



Technology Transfer

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Design Manual

Fine Pore Aeration Systems



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Design Manual

Fine Pore Aeration Systems

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Notice

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Contents

Chapter	Page
1 INTRODUCTION AND OVERVIEW	1
1.1 Historical Overview	1
1.2 Objectives of the Manual	2
1.3 References	2
2 FINE PORE DIFFUSER CHARACTERISTICS	3
2.1 Introduction	3
2.2 Types of Fine Pore Media	3
2.2.1 Ceramics	3
2.2.2 Porous Plastics	4
2.2.3 Perforated Membranes	5
2.3 Types of Fine Pore Diffusers	6
2.3.1 Plate Diffusers	6
2.3.2 Tube Diffusers	6
2.3.3 Dome Diffusers	10
2.3.4 Disc Diffusers	10
2.4 Diffuser Layout	14
2.4.1 Plate Diffusers	14
2.4.2 Tube Diffusers	14
2.4.3 Disc and Dome Diffusers	16
2.5 Characteristics of Fine Pore Media	16
2.5.1 Physical Description	16
2.5.2 Dimensions	17
2.5.3 Weight and Specific Weight	17
2.5.4 Permeability	17
2.5.5 Perforation Pattern	18
2.5.6 Strength	18
2.5.7 Hardness	18
2.5.8 Environmental Resistance	18
2.5.9 Miscellaneous Physical Properties	19
2.5.10 Oxygen Transfer Efficiency	19
2.5.11 Dynamic Wet Pressure	20
2.5.12 Bubble Release Vacuum	20
2.5.13 Uniformity	22
2.6 Clean Water Performance	24
2.6.1 Introduction	24
2.6.2 Clean Water Data Base	25
2.7 References	33
3 PROCESS WATER PERFORMANCE	37
3.1 Introduction	37
3.2 Factors Affecting Performance	40

Contents (continued)

Chapter	Page
3.3 Diffuser Fouling	40
3.3.1 Background	40
3.3.2 Types of Fouling	41
3.3.3 Foulant Characteristics	42
3.3.4 Fouling Rates	53
3.4 Process Water Data Base	57
3.4.1 General Data Summary	57
3.4.2 Selected Variables Affecting Process Water Performance	58
3.5 References	73
4 OPERATION AND MAINTENANCE	77
4.1 Introduction	77
4.2 Operation	77
4.2.1 Start-up	77
4.2.2 Shutdown	77
4.2.3 Normal Operation	78
4.3 Maintenance	85
4.3.1 Blowers	85
4.3.2 Air Systems	85
4.3.3 Diffusers	85
4.3.4 Troubleshooting	95
4.4 References	95
5 SYSTEM DESIGN AND INSTALLATION	97
5.1 Introduction	97
5.2 Process and O&M Considerations	97
5.2.1 Process-Related Considerations	97
5.2.2 O&M-Related Considerations	100
5.3 Process Oxygen and Mixing Requirements	101
5.3.1 Process Oxygen Requirements	101
5.3.2 Process Mixing Requirements	113
5.4 Air Diffusion System	115
5.4.1 Diffuser Selection	115
5.4.2 Basin Arrangement	118
5.4.3 Airflow Distribution	118
5.4.4 Diffuser Cleaning and Maintenance	119
5.4.5 Diffuser Installation	120
5.4.6 Specifications	121
5.4.7 Retrofit Considerations	121
5.4.8 Air Diffusion System Design Example	122
5.4.9 Flexibility of Design	122
5.5 Air Supply System	122
5.5.1 Air Piping	132
5.5.2 Air Filtration	134
5.5.3 Blowers	134
5.5.4 Design and Installation	136
5.5.5 Retrofit Considerations	137
5.5.6 Air Supply System Design Example	138
5.6 Summary of Aeration System Design Procedure	138
5.6.1 Outline of Approach	143
5.6.2 Steps in Design	143
5.7 References	146

Contents (continued)

Chapter	Page
6 AERATION CONTROL	149
6.1 Introduction	149
6.2 Benefits of Aeration Control	149
6.2.1 Process Implications	149
6.2.2 Economic Considerations	149
6.3 Control Strategy Development	151
6.3.1 Degree of Control	151
6.3.2 Control Systems	152
6.3.3 DO Control Strategies	154
6.4 Control System Components	156
6.4.1 Instrumentation	156
6.4.2 Final Control Elements	158
6.4.3 Controller	159
6.4.4 Software	159
6.5 Aeration Control Example	160
6.5.1 Air Delivery Control	160
6.5.2 Air Distribution Control	162
6.5.3 DO Probe Location and DO Set-Point	168
6.6 Experiences with Automated Aeration Control	169
6.6.1 Piscataway, MD	169
6.6.2 Madison, WI	171
6.7 Summary	173
6.8 References	174
7 ECONOMIC ANALYSIS	177
7.1 Introduction	177
7.2 Cost Components	177
7.3 Economic Analysis Procedure	177
7.3.1 Calculate Initial Costs	179
7.3.2 Calculate Energy Costs	179
7.3.3 Calculate Maintenance Costs	181
7.3.4 Calculate Diffuser Cleaning Costs	181
7.3.5 Calculate Replacement Costs	181
7.3.6 Calculate Total Present Worth Cost	181
7.3.7 Determine Lowest Total Present Worth Cost	181
7.4 Sample Desktop Economic Analysis	181
7.4.1 Fine Pore System Design	182
7.4.2 Coarse Bubble System Design	183
7.4.3 Comparison of Present Worth Costs	184
7.4.4 Sensitivity Analysis	184
7.4.5 Retrofit Comparison	184
7.5 Lotus Spreadsheet	184
7.6 Compendium of Empirical Cost Data	186
7.6.1 Basin Cleaning and Preparation Costs	186
7.6.2 Diffuser Costs	186
7.6.3 Air Filtration Costs	187
7.6.4 Blower Costs	188
7.6.5 Ceramic Diffuser Gas Cleaning Costs	192
7.6.6 Other Diffuser Cleaning Methods and O&M Costs	194
7.6.7 Power Charges	198
7.7 References	202

Contents (continued)

Chapter	Page
8 CASE HISTORIES	205
8.1 Introduction	205
8.2 Performance Evaluation by Off-Gas Testing	207
8.2.1 Frankenmuth Wastewater Treatment Plant	207
8.2.2 Glastonbury Water Pollution Control Plant	212
8.2.3 Green Bay Wastewater Treatment Plant	217
8.2.4 Hartford Water Pollution Control Plant	225
8.2.5 Jones Island Wastewater Treatment Plant	235
8.2.6 Nine Springs Wastewater Treatment Plant	239
8.2.7 Ridgewood Wastewater Treatment Plant	247
8.2.8 Whittier Narrows Water Reclamation Plant	254
8.3 Performance Evaluation by Means Other Than Off-Gas Testing	260
8.3.1 Cleveland Wastewater Treatment Plant	260
8.3.2 Plymouth Wastewater Treatment Plant	262
8.3.3 Renton Wastewater Treatment Plant	265
8.3.4 Ripon Wastewater Treatment Plant	267
8.3.5 Saukville Wastewater Treatment Plant	269
8.4 Sources of Information	271
APPENDIX A Abstracts of Contractor Studies Completed Under EPA/ASCE Fine Pore Aeration Project	273
APPENDIX B Selected Diffuser Characterization and Cleaning Methods	275
APPENDIX C Selected Physical and Chemical Tables and Graphs	285
APPENDIX D Economic Analysis Spreadsheet	293
APPENDIX E Symbols, Terms, and Acronyms Used in this Manual	301
APPENDIX F Conversion Factors	305

Figures

Number		Page
2-1	Typical ceramic plate diffusers	7
2-1	(continued)	8
2-2	Typical ceramic or rigid porous plastic tube diffuser	8
2-3	Typical perforated membrane tube diffusers	9
2-4	Typical nonrigid porous plastic tube diffuser	10
2-5	Typical ceramic dome diffusers	11
2-6	Typical ceramic and rigid porous plastic disc diffusers	12
2-7	Typical perforated membrane disc diffusers	13
2-7	(continued)	14
2-7	(continued)	14
2-7	(continued)	15
2-8	Typical diffuser layouts	15
2-9	On-line device for monitoring DWP of fine pore diffusers	21
2-10	Removable test header	22
2-11	Apparatus for measuring DWP in the laboratory	23
2-12	BRV relationships	23
2-13	Effect of diffuser submergence on $C^*_{\infty 20}$ for three diffuser types	26
2-14	$C^*_{\infty 20}$ vs. diffuser submergence for perforated membrane disc and tube diffusers	26
2-15	Effect of unit airflow rate on SOTE for fine pore tube diffusers	29
2-16	Effect of unit airflow rate on SOTE for ceramic dome/disc diffusers	29
2-17	Effect of unit airflow rate on SOTE for rigid porous plastic disc diffusers	30
2-18	Effect of diffuser density on SOTE for ceramic disc/dome grid configurations	30
2-19	Effect of unit airflow rate on SOTE for perforated membrane disc diffusers	31
2-20	Clean water test data - Monroe, WI	31
2-21	Effect of water depth on SOTE for three diffuser types	32
2-22	Effect of water depth on SAE for three diffuser types	32
3-1	Hypothetical fouling patterns	39
3-2	Linear fouling factor model	40
3-3	Schematic structure of Type I fouling	42
3-4	Idealized plot showing effects of Type I fouling on DWP and OTE	42
3-5	Schematic structure of Type II fouling	43
3-6	Idealized plot showing effects of Type II fouling on DWP and OTE	43
3-7	F vs. foulant accumulation - Interplant Fouling Study	45
3-8	Relationship between BRV and F - Interplant Fouling Study	45
3-9	F vs. DWP:BRV - Interplant Fouling Study	46
3-10	Progression of foulant accumulation - Interplant Fouling Study	47
3-11	$\alpha F(\text{SOTE})$ vs. time in service - Monroe, WI	48
3-12	$\alpha F(\text{SOTE})$ vs. tank length before and after load reduction - Madison, WI	48
3-13	DWP fouling rates for eight wastewater treatment plants - Interplant Fouling Study	54
3-14	$\alpha F(\text{SOTE})$ vs. time in service for Basin 5 - Frankenmuth, MI	56
3-15	$\alpha F(\text{SOTE})$ and airflow rate vs. time since initial liquid acid cleaning for Basin 1 - Whittier Narrows, CA	57

Figures (continued)

Number		Page
3-16	EF vs. time in service - Green Bay, WI	58
3-17a	24-hr variations in αF and $\alpha F(SOTE)$ - Ridgewood, NJ	64
3-17b	Variations in αF , $\alpha F(SOTE)$, and COD - Whittier Narrows, CA	64
3-17c	Variations in αF , $\alpha F(SOTE)$, and TOC at influent end of aeration tank - Madison, WI	65
3-18	$\alpha F(SOTE)$ and SOTE vs. applied airflow rate for ceramic disc diffusers - Monroe, WI	66
3-19	Mean $\alpha F(SOTE)$ vs. airflow rate per unit area of diffuser media	66
3-20	$\alpha F(SOTE)$ vs. time in service for ceramic disc diffusers in first pass - Madison, WI	67
3-21	αF vs. organic loading for selected plants in the Minneapolis/St. Paul area	67
3-22	$\alpha F(SOTE)$ vs. MLVSS for ceramic disc diffusers - Whittier Narrows, CA	68
3-23	$\alpha F(SOTE)$ vs. SRT for ceramic diffuser facilities	68
3-24	$\alpha F(SOTE)$ vs. tank length for plug flow and step feed aeration systems - Madison, WI	69
3-25	αF vs. time in service for three passes of a plug flow aeration system - Madison, WI East Plant	69
3-26	αF vs. time in service for three passes of a step feed aeration system - Hartford, CT	69
3-27	αF vs. basin distance for plug flow aeration system - Whittier Narrows, CA	71
3-28	$\alpha F(SOTE)$ and αF vs. basin position for step feed aeration systems - Monroe, WI	71
3-29	αF and $\alpha F(SOTE)$ vs. basin distance for plug flow aeration system - Ridgewood, NJ	72
3-30	$\alpha F(SOTE)$ vs. basin distance for plug flow aeration system - Milwaukee, WI Jones Island East Plant	72
3-31	$\alpha F(SOTE)$ vs. basin distance for step feed aeration system - Milwaukee, WI South Shore Plant	72
4-1	Trend charts for aeration system monitoring,	83
4-2	Idealized plot of optimum cleaning frequency to minimize power and cleaning costs	90
4-3	Power ratio vs. time for $\Delta DWP = +2.5$ in w.g./month	91
4-4	Schematic of Green Bay wastewater treatment plant	92
4-5	EF vs. time in service for ceramic disc diffusers - Green Bay, WI	92
4-6	Power cost vs. time for ceramic disc diffusers - Green Bay, WI	93
4-7	Effects of cleaning frequency on annual average F ($f_F = 15$ percent/month)	93
4-8	Cost tradeoff analysis for determining cleaning frequency based on fouling patterns shown in Figure 4-7	94
4-9	Cost tradeoff analysis for $f_F = 1$ percent and 5 percent/month	94
5-1	Schematic of a fine pore aeration system	98
5-2	Representative (commonly-used) biological wastewater treatment systems using fine pore aeration	99
5-3	Effect of process loading on carbonaceous oxygen requirement	102
5-4	Example oxygen consumption ratios for carbonaceous oxygen demand	103
5-5	Nitrogen metabolism in nitrifying activated sludge systems	106
5-6	Example diurnal BOD_5 loading for a municipal wastewater treatment plant	111
5-7	Activated sludge system for Example 5-8	113
5-8	Spatial variation in process oxygen requirements along the length of a biological reactor	113
5-9	Manufacturer's SOTE data for Design Example 5-10	132

Figures (continued)

Number		Page
5-10	General arrangement of diffusers in in-tank air piping for Design Example 5-10	133
5-11	Air supply system schematic	133
5-12	Types of compressors and blowers	135
5-13	General operating characteristics of blowers	135
5-14	General arrangement of process air piping for Design Example 5-11	144
6-1	Comparative DO profiles for automated control vs. manual operation	150
6-2	Comparative energy consumption for automated control vs. manual operation	151
6-3	Block diagram for feedback control loop	153
6-4	Block diagram for feedforward-feedback control loop	153
6-5	Two-stage DO control system for a compartmentalized plug flow aeration train	155
6-6	Block diagram of a self-tuning regulator	155
6-7	Blower inlet guide vane control schematic	161
6-8	Blower control schematic	162
6-9	Low-complexity control schematic	164
6-10	Moderate-complexity control schematic	166
6-11	High-complexity control schematic	167
6-12	Significance of additional DO measuring probes on interpolation of DO profile	168
6-13	Manual control of DO at Piscataway	170
6-14	Automated control of DO at Piscataway	171
6-15	Plant schematic for Nine Springs wastewater treatment plant – Madison, WI	172
7-1	Present worth operating costs of example fine pore aeration system for Case 3 fouling rate	189
7-2	Optimal cleaning intervals and costs for example fine pore aeration system for alternative fouling rates	190
7-3	Present worth costs generated by economic analysis spreadsheet – example fine pore aeration system: Case 3 fouling rate	194
7-4	Monthly operating costs generated by economic analysis spreadsheet during first 5 years of operation – example fine pore aeration system: Case 3 fouling rate	195
7-5	Monthly airflow generated by economic analysis spreadsheet during first 5 years of operation – example fine pore aeration system Case 3 fouling rate	196
7-6	Blower costs as a function of capacity	199
8-1	Aeration tank arrangement – Frankenmuth, MI	208
8-2	Aeration tank schematic – Glastonbury, CT	213
8-3	Treatment plant schematic – Green Bay, WI	219
8-4	OTE (off-gas method) vs. time – Green Bay, WI	222
8-5	Secondary treatment process schematic – Hartford, CT	226
8-6	OTE characteristics – Hartford, CT	229
8-7	Typical diffuser layout for one aeration tank – Hartford, CT	230
8-8	Oxygen transfer performance for Aeration Tank 2 – Hartford, CT	232
8-9	Power consumption profile for Aeration Tank 2 – Hartford, CT	234
8-10	Plant layout - Madison, WI	240
8-11	$\alpha F(SOTE)$ profile for East plant Tanks 1-3 - Madison, WI	242
8-12	$\alpha F(SOTE)$ profile for Tank 21 (showing influence of high SRT and cleaning) - Madison, WI	244
8-13	$\alpha F(SOTE)$ profile for Tank 25 (showing influence of low SRT) - Madison, WI	245

Figures (continued)

Number		Page
8-14	Plant flow diagram (original coarse bubble aeration system) - Ridgewood, NJ	248
8-15	Plant flow diagram (retrofitted fine pore aeration system) - Ridgewood, NJ	249
8-16	SOTE vs. airflow rate (fine pore system) - Ridgewood, NJ	250
8-17	Savings in power consumption - Ridgewood, NJ	253
8-18	Aeration basin schematic - Whittier Narrows, CA	256
8-19	$\alpha F(SOTE)$ vs. time (ceramic dome diffusers) - Whittier Narrows, CA	258
8-20	Comparison of ceramic dome and disc diffuser performance - Whittier Narrows, CA	259
8-21	Air header and distribution system used to retrofit fine pore ceramic discs into a tank formerly equipped with surface aeration - Plymouth, WI	263
8-22	Checking for leaks and uniform air distribution - Ripon, WI	268
B-1	BRV test points for ceramic dome	276
B-2	BRV apparatus	277
B-3	BRV flow calibration	278
B-4	Measurements of air line and diffuser pressure	279
B-5	Airflow profile apparatus	280
B-6	Steady-state clean water OTE test apparatus	282
C-1	Standard atmospheric pressure for altitudes of sea level to 10,000 ft	289
C-2	Moody diagram for friction factor in pipes	290
C-3	Equivalent air pressure (EAP) curves for use in blower selection	291

Tables

Number		Page
2-1	Standard Equations for Clean Water Oxygen Transfer Tests	26
2-2	Clean Water Oxygen Transfer Efficiency Comparison for Selected Diffusers	27
2-3	SOTE vs. Airflow for Selected Fine Pore Diffusers in Clean Water	28
2-4	Clean Water Oxygen Transfer Efficiencies of Fine Pore Tube Diffuser Systems	28
2-5	Clean Water Oxygen Transfer Efficiencies of Fine Pore Disc/Dome Grid Systems	29
2-6	Clean Water Oxygen Transfer Efficiencies of Perforated Membrane Diffuser Systems	31
3-1	Guide to Application of Equation 3-3	38
3-2	Results of Interplant Fouling Study	44
3-3	Diffuser Characteristics in 3-Pass, Step Feed Aeration Basin - Madison, WI	49
3-4	Characteristics of Diffuser Residue Samples in 3-Pass, Step Feed Aeration Basin - Madison, WI	49
3-5	Air-side Analysis of Ceramic Disc Diffusers from Test Headers	50
3-6	Characteristics of Perforated Membrane Diffusers in Service	52
3-7	Operating Conditions for Two Food Processing Industrial Treatment Sites Using Perforated Membrane Tube Diffusers	53
3-8	Fouling Rates (f_F) and Fouling Factors (F) for Selected Treatment Plants	56
3-9	Fouling Rates Estimated by Clean Water Column Testing	58
3-10	Physical Characteristics of Wastewater Treatment Facilities Providing Oxygen Transfer Data	60
3-11	Oxygen Transfer and Plant Process Data	62
3-12	24-hr αF and $\alpha F(\text{SOTE})$ Variations at Selected Municipal Treatment Plants	63
3-13	$\alpha F(\text{SOTE})$ for Aeration Systems with Different SRTs at Madison, WI West Plant ..	67
3-14	αF Profiles for Various Aeration Systems	70
4-1	Cleaning Experiences with Fine Pore Diffusers	89
4-2	Annualized Costs for a Fine Pore Aeration System Experiencing a DWP Increase of 1.0 in w.g./month (see Example 4-2)	91
4-3	Fine Pore Aeration System Troubleshooting Guide	94
5-1	Suggested Worksheet for List of Process Oxygen Requirements	101
5-2	Properties of Airflow Measurement Devices	119
5-3	Control Methods for Blowers	136
5-4	Air Piping Headloss Calculations for Example 5-10 – First Iteration	144
5-5	Air Piping Headloss Calculations for Example 5-10 – Second Iteration	145
7-1	Information Needed to Perform Desktop Economic Analysis of Diffused Aeration Systems	179
7-2	Design Information for Example Fine Pore Aeration System	183
7-3	Initial Costs of Design Example Fine Pore and Coarse Bubble Aeration Systems	183
7-4	Design Information for Example Coarse Bubble Aeration System	183
7-5	Sample Desktop Calculations: Case 3 Fouling Rate for Fine Pore Aeration Design Example (18-month Cleaning Interval)	185
7-6a	Sample Desktop Calculations (Case 3 Fouling Rate): Zone 1 of Fine Pore Aeration Design Example (18-month Cleaning Interval)	186

Tables (continued)

Number		Page
7-6b	Sample Desktop Calculations (Case 3 Fouling Rate): Zone 2 of Fine Pore Aeration Design Example (18-month Cleaning Interval)	187
7-6c	Sample Desktop Calculations (Case 3 Fouling Rate): Zone 3 of Fine Pore Aeration Design Example (18-month Cleaning Interval)	188
7-7	Present Worth Costs as a Function of Cleaning Interval for Case 3 Fouling Rate	188
7-8	Economic Comparison of Newly Constructed Fine Pore and Coarse Bubble Aeration Systems	189
7-9	Sample Desktop Calculations for Coarse Bubble Aeration Design Example	191
7-10	Sample Desktop Calculations for Zone 1 of Coarse Bubble Aeration Design Example	191
7-11	Sensitivity of Fine Pore Aeration Costs to Changes in Price of Power and Diffuser Cleaning	192
7-12	Economic Comparison of Retrofit Fine Pore Aeration and Existing Coarse Bubble Aeration Systems	192
7-13	Input Data Form for Oxygen Requirements for Economic Analysis Spreadsheet - Case 3 Fouling Rate	192
7-14	Input Data Form for Diffuser Characteristics for Economic Analysis Spreadsheet - Case 3 Fouling Rate	193
7-15	Input Data Form for Economic Factors for Economic Analysis Spreadsheet - Case 3 Fouling Rate (9-month Cleaning Interval)	193
7-16	Input Data Form for Blower Characteristics for Economic Analysis Spreadsheet - Case 3 Fouling Rate	193
7-17	Output Display from Economic Analysis Spreadsheet - Case 3 Fouling Rates (9-month Cleaning Interval)	193
7-18	Initial Cost Information for Selected Fine Pore Aeration Systems	197
7-19	Costs Associated with Gas Cleaning	200
7-20	Estimated Time Requirements for Basin and Diffuser Cleaning	200
7-21	Diffuser Cleaning and Repair Costs – Ridgewood, NJ	200
7-22	Milwaukee Method Diffuser Cleaning Costs – Hartford, CT	200
7-23	Wisconsin Public Service Corporation Rate Schedule	201
7-24	Cost of Operating a 750-kW (1000-hp) Motor at 70 percent of Rated Load for Various Periods Over a Year (Demand = 522 kW)	201
8-1	Summary of Case Histories	206
8-2	Comparison of Fine Pore and Coarse Bubble Aeration Energy Requirements: Pre-design Estimates – Frankenmuth, MI	209
8-3	1986 Performance Summary – Frankenmuth, MI	210
8-4	Off-Gas Test Results – Frankenmuth, MI	210
8-5	Estimated Energy Cost Savings – Frankenmuth, MI	211
8-6	Summary of αF (SOTE) Determinations – Glastonbury, CT	215
8-7	Fine Pore Aeration System Design Criteria – Green Bay, WI	219
8-8	Fine Pore Diffuser Configuration Summary – Green Bay, WI	220
8-9	Operating Data – Green Bay, WI	221
8-10	αF (SOTE) Values from Off-Gas Testing – Green Bay, WI	222
8-11	αF as a Function of Time in Service – Green Bay, WI	223
8-12	Cost Summary Comparison for Alternative Aeration Systems – Green Bay, WI	224
8-13	Tank Average Off-Gas Results (Aeration Tank 2) – Hartford, CT	233
8-14	Average Off-Gas Test Results Before and After May 1987 Cleaning (Aeration Tank 2) – Hartford, CT	233
8-15	Diffuser Cleaning Costs – Hartford, CT	233
8-16	Summary of Oxygen Transfer Tests – (Jones Island) Milwaukee, WI	237

Tables (continued)

Number		Page
8-17	East Plant Operating and Performance Data (Annual Averages) – (Jones Island) Milwaukee, WI	238
8-18	Oxygen Transfer Performance (1985-1988) for Tapered, Full-Floor Plate Configuration (Jones Island East Plant, Basin 6) – Milwaukee, WI	238
8-19	Oxygen Requirements - Madison, WI	241
8-20	Blower Capacities - Madison, WI	241
8-21	East Plant αF Values - Madison, WI	243
8-22	Off-Gas Test Results: West Plant (Plant 3) - Madison, WI	245
8-23	Air Usage - Madison, WI	246
8-24	Physical Characteristics of Original Coarse Bubble Aeration System (Tanks 1 and 2) - Ridgewood, NJ	248
8-25	Projected Energy Savings - Ridgewood, NJ	248
8-26	Physical Characteristics of Fine Pore Retrofit System (Tanks 3 and 4) - Ridgewood, NJ	250
8-27	Estimated Yearly Average αF (SOTE) and αF - Ridgewood, NJ	250
8-28	Average Blower Power Reduction - Ridgewood, NJ	252
8-29	Dome Diffuser System Maintenance Costs - Ridgewood, NJ	252
8-30	Dome System Economic Summary- Ridgewood, NJ (1983-1986)	252
8-31	Diffuser Layout Summary - Whittier Narrows, CA	256
8-32	Project Chronology - Whittier Narrows, CA	257
8-33	Monthly Average Performance - Renton, WA	266
8-34	DWP Monitoring Results - Saukville, WI	270
B-1	Example Diffuser Flux Calculations	281
C-1	DO Saturation Values	285
C-2	Hydraulic Headlosses for Appurtenances	286
C-3	Typical Air Velocities in Air Delivery Systems	287
C-4	Properties of Standard Atmosphere	288
C-5	Physical Properties of Water	288
D-1	Cell Entries for Economic Analysis Spreadsheet	294
D-2	Command Script for Economic Analysis Spreadsheet	299

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A substantial amount of the technical information in this manual was derived from subcontracted research on fine pore aeration. Appendix A lists these research projects and the subcontractors who performed the work.

Individuals who provided specific information on fine pore aeration plant case histories are acknowledged in Section 8.4.

Manufacturers of fine pore aeration equipment were contacted on several occasions relative to the contents of this manual. Their contributions to the manual are also acknowledged.

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Chapter 1

Introduction and Overview

The supply of oxygen for aeration is the single largest energy consumer at activated sludge wastewater treatment plants, representing 50-90 percent of total plant energy requirements (1). Replacement of less efficient aeration systems with fine pore aeration devices can save up to 50 percent of aeration energy costs and has resulted in typical simple payback periods of 2-6 years (see Chapter 8). As a result of these very impressive cost savings, more than 1,300 municipal and industrial wastewater treatment facilities in the United States and Canada now use fine pore aeration.

Fine pore aeration technology remains relatively new in North America, and new materials and configurations continue to be developed. This manual provides designers, end users, and regulators information on the nature of fine pore aeration devices, their performance, and related operation and maintenance (O&M) requirements to promote the intelligent application of fine pore aeration technology.

Standardized testing of oxygen transfer devices in both clean and process waters is a recent major advancement in the field. A consensus Standard for testing aeration devices in clean water has been adopted by a large segment of the industry (2). Extensive testing of aeration equipment using this Standard has led to the development of a large data base on the performance of aeration devices in clean water. In addition, over the past 10 years, the development of improved (more precise and accurate) field test methods have permitted generation of data that can be used to better characterize the translation of clean water test results to process conditions (3).

In 1985, The U.S. Environmental Protection Agency (EPA) funded a Cooperative Research Agreement (No. CR812167) with the American Society of Civil Engineers (ASCE) (hereinafter referred to as the EPA/ASCE Fine Pore Aeration Project) to evaluate the existing data base on fine pore diffused aeration systems in both clean and process waters, to conduct field studies at a number of municipal wastewater treatment facilities employing fine pore aeration, and to prepare this manual. Appendix A summarizes the field studies that were conducted. A Summary Report on fine pore aeration systems (4) was published in October 1985 to summarize the early findings of this study.

This manual has been assembled based on the evaluation and analysis of data collected over the last 4 years. It has been written to provide engineers, regulatory personnel, and others involved in fine pore aeration system design and installation the most current design and O&M information available.

1.1 Historical Overview

Experiments on wastewater aeration in England date back to as early as 1882 (5). In these experiments, air was introduced through open tubes or perforations in air delivery pipes. In the early years, patents were granted - primarily in the United Kingdom (U.K.) - for a variety of diffusers, including perforated metal plates, porous tubes with fibrous materials, and nozzles (6). As activated sludge process investigations progressed, greater oxygen transfer efficiency was sought with the production of smaller bubbles created by passing compressed air through porous media of various types. Experiments conducted in the U.K. seeking a better porous material included evaluations of limestone, fire brick, sand and glass mixtures, pumice, and other materials. The first porous plates were made available as early as 1915 in the U.K. In the following years, several U.S. companies (Carborundum Co., Ferro Corp., and Norton Co.) offered porous plates that became the most popular method of aeration in this country in the 1930s and 1940s.

It became clear, shortly after the emergence of porous diffusers that media clogging could be a problem. Work in Chicago between 1922 and 1924 prompted the use of coarse media to avoid clogging (7). Clogging was attributed to liquid-side fouling and air-side clogging due to dirt and oil in the air delivery system. Emphasis at that time was on improving air filtration (8-10). Substantial experimentation was performed to develop effective air filtration devices (9,10), and the results of that early work have led to the high-efficiency air filters used today in many porous diffused air systems (8).

Mechanical aeration was one answer to the clogging problem. Since the introduction of Archimedean screw-type aerators in 1916, a multitude of mechanical aeration devices has been developed and used. Today, mechanical aeration devices serve an

important function in many applications for treatment of industrial and municipal wastewaters.

Another approach to the clogging problem emerged with the development of large orifice-type (coarse bubble) diffusers. First marketed as early as 1904 in the U.K., updated versions evolved in the 1950s in an effort to improve on earlier perforated pipe devices and were designed for easy access and maintenance. In general, the principles that resulted in easily maintained and accessible aeration systems also produced low oxygen transfer efficiencies.

With the renewed emphasis on more energy efficient aeration systems in the 1970s, North America again turned to European technology for more efficient oxygen transfer devices. As a result, newer generation porous diffusers, producing fine bubbles with accompanying high oxygen transfer efficiencies, became popular. Yet, considerable concern has been registered regarding the performance and maintenance of these porous diffusers owing to their historical susceptibility to clogging.

Today, the aeration market is in a state of flux. Emphasis on high efficiency oxygen transfer has led to intensive research and development programs aimed at providing high transfer efficiency devices with low maintenance requirements. The search for a better oxygen transfer device will continue to occupy the time and resources of a number of manufacturers and researchers.

1.2 Objectives of the Manual

The term "fine bubble" diffused aeration is elusive and difficult to define and comprises a wide variety of diffuser types. The term "fine pore" was adopted in the previous Summary Report (4) to more nearly reflect the porous characteristics of one class of high efficiency diffusers marketed today. Typically, fine pore diffusers will produce a headloss due to surface tension in clean water of greater than about 5 cm (2 in) water gauge. For the purposes of this manual, fine pore diffusers are defined as including the following devices:

- Porous ceramic plates, discs, domes, and tubes
- Rigid porous plastic plates, discs, and tubes
- Nonrigid porous plastic tubes
- Perforated membrane tubes and discs

The major objective of this manual is to provide the technical community with the most current information available on fine pore aeration systems. Because of the rapid changes that are taking place with this technology, it is possible that some systems have unintentionally not been described. The manual presents what are considered the best current practices for selecting, designing, operating,

maintaining, and controlling fine pore aeration systems.

Example calculations are presented throughout the manual to illustrate concepts and are not intended to set a rigid standard in design protocol. Case histories are presented to give the user an appreciation for the highly site-specific nature of this technology.

1.3 References

When an NTIS number is cited in a reference, that reference is available from:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650

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Chapter 2

Fine Pore Diffuser Characteristics

2.1 Introduction

Since introduction of the activated sludge process in the early 1900s, many different types of diffused aeration devices have been designed and developed to dissolve oxygen into wastewater. These have ranged from simple individual orifices (holes or slots) drilled in a section of pipe to elaborate devices made up of small diameter particles fused together.

Although their size, shape, and materials of construction may vary considerably, diffused aeration devices are usually classified as either fine or coarse bubble - referring to the relative diameter of the bubble produced. The demarcation between fine and coarse bubbles is not well defined.

Coarse bubble diffusers normally produce a bubble diameter of 6-10 mm (1/4-3/8 in) in clean water. Although the actual orifice may be much larger, the bubbles produced tend to shear and break into smaller bubbles as they are produced and rise to the surface. For this type of device, as long as the mixing intensity stays roughly the same, bubble size is usually independent of the airflow rate through the diffuser. However, mixing intensity increases with increasing airflow, which most likely shears the bubbles into bubbles with smaller diameters. This may explain the apparent gradual increase in oxygen transfer efficiency (OTE) with increasing airflow rate for some coarse bubble systems.

Fine bubble diffusers, when new, produce bubbles with a diameter of approximately 2-5 mm (0.08-0.20 in) in clean water (1-5). One class of diffusers defined in Chapter 1 as fine pore diffusers will normally generate fine bubbles. The bubble size produced by fine pore devices is affected by airflow, becoming somewhat larger as airflow increases.

This chapter discusses the important characteristics of fine pore aeration devices. Included are sections on material types, diffuser shapes, typical layouts, physical properties, and clean water performance (OTE) data.

2.2 Types of Fine Pore Media

Although several materials capable of serving as effective fine pore diffusion media exist, few are being

used in the wastewater treatment field because of cost considerations, specific characteristics, market size, or other factors. Fine pore media in use today can be divided into the following three general categories:

1. Ceramics
2. Porous plastics
3. Perforated membranes

2.2.1 Ceramics

Ceramics are the oldest, and currently most common, porous media on the market. Ceramic media consist of irregular or spherically shaped mineral particles that are sized, blended together with bonding materials, compressed into various shapes, and fired at an elevated temperature to form a ceramic bond between the particles. The result is a network of interconnecting passageways through which air flows. As air emerges from the surface pores, pore size, surface tension, and flow rate interact to produce the characteristic bubble size (6). Ceramic diffusers have been manufactured from alumina, aluminum silicate, and silica.

Alumina (aluminum oxide) media used for fine pore diffusers are produced from bauxite, a naturally-occurring ore consisting primarily of aluminum hydroxide. Calcination followed by electrolysis produces a material that exceeds 80 percent alumina. The refined molten mineral is allowed to solidify and is subsequently crushed and screened to select the desired sizes (7). This raw material is called regular or brown fused aluminum oxide.

Other materials used for fine pore media that are similarly crushed and then sized are produced from either man-made or naturally-occurring aluminum silicates such as cyanotic. All these minerals are combinations of alumina (aluminum oxide) and silica (silicon oxide) with an alumina content of 50 percent to slightly over 70 percent. On heating at high temperatures, they tend to form the equilibrium species of the mineral (mullite) and a siliceous glass. Mullite consists of three parts alumina to two parts silica.

Silica used in the manufacture of fine pore diffusers is a mined material with a somewhat limited particle size range. As a result, the pore sizes that can be produced are restricted to naturally-occurring grain sizes. Some sources of silica are less angular than the more jagged crushed alumina or aluminum silicate particles. It has been claimed that the silica material may be more resistant to fouling and more easily cleaned (2). Although this claim has not been well documented based on controlled experiments, silica plates have been used for years in at least one facility (see Section 8.2.5).

No studies have been published that suggest there is a difference in process performance between diffusers made with either alumina or aluminum silicate media. Experience would seem to indicate that the two materials may have been used interchangeably. As a raw material, alumina is more abrasion resistant than either silica or aluminum silicate; however, actual strength and abrasion resistance also depends on the nature of the ceramic bond itself. Silica porous media, as manufactured, are generally considered to have the lowest overall strength, and their thickness is usually increased to compensate for this weakness.

Sources of ceramic diffuser media are comprised primarily of companies supplying industrial abrasives or refractory materials. In the past, these basic porous media manufacturers have both marketed diffusers directly and supplied various media shapes to aeration equipment manufacturers. The aeration equipment manufacturers, in turn, marketed the diffuser, holder, piping, and other ancillary equipment. Today, the basic porous media manufacturers will market finished diffuser assemblies directly to the end user with warranties covering only mechanical specifications for materials, dimensions, and permeability. They will not warranty oxygen transfer performance.

Ceramic diffusers have been in use for a long period and their advantages, as well as operational problems, are well documented. Because of this longevity, ceramic materials have, in effect, become the standard for comparison. Each new generation of fine pore media reportedly offers some advantage, either in performance or cost, over ceramic diffusers. In the past, the new devices have often not lived up to their expectations. As a result, ceramic diffusers continue to capture a significant share of the fine pore aeration market.

2.2.2 Porous Plastics

A recent development in the fine pore diffuser field is the use of porous plastic materials. As with ceramics, a medium is created consisting of several interconnecting channels or pores through which compressed air can travel. The manufacturing process can be controlled to produce different pore sizes. Some of the advantages of plastic materials over ceramics are their ease of manufacture, lighter weight

(which makes them especially suited to liftout applications), durability, cost effectiveness, and, depending on the individual material, greater resistance to breakage. Some disadvantages include their lower strength, greater susceptibility to creep, and lower environmental resistance.

To provide further definition, porous plastics are classified as either rigid or nonrigid. The basic difference between the two is that a nonrigid porous plastic requires some form of internal structural support.

2.2.2.1 Rigid Porous Plastics

Rigid porous plastics are made from several thermoplastic polymers including polyethylene, polypropylene, polyvinylidene fluoride, ethylene-vinyl acetate, styrene-acrylonitrile, and polytetrafluoroethylene (8). Besides their application in the aeration field, these materials are used extensively as filtration media (air, water, chemicals). When used as a fine pore aeration device, the two most common types of plastic media are high density polyethylene (HDPE) and styrene-acrylonitrile (SAN).

HDPE is relatively inexpensive and easy to process when compared with other thermoplastics. In addition, shrinkage is low, a uniform quality product can be obtained, and small pore sizes can be produced. HDPE diffusers are manufactured by proprietary extrusion processes. A HDPE diffuser is usually made from a straight homopolymer (not a blend), is nonpolar, and contains no additives or binders.

A European manufacturer produces a double-layer HDPE material (9). It consists of a grainy, open-pore structure approximately 6-mm (1/4-in) thick covered by a thinner [(3-mm (1/8-in) thick)], less porous layer. The manufacturer claims that the double layer results in a filtering effect that decreases maintenance. Allegedly, this lower maintenance would result from a reduction in air-side fouling of the diffuser. However, recent studies have demonstrated that air-side fouling does not appear to be an important fine pore diffuser operation and maintenance (O&M) factor (10,11). The manufacturer also claims that the thin outer layer is potentially beneficial in helping to produce a small diameter bubble uniformly over the diffuser surface. The manufacturer further suggests the thin film layer may act as a barrier in preventing precipitates from forming deep within the media. If the foulants are restricted to the surface, they can be more easily removed (9). Any tendency for increased external fouling in such diffusers is unknown.

The major advantages of HDPE media compared with other plastic media are their lighter weight (approximately 560 kg/m³ [35 lb/cu ft]), inert composition, and resistance to breakage, even under freezing conditions.

SAN diffusers are manufactured from a copolymer. The raw material is a mixture of four different molecules. Physically, SAN media are composed of very small resin spheres fused together under pressure. SAN has a density only slightly greater than HDPE. The presence of the styrene, however, makes the material brittle, and the media can break if dropped, even at room temperature. A major advantage of the SAN material is that it has been successfully used for about 20 years.

Although rigid plastic media diffusers (especially the HDPE material) were installed in several wastewater treatment plants in the early 1980s, they are no longer as popular. SAN diffusers, which seemed to work well, are no longer being actively marketed. HDPE diffusers, on the other hand, were plagued by several problems that contributed to their decline in popularity. These included media fouling, lack of quality control in the manufacturing process (diffusers did not always produce uniform air distribution), and the emerging cost competitiveness of other fine pore diffusion products.

2.2.2.2 Nonrigid Porous Plastic

Only one type of diffuser material is being marketed that could be considered a nonrigid porous plastic (12). This material, which is extruded from a combination of rubber and HDPE, is soft and somewhat flexible. When air is applied at normal pressures, this type of media does not expand. However, some expansion will occur at higher pressures. It has been demonstrated that a high pressure water flush can be used to remove foulants that may have become trapped in the pores (11).

2.2.3 Perforated Membranes

Membrane diffusers differ from the first two groups (ceramics and porous plastics) in that the diffusion material does not contain the network of interconnecting passageways through which air must travel. Instead, mechanical means are used to create preselected patterns of small, individual orifices (perforations) in the membrane to allow passage of air through the material.

Membrane diffusers have been in use for about 40 years. They initially were called "sock" diffusers and were made from materials such as plastic, synthetic fabric cord, or woven cloth. A metallic or plastic core material was required with the woven sheaths to provide structural support. Although sock diffusers were capable of achieving high oxygen transfer rates, fouling problems were often severe. Today, there is essentially no market for the early sock design.

A new type of perforated diffuser has been introduced within the last decade. It consists of a thin flexible membrane made from either a thermoplastic material or an elastomer. Because of their physical properties, current literature usually describes diffusers made

from these materials as "flexibles" or "flexible membrane" diffusers. However, since the patterned orifices in the membrane material are intentionally made during the manufacturing process, this new generation of membrane diffusers is referred to herein as "perforated" membrane diffusers.

ASTM D-883 (13) defines a thermoplastic as "a plastic that repeatedly can be softened by heating and hardened by cooling through a temperature range characteristic of the plastic, and, in the softened state, can be shaped by flow into articles by molding or extrusion." The most common thermoplastic material is polyvinyl chloride (PVC). Plasticizers are added to produce a soft, flexible membrane.

The term elastomer includes the complete spectrum of elastic or rubberlike polymers that are sometimes randomly referred to as rubbers, synthetic rubbers, or elastomers (14). Rubber is a natural material, while all other elastomers are synthetic. ASTM D-883 (13) defines an elastomer as "macromolecular material that returns rapidly to approximately the initial dimensions and shape after substantial deformation (defined as twice its length in an earlier addition) by a weak stress and release of the stress."

Most elastomer membranes are made from ethylenepropylene dimer (EPDM). Although the main ingredient may be EPDM, proprietary additives are usually included to enhance the material characteristics. As a result, it may not always be possible to establish media characteristics or physical properties simply by consulting a table in a reference text or handbook.

After the membrane material is produced, air passages are created by punching or cutting minute holes or slits in the membrane. When the air is turned on, the material expands. Each hole acts as a variable aperture opening; the higher the airflow rate, the greater the size of the opening. When the air is turned off, the membrane relaxes down against the support base and a seal is formed between membrane and support in systems where the membrane area conforms to the support. This closing action will reportedly eliminate or at least minimize the backflow of liquid into the diffuser (15-20).

Perforated membrane diffusers have been developed over the last 10-15 years in the United States and Europe. The most significant advantage claimed for the perforated membrane diffuser is that its smooth surface and apertures may be more resistant to fouling than are other types of media. Formation of biological and chemical foulants has been noted on the surfaces of the thermoplastic media, however (10). One of the disadvantages of the perforated membrane diffusers is that thermoplastic and elastomer materials can experience physical property changes with time. These changes depend, to varying

degrees, on the materials used, their shape and dimensions, and environmental conditions.

