe tip was stored in a wet environment when not in use.
3. Prior to testing on a given day, the probe calibration setting was adjusted as follows:
    a. With the vacuum cleaner on, using reference gas at approximately 5 scfm and a probe pressure near zero, the oxygen probe millivolt reading was set to 190.
    b. The line temperature was recorded.

E.4.b.2 Oxygen Probe Linearity--

It is essential in any off-gas analysis to have a probe that responds linearly to changes in the partial pressure of oxygen. The probes response can be checked in the field with reference or ambient air at two or more widely different probe pressures. Readings are taken of oxygen millivolts and probe pressure at both "low" and "high" pressures. Simple calculations are then performed to verify the probe's linearity.

The linearity check was conducted on the reference gas stream as follows:

a. Barometric pressure was measured.

b. "Low" pressure oxygen millivolt readings were taken in accordance with Section E.4.b.5 of these procedures.

c. "High" pressure oxygen millivolt readings were taken as follows:

    1. The flow meter and probe pressure taps were closed.
    2. The off-gas analyzer discharge throttling value was opened.
    3. The reference gas inlet throttling valve(s) was adjusted until the probe pressure was 4 in. Hg gauge pressure.
    4. The off-gas analyzer discharge throttling valve and reference gas inlet throttling valve(s) were adjusted until the gas flow was 5 scfm and the probe pressure was approximately 4 in. Hg gauge pressure. The exact readings were recorded.
    5. After several minutes of stabilization, oxygen millivolt, probe pressure, and line temperature readings were taken.

6. The expected oxygen millivolt reading under the low pressure condition was then calculated from the measured oxygen millivolt reading under the high pressure condition, assuming a linear probe response as follows:

$$mve_l = mvm_h \frac{p_a + p_{p\,low}}{p_a + p_{p\,high}} \tag{E.1}$$

where

mve_l = expected oxygen millivolts under low pressure conditions

mvm_h = measured oxygen millivolts under high pressure conditions

p_a = measured ambient barometric pressure (psia)

$p_{p\,low}$ = measured probe pressure under low pressure conditions (psig)

$p_{p\,high}$ = measured probe pressure under high pressure conditions (psig)

7. The ratio of expected to measured low pressure oxygen millivolt readings, R, was determined.

8. A decision was made as to the acceptability of the probe linearity.

Linearity was considered acceptable if $0.995 < R < 1.005$.

E.4.b.3 Reference Gas/Ambient Gas Comparison--

The off-gas analysis requires that the composition of the reference gas be known. The reference gas used during this project was taken from the same gas stream used to supply the aeration system, and was withdrawn from under the primary clarifier covers. To use this gas as a reference gas, an assumption was made that it was essentially standard air, except for water vapor content. To verify this assumption, a comparison was made between the reference gas from under the primary clarifier covers and ambient air (assumed to be of standard composition, except for water vapor).

The comparison of the two gas streams showed that the air from under the primary clarifier covers and ambient air were identical in composition when corrected for water vapor content. It was felt therefore, that there was little error involved in using air from under the primary tank covers as the reference gas stream.

E.4.b.4 Routine Off-Gas Analysis--

The following procedures were used to make the necessary determinations on the off-gas stream at each station:

1. A check was made to insure that the off-gas vacuum hose and hood pressure lines were

connected properly to the instrumentation panel.

2. The following valve settings were made:

    1. probe pressure tap - closed
    2. flow meter pressure tap - closed
    3. off-gas discharge throttling valve - at least partially open
    4. a set of metering line shut off valves - open
    5. off-gas isolation valve - open
    6. off-gas bypass valve - closed
    7. reference gas bypass valve - open
    8. reference gas isolation valve - closed

3. The vacuum cleaner was on.

4. The off-gas analyzer discharge throttling valve was adjusted so that the hood pressure was near zero.

5. The system was allowed to stabilize for at least 5 minutes.

6. During this time, throttling valve adjustments were made as necessary to maintain the hood pressure near zero.

7. After the stabilization period, the following readings were taken:

    1. hood pressure
    2. oxygen millivolts
    3. probe pressure
    4. line temperature
    5. flow meter line pressure
    6. Annubar differential pressure or rotameter flow (the rotameter was used only for flows less than 3 scfm)
    7. CO_2 concentration
    8. off-gas analyzer discharge pressure

    9. oxygen millivolts (repeat)
    10. probe pressure (repeat)

8. After one additional minute, the following readings were taken:

    1. oxygen millivolts
    2. probe pressure
    3. line temperature
    4. hood pressure

    Time was recorded for all readings.

E.4.b.5 Routine Reference Gas Analysis--

The following procedures were used to make the necessary determinations on the reference gas stream at each station:

a. The vacuum cleaner was on with the off-gas analyzer discharge throttling valve and metering line shut off valves in the same position used for the respective off-gas test.

b. The following valve settings were made:

    1. probe pressure tap - closed
    2. flow meter pressure tap - closed
    3. reference gas isolation valve - open
    4. reference gas bypass valve - closed
    5. off-gas bypass valve - open
    6. off-gas isolation valve - closed

c. The reference gas inlet throttling valve(s) was adjusted to produce the same gas flow obtained during the off-gas test.

d. The probe pressure valve was opened slowly.

e. The reference gas inlet throttling valve was adjusted as necessary to maintain the same probe pressure obtained during the off-gas test.

f. A check was made to insure that the reference gas flow was still close to that obtained during the off-gas test.

g. After a stabilization period of at least 5 minutes, the following readings were taken:

  1. oxygen millivolts
  2. probe pressure
  3. line temperature
  4. flowmeter line pressure
  5. Annubar differential pressure or rotameter flow
  6. off-gas analyzer discharge pressure
  7. oxygen millivolts (repeat)
  8. probe pressure (repeat)
  9. line temperature

h. If the gas flow was less than 15 scfm, the off-gas analyzer discharge throttling valve and the reference gas inlet throttling valves were adjusted to provide a minimum gas flow of 15 scfm with a probe pressure near zero.

i. Once accomplished, the following readings were taken:

  1. line dry bulb temperature
  2. line wet bulb temperature
  3. line probe pressure

Time was recorded for all readings.

The off-gas and reference gas analyses were repeated in similar fashion at each station throughout the tank.

It should be noted that slight variations on the above procedures were utilized at various times. In particular, the "bypass" of reference gas during off-gas analysis was only performed during the latter portion of Part 1 of the project. At other times, the reference gas flow was completely shut off during off-gas analysis.

E.5 OFF-GAS METHOD - DATA ANALYSIS

E.5.a Station OTE Results

The station OTE calculations were performed in a fashion similar to that developed by Redmon, et al. (1983).

E.5.b Station Hood Flow Results

The hood flows were normally measured with the 1/2" Annubar. Very low flows were measured with the rotameter. The pertinent flow equations for these meters in air are shown in Appendix F. The intent of this section is to show how these air based flow determinations were corrected for a gas specific gravity different than air.

It can be shown from basic flow metering principles that

$$Q_{he} = \frac{Q_{ha}}{Fwv_a'} \frac{1}{\sqrt{G_o}} , \tag{E.25}$$

where

Q_{he} = the exact hood gas flow reported at standard temperature and pressure (cfm)

Q_{ha} = the hood gas flow reported at standard temperature, pressure and relative humidity, assuming the gas had been air, scfm (as determined in Appendix F)

Fwv_a' = the water vapor correction factor assuming the gas had been air (see Appendix F)

G_o = the off-gas specific gravity

The off-gas specific gravity is related to the mole fractions of its constituents as follows:

$$G_o = \frac{31.999\ Y_{O_{2(o)}} + 44.010\ Y_{CO_{2(o)}} + 18.015\ Y_{H_2O(o)} + 28.155\ Y_{inerts(o)}}{28.967} \tag{E.26}$$

where

$Y_{i(o)}$ = the mole or volumetric fraction of various constituents in the off-gas, decimal %

In the above equation, 28.967 is the molecular weight of dry air. The inert gases usually present are nitrogen and argon.

For the purposes of flow weighting the station standard OTE_f results and for comparison of the captured gas flows with the applied gas flows, it is not the actual off-gas flows that are important, but the associated gas flows at the inlet to the aeration system. These flows are related to the off-gas flows as follows:

$$Q_{hei} = Q_{he} + Q_{ha}' \tag{E.27}$$

where

Q_{hei} = the inlet air flow associated with the hood off-gas flow reported at standard temperature and pressure, cfm

Q'_{ha} = the inlet gas flow absorbed in the aeration tank reported at standard temperature and pressure, cfm

It can be shown from basic principles that

$$Q_h = 1.0084 \frac{Y_{inerts(o)}}{Y_{inerts(s)}} Q_{he} \quad (E.28)$$

where

Q_h = the inlet air flow associated with the hood off-gas flow reported at standard temperature, pressure, and relative humidity, scfm

$Y_{inerts(s)}$ = the mole or volumetric fraction of inerts (nitrogen and argon) present in standard air = 0.7900, decimal %

Upon substitution, Equation E.28 reduces to

$$Q_h = 1.2765\, Y_{inerts(o)}\, Q_{he} \quad (E.29)$$

Substituting Equation E.2 in Equation E.29 yields

$$Q_h = 1.2765\, Y_{inerts(o)} \frac{Q_{ha}}{fwv'_a} \frac{1}{\sqrt{G_o}} \quad (E.30)$$

Equation E.30 is a considerable refinement and as a result, it was not utilized during most of the project. Only the hood flows during the 18 mgd Step Feed Mode were corrected in this manner. It is estimated that the use of Q_{ha} in place of Q_h during the project resulted in an error of only -0.3 to -1.5% in flow at any given station. More importantly, since these flows were used only for flow weighting purposes, the effect on the final $SOTE_f$ results was negligible.

E.5.c Independent Station OTE and Hood Flow Results

Due to the length of the off-gas hood relative to the width of the aeration tank at wye wall level, it was not possible to sample the entire width of a tank without overlapping the hood positions. This is clear from Figure E-5. Shown are the typical A, B, and C hood positions used during the study. If three hood positions are used, it can be seen that the middle hood position (B) overlaps each end position (A and C) by approximately 1.5 ft.

In order to obtain independent OTE_f and gas flow readings, it was necessary to correct some of the hood determinations so that the results from overlapping regions were not included twice in the analysis. The correction process essentially "subtracted" the overhap gas flow and OTE_f results from one of the two hood positions (the "altered" position) wherever an overlap occurred.

The decision as to which of the two hood positions was considered the "unaltered" position was a function of the aeration system tested. The general rule was that the station with the most uniform gas flow was given this designation. This provided more accurate estimates of the overlap gas flow and OTE_f. The "subtraction" process was only accurate to the extent that conditions at the unaltered position were uniform. The altered and unaltered hood positions utilized for the various aeration systems are shown in Table E-2.

Because of the various aeration system off-gas patterns, the following unaltered and altered hood positions were selected:

The equations which follow determine the altered station gas flows and OTE_f's as a function of the determinations for each of the two overlapping stations involved. Both equations are easily derived from basic principles assuming uniform conditions at the unaltered hood position.