2.3 Types of Fine Pore Diffusers

There are four general types (shapes) of fine pore diffusers on the market: plates, tubes, domes, and discs. Each is discussed in detail below.

2.3.1 Plate Diffusers

The original fine pore diffuser design was a flat rectangular ceramic plate. These plates are usually 30 cm (12 in) square and 25-38 mm (1-1.5 in) thick. They are manufactured from either glass-bonded silica or ceramically-bonded aluminum oxide and aluminum silicate. The plates are installed by grouting them into recesses in the basin floor, cementing them into prefabricated holders, or clamping them into metal holders. Of the three, the metal holders are the least attractive because corrosion of some of the holders may result in fouling of the underside of the diffusers. A chamber underneath the plates acts as an air plenum. The number of plates fixed over a common plenum is not standard and can vary from a single plate to 500 or more. Individual control orifices are normally not provided for this original plate design.

Fine pore ceramic plates were used almost exclusively as the method of air diffusion in the early activated sludge plants through the 1920s. Other than retrofits or expansions of existing plants in Milwaukee, WI (21) and Chicago, IL (22), the original ceramic plate design is seldom specified today. Some possible explanations for its decline in popularity include:

1. problems obtaining uniform air distribution with several plates attached to the same plenum,
2. inconvenience of removing plates that are grouted or cemented in place,
3. difficulty in adding diffusers to meet future increases in plant loading, and
4. lack of active marketing by any equipment supplier or media manufacturer.

Some of the advantages of plate diffusers are their documented service life, high oxygen transfer, and ease of in-situ cleaning.

A recently-developed plate design offers both ceramic and porous plastic media options (23). Both these alternatives are marketed in sizes of 30 cm × 61 cm (12 in × 24 in) and 30 cm × 122 cm (12 in × 48 in), although other specialty sizes are also available. The ceramic plates, made of ceramically-bonded aluminum oxide, are 19 mm (3/4 in) thick, whereas the porous plastic (35-micron HDPE) design uses a media

thickness of only 6 mm (1/4 in). Both the ceramic and plastic media are mounted on top of vacuum-formed, ABS plastic plenums. The undersides of the plenums are filled with concrete at the job site to provide position stability on the basin floor and adequate ballast to prevent floating of the diffusers. The porous HDPE media sheets are sealed to their individual plenums by 25-mm (1-in) wide stainless steel frames bolted into the concrete ballast, whereas the ceramic plates are mastic bonded to ledges set into the inner periphery of their plenums.

Air is fed to each diffuser of this new generation plate design through a separate 3.8-cm (1.75-in) diameter rubber hose. The hoses are connected by saddles to common air delivery headers. Individually-drilled orifices are inserted into the feed nipple of each plate, promoting improved air distribution control compared with the original plate design. Typical plate diffusers of both the original and new designs are shown in Figure 2-1.

2.3.2 Tube Diffusers

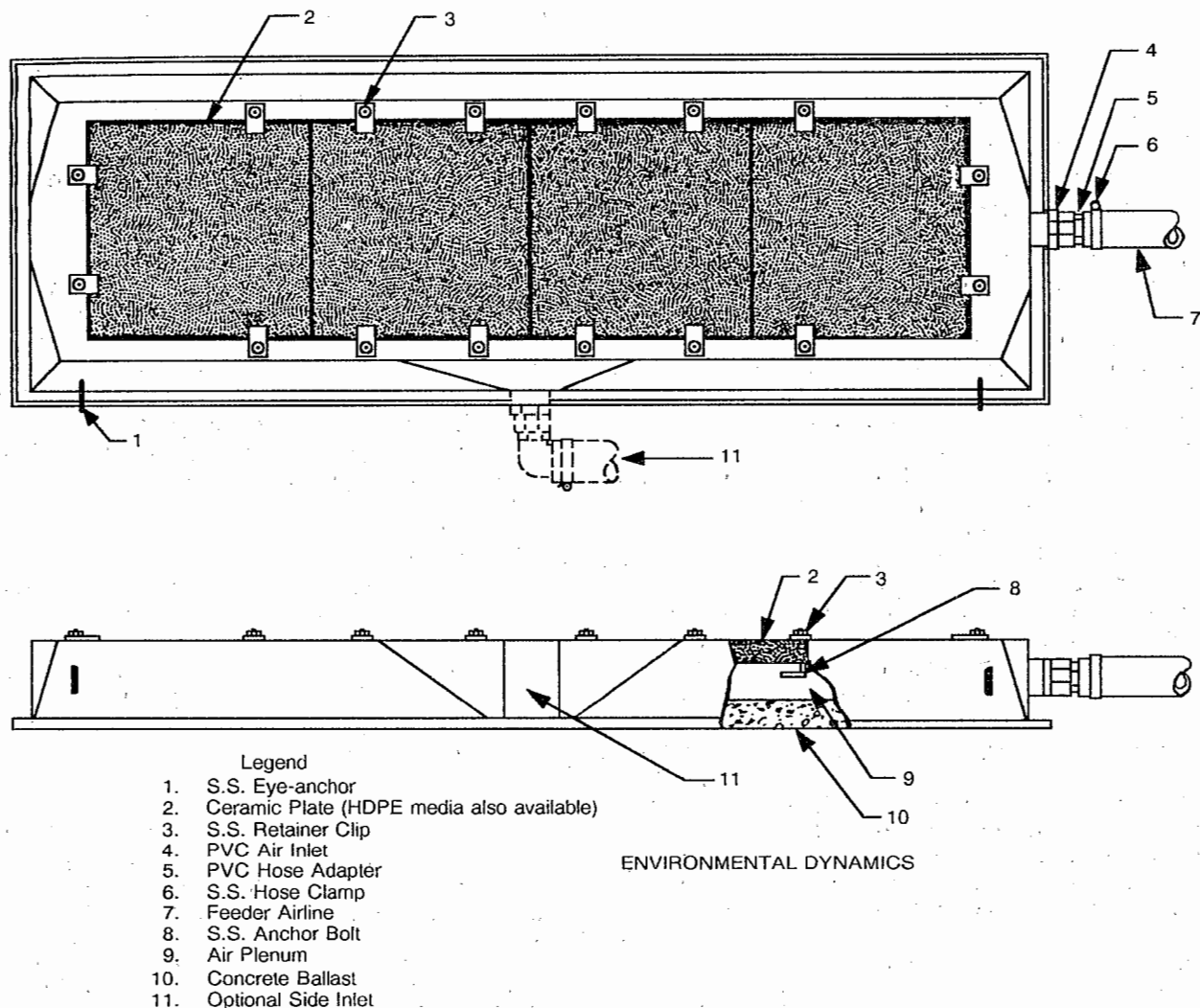
Like plates, fine pore tubes have been used in wastewater treatment for many years (12,15,20,24-28). The early tubes, Saran wound or made from aluminum oxide, have been followed by the introduction of SAN copolymer, porous HDPE, and, most recently, the new generation of perforated membranes and nonrigid porous plastic.

Most tube diffusers on the market are of the same general shape. Usually, the media portion is 51-61 cm (20-24 in) long and has an outer diameter (O.D.) of 6.4-7.6 cm (2.5-3.0 in). A tee assembly is sometimes placed in the middle, increasing total length to nearly 100 cm (40 in). The thickness of the media is variable. Perforated membranes are very thin, commonly 0.6-2.5 mm (0.025-0.10 in). HDPE media are usually supplied at a thickness of 6.4 mm (1/4 in), SAN media at approximately 15 mm (0.6 in), and fused ceramic media at 9.5-12.7 mm (3/8-1/2 in).

The dimensions of the rubber-HDPE (nonrigid porous plastic) tube diffuser differ from those just mentioned. This diffuser has an O.D. of 25 mm (1.0 in), comes in lengths of up to 91 cm (36 in), and has a media thickness of approximately 3 mm (1/8 in).

The holder designs for the ceramic and rigid porous plastic media are very similar. Most consist of two end caps held together by a connecting rod through the center. The rod is threaded into the feed end of the holder, the media and outer end cap installed, and a hex nut placed on the threaded rod to secure the assembly. When ceramic media are used, the end caps and connecting rod are usually metallic (stainless steel). With HDPE media, because of their lighter weight, PVC, polypropylene, or some other thermoplastic is often used. When plastic holders or pipe connectors are used, the effects of creep should

Figure 2-1. Typical ceramic plate diffusers.



be considered. Threaded plastic connectors are also susceptible to failure unless properly designed.

In another slightly different version, the feed end cap and inner support are one piece with the assembly held together by a bolt installed through the outer end cap and threaded into the support frame. For both designs, gaskets are placed between the media and the end caps to provide an airtight seal. Sometimes, a gasket or O-ring is also used with the retaining bolt or hex nut. A typical rigid porous plastic (or ceramic) tube diffuser assembly is shown in Figure 2-2.

Because of their flexible nature, perforated membrane diffusers require an internal support structure. The frame is made from plastic (e.g., PVC or polypropylene) and has a tubular shape. The tube provides support either around the entire circumference or, in

one modification, only the bottom half. With the full tubular frame, holes in the inlet connector or slots in the tube itself allow distribution of the air below the membrane surface. The membrane is usually not perforated at the air inlet point. Thus, when the air is turned off, the liquid head collapses the membrane against the support frame. With the cutaway support frame, an internal flap prevents backflow into the piping system. The ends of the support frame are plugged, and stainless steel hose clamps are used on each end to secure the membrane tightly to the frame. Typical perforated membrane diffusers are illustrated in Figure 2-3.

With the rubber-HDPE (nonrigid porous plastic) diffuser, either a permanent (crimped) stainless steel or a removable acetal clamp is provided on the feed end only. The opposite end of the media is bonded to

Figure 2-1. (continued)

MILWAUKEE, WI, CERAMIC PLATE DIFFUSER CONFIGURATION

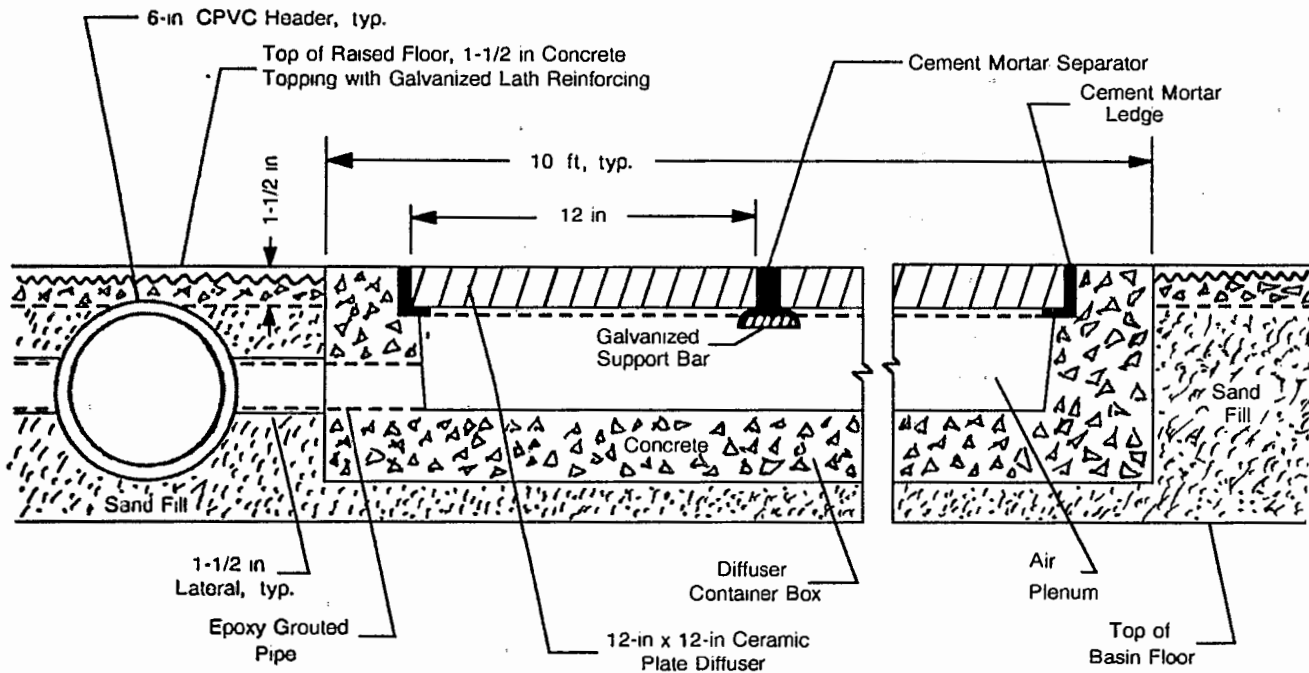
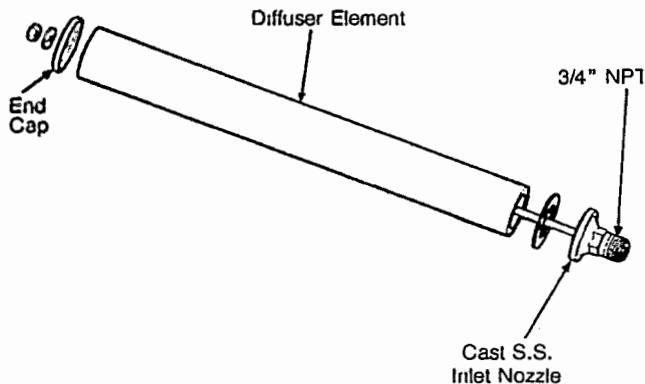


Figure 2-2. Typical ceramic or rigid porous plastic tube diffuser.

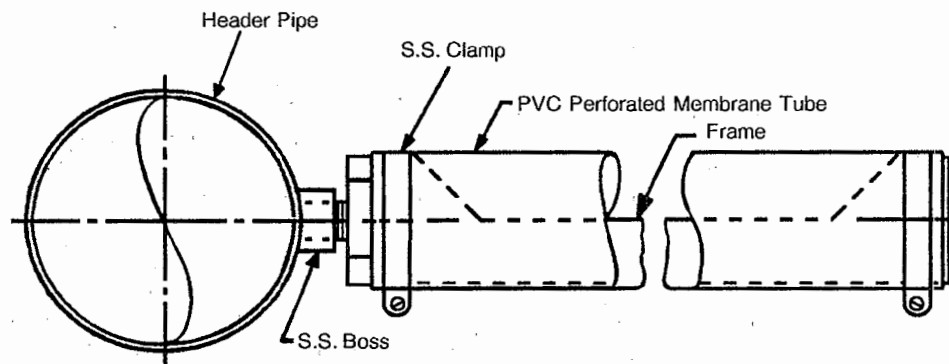


itself and requires no clamp. The tubular support frame is made from either stainless steel or fiberglass reinforced plastic. To prevent liquid backflow into the air distribution piping, a rubber check valve can be provided. A nonrigid porous plastic diffuser is shown in Figure 2-4.

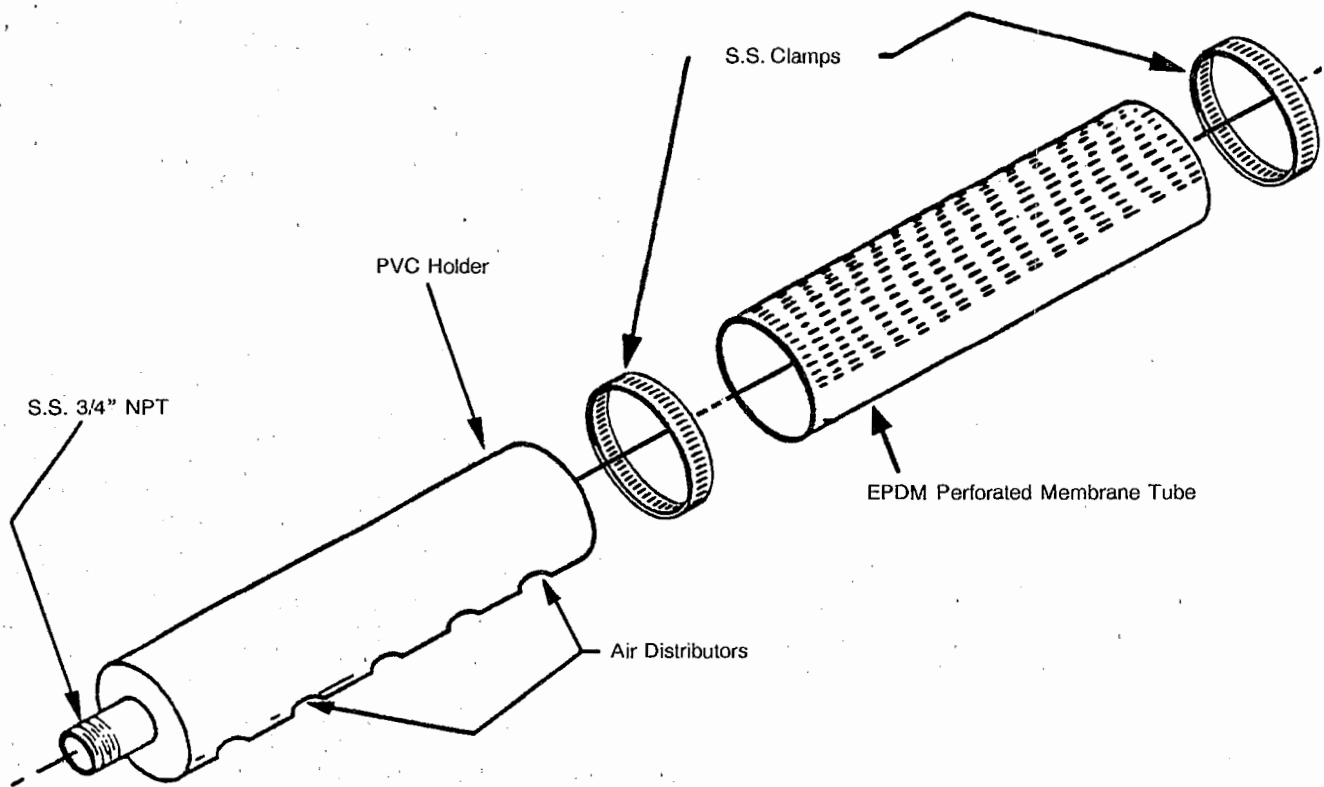
To avoid corrosion problems, most components of the various tube assemblies are made of either stainless steel or durable plastic. The gaskets are usually of a soft rubber material. Tube assemblies with a length of 51-61 cm (20-24 in) are generally designed to operate in the airflow range of 0.5-4.7 L/s (1-10 scfm)/diffuser. To obtain maximum OTE, the diffusers are usually operated near the lower end of this range (0.5-2.4 L/s [1-5 scfm]/diffuser). Because of their inherent shape, it is sometimes difficult to obtain air discharge around the entire circumference of the tube. The air distribution pattern will vary with different types of diffusers. The extent of the inoperative area will normally be a function of airflow rate and headloss across the media. As a rule-of-thumb, flow distribution around the tube will improve as headloss increases. Laboratory- or pilot-scale tests should be conducted before selecting a particular tube design since dead areas can provide sites for foulant development.

Some tube assemblies are fitted with an airflow rate control orifice inserted in the inlet nipple to aid in air distribution. The orifice is normally about 13 mm (0.5 in) in diameter, although different sizes can be used for various design airflow rates.

Figure 2-3. Typical perforated membrane tube diffusers.

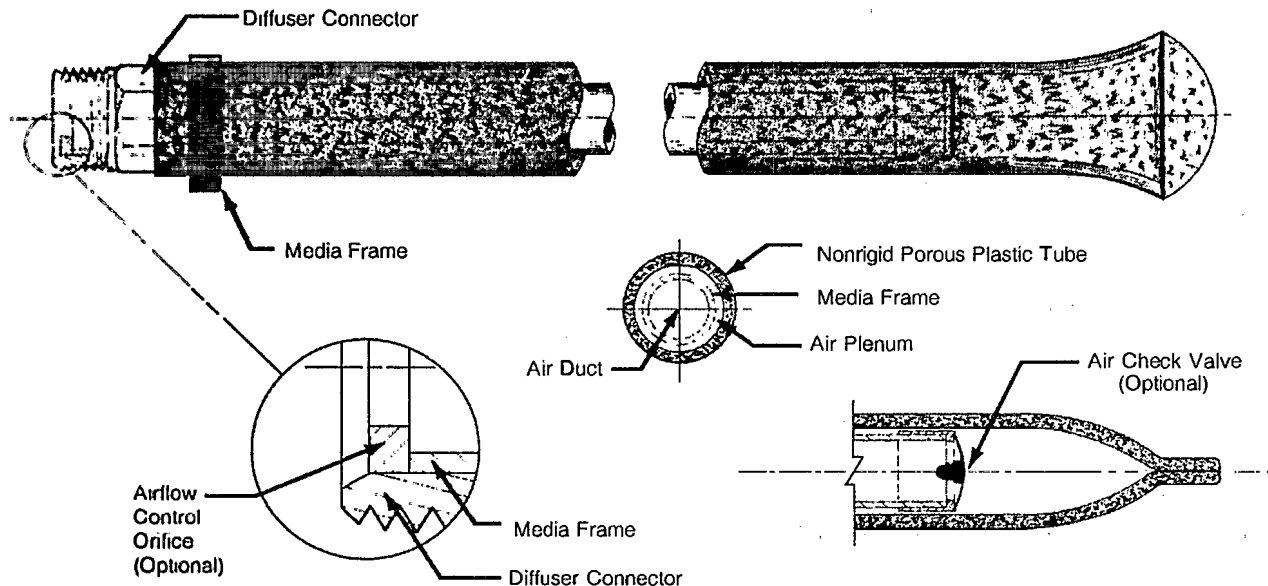


PARKSON



SANITAIRE

Figure 2-4. Typical nonrigid porous plastic tube diffuser.



AERTEC

2.3.3 Dome Diffusers

The fine pore dome diffuser was developed in Europe in the 1950s and introduced in the U.S. market in the early 1970s (29). Long considered the standard in England and some parts of Europe, domes are now installed in a large number of U.S. plants (30).

The dome diffuser is a circular disc with a downward-turned edge (31-33). These diffusers are 18 cm (7 in) in diameter and 38 mm (1.5 in) high. Media thickness is approximately 15 mm (5/8 in) on the edges and 19 mm (3/4 in) on the top or flat surface. Domes are now being made predominately of aluminum oxide.

The dome diffuser is mounted on either a PVC or mild steel saddle-type baseplate and attached to the baseplate by a bolt through the center of the dome. The bolt can be made from a number of materials including brass, plastics, and stainless steel. Care must be taken when specifying the bolt material and installing the dome to prevent overtightening of the center bolt. Applying too much force can lead to immediate diffuser breakage or future air leakage due to compression set of gaskets and bolt stretching, or failures if a plastic bolt is used. A soft, rubber gasket is placed between the diffuser and the baseplate. Ideally, the gasket material should not take excessive permanent compression set with the specified torque. A washer and gasket are also used between the bolt head and the top of the diffuser. Schematics of several dome diffusers are shown in Figure 2-5.

Usually, the PVC saddles are solvent cemented to the air distribution piping at the factory. This minimizes

bonding, joining, and assembly problems that could occur in the field. For one alternative design (31), the baseplate includes an expansion plug that is inserted into a hole drilled into the air header. It is easier with this design to replace damaged supports than with the solvent-cemented base, but it is more difficult to level or align the baseplates.

The slope of a headloss vs. airflow rate curve for a ceramic diffuser is very flat. A variation from the average of ± 10 percent in the specific permeability (see Section 2.5.4) of a diffuser can result in a 200-percent change in airflow rate for the same headloss under operating conditions (34). To better distribute the air throughout the system, control orifices are placed in each diffuser assembly to create additional headloss and balance the airflow. The fastening bolt is hollowed out and a small hole drilled in the side, or the orifice is drilled in the base of the saddle. The size of the orifice is normally 5 mm (0.2 in).

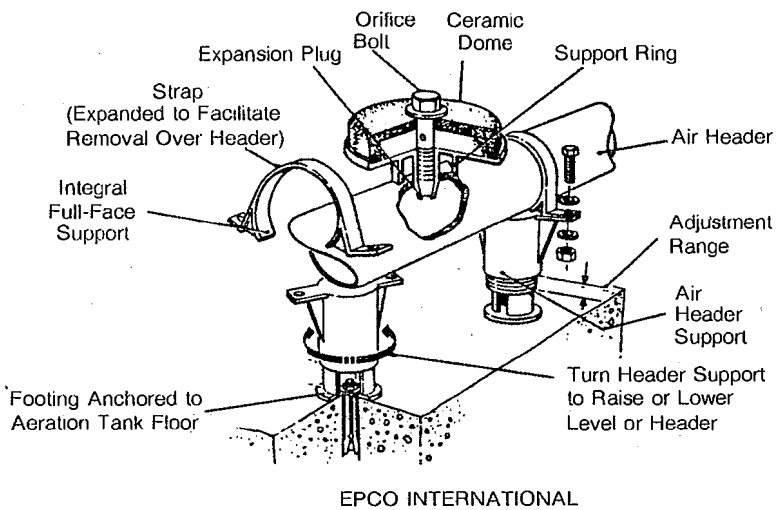
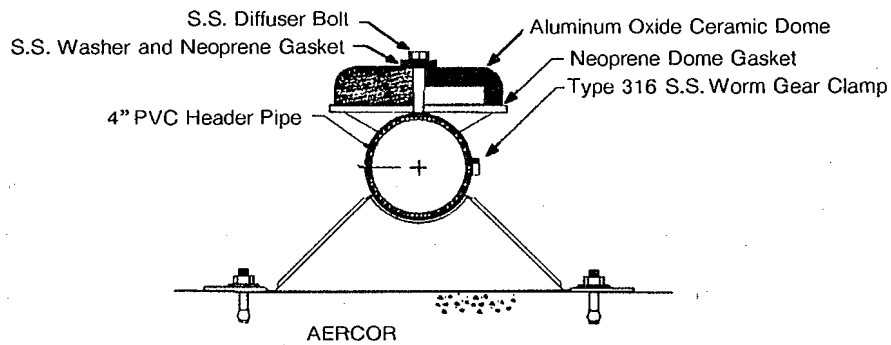
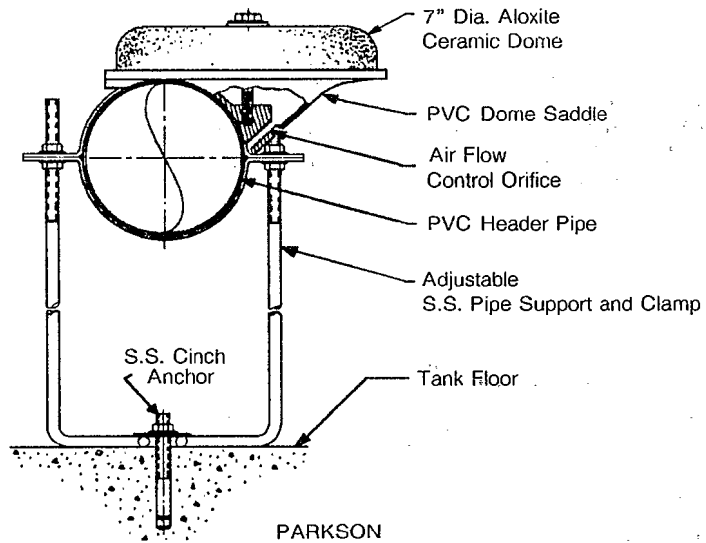
Dome diffusers are usually designed to operate at an airflow rate of 0.5 L/s (1 scfm)/diffuser with a range of 0.24-1.2 L/s (0.5-2.5 scfm)/diffuser. Operation above 1.2 L/s (2.5 scfm)/diffuser is possible, but may not be economical (see Section 2.6). Increasing the airflow rate above 0.9 L/s (2 scfm) results in a continuing increase in backpressure and decrease in OTE and may require a larger control orifice.

2.3.4 Disc Diffusers

2.3.4.1 Ceramic and Rigid Porous Plastic Media

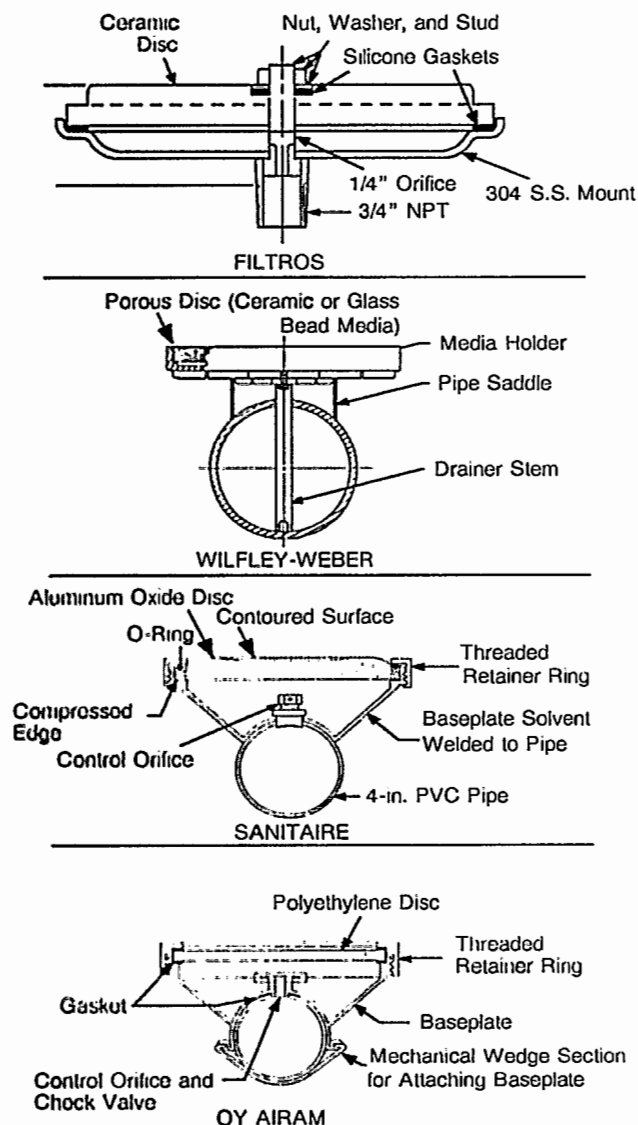
Disc diffusers are a recent development. Discs are flat, or relatively so, and are differentiated from dome

Figure 2-5. Typical ceramic dome diffusers.



diffusers in that they do not include a downward-turned peripheral edge. While the dome design is relatively standard, available disc diffusers differ in size, shape, method of attachment, and type of material (9,35,36). Schematics of typical ceramic and porous plastic diffusers are presented in Figure 2-6. One design can be equipped with either ceramic or glass bead media.

Figure 2-6. Typical ceramic and rigid porous plastic disc diffusers.



Disc diffusers are available in diameters of approximately 18-24 cm (7-9.5 in) and thicknesses of 13-19 mm (1/2-3/4 in). Except for one design, all discs consist of two flat parallel surfaces. For this exception, a raised ring slopes slightly downward toward both the outer edge and center of the disc. It is claimed that

the uniform profile aids in producing uniform air discharge across the entire disc surface (37).

Two disc designs include a step on the outer edge for the purpose of improving uniformity of air flux and effectiveness of the seal at the diffuser edge. The step also facilitates the use of an O-ring seal that is less subject to the adverse effects of compression set of the seal element.

As with dome diffusers, the disc is mounted on a plastic (usually PVC) saddle-type baseplate. Two basic methods are used to secure disc media to the holder: a center bolt or a peripheral clamping ring. The center-bolt method is similar to that used with domes. A soft, rubber gasket is placed between the diffuser and baseplate. The bolt assembly includes a washer and a gasket. The same precautions should be taken for bolt and gasket materials, as described above for domes.

The more common method of attaching the disc to the holder is to use a screw-on retainer ring. Several different gasket arrangements are used with the threaded collar. They include a flat gasket placed below the disc, a U-shaped gasket that covers a small portion of the top and bottom and the entire edge of the disc, and an O-ring gasket placed between the top of the outer periphery of the disc and the retainer ring. The latter arrangement provides a seal between the vertical outer surface of the diffuser and the vertical inner surface of the holder. The baseplate normally includes small raised ribs to aid in obtaining an airtight seal between the gasket and the baseplate.

The retainer ring method of attaching the diffuser to the holder has potential advantages over the center-bolt method. As diffusers become fouled, excessive amounts of air are discharged from the edges and the area around the center-bolt washer (38). Although not specifically documented for discs under controlled conditions, this nonuniform airflow could reduce system OTE. The retainer ring is likely to minimize these problems. In addition, breakage of diffusers from overtightening the bolt, or air leakage problems from gasket compression set or stretching of a nonmetallic bolt can be eliminated.

Two methods are used to attach disc diffusers to air piping. The first is to solvent cement the baseplate to the PVC header prior to shipment to the job site. To avoid future additional costs associated with replacing sections of pipe, the original design should include all the baseplates needed to meet future design requirements for the system. During the early life of the treatment plant, not all the diffusers are installed and plugs are simply inserted in the unused baseplates.

The second disc diffuser attachment method uses mechanical means. Either a bayonet-type holder is

forced into a saddle on the pipe, or a wedge section is placed around the pipe and clamps the holder to the pipe. Except for one manufacturer that employs the wedge clamp method of attachment and ships units preassembled, the pipe arrives at the job site with only the holes drilled. This technique makes shipping the pipe somewhat easier (less bulky) and can reduce damage that may occur during shipment or installation. With these types of designs, holes for additional diffusers can be predrilled and plugged or drilled later.

Disc diffusers also include individual control orifices in each diffuser unit. Designs employing the bolt method of attachment usually use a hollow bolt with an orifice drilled in its side. The other designs use either an orifice drilled in the bottom of the diffuser holder or a threaded inlet in the base where a small plug containing the desired orifice can be inserted. The diameter of the orifice is similar to that used with dome diffusers.

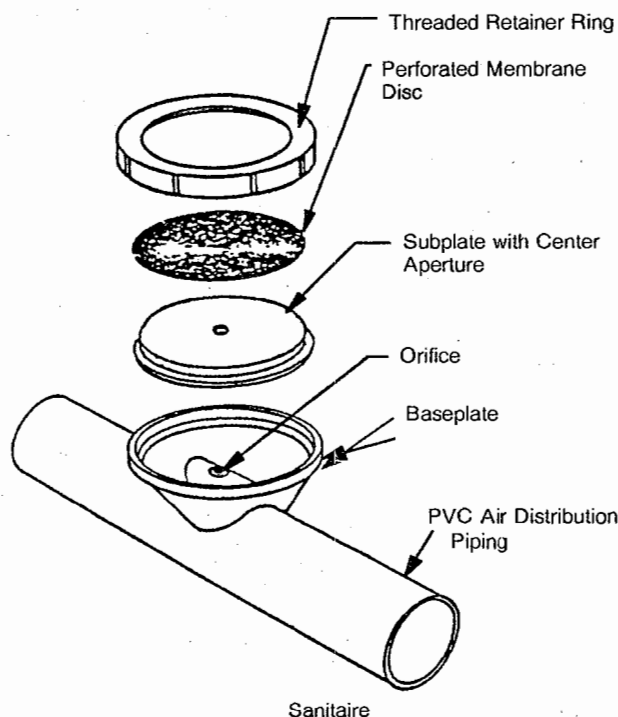
Ceramic and plastic media disc diffusers usually have a design airflow of 0.24-1.4 L/s (0.5-3 scfm)/diffuser. The most economical operating range will, however, depend somewhat on diffuser size. The smaller 18-cm (7-in) diameter discs are usually operated at airflow rates of 0.24-0.9 L/s (0.5-2 scfm)/diffuser, similar to those used for dome diffusers. For the larger discs, with diameters of 22-24 cm (8.5-9.5 in), typical lower and upper airflow limits are 0.26-0.43 L/s (0.6-0.9 scfm)/diffuser and 1.2-1.4 L/s (2.5-3 scfm)/diffuser, respectively. Prolonged operation at flow rates <0.24 L/s (0.5 scfm)/diffuser is not desirable with discs because insufficient air is available to ensure good distribution across the entire surface of the media. In those applications where operation above 0.9 L/s (2 scfm)/diffuser is desirable, the control orifice should be sized so that the headloss produced does not adversely affect the economics of the system.

2.3.4.2 Perforated Membranes

Like their ceramic and rigid porous plastic media counterparts, several different sizes and shapes of perforated membrane disc diffusers are available (16,18-20). They range in diameter from approximately 20 to 51 cm (8-20 in). Although one design uses a convex shape, most are flat in the air-off position. The convex shape reportedly helps prevent the media from wrinkling (19). Figure 2-7 shows schematics of several perforated disc diffusers.

As with perforated membrane tube diffusers, perforated membrane discs require support. The support base is made from a number of different types of thermoplastic materials including polyamide, PVC, and polypropylene. The membrane is usually secured to the base around the periphery by a clamping ring or wire, or a screw-on retaining ring. In one case, however, the elasticity of the membrane is enough to secure it to the base. When the air is

Figure 2-7. Typical perforated membrane disc diffusers.



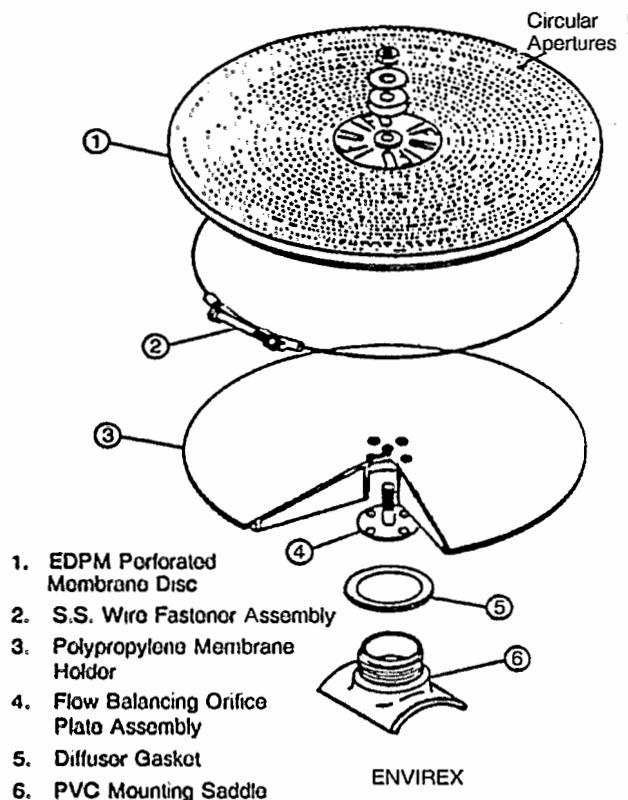
applied, the membranes will flex upward approximately 6-64 mm (0.25-2.5 in). If the membrane flexes in excess of the manufacturer's recommendations, difficulty could be experienced in maintaining good airflow distribution. Therefore, some designs include an additional means of support in the center to prevent overflexing or ballooning. This center support can consist of a piston-type arrangement or a retaining bolt. The piston type is designed to prevent backflow.

It is common with the disc design to feed air through one or several small holes in the center of the support base. The membrane is normally not perforated near these holes. When the air is turned off, the liquid head forces the unperforated section of the membrane down over the air inlet ports. This provides an additional means of closure to that of the perforations that form a seal against the support member.

The base of the support frame is usually threaded. Common practice is to use a special saddle that is either glued or clamped to the air header for attaching the diffuser. In Europe, where rectangular stainless steel piping is often used for the air header, a nipple is welded to the pipe for attaching the diffuser.

One membrane disc diffuser utilizes a holder identical to that used for a ceramic disc (16), while another utilizes a holder identical to that used for a rigid porous plastic disc (9). By replacing the ceramic or

Figure 2-7. (continued).



porous plastic disc medium with a membrane disc subplate and the membrane itself, a ceramic or rigid porous plastic system can be converted to a membrane system, or vice versa (Figure 2-7).

For the smaller diameter (20-30 cm [8-12 in]) perforated membrane disc diffusers, the recommended airflow range is approximately 0.5-4.7 L/s (1-10 scfm)/diffuser. For the larger diameter (51 cm [20 in]) disc, the recommended range is 1.4-9.4 L/s (3-20 scfm)/diffuser.

2.4 Diffuser Layout

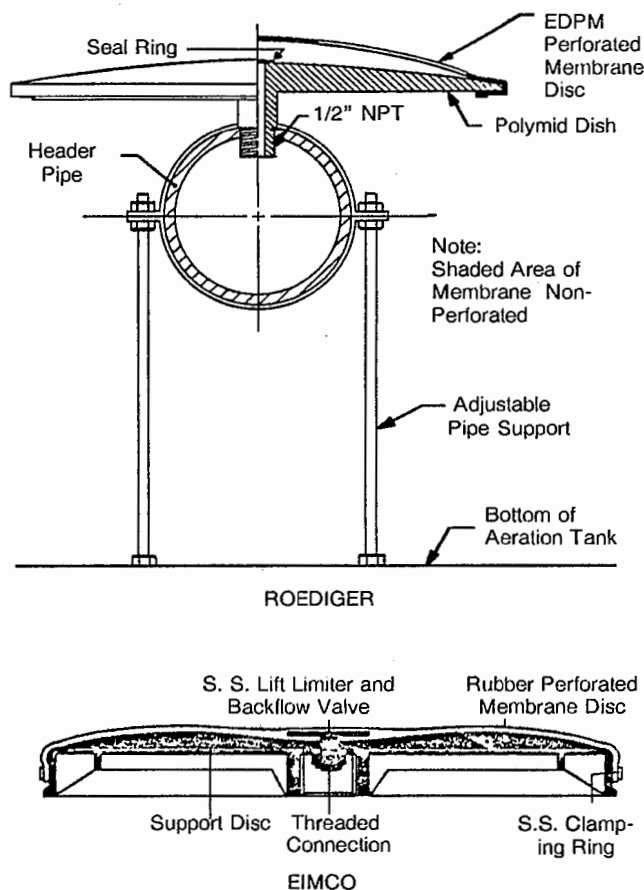
Figure 2-8 presents schematics of typical diffuser layouts. These layouts are discussed below as they apply to each of the fine pore diffuser types described above.

2.4.1 Plate Diffusers

Fine pore ceramic plates of the original 30-cm (12-in) square design (21,22) are most often grouted into the basin floor. Downcomer pipes deliver the air to open concrete channels below the plates. The channels act as distribution manifolds.

The original plate diffusers can be installed in either a total floor coverage or spiral roll pattern. Total floor arrangements may include closely spaced rows of diffusers running either the width (transverse) or

Figure 2-7. (continued).



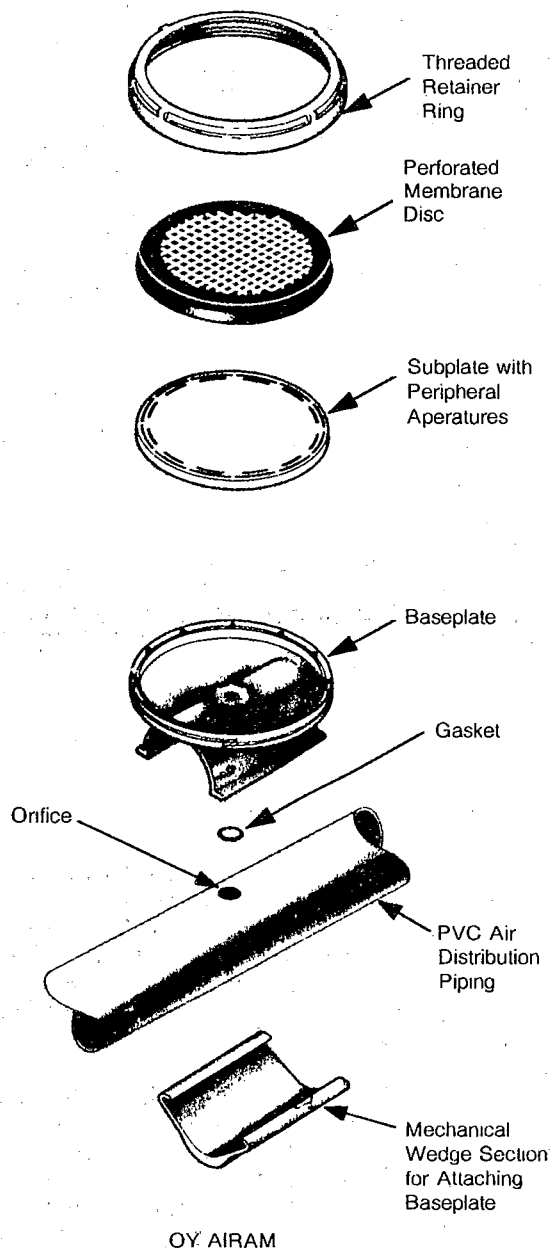
length (longitudinal) of the basin or incorporated into a ridge and furrow design (21). Spiral roll arrangements include rows of plate diffusers typically located along one or both sidewalls of aeration basins. The total floor layout will produce a higher OTE, whereas the spiral roll pattern will produce more effective bulk mixing of the mixed liquor.