The altered station gas flow equation can be stated as:

$$Q_{haa} = Q_{hab} - \frac{L_o}{L_h} \times Q_{hu} \tag{E.31}$$

where

Q_{haa} = the altered station inlet air flow associated with the hood off-gas flow, after alteration and reported at standard temperature, pressure and relative humidity, scfm

Q_{hab} = the altered station hood inlet air flow associated with the hood off-gas flow, before alteration, and reported at standard temperature, pressure, and relative humidity, scfm

Q_{hu} = the unaltered station inlet air flow associated with the hood off-gas flow reported at standard conditions of temperature, pressure, and relative humidity

L_o = the hood overlap length, ft

L_h = the length of the hood, ft

The altered station OTE_f equation can be stated:

$$OTE_{faa} = \frac{OTE_{fab}Q_{hab} - OTE_{fu}\,(L_o/L_h)\,Q_{hu}}{Q_{haa}} \tag{E.32}$$

where

OTE_{faa} = the altered station process water oxygen transfer efficiency under actual conditions, after alteration, %.

Table E-2 Altered and Unaltered Hood Positions

System	A-B Overlap		B-C Overlap	
	A Position	B Position	B Position	C Position
Disks and Domes	Altered	Unaltered	Unaltered	Altered
Tubes	Altered	Unaltered	Unaltered	Altered
Tests	Unaltered	Altered	Unaltered	Altered

OTE_{fab} = the altered station process water oxygen transfer efficiency under actual conditions, before alteration, %.

OTE_{fu} = the unaltered station process water oxygen transfer efficiency under actual conditions, %.

The steps in this section were only used if the hood positions overlapped. Furthermore, it was assumed for most of the project that $Q_h = Q_{ha}$ (see Section E.5.b).

E.5.d Independent Station αFSOTE Results

The basic oxygen transfer relationship can be stated

$$\frac{dC}{dt_f} = \alpha K_L a\ (\beta C^*_\infty - C) \tag{E.33}$$

where

dC/dt_f = the process water volumetric oxygen transfer rate at process water temperature and ambient pressure, mg/L-hr

α = the ratio of the overall volumetric mass transfer coefficient in process water to the overall volumetric mass transfer coefficient in clean water.

K_La = the clean water overall volumetric mass transfer coefficient at temperature T, hr^{-1}.

β = the ratio of the oxygen saturation in process water to the oxygen saturation in clean water.

C^*_∞ = the clean water oxygen saturation concentration at process water temperature and ambient pressure, mg/L.

C = the dissolved oxygen concentration, mg/L.

Multiplying both sides of this equation by the weight of water in the aeration zone yields the oxygen transfer rate, OTR_f.

$$OTR_f = \alpha K_L a(\beta C^*_\infty - C)W \tag{E.34}$$

where

OTR_f = the process water oxygen transfer rate at process water temperature and ambient pressure, lbs/hr.

W = the weight of water in the aeration zone, 10^6 lbs.

By definition

$$OTE_f = \frac{OTR_f}{OSR} \times 100 \qquad (E.35)$$

where

OTE_f = the process water oxygen transfer efficiency at process water temperature and ambient pressure, percent.

OSR = the oxygen supply rate, lbs/hr

Furthermore, an expression often used to relate K_La to K_La_{20} is the following:

$$K_La = K_La_{20}\,\theta^{T-20} \qquad (E.36)$$

where

K_La_{20} = the overall volumetric mass transfer coefficient at 20°C in clean water, 1/hr.

T = water temperature, °C.

θ = theta factor, 1.024 for this case.

Substituting Equations E.35 and E.36 into Equation E.34 yields

$$K_La_{20} = \frac{OTE_f\,OSR}{100\alpha W(\beta C^*_\infty - C)\theta^{T-20}} \qquad (E.37)$$

At standard conditions of 20°C, 14.70 psia, and 0 mg/L, the above expression reduces to

$$K_La_{20} = \frac{\alpha FSOTE\ OSR}{100\alpha W\ \beta C^*_{\infty 20}} \qquad (E.38)$$

where

αFSOTE = the process water oxygen transfer efficiency at standard conditions of 20°C, 14.70 psia and 0 mg/L DO, percent

$C^*_{\infty 20}$ = the clean water oxygen saturation at standard conditions of 20°C and 14.70 psia, mg/L.

Equating Equations E.37 and E.38 and rearranging, the following expression is obtained:

$$\alpha F\ \mathrm{SOTE} = \frac{\beta C^*_{\infty 20}\ \mathrm{OTE}_f}{(\beta C^*_{\infty} - C)\theta^{T-20}} \tag{E.39}$$

According to the concept of equivalent depth, the clean water oxygen saturation concentration can be expressed as

$$C^*_{\infty} = \left[\frac{p_a + 0.434\ z_e - \mathrm{pvpt}}{14.70}\right] C^*_{ht} \tag{E.40}$$

where

z_e = the equivalent depth (from previous clean water test results), ft

C^*_{hT} = the handbook dissolved oxygen saturation in clean water at temperature, T, and 14.70 psia (dry air, 20.9% O_2 by volume), mg/L.

The following values for z_e were used based on clean water test results at the Whittier Narrows plant.

System	z_e (as a fraction of submergence)
Disk and Dome Systems	0.451
Tube System	0.403
Jet System	0.447

It should be noted that the result shown for the disk and dome systems was based on tests with the disk system only.

At standard conditions of 20°C and 14.70 psia, Equation E.40 reduces to

$$C^*_{\infty 20} = \left[\frac{14.70 + 0.4335 z_e - 0.34}{14.70}\right] 9.17 \tag{E.41}$$

$$C^*_{\infty 20} = 0.624(14.36 + 0.4335 z_e) \tag{E.42}$$

A relationship for β has been postulated in *Standard Methods* (1980) as

$$\beta = 1 - 0.05\left[\frac{TDS}{5000}\right] \tag{E.43}$$

where

TDS = the process water total dissolved solids, mg/L.

For the purposes of this study, the TDS of the plant final effluent was used.

Upon substitution of Equations E.40, E.42, and E.43 in Equation E.39, αFSOTE can be determined. This procedure was used at each test station.

E.5.e Flow Weighted αFSOTE Results

An air flow rate weighting procedure was utilized to determine average cross section, average zone and average tank results. Average cross section results were determined as follows:

$$Q_{hci} = Q_{hciA} + Q_{hciB} + Q_{hciC} \tag{E.44}$$

$$\alpha FSOTE_{ci} = \frac{\alpha FSOTE_{ciA}\, Q_{hciA} + \alpha FSOTE_{ciB}\, Q_{hciB} + \alpha FSOTE_{ciC}\, Q_{hciC}}{Q_{hciA} + Q_{hciB} + Q_{hciC}} \tag{E.45}$$

where

Q_{hci} = the cross section i inlet air flow associated with the independent hood off-gas flow rates, reported at standard temperature, pressure, and relative humidity, scfm

$Q_{hciA,B,\text{ or }C}$ = the inlet air flow associated with the independent hood off-gas flow at cross section i, position A, B or C, respectively, reported at standard temperature, pressure, and relative humidity, scfm

$\alpha FSOTE_{ci}$ = the cross section i process water oxygen transfer efficiency reported standard conditions of 20°C, 14.70 psia, and 0 mg/L DO.

$\alpha FSOTE_{ciA,B\text{ or }C}$ = the process water oxygen transfer efficiency at cross section i, position A, B or C, respectively, reported at standard conditions of 20°C, 14.70 psia, and 0 mg/L DO.

Average zone results were determined in similar fashion:

$$Q_{hzi} = \sum_{i=k_1}^{k_2} Q_{hci} \tag{E.46}$$

$$SOTE_{fzi} = \frac{\sum_{i=k_1}^{k_2} (SOTE_{fci}\, Q_{hci})}{Q_{hzi}} \tag{E.47}$$

where

Q_{hzi} = the zone i inlet air flow resulting from the sum of the zone i cross section flows, scfm

k_1 = the number of the first cross section in zone i

k_2 = the number of the last cross section in zone i

$\alpha FSOTE_{fzi}$ = the zone i process water oxygen transfer efficiency reported at standard conditions of 20°, 14.70 psia, and 0 mg/L DO

The average tank results were calculated in a slightly different fashion. Because the aeration system zone flows were accurately measured at each downcomer, a decision was made to use these flows, rather than the hood zone flows, to determine the average tank αFSOTE results. Thus

$$Q_{at} = \sum_{i=1}^{3} Q_{azi} \tag{E.48}$$

$$\alpha FSOTE_t = \frac{\sum_{i=1}^{3} (SOTE_{fzi}\, Q_{azi})}{Q_{at}} \tag{E.49}$$

where

Q_{at} = the total tank aeration system flow scfm

Q_{azi} = the zone i aeration system flow, scfm

$\alpha FSOTE_t$ = the total tank process water oxygen transfer efficiency reported at standard conditions of 20°C, 14.70 psia, and 0 mg/L DO

E.5.f Special Circumstances

There were certain circumstances during the project that required special data analysis techniques. Most of these circumstances involved the jet aeration systems.

As mentioned previously, the early jet system tests were conducted over a 2 day period because of the more extensive sampling required. While the limitations of this type of test were realized, some procedure was necessary to combine the results of two day's testing. It was standard procedure on the second day of the testing to repeat the tests at the last cross section of the first day. This was sometimes done at the start as well as the finish of the second day's test. In this way any changes due to different process water conditions could be observed. The data from these repeat tests, including all associated parameters, were averaged to produce a single set of cross section results. The data from the two test days were then analyzed as if it had been performed on a single day.

During the later tests on the jet system, a given test was completed in a single day. In order to accomplish this with the rather slow off-gas analyzer available, it was necessary to eliminate some sampling positions. With the jet system, as configured during our study, there were regions on the surface of the tank with extremely low off-gas flow rates and very high αFSOTE's. These regions were located on the opposite side of the tank from the long jet manifold and were of relatively minor importance in determining the overall efficiency of a cross section, zone or tank. For this reason, a decision was made to dispense with these areas during the latter jet system tests.

An attempt was made to account for this analytically by using information from the earlier jet system tests. Plots of relative gas flows and αFSOTE's were made which helped predict the missing station information. It is felt that this procedure improved the overall accuracy of the tests, but was not of major consequence.

It should also be noted that during the disk and dome system tests, it was common to sample less than three positions at a given cross section. This was handled analytically by assuming that the average αFSOTE results at the cross section were representative of the missing station results. Overall cross section gas flows were obtained by prorating the existing gas flows. It was felt these procedures were adequate in light of the relative uniformity of the disk and dome system off-gas patterns.

It should also be mentioned that Zone 2 of the jet aeration system was analyzed as if there were two separate aeration zones. The reason for this was that there were basically two different diffuser spacings within the main zone. An aeration system air flow split was made based on the number of diffusers in each sub-zone. For reporting purposes however, the sub-zone results were combined to produce the overall Zone 2 results.