The newer 30 cm x 61 cm (12 in x 24 in) and 30 cm x 122 cm (12 in x 48 in) ceramic and porous plastic plate diffusers (23) are not attached to the basin floor. With the flexibility afforded by their individual rubber air feed hoses, they can be moved, within limits, about the basin floor to form different layout configurations. If a change to a significantly different configuration is desired, new hoses may have to be provided to accommodate the revised diffuser positions.

2.4.2 Tube Diffusers

Most tube diffuser assemblies include a 19-mm (3/4-in NPT) threaded nipple (stainless steel or plastic) for attachment to the air piping system. This design makes the tubes especially well suited for retrofit or upgrade applications since many coarse bubble

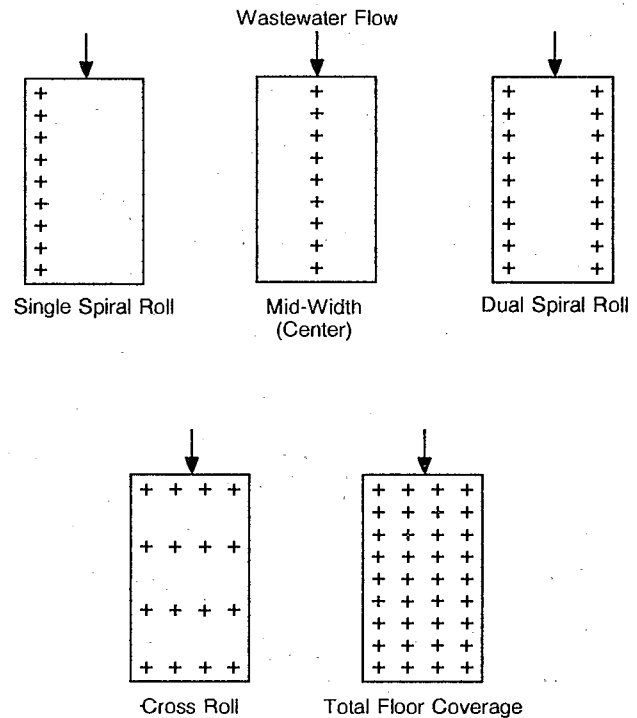
Figure 2-7. (continued).



diffuser systems use the identical method of attachment.

The air headers on which the tubes are mounted are usually fabricated from PVC, CPVC, stainless steel, or fiberglass reinforced plastic. Carbon steel is sometimes used but is less desirable because of corrosion inside the pipe. Thus, threaded adapters or saddles are either glued, welded, or mechanically

Figure 2-8. Typical diffuser layouts.



attached to the pipe at the points where the tubes are to be connected. The actual diameter of the air headers will vary depending on the number of diffusers to be installed and the design airflow rate.

The depth of tube submergence in the basin varies depending on the application. In new installations, the tubes are usually placed as close to the floor as possible, typically within 30 cm (1 ft) of the bottom. In retrofit applications, the discharge pressure of the existing blowers may control the depth of submergence. The tubes are normally installed at either the same elevation as the original system or possibly at a somewhat greater distance off the floor to compensate for any increase in headloss incurred through the fine pore media compared with the coarse bubble devices they are replacing. The air headers are usually secured to the basin floor with adjustable-height, stainless steel pipe supports.

Tube diffusers are often installed down the center or along one or both long sides of the aeration basin (mid-width, single spiral roll, or dual spiral roll pattern, respectively). In some cases, the headers are mounted on mechanical lifts to allow removal of air headers and diffusers for inspection and cleaning without dewatering the basin. On the header itself, the tubes can be installed along either one side (narrow band) or both sides (wide band) of the pipe.

Tubes can also be installed in either a cross roll or total floor coverage pattern. In the cross roll design, the headers are placed across the basin width and the spacing between diffusers, 30-91 cm (12-36 in), is small in comparison with the spacing between headers, 3-9 m (10-30 ft). In the total floor coverage pattern, in which the headers can be placed either across the basin width or along its length, the distance between headers and the spacing between diffusers on the headers approach the same value. Total floor coverage will usually achieve higher OTEs than the other configurations.

Spiral roll configurations normally provide better bulk mixing throughout the basin than either total floor coverage or cross roll patterns. Some designers believe that cross-roll patterns may not provide adequate mixing. One potential disadvantage of the cross roll and total floor coverage designs is that the location and amount of piping required usually makes the use of mechanical liftouts impractical. There is only one known installation in this country (39) where a total floor coverage liftout system has been installed.

2.4.3 Disc and Dome Diffusers

Although their shape and operating characteristics may differ, the typical air piping and diffuser layout is identical for both disc and dome diffuser systems. The air distribution manifold should preferably be PVC, the compounds of which are described in ASTM D-1784 or ASTM D-3915 (13), cell classification 12454B or 124524, respectively. If D-1784 is specified, the pipe material should be limited to stress-related compounds. The PVC should be UV-stabilized with 2-percent minimum TiO_2 , or equivalent. The specifications, dimensions, and properties of the pipe itself conform to either ASTM D-2241 (13) or D-3034 (13), depending on the outside pipe diameter.

The piping network usually has a nominal 10-cm (4-in) diameter, with an actual O.D. of 10.7-11.4 cm (4.2-4.5 in). The wall thickness is also variable, typically 3.0-4.3 mm (0.12-0.17 in). Sections of pipe are connected with gusseted, mechanical expansion joints to allow for expansion and contraction of the PVC over a temperature range, typically about 100F, appropriate to climatic temperature extremes anticipated. Pipe supports, usually made from PVC or stainless steel, are provided to secure the system to the basin floor. The support consists of a cradle or saddle and a holddown strap. The strap is either secured with a bolt or snaps into place. Pipe supports are adjustable to compensate for variations in the basin floor elevation. Extreme variations in basin floor elevation can cause problems in using standard pipe supports. The pipe support is attached to the basin floor with one or two stainless steel bolts and concrete anchors. The PVC strap and pipe support have experienced some breakage problems in the past. To eliminate these problems, or in cases where the diffusers are to be mounted a significant distance above the basin floor,

i.e. 61 cm (24 in), stainless steel pipe supports can be used.

Discs and domes are generally installed in a total floor coverage or grid pattern. In some cases where oxygen demand is low and mixing may control the design (near the end of long narrow basins), the diffusers can be placed in tightly spaced rows along the side or middle of the basin to create a spiral or mid-width mixing pattern, respectively (40). The diffusers are usually mounted as close to the basin floor as possible, within 23 cm (9 in) of the highest point of the floor being typical. As mentioned in the discussion of tube diffusers, the depth of submergence in some retrofit applications may be controlled by the available blower discharge pressure.

2.5 Characteristics of Fine Pore Media

Many properties can be used to characterize fine pore media. Knowledge of these characteristics promotes a better aeration system design for a specific set of site conditions. Appropriate attention to these characteristics in the design phase may also lead to reduced O&M problems during the life of the system. Many of these characteristics are not routinely defined or available for specific media.

Reasons for defining media characteristics as thoroughly as possible include providing:

1. a means of short-term (batch-to-batch) and long-term (year-to-year) quality control,
2. baseline performance and a basis for determining changes in media properties under process conditions over time,
3. quantitative information needed in design specifications, and
4. an indirect indication of changes in field performance.

The following sections present a general discussion of selected fine pore media characteristics.

2.5.1 Physical Description

For each specific aeration medium, a raw material description should be provided. Usually, the equipment supplier (in conjunction with the manufacturer) selects the optimum materials. By knowing what these materials are, the designer can ascertain whether any unique constituents in the wastewater or cleaning chemicals will be incompatible with the diffusion media. Materials that should be specified include the grit and type of binder for ceramic media, and the chemical composition of the principal constituents comprising porous plastic media and perforated membranes.

2.5.2 Dimensions

For each type of diffuser element, all critical dimensions should be stated. Other than the obvious reason of assuring compatibility with the mounting base or holder, these dimensions also serve to establish a baseline. After a certain period of operation, the dimensions can be checked to determine whether changes have occurred. It is possible that some materials may warp, expand, or stretch with time. Only if baseline dimensions have been established can these changes be detected.

2.5.3 Weight and Specific Weight

The weight of the diffuser and its apparent specific weight (calculated) should also be determined. These two characteristics can be used for quality control. A wide range in weight or specific weight between several apparently similar diffusers could indicate an unacceptable product (21). In this situation, it is likely that a variance in weight will also result in a variance in some of the other parameters such as dynamic wet pressure (DWP - see Section 2.5.11), bubble release vacuum (BRV - see Section 2.5.12), or uniformity (see Section 2.5.13).

Initial or clean media weight and specific weight should also be determined to establish baseline conditions. As with media dimensions, changes in media weight and specific weight can occur with time. These changes can result from absorption of liquids, leaching of certain resins or additives, or dissolution of the base material. A single weight measurement should usually detect any changes. A better approach, however, is to obtain a series of measurements over time. Also, if media weight is determined in conjunction with other physical or mechanical testing (e.g., tensile strength), an indication of any degradation can be determined.

2.5.4 Permeability

The permeability test may have some application for quality control. However, because permeability is such an inexact parameter, it is of little practical significance in characterizing even ceramic-type diffusers. The following discussion is included to define the term since it is often mentioned in regard to fine pore aeration media and point out some of the many shortcomings of the test. Other more meaningful parameters are discussed in Sections 2.5.11 and 2.5.12.

Ceramic diffuser media are usually available in a number of different grades. Grades are distinguished by pore size, which is controlled by the size of the grit material, binder type and content, and firing temperature. Because measurement of pore size was not practical for a large number of samples, the ceramic manufacturing industry developed a simple but somewhat arbitrary test to differentiate between

grades of media. This test was referred to as the permeability rating.

Permeability is a measure of a porous medium's frictional resistance to airflow. It is an empirical rating that relates flux rate to pressure loss and pore size or pore volume. Permeability is usually defined as the amount of air at standard conditions that will pass through 929 cm² (1 sq ft) of 25-mm (1-in) thick dry porous media under a differential pressure equivalent to 5 cm (2 in) w.g. when tested at room temperature. The airflow value obtained (scfm) under these conditions is called the permeability (perm) rating.

Unfortunately, the permeability measurement does not provide a true basis for comparison of media performance. The same permeability rating could be obtained from a diffuser with a few relatively large pores or a multitude of small pores. Also, two diffusers with the same pore structure would have different ratings if they have different thicknesses.

Most ceramic and some plastic media specifications now include a test for permeability. Unfortunately, the ceramic industry has not "standardized" this test procedure. The early specifications were developed for 30 cm x 30 cm (12 in x 12 in) plates, 25 or 38 mm (1 or 1.5 in) thick. Today, specifications are needed for products of various shapes, densities, and thicknesses, often of poorly defined effective area. Attempts have been made to apply the principles of the test through a parameter known as specific permeability (41). The procedure for determining specific permeability generally consists of mounting and sealing the test diffuser in a fixture similar to the manner in which it is mounted in the field. Sufficient air is then passed through the dry element to produce a pressure differential of 5 cm (2 in) w.g. This measurement and the geometry of the diffusers are then used to estimate what the airflow would have been had the dimensions of the test diffuser been 30 cm x 30 cm x 25 mm (12 in x 12 in x 1 in).

The specific permeability procedure has served to improve the utility of this test to a degree. However, it still suffers from the following deficiencies:

1. Clamping and sealing details are not well enough defined to provide acceptable precision.
2. Depending on the degree of complexity of the media geometry, effective diffuser area and effective air path length cannot always be easily defined and accounted for.
3. Correction factors to account for pressure, temperature, and humidity of the air have not been developed.

4. The effects of surface tension are not accounted for since the test is conducted on a dry basis.

2.5.5 Perforation Pattern

Each perforated membrane diffuser manufacturer uses a slightly different perforation pattern. In fact, the same manufacturer may use one type for a disc diffuser and a different one for a tube assembly. One reason for changing the perforation pattern between diffuser types is that the various shapes result in different stresses and resulting strains on the membrane. Thus, a pattern is developed that will best be able to withstand the magnitude and direction of the loads that will be applied.

Perforations can differ in regard to type (holes or slits), size, orientation, and density (number perforations/diffuser surface area). Usually, the specific pattern has been developed over time and is not a feature that changes from job to job. It is important, however, to detect any changes that may occur to the membrane over time. Measurements or photomicrographs can be made and compared to baseline conditions to determine if the perforations have either expanded or taken on a permanent set. Also, in situations where replacement diffusers are purchased, the perforations should be similar to the original diffusers to ensure compatibility.

2.5.6 Strength

Structural or physical strength is also an important media characteristic. The diffusion media must be strong enough to withstand: 1) the static head of the water above the diffuser (in cases where the air supply is shut off), 2) the forces applied when attaching the media to the diffuser holder, and 3) stresses and shocks of reasonable handling, shipping, and maintenance. Strength, as described in this section, applies only to rigid diffusion media (ceramic and porous plastic).

For discs and domes, measurement of strength usually involves supporting the diffuser in a fashion similar to that used for the final assembly and then applying a load to a 25-mm (1-in) diameter area in the center of the diffuser. Using this method, developed primarily for ceramic diffusers, acceptable loads for the ceramic material are 270-455 kg (600-1,000 lb). Diffusers that use a peripheral clamping method do not require the same flexural strength as those that utilize the center bolt method of attachment. Slightly different techniques have been developed to evaluate the strength of nonrigid diffusion material.

2.5.7 Hardness

Hardness is an important media characteristic for perforated membranes because it is an index of the resistance of an elastomer to deformation. It is measured by pressing a ball or blunt point into the surface of the material (13). The most commonly used instrument to measure hardness is the durometer.

Different types of instruments are available that produce a range of overlapping scales. Shore A durometer readings are the most common, although Shore D readings are sometimes specified. For each range, the higher the durometer reading, the harder the material.

Hardness can be used to detect changes in membranes. Softening or hardening of the membrane material may be indicative of environmental attack. A softening, for instance, may indicate the absorbency of a solvent into a thermoplastic. On removal from the wastewater, the solvent may evaporate and the plastic may resume its original hardness. Hardening, on the other hand, may indicate the loss of an additive or plasticizer over time or attack by some type of acid. In any regard, changes in hardness should be noted and other characteristics (BRV, DWP, and OTE) evaluated to determine if media performance has been affected. In some cases, changes in hardness may denote a change in media characteristics that will not necessarily shorten service life.

2.5.8 Environmental Resistance

The constituents found in typical domestic wastewater are usually not excessively harmful to fine pore diffuser media. Some industrial wastes, however, may contain compounds that will result in physical degradation of the media, especially for the porous plastics and perforated membranes. Some compounds of potential concern include mineral and vegetable oils, organic solvents, and strong oxidizing agents.

It is common practice to use chemicals to clean fine pore diffusers when they become fouled. Although hydrochloric acid (HCl) is the most common cleaning chemical (either as a liquid or gas), other compounds have been used. These include inorganic acids (sulfuric, nitric), bases (sodium hydroxide, potassium hydroxide, ammonium hydroxide), carboxylic acids (formic, acetic), detergents, and organic solvents.

Air-phase foulants including oxidants such as ozone are also of concern. Ambient concentrations of these oxidants are aggressive to a number of elastomers used in wastewater treatment (e.g., nitrile, styrene butadiene rubber, polyisoprene, and natural rubber). The effect is intensified when the materials are under stress. Ozone-resistant membrane materials should be developed. In all cases, assurance should be obtained (from the literature, supplier, or tests) that the material selected has the requisite resistance to these oxidants in the concentrations expected in service. The same assurances should be obtained for those applications in which fine pore devices are used to disperse ozone.

Most ceramic diffusers have been marketed for many years and, except for some slight degradation when acids are used for cleaning, appear to be quite

resistant to chemical attack. Porous plastics and perforated membranes have been developed in the last 10-15 years. Testing has shown that wide variations exist among the generic groups of plastics in their chemical resistance and physical and mechanical properties (14).

Even within a generic classification, different formulations may result in a wide variation in performance in a particular environment. To enhance the physical properties of plastics and elastomers, manufacturers often incorporate additives into their membrane formulations. Therefore, the actual material may differ in composition from published data. As a result, environmental resistance testing should be conducted with the actual diffuser media in both stressed and unstressed conditions. Much of such testing may serve as a qualification rather than a routine requirement.

In conducting these tests, several of the media characteristics discussed in this section can be used to establish if any chemical degradation is occurring. Some of the more important include changes in dimensions, weight, strength, and DWP.

2.5.9 Miscellaneous Physical Properties

Several additional physical properties can be used to characterize fine pore aeration media. A partial list of those properties that may be of importance, especially for porous plastics and perforated membranes, is:

1. Tensile strength (stress and strain)
2. Elongation at failure
3. Modulus of elasticity
4. Creep
5. Compression set
6. Tear resistance
7. Strain corrosion
8. Solvent extraction
9. Ozone resistance

Since most of these properties are temperature dependent, data should be developed over the expected range in temperature. Definitions and procedures can be found in the ASTM Standard (13).

Since very little information exists regarding the above six items, it is premature to attempt to place guidelines on what would be considered acceptable. It is possible, however, to use these parameters for assessing the effects of field operation. Any changes over time may be an indication of degradation of the media or impending problems (e.g., significant creep with a polyethylene tube diffuser may eventually lead to air leaks at the end caps). These properties may also be important in evaluating the general quality of a membrane material. For example, the ratio of the tensile strength at design operating conditions and at

failure could be calculated. The higher the ratio, the greater the safety factor.

2.5.10 Oxygen Transfer Efficiency

The OTE that can be achieved with fine pore diffuser media over their design life is likely their most important characteristic. Most projects require a shop or field oxygen transfer test to verify diffuser performance with regard to OTE. OTE information can also be obtained in using laboratory (bench-scale) apparatus to aid in characterizing the media. Laboratory tests are not intended to be a substitute for shop or field testing, or for predicting field OTE. Rather, they should be used to evaluate relative differences in performance between two or more diffusers.

A typical laboratory setup will consist of a small column, 61-91 cm (2-3 ft) in diameter and 2-3 m (7-10 ft) high. The diffuser(s) to be tested is installed in the column and clean water OTE is determined over a range of airflows (ideally two or three different rates).

Clean water OTE is usually determined by the nonsteady-state test procedure described in an ASCE Standard (42). A second procedure that also seems to produce excellent results involves a steady-state test (10,43). With this technique, two diffusers are usually placed in the test basin. The airflow to the first diffuser is set at the desired rate; a very low airflow rate (<5 percent of the first) is set for the second diffuser. The basin is covered, sodium sulfite is added at a constant rate to achieve steady-state DO conditions, and the off gas is analyzed for oxygen content. After sufficient data are obtained on one diffuser, the air supply is rapidly switched, causing the second diffuser to operate at the specified rate and the air to the first diffuser to be reduced to maintain only a slight positive pressure. By repeating the cycle several times, the relative oxygen transfer performance of the two diffusers can be obtained. Details of this test procedure are presented in Appendix B.

Both techniques (steady- and nonsteady-state) produce acceptable results. If an off-gas analyzer is available, the steady-state procedure is more desirable. Data can be generated more quickly, and the ability to compare two diffusers on a side-by-side basis is an additional advantage.

It must be emphasized that OTE values determined in laboratory tests are for comparison purposes only. They can be used as a quality control technique, for detecting changes in performance that may occur during field operation, or for assessing the effectiveness of various cleaning agents. Ideally, laboratory OTE tests will be conducted in conjunction with other media characterization tests (e.g., DWP and BRV) to examine what correlations might exist.

2.5.11 Dynamic Wet Pressure

DWP is a very important characteristic in evaluating and selecting porous media. DWP, the pressure differential (headloss) across the diffusion element when operating in a submerged condition, is expressed in cm (in) w.g. at some specified airflow rate (38). As a general rule, the smaller the bubble size, the higher the DWP. While small bubbles may increase OTE, the additional power required to overcome the higher headloss may negate any potential savings.

DWP can be measured in the laboratory or in the field. Accurate field measurements are often more difficult to obtain. Figure 2-9 presents a schematic of a typical field setup for in-situ monitoring of DWP. This particular arrangement includes a bubbler or static line (Tap 3), a line to sense pressure in the air header (Tap 1), and a connection in the body of the diffuser holder immediately below the media (Tap 2). Tap 2 is considered optional since the physical design of some diffusers makes it very difficult or impossible to locate this connection.

Using the three taps shown in Figure 2-9, it is possible to measure the headloss across the diffusion media (Taps 1 and 3) as well as estimate the airflow rate through the diffuser based on the headloss across the control orifice (Taps 1 and 2). If Tap 2 is omitted, the DWP measured will include inlet losses as well as media losses.

Extreme care must be taken to purge all moisture from both pressure sensing lines and set the airflow through the bubbler tube at the lowest possible rate that will not induce a significant headloss. Also, because of the relationship between standard and actual airflow rates, the headloss in the field will be a function of diffuser submergence. If a field measurement of DWP is made, the units used in describing the flow (standard or actual) must be known and corrections made before different media are compared.

An alternative to measuring DWP in the field is laboratory measurement of DWP for selected diffusers removed from the aeration basin. A supply of test diffusers may be provided from removable test headers. Test headers having four diffusers have been used in several plants (10,44,45). A typical test header is shown in Figure 2-10. To reduce the weight of the test header assembly so that diffusers can be more easily removed, a two-diffuser arrangement may be used in place of the four-diffuser assembly.

The removable headers can be equipped with pressure taps for in-situ monitoring of DWP. These field readings can be supplemented with more precise measurements of DWP in the laboratory. It is imperative that the test header be operated at airflow rates similar to the full-scale system. Airflow rates to

individual diffusers can be easily determined for units having fixed-size flow control orifices by measuring the pressure drop across the orifice. Airflow rates can also be measured using one or more rotameters. The use of removable headers requires significant operator attention and commitment if the data collected are to be of value.

Although the diffusers must first be removed from the aeration basin, laboratory measurement of DWP will usually be more accurate. However, the diffusers must be kept wet and rapidly transported to the laboratory (ideally, within 24 hours) to prevent changes in the characteristics of the foulant from occurring. In determining DWP, it is important that porous diffusers (ceramic and plastic) be allowed to soak for several hours (plastic materials may require a much longer period) prior to testing to completely saturate all the pores. Since the actual headloss will be a function of the degree of water saturation in the diffusers, a slightly different curve will be obtained if the air is started at a low flow rate and is increased, or vice versa. Standard practice is to purge the media at the upper airflow rate for a predetermined interval (5-10 minutes), then record subsequent headloss values as the airflow rate is decreased. At least three different airflow rates should be used to define DWP adequately.

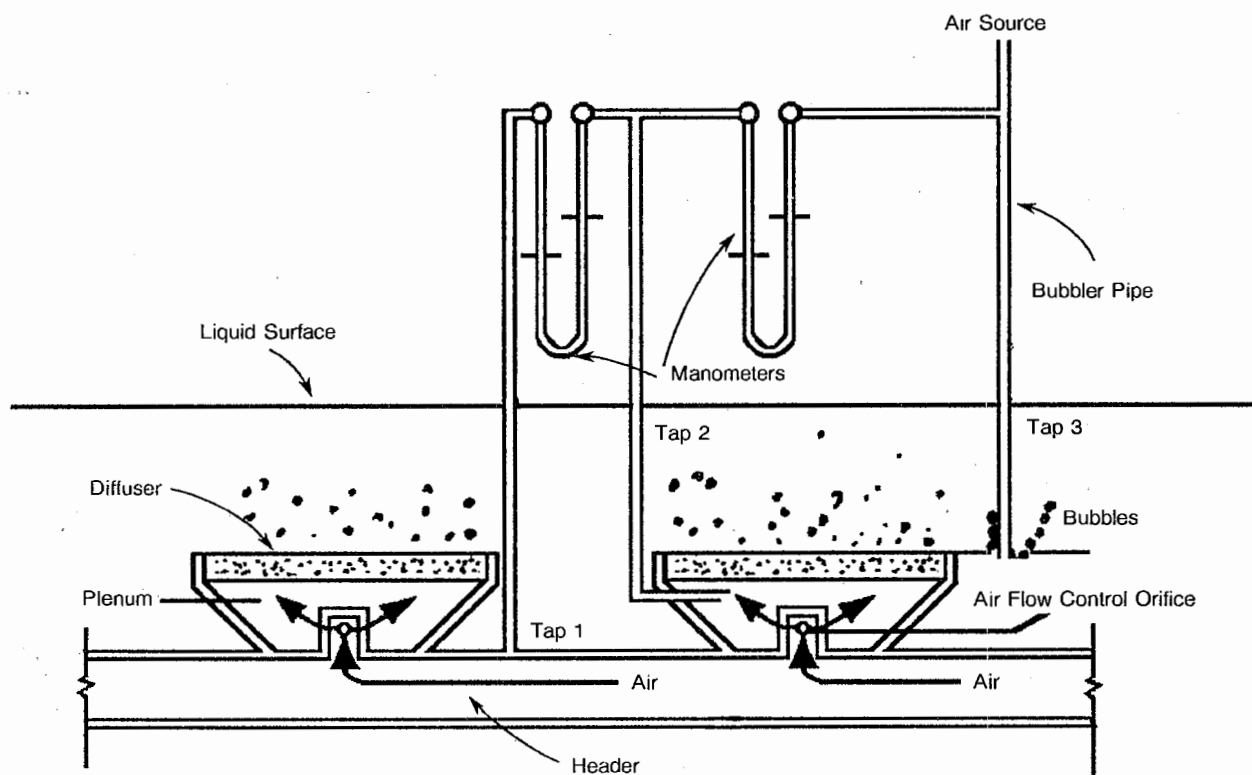
DWP testing can be conducted in an aquarium or similar small basin using an apparatus depicted in Figure 2-11. Usually, the diffuser holder will contain a control orifice to aid in airflow distribution throughout the system. In conducting the DWP test, the apparatus should be set up so that the losses across the orifice are not included in the DWP determination. Orifice losses, depending on the airflow rate, can become quite high. This may mask the losses associated with the media that represent the main purpose of the DWP test.

The porous media now in use have a DWP of about 8-51 cm (3-20 in) w.g. when operated within the typical or specified airflow ranges. The specific value depends on the type of material, surface properties, airflow rate, and diffuser thickness. For ceramic and porous plastic materials, the headloss vs. airflow curve is linear over the typical operating range and the slope is relatively flat. For these two types of material, most of the DWP is associated with the pressure required to form bubbles against the force of surface tension. Only a small fraction of the DWP is required to overcome frictional resistance. Because surface tension is not affected significantly by material thickness or airflow rate, these two factors are only minor contributors to the overall DWP (38).

2.5.12 Bubble Release Vacuum

The BRV test provides a means of determining the bubble release vacuum at any point on the surface of a diffuser element relative to other points on its

Figure 2-9. On-line device for monitoring DWP of fine pore diffusers.



surface. Normally, BRV denotes the average of the point BRV values for a specific diffuser. This test procedure is useful for assessing the uniformity of pores on the surface of diffusers under clean as well as fouled conditions (46) (see Appendix B for test details).

BRV, as suggested by the name, is a measure of the negative pressure in cm (in) w.g. required to form and release bubbles in tap water from a localized point on the surface of a thoroughly-wetted porous diffuser element. This is accomplished by applying a vacuum to a small area on the working surface of a wetted diffuser and measuring the differential pressure when bubbles are released from the diffuser at the specified air flux at the point in question. The air flux is usually set quite low (10 L/s/m^2 [2 scfm/sq ft], which is within the range of flux values used for porous diffusers) to minimize frictional drop in the BRV measurement and, in cases where the diffusers are fouled, to avoid removing the fouling material during the BRV test.

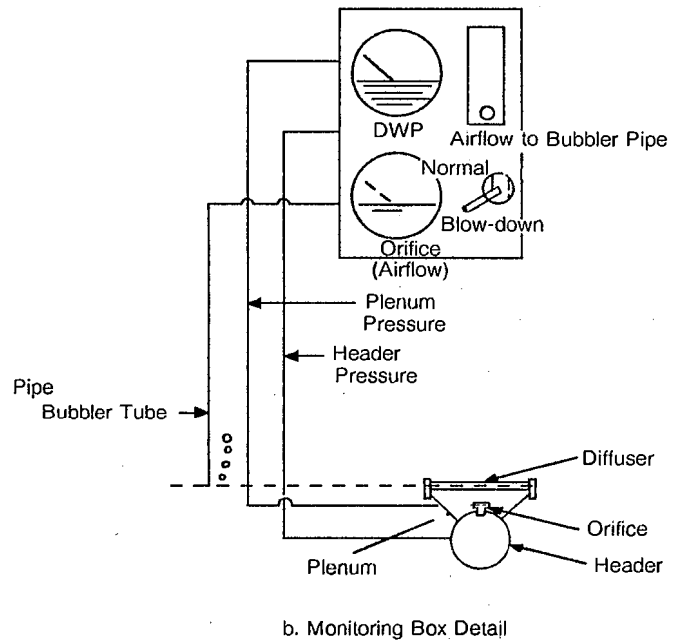
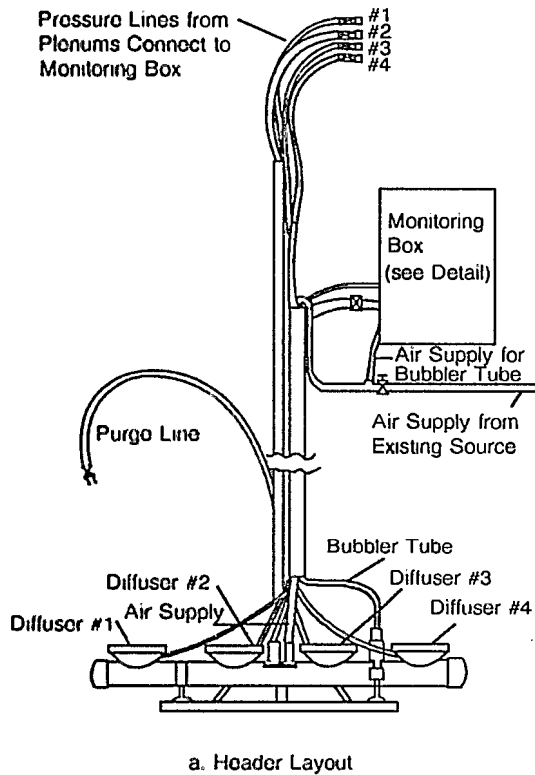
The BRV test was initially developed for use on ceramic and porous plastic diffusers. It can also be used on perforated membrane diffusers if the test equipment is modified to account for the greater

distance between pores - holes or slots in this case (10).

Both DWP and BRV provide a measure of the bubble release pressure. For the DWP test, the measurement is made across the entire diffuser. In cases where the diffuser is partially fouled, air may simply short circuit the fouled area. Thus, DWP may not indicate the true condition of the media. The BRV test, on the other hand, measures the pressure at a small localized area. For this reason, BRV has been found to be the more sensitive test. In studies evaluating diffuser fouling, the use of BRV data, averaged for the entire diffuser, permits significant shortening of the test period required to obtain definitive conclusions regarding diffuser fouling (46).

It should also be noted that it may be possible to combine various measurement parameters in characterizing fine pore diffusion media. It has been suggested that the ratio of DWP to BRV, when measured at the same air flux, may be a better indicator of diffuser fouling than either parameter alone (44,46,47). DWP measures the overall pressure that forms bubbles at a specific air flux over the entire diffuser surface. BRV measures the average negative

Figure 2-10. Removable test header.



pressure required to form bubbles at a specific air flux over a limited region of the diffuser surface.

The ratio of DWP to BRV is closely related to the fraction of the diffuser area that is actually emitting bubbles. As the ratio decreases, less of the diffuser area is operating for the same airflow rate. This means that the active areas are operating at higher localized air fluxes, potentially causing the formation of larger bubbles and resulting in lower OTEs. A DWP:BRV of 1 (both measured at the same air flux) suggests clean uniform media, whereas fouled diffusers frequently exhibit DWP:BRV values substantially lower than 1 (see Chapter 3).

The relationship between permeability and BRV is of interest from specification and quality control points of view. Many specifications require that permeability tests be conducted to control uniformity, effective pore size, and backpressure of the diffuser elements in service. As discussed in Section 2.5.4, there is no recognized standard procedure for determining permeability. Furthermore, since the test measures only an overall resistance to flow, it gives no indication of uniformity within an individual diffuser being tested.

On the other hand, the BRV test, which is conducted at air fluxes and pressure differences comparable to service values and includes the effects of surface tension, is not subject to the deficiencies of the

permeability test. Additionally, the coefficient of variation of this measurement provides a measure of diffuser uniformity (see Section 2.5.13). It has been suggested, therefore, that the BRV test is a far more applicable and meaningful field test than the permeability test as presently practiced for specifying diffuser uniformity and effective pore size (48).

In reasonably uniform diffusers of a given geometric shape, a relatively good correlation exists between the new or original BRV (BRV_0) and specific permeability. Figure 2-12a presents data obtained from four ceramic disc diffusers of equal size having a specific permeability of 14-50 (48). Since BRV is a measure of diffuser pore size, it is reasonable to assume that as pore size increases and BRV decreases, standard oxygen transfer efficiency (SOTE) decreases. Using a laboratory oxygen transfer test procedure described in Section 2.5.10 (see also Appendix B), the relationship between relative SOTE and specific permeability and BRV shown in Figure 2-12b was developed (48). It is apparent for these diffusers that little difference in relative SOTE exists for specific permeabilities between 14 and 38 ($BRV_0 = 23$ to 10 cm [9 to 4 in] w.g.).

2.5.13 Uniformity

Uniformity of individual diffusers and the entire aeration system is important if high OTEs are to be attained. On an individual basis, the diffuser must be

Figure 2-11. Apparatus for measuring DWP in the laboratory.

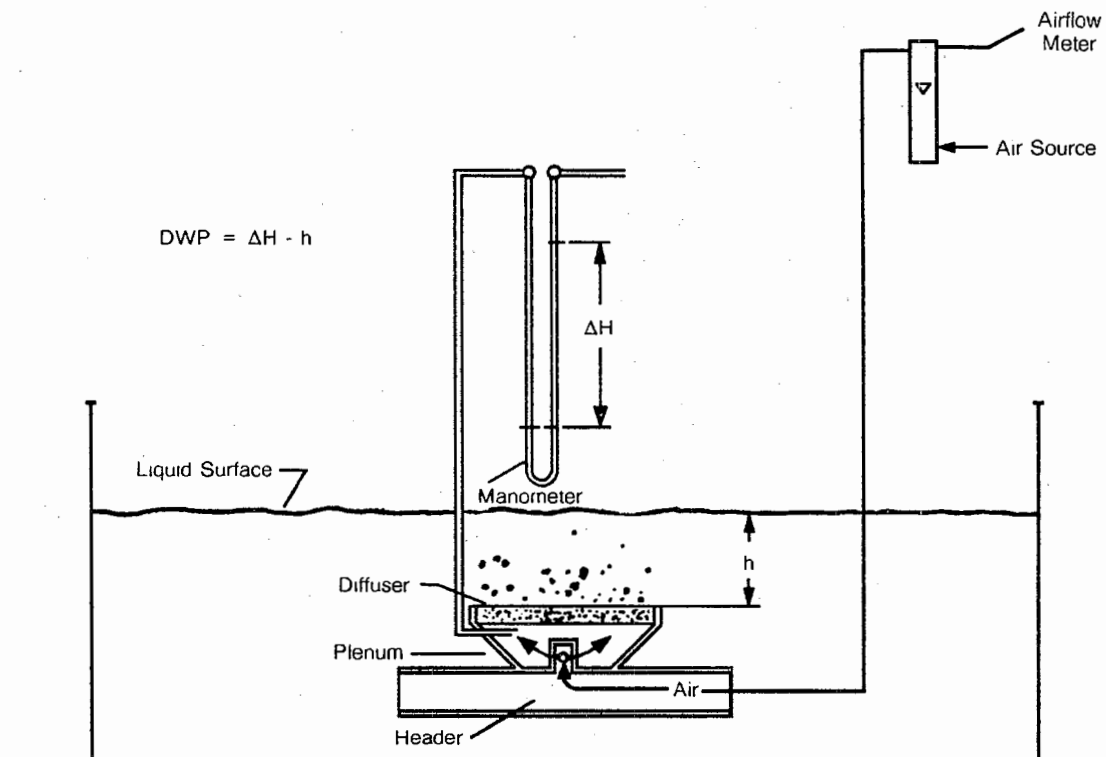
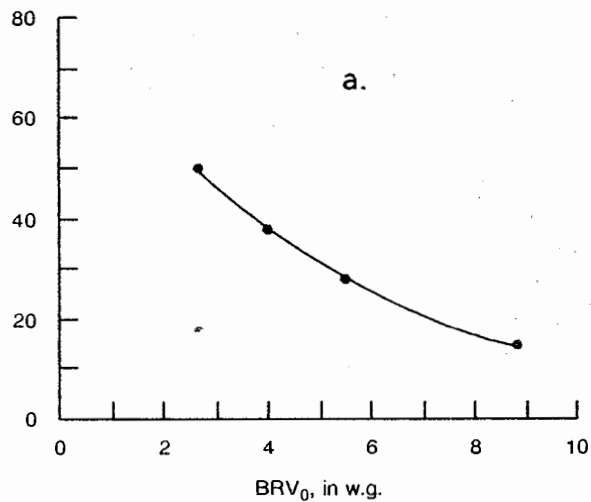
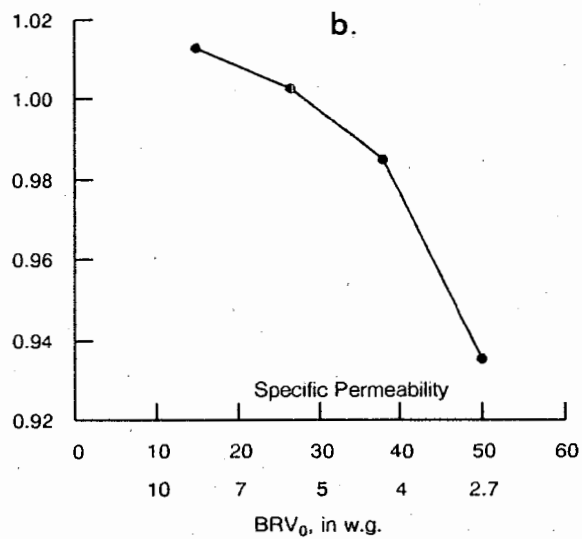


Figure 2-12. BRV relationships.

Specific Permeability



Relative SOTE



capable of delivering uniform air distribution across the entire surface of the media. If dead spots exist, chemical or biological foulants may form and eventually lead to premature fouling of the diffuser. Also, if small areas of extremely high air flux are present, larger bubbles may form and OTE will decrease.

Most system designers recognize the importance of uniformity and, as a result, will include a uniformity testing procedure as part of the job specification. A common practice has been to select random samples of media from each batch during the manufacturing run. The diffusers are placed in water for a fixed period to saturate them and then tested in a shallow basin at a predetermined airflow rate. Usually, a visual observation is the basis for the test. This type of qualitative method is obviously quite arbitrary. Two people are likely to have somewhat different definitions for what constitutes uniform airflow. In other cases, a high airflow from around the periphery may tend to mask the view of the center of a diffuser that is completely dead. Because of these problems, a visual test is not considered an acceptable method of characterizing fine pore media for uniformity.

The use of quantitative techniques is a much better approach for measuring uniformity. These procedures actually measure the rate of air release from different areas of the diffuser (38). With the diffuser submerged in 5-20 cm (2-8 in) of water and at an airflow rate of approximately 10 L/s/m² (2 scfm/sq ft) (or at the recommended design rate), the rate of air release is determined by measuring the displacement of water from an inverted cylinder. Based on air volume, time, and area of the collection cylinder, an air flux rate is calculated.

Air flux may be expressed in several ways. Apparent flux is the airflow rate per diffuser divided by the effective diffuser area. For planer diffusers, the exposed surface area is considered the effective area. For dome and tube diffusers, the projected area has normally been used to calculate apparent flux. Local flux is the local airflow rate per unit area of a small defined segment of a given diffuser. Effective flux is the weighted average (based on area) of the local flux measurements for one or more diffusers. Additional information on diffuser flux calculations is presented in Appendix B.

For diffusers that provide uniform air release (i.e., all local flux values are equal), the effective flux and apparent flux are equal and the ratio of effective flux to apparent flux, the effective flux ratio (EFR), is unity. If air is released unevenly, the EFR would be greater than one. High values of EFR may produce poor OTE values and promote fouling (see Chapter 3). In measuring air flux, the same or varying size collection cylinders can be used. With varying size cylinders (sometimes referred to as the three bucket

catch), air flux is determined for progressively larger rings on the surface. This method involves a certain degree of averaging and as a result may not be very sensitive. For example, results obtained using this technique could indicate that air flux is uniform even though one quadrant of the surface could be discharging no air at all.

A more effective procedure is to use a relatively small diameter cylinder and test several points on the media surface. These individual points can be plotted to produce a flow profile or simply compared. It is also useful to calculate s/x , where s is the sample standard deviation and x is the average of the individual readings. In this case, the smaller the s/x value, the more uniform the diffuser.

Besides measuring flux, BRV values can also be used as a measure of uniformity. Based on individual point values, s/x can be calculated. The smaller the value, the more uniform the specific diffuser.

The previous paragraphs have presented several procedures for establishing uniformity. Unfortunately, no well-defined guidelines have been developed concerning the variations between points that can be tolerated before the diffuser should be rejected as nonuniform. The calculated values should be used only for comparison purposes.

2.6 Clean Water Performance

2.6.1 Introduction

The following discussion summarizes clean water performance data for fine pore diffusion devices. Only some of the data were generated using the current ASCE recommended clean water Standard (42). Thus, the oxygen transfer results summarized in this section reflect use of the current Standard as well as earlier methods for clean water testing. The data bases for all performance tests were carefully reviewed before incorporating the results in this manual. Performance data were used only if data collection and analysis closely paralleled the current Standard.

The clean water performance data presented in most of the tables and graphs in this section were generated from 1975 to 1988. Besides the changes in data generation and analysis procedures occurring during this period, it should also be recognized that some diffuser design and production changes also may have occurred. Data have been screened to best depict the trends and ranges of performance of representative types of fine pore diffusers. It must be emphasized that the information presented in this section provides general trends in clean water performance; these data should not be used in final design calculations.

The results of clean water oxygen transfer tests are reported in a standardized form as standard oxygen transfer rate (SOTR), standard oxygen transfer efficiency (SOTE), or standard aeration efficiency (SAE) as shown in Table 2-1. The standard conditions for reporting clean water tests are also delineated in this table. All data reported in this section are given as standard transfer values unless otherwise noted.

The performance of diffusers under clean water test conditions is dependent on several factors. Among the important factors are:

- diffuser type (material, shape, and size),
- diffuser placement and density,
- gas flow rate per diffuser,
- basin geometry,
- diffuser submergence, and
- uniformity of air flux.