A problem of relatively minor significance was experienced during some of the off-gas tests on the disk and jet aeration systems during Part 1 of the project. In 1981, after running the disk system tests on November 10, 12, and 19 and the jet system tests on November 24 and 25, it was discovered that the hood gas flow rates for these runs were in error. Apparently some of the Annubar pressure ports were obstructed by a foreign object that had entered the off-gas analyzer piping. Since the Ewing variation of the off-gas method uses hood flow rates for flow rate weighting purposes, an attempt was made to salvage the test results by analyzing the data in a slightly different manner.

No attempt was made to correct the hood flow rate results obtained during this period. Instead, the following procedure for flow rate weighting purposes was used. For the disk system, an arithmetic average was taken of the pertinent station αFSOTE results within a zone to obtain average cross section and zone results. Average tank results were obtained by using the aeration system zone air flow rates for weighting purposes. For the jet system, hood air flow rates within a zone were determined from other test runs and used to predict the hood air flow rates during the affected tests. These were used to determine the average cross section and zone results. As with the disk system, average tank results were obtained by using the aeration system zone air flows for flow weighting purposes.

E.5.g Support Parameter Results

E.5.g.1 Primary Effluent and Return Sludge Flows--

The primary effluent flow rates during the off-gas tests were based on head gate measurements, rather than on the plant final effluent flow meter. The main reason for this was that the final effluent meter, over a short period of time (e.g., 1 hr.), was not necessarily indicative of the flow rate through the aeration system. The batch backwash cycles at the plant result in effluent going into and out of storage downstream of the aeration system and upstream of the final effluent meter. Furthermore, several sidestreams, including skimmings, waste sludge and backwash sludge, are wasted to the sewer upstream of the final effluent meter. Over a larger period of time (e.g. 1 day) the plant meter is indicative of the aeration system flow rate when the sidestreams are taken into account.

Return sludge flows were based on totalizer measurements on the tank propeller meters.

E.5.g.2 Air Flow Rates--

The air flow rates during the off-gas tests were based on temperature, pressure and humidity compensated results from the various downcomer meters. During the tube and jet system tests, header meter readings were also used because some of the air downcomers were without meters.

Once each hour, air flows were taken throughout the entire tank. Only the zone flows associated with the stations tested were used in any analytical way, however.

E.5.g.3 DO Determinations--

DO readings were taken at each station. Additional readings were sometimes taken upstream and downstream of a station to show the spatial variation of DO concentration in the tank. Only DO readings taken at the station itself were used in the αFSOTE calculations.

The DO probe used was lab calibrated in distilled water. As a result, the process water DO readings obtained were corrected for β factor as follows:

$$\begin{array}{l}\text{Process Water}\\ \text{DO Concentration}\\ \text{(Corrected)}\end{array} = \beta \times \begin{array}{l}\text{Process Water}\\ \text{DO Concentration}\\ \text{(Uncorrected)}\end{array} \qquad \text{(E.50)}$$

Equation E.20 was used to determine the β factor.

The probe calibration was checked again at the end of a day's test. An average calibration factor was then applied to all readings for the day.

E.5.g.4 Total Dynamic Head (TDH)--

Pressure readings were taken in the pump discharge line for each pump station before and after the tests on the jet system. These readings were converted to total dynamic head determinations (TDH) according to the following equation:

$$TDH = p_{mt} + \frac{V_t^2}{2g} + h_{Ldt} + \Delta \qquad \text{(E.51)}$$

where

p_{mt} = the measured static pressure at the backflush tee, ft H_2O

$\frac{V_t^2}{2g}$ = the velocity head at the backflush tee, ft H_2O

h_{Ldt} = the headloss between the pump discharge and the backflush tee, ft H_2O

Δ = the distance between the inside top of the backflush line and its horizontal centerline, 0.3624 ft for this study.

The resulting TDH determinations were used to calculate pump flow and power draw from the certified performance curves supplied.

E.5.h Time Dependence of Test Condition Measurements

Because of the finite amount of time required to conduct the off-gas tests, the time dependence of all test condition measurements was considered as follows:

1. Parameter/time profiles were used to estimate process water depth, temperature and ambient barometric pressure at the point in time corresponding to the off-gas test at each station.
2. Parameter/time profiles were used to estimate aeration system air flow rate, primary effluent flow rate, return activated sludge flow rate, and total hydraulic head at the midpoint in time between the start and finish of tests at a given cross section.
3. Arithmetic averages of process water depth, temperature and ambient barometric pressure were used to determine cross section results from station results.
4. Arithmetic averages of the above mentioned parameters were used to estimate zone results from the cross section results and the tank results from the zone results.

As discussed previously, all cross section, zone, and tank αFSOTE determinations were made from the individual station results on an air flow weighted basis.

APPENDIX F. OTHER TEST PROCEDURES

F.1 ORIFICE PLATE EQUATIONS

Air flow computations were in accordance with Cusick (1968) and Spink (1967). The basic flow equation for an orifice plate can be expressed as follows:

$$Q_{scfm} = 3.641\, F_p\, F_a\, F_{hm}\, F_m\, F_{pb}\, F_{Tb}\, F_{pf}\, F_{TF}\, F_g\, F_{pv}\, F_{wv'}\ S_o D^2 Y F_{vc} \qquad \text{(F.1)}$$

where

Q_{scfm} = air flow, scfm (68°F, 14.70 psia, 36% humidity)

p_b = base pressure = 14.70 psia

T_b = base temperature = 528°R

p_f = flowing pressure, psia

T_f = flowing temperature, °R

F_p = pipe expansion correction factor = $1.333 \times 10^{-5} T_f + 0.9930$

F_a = orifice area correction factor = $2 \times 10^{-5}\, T_f + 0.9891$

F_{hm} = $\sqrt{D.P.}$

F_m = manometer correction factor (assume 1.0)

F_{pb} = base pressure factor = $1/p_b$

F_{Tb} = base temperature factor = T_b

F_{pf} = operating gas pressure factor = $\sqrt{p_f}$

F_{Tf} = operating gas pressure factor = $\sqrt{1/T_f}$

F_q = dry gas specific gravity = 1.0 for air

F_{pv} = supercompressibility factor (assume 1.0)

$F_{wv'}$ = water vapor correction factor (converts a dry basis flow to that at standard humidity (36%) - see Part F.5 of this Appendix)

S_o = orifice factor

D = pipe inside diameter, in.