The information that follows is presented to illustrate the effects of these factors.

2.6.2 Clean Water Data Base

2.6.2.1 Steady-State DO Saturation Concentration (C^*_∞)

An examination of Table 2-1 indicates that one of the critical parameters required in the calculation of oxygen transfer rate is the steady-state DO saturation concentration, C^*_∞ . For submerged aeration applications, C^*_∞ is significantly greater than the surface saturation value, C^*_s , tabulated in most standard tables. It is necessary, therefore, to either measure C^*_∞ (42) during clean water tests or to calculate it based on comparable full-scale test data. The value of C^*_∞ is primarily dependent on diffuser submergence and diffuser type. Typical results of clean water test measurements are presented in Figures 2-13 and 2-14. Suppliers of aeration equipment should be able to provide appropriate clean water test data.

Alternatively, C^*_∞ can be estimated for design purposes from the surface saturation concentration and effective saturation depth, d_e , by:

$$C^*_\infty = C^*_s [(P_b - P_{VT} + 0.007\gamma_w d_e)/(P_s - P_{VT})] \quad (2-1)$$

where,

C^*_∞ = steady-state DO saturation concentration attained at infinite time at water temperature T and field atmospheric pressure P_b , mg/L

C^*_s = tabular value of DO surface saturation concentration at water temperature T and standard atmospheric pressure P_s , mg/L

d_e = effective saturation depth, ft

P_s = atmospheric pressure at standard conditions, 14.7 psia or 1 atm at 100 percent relative humidity

P_b = field atmospheric pressure, psia

P_{VT} = saturated vapor pressure of water at temperature T , psia

γ_w = specific weight of water at temperature T , lb/cu ft

T = water temperature, °C

The effective saturation depth, d_e , represents the depth of water under which the total pressure (hydrostatic plus atmospheric) would produce a saturation concentration equal to C^*_∞ for water in contact with air at 100 percent relative humidity. The value of d_e is usually calculated, using Equation 2-1, based on a spatially-averaged value of C^*_∞ from a clean water test. For design purposes, d_e can be estimated from clean water test results on similar systems. For diffusers submerged to about 90 percent or more of basin depth, d_e is normally 21-44 percent of basin liquid depth for fine pore systems (49).

2.6.2.2 Oxygen Transfer Data

Typical SOTEs for fine pore diffused air systems are presented in Table 2-2 for a diffuser submergence of 4.6 m (15 ft). The effects of diffuser type, placement, and airflow rate per diffuser are delineated from this summary of different clean water studies. With the increasing number of materials and shapes being marketed as fine pore diffusers, it is becoming increasingly difficult to make generalizations about diffuser performance. For example, Table 2-2 presents data for perforated membrane discs that are available in a wide range of diameters. This accounts for the corresponding wide ranges in airflow rate and SOTE for these devices. It would appear, based on Table 2-2, that there is little difference between the oxygen transfer performance of disc/dome and tube fine pore devices. However, it is evident that the clean water oxygen transfer performance of all fine pore diffusers shown in Table 2-2 is superior to that of coarse bubble diffusers.

For a given diffuser type, spreading the diffusers more uniformly along the basin bottom area (moving from a single spiral roll to a dual spiral roll to a grid configuration) tends to improve clean water performance (69). The effects of basin and diffuser geometry on diffuser performance have been reported by many investigators. One of the early, notable studies (70), conducted in a 1.2 m x 7.3 m (4 ft x 24 ft) test basin using coarse bubble spargers and fine

Table 2-1. Standard Equations for Clean Water Oxygen Transfer Tests (42)

Standard Oxygen Transfer Rate (SOTR), lb/hr:

$$\text{SOTR} = 8.34 K_L a_{20} C^*_{w20} V$$

Standard Oxygen Transfer Efficiency (SOTE), percent:

$$\text{SOTE} = 100 (\text{Mass Transferred/Mass Supplied}) = \text{SOTR}/W_{O_2}$$

Standard Aeration Efficiency (SAE), lb/hp-hr:

$$\text{SAE} = \text{SOTR}/\text{Power Input (specified as delivered, brake, wire, or total wire)}$$

$K_L a$ = apparent volumetric mass transfer coefficient in clean water at temperature T, 1/hr

$K_L a_{20}$ = $K_L a$ @ 20°C, 1/hr

V = clean water volume, mil gal

W_{O_2} = mass rate of oxygen, lb/hr

C^*_{w20} = steady-state DO saturation concentration attained at infinite time at 20°C and 1 atm, mg/L

T = clean water temperature, °C

Standard Conditions:

DO = 0.0 mg/L $\alpha = 1.0$

Water temperature = 20°C $\beta = 1.0$

Pressure = 1.00 atm $F = 1.0$

α = (process water $K_L a$ of a new diffuser)/(clean water $K_L a$ of a new diffuser)

β = (process water C^*_{w})/(clean water C^*_{w})

F = (process water $K_L a$ of a diffuser after a given time in service)/($K_L a$ of a new diffuser in the same process water)

Figure 2-13. Effect of diffuser submergence on C^*_{w20} for three diffuser types.

Tank: 20 ft x 20 ft

Power: ~1 hp delivered/1,000 cu ft for rigid porous plastic tubes

Power: ~5 hp delivered/1,000 cu ft for ceramic domes

C^*_{w20} , mg/L

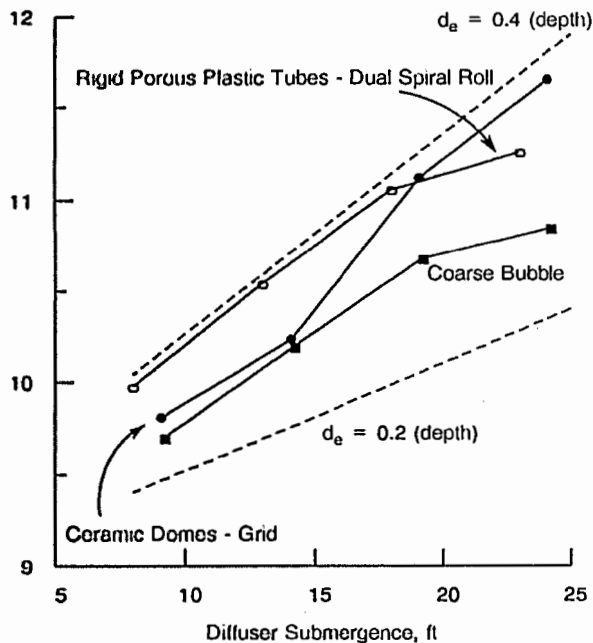


Figure 2-14. C^*_{w20} vs. diffuser submergence for perforated membrane disc and tube diffusers.

C^*_{w20} , mg/L

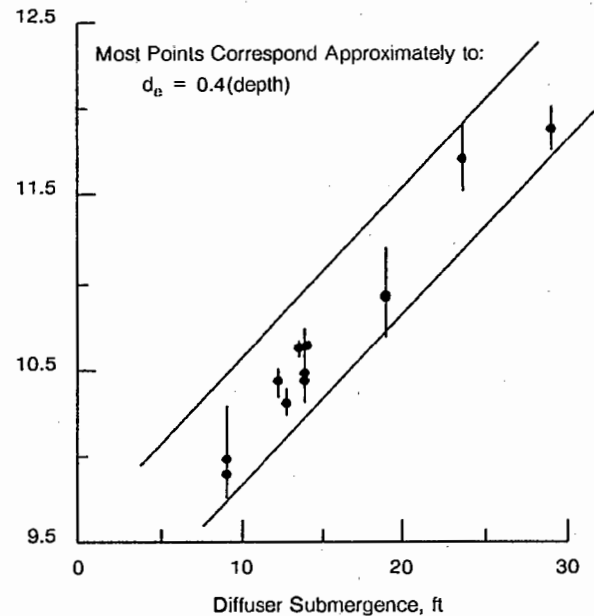


Table 2-2. Clean Water Oxygen Transfer Efficiency Comparison for Selected Diffusers

Diffuser Type and Placement	Airflow Rate, scfm/diffuser ^a	SOTE at 15-ft Submergence, percent	Ref.
Ceramic Plates - Grid	2.0-5.0 scfm/sq ft	26-33	50
Ceramic Discs - Grid	0.4-3.4	25-40	51-53
Ceramic Domes - Grid	0.5-2.5	27-39	53-58
Porous Plastic Discs - Grid	0.6-3.5	24-35	59-61
Perforated Membrane Discs - Grid	0.5-20.5	16-38	61-64
Rigid Porous Plastic Tubes			
Grid	2.4-4.0	28-32	65
Dual spiral roll	3-11	17-28	53,58,66
Single spiral roll	2-12	13-25	59,66
Nonrigid Porous Plastic Tubes			
Grid	1-7	26-36	67
Single spiral roll	2-7	19-37	67
Perforated Membrane Tubes			
Grid	1-4	22-29	25
Mid-width	2-6	16-19	25
Mid-width	2-12	21-31	68
Single spiral roll	2-6	15-19	25
Coarse Bubble Diffusers			
Dual spiral roll	3.3-9.9	12-13	58
Mid-width	4.2-45	10-13	58
Single spiral roll	10-35	9-12	58

^a Except for plates.

pore Saran tubes, demonstrated similar effects of placement.

The OTE produced by fine pore diffusers in clean water generally decreases as the airflow rate per diffuser increases. Over the normal range of operation for a given diffuser submergence, type, density, and geometry, the relationship between SOTE and diffuser airflow rate, q_s , can be described by the following empirical relationship:

$$(SOTE_a/SOTE_b) = [(q_a)/(q_b)]^m \quad (2-2)$$

where,

$SOTE_a$ = SOTE at a diffuser airflow rate of q_a

$SOTE_b$ = SOTE at a diffuser airflow rate of q_b

m = a constant for a given diffuser and system configuration (usually a fractional negative number for fine pore diffusers)

It is convenient to select q_b at a rate of 0.47 L/s (1 scfm) so that:

$$SOTE_a = SOTE_1 (q_a)^m \quad (2-3)$$

where,

$SOTE_1$ = SOTE at diffuser airflow rate of 0.47 L/s (1 scfm)

Data from a number of clean water studies have been used to estimate the value of m in Equation 2-3. Table 2-3 presents the results of these clean water tests.

Table 2-4 and Figure 2-15 demonstrate the effect of unit airflow rate on SOTE for tube diffusers. SOTEs decrease with increased airflow per diffuser, whereas coarse bubble SOTEs are relatively unaffected by unit airflow rate with some indication of a slight increase in SOTE at higher airflows. Very similar patterns were reported in 1964 for coarse bubble spargers and fine pore tubes (70).

Figure 2-15 demonstrates that there are some overlapping regions of similar SOTE performance for the various tube diffusers represented, especially in the typical design region of 1.4-2.6 L/s (3-6 scfm)/diffuser. These data are for a number of diffuser placements and diffuser densities.

In this manual, diffuser density is defined as the number of installed diffusers per 100 sq ft of tank floor area. Another expression used as an indicator of diffuser density is the total projected media surface area of the installed diffusers (AD) divided by the area of the tank floor (AT).

Table 2-5 and Figures 2-16 and 2-17 illustrate the effect of airflow rate on SOTE for disc/dome grid systems. SOTE decreases with increasing airflow rate per disc/dome diffuser. At rates >0.9 L/s (2 scfm)/diffuser, SOTE is less sensitive to airflow rate changes.

Table 2-3. SOTE vs. Airflow for Selected Fine Pore Diffusers in Clean Water

Diffuser Type	Layout	Diffuser Submergence, ft	Diffuser Density, No./100 sq ft	SOTE ₁ , percent	m	Ref.
Ceramic Dome	Grid	14	32	29.6	-0.150	58
Ceramic Disc	Grid	12.3	26	31.7	-0.133	11
Ceramic Disc	Grid	12.3	15	26.0	-0.126	11
Rigid Porous Plastic Disc	Grid	13	34	27.9	-0.097	71
Rigid Porous Plastic Tube	Double Spiral Roll	13	10.5	26.7	-0.240	58
Nonrigid Porous Plastic Tube	Spiral Roll	15	8.6	27.1	-0.276	11
Perforated Membrane Disc	Grid	14	8.8	29.2	-0.195	62
9-in Perforated Membrane Disc	Grid	10	20 ^a	18.9	-0.110	72
EPDM Perforated Membrane Tube	Grid	10	20 ^b	21.0	-0.150	72

Data fit to: SOTE = SOTE₁ (q)^m (see Equation 2-3).

^a One 9-in diameter disc in a 30-in diameter column.

^b One 24-in long tube in a 30-in diameter column.

Table 2-4. Clean Water Oxygen Transfer Efficiencies of Fine Pore Tube Diffuser Systems

Diffuser Type and Placement	Airflow, scfm/diffuser	SOTE at Following Water Depth, percent			Ref.
		10 ft	15 ft	20 ft	
Rigid Porous Plastic Tubes					
Grid ^a	2.4-4.0	-	28-32	-	65
Dual spiral roll	3-7	10-16	16-24	22-32	53,58,66
	9-11	10-14	15-17	21-26	53,58,66
Single spiral roll	2-7	12-15	15-20	22-25	53,58,59,66
	8-12	10-15	10-17	22	53,58,59,66
Perforated Membrane Tubes					
Floor cover (grid)	1-4	14-18	21-27	29-35	25
Quarter points	2-6	13-15	18-22	24-29	25
Mid-width	2-6	9-11	15-18	23-27	25
Mid-width	2-12	15-21	21-31	27-36	68
Single spiral roll	2-6	7-11	14-18	21-28	25
Nonrigid Porous Plastic Tubes					
Grid ^a	1-7	-	20-34	-	67
Spiral roll	1-7	-	18-35	-	67

^a Diffuser density = 13.0 tubes/100 sq ft basin floor. Basin is 14.4 ft x 108.2 ft.

The effect of diffuser density on SOTE for disc/dome grid configurations is shown in Table 2-5 and Figure 2-18. Generally, an increase in disc/dome diffuser density (or AD/AT) results in an increase in SOTE (52-54,56). However, there is some indication that a maximum value of AD/AT exists above which little improvement in SOTE occurs. The upper limit is dependent on diffuser size, airflow, and spacing. For example, a 23-cm (9-in) ceramic disc diffuser at a submergence of 4.3 m (14.2 ft) exhibited SOTE values that did not increase at AD/AT values above 0.14 for airflows of 0.5 L/s (1 scfm)/diffuser (51).

As can be seen from Figures 2-16 and 2-17, the oxygen transfer performance of ceramic dome/disc diffusers and rigid porous plastic disc diffusers is similar throughout the range of airflows presented. However, the ceramic diffusers demonstrate a higher upper limit of oxygen transfer performance throughout the airflow range and are generally more efficient at airflows less than about 0.7 L/s (1.5 scfm)/diffuser.

An OTE increase of 5-15 percent, varying with depth, for a 24-cm (9.4-in) diameter ceramic disc compared with an 18-cm (7-in) diameter ceramic disc has been reported (53). This increase was attributed to a 70-percent higher effective surface area for the 24-cm (9.4-in) disc. A similar relationship between dome/disc diameter and oxygen transfer per diffuser has also been reported (29,73).

Table 2-6 and Figure 2-19 demonstrate the performance of perforated membrane discs. At airflows of 0.24-3.8 L/s (0.5-8 scfm)/diffuser, SOTE significantly decreases with increasing airflow in a manner similar to other fine pore diffusers. At higher airflow rates, SOTE is less sensitive to airflow. Perforated membrane discs are usually larger than ceramic and porous plastic dome/disc units. As a result, they are often operated at higher airflows per diffuser than ceramic/porous plastic diffusers. In addition, density of perforated membrane discs is normally lower than for ceramic/plastic units.

Figure 2-15. Effect of unit airflow rate on SOTE for fine pore tube diffusers.

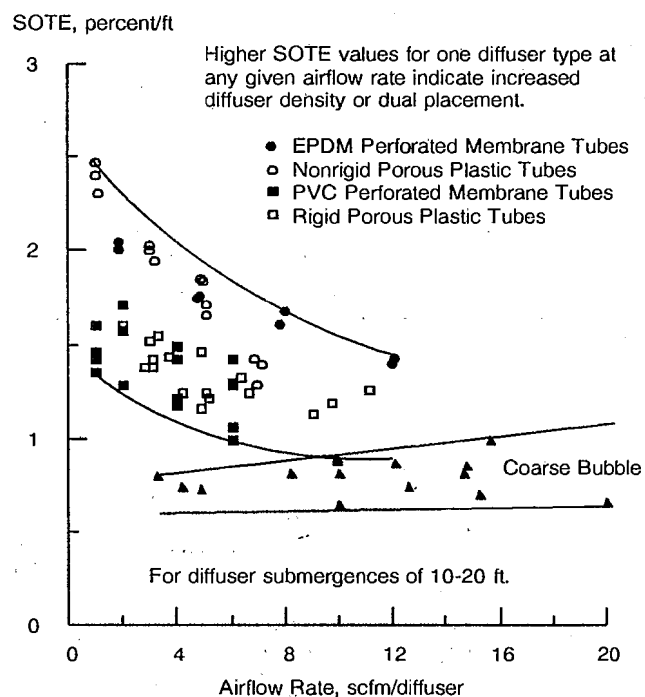


Figure 2-16. Effect of unit airflow rate on SOTE for ceramic dome/disc diffusers.

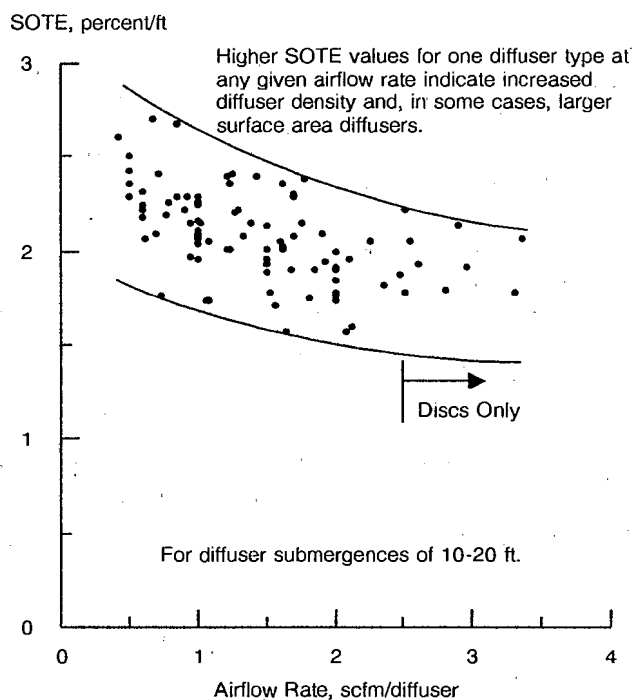


Table 2-5. Clean Water Oxygen Transfer Efficiencies of Fine Pore Disc/Dome Grid Systems

Diffuser Type	Diffuser Density, No./100 sq ft	Airflow, scfm/diffuser	SOTE at Following Water Depth, percent			Ref.
			10 ft	15 ft	20 ft	
Ceramic Disc - 9.4 in	15.6	0.9-3.0	20-22	27-33	34-37	69
	24.4	0.8-2.9	21-24	30-34	35-41	69
	31.3	0.7-2.6	22-25	31-34	38-41	70
Ceramic Disc - 8.7 in	14.7-15.4	1.5-3.2	-	25-29	32-38	51,52
	16.9-18.9	0.6-2.5	-	26-30	33-40	51,52
	21.3-25.0	0.6-3.4	-	27-34	31-40	51,52
	29.4-31.3	0.4-2.8	-	25-36	34-39	51,52
	40.0-52.6	0.7-3.1	-	27-38	31-38	51,52
Ceramic Dome - 7 in	17.9	0.5-2.0	-	25-31	28-40	54,57
	22.7-23.8	0.5-2.5	16-23	25-32	30-41	54-56
	30.3-31.3	0.5-2.5	20-24	27-37	31-44	55,56,58,69
	40.0-45.4	0.5-2.5	17-23	27-35	33-47	55-57
	66.7	0.5-2.5	18-26	27-34	-	55,56
Porous Plastic Disc - 7 in	14.5-14.7	0.6-3.5	15-18	22-27	-	59-61
	21.7	0.6-3.5	16-21	24-28	-	59-61
	25.6	0.5-2.3	-	25-31	-	59-61
	34.5	0.4-1.5	19-22	26-32	-	59-61

Figure 2-17. Effect of unit airflow rate on SOTE for rigid porous plastic disc diffusers.

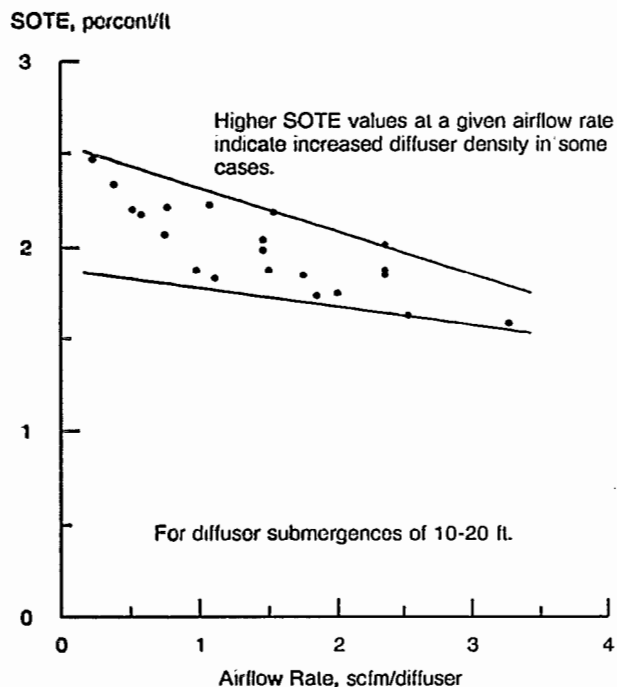
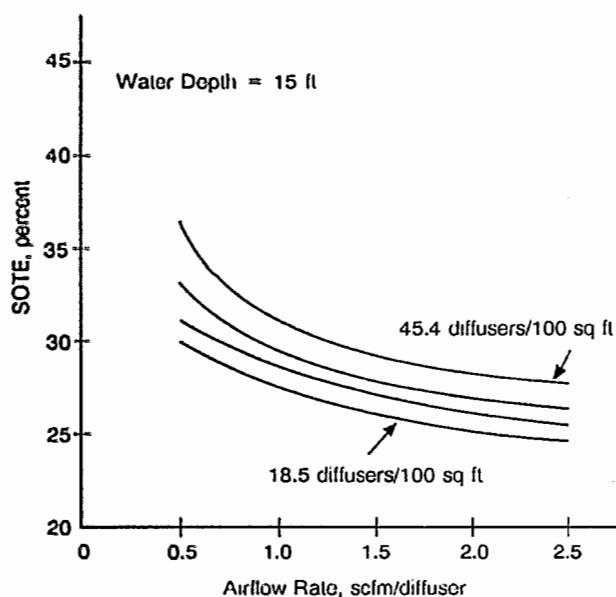


Figure 2-18. Effect of diffuser density on SOTE for ceramic disc/dome grid configurations (56).



The effect of density and placement of perforated membrane discs on SOTE appears to be variable as indicated in Table 2-6. Results of field testing on 51-cm (20-in) discs indicate OTE increases with increasing diffuser density or increasing AD/AT, at least to an AD/AT of 0.26 (62). The data suggest, however, that, at the same airflow rate per diffuser, OTE approaches a limiting value as diffuser density increases. A 40-percent increase in the number of diffusers (producing a increase in AD/AT from 0.18 to 0.26) resulted in an increase in OTE of only about 5 percent. Prior pilot-scale testing on 51-cm (20-in) perforated membrane discs up to an AD/AT of 0.59 also indicated OTE approaches a maximum value with increasing density or increasing AD/AT at the same airflow rate per diffuser (74).

As discussed above for ceramic disc/dome diffusers, SOTE of perforated membrane disc diffusers is also affected by airflow per diffuser, diffuser spacing, and diffuser density. Thus, it is evident diffusers of different size will exhibit different maximum densities or AD/AT values above which little improvement in SOTE will be achieved.

As described in Section 2.5.12, the specific permeability (or BRV_0) of a ceramic diffuser will have some effect on OTE; as pore size increases (permeability usually increases), bubble size increases and SOTE may decrease. Figure 2-20 depicts the results of a clean water test series using ceramic discs with specific permeabilities of 14-50 ($BRV_0 = 22.4-7.1$ cm [8.8-2.8 in] w.g.) (48). The results of this study indicate that, for specific permeabilities of 14-38 ($BRV_0 = 22.4-10.4$ cm [8.8-4.1 in] w.g.), SOTE is relatively unaffected. However, at a specific permeability of 50 ($BRV_0 = 7.1$ cm [2.8 in] w.g.), there appears to be a significant decline in SOTE, especially at the lower airflow rates.

The effects of water depth on SOTE and SAE for several types of diffusers are illustrated in Figures 2-21 and 2-22, respectively. Although these data are for one specific test basin and airflow rate (58), they represent the typical effects of depth on performance. In general, SOTE values increase with increasing depth since mean oxygen partial pressure is higher (thereby resulting in a greater driving force) and opportunity is present for longer bubble residence time in the aeration basin. SAE, however, remains relatively constant (or may increase slightly [29,64]) for fine pore diffusers as depth increases since power requirements to drive the required air through diffusers may increase at the greater depths. In contrast, coarse bubble diffusers exhibit a gradually increasing SAE with increasing depth, though not reaching the overall efficiencies demonstrated by fine pore systems.

Figure 2-19. Effect of unit airflow rate on SOTE for perforated membrane disc diffusers.

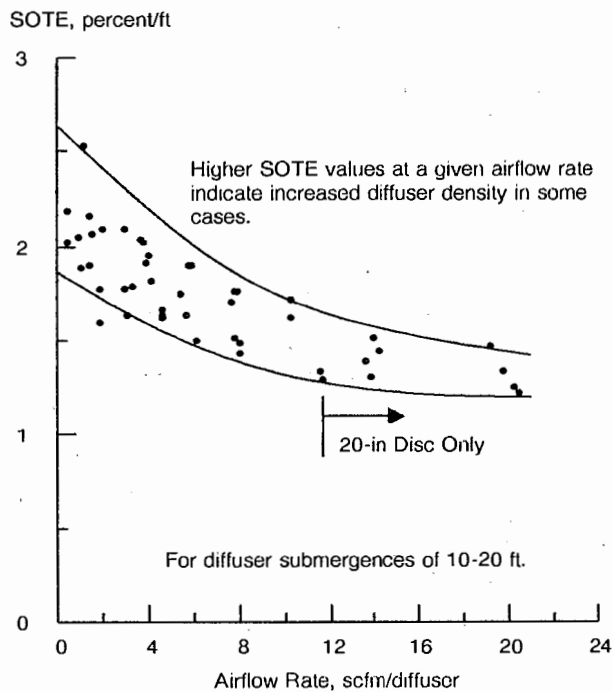


Figure 2-20. Clean water test data - Monroe, WI.

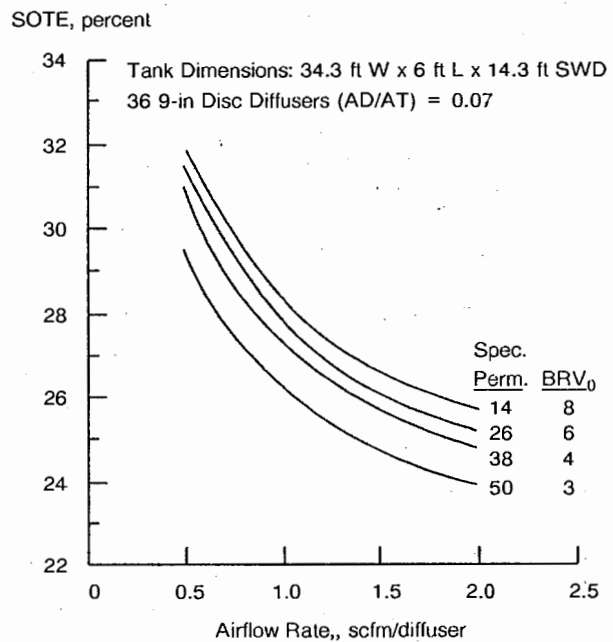


Table 2-6. Clean Water Oxygen Transfer Efficiencies of Perforated Membrane Diffuser Systems

Diffuser Type	Diffuser Density, No./100 sq ft	Airflow, scfm/diffuser	SOTE at Following Water Depth, percent			Ref.
			10 ft	15 ft	20 ft	
20-in Disc	3.0	3.3-20.5	11-16	19-25	24-29	62
	8.8	2.9-19.4	12-19	21-29	27-38	62
12-13-in Discs	6.3	1.9-12.0	11-15	19-26	28-37	64
	8.7-9.3	2.0-12.9	16-23	20-31	34-48	61,63
	11.1	1.5-10.3	9-21	24-36	27-43	64
	17.2	2.0-5.9	18-24	25-30	31-36	63
9-in Disc	4.0	0.5-7.1	-	15-36	-	61
	8.0	0.5-6.2	-	21-31	-	61
	14.1-18.5	0.5-6.8	-	23-29	-	61
7-8.5-in Discs	18.5-22.2	0.9-4.7	-	23-26	-	61

Figure 2-21. Effect of water depth on SOTE for three diffuser types.

Tank: 20 ft x 20 ft
 Power: ~1 hp delivered/1,000 cu ft for rigid porous plastic tubes
 Power: ~5 hp delivered/1,000 cu ft for ceramic domes

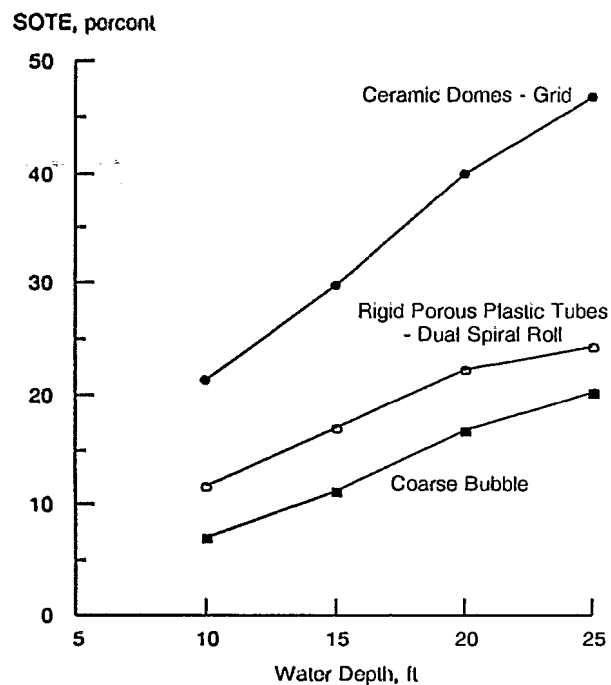
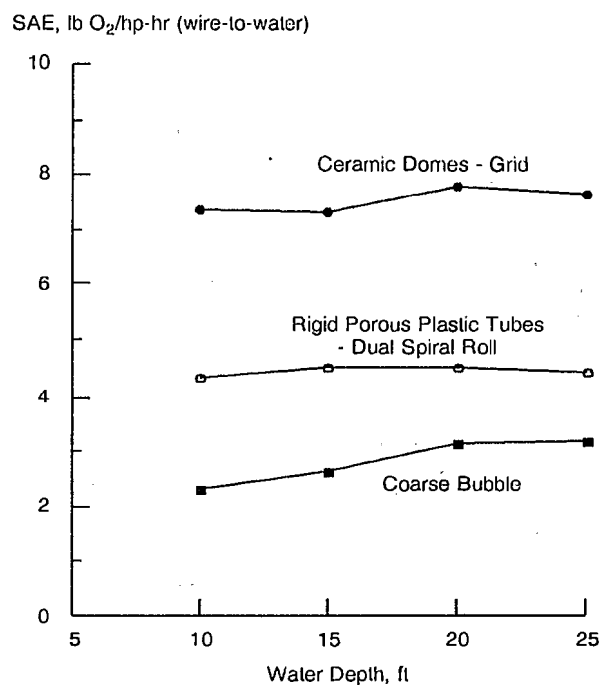


Figure 2-22. Effect of water depth on SAE for three diffuser types.

Tank: 20 ft x 20 ft
 Power: ~1 hp delivered/1,000 cu ft for rigid porous plastic tubes
 Power: ~5 hp delivered/1,000 cu ft for ceramic domes



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National Technical Information Service
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(703) 487-4650

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Chapter 3

Process Water Performance

3.1 Introduction

As described in Chapter 2, a substantial data base exists on the performance of fine pore diffusers in clean water. In designing aeration systems to operate under process conditions, clean water data are corrected to account for the influences of wastewater characteristics, temperature, and pressure. Throughout this manual, the term "process water" is used to refer to mixed liquor under aeration. The corrections are made using the following equations:

$$OTR_f = 8.34 K_{La20} \alpha F \theta^{(T-20)} (\beta \Omega C_{\infty 20}^* - C) V \quad (3-1)$$

where,

OTR_f = oxygen transfer rate under process conditions, lb/hr

K_{La20} = apparent volumetric mass transfer coefficient in clean water at 20°C, 1/hr

V = process water volume, mil gal

$C_{\infty 20}^*$ = steady-state dissolved oxygen (DO) saturation concentration attained at infinite time at 20°C and 1 atm, mg/L

C = process water DO concentration, mg/L

α = (process water K_{La} of a new diffuser) ÷ (clean water K_{La} of a new diffuser)

β = (process water C_{∞}^*) ÷ (clean water C_{∞}^*)

C_{∞}^* = steady-state dissolved oxygen (DO) saturation concentration attained at infinite time at water temperature T and field atmospheric pressure P_b , mg/L

P_b = field atmospheric pressure, psia

$\theta^{(T-20)} = K_{La} \div K_{La20}$

K_{La} = apparent volumetric mass transfer coefficient in clean water at temperature T , 1/hr

T = process water temperature, °C

$\Omega = (P_b + 0.007 \gamma_w d_e - P_{vT}) \div (P_s + 0.007 \gamma_w d_e - P_{vT})$

$\Omega \sim P_b/P_s$ (for basin depths <6.1 m [20 ft] and for elevations <600 m [2,000 ft])

γ_w = specific weight of water at temperature T , lb/cu ft

P_s = atmospheric pressure at standard conditions, 14.7 psia or 1.0 atm at 100 percent relative humidity

P_{vT} = saturated vapor pressure of water at temperature T , psia

d_e = effective saturation depth at infinite time (see Section 2.6.2.1), ft

$\tau = C_{\infty}^* \div C_{\infty 20}^* = C_s^* \div C_{s20}^*$

C_s^* = tabular value of DO surface saturation concentration at water temperature T , standard atmospheric pressure P_s , and 100 percent relative humidity, mg/L

F = (process water K_{La} of a diffuser after a given time in service) ÷ (K_{La} of a new diffuser in the same process water)

Since standard oxygen transfer rate, SOTR, is:

$$SOTR = 8.34 K_{La20} C_{\infty 20}^* V \quad (3-2)$$

Equations 3-1 and 3-2 may be combined to calculate the process water oxygen transfer rate, OTR_f :

$$OTR_f = \alpha F (SOTR) \theta^{T-20} (\beta \Omega C_{\infty 20}^* - C) \div C_{\infty 20}^* \quad (3-3)$$

This equation can be rearranged as follows:

$$\alpha F (SOTR) = (OTR_f C_{\infty 20}^* \theta^{20-T}) \div (\beta \Omega C_{\infty 20}^* - C) \quad (3-4)$$

The term $\alpha F (SOTR)$, or $\alpha F (SOTE)$, is often used to express oxygen transfer under field conditions corrected to standard temperature and pressure and a driving force of $C_{\infty 20}^*$ (i.e., $C = 0$).

Further, since standard oxygen transfer efficiency, SOTE (in percent), is:

$$SOTE = 100 (SOTR/W_{O_2}) \quad (3-5)$$

where,

W_{O_2} = mass rate of oxygen supplied, lb/hr

Equation 3-3 may also be used to describe oxygen transfer efficiency under field conditions, OTE_f , by direct substitution.

Although employing clean water SOTR values to estimate oxygen transfer rates in process water is conceptually straightforward, the estimate of OTR_f is subject to considerable doubt because of the uncertainties contained in α and F . These uncertainties are magnified when the process water application is based on a basin geometry and process temperature that differ from those of the clean water test.

Table 3-1 is a guide for applying Equation 3-3 and indicates the source of information for the parameters needed to estimate OTR_f . Values of $C^*_{\infty 20}$ and SOTR must be calculated from the clean water oxygen transfer test. The average DO value, C , should represent the desired process water DO concentration averaged over the entire aeration volume. The temperature correction factor, τ , and pressure correction factor, Ω , are estimated using the definitions given above.

Table 3-1. Guide to Application of Equation 3-3

Parameter	Source of Information
$C^*_{\infty 20}$	clean water test results
SOTR	clean water test results
d_a	clean water test results
C	process water conditions
T	process water conditions
τ	calculated based on tabulated DO surface saturation values
Ω	calculated based on site barometric pressure and effective depth data
α	estimated based on experience or on measured values of $K_L a$ in clean and process waters using a clean diffuser
β	calculated based on total dissolved solids measurements
θ	taken as 1.024 unless experimentally proven different
F	estimated based on field experience, field measurements, or laboratory analysis of diffusers taken from the field (see Section 3.3.3)

α is the ratio of the process water $K_L a$ of a new diffuser to the clean water $K_L a$ of a new diffuser. It is probably the most controversial and investigated parameter used in translating clean water oxygen transfer data to anticipated field performance. Variables affecting α include aerator type, nature of the wastewater contaminants, position within the treatment scheme, process loading rate, bulk liquid DO, and airflow rate. Reliable data on α for various

aeration devices are limited. Much of the reported data were obtained from bench-scale units that did not properly simulate mixing and $K_L a$ levels, aerator type, water depth, or the geometry effects of their full-scale counterparts. Reliable full-scale test procedures for use under process conditions, coupled with clean water performance data, are required to overcome these deficiencies. Several references provide further information on α and its measurement (1-3).

In the past, the effects of fouling as well as process water effects on $K_L a$ were included in α . The term apparent α , α' , was used to indicate the effects of fouling on OTE (4). In this manual, fouling is defined as an impairment of diffuser performance caused by material attached to the diffuser and deterioration of diffuser materials or appurtenances. Examination of the data collected during conduct of the EPA/ASCE Fine Pore Aeration Project has led to the elimination of the term α' . The term αF , where α continues to describe the process water effects on $K_L a$ as before and a new term, F , describes the impairment of diffuser performance caused by material attached to the diffuser and/or deterioration of diffuser materials or appurtenances, is used in its place. In most cases, it is believed that impairment of diffuser performance is caused by attached material. In some cases, however, deterioration of diffuser materials or appurtenances may have a significant impact on F (see Section 3.3.3.6).

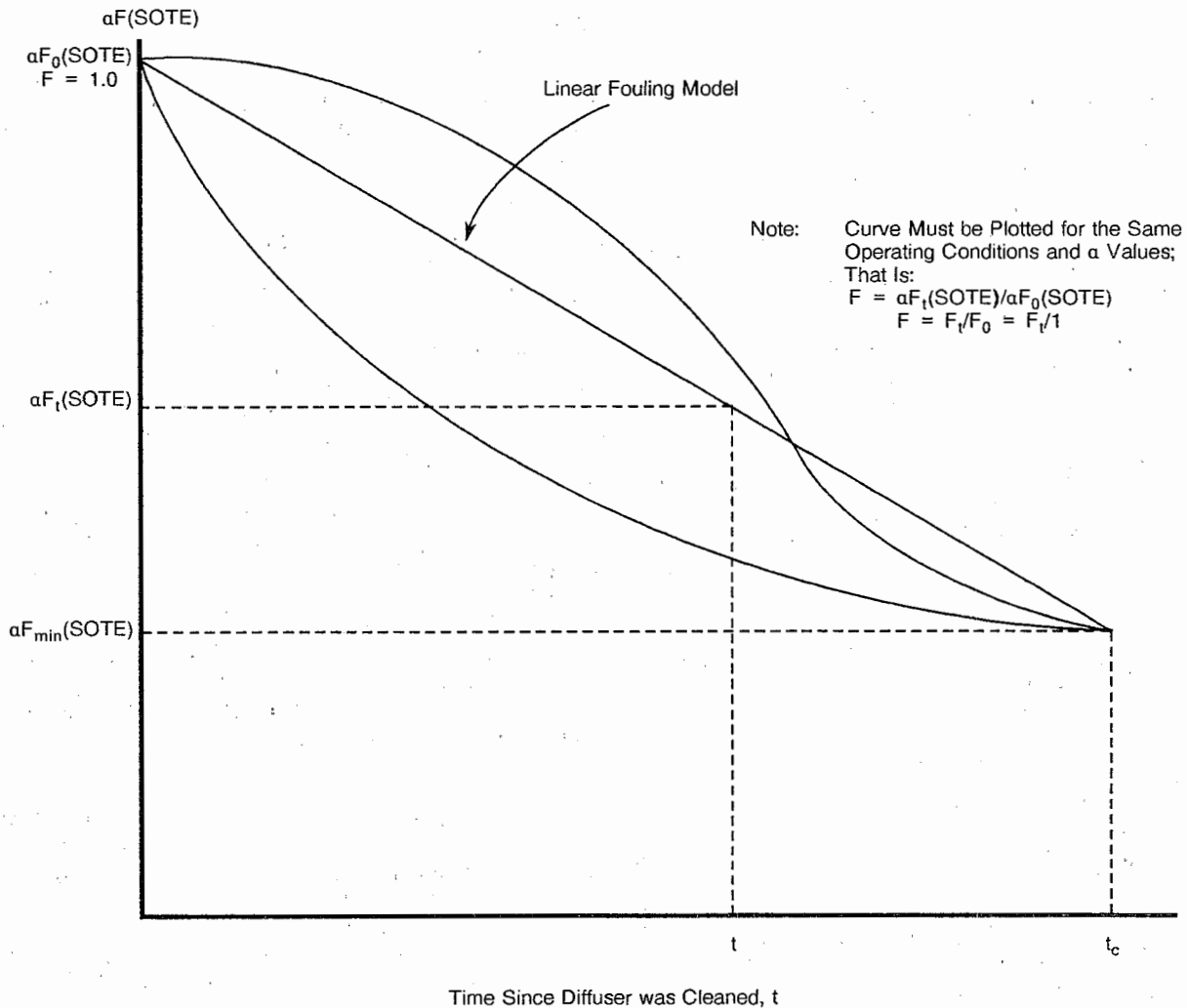
F is the ratio of $K_L a$ [or $\alpha F(\text{SOTR})$ or $\alpha F(\text{SOTE})$] of a fouled diffuser to the $K_L a$ [or $\alpha F(\text{SOTR})$ or $\alpha F(\text{SOTE})$] of a new diffuser, both measured in the same process water. F generally decreases from 1.0 with time of service in the process water. The characteristics of fouling dynamics are site and diffuser specific. Hypothetical fouling patterns are depicted in Figure 3-1.

Data on the decrease in F with service time are limited, and what data are available generally consist of only a few points along the F vs. time profile (see Section 3.3.4). Although these limited data are consistent with the hypothetical profiles shown (Figure 3-1), the data points are too few and imprecise to accurately define a fouling profile. For simplicity, and because the precision of the data does not justify a complex model, the fouling profile is approximated at this time by the linear model shown in Figure 3-1.

The conceptual model is illustrated in Figure 3-2. The plot of F vs. time is developed from a linearized plot of an oxygen transfer function such as $\alpha F(\text{SOTE})$, $\alpha F(\text{SOTR})$, or $K_L a$ vs. time (e.g., Figure 3-1). The slope of the F vs. time curve represents the fouling rate, f_F , expressed in terms of a unit decrease per month. Note that f_F is also equal to the slope of the linearized curve in Figure 3-1 divided by SOTE, i.e.:

$$f_F = (1.0 - F) \div t \\ = [\alpha F_0(\text{SOTE}) - \alpha F_t(\text{SOTE})] \div [t(\alpha F_0)(\text{SOTE})] \quad (3-6)$$

Figure 3-1. Hypothetical fouling patterns.



F relationships are described by the following equations:

$$F = 1.0 - t(f_F) \quad \text{for } t \leq t_c \text{ and } F > F_{\min} \quad (3-7)$$

and,

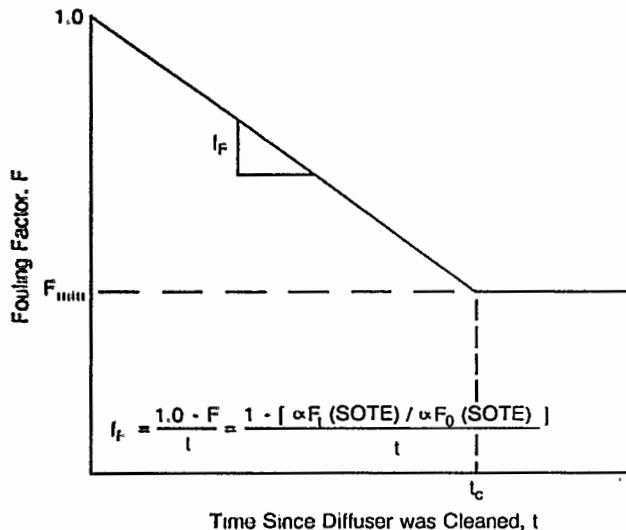
$$F = F_{\min} \quad \text{for } t \geq t_c \quad (3-8)$$

This model assumes that there is a minimum value of F , $F_{\min}$, that occurs after some critical service period, t_c . It may be reasonable to assume $F_{\min}$ for a system unusually susceptible to fouling approaches the ratio of the oxygen transfer performance of a coarse bubble diffuser to that of an unfouled fine pore diffuser in question, with both diffusers in the same physical basin configuration and operating under the same process loadings.

This model is applied to the design and operation of fine pore aeration systems discussed in Sections 4.3.3.3, 5.4.8, and 7.4. F is discussed in more detail in Section 3.3.

β is the ratio of the average saturation concentration, C^* , in process water to the corresponding value in clean water. β can vary from approximately 0.8 to 1.0 and is generally close to 1.0 for municipal wastewaters. β cannot be measured by a membrane probe, and many wastewaters contain substances that interfere with the Winkler method of DO measurement. Therefore, the value of β for use in Equation 3-3 may be calculated as the ratio of the DO surface saturation concentration in process water to the DO surface saturation concentration in clean water. The corresponding surface saturation concentrations can be interpolated from DO saturation

Figure 3-2. Linear fouling factor model.



tables (Table C-1) based on the total dissolved solids contents of the process water and clean water.

θ is employed to correct $K_L a$ for changes in temperature. Values of θ range from 1.008 to 1.047 and are influenced by geometry, turbulence level, and type of aeration device (5). θ is usually taken as equal to 1.024. Little consensus exists regarding the accurate prediction of θ , and, for this reason, clean water testing for the determination of SOTR values should be at temperatures close to 20°C (68°F) (6).

3.2 Factors Affecting Performance

The performance of diffused aeration systems under process conditions is affected by a myriad of factors. Some of the more important are:

- fouling, aging, fatigue, etc.,
- wastewater characteristics,
- loading conditions,
- process type and flow regime,
- basin geometry and diffuser placement,
- diffuser performance characteristics,
- mixed liquor DO control and air supply flexibility,
- mechanical integrity of the system, and
- quality of preventive maintenance.

Manual of Practice FD-13 (7) is a good general reference on the importance of the above factors. To minimize life-cycle costs of an aeration system, all these factors must be considered during design and some must be controlled during operation.

The areas of greatest concern in process water oxygen transfer performance are wastewater characteristics, process type and flow regime, loading conditions, and diffuser fouling and material deterioration. In a given case, any combination of

these factors can have a significant effect on the α profile of a system, DO control, and changes in aerator performance with time due to diffuser fouling. These factors are discussed in greater detail later in this chapter.

3.3 Diffuser Fouling

All fine pore diffusers are susceptible to buildup of biofilms and/or deposition of inorganic precipitates that can alter the operating characteristics of the diffusers. Porous diffuser media are also susceptible to air-side clogging of pores due to particles in the supply air. Therefore, practical and cost-effective preventive maintenance designed to keep diffusers as clean and efficient as possible is very important. The appropriate preventive maintenance procedure and frequency depend on the system provided, service conditions, and trade-offs between operating costs and cleaning costs.

The effects of fouling on dynamic wet pressure (DWP) and OTE should not be confused with changes in the air diffusion media or the integrity of the installation. These types of changes, which include alteration of diffuser media properties over time and leaks in the air piping or around diffuser gaskets, may be caused by poor equipment design, improper installation, or inadequate inspection and maintenance.

3.3.1 Background

Porous ceramic plate diffusers, introduced in the United States in the 1910s, had become the predominant air diffusion device by mid-century (8-10). Various types of foulants were identified by early investigators, and the list has been expanded by recent studies to include the following (11):

Air Side

- Dust and dirt from unfiltered air
- Oil from compressors or viscous air filters
- Rust and scale from air pipe corrosion
- Construction debris from poor cleanup
- Wastewater solids entering through broken diffusers or pipe leaks

Liquid Side

- Fibrous material attached to sharp edges
- Inorganic fines entering media at low or zero air pressure
- Organic solids entering media at low or zero air pressure
- Oils or greases in wastewater
- Precipitated deposits, including iron and carbonates
- Biological growths on diffuser media
- Inorganic and organic solids trapped by biological growths on diffuser media

The rate of fouling has historically been gauged by the rise in backpressure while in service. Since significant levels of fouling can take place with little or no

increase in backpressure but with substantial reductions in OTE, this provided a crude and qualitative measure at best.

It was common practice in earlier times to operate several diffusers from a common plenum. This practice resulted in less uniformity of air distribution than is obtained today with the use of restrictive orifices on individual diffusers. The lack of airflow uniformity probably exacerbated the rate of biological fouling experienced in the past.

In the 1950s and 1960s, the relative cost of fuel vs. labor was low. As a consequence, many of the ceramic plate installations were replaced with less efficient, fixed-orifice coarse bubble diffusers. By the middle 1970s, the fuel cost-to-labor cost ratio increased dramatically and many of those installations were replaced by porous media diffusers with individual airflow control.

Better methods of measuring the degree of fouling and the effectiveness of cleaning became available in the early 1980s. These methods include DWP, bubble release vacuum (BRV), the ratio of one to the other, and chemical and microbiological analysis. The practice of employing pilot diffusers that could be removed from the basin and individually analyzed also came into use during this period (11).

Concurrently, better methods were being developed to measure the oxygen transfer performance of operating aeration systems. These methods permitted better appraisal of the effects of fouling and facilitated improved preventive maintenance scheduling. These methods include inert gas tracers, off-gas analysis, a nonsteady-state technique that uses hydrogen peroxide, and DO and respiration rate profiles (12-16). Off-gas analysis equipment has been effectively used to evaluate the adverse effects of fouling on both full-scale diffused air systems and individual diffusers (13).

3.3.2 Types of Fouling

Fouling can be classified as one of two general types, Type I or Type II. The two types have distinct characteristics and can occur alone or in combination, with variable dominance from treatment plant to treatment plant and within the same treatment plant from time to time.

3.3.2.1 Type I Fouling

Type I fouling is characterized by clogging of the diffuser pores, either on the air side by airborne particulates or on the liquid side by precipitates such as metal hydroxides and carbonates. A schematic representation of Type I fouling is illustrated in Figure 3-3. During the process of fouling, the areas of the diffusers with the highest local air flux foul more rapidly. This serves to reduce the flux in the high-flow areas and increase it in low-flow areas. The combined

effect is to improve uniformity of air distribution. As fouling progresses, the BRV coefficient of variation decreases and the effective flux ratio approaches unity (17).

Eventually, the accumulation of foulant in the pores reduces the pore size and DWP rises correspondingly. The increase in DWP can exceed the capabilities of the air supply system, and process air delivery may fall short of requirements. Also, the reduced effective pore diameters produce smaller bubbles such that OTE does not decline and can actually increase slightly. An idealized plot of how OTE and DWP change with time during Type I fouling is shown in Figure 3-4.

3.3.2.2 Type II Fouling

Type II fouling is characterized by the formation and accretion of a biofilm layer on the surface of the diffuser. In a study of fouled ceramic diffusers collected from seven wastewater treatment plants, scanning electron microscopy (SEM) was used (18) to determine the structure of biofilms with thicknesses of at least 1 mm (0.04 in). Thinner films were not amenable to the investigative methods used. Figure 3-5 is a model of Type II fouling proposed (18) based on SEM data collected on the biofilms that had thicknesses >1 mm (0.04 in). The microscopic work showed that the biofilms were composed of bacterial cells enmeshed in a matrix of their own amorphous exopolysaccharides. Inorganic particles were trapped within the bacterial matrix. This composition has been observed in other biofilms found in natural and industrial aquatic systems (19).

The biofilms were not connected to the diffuser surface at all available points, so large spaces existed at the diffuser-biofilm interface. One large (10-14 mm [0.4-0.55 in]) air bubble was seen within the thick biofilm on a heavily fouled diffuser. The biofilms were traversed by large (>0.5 mm [0.02 in]) structured air passages that originated at the diffuser surface and branched towards the biofilm surface where they terminated in large (0.5-1.0 mm [0.02-0.04 in]) round apertures. Although these observations were made on fouled ceramic diffusers, similar fouling characteristics have also been observed on perforated membrane diffusers (20).

When a biofilm of this structure develops on a fine pore diffuser, the bubble release surface changes dramatically. The partial attachment allows larger spaces to develop between the diffuser surface and the biofilm. It is hypothesized that air is conveyed from the diffuser pores through these spaces to openings at the foulant surface where bubble formation occurs. The bubbles are larger than those previously formed at the diffuser surface because the apertures are visually or measurably larger than the diffuser pores. Photographs of bubbles emitted from clean and heavily fouled diffusers have shown that

Figure 3-3. Schematic structure of Type I fouling.

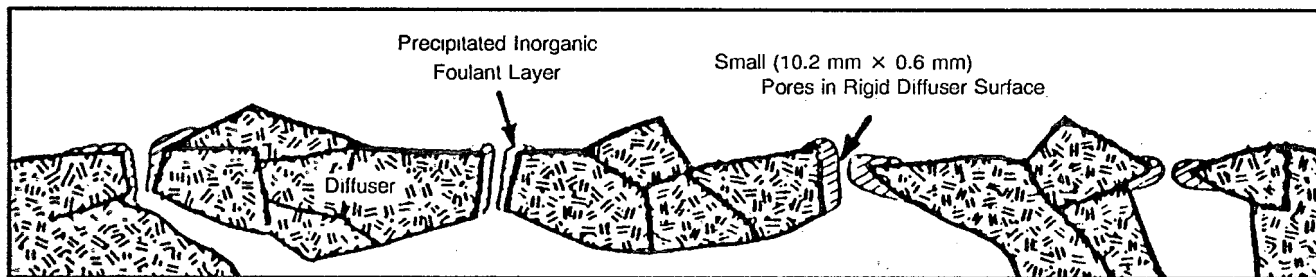
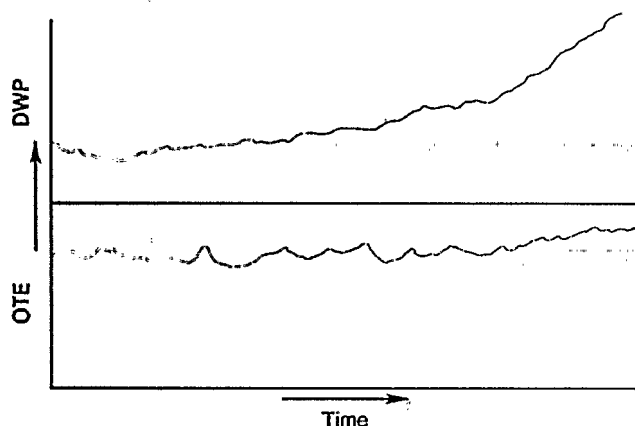


Figure 3-4. Idealized plot showing effects of Type I fouling on DWP and OTE.



bubble size increases as biofilm thickness increases (18). The dynamics of such slimes are also thought to play a role in bubble size and localization of flux.

Thin biofilm layers are usually not a problem, but, as the biofilm thickness increases, BRV and its coefficient of variation will increase, DWP will increase slightly or not at all, and OTE will decrease substantially. Values of BRV increase because the BRV test measures the pressure differential needed to draw air through the biofilm even in areas where there are no established passages. Since air passages in the biofilm layer are usually not uniform across the entire diffuser surface, individual BRV readings exhibit more variability (the coefficient of variation increases).

There may or may not be an increase in DWP. When bubbles are emitted from a clean diffuser, most of the pressure differential is due to the force required to form bubbles against the force of surface tension, and only a small fraction of the total gradient is required to overcome frictional resistance (11). Also, surface tension forces tend to cause equal size bubbles to be produced from orifices of a given pore size in a well-mixed liquid. The effects of surface tension would be essentially eliminated in those areas where the bubbles are released to an air pocket. If the subsequent frictional losses associated with flow

through the biofilm air passages are small, DWP changes would be minimal and, perhaps, even negative.

The net result of non-uniform bubble release and an increase in bubble size is a substantial reduction in OTE. Figure 3-6 is an idealized representation of OTE and DWP changes with time under Type II fouling conditions.

3.3.3 Fouling Characteristics

Categorizing foulants as either Type I or Type II provides a basis for discussion of diffuser fouling. However, in practice, it can be difficult to distinguish between the two types because they occur together, with one or the other dominating from treatment plant to treatment plant, and from time to time in the same treatment plant. For example, the Green Bay wastewater treatment plant, which has both contact and return sludge reaeration basins, demonstrated Type II fouling in its contact basins and both Type I and Type II fouling in two distinct layers in its reaeration basins (20). The same fouling phenomena were observed with both ceramic disc and perforated membrane tube diffusers. Ceramic dome diffusers removed from aeration basins at the South Meadows wastewater treatment plant in Hartford County, CT were fouled in two layers similar to those observed at the Green Bay treatment plant (21).

Fouling can be evaluated in several ways, the simplest of which is by visual observation. Visual observations, however, can be very misleading. Although rarely the case, diffusers that appear to be heavily fouled may not operate very differently than clean diffusers (22). In other cases, diffusers that appear relatively clean may operate poorly. To characterize fouling properly, physical measurements must also be made. The two key operating parameters are DWP, which affects blower discharge pressure, and OTE, which affects the volume of air required to provide a given oxygen transfer rate (see Sections 2.5.10 and 2.5.11).

3.3.3.1 Characterization Tests

Changes in DWP due to fouling can be measured directly by collecting pressure data with the apparatus shown in Figures 2-9 through 2-11. The pressure measurements can be made by installing pressure

Figure 3-5. Schematic structure of Type II fouling.

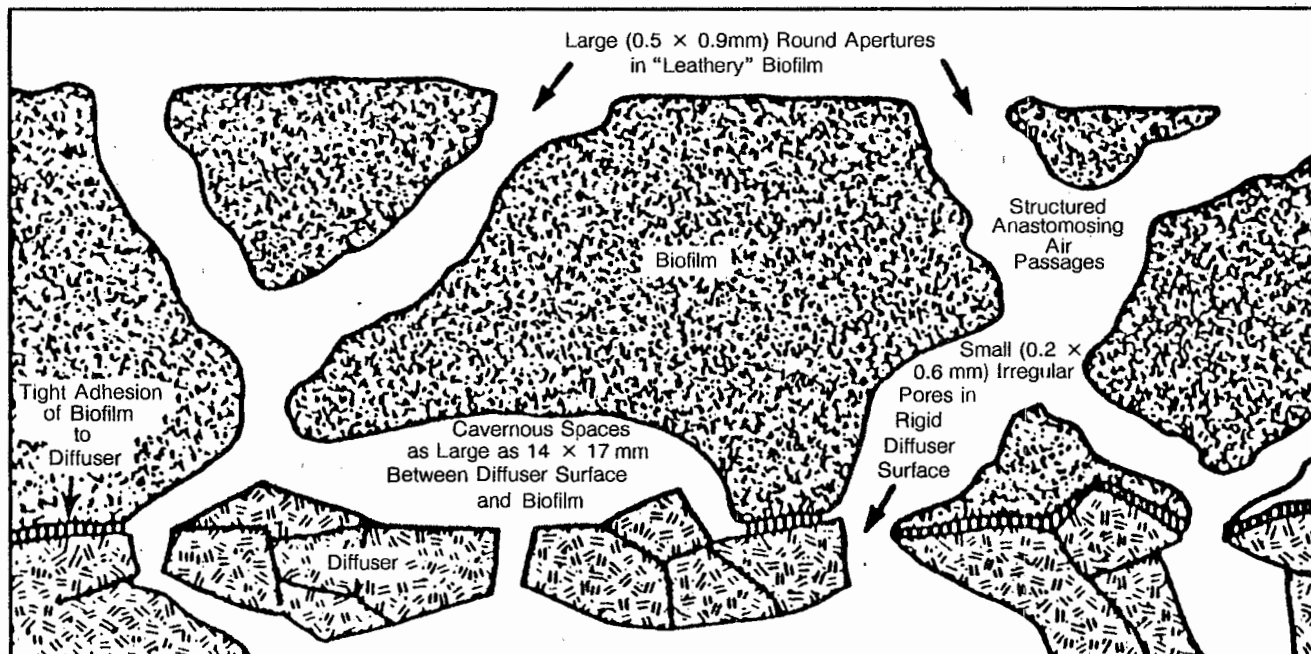
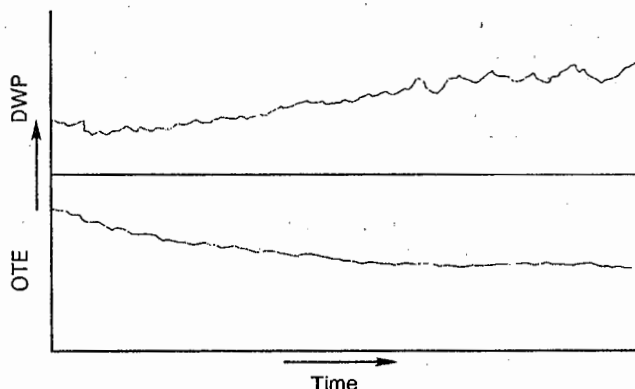


Figure 3-6. Idealized plot showing effects of Type II fouling on DWP and OTE.



taps in the full-scale aeration system or by obtaining diffusers from removable test headers for laboratory testing without having to disrupt the process. The removable header method will generally provide more precise data than can be obtained with field measurements.

Determining the effects that fouling has on OTE is more difficult because the tests used for measuring OTE are more involved. Full-scale testing can be costly, and the results can be obfuscated by other variables such as α . An alternative is to evaluate individual diffusers in controlled laboratory or on-site tests. This has been done with success (20,22-25), but it requires special equipment. Other more easily measured parameters such as DWP, BRV, and foulant accumulation have also been investigated to

determine if they are correlated with loss of OTE (reduced F).

In the interplant fouling study conducted as part of the EPA/ASCE Fine Pore Aeration Project (23), fouling of ceramic disc diffusers was characterized by measuring DWP, BRV, and foulant mass accumulation (dry solids per unit area). The data, which are summarized in Table 3-2, were collected from tests conducted on diffusers mounted on removable test headers equipped with four diffusers. One diffuser holder was isolated and operated separately so that a diffuser could be removed for evaluation and replaced with a new diffuser about every 4 months without disturbing the operation of the other three diffusers. At the 8-, 12-, and 16-month intervals, one of the non-isolated diffusers was removed for evaluation. In this way, incremental and cumulative data were collected. The effect that fouling had on OTE was determined by testing a fouled diffuser side-by-side with a new diffuser. OTE was measured using a clean water steady-state test based on off-gas techniques (see Appendix B). The results were reported as the ratio of fouled-to-new diffuser SOTE, i.e., F, after 1 year in service.

Figure 3-7 is a plot of F vs. foulant accumulation (23). Plants with small accumulations of foulant had higher OTEs, as indicated by higher values of F. Likewise, treatment plants with higher accumulations of foulant had lower OTEs. The scatter at low foulant accumulations was probably related to the difficulty in measuring foulant accumulation. It may also indicate that the nature of the foulant layer, in addition to the quantity of foulant, affected OTE.

Table 3-2. Results of Interplant Fouling Study

Sito No.	City - Plant	Elapsed Time, months	Time in Service, months	DWP @ 1 scfm/diffuser	BRV, in w.g.	F	Foulant Accumulation, mg/cm ²	VS, percent
1	Frankenmuth, MI	5.3	5.3	17.3	20.2	-	95	5
		12.8	12.8	19.0	57.3	0.74	96	11
2	Green Bay, WI	4.6	4.6	10.1	15.0	-	13	10
		8.8	4.2	10.5	16.5	-	10	12
		8.8	8.8	11.0	20.0	-	63	6
		14.0	14.0	15.0	24.8	0.71	30	12
		16.8	4.2	15.8	13.9	-	33	8
3	Milwaukee, WI; Jonas Island	4.1	4.1	13.0	19.0	-	100	10
		8.5	4.4	10.8	34.9	-	26	14
		8.5	8.5	8.7	43.0	-	107	13
		13.6	13.6	10.0	75.7	0.56	152	14
4	Milwaukee, WI; South Shore	4.3	4.3	7.6	10.2	-	6	13
		8.8	4.5	10.1	12.3	-	5	14
		8.8	8.8	10.6	19.6	-	7	33
		13.7	13.7	11.5	18.0	0.99	23	24
5	Madison, WI; Nine Springs	4.7	4.7	5.7	12.4	-	7	50
		7.9	3.2	5.4	7.7	-	5	42
		7.9	7.9	8.6	9.3	-	8	44
		12.0	12.0	6.2	9.3	0.99	7	52
6	Monroe, WI	4.5	4.5	7.2	8.1	-	50	25
		8.0	3.5	5.2	7.8	-	13	55
		8.0	8.0	6.5	8.2	-	81	27
		12.0	12.0	6.9	9.3	0.98	2.6	55
7	Plano, TX; North Texas	4.4	4.4	11.0	27.4	-	42	5
		7.0	7.0	11.9	14.3	-	8	6
		11.0	11.0	12.4	21.4	-	29	4
		18.0	3.0	8.7	9.5	-	0.2	23
		18.0	18.0	37.0	40.7	-	18	12
8	Los Angeles County, CA; Whittier Narrows	9.6	9.6	12.1	25.0	0.90	-	-
9	Houghton, MI; Portage Lake	4.4	4.4	8.9	14.8	-	22	15
		8.4	4.0	6.5	13.5	-	Nil	-
		8.4	8.4	7.5	18.3	-	4	22
		12.7	4.3	6.4	13.0	-	3	12
		12.7	12.7	7.5	19.9	0.83	2	35

Figures 3-8 and 3-9 plot F as a function of BRV and the ratio of DWP (at 0.5 L/s [1 scfm]) to BRV, respectively (23). These parameters yield better correlations, probably because they provide a measure of the physical nature of the foulant structure and how the structure affects OTE. No relationship was found in these studies between DWP and F or DWP and foulant accumulation. The increase in BRV without a corresponding increase in DWP indicates that the dominant fouling in these studies was Type II.

Based on the fouling data presented in Table 3-2, diffuser fouling can be divided into three categories:

	BRV, in w.g.	DWP:BRV	F (after 1 yr)
Severe	>40	<0.3	<0.7
Moderate	15-40	0.3-0.6	0.7-0.9
Light	<15	>0.6	>0.9

Note that diffusers from the same treatment plant could fit into more than one category depending on the time in service and other conditions associated with treatment plant operations.

3.3.3.2 Foulant Properties

Several physical and chemical properties of the foulant samples collected during the interplant fouling comparison study mentioned above were measured (23). The two most notable characteristics were the volatile solids and silica contents. The volatile solids content was often very low (less than 15 percent), even when the foulant appeared to be a biofilm. This is reasonable considering that biofilm is mostly water and thus constitutes a large volumetric fraction of the foulant even though the gravimetric fraction is small. The highest volatile fractions, 50-55 percent, were less than those of a typical mixed liquor. In most cases, the silica content was high, about 10-20 percent of the residual solids after ignition. The

Figure 3-7. F vs. foulant accumulation - Interplant Fouling Study.

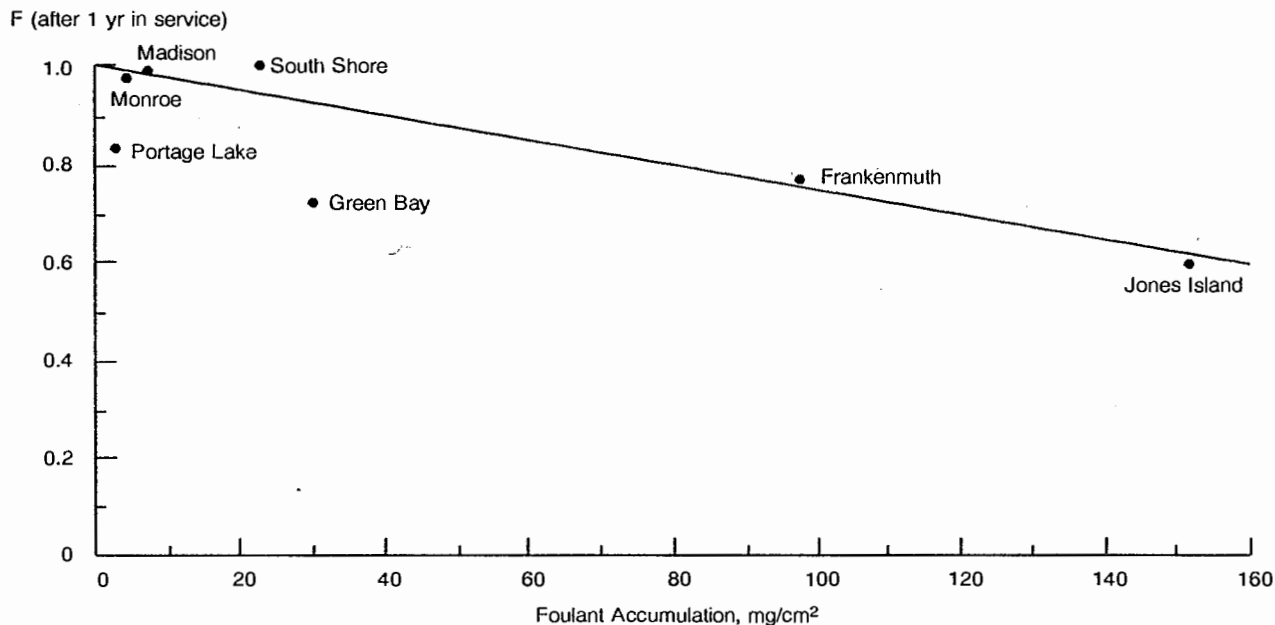
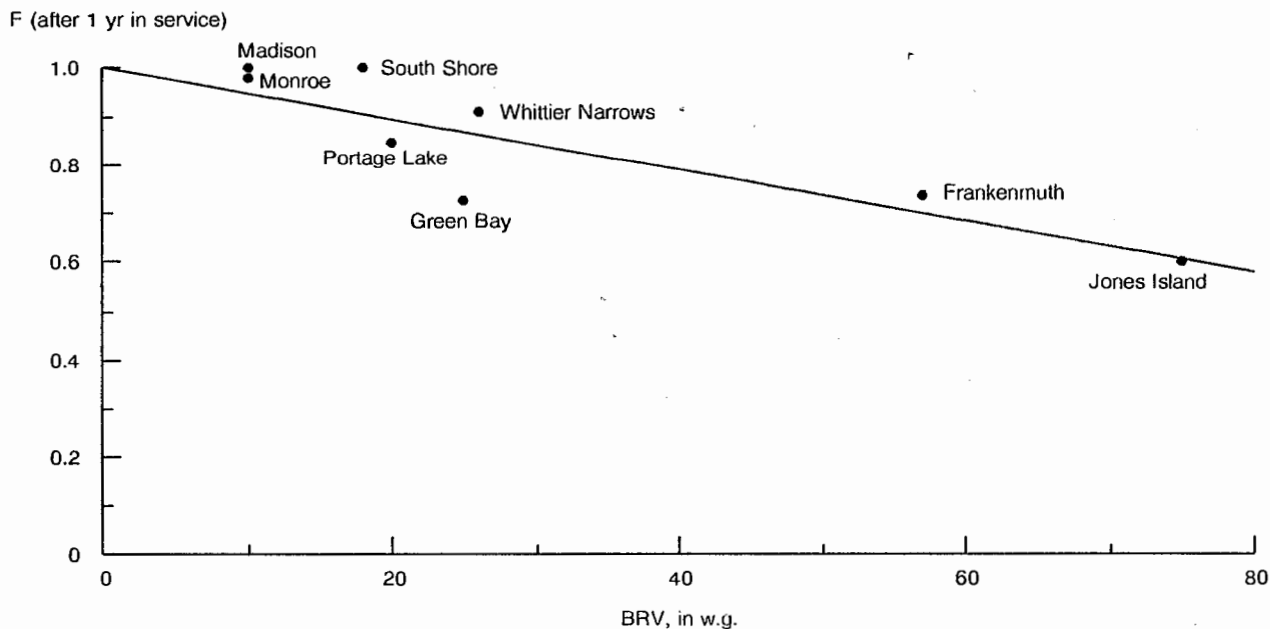


Figure 3-8. Relationship between BRV and F - Interplant Fouling Study.



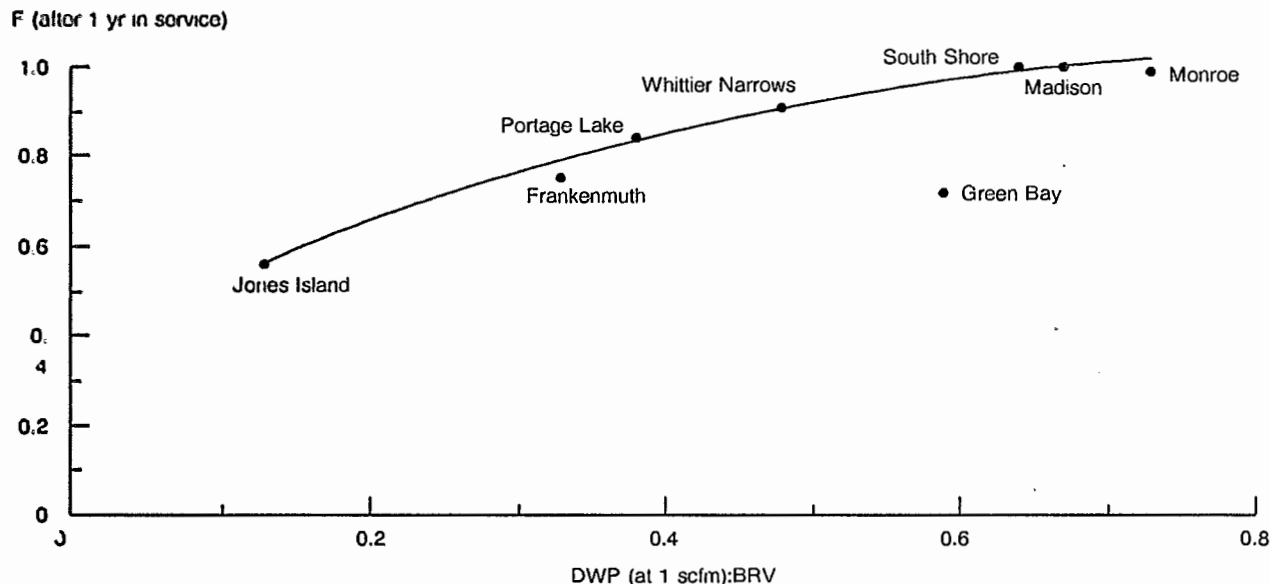
combination of low volatile solids content and high silica content has been explained by microscopic observations (18), which revealed that bacterial biofilms entrap inorganic materials.

3.3.3.3 Temporal Variations

The relationship between accumulated foulant mass and time in service for eight of the treatment plants covered in the interplant fouling study is shown in

Figure 3-10. Incremental and cumulative foulant accumulations at most of the treatment plants fluctuated throughout the study period. Although some of the fluctuations undoubtedly resulted from problems associated with sample collection and analysis, it is apparent that the accumulation of foulant varied considerably throughout the study period. The data were evaluated to determine if treatment plant operational parameters affected the severity of fouling

Figure 3-9. F vs. DWP:BRV - Interplant Fouling Study.



as indicated by BRV. No correlation between BRV and food-to-microorganism (F/M) loading and solids retention time (SRT) was found. It did appear, however, that fouling was more severe at treatment plants that did not have primary clarifiers or had substantial industrial waste contributions.

The dynamic nature of fouling and how fouling can be affected by plant operations were observed at the Monroe, WI wastewater treatment plant (22). Figure 3-11 plots $\alpha F(SOTE)$ vs. time in service over an 18-month period during which the plant was operated with and without an aerated flow equalization basin in service. During the first 6 months, the equalization basin was bypassed. $\alpha F(SOTE)$ s were low and foulant accumulation was high (up to 50 mg/cm²) during this period. At about the 7th month, the aerated equalization basin was placed in service. Not only did $\alpha F(SOTE)$ increase, but foulant accumulation eventually decreased to a negligible amount. When the pond was again bypassed in the 18th month, $\alpha F(SOTE)$ once again decreased and foulant accumulation increased.

A similar type of investigation was undertaken at the Madison, WI treatment plant (26). Influent flow to an aeration basin was stopped for 1 week while the mixed liquor continued to be aerated. Off-gas tests were conducted before the influent flow was stopped, 2 days after influent feed was resumed, and after another 10 days of operation (Figure 3-12). Two days after resumption of flow, $\alpha F(SOTE)$ was significantly higher than before flow was stopped. After another 10 days of operation, however, $\alpha F(SOTE)$ had fallen. Under all the circumstances described, SRT in this basin was approximately 2 days. Observations at

Monroe and Madison suggest αF is a dynamic parameter that changes with loading conditions and wastewater characteristics, among other variables. It is important to recognize this when estimating values of F for a given facility.

3.3.3.4 Spatial Variations

In a survey of fine pore aeration treatment plants in the United Kingdom (27), diffuser fouling was reported to be more severe at the inlet end of highly loaded plug flow aeration basins. Data from treatment plants in the United States show that these spatial variations in fouling are not a common occurrence.

At the Madison, WI treatment plant (26), diffusers were collected from each of six grids in a three-pass, step feed aeration basin after being in service for 14 months (Table 3-3). Fouling was fairly uniform as measured by DWP:BRV. Foulant quantities were only slightly higher in the inlet grid. Varying amounts of inorganic materials incorporated in the biofilm layer probably caused the lower volatile solids measured at the basin inlet. Table 3-4 presents the results of inorganic analyses of foulants obtained from the samples in each grid. Silica content was less in the samples collected furthest downstream while precipitation of phosphorus, magnesium, calcium, and iron increased in the downstream grids, likely because of changes in pH.

An evaluation of another basin at the Madison treatment plant (26) indicated little variation in BRV and DWP from grid to grid down the length of the first two passes of the three-pass, plug flow system. The last pass was a little less fouled. The percent volatile solids content in the foulant samples did not vary from

Figure 3-10. Progression of foulant accumulation - Interplant Fouling Study.

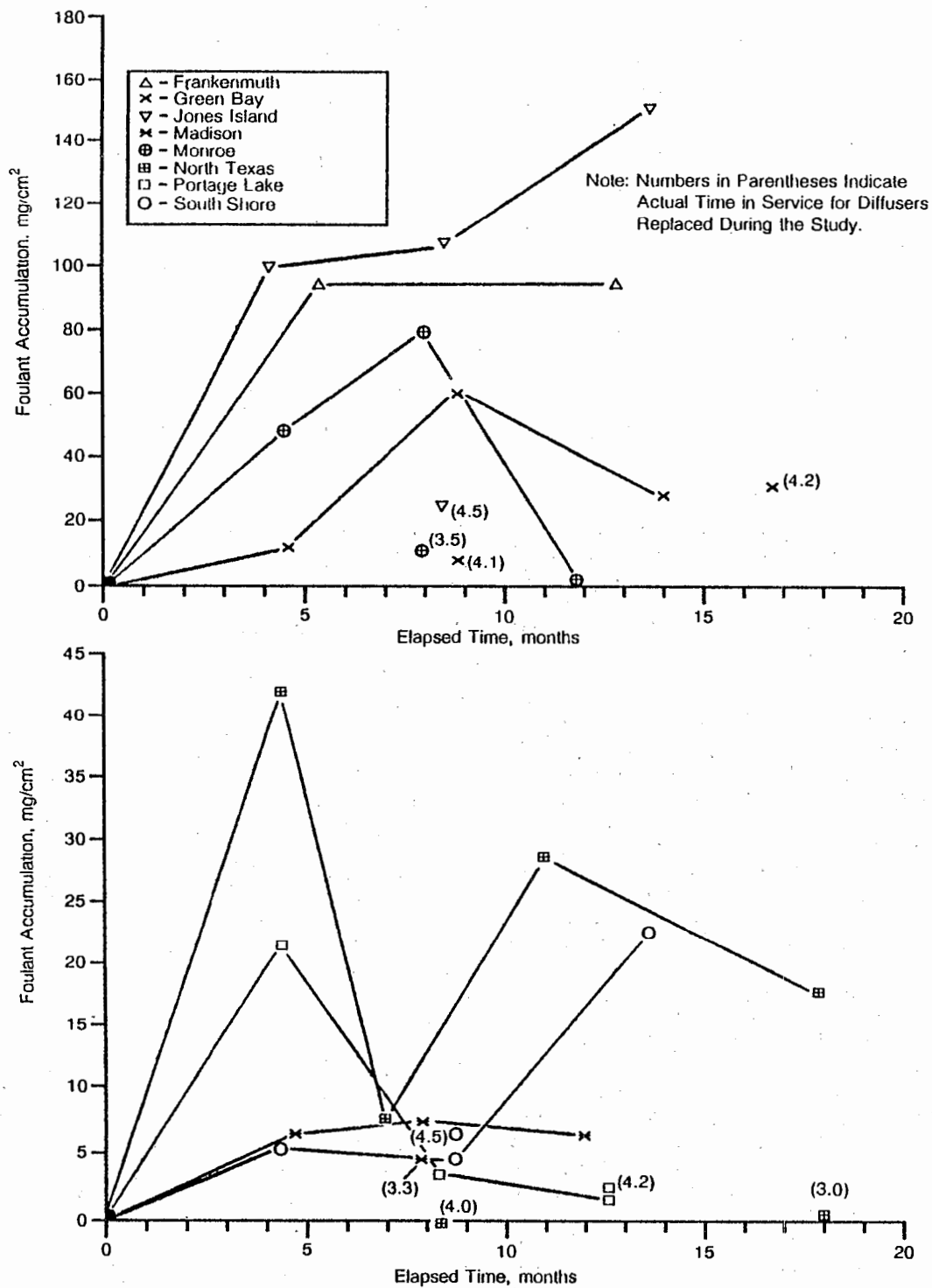


Figure 3-11. $\alpha F(\text{SOTE})$ vs. time in service - Monroe, WI.

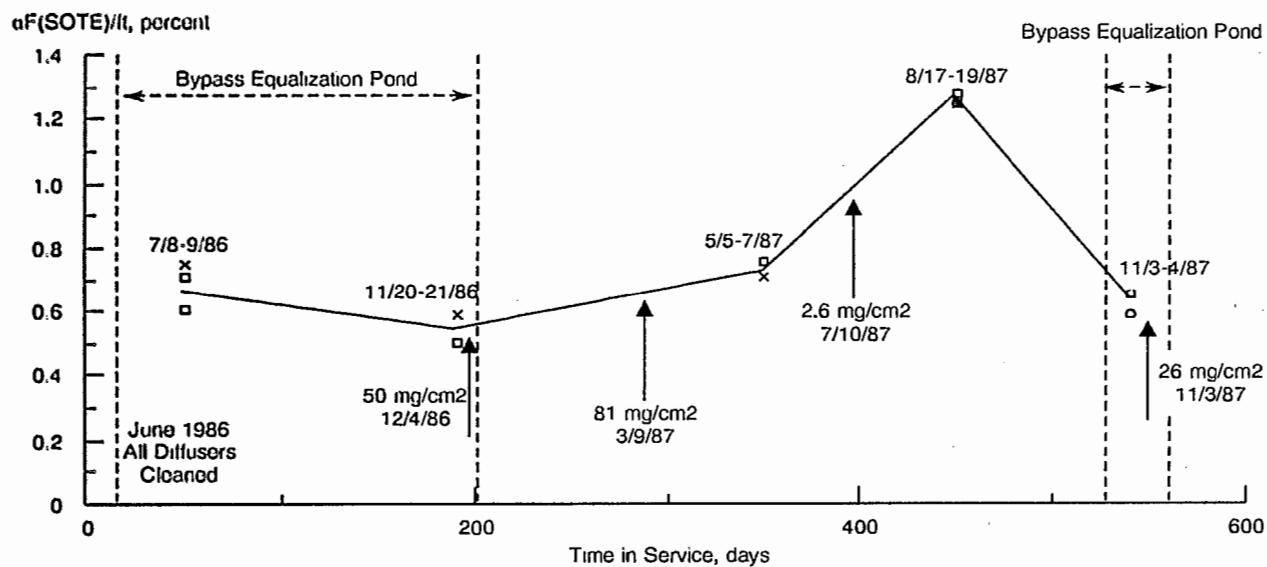


Figure 3-12. $\alpha F(\text{SOTE})$ vs. tank length before and after load reduction - Madison, WI.

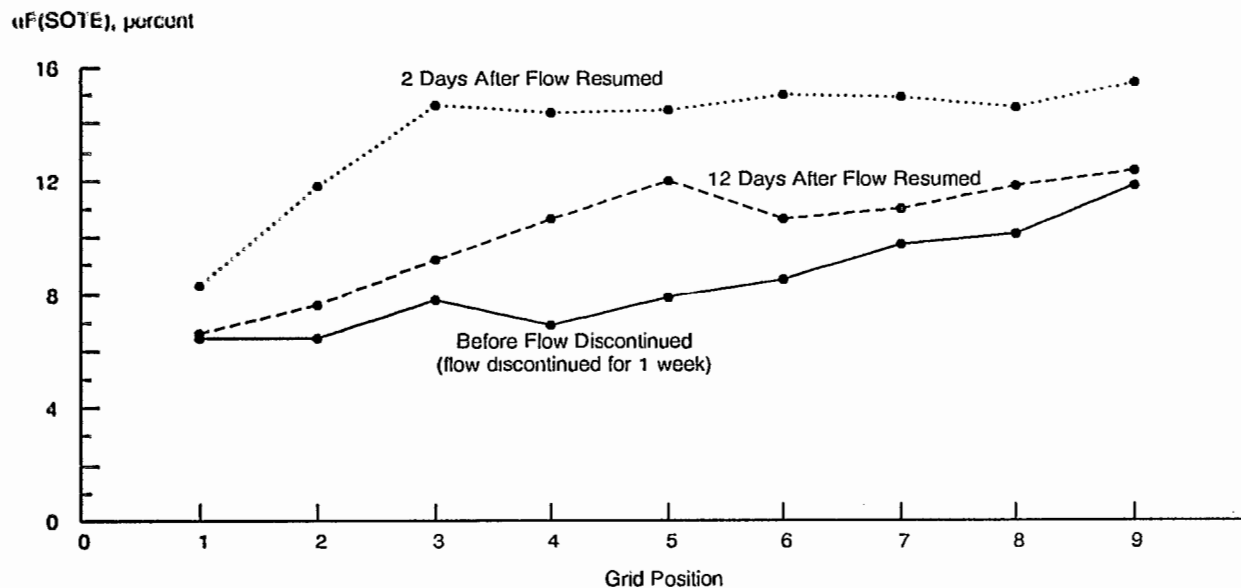


Table 3-3. Diffuser Characteristics in 3-Pass, Step Feed Aeration Basin - Madison, WI

Pass	Grid	BRV, in w.g.	s/x	DWP @ 0.75 scfm/diffuser, in w.g.	DWP:BRV	Residue	
						Volatile, percent	Mass, mg/cm ²
	Clean Dome	6	0.06	6.2	1.03	-	-
1	1	48	0.32	17.7	0.37	26	26
1	2	52	0.22	18.8	0.36	47	16
2	3	45	0.27	17.3	0.38	52	19
2	4	70	0.41	21.5	0.31	55	14
3	5	46	0.34	20.3	0.44	65	12
3	6	41	0.23	15.3	0.37	72	9

* Mean values for 4 samples after 14 months in service.