D.P. = meter differential pressure, in. H_2O

Y = gas expansion factor = $1- [10.61 + 9.053\ \beta^4] \times 10^{-3} \frac{D.P.}{p_f}$ (for Vena Contracta taps)

β = orifice diameter ratio, d/D

F_{vc} = vena contracta correction factor (see Cusick)

Upon substitution, of the above, Equation F.1 reduces to:

$$Q = 130.77 \sqrt{\frac{D.P.\ p_f}{T_f}}\ S_o D^2 F_{wv'} F_{vc} (1.333 \times 10^{-5} T_f + 0.9930) \qquad (F.2)$$

$$\times (2 \times 10^{-5} T_f + 0.9891)[1 - (10.61 + 9.053\ \beta^4) \times 10^{-3} \frac{D.P.}{P_f}]$$

The last four parameters in Equation F-1 were specific to each orifice plate. Table F-1 shows the specific orifice plate data for this project.

F.2 ANNUBAR EQUATIONS

Air flow computations were in accordance with Dietrich Standard Corporation (1979), Cusick (1968) and Spink (1967). A basic air flow equation for an Annubar can be expressed as follows:

$$Q_{scfm} = 3.641\ F_p\, F_{hm}\, F_m\, F_{pb}\, F_{Tb}\, F_{pf}\, F_{Tf}\, F_g\, F_{wv'}\, V_a\, S D^2 \qquad (F.3)$$

where all parameters are as defined for the orifice plate equations with the following exceptions and additions:

F_p = pipe expansion correction factor

Table F-1. Orifice Plate Information

Meter Designation	Meter Type	Meter Usage*	Pipe I.D. (in.)	Meter Bore	Meter Beta Ratio+	Orifice Factor++	Approx. Reynolds Number Range Applicable to Orifice Factor	Vena Contracta Correction Factor
A	Orifice Plate	TK2-DC1-PT1	6.065	3.636	0.5995	$S_o = -0.0005\sqrt{40.419-(\frac{Re-153{,}400}{20{,}000})^2}+0.23805$	30,000-140,000	1.00000
B	Orifice Plate	TK3-DC3-PT1 TK2-DC3-late PT1	6.065	3.878	0.6394	$S_o = -0.001\sqrt{28.266-(\frac{Re-124{,}264}{20{,}000})^2}+0.27982$	19,000-100,000	1.00000
C	Orifice Plate	TK3-DC1-All CWT's	6.065	3.940	0.6496	$S_o = -0.0005\sqrt{87.022-(\frac{Re-213{,}600}{20{,}000})^2}+0.28936$	30,000-120,000	1.00000
D	Orifice Plate	TK2-DC2-LATE PT1	6.065	4.356	0.7182	$S_o = -0.001\sqrt{54.564-(\frac{Re-174{,}200}{20{,}000})^2}+0.37751$	30,000-110,000	1.00000
E	Orifice Plate	TK3-DC2-PT1	6.065	4.856	0.8007	$S_o = -0.002\sqrt{37.288-(\frac{Re-660{,}853}{100{,}000})^2}+0.51885$	50,500-500,000	1.00590
F	Orifice Plate	TK3-MAIN-ALL CWT's	10.020	5.920	0.5908	$S_o = -0.0005\sqrt{21.794-(\frac{Re-278{,}000}{50{,}000})^2}+0.22876$	50,000-250,000	1.00027
F	Orifice Plate	TK3-MAIN-ALL CWT's	10.020	5.920	0.5908	$S_o = -0.0005\sqrt{69.789-(\frac{Re-446{,}000}{50{,}000})^2}+0.22959$	30,000-100,000	1.00027
G	Orifice Plate	TK3-MAIN-PT1-MLT's	10.020	8.016	0.8000	$S_o = -0.002\sqrt{71.804-(\frac{Re-899{,}000}{100{,}000})^2}+0.51921$	52,000-270,000	1.03100++
H	Orifice Plate	TK2-MAIN-PT1	23.500	7.341	0.3124	$S_o = 0.057796 + \frac{0.099068}{\sqrt{Re}}$	Based on tests in the 147,000-257,000 range	1.00000

* The following abbreviations apply: TK-Tank, DC-Downcomer, PT-Part, CWT's- clean water tests, MLT's-mixed liquor tests.

\+ Meter bore/inside pipe diameter.

++ Re = Reynolds Number = $\frac{28.50}{\mu}$, where μ = absolute viscosity = $(32.2 + 0.28\ T_f) \times 10^{-4}$, cps. All orifice factors apply to vena contracta differential pressure taps.

‡ Changed to 1.000 after 7/30/81.