Table 3-4. Characteristics of Diffuser Residue Samples in 3-Pass, Step Feed Aeration Basin - Madison, WI*

	Percent by Weight					
	Pass 1		Pass 2		Pass 3	
	Grid 1	Grid 2	Grid 3	Grid 4	Grid 5	Grid 6
Mg	0.7	0.9	1.2	1.1	1.0	1.3
Al	1.2	1.3	2.0	2.0	1.5	1.8
Si	11.5	10.5	10.9	11.4	8.0	9.4
P	4.1	4.9	4.8	5.7	4.9	6.7
S	0.8	0.3	0.6	0.9	0.5	0.5
Cl	0.4	0.8	0.2	0.4	0.3	0.7
K	1.1	1.1	1.3	1.5	1.0	2.0
Ca	7.5	8.9	9.3	10.4	9.0	10.7
Ti	0.4	0.7	0.6	0.8	0.6	0.7
Cr	0.1	-	-	-	-	0.1
Mn	-	-	0.2	0.3	0.2	0.2
Fe	2.5	3.1	3.6	3.7	2.9	3.8
Cu	0.3	-	-	0.7	0.2	0.7
Zn	0.5	0.9	0.9	1.0	0.6	1.6
Cd	-	-	-	0.3	-	0.4

* After 550°C firing.

the inlet to the outlet of the basin. Silica and phosphorus did not increase downstream; calcium, iron, and aluminum did.

In a 28-month study at the Whittier Narrows treatment plant in Los Angeles County, CA (28), ceramic disc and dome diffusers were removed from each of three grids of plug flow aeration basins each time the basins were drained. Analyses included DWP, BRV, DWP:BRV, and foulant accumulation. An analysis of variance was performed on the data to determine the effects on fouling of time in service, treatment with HCl gas, basin number, and grid number. The analysis showed that the grid number (inlet, middle, and outlet) had the least significant effect on fouling.

Mean foulant accumulations were 10.0, 6.7, and 4.7 mg/cm² for Grids 1, 2, and 3, respectively. This decrease was not statistically significant due to the

variability in the data. However, visual observations tended to confirm the mean values reported. The results of the variance analysis were also affected by the differences in mechanical integrity of the disc and dome diffusers evaluated during the study.

In a similar study at Green Bay, WI (20), foulant accumulation varied substantially from diffuser to diffuser, but the variations were random. The influent consisted of a mixture of domestic and pulp and paper wastewater. There was no clear pattern of more foulant at a basin inlet or outlet end. The volatile fraction in the biofilm layer was relatively constant. These observations applied to both ceramic disc and perforated membrane tube diffusers. The perforated membrane tube diffusers were found to have a greater accumulation on the top of the diffuser. The top portion of the foulant was very similar to the foulant found on the ceramic diffusers, suggesting that the fouling mechanisms for the ceramics and the tops of the membranes were similar. Less foulant accumulated on the bottom of the tube diffusers, and it had much higher volatile fractions. These differences indicate that gravity settling may have played a role in the deposition of inert solids in the biofilm layer at this facility.

3.3.3.5 Air-Side Fouling

Many of the early installations of ceramic fine pore diffusers had significant plugging problems resulting in substantial DWP increases. The clogging problems were often attributed to air-side fouling (9,10). More recent experience has shown that air-side fouling of porous media diffusers is not a common problem. Better air filtration and use of corrosion-resistant air distribution materials have eliminated plugging caused by airborne dirt. Clogging caused by intrusion of mixed liquor can be minimized by selecting and carefully installing systems with good mechanical integrity and by providing good preventive maintenance, i.e., inspecting the system on a regular basis and fixing leaks, not operating the aeration system below the recommended minimum airflow rate, and avoiding loss of the air supply due to power outages or other causes.

The effects of air-side fouling can be measured by conducting BRV tests on the air-side diffuser surfaces. Such measurements were made on the air side of the ceramic disc diffusers taken from the test headers used in the EPA/ASCE interplant fouling study (23). The test header diffusers received air that had undergone varying degrees of particulate removal. The diffusers were in service for 10-14 months. The results of the tests are summarized in Table 3-5. Air-side fouling was not a problem in any of the treatment plants tested.

Table 3-5. Air-side Analysis of Ceramic Disc Diffusers from Test Headers

City - Plant	Time in Service, months	Air-side BRV ^a , in w.g.	Air Filtration
Houghton, MI; Portage Lake	15	5.5	12 in of glass wool
Green Bay, WI	14	5.1	Coarse roll filter only
Madison, WI	12	4.7	Static air filters preceded by roll filter
Milwaukee, WI; South Shore	13	5.5	Precoat bag house
Milwaukee, WI; Jones Island	13	4.9	Electrostatic
Los Angeles County, CA; Whittier Narrows	NA	5.4 ^b	Glass fiber prefilters and high-efficiency paper filters (not used 4/86-9/87)

^a New diffuser BRV = 5.0-5.5 in w.g.

^b Two diffusers removed and tested in September 1987.

While clean air is essential for satisfactory operation of porous media diffusers, the degree of filtration required is not firmly established. Recommended design standards for porous diffusers have been 0.1-1.0 mg dirt/1,000 cu ft air (8,9). Another common design criterion for air filtration is to remove 95 percent of all particles /0.3 micron in size (21). Experience indicates that these stringent air filtration criteria may not always be necessary (see Chapter 8).

Data from the following treatment plants suggest that air-side fouling did not occur or its effects were removed by the injection of acid gas:

- At the Whittier Narrows, CA treatment plant, BRV data were collected after the air filter system had been out of service for 18 months (28). The blowers take suction from the covered space above the primary clarifiers. The average air-side BRV of ceramic dome diffusers that had been periodically acid gas cleaned was 14.2 cm (5.6 in) w.g. (essentially equal to that of a new diffuser) compared to 24.4 cm (9.6 in) for untreated dome diffusers.
- The Glendale, CA treatment plant uses a combination of ambient air and air from covered

headworks and primary clarifiers (29). The ambient air receives coarse filtration from oil-coated fiberglass frame filters on the inlet to the blowers, whereas the primary clarifier air is not filtered. The air-side BRVs for ceramic domes after 10 years of service were 14.0-22.4 cm (5.5-8.8 in) w.g. (essentially equal to that of a new diffuser).

- The rated efficiency of a modified 2-stage filter at the Green Bay, WI treatment plant is 98 percent removal of all particles ≥ 1.0 micron in size (20). After 14 months in service, the ceramic disc diffuser quadrant was cleaned by hosing, injection of 45 g (0.1 lb) HCl gas/diffuser, and rehosing. DWP measurements on the cleaned diffusers produced values equivalent to those for new diffusers. Air-side BRV data on diffusers from the EPA/ASCE test header showed no air-side fouling (23).
- The air filtration system at the Hartford, CT treatment plant is rated to remove 95 percent of all particles ≥ 0.3 micron in size (21). Visual observation of ceramic dome diffusers from the treatment plant revealed small amounts of dried-on scale on the air-side. These deposits were believed to have originated from mixed liquor intrusion into the air supply piping due to broken dome bolts (plastic), cracked gaskets, and other leaks and did not appear to be significant.
- At the Frankenmuth, MI treatment plant, blower inlet air filters were modified to remove only particles ≥ 20 microns in size (30). Air-side BRV values for the ceramic disc diffusers over a 17-month study period were 14-17 cm (5.5-6.9 in) with acid gas cleaning performed about once a month.

3.3.3.6 Media Effects

Fine pore aeration systems have sometimes exhibited reductions in OTE that could be attributed to mechanical failures or material changes rather than a or fouling effects.

Two fine pore ceramic diffuser systems were evaluated at the Whittier Narrows treatment plant in Los Angeles County, CA (28). Ceramic disc diffusers were installed in one aeration basin in December 1980, and ceramic dome diffusers were installed in two aeration basins in Spring 1982. The disc diffusers were installed in their holders with O-rings and peripheral retainer rings. Plastic hold-down bolts and soft gaskets were used to install the dome diffusers.

At Whittier Narrows, ceramic disc diffusers outperformed ceramic dome diffusers based on numerous off-gas tests conducted over more than 2 years, starting in April 1986. The dome diffusers were inspected in the fall of 1987 by draining the basins to just a few inches above the diffusers and observing the air release pattern. In the inlet grid of one of the basins, only 26 percent of the diffusers were

performing properly. In the middle and outlet grids, <15 percent of the diffusers were operating properly. Nearly 40 percent of the diffuser gaskets were leaking. Much of the reduced OTE measured in the off-gas tests could be attributed to diffuser design deficiencies in conjunction with fouling that resulted in increased DWP and eventual gasket failure. In contrast, inspection of the disc diffuser system in the summer of 1988 revealed only five leaking O-rings in the entire basin.

Similar gasket failures and broken plastic bolts were experienced with ceramic dome diffusers at the Hartford, CT treatment plant (21). Ceramic dome diffuser systems at the Madison, WI (26) and Glendale, CA (29) treatment plants, which use metal bolts and pipe inserts, have performed well for many years.

Changes in diffuser media properties can also affect DWP and OTE. As described in Section 2.2.3, plasticized PVC (a thermoplastic elastomer) and EPDM (a thermoset elastomer), the two principal perforated membrane materials in use, can experience various physical property changes with time when used as wastewater aeration devices. These changes, however, may differ significantly in nature and degree between the two materials. Specific, comprehensive descriptions of the materials employed in media production are therefore essential for prediction of perforated membrane diffuser performance.

Conditions that can substantially affect perforated membrane performance and life include loss of plasticizer, hardening or softening of the material, loss of dimensional stability through creep, absorptive and/or extractive exchange with wastewater, and chemical changes resulting from environmental exposure.

Plasticizer migration can cause hardening and reduction in membrane volume, resulting in dimensional changes. Absorption by the membrane of various constituents, including oils, can result in softening of the membrane with volumetric changes and subsequent dimensional changes.

Membrane creep, which may be influenced by the above factors, will reduce OTE in some cases. It may also be accompanied by a reduction in DWP to lower than the original value after cleaning. This reduction is not recoverable by known maintenance procedures.

Reported data on performance and changes in characteristics of perforated membranes under service conditions, although limited, are becoming increasingly available. In three of the studies conducted under the ASCE/EPA Fine Pore Aeration Project, plasticized PVC membrane tube diffusers were evaluated. Information on four types of perforated membrane diffusers (plasticized PVC tubes

of U.S. manufacture, EPDM tubes of European manufacture, and EPDM discs of both U.S. and European manufacture) are summarized in Table 3-6.

At Green Bay, ceramic disc and perforated membrane tube diffusers that had been in operation for 18 months were tested to determine if any changes in diffuser media had occurred (20,31). As expected, the dimensions and strengths of the ceramic disc diffusers had not changed. After thorough cleaning, DWPs of these diffusers were restored to "near new" values.

On the other hand, the Green bay perforated membrane tube diffusers made from plasticized PVC (Site A-1, Table 3-6) experienced changes in dimensions, weight, and elasticity. Visual observations indicated a widening of the slit-type perforations. The combination of reduced weight, length, and thickness and increased tensile modulus suggested a loss of plasticizer. Creep was also considered to be a contributing factor in the enlargement of the perforations. The relatively high mixed liquor temperatures (29°C [85°F]) experienced during the study probably increased the rates of both creep and plasticizer loss over what they would have been at lower, more typical municipal wastewater temperatures.

Perforated membrane tube diffusers of the same material (plasticized PVC) were installed in the Cedar Creek treatment plant in Nassau County, NY (Site B, Table 3-6) in 1984-1985 (37). After about 4 years of service, 6 diffusers were removed and tested (32). Little or no change was evident in dimensions, but media weight was reduced by approximately 10 percent. The membranes were more rigid after exposure to wastewater, as indicated by the increase in tensile modulus from about 4,140 kPa (600 psi) to 8,825-41,370 kPa (1,280-6,000 psi). Following laboratory cleaning, DWP and OTE were both less than for a new diffuser.

Inspection of the same type diffusers at the Terminal Island treatment plant in Los Angeles County, CA after 1 year of service revealed that the membranes were no longer as flexible or loose as they were when new (28). No significant changes in $\alpha F(SOTE)$ were observed over the test period, however.

Certain industrial wastewaters may have a dramatic effect on both plasticized PVC and EPDM perforated membrane tube diffusers. Site C is equipped with U.S. PVC membrane tubes and Site D European EPDM tubes. Both sites are industrial wastewater treatment plants handling food processing wastes. Pertinent conditions existing at each site are shown in Table 3-7. The apparent loss of plasticizer was extreme in both cases, as reflected by losses in weight, wall thickness, DWP, and OTE, and the increase in tensile modulus. Neither waste was considered representative of typical domestic wastewaters.

Table 3-6 Characteristics of Perforated Membrane Diffusers in Service

Site	Diffuser Type	Membrane Type	Wastewater Type	Time in Service, months	Diffuser Condition ^a	Diffuser Physical Characteristics							Ref.
						Weight, g	Thickness, in	Durometer Shore A	Tensile Modulus ^b , psi	Type of Test Specimen	DWP (@ 1 scfm/diffuser), in	SOTE ^c (@ 1 scfm/diffuser), %	
A-1 ^d	Tube	PVC (U.S.)	Municipal/Industrial	7	New AS ^e	120	0.031	63	630		7.3	18.0	20,31
					AC	114	0.028	63	900	Pilot	6.1	11.9	
A-2 ^d	Disc	EPDM (U.S.)	Municipal/Industrial	14	New AS	174	0.105	60	612 ^f	Pilot	3.2	13.2	32
					AC	174	0.106	68	728 ^f	Pilot	12.0	19.5	
											12.7	18.2	
B	Tube	PVC (U.S.)	Municipal	48	New AS ^e	118	0.028	63	653		10.7	18.0	32
					AC ^e	108	0.028	75	3,273	Field	5.5	13.5	
C	Tube	PVC (U.S.)	Industrial	13	New AS	117	0.030	60	600		4.3	14.2	32
					AC	87.5	0.024	81	17,000	Field	8.8	18.0	
D	Tube	EPDM (Eur.)	Industrial	24	New AS	280	0.080		375		3.8	14.8	32
					AC	222	0.062		1,450	Field	15.3	23.0	
E	Tube	EPDM (Eur.)	Industrial	8	New AS		0.083		360		6.3	17.5	33
					AC		0.078		487	Pilot	11.7 ^g	21.8	
F	Tube	EPDM (Eur.)	Municipal	13	New AS		0.078		375		14.5 ^g	19.8	34
					AC		0.075		560	Field	9.65 ^g	21.8	
G	Disc	EPDM (Eur.)	Municipal	12	New AS	263	0.086	50.8	334 ^f		11.0	23.0	35
					AC	243	0.078	51.1	318 ^f	Field	8.4	17.8 ^h	
										Field	15.5	16.7 ^h	
H	Disc	EPDM (U.S.)	Municipal	11.5	New AS	174	0.105	60			7.7	18.0 ^h	36
					AC	178	0.106	62		Field	12.0	19.5	
I	Disc	EPDM (U.S.)	Municipal	7	New AS	174	0.105	60		Field	16.3	18.5	32
					AC	177	0.103	61		Field	11.6	20.0	
J	Disc	EPDM (U.S.)	Municipal	3	New AS	175	0.105	54			12.0	19.5	32
					AC	179	0.099	59		Pilot	19.4	19.5	
										Pilot	11.1	19.4	
K	Disc	EPDM (U.S.)	Municipal	7	New AS	174	0.105	60			10.0	19.5	32
					AC	176	0.105	64		Pilot	15.9	17.9	
										Pilot	11.3	20.5	
											12.0	19.5	32
											12.5	18.9	
											11.0	19.5	

^a AS - after indicated period of service; AC - after cleaning (performed after indicated period of service).

^b Radial for discs; circumferential for tubes.

^c Clean water test in laboratory column at 10-ft diffuser submergence.

^d Not concurrent in time.

^e Mean of 6 samples.

^f @ 30 psi stress.

^g DWP @ 0.75 scfm/diffuser.

^h @ 3 scfm/diffuser.

Table 3-7. Operating Conditions for Two Food Processing Industrial Treatment Sites Using Perforated Membrane Tube Diffusers

Site	C*	D*
Membrane Type	Plasticized PVC	EPDM
Waste Type	Hydrolized Protein and Dairy Waste	Potato Processing Waste
Average Daily Flow, mgd	0.10	2.1
Wastewater Temperature, °C	28	29-33
pH	6.8	6.9
Air Temperature (at blower), °C	-	107
Diffuser Submergence, ft	8.0	20.5
Airflow, scfm/diffuser	5.0	3.3
MLSS, mg/L	8,000	5,000
BOD ₅ Loading, lb/d/1,000 cu ft	-	42
COD Loading, lb/d/1,000 cu ft	50	-

* Diffuser characteristics and performance are summarized in Table 3-6.

Vegetable oils have been suspected as the causative agents for plasticizer loss in some of the studies cited in Table 3-6, but definitive investigations were not performed. A laboratory study was conducted, however, on European and U.S. EPDM and plasticized PVC materials (32). The membranes were stretched 15 percent on a fixture that was then immersed in vegetable oil. The specimens were periodically weighed and tested for hardness.

Over the 1,800-hr test period, all three products exhibited significant, although different, changes. The plasticized PVC material lost weight and hardened rapidly. The U.S. EPDM material lost weight and softened gradually. The European EPDM material remained at a relatively constant weight, but also softened gradually. One possible explanation for these observations is that the PVC lost plasticizer to the oil and the two EPDMs exchanged plasticizer with the oil. Although this study does not represent field conditions, it does indicate that constituents commonly found in wastewater can significantly affect perforated membrane diffuser characteristics and that the nature of the changes can differ among the various diffuser materials.

The data in Table 3-6 suggest that changes in tensile modulus, SOTE, and DWP may have been occurring for Sites A-2 and E through K. If so, loss of plasticizer is considered to be the most likely cause. In any event, the changes appear to be gradual.

Based on the data in Table 3-6, direct comparisons of the different membrane diffuser types and materials are not considered to be quantitatively appropriate. The data represent a spectrum of wastewaters, plant

operating conditions, and exposure times over which the actual conditions are not well known.

Only at Sites A-1 and E were conditions accurately known and controlled and the different membrane types evaluated under near identical conditions and concurrent exposures. These results are inconclusive or not universally applicable since the existence of situations with comparable wastewaters, treatment plants, and modes of operation is unlikely. Nevertheless, the data clearly indicate that significant differences in perforated membrane performance and characteristics may occur after relatively short periods of service. These differences should be assessed in the design phase of a project and allowances provided. This assessment is the joint responsibility of the designer, supplier, and end user.

3.3.4 Fouling Rates

Fouling rates and, more importantly, the effects that foulants have on DWP and OTE constantly change in response to operating conditions, changes in wastewater characteristics, and time in service. The net result is that data collected from operating treatment plants contain sufficient variability that it is usually difficult to obtain precise measurements of fouling rates. Nevertheless, it is still instructive to investigate and quantify the possible extremes of fouling rates. The expected ranges can be used for evaluating cleaning frequencies and selecting pressure and air volume requirements for use in the design of fine pore aeration systems.

3.3.4.1 Dynamic Wet Pressure

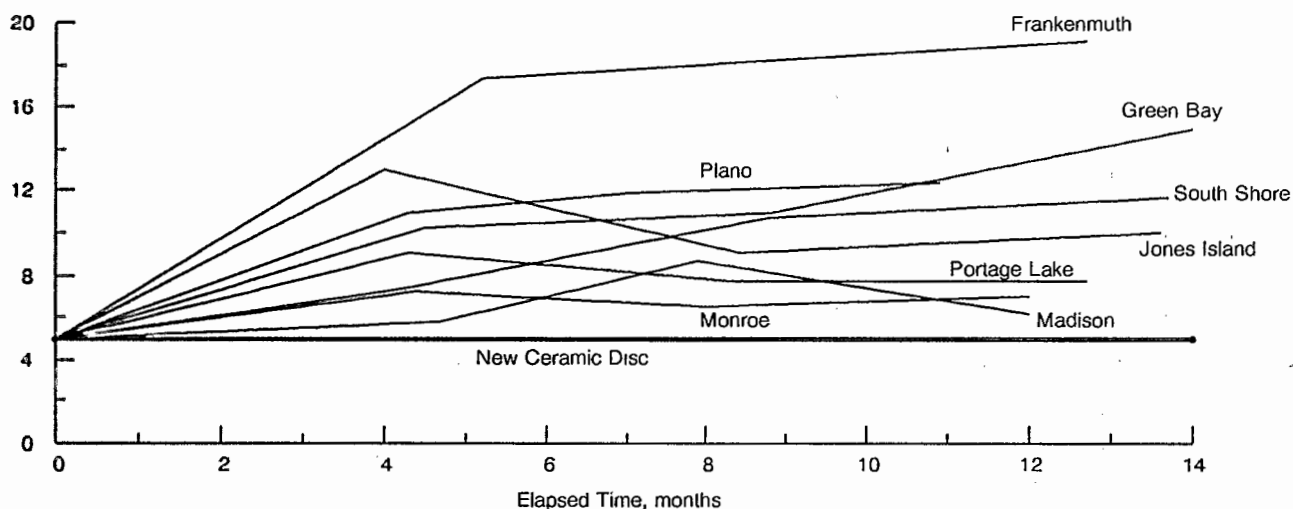
Significant increases in DWP have not been observed in most fine pore diffuser installations. DWP vs. time in service is plotted in Figure 3-13 for ceramic disc diffusers tested as part of the EPA/ASCE interplant fouling study (23). Results of testing similar diffusers taken from the full-scale aeration basins at Madison and Green Bay were consistent with the interplant study data. At Madison, diffusers that had been in service for more than 21 months had DWPs <25 cm (10 in) w.g. at an airflow of 0.5 L/s (1 scfm)/diffuser (26). At Green Bay, DWPs of 25-38 cm (10-15 in) w.g. at an airflow of 0.5 L/s (1 scfm)/diffuser were measured after 6 months in service (20).

The highest rate of increase in DWP was measured for the diffusers from the Frankenmuth, MI treatment plant. After only 4 months in service, the DWP was about 44.5 cm (17.5 in) w.g. (30). Although such an increase in DWP would affect blower efficiency and operating cost, it would not exceed the blower discharge pressure provided an adequate safety factor had been included in the original blower design.

Most of the treatment plants evaluated in the EPA/ASCE interplant fouling study exhibited much smaller effects of fouling on DWP than experienced at Frankenmuth (23). This finding was in agreement with

Figure 3-13. DWP fouling rates for eight wastewater treatment plants - Interplant Fouling Study.

DWP (@ 1 scfm)/diffuser, in w.g.



that of other investigators (11). Increases in DWP over the first 4 months ranged from 2.5 mm (0.1 in) w.g./month at the Madison, WI treatment plant to 5 cm (2 in) w.g./month at the Jones Island, Milwaukee, WI treatment plant. Considering the lack of consistent trends in the data, regular monitoring and preventive maintenance activities, as described in Chapter 4, are recommended to keep a system operating as efficiently as possible.

3.3.4.2 Oxygen Transfer Efficiency

The effect of fouling on OTE at any time is described by F . The rate at which F decreases is designated as f_F , which is the slope of the F vs. time curve (see Figures 3-1 and 3-2). While F is dimensionless, the fouling rate factor, f_F , is expressed as the decimal fraction of OTE lost per unit time. The time period of 1 month is used in this manual. For example, if OTE decreases as a linear function of time and F is found to be 0.8 after 2 months, then f_F would equal $(1.0 - 0.8) \div 2$ or 0.1/month. If OTE does not decrease as a linear function of time, then f will vary as a function of time and will not approximate a constant rate.

F and its functional relationship with time can be estimated by:

- conducting full-scale OTE tests in the process water over a period of time,
- monitoring aeration system efficiency using operational data as described in Chapter 4, or
- conducting OTE tests on fouled and new diffusers, ex situ, in an aeration column.

None of these methods is ideal; each has advantages and disadvantages.

The full-scale methods have the advantage of collecting data on the actual operating system so that

temporal and spatial variations can be taken into account. At the same time, temporal loading and a variations may mask the fouling effects that are of interest. To sort out these various effects, frequent data collection over a relatively long time period is required. Although full-scale OTE tests are the most accurate way to determine F as a function of time, the required testing can be quite expensive. Monitoring operational data offers a cost-effective alternative for determining F , but care must be exercised in collecting and analyzing the data to ensure meaningful results.

Since the ex-situ method involves removal of the diffusers from the actual operating system, greater control over test conditions is gained at the expense of handling the diffusers before testing, which could have some effect on foulant characteristics.

Two ex-situ testing techniques have been used to evaluate fine pore diffusers (24,25). One method involves conducting tests at the plant site using mixed liquor pumped continuously from the operating aeration system. Off-gas techniques are used to determine OTE. A second method involves tests conducted in clean water using sodium sulfite to provide an oxygen demand. These tests can be conducted on site or at a remote location (see Appendix B). The main disadvantages of remote clean water testing are the need to transport the diffusers, which could affect foulant characteristics, and not conducting the tests in process water. This technique has been used with success, however, to screen fouled diffusers (20,22,23). In these studies, the diffusers were sealed in plastic bags immediately after removal and shipped by same-day or overnight transport to the testing facility.

When testing diffusers that have been in service for any length of time, it is also important to assess the

integrity of the diffuser media. Experience has shown that some diffuser material properties can change, resulting in permanent reductions in DWP and OTE (20). If diffuser material characteristics are not evaluated, the effects of material changes can be misinterpreted as fouling effects.

The following subsections present results of tests and data evaluations to illustrate how the methods described above can and have been used to determine or estimate F .

a. Full-Scale OTE Testing

Off-gas testing was conducted as part of the EPA/ASCE Fine Pore Aeration Project (see Appendix A). For those studies where it was possible, OTE data were plotted vs. time in service since the last cleaning of the diffusers. If the data decreased as a function of time, linear regression was used. The results of the analyses are summarized in Table 3-8.

Although the results of all regression analyses are presented, not all the lines of best fit were statistically significant. These data were collected at operating treatment plants that were being tested with several different objectives in mind. They were not controlled tests for F .

One of the objectives of the studies conducted at the Frankenmuth and Whittier Narrows treatment plants was to determine the effectiveness of HCl gas injection cleaning in maintaining or restoring fine pore diffuser OTE.

At Frankenmuth (30), Basin 5 was used as the first basin in a two-basins-in-series aeration system or as the second basin in a three-basins-in-series system. Use of acid gas injection in Basin 5 did not prevent OTE decline. Off-gas tests before and after HCl gas injection showed little or no change in $\alpha F(\text{SOTE})$ values (Figure 3-14). It is important to note, however, that HCl gas injection did result in a significant decrease in DWP in most cases. Furthermore, it is possible that HCl gas injection reduced the rate of fouling, f_F . Since no controlled studies were conducted, it was not possible to substantiate whether f_F was reduced by the acid gas treatment.

Figure 3-15 plots $\alpha F(\text{SOTE})$ vs. time since the ceramic disc diffusers in Basin 1 at the Whittier Narrows treatment plant were initially cleaned with liquid acid (28). Data were collected over a 26-month period. HCl gas injection was performed during the test period at intervals of 2-4 months. As shown in Table 3-8, f_F from the 3rd through the 7th period was 0.027/month. The use of HCl gas did not prevent long-term deterioration in $\alpha F(\text{SOTE})$. It appears, however, that the HCl gas injections may have slowed the rate of decline. The cost effectiveness of the acid gas treatments was not determined.

At the Green Bay treatment plant (20), both ceramic disc and perforated membrane tube diffusers were tested. The data used for the ceramic disc diffusers were from three operating periods, one of 6-months duration, one of 6.5-months, and one of 4-months. Only data from the 6-month period were used for the membrane diffuser system because the membrane material properties changed and the observed effects on OTE after this period could not be attributed solely to fouling.

A relatively low fouling rate was indicated at the Jones Island treatment plant (38) by the linear regression of OTE data from 15 tests conducted in each of two passes in one aeration basin that were operated in parallel. Visual inspection of the data indicated that fouling may have been rapid during the first few months after cleaning, followed by no additional loss in OTE for the next 27 months. Results of the EPA/ASCE interplant fouling study (23) also suggested an initial period of rapid fouling at the Jones Island treatment plant.

b. Operational Data Analysis

In the Green Bay study (20), nine off-gas tests were conducted over an 18-month period. To fill in the gaps between off-gas testing, operational data were used to evaluate changes in OTE. An efficiency factor, EF , based on BOD_5 loading and air usage corrected to zero DO, was calculated employing monthly average data (see Section 4.2.3.2b). The results are shown in Figure 3-16.

When all the off-gas data were pooled and regression analyses performed, a linear fouling rate appeared to be a reasonable assumption. The operational data analysis, however, suggested two types of fouling curves. The first, between May and November 1986, demonstrated a rapid decrease in OTE over a 2-month period followed by a relatively constant efficiency for the next 4 months. The data could be fit by a logarithmic curve or two linear segments. The two linear segment approach is used later in an example in Chapter 4. During the second operating period, OTE appeared to reduce at a reasonably linear rate. The calculated value of f_F for the second period was 0.064/month.

A review of these operating data illustrates the limitation of the linear fouling rate model based on too few data. While the fouling rate may be linear for a period of time, a minimum OTE will likely be reached at some time beyond which the effect of additional fouling will not be noted. Since fouling was not rapid in most of the studies conducted under the EPA/ASCE Fine Pore Aeration Project, the limiting OTE was seldom reached. One exception was at Green Bay (20) where the minimum OTE was apparently reached between July and November 1986. Full-scale off-gas tests indicated the minimum value of F was about 0.7 in both the contact and

Table 3-8. Fouling Rates (f_F) and Fouling Factors (F) for Selected Treatment Plants

City - Plant	Time in Service, ^a years	Test Period, months	No. Tests	f_F , month ⁻¹	Correlation, r	F (@ 1 month)	Comments	Ref.
Frankenmuth, MI	3.3	13.0	17	0.029	-0.52 ^b	0.97	Ceramic disc diffusers; Basin 5	30
		11.7	16	0 ^c		1.0	Ceramic disc diffusers; Basin 6	
Groen Bay, WI	3.0	6.5	9	0.064	-0.43	0.94	Ceramic disc diffusers; contact basin	20
(2nd operating period)		6.5	9	0.067	-0.66 ^b	0.93	Ceramic disc diffusers; reaeration basin	
Groen Bay, WI	3.3	6.0	5	0.028	-0.56	0.97	Perforated membrane tube diffusers; contact basin	20
(1st 6 months only)		6.0	5	0.046	-0.65 ^b	0.95	Perforated membrane tube diffusers; reaeration basin	
Milwaukee, WI; Jones Island East	6.0	30.0	20	0.002	-0.22	1.0	Ceramic plate diffusers	38
Milwaukee, WI; South Shore	15.0	56.7	20	0 ^c	-	1.0	Ceramic plate diffusers; various basins	39
Madison, WI; Nino Springs	3.5	26.7	37	0 ^c	-	1.0	Ceramic disc diffusers	26
Monroe, WI	3.0	4.5	5	0.043	-0.81	0.96	Ceramic disc diffusers during bypass of aerated flow from equalization basin	22
Los Angeles County, CA; Whittier Narrows	9.3	24.0	23	0.027	-0.82 ^b	0.97	Ceramic disc diffusers injected with HCl gas 5 times about every 3 months	28
Ridgewood, NJ	6.0	5.0	48	0.074	-0.15	0.93	Ceramic dome diffusers cleaned often by hosing or brushing with HCL solution	40

^a As of 4/1/89.

^b Significant at 95 percent confidence level.

^c Zero fouling rate based on visual inspection.

Figure 3-14. $\alpha F(\text{SOTE})$ vs. time in service for Basin 5 - Frankenmuth, MI.

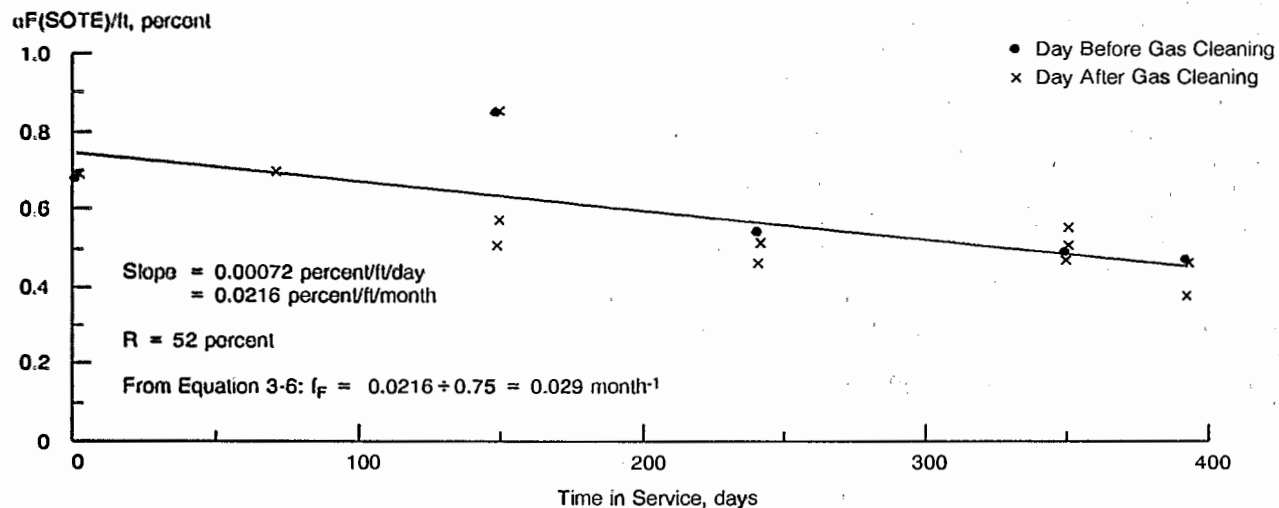
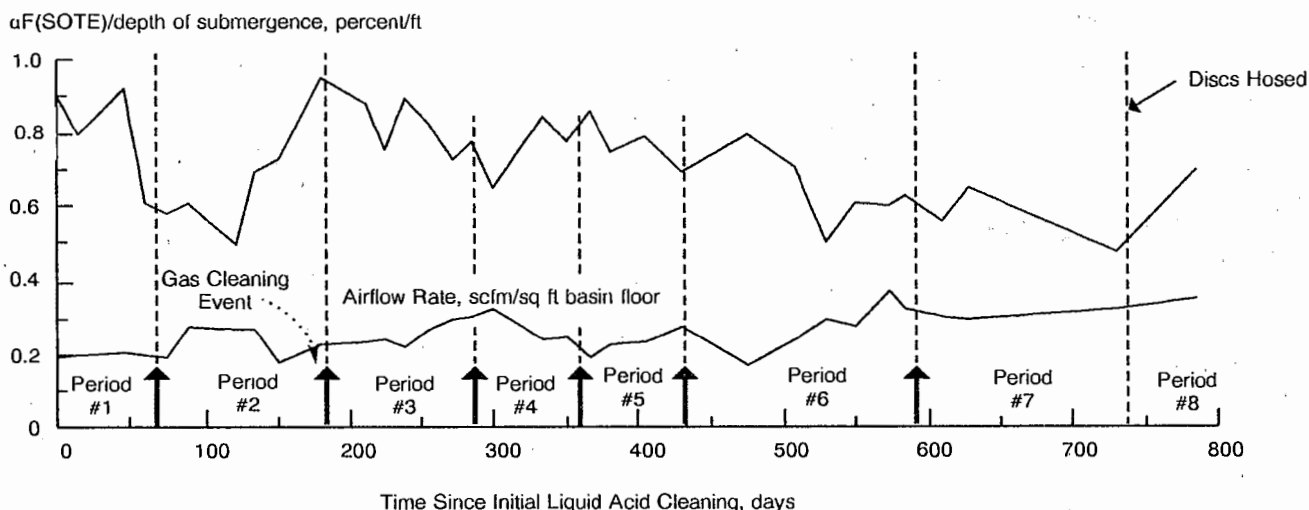


Figure 3-15. $\alpha F(\text{SOTE})$ and airflow rate vs. time since initial liquid acid cleaning for Basin 1 - Whittier Narrows, CA.



reaeration basins for this period. To estimate an absolute minimum value of OTE that might occur under unusually severe fouling conditions, one could assume that fine pore diffusers in their most fouled condition would operate at least as efficiently as a coarse bubble grid system.

c. Ex-Situ Column Tests

Ex-situ clean water column tests were used to compare the effects of fouling on OTE as part of the EPA/ASCE interplant fouling study (23). Diffusers that

had been in service for 10-14 months were sent to a laboratory for OTE testing. The tests were conducted in a 76-cm (30-in) diameter basin with a 3-m (10-ft) water depth. Steady-state conditions were achieved by feeding a solution of sodium sulfite to maintain DO at 1-3 mg/L. OTE was determined by off-gas analysis. The results of the tests are summarized in Table 3-9.

A column testing program has been used to test fine pore ceramic dome diffusers for use in the retrofit of coarse bubble diffusion systems (24). A test column was submerged in an aeration basin, and mixed liquor was pumped through the column. Off-gas analysis was used to measure OTE. To evaluate the effects of diffuser fouling on OTE, tests were conducted consecutively on a fouled and a new diffuser. To avoid significant changes in wastewater characteristics, testing was completed within 1 hour. F values of 0.63 and 0.69 were measured at two different treatment plants. The time in service was not reported.

d. Summary

F and f_F were estimated for eight operating treatment plants using off-gas testing data generated in full-scale aeration basins. f_F ranged from 0 to 0.074/month, based on the assumption that F was a linear function of time. Although some of the linear regressions were

not statistically significant, the results are useful for comparison purposes.

Analysis of full-scale operation data from the Green Bay, WI treatment plant showed that OTE decreased to a minimum value equivalent to $F = 0.7$. Therefore, when assuming that F is a linear function of time, a minimum value of OTE must also be assumed.

3.4 Process Water Data Base

3.4.1 General Data Summary

As described earlier, a substantial data base exists for the clean water performance of the diffused aeration systems considered in this manual. The process water oxygen transfer data base is more limited. Although many techniques are available for measuring in-process oxygen transfer rates, most of the process water data base reported in this manual was collected using off-gas analysis techniques (13).

A summary of process water oxygen transfer performance data from several evaluations at sites employing a variety of aeration devices is presented in Tables 3-10 and 3-11. The term AD/AT in Table 3-10 is the ratio of the total projected media surface area of the installed diffusers to the aeration basin floor area. Footnote b in Table 3-10 defines the specific diffuser areas used to calculate AD/AT values. The information in Table 3-10 provides a detailed summary of the physical characteristics of the various test sites. It may be used, in conjunction with Table 3-11, to better evaluate the results of oxygen transfer performance at the respective sites. In most instances, the data reported herein were generated during field investigations conducted as a part of the EPA/ASCE Fine Pore Aeration Project.

The data in Table 3-11 include the mean weighted values for $\alpha F(\text{SOTE})$ and αF . The ranges represent

Figure 3-16: EF vs. time in service - Green Bay, WI.

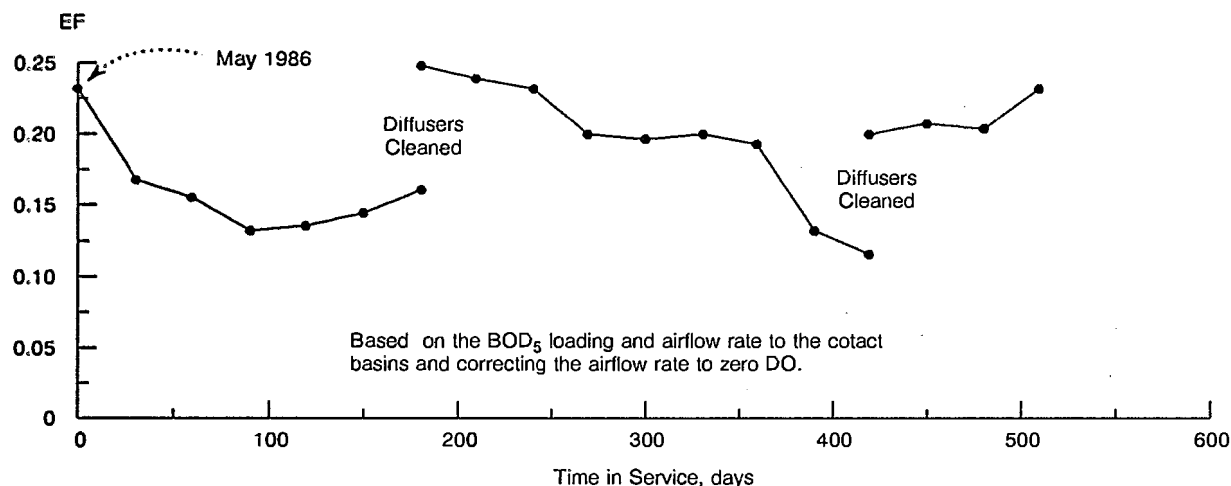


Table 3-9. Fouling Rates Estimated by Clean Water Column Testing

City - Plant	Time in Service, months	F*	f _F , 1/month	Comments
Frankenmuth, MI	12.8	0.74	0.021	Lower than measured by full-scale testing (0.029)
Green Bay, WI	14.0	0.71	0.020	Lower than measured by full-scale testing (0.064); linear model not appropriate for 1st period (see text)
Milwaukee, WI; Jones Island West	13.6	0.56	0.033	No comparison with full-scale data available
Milwaukee, WI; South Shore	13.7	0.99	<0.001	Agrees with full-scale test results
Madison, WI; Nino Springs	12.0	0.99	<0.001	Agrees with full-scale test results
Monroe, WI	12.0	0.98	0.002	No comparison with full-scale data available (see text)
Los Angeles County, CA; Whittier Narrows	9.6	0.90	0.011	Lower than measured by full-scale testing (0.027)
Houghton, MI; Portage Lake	12.7	0.83	0.013	No comparison with full-scale data available

* After indicated time in service.

temporal variations in these mean weighted values and not spatial variations in oxygen transfer within the reactors. Spatial variations are addressed in detail in Section 3.4.2.5. αF was estimated using clean water test data for similar reactor geometries, airflow rates per diffuser, and diffuser placements. Since many of the data were collected after the diffusers had been in service for significant periods of time, the term αF was used instead of α (see Sections 3.1 and 3.3 for more discussion on F). OTE_f values collected in the field were always corrected to standard conditions of temperature and pressure and a basin DO of 0 mg/L to calculate $\alpha F(SOTE)$ values.

It must be emphasized that the oxygen transfer data presented in Table 3-11 represent the results of many oxygen transfer tests, each conducted over a period

of several hours duration. Caution should be exercised in using these data directly for design purposes. The intent of this table is to give the reader a general feeling for the range of performance of the systems listed under a variety of operating conditions.

3.4.2 Selected Variables Affecting Process Water Performance

A review of many oxygen transfer process water studies indicates that several design and operational variables affect the oxygen transfer performance of fine pore aeration systems. However, the relative lack of controlled studies makes it difficult to draw strong conclusions regarding the impact of these variables. The following sections discuss the observations made to date.

3.4.2.1 Wastewater Characteristics

The literature is replete with studies on the effects of wastewater characteristics on oxygen transfer. Both α and the nature and dynamics of fouling are attributed to wastewater properties. Surfactants (surface active agents) are believed to play an instrumental role in the depression (and occasionally the increase) of α in wastewaters (47-49). The rise in α as treatment progresses down the length of plug flow aeration basins has been attributed to surfactant removal from the wastewater. Other wastewater properties may also have an impact on α , including total dissolved solids (1,2) and transition elements such as iron and manganese (50).

The reader is referred elsewhere (1-3) for an in-depth discussion of the impact of wastewater properties on α . The effect of wastewater characteristics on fouling has been discussed in detail in Section 3.3.3.

It is instructive to note that αF values obtained from a significant number of in-process studies (Table 3-11) are lower than first anticipated for fine pore aeration systems in municipal wastewater. Although αF values presented in this table are dependent on several process and design variables for the specific treatment plants tested, it is apparent that the average mean weighted αF is usually <0.5 . The impacts of process loading and flow regime on this value are described in Sections 3.4.2.4 and 3.4.2.5, respectively.

The variability of αF is site specific. Examples of typical variations over a 24-hr period are presented in Table 3-12 and illustrated in Figure 3-17. As described previously, αF is affected by several factors, including wastewater characteristics and process conditions. This abbreviated data base reveals that wastewater strength may have affected hour-to-hour variations of αF , at least at two sites. αF variations at Ridgewood, NJ (Figure 3-17a) appear to correlate with primary effluent soluble TOC (40). It was also demonstrated at Ridgewood that αF decreased with an increase in oxygen uptake rate. $\alpha F(\text{SOTE})$ and αF were sensitive to influent strength, as measured by COD (Figure 3-17b), at the Whittier Narrows treatment plant (28). At this facility, operated at a low average SRT (Table 3-11), the effect of COD on αF extended down the basin to all three grids.

In contrast, the results of a 24-hr survey at Madison, WI did not reveal a strong relationship between αF and influent wastewater strength (Figure 3-17c). αF varied from 0.22 to 0.29 at the inlet end of the aeration basin, yet influent TOC load varied by a factor of greater than 2. It is likely the low αF variability at Madison was due primarily to the low strength of the primary effluent (average $\text{BOD}_5 = 90 \text{ mg/L}$).

A review of 24-hr αF variations at these sites (Table 3-12) revealed a maximum αF :average αF of 1.21, with a range of 1.08-1.47. The average value of minimum αF :average αF was 0.86, while the range was 0.77-0.96.

3.4.2.2 Diffuser Airflow Rate

OTEs achieved by fine pore diffusers in clean water normally decrease as airflow rate per diffuser increases, as described in Section 2.6.2.2. Equations 2-2 and 2-3 are also valid in process waters. The values of the constants will change, however, to reflect the effects of process waters and diffuser foulants on OTE.

The results of several recent studies (20-22,26,28,40,46) on fine pore aeration systems indicate that the effect of process conditions on the airflow rate- $\alpha F(\text{SOTE})$ relationship is to shift the curves downward from the corresponding clean water curve (a typical example is shown in Figure 3-18). The shape of the in-process curves varies from site to site, however. At Ridgewood (41), the slope of the curve was steeper than that for clean water, while at Green Bay (20), no discernible effect of airflow on $\alpha F(\text{SOTE})$ was reported. At Madison (26), Monroe (22), Glastonbury (47), and Hartford (21), the curves were roughly parallel but lower than the respective clean water curves. At the Jones Island East treatment plant, $\alpha F(\text{SOTE})$ was constant over a range of airflow rates at the inlet end of the basin and actually increased at the effluent end with increased airflow rates (38).

In-process data with values of the exponent m in Equation 2-3 dramatically different from those typically determined in clean water tests have been reported (51). In-process values of m ranged from -0.63 to -0.82 compared with clean water values of -0.1 to -0.3. The apparent extreme change in the relationship between diffuser airflow rate and OTE may have been caused by the configuration of the test grids rather than process-related changes in diffuser performance. Three 9.1-m (30-ft) square grids of fine pore diffusers were interspersed between sections of coarse bubble diffusers. Bulk mixing patterns probably changed when the airflow rates were adjusted in this study.

An analysis of data plotted in Figure 3-19 from selected treatment plants listed in Table 3-10 reveals that a trend exists between airflow and $\alpha F(\text{SOTE})$. Plants that were nitrifying have been highlighted since process conditions will greatly affect $\alpha F(\text{SOTE})$ (see Section 3.4.2.4). Diffuser density may also play an important role in this relationship. High diffuser densities (numbers of diffusers/unit area of basin floor) or high AD/AT values will usually result in both lower airflow/unit area of diffuser media and higher SOTE values. It has been reported (44) that increasing diffuser density increased $\alpha F(\text{SOTE})$ more (from 0.75 to 1.02 percent/ft) than would have been predicted

Table 3-10. Physical Characteristics of Wastewater Treatment Facilities Providing Oxygen Transfer Data

Site No	City - Plant	No Passes per Basin	Process Type	Flow Regime	Air Dist.	Dimensions of Each Pass, ft			Diff. Sub., ft	Diffuser Type	No. Aeration Zones per Pass	No Diffusers per Basin	Diffuser Density, No./100 sq ft	AD/AT ^a	Ref
						L	W	SWD							
1	Frankenmuth, MI	2	Contact	Plug	Uniform	44	22	15	14.1	Ceramic	1	400	41.7	0.17	30
		1	Stabilization	Flow		44	22	15	14.1	Discs	1	400			
2	Green Bay, WI	1	Contact	Plug	Tapered	244	73	20.5	19.1	Perf. PVC	3	4,620	21.2	0.22	20
		1	Stabilization	Flow	Uniform	244	36.3	22.5	19.1	Membrane Tubes	1	1,398			
3	Green Bay, WI	1	Contact	Plug	Tapered	244	73	20.5	19.1	Ceramic	3	6,128	30.3	0.12	20
		1	Stabilization	Flow	Uniform	244	36.3	22.5	19.1	Discs	1	2,148			
4	Hartford, CT	3	Contact	Step		194	20	15.5	15	Ceramic	7	2,265	21.3	0.07	21
		1	Stabilization	Feed		194	20	15.5	15	Domes	7	1,064			
5	Milwaukee, WI; Jones Island East	1	Conventional	Plug Flow	Tapered	370	21.5	14	14	Ceramic Plates	3	1,450	18.2	0.18	38
6	Milwaukee, WI; Jones Island West	2	Conventional	Plug Flow	Uniform	222	22	15	15	Ceramic Plates	1	2,222	22.7	0.23	41
7&8	Madison, WI; East	3	Conventional	Plug Flow	Tapered	135	29.5	15.5	15	Ceramic Domes	2	3,180	26.3	0.09	26
9	Madison, WI; West	3	Conventional	Plug Flow	Tapered	258	25.7	17	16.1	Ceramic Discs	3	3,894	19.6	0.08	26
10	Ridgewood, NJ	1	Conventional	Plug Flow	Uniform	116	24	14.8	14	Ceramic Domes	4	650	23.3	0.07	40
11	Milwaukee, WI; South Shore	1	Conventional	Step Feed	Uniform	370	30	15	15	Ceramic Plates	1	2,448	22.2	0.22	39
12	Los Angeles County, CA; Whittier Narrows	1	Conventional	Plug Flow	Tapered	300	30	14.3	12.5	Ceramic Discs	3	2,026	22.7	0.09	28
13	Los Angeles County, CA; Whittier Narrows	1	Conventional	Plug Flow	Tapered	300	30	14.3	12.5	Ceramic Domes	3	2,686	29.4	0.09	28
14	Los Angeles, CA; Terminal Island	1	Conventional	Plug Flow	Tapered	300	30	15	-	Perf. PVC Membrane Tubes	3	1,000	11.1	0.12	28
15	Los Angeles, CA; Terminal Island	1	Conventional	Plug Flow	Tapered Spiral	300	30	15	-	Nonrigid Porous Plastic Tubes	3	384 2' 383 3'	8.5	0.07	28
16	Los Angeles County, CA; Valencia	2	Contact	Plug	Tapered	54.6	26.5	15	13	Rigid Porous	2	841	30.3	0.08	28
		1	Stabilization	Flow		25.6	26.5	15	13	Plastic Tubes	1	257			
17	Monroe, WI	2	Conventional	Step Feed	Uniform	102	25	15	14.3	Ceramic Discs	2	900	17.5	0.07	22

Table 3-1b. (continued)

Site No.	City - Plant	No. Passes per Basin	Process Type	Flow Regime	Air Dist.	Dimensions of Each Pass. ft			Diff. Sub., ft	Diffuser Type	No. Aeration Zones per Pass	No. Diffusers per Basin	Diffuser Density, No./100 sq ft	AD/AT ^a	Ref.
						L	W	SWD							
18	Phoenix, AZ; 23rd Ave.	4	Conventional	Step Feed	Tapered	310	25	15.8	15	Ceramic Domes	3	7,280	23.3	0.08	42
19	Phoenix, AZ; 91st St.	4	Conventional	Plug Flow	Tapered	250	25	15.75	13.75	Ceramic Domes	1	7,500	30.3	0.10	43
20	Phoenix, AZ; 91st St.	5	Conventional	Plug Flow	Tapered	50	50	15.75	13.75	Ceramic Discs	1	3,286	26.3	0.11	43
21 & 22	Minneapolis, MN; Metro	4	Conventional	Step Feed	Uniform	375	30	15.5	13.5	Ceramic Domes	1	7,700	17.2	0.05	44
23	Minneapolis, MN; Metro	4	Conventional	Step Feed	Uniform	375	30	15.5	13.5	Ceramic Domes	1	19,400	43.5	0.14	44
24	U.K.; Rye Meads	2	Conventional Incl. Anoxic	Plug Flow	Tapered	230	14.1	10.5	9.75 ^b	Ceramic Domes	3	1,377	21.3	0.07	45
25	U.K.; Rye Meads	2	Conventional	Plug Flow	Tapered	230	14.1	10.5	9.75 ^c	Ceramic Domes	3	1,197	18.5	0.06	45
26	Glastonbury, CT	3 1	Contact Stabilization	Plug Flow	Uniform (spiral)	82.5	20	15.3	12.3	Rigid Porous Plastic Tubes	1	320	48.5	0.05	46

^a Effective (total projected) surface area of diffuser media/basin floor area.

Ceramic disc = 0.41 sq ft; ceramic dome = 0.32 sq ft; ceramic plate = 1.0 sq ft; perforated PVC membrane tube = 1.047 sq ft; rigid porous plastic disc = 0.33 sq ft; nonrigid porous plastic tube = 0.33 sq ft/ft tube length; rigid porous plastic tube = 1.08 sq ft.

^b Estimated.

Table 3-11. Oxygen Transfer and Plant Process Data

Site No.	City - Plant	$\alpha F(SOTE)/ft$, percent			αF			scfm/sq ft ^a			lb BOD ₅ /d/ 1,000 cu ft	F/M ^b , day ⁻¹	SRT ² , days	scfm/BOD ₅ ^c	No. Samples
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max					
1	Frankenmuth, MI	0.73	0.58	0.95	0.37	0.30	0.48	0.80	0.63	0.97	95	0.52	11.0	0.56	9
2	Green Bay, WI	0.71	0.57	0.91	0.43	0.35	0.54	0.73	0.46	1.02	149	0.59	3.0	0.36	9
3	Green Bay, WI	0.86	0.54	1.19	0.49	0.36	0.64	0.62	0.39	0.93	149	0.59	3.0	0.30	9
4	Hartford, CT	0.64	0.46	0.84	0.36	0.24	0.48	0.36	0.18	0.52	52	0.16	7.6	0.45	12
5	Milwaukee, WI; Jones Island East	1.09	0.81	1.36	-	-	-	0.20	0.12	0.35	72	0.77	3.8	0.20	30
6	Milwaukee, WI; Jones Island West	0.77	0.44	1.04	-	-	-	0.17	0.08	0.28	71	0.82	3.3	0.16	21
7	Madison, WI; East	0.74	0.54	1.04	0.43	0.31	0.57	0.28	0.15	0.38	36	0.63	2.2	0.49	21
8	Madison, WI; East	1.14	0.97	1.36	0.66	0.56	0.79	0.23	0.19	0.27	12	0.12	14.0	1.25	8
9	Madison, WI; West	0.92	0.87	0.98	0.48	0.44	0.51	0.20	0.19	0.22	16	0.15	9.6	0.74	5
10	Ridgewood, NJ	0.67	0.38	0.94	0.41	0.23	0.58	0.39	0.11	0.67	20	0.24	3.1	1.32	48
11	Milwaukee, WI ; South Shore	1.25	0.99	1.48	-	-	-	0.14	0.08	0.26	26	0.37	7.5	0.36	20
12	Los Angeles County, CA; Whittier Narrows	0.72	0.47	0.94	0.31	0.21	0.40	0.25	0.15	0.38	30	0.61	2.6	0.56	35
13	Los Angeles County, CA; Whittier Narrows	0.55	0.25	0.89	0.24	0.11	0.39	0.32	0.20	0.55	30	0.61	2.6	0.71	34
14	Los Angeles, CA; Terminal Island	0.48	0.27	0.67	-	-	-	0.68	0.39	1.32	-	0.27	6.6	-	8
15	Los Angeles, CA; Terminal Island	0.80	0.62	1.19	0.45	0.30	0.74	0.47	0.23	0.94	-	0.27	6.6	-	7
16	Los Angeles County, CA; Valencia	0.56	0.40	0.62	0.28	0.26	0.29	0.43	0.27	0.47	-	-	-	-	7
17	Monroe, WI	0.63	0.54	0.80	0.35	0.28	0.54	0.36	0.29	0.42	33	0.40	8.1	0.73	12
18	Phoenix, AZ; 23rd Ave.	0.47	0.44	0.51	0.27	0.24	0.31	0.53	0.31	0.66	38	0.76	1.0	0.75	6
19	Phoenix, AZ; 91st St.	0.58	-	-	0.29	-	-	0.37	-	-	34	-	2.0	0.70	1
20	Phoenix, AZ; 91st St.	0.59	-	-	0.28	-	-	0.33	-	-	33	-	1.6	0.70	1
21	Minneapolis, MN; Metro	0.70	0.56	0.84	0.37	0.29	0.45	0.43	-	-	62	-	5	0.45	6
22	Minneapolis, MN; Metro	0.75	0.64	0.86	0.40	0.34	0.46	0.43	-	-	28	-	10	0.99	18
23	Minneapolis, MN; Metro	1.02	0.92	1.11	0.52	0.45	0.59	0.39	-	-	24	-	9	1.04	44
24	U.K.; Rye Meads	1.00	0.90	1.10	-	-	-	0.21	0.19	0.24	36	-	11.7	1.32	-
25	U.K.; Rye Meads	0.67	0.57	0.89	-	-	-	0.21	0.19	0.22	66	-	2.7	0.73	-
26	Glastonbury, CT	0.55	0.41	0.70	0.56	0.42	0.67	0.19	0.14	0.29	27	0.19	-	0.46	6

^a scfm of airflow/sq ft basin floor area.^b Based on MLSS under aeration.^c Average scfm of airflow based on measured off-gas flux rate per unit area of basin floor/average lb BOD₅ applied per day.

Table 3-12. 24-hr αF and $\alpha F(SOTE)$ Variations at Selected Municipal Treatment Plants

Site No.	City - Plant	αF			$\alpha F(SOTE)$			Position in Basin
		Average	Minimum	Maximum	Average	Minimum	Maximum	
4	Hartford, CT	0.30	0.23	0.44	8.3	6.4	11.2	Influent pass
9	Madison, WI; West	0.24	0.22	0.29	8.7	7.7	10.4	Inlet end
10	Ridgewood, NJ	0.46	0.44	0.59	10.7	9.5	13.1	Entire basin weighted
12	Los Angeles* County, CA; Whittier Narrows	0.25	0.21	0.27	7.8	6.4	8.7	Influent grid
12	Los Angeles* County, CA; Whittier Narrows	0.26	0.20	0.30	8.7	6.6	9.9	Middle grid
13	Los Angeles County, CA; Whittier Narrows	0.45	0.41	0.50	12.2	11.1	13.5	Effluent grid
17	Monroe, WI	0.23	0.19	0.28	-	-	-	Influent pass
17	Monroe, WI	0.39	0.33	0.45	-	-	-	Effluent pass

* Data for 6-hr period.

because of an increase in AD/AT (from 0.05 to 0.14) alone (see Site 22 vs. Site 23 in Figure 3-23).

The envelope depicted in Figure 3-19 follows the general shape of the SOTE vs. airflow curve for ceramic diffusers (Figure 2-16). It is not realistic to use this curve directly for design since many other variables affected the oxygen transfer performance shown in this figure. However, it does provide an explanation for the excellent performance of two of the three ceramic plate installations in Milwaukee. It should be noted that the performance of the Milwaukee Jones Island West treatment plant (Site 6 in Figure 3-19) falls below that of the other two Milwaukee plate facilities (Sites 5 and 11). This is likely because of the age of the plates in this facility and the air distribution problems associated with the condition of the plates (10). Despite the reported condition of this highly-loaded facility, which is scheduled for rehabilitation, it is operating at a very low and favorable air utilization rate per pound of applied BOD.

3.4.2.3 Diffuser Layout and Characteristics

Insufficient data are available to demonstrate significant differences in $\alpha F(SOTE)$ values for different fine pore diffuser types. Few controlled studies have been reported, and site-to-site variations obscure any clear delineation between diffuser materials, shapes, or sizes. Evidence previously presented in Section 3.3.3 indicates that fouling of different diffuser materials may significantly affect long-term performance.

At least one study (22) has demonstrated that ceramic diffuser specific permeabilities of 26-50 (BRV₀ of 15-8 cm [6-3 in w.g.]) did not have a dominant effect on $\alpha F(SOTE)$ s in a municipal wastewater. Operating conditions and wastewater characteristics appeared to have a greater influence on $\alpha F(SOTE)$ than did diffuser pore size except for values of BRV₀ less than

10 cm (4 in) w.g. If an optimum situation from the standpoint of $\alpha F(SOTE)$, operating pressure, and cleanability exists, it would appear to be in the range of specific permeabilities of 20-40 (BRV₀ of 18-10 cm [7-4 in w.g.]). The Milwaukee experience has been developed from slightly lower specific permeabilities of 15-21 (10,38,39).

It is not possible at this time to predict important differences in $\alpha F(SOTE)$ as a function of diffuser layout. All the treatment plants reported in Table 3-10 used a grid layout pattern with two exceptions, Glastonbury and Terminal Island. Generally, clean water test data (Section 2.6.2.2) indicate that grid patterns should produce higher transfer efficiencies than single spiral roll, mid-width, dual spiral roll, and cross roll configurations.

The performance of the three Milwaukee ceramic plate diffuser installations - Jones Island East (JIE), Jones Island West (JIW), and South Shore (MSS) - are of interest relative to other grid systems (38,39,41). As described in Section 2.6.2.2, diffuser density affects oxygen transfer; as density or AD/AT increases, SOTE increases. The JIW and the MSS plate systems have two of the highest AD/AT values (0.23 and 0.22, respectively) of the treatment plants presented in Table 3-9. The JIE treatment plant AD/AT is also high at 0.18. As a result of their associated high diffuser densities, these three treatment plants also operate at very low airflow rates per unit area of basin floor (0.7-1.0 L/s/m² [0.14-0.20 scfm/sq ft]) and low diffuser air flux rates (3.2-5.6 L/s/m² [0.63-1.1 scfm/sq ft]).

SOTE and $\alpha F(SOTE)$ typically increase as unit airflow rate decreases, as shown in Figure 3-18. Two of the three facilities (MSS and JIE) report two of the highest average $\alpha F(SOTE)$ values in Table 3-11 for those

Figure 3-17a. 24-hr variations in αF and $\alpha F(\text{SOTE})$ - Ridgewood, NJ.

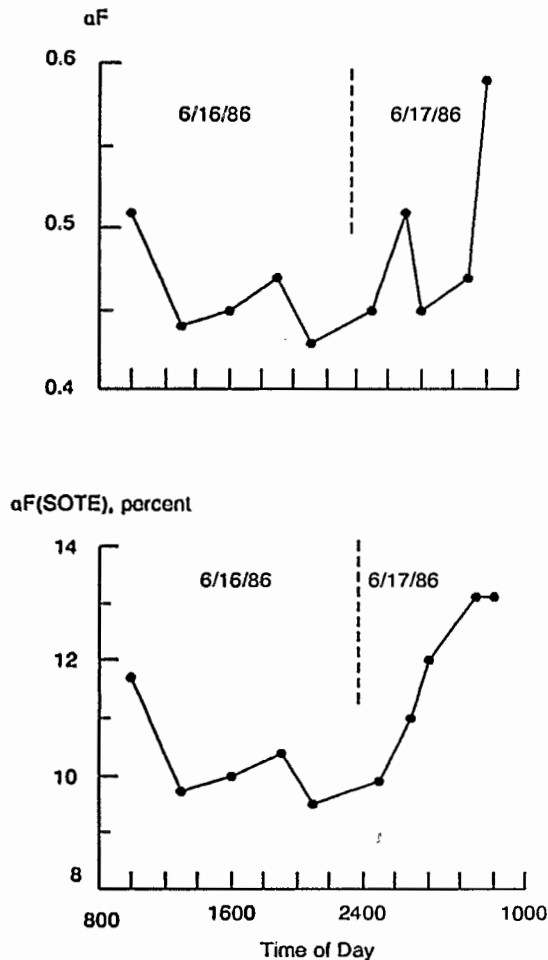
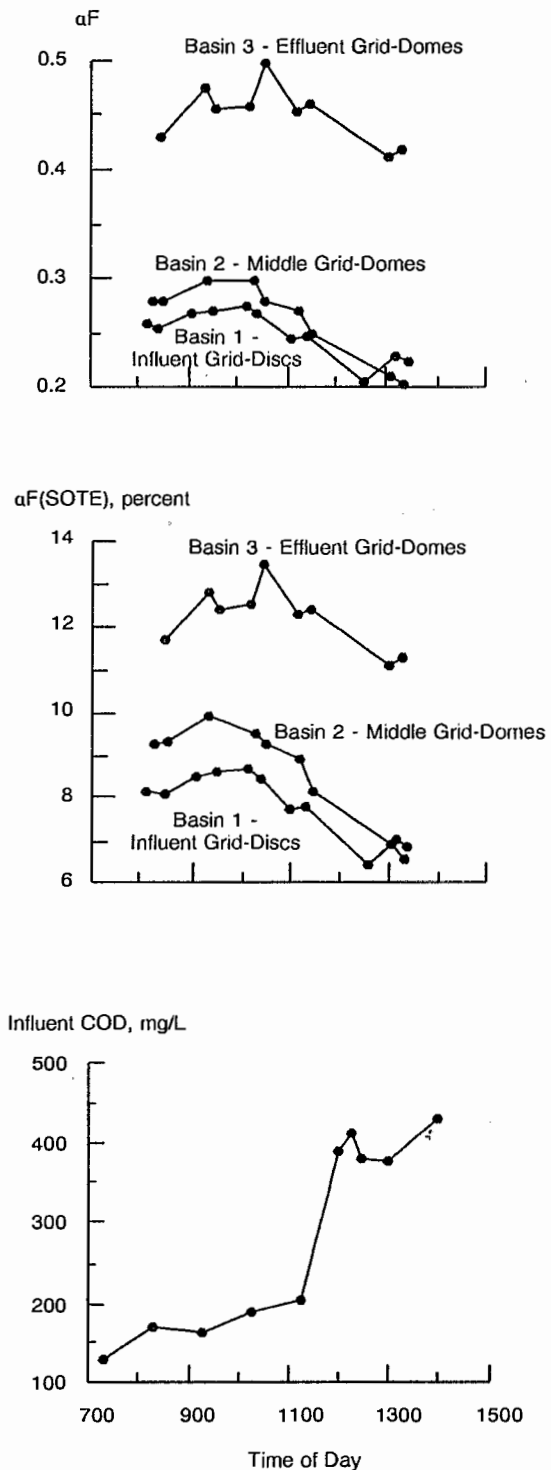


Figure 3-17b. Variations in αF , $\alpha F(\text{SOTE})$, and COD - Whittier Narrows, CA.



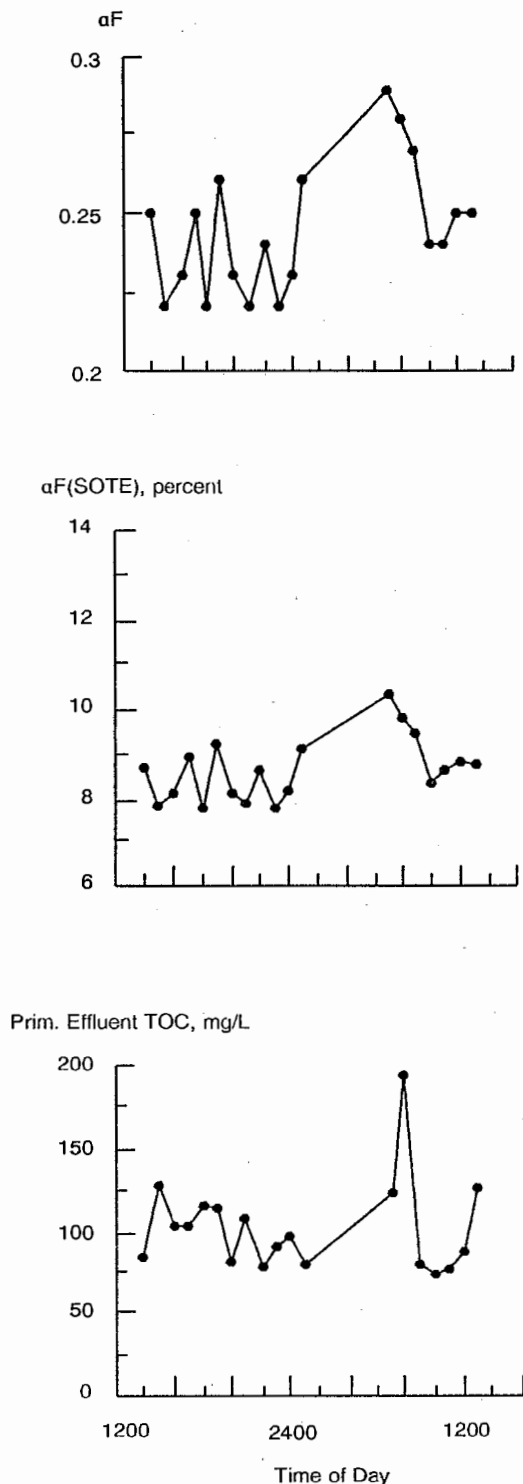
treatment plants with higher process loadings (SRTs <8 days, neither plant nitrifying). Additional support for reducing the airflow rate through each diffuser is that fouling is believed to be associated with the rate of local flux through the ceramic media (see Section 3.3.2). It may also be associated with the overall flux rate as well.

These data indicate fine pore aeration systems configured with high AD/AT values (thereby incurring low airflow rates per unit area of diffuser media) will usually produce higher OTEs than systems with lower AD/AT values and higher airflows. Although no controlled studies are available to support this hypothesis, the concepts presented in Section 2.6.2.2 support this general statement.

3.4.2.4 Process Loading Effects

A review of the dynamics of $\alpha F(\text{SOTE})$ in a variety of activated sludge systems suggests that several process variables affecting oxygen transfer are not

Figure 3-17c. Variations in αF , $\alpha F(\text{SOTE})$, and TOC at influent end of aeration tank - Madison, WI.



clearly identifiable based on our current knowledge of the process. For example, $\alpha F(\text{SOTE})$ data collected at Madison, WI (26) over an 800-day period (Figure 3-20) in the first pass of a three-pass plug flow system demonstrate a significant variability in $\alpha F(\text{SOTE})$ with time. Some of this variability may be attributed to the properties of the wastewater (i.e., composition and strength), but cannot account for all of it. Multiple linear regressions of the data including SRTs, F/M loadings, volumetric organic loadings, MLVSS concentrations, and airflow rates could account for up to about 60-70 percent of the variability.

Similar findings were described for the Whittier Narrows treatment plant (28), where 30-74 percent of the variability in $\alpha F(\text{SOTE})$ could be accounted for by F/M loadings, airflow rates, and time-in-service.

These studies suggest that elements of process loading may have some impact on diffuser performance. There are theoretical reasons why αF should be a function of SRT, F/M loading, or MLVSS concentration (28). Current biological treatment models developed for activated sludge predict substrate concentration as a function of these parameters. Since the substrates are partially comprised of surfactants, lower substrate concentrations imply lower surfactant levels and higher α values. Furthermore, biomass production is also related to these variables. The dynamics of biomass accumulation and depletion on diffuser surfaces will very likely influence F (see Sections 3.3.2 and 3.3.4). The impact of these process loading factors may be short or long term depending on their effects on both α and F .

Studies conducted at the Madison, WI East treatment plant equipped with dome diffusers revealed significant increases in $\alpha F(\text{SOTE})$ with increasing SRTs (26). In 1984-85 when the East plant was not nitrifying, SRT averaged 2.4 days ($s = 1.2$) and the average $\alpha F(\text{SOTE})$ was 11.5 percent ($s = 2.4$). In 1987 when the East plant was nitrifying, the average SRT was 14.0 days ($s = 3.3$) and the average $\alpha F(\text{SOTE})$ was measured at 17.1 percent ($s = 2.1$).

The Metropolitan Waste Commission of Minneapolis/St. Paul (44) also conducted studies with dome diffusers that suggest a relationship between process loading and αF , as depicted in Figure 3-21. These data were collected at four sites in the Minneapolis/St. Paul area.

To evaluate the impact of process loading on $\alpha F(\text{SOTE})$, a controlled study was performed at the Madison, WI West treatment plant in 1986 (26). Over a 50-day period, two parallel systems were operated at two different SRTs: one at about 11 days and the other at about 6 days. $\alpha F(\text{SOTE})$ was monitored in the first pass of each three-pass system. Both systems were operated at the same volumetric BOD_5 loading

Figure 3-18. $\alpha F(\text{SOTE})$ and SOTE vs. applied airflow rate for ceramic disc diffusers - Monroe, WI.

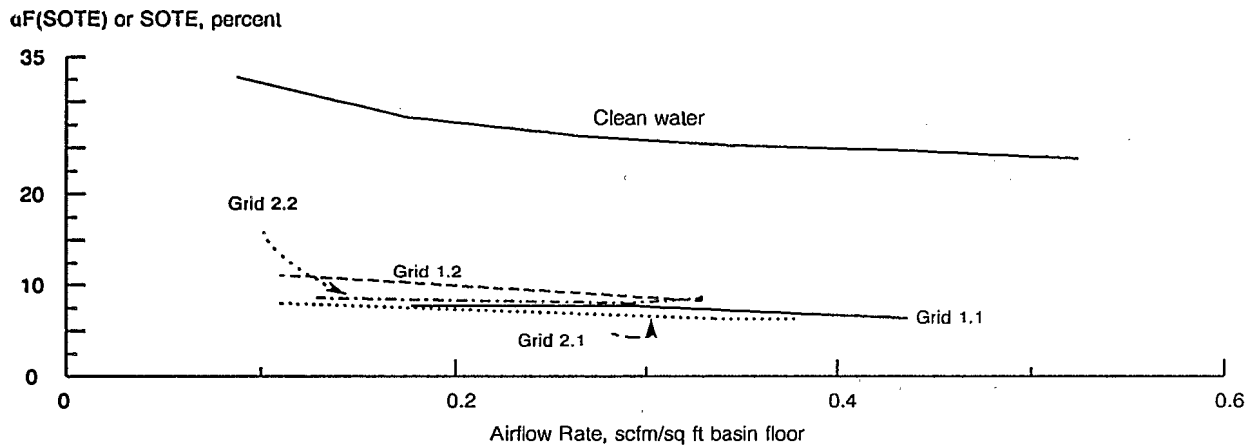
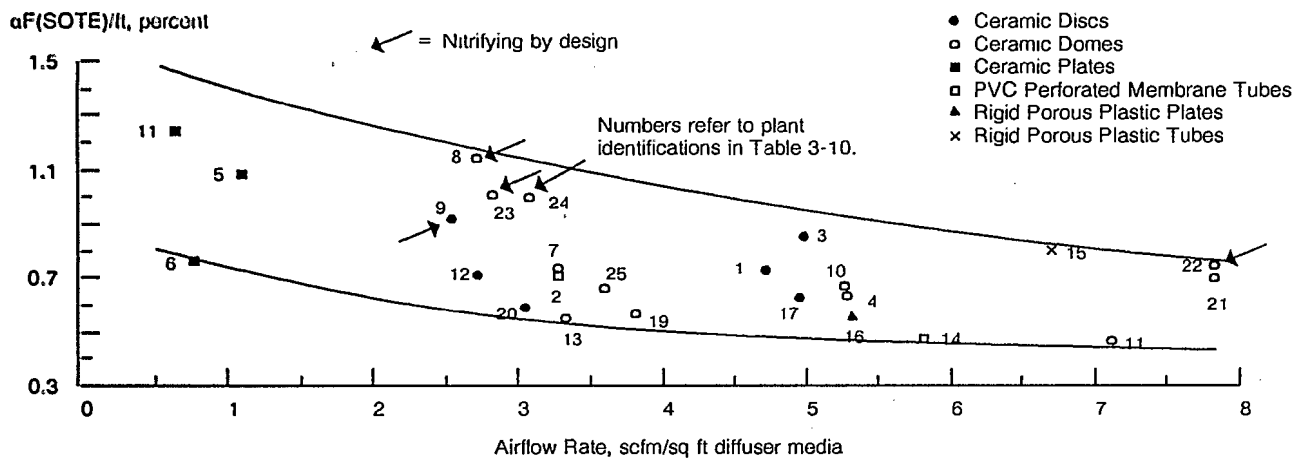


Figure 3-19. Mean $\alpha F(\text{SOTE})$ vs. airflow rate per unit area of diffuser media.



and both were nitrifying. Results of this study are presented in Table 3-13.

In every instance, $\alpha F(\text{SOTE})$ for the high-SRT system was higher than that of the low-SRT system. At the 95 percent confidence level, however, a significant difference in $\alpha F(\text{SOTE})$ could not be demonstrated for these two operating conditions. Because of the wide variations in $\alpha F(\text{SOTE})$ s observed during the test period, it is difficult to prove that SRT alone affected oxygen transfer in this facility. It should be emphasized, however, that the study was conducted in the first pass of a three-pass system. Other studies at the Madison East treatment plant indicated that the first-pass basins were less sensitive to variations in operation than the subsequent passes.

It has been shown that, for treatment plants with low SRTs (1-2 days), use of the "working definition" of

SRT [e.g., $\text{SRT} = X(V/Q_w)X_w$, where X and X_w are MLVSS and waste VSS, respectively, V is process water volume, and Q_w is waste solids flow rate] significantly underestimates the true SRT when nonsteady-state conditions occur (28). Furthermore, the sampling frequency required for accurately assessing the true SRT in low-SRT systems is far greater than is practical (1.5-2 times per day).

A correlation between $\alpha F(\text{SOTE})$ and SRT at the Whittier Narrows treatment plant was not demonstrated because of the very low SRT. On the other hand, a regression of $\alpha F(\text{SOTE})$ vs. MLVSS concentration was much more successful at this treatment plant (28), as shown in Figure 3-22. MLVSS concentration should be correlated with growth rate and substrate removal since it is a component in the calculations of SRT and F/M loading.

Figure 3-20. $\alpha F(\text{SOTE})$ vs. time in service for ceramic disc diffusers in first pass - Madison, WI.

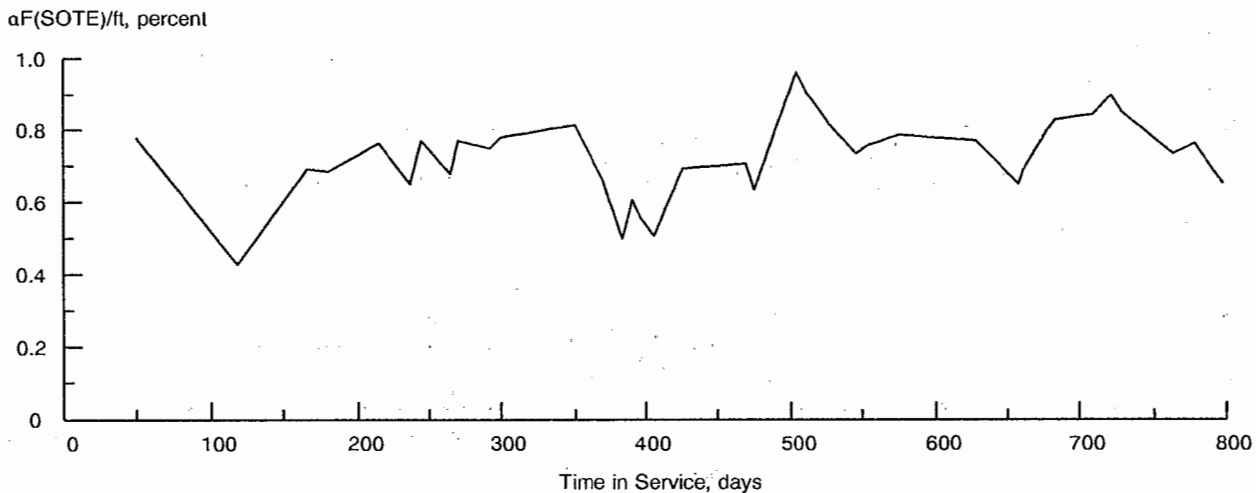
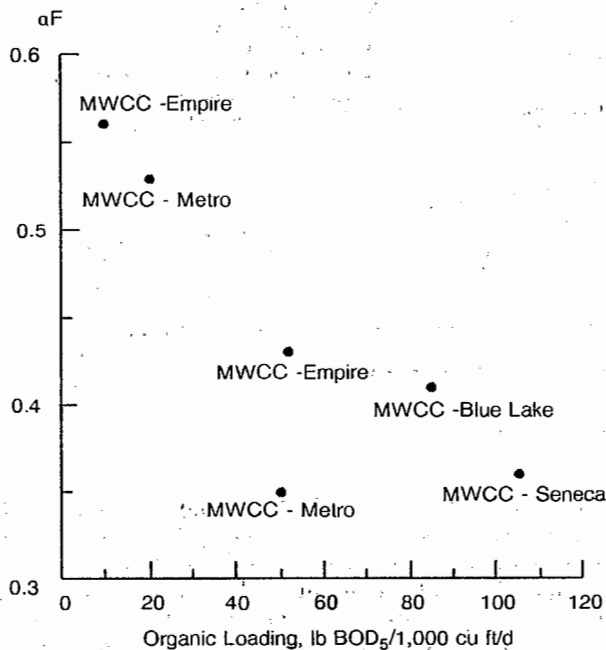


Figure 3-21. αF vs. organic loading for selected plants in the Minneapolis/St. Paul area.



Data from Table 3-11 were analyzed to determine whether a relationship between process loading and $\alpha F(\text{SOTE})$ may exist. A plot for the ceramic diffuser installations in this table, using SRT as the loading parameter, is given in Figure 3-23. Although wide variations in system design and operation, as well as wastewater characteristics, are evident at these sites, it appears a trend does exist between process loading and $\alpha F(\text{SOTE})$. Nitrifying treatment plants have been highlighted in this figure to indicate their relative importance to the relationship. Similar efforts to

Table 3-13. $\alpha F(\text{SOTE})$ for Aeration Systems with Different SRTs at Madison, WI West Plant

Date	$\alpha F(\text{SOTE})$, percent	
	System 1*	System 2*
9/11/86	14.39	13.06
10/9/86	10.13	9.37
10/14/86	9.89	7.99
10/16/86	10.07	9.29
10/21/86	10.51	9.74
10/23/86	9.62	9.20
10/28/86	9.85	8.91
10/30/86	9.71	9.40
x	10.52	9.62
s	1.59	1.48
SRT, days	11.1	5.9
MLSS, mg/L	1,770	1,140

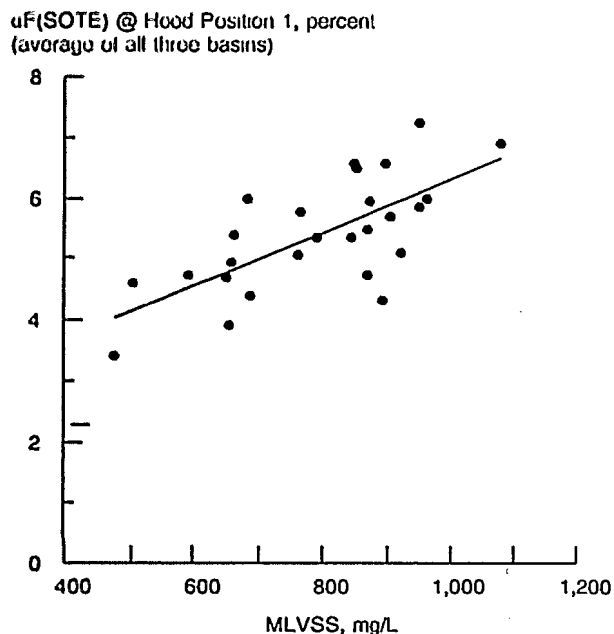
* Results are for first pass of a 3-pass system.

develop correlations between $\alpha F(\text{SOTE})$ and MLVSS concentration and F/M loading at these ceramic diffuser installations produced less definitive trends than that exhibited between $\alpha F(\text{SOTE})$ and SRT.

3.4.2.5 Flow Regime

Aeration basin flow regime affects the mixing pattern of the basin and, therefore, the residence time distribution of the influent wastewater. Because wastewater components may have an impact on $\alpha F(\text{SOTE})$, it is reasonable to expect that mixing patterns will also affect $\alpha F(\text{SOTE})$. A study conducted on the Madison, WI ceramic dome diffuser system (26) illustrates this concept (Figure 3-24). Single-day $\alpha F(\text{SOTE})$ profiles are compared as a function of grid position for one aeration basin when it was operated

Figure 3-22. $\alpha F(\text{SOTE})$ vs. MLVSS for ceramic disc diffusers - Whittier Narrows, CA.



first in a step feed mode vs. 2 months later when it was operated in a plug flow pattern of three passes in series. The switch from step feed to plug flow was made approximately half way between the two off-gas test days. In both cases, SRT was approximately 2.2 days.

The plug flow configuration produced an improved mean weighted $\alpha F(\text{SOTE})$ compared with the step feed mode of operation (9.4 vs. 7.1 percent). Addition of primary effluent at several points along the step feed basin resulted in depressed $\alpha F(\text{SOTE})$ s at each feed point. Apparently, the reduced α (or αF) values associated with each feed point had a significant impact on the mean weighted value of $\alpha F(\text{SOTE})$ for the step feed train. This same phenomenon is also demonstrated, respectively, in Figures 3-25 and 3-26 as a function of time for the same Madison basin (operated for 70 days in a plug flow mode) (26) and for an aeration basin at Hartford operated more than 500 days in a step feed flow regime (21).

The αF profile along the length of any aeration basin will depend on the degree of mixing that exists in that basin. Typical results for a variety of basin geometries are presented in Table 3-14. The site key given in the first column refers to the treatment plants described in Table 3-10. An examination of this table indicates that treatment plants with high length-to-width ratios, operating as plug flow basins, generate significant αF gradients. Conversely, treatment plants that are short and wide (such as Green Bay), or that employ step feed configurations (such as Hartford, Milwaukee South Shore, and Phoenix - 23rd Ave.) exhibit much less variability in αF along the basin length. Typical αF and $\alpha F(\text{SOTE})$ profiles for several treatment plants are illustrated in Figures 3-27 through 3-31.