$1.699 \times 10^{-5} T_f + 0.9910$ for stainless steel pipe (1/2" annubar)

$1.333 \times 10^{-5} T_f + 0.9930$ for carbon steel pipe (4" annubars)

V_a = gas adiabatic compression factor (see below)

S = Annubar factor

The gas adiabatic compression factor, V_a can be stated as follows:

$$V_a = \sqrt{\frac{k}{(k-1)} \frac{p_f}{(p_t - p_f)} \left[\left(\frac{p_t}{p_f} \right)^{\frac{k-1}{k}} - 1 \right]} \tag{F.4}$$

where

k = the ratio of the specific heats, C_p/C_v.
p_T = line stagnation pressure, psia

Substituting $\frac{V^2}{2g} + p_f$ for p_T and assuming k = 1.395 (for dry air), this equation reduces to:

$$V_a = 1.879 \sqrt{\frac{p_f}{V^2/2g} \left[\left(\frac{p_f + V^2/2g}{p_f} \right)^{0.283} - 1 \right]} \tag{F.5}$$

where

$V^2/2g$ = the velocity head under actual conditions, psia

$= 1.007 \times 10^{-3} \dfrac{Q_{cfm}^2 \gamma_{actual}}{D^4}$

Q_{cfm} = the volumetric flow rate under actual conditions, psia

$= \dfrac{0.02760\, Q_{scfm} x T_f}{p_f - p_w}$

p_w = the partial pressure of water vapor in the line, psia

$\gamma_{actual} = 2.702 \dfrac{p_f}{T_f} \left[\left[\dfrac{p_f - p_w}{p_f} \right] 1.0 + \dfrac{p_w}{p_f} \left[0.6225 \right] \right]$

Upon substitution, Equation F.3 reduces to:

$$Q_{scfm} = 130.77 \sqrt{\frac{(D.P.) p_f}{T_f}} S D^2 F_{wv'} F_p V_a$$

(F.6)

For specific Annubar data, see Table F.2.

F.3 FLOW TUBE EQUATIONS

A basic air flow equation for a flow tube can be expressed as follows:

$$Q_{scfm} = 3.641\ F_p\ F_a\ F_{hm}\ F_m\ F_{pb}\ F_{Tb}\ F_{pf}\ F_{Tf}\ F_g\ F_{pv}\ F_{wv'}\ S_o'\ D^2\ Y' \qquad (F.7)$$

where all parameters are as defined for the orifice plate equations with the following exceptions and additions:

F_p = pipe expansion correction factor (assume 1.0)

F_a = orifice area correction factor (assume 1.0)

S_o' = flow tube factor

Y' = gas expansion factor (assume 1.0)

Upon substitution, Equation F.7 reduces to:

$$Q_{scfm} = 130.77 \sqrt{\frac{(D.P.)p_f}{T_f}}\ S_o'\ D^2\ F_{wv'}$$

The last three parameters in Equation F.7 were specific to each flow tube. For specific flow tube data, see Table F-2.

F.4 ROTAMETER EQUATIONS

An approximate air flow equation for a rotameter can be expressed as follows:

$$Q_{scfm} = F_{pb}\ F_{Tb}\ F_{pf}\ F_{Tf}\ F_{wv'}\ Q_R\ F_{pbc}\ F_{Tbc}\ F_{pfc}\ F_{Tfc} \qquad (F.8)$$

where all parameters are as defined for the orifice plate equations with the following additions:

Q_R = indicated rotameter air flow, cfm

p_{bc} = calibration base pressure, psia

T_{bc} = calibration base temperature, °R

p_{fc} = calibration operating gas pressure, psia

T_{fc} = calibration operating gas temperature, °R

Table F-2 Annubar and Flow Tube Information

Meter Designation	Meter Type	Meter Usage*	Pipe I.D. (in.)	Meter Bore (in.)	Meter Beta Ratio+	Meter Factor
I1-2	Dieterich Standard Model AWR 71 Annubar	1. Off-gas Analyzer 2. Diffuser test header	0.622			$S = 0.528$
J1-3	Dieterich Standard Model AWR 73 Annubar	TK1-DC1-3-PT1	4.026			$S = 0.717$
K1-3	Bif Universal Venturi Flow Tube	TK1-3-DC3-PT2	6.065	2.709	0.4467	$S_o' = 0.1925$
L1-6	Bif Universal Venturi Flow Tube	TK1-3-DC1-2-PT2	7.981	3.610	0.4523	$S_o' = 0.2012$
M	Dall Model 122 Flow Tube	TK1-MAIN-PT1&2	17.50	11.84	0.6578	$S_o' = 0.3101$
N	Dall Model 122 Flow Tube	TK2-3-MAIN-PT2	23.50	15.84	0.6740	$S_o' = 0.3070$

* The following abbreviations apply: TK - tank, DC - Downcomer, PT - Part, CWT's - clean water tests, MLT's - mixed liquor tests.

\+ Meter bore/pipe I.D.

F_{pbc} = calibration base pressure factor = p_{bc}

F_{Tbc} = calibration base temperature factor = $\frac{1}{T_{bc}}$

F_{pfc} = calibration operating gas pressure factor = $\sqrt{\frac{1}{p_{fc}}}$

F_{Tfc} = calibration operating gas temperature factor = $\sqrt{T_{fc}}$

Upon substitution, Equation F.8 reduces to

$$Q_{scfm} = 35.92 \frac{p_{bc}}{T_{bc}} Q_R \sqrt{\frac{p_f T_{fc}}{T_f p_{fc}}} F_{wv'} \qquad \text{(F.9)}$$

F.5 WATER VAPOR CORRECTION FACTOR

For all types of meters, the water vapor correction factor, $F_{wv'}$, can be calculated as follows:

$$F_{wv'} = K \text{ x } F_{wv} = \left[\frac{p_s}{p_s - p_{ws}}\right] \text{ x } \frac{\left[1 - \frac{p_w}{p_a}\right]}{\sqrt{1 - 0.3775 \frac{p_w}{p_a}}} \qquad \text{(F.10)}$$

where

K = a factor relating the flow of gas on a "dry" basis at standard conditions to that on a standard humidity basis (36%) at standard conditions

F_{wv} = a factor relating the flow of gas on an actual humidity basis at otherwise standard conditions to that on a "dry" basis at standard conditions

p_s = standard pressure of 14.70 psia

p_{ws} = water vapor partial pressure at standard conditions of 36% humidity and 68°F (0.122 psia)

p_w = water vapor partial pressure at actual ambient conditions, psia (see below)

p_a = barometric pressure at actual ambient conditions, psia

It is assumed here that no change in water vapor content occurs between ambient and line conditions.

Upon substitution, Equation F.10 reduces to:

$$F_{wv'} = 1.0084 \times \frac{\left(1 - \frac{p_w}{p_a}\right)}{\sqrt{1 - 0.3775 \frac{p_w}{p_a}}} \tag{F.11}$$

The water vapor partial pressure at actual conditions, p_w, can be calculated as follows:

$$p_w = p_{vp} \times \left(\frac{RH}{100}\right) \tag{F.12}$$

where

P_{vp} = water vapor pressure at ambient temperature, psia

$$= \frac{\text{antilog}_{10}\left[\frac{-4985.76}{T_a} - 3.58984 \log(T_a) + 20.4602\right]}{51.714}$$

RH = relative humidity at ambient conditions

F.6 DYNAMIC WET PRESSURE MEASUREMENTS

Dynamic wet pressure was periodically measured to determine the increase in pressure losses through both the disk and dome diffusers. Figure F-1 shows the portable apparatus used to measure DWP. A single diffuser was selected in each of the three grids and plumbed as shown in Figure F-1. Total diffuser headloss (including the control orifice) was also measured.

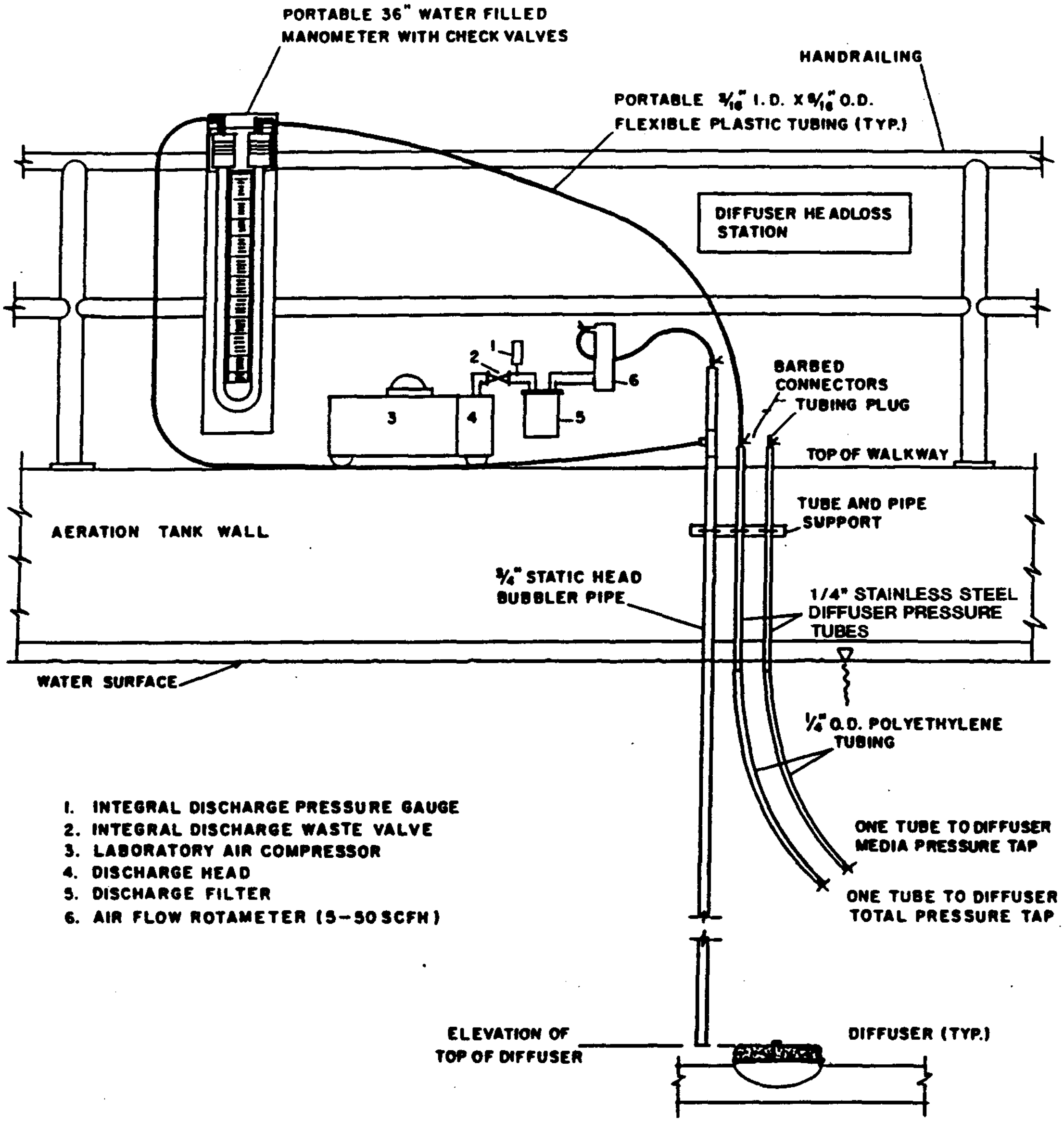


Figure F-1. Diffuser Headloss Test Schematic