Figure 3-23. $\alpha F(\text{SOTE})$ vs. SRT for ceramic diffuser facilities.

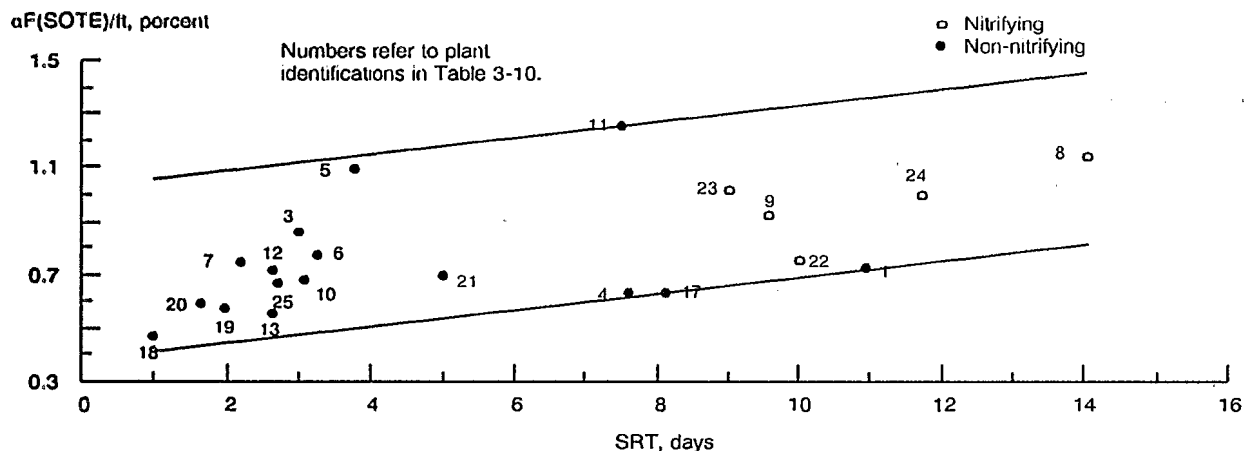


Figure 3-24. $\alpha F(\text{SOTE})$ vs. tank length for plug flow and step feed aeration systems - Madison, WI.

$\alpha F(\text{SOTE})$, percent

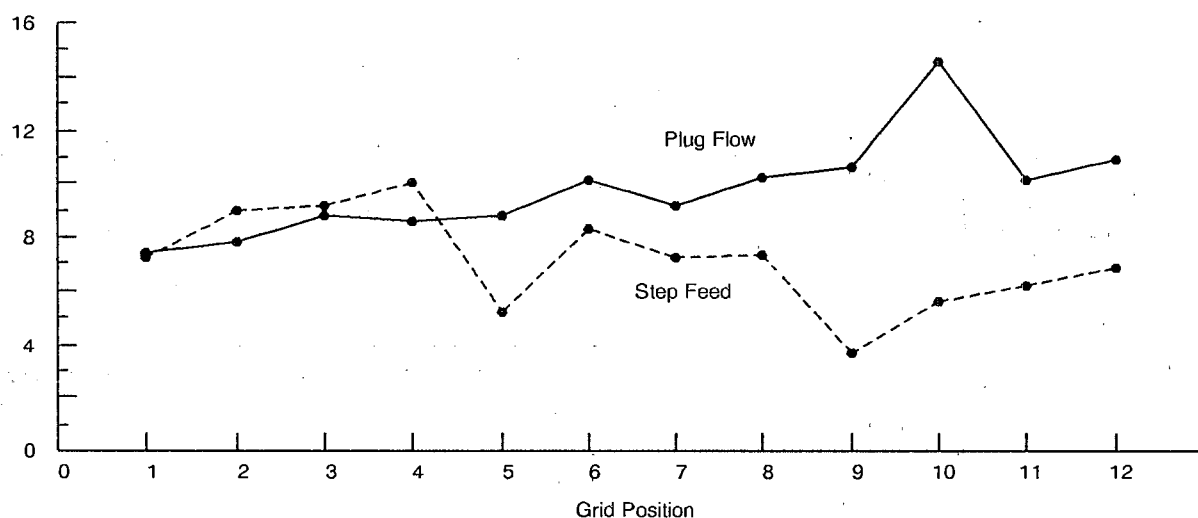


Figure 3-25. αF vs. time in service for three passes of a plug flow aeration system - Madison, WI East Plant.

αF

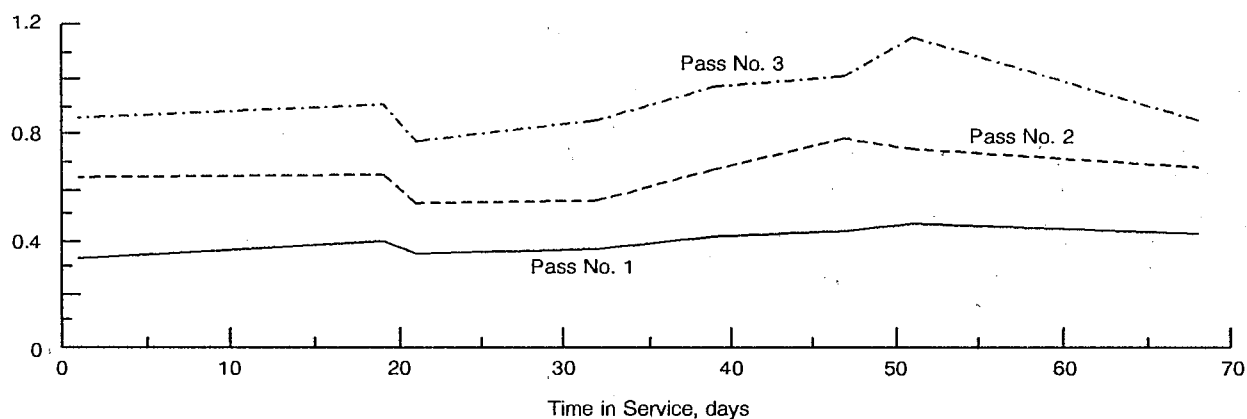


Figure 3-26. αF vs. time in service for three passes of a step feed aeration system - Hartford, CT.

αF

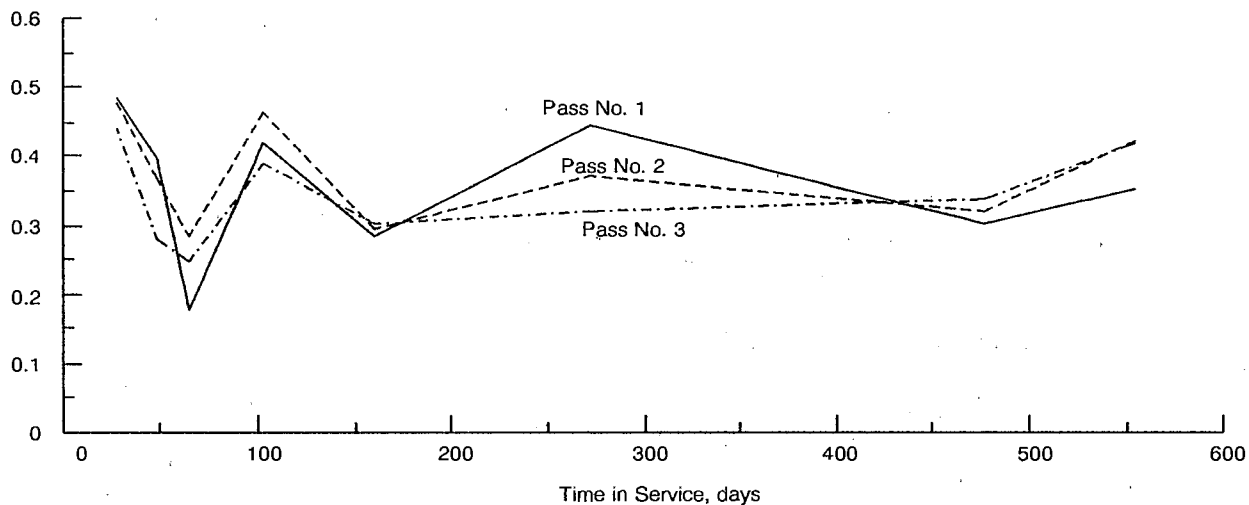


Table 3-14. αF Profiles for Various Aeration Systems^{a,b,c}

Site No.	City - Plant	aF												Diffuser Type	Flow Regime
		Zone 1			Zone 2			Zone 3			Total Basin				
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max		
2	Green Bay, WI	0.45	0.35	0.55	0.43	0.35	0.59	0.40	0.31	0.54	0.43	0.36	0.53	PVC Perf. Memb. Tubes	Plug Flow
3	Green Bay, WI	0.49	0.41	0.68	0.50	0.34	0.67	0.46	0.30	0.64	0.49	0.36	0.64	Ceramic Discs	Plug Flow
4	Hartford, CT	0.37	0.18	0.49	0.37	0.28	0.49	0.35	0.24	0.45	0.36	0.24	0.48	Ceramic Domes	Step Feed
5	Milwaukee, WI; Jones Island East	0.45	0.32	0.60	0.58	0.44	0.79	0.60	0.47	0.77	0.54	0.44	0.68	Ceramic Plates	Plug Flow
6	Milwaukee, WI; Jones Island West	0.34	0.18	0.46	0.40	0.27	0.49	0.43	0.25	0.60	0.39	0.23	0.52	Ceramic Plates	Plug Flow
7	Madison, WI; East	0.32	0.24	0.44	0.44	0.29	0.62	0.52	0.36	0.76	0.43	0.31	0.57	Ceramic Domes	Plug Flow
8	Madison, WI; East	0.40	0.33	0.47	0.64	0.54	0.78	0.92	0.77	1.00	0.66	0.56	0.79	Ceramic Domes	Plug Flow
9	Madison, WI, West	0.33	0.26	0.40	0.54	0.52	0.56	0.55	0.52	0.58	0.48	0.44	0.51	Ceramic Discs	Plug Flow
11	Milwaukee, WI; South Shore	0.64	0.50	0.92	0.62	0.47	0.83	0.64	0.51	0.83	0.63	0.51	0.75	Ceramic Plates	Step Feed
12	Los Angeles County, CA; Whittier Narrows	0.25	0.15	0.42	0.30	0.15	0.40	0.38	0.22	0.51	0.31	0.21	0.40	Ceramic Discs	Plug Flow
13	Los Angeles County, CA; Whittier Narrows	0.16	0.09	0.27	0.23	0.08	0.40	0.31	0.17	0.49	0.24	0.11	0.39	Ceramic Domes	Plug Flow
18	Phoenix, AZ; 23rd Ave.	0.29	0.25	0.34	0.27	0.23	0.31	0.25	0.21	0.30	0.27	0.24	0.31	Ceramic Domes	Step Feed
21	Minneapolis, MN; Metro	0.36	0.32	0.40	0.36	0.23	0.42	0.37	0.24	0.45	0.37	0.29	0.45	Ceramic Domes	Step Feed
22	Minneapolis, MN; Metro	-	-	-	-	-	-	-	-	-	0.40	0.34	0.46	Ceramic Domes	Step Feed
23	Minneapolis, MN; Metro	0.50	-	-	-	-	-	-	-	-	0.52	0.45	0.59	Ceramic Domes	Step Feed
26	Glastonbury, CT	0.59	0.43	0.69	0.54	0.56	0.77	0.56	0.37	0.65	0.56	0.42	0.67	Rigid Porous Plastic Tubes	Plug Flow

^a Each zone represents 1/3 of the aeration volume.

^b Recirculation volume not included for contact stabilization systems.

^c SOTE for plate diffusers was assumed to be 2 percent/ft submergence.

Figure 3-27. αF vs. basin distance for plug flow aeration system - Whittier Narrows, CA.

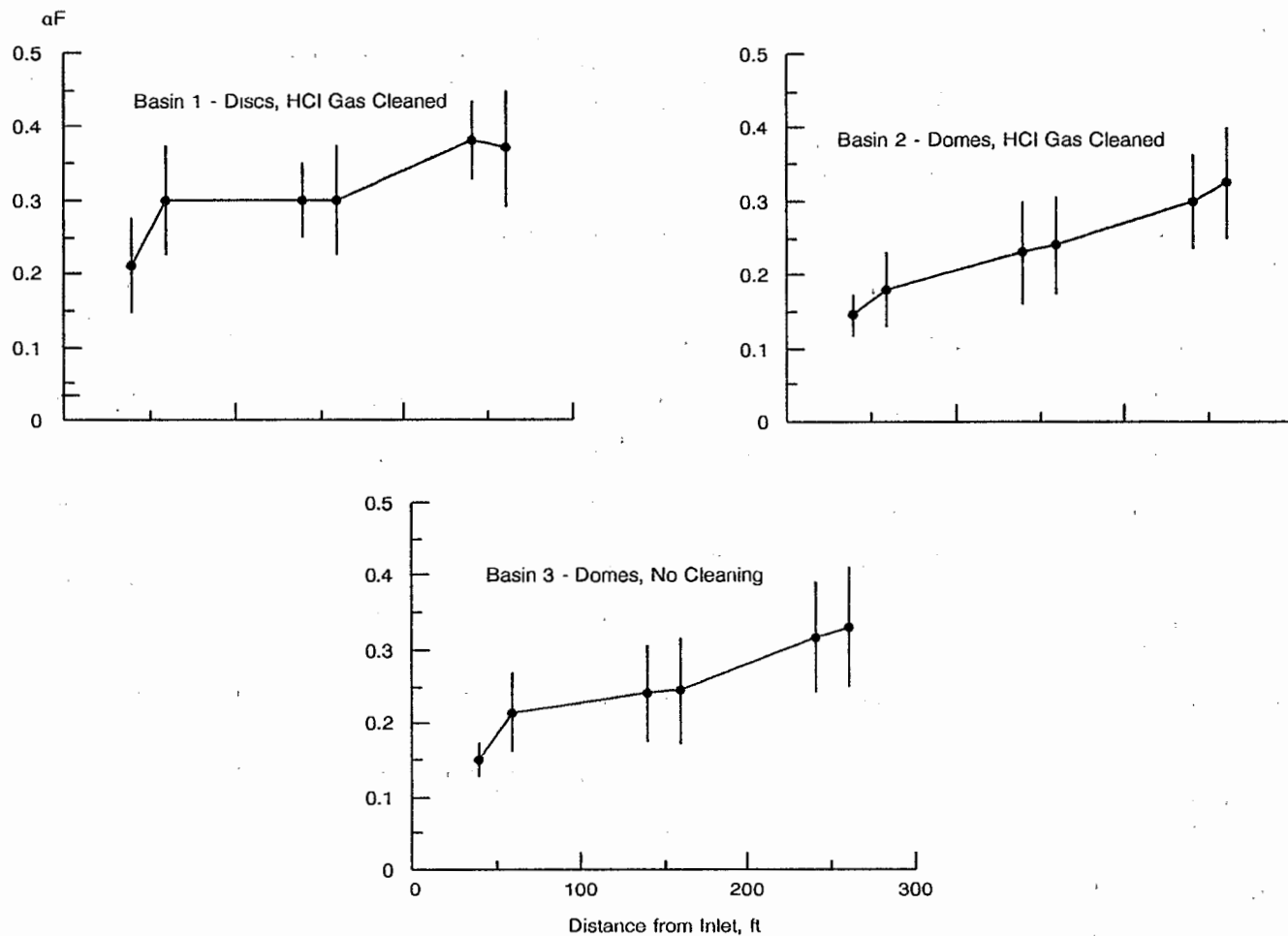


Figure 3-28. αF (SOTE) and αF vs. basin position for step feed aeration systems - Monroe, WI.

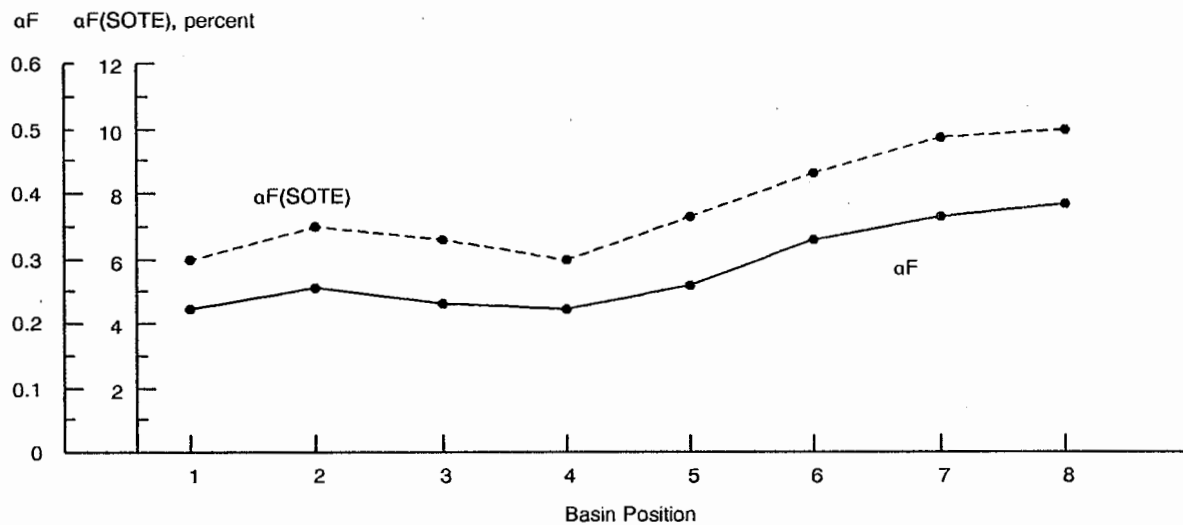


Figure 3-29. αF and $\alpha F(SOTE)$ vs. basin distance for plug flow aeration system - Ridgewood, NJ.

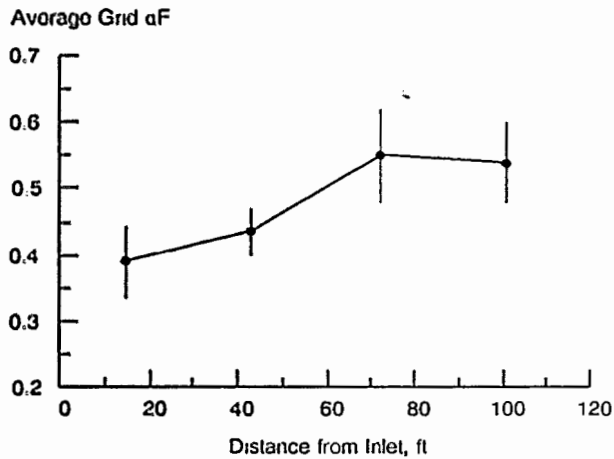
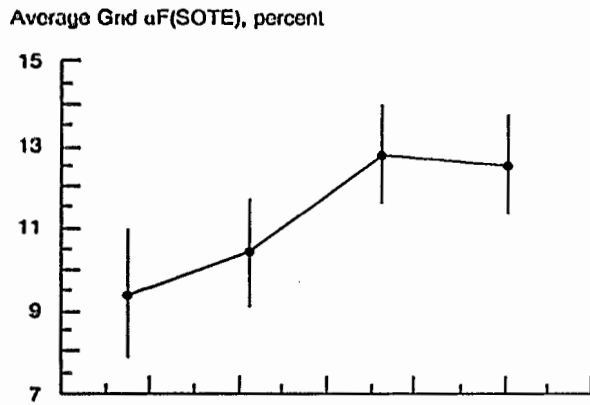


Figure 3-30. $\alpha F(SOTE)$ vs. basin distance for plug flow aeration system - Milwaukee, WI Jones Island East Plant.

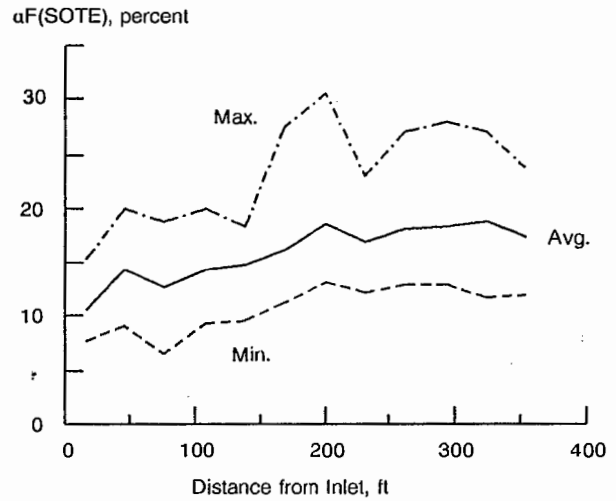
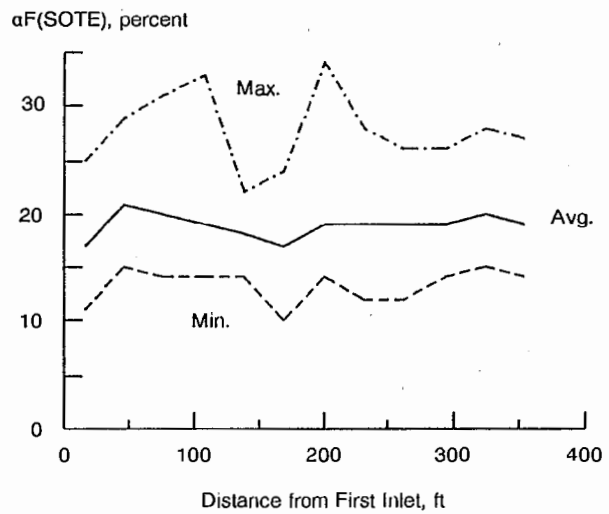


Figure 3-31. $\alpha F(SOTE)$ vs. basin distance for step feed aeration system - Milwaukee, WI South Shore Plant.



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When an NTIS number is cited in a reference, that reference is available from:

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Springfield, VA 22161
(703) 487-4650

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Chapter 4

Operation and Maintenance

4.1 Introduction

The principal objective in the design of fine pore aeration systems is to provide an effective system with the lowest possible present worth cost, maintaining a balance between initial investment and long-term operation and maintenance (O&M) expenditures. Many long-term O&M characteristics are determined by the capabilities and constraints originally designed into the system. However, several factors under the control of the O&M staff will have a significant effect on long-term O&M costs.

This chapter provides guidelines for start-up and shutdown, normal operation, preventive maintenance, restorative maintenance, and troubleshooting of fine pore aeration systems. The intent is to provide sufficient information for optimizing O&M activities. While the sections are written specifically for applications involving the activated sludge process, the information is readily adaptable to other process applications.

4.2 Operation

4.2.1 Start-up

The following steps should be followed when placing an empty aeration basin into service.

1. Before starting up any rotating equipment, such as blowers, verify that the equipment has been properly checked out and lubricated according to the manufacturer's instructions.
2. Check the air piping and diffuser system, and repair any loose joints, cracked piping, and other defects. Confirm that piping is free from debris such as rust, mixed liquor, and other residual matter. Leaks or faulty joints that will not stand up under normal operating stresses could result in wastewater solids entering the system after start-up and lead to air-side fouling. If the system is equipped with pressure taps and tubing for monitoring dynamic wet pressure (DWP), make sure all tubing connectors are tight.
3. Check to make sure the diffusers are installed in accordance with the manufacturer's specifications, e.g., tube diffusers are tightened and oriented

properly, gaskets and O-ring seals are elastic and properly seated, the system is level, and the bolts or other hardware used to apply an external sealing force are properly adjusted.

4. Follow the manufacturer's specifications in feeding air to the diffuser system before the diffusers become submerged. Always feed at least the manufacturer's minimum recommended airflow rate per diffuser to prevent backflow of wastewater through the diffusers and into the air distribution piping.
5. Fill the aeration basin to a level of about 30 cm (1 ft) above the diffusers. Observe the air distribution, and check for significant leaks. Service water, if available, is preferable to wastewater or mixed liquor for the initial filling. Repair leaks before continuing to fill the basin. Use caution during the early stages of filling to prevent the force of incoming water from damaging the air diffusion system or its supports.
6. Continue to fill the aeration basin while monitoring and adjusting the air feed rate. Unless it is adjusted, the air feed rate will decrease as the water level in the basin rises and the increase in backpressure causes the blower output to decrease or the distribution among basins to change.
7. Operate the condensate blowoffs one at a time until the system is free of moisture.
8. Adjust the flow rates of wastewater, return activated sludge, and air to the basin to meet the desired process operating conditions.

If a basin is put into service during cold weather and an ice layer has formed, care must be taken to avoid damage due to buoyant forces exerted by ice trying to float when the basin is filled.

4.2.2 Shutdown

If an aeration basin must stand idle for more than 2 weeks, it should be drained and thoroughly cleaned. Once cleaned, the basin should be filled with clean water to a level above the air diffusion system.

Although the air distribution piping should be designed to withstand the full range of temperatures encountered in the region, observance of the above precautions will provide a safety factor from the standpoint of thermal expansion and contraction. Groundwater levels and basin buoyancy must also be considered.

If a basin must be taken out of service during freezing weather, follow the manufacturer's recommended procedures to avoid damage. The aeration system can be idled by continuing to feed at least the minimum recommended airflow rate per diffuser or the minimum airflow rate required to keep solids in suspension, whichever is greater.

Do not drain aeration basins during freezing weather unless absolutely necessary because ice formation and frost heave can cause serious damage. Ice formation can be alleviated by feeding some air to the basin through the diffusion system. Covering the basin floor with straw or providing heat may be required to prevent frost heave.

When taking a basin out of service for more than 2 weeks, the following actions should be taken provided they agree with the manufacturer's recommendations:

1. Stop the wastewater and return sludge flows to the basin, but continue to feed air to the diffusers at or above the recommended minimum rate.
2. Open drain lines, and start drain pumps if necessary. Continue to feed air to the system until the water level is below the diffusers and the diffusers are washed off. Monitor and adjust the airflow rate as the water level falls.
3. Once the basin is drained, verify that groundwater pressure relief valves are operational to prevent damage due to uplift pressures.
4. Wash down basin walls and floor, air piping, and diffusers to avoid odor problems. Materials accumulated on the diffusers should be removed or at least not allowed to dry.
5. Inspect the air piping and diffusers. Check to ascertain that gaskets requiring an externally applied sealing force, e.g., as with ceramic dome diffusers, are adjusted to the manufacturer's requirements.
6. For above-freezing conditions, fill the basin with clean water to an elevation of about 1 m (3 ft) above the diffusers or until all plastic piping is covered. This will provide additional protection against UV light exposure and excessive temperature changes. Feed air at a flow rate equal to or greater than the manufacturer's recommended minimum. For freezing conditions,

more water may be needed to protect other normally submerged piping. Although the air being fed will normally prevent serious ice damage, if an ice layer does form, do not drain the water from the basin. Falling ice can cause serious damage to the air diffusion system.

While the above procedures are considered proper for idling a basin, continuing to feed air for a long time, even at the manufacturer's minimum recommended rate, may be costly. As long as the basin is filled with relatively clean water, a less costly alternative would be to shut off the airflow completely and allow the air distribution system to fill with water.

In warm weather, an algicide should be added to prevent algae growth. Continuous airflow is recommended if freezing is possible. Otherwise, airflow can be turned on periodically to turn over the water and just prior to placing the basin back into service as a check on system integrity and diffuser performance. Appropriate start-up procedures (see Section 4.2.1) should be followed.

If a basin or several basins are to remain idle for an extended period because the capacity is not needed, the diffusers should be removed and stored in accordance with the manufacturer's recommendations.

If a basin is to be taken out of service to effect repairs that can be completed in a few hours, no special cleaning is required except in the work area. If the work requires several days to complete, the basin and air diffusion system should be washed down. As a general rule, inspection and housekeeping are recommended whenever the basin is drained regardless of the duration of the shutdown.

4.2.3 Normal Operation

Within the constraints placed on the activated sludge system, the primary operational objective is to achieve acceptable effluent quality while maximizing aeration efficiency.

4.2.3.1 Factors Affecting Aeration System Efficiency

As described in Chapters 2 and 3, aeration efficiency is affected by several controllable parameters. Among these are:

- solids retention time (SRT),
- food-to-microorganisms (F/M) loading,
- wastewater flow regime,
- diffuser airflow rate,
- dissolved oxygen (DO) concentration,
- degree of diffuser fouling, and
- blower efficiency.

SRT (or F/M loading) and wastewater flow regime will normally constitute part of the long-term process

control strategy, ranging from seasonal (to respond to changes in raw wastewater characteristics or effluent limits) to many years if stable operation can be achieved. Diffuser airflow rate and mixed liquor DO concentration are part of the short-term, day-to-day operating strategy. An understanding of how each of these parameters affects aeration efficiency is mandatory in developing optimum short- and long-term operating strategies.

Although diffuser fouling and blower efficiency affect aeration efficiency, control of these factors is a matter of minimizing adverse effects rather than optimizing an operating condition.

a. SRT and F/M Loading

There is evidence that SRT or F/M loading affects in-process or field oxygen transfer efficiency (OTE_f), increasing as SRT increases (F/M loading decreases) over a range of values dependent on the biological treatment system (see Chapter 3). It appears this relationship is dependent on the degree of stabilization achieved in the system rather than the absolute value of SRT or F/M loading.

Other benefits of operating at longer SRTs include greater biological process stability, better settling characteristics, lower sludge yields, and improved sludge thickening properties. Limitations to operating at longer SRTs include the solids loading capacity of the secondary clarifiers, sometimes unwanted nitrification, floating sludge in final clarifiers, and higher oxygen requirements for removing a unit mass of BOD. Other site-specific considerations may also make operation at high SRTs infeasible or undesirable. The determination of whether it is advantageous to operate at higher SRTs (lower F/M loadings) is site specific and should be evaluated over a period of time sufficiently long to produce meaningful information.

b. Wastewater Flow Regime

Limited data collected under field conditions indicate that aeration basin flow regime may affect OTE_f . This effect is most likely site specific. If the facility has flexibility to operate under different flow schemes (e.g., step aeration, plug flow, and contact stabilization), it may be advantageous to experiment with them to achieve the maximum aeration efficiency. Note that these alterations, like SRT changes, will affect other process performance parameters (e.g., BOD removal and sludge settleability) that may override advantages gained in oxygen transfer.

c. Diffuser Airflow Rate

Diffuser airflow rate affects aeration efficiency by changing OTE and system pressure. OTE normally decreases as airflow rate increases. Operating diffusers at the lowest airflow rate possible, while not going below the manufacturer's recommended minimum rate, achieves maximum OTE . Based on the

clean water performance data presented in Chapter 2, fine pore diffuser OTE decreases by 15-25 percent when the diffuser airflow rate is increased from 0.5 L/s (1 scfm)/diffuser to 1.4 L/s (3 scfm)/diffuser.

Increasing the diffuser airflow rate also adversely affects aeration efficiency by increasing the pressure drop across the flow control orifices and/or diffuser elements. The pressure drop across a clean diffuser element, as measured by DWP, is relatively small over the normal operating range. For example, the change in DWP for ceramic disc diffusers operating at 0.5 and 1.4 L/s (1 and 3 scfm)/diffuser is only 5 cm (2 in) water gauge (w.g.) or 0.5 kPa (0.07 psia). The pressure drop across a fixed-size orifice for the same increase in airflow rate could be substantial, however, because the drop increases as the square of the flow rate. For a 5-mm (3/16-in) orifice, the increase in pressure drop resulting from an increase in diffuser airflow rate from 0.5 to 1.4 L/s (1 to 3 scfm) is about 25 cm (10 in) w.g.

There are two practical ways to adjust diffuser airflow rate while continuing to meet total process oxygen needs: change the number of aeration basins in service or change the number of diffusers installed in the basins.

If the long-term total airflow rate required to satisfy process needs results in high diffuser airflow rates, more aeration basins can be put into service to increase the number of operating diffusers. This will reduce the airflow rate to all portions of an in-service basin. If the airflow rate per diffuser problem is localized, diffusers may have to be added to or removed from the system. Diffusers are added to provide more transfer capacity where oxygen demand is high, and diffusers are removed to avoid overaeration where demand is low. To facilitate adding diffusers after start-up, extra diffuser holders or taps should be provided as part of the original installation. If diffusers are removed, the airflow rate to the affected portion of the basin must be maintained at or above the acceptable level required for mixing (see Chapter 5).

Adding basins to or eliminating basins from service or changing the number of diffusers in a basin requires a substantial effort and should be considered long-term adjustments. It is not possible to adjust basin or diffuser configuration for normal short-term (daily or weekly) changes in process demands. The aeration system must be designed with sufficient flexibility to meet these anticipated operating requirements.

d. Dissolved Oxygen Concentration

Residual DO concentration affects OTE_f by changing the oxygen transfer driving force, which is the difference between the in-process saturation DO concentration and the residual mixed liquor DO concentration. The relationship between OTE_f and

driving force was presented as Equation 3-1. For illustrative purposes, the equation can be simplified by assuming barometric pressure = 101.3 kPa (1 atm) ($\Omega = 1.0$) and process water temperature = 20°C (τ and $\theta^{T-20} = 1.0$).

The maximum driving force ($\beta C_{\infty 20}^* - C$) is achieved when the system is operated with a residual DO of zero. Since a positive DO residual is usually required to obtain desired process performance, the driving force will be reduced, resulting in an OTE_f of less than the maximum. To meet the process oxygen demand at the lower OTE_f , the airflow rate must be increased. As shown previously, higher airflow rates will result in additional reductions in OTE_f .

The reduction in OTE_f caused by operating at the mixed liquor DO dictated by process needs must be considered a normal cost of operation. However, operating at a DO concentration above that needed for the process should be avoided because power costs will increase with no improvement in process performance. The effect of operating at a residual DO of 4 mg/L vs. 2 mg/L is presented in Example 4-1.

Example 4-1 - Effect of Residual DO on Air Requirements:

The basis for comparison is as follows:

1. Process oxygen demand is constant.
2. Aeration system consists of ceramic dome diffusers operating at a submergence of 14 ft; basin water depth = 15 ft.
3. Diffuser airflow rate, q , at DO of 2 mg/L is 1 scfm/unit.
4. Relationship between SOTE and q in clean water is:

$$SOTE = 0.3 q^{-0.15} \quad (4-1)$$

5. Relationship between OTE_f and q in process water has the same exponent (-0.15).
6. Aeration system operating parameters are:

$$C_{\infty 20}^* = 10.5 \text{ mg/L}$$

$$\alpha = \text{constant}$$

$$F = \text{constant}$$

$$\beta = 0.99$$

$$\text{Wastewater temp.} = 20^\circ\text{C} (\tau \text{ and } \theta^{T-20} = 1.0)$$

$$\text{Barometric pressure} = 1.0 \text{ atm } (\Omega = 1.0)$$

The in-process oxygen transfer efficiency is given by:

$$OTE_f = \alpha F (SOTE) [\beta(C_{\infty 20}^* - C)] / C_{\infty 20}^* \quad (4-2)$$

Substituting the expression for SOTE as a function of q yields:

$$OTE_f = \alpha F [0.3 q^{-0.15}] [\beta(C_{\infty 20}^* - C)] \div C_{\infty 20}^* \quad (4-3)$$

At a residual DO of 2 mg/L, the in-process oxygen transfer efficiency is equal to:

$$\begin{aligned} OTE_{f2} &= \alpha F [0.3(1.0)^{-0.15}] [0.99(10.5) - 2] \div 10.5 \\ &= \alpha F (0.24) \end{aligned}$$

To achieve a residual DO of 4 mg/L, the airflow rate to the basin must be increased. The in-process oxygen transfer efficiency now becomes:

$$\begin{aligned} OTE_{f4} &= \alpha F [0.3(q_4)^{-0.15}] [0.99(10.5) - 4] \div 10.5 \\ &= \alpha F (0.183) (q_4)^{-0.15} \end{aligned}$$

Remembering that the basis for the example was the oxygen demand remained constant, the field oxygen transfer rate (OTR_f) for the two operating conditions must be equal:

$$OTR_{f2} = OTR_{f4} \quad (4-4)$$

or:

$$(OTE_{f2})(q_2) = (OTE_{f4})(q_4) \quad (4-5)$$

or:

$$\alpha F (0.24) (1.0) = \alpha F (0.183) (q_4)^{-0.15} (q_4)$$

Solving for q_4 yields the following:

$$q_4^{0.85} = 1.31$$

$$q_4 = 1.37 \text{ scfm } (0.65 \text{ L/s})/\text{diffuser}$$

For the aeration system in the example described above, it takes 37 percent more air to operate at 4 mg/L DO than at 2 mg/L. Of the 37 percent increase, about 5 percent is caused by a decrease in OTE_f resulting from the increase in diffuser airflow rate. The balance of the increase is the result of the lower OTE_f caused by the reduction in driving force. The attendant increase in backpressure would be about 0.7 kPa (0.1 psi).

Assuming constant blower efficiency and ignoring the headloss through the system, power consumption for air compression is directly proportional to the volume of air compressed. Therefore, the 37-percent increase in airflow rate would result in a 37-percent increase in power usage. If the aeration system is properly designed and installed, the increase in power consumption caused by the increases in diffuser and air piping headlosses would be small.

The penalty paid in increased power consumption demonstrates the importance of incorporating

appropriate control strategies that minimize power draw. This issue is addressed in Chapter 6.

4.2.3.2 Aeration System Monitoring

The aeration system must be monitored to provide data for optimizing system performance and maintenance schedules. Monitoring can lead to optimization of system aeration efficiency in three ways. First, the optimization of DO control, by which most of the power savings are achieved, relies on frequently-collected DO concentration data. Second, the effects of process operational parameters such as SRT and F/M loading on OTE_f can be better defined for the specific application. Third, the adverse effects of diffuser fouling on backpressure and OTE_f can be identified so that maintenance procedures can be initiated. Data should be collected often enough to define normal variations and to permit recognition of long-term changes. In some cases, however, collection frequency may be dictated by controller requirements.

To augment full-scale monitoring, it is often helpful to have a source of diffusers from the operating system for laboratory testing. For fixed-grid systems, removable test headers (described in Section 2.5.11) are recommended for this purpose. Since fouling rates can vary with location in plug flow aeration basins, several test headers or monitoring stations should be provided.

The removable headers can be equipped with pressure taps for in-situ monitoring of DWP. This is not essential, however, since DWP can be measured in the laboratory, eliminating problems associated with field measurement. It is important, however, that the test units be operated at airflow rates similar to the full-scale system. Airflow rate to individual diffusers can easily be determined for units having fixed-size flow control orifices by measuring the pressure drop across the orifice. Airflow rate can also be measured using one or more rotameters.

a. Air Delivery System Pressure

Air-side or liquid-side fouling may cause an increase in diffuser headloss at constant airflow rates. Increases in wet headloss can be detected by monitoring operating conditions within the air supply system. Depending on the specific design approach, an increase in air supply system pressure (monitored, for example, in the blower discharge header or by increased opening of the flow control valves) can indicate an increase in diffuser headloss. Significant increases in blower pressure may be indicative of extensive fouling of major portions of the diffuser system. For this reason, blower pressure along with airflow rate should be monitored on a daily basis.

While overall system pressure monitoring serves as a potential indicator of extreme fouling, it does not provide a very sensitive indication of increased

diffuser headloss. The precision of this method is usually inadequate because the differential pressure across the diffuser element is small compared with the pressure in the air main. Other factors - such as surface elevation, water temperature, airflow rate, and variable line losses - further limit precision. In addition, fouling of only a portion of the diffusion system may lead to a substantial redistribution in airflow but little increase in overall system pressure. For many fine pore systems, use of a monitoring technique more sensitive to fouling than system pressure is desirable and often necessary.

Increased headloss sensitivity is provided by measuring DWP rather than system pressure (see Section 2.5.11). DWP can be measured by fixed pressure monitoring stations located throughout the aeration system (see Figure 2-9). Fixed station monitors require continual maintenance to ensure accurate and precise DWP measurements, as discussed in Section 2.5.11.

DWP measurements can also be performed in a laboratory using diffusers taken from removable test headers (see Figure 2-11). These diffusers can also be used in other analyses described later. Removable test headers require careful maintenance and operation, however, if the data collected are to be of value. Furthermore, raising the test header out of the mixed liquor to remove the diffusers may be a considerable nuisance to the operator.

DWP measurements should be made and recorded weekly for the first 6 months of operation to provide baseline data and determine if DWP is increasing rapidly. After the first 6 months, the frequency can be reduced to monthly or even less often. Since DWP is a function of diffuser airflow rate, all readings should be made at approximately the same airflow rate.

b. Aeration System Efficiency

Since diffuser fouling can substantially decrease OTE_f without significant attendant increases in backpressure, effective process monitoring must include other parameters besides diffuser headloss and system pressure measurements. Rigorous methods for measuring OTE under process conditions are available (1-3). One or more methods may be appropriate for a particular aeration system. However, these methods usually are time consuming and may be too costly for use in day-to-day monitoring. As an alternative, calculated ratios of operating data can provide good indications of overall system efficiency. If the monitoring program indicates a need for more detailed data, a more rigorous test can be performed.

A parameter based on the ratio of the rate of oxygen demand removed to rate of oxygen supplied can be conveniently computed from operating data and used to assess changes in aeration system efficiency for a

particular plant. This parameter, termed the efficiency factor (EF), is expressed as:

$$EF = (W_{ODR} \div W_{O2}) [C_{\infty} \div (C_{\infty} - C)] \quad (4-6)$$

where,

W_{ODR} = mass rate of oxygen demand removed, lb/hr

W_{O2} = mass rate of oxygen supplied, lb/hr

C_{∞} = steady-state DO saturation concentration attained at infinite time at water temperature T and field atmospheric pressure P_b
 $= \beta \Omega \cdot C_{\infty 20}$, mg/L

C = process water DO concentration, mg/L

The rate of oxygen supplied can be calculated based on the standardized volumetric airflow rate, q_s (4):

$$W_{O2} = 1.036 q_s \quad (4-7)$$

where q_s is expressed in scfm.

W_{ODR} can be calculated in various ways and is typically expressed as the carbonaceous oxygen demand removed (W_{CARB}) plus nitrogenous oxygen demand removed (W_{NITR}):

$$W_{ODR} = W_{CARB} + W_{NITR} \quad (4-8)$$

W_{CARB} is usually approximated based on BOD_5 removed in the process:

$$W_{CARB} = 8.34 Q (\text{Influent } BOD_5 - \text{Effluent } BOD_5) \quad (4-9)$$

where W_{CARB} is in lb/hr, BOD_5 is in mg/L, and Q is the wastewater flow rate in mgd.

For a particular plant, effluent BOD_5 may be taken to include either total BOD_5 or soluble BOD_5 . Alternatively, COD or ultimate BOD can be used.

W_{NITR} can be approximated from the nitrate nitrogen concentration of the effluent:

$$W_{NITR} = 8.34 Q (\text{Eff. } NO_3\text{-N})(4.57 \text{ lb } O_2/\text{lb } NH_3\text{-N}) \quad (4-10)$$

where W_{NITR} is in lb/hr and $NO_3\text{-N}$ is in mg/L.

The nitrogenous demand removed can also be estimated by considering both nitrification and denitrification (see Section 5.2.2.2b). The BOD_5 analysis should be performed using a nitrification inhibitor to prevent incorporation of nitrogenous demand.

EF is a useful operational parameter and is generally related to OTE_f . However, it should not be interpreted as a measure of OTE_f . EF is based on the mass rates of oxygen demand removed (W_{ODR}) and oxygen supplied (W_{O2}). Changes in SRT within the normal range of operating values will not significantly affect W_{ODR} ; however, they will affect the rate of oxygen demand satisfied and the associated W_{O2} . Therefore, EF is a function of SRT as well as OTE_f .

Figure 4-1 shows an EF plot based on actual monthly average data (5). The monthly averages are used to smooth daily variations to distinguish longer-term trends.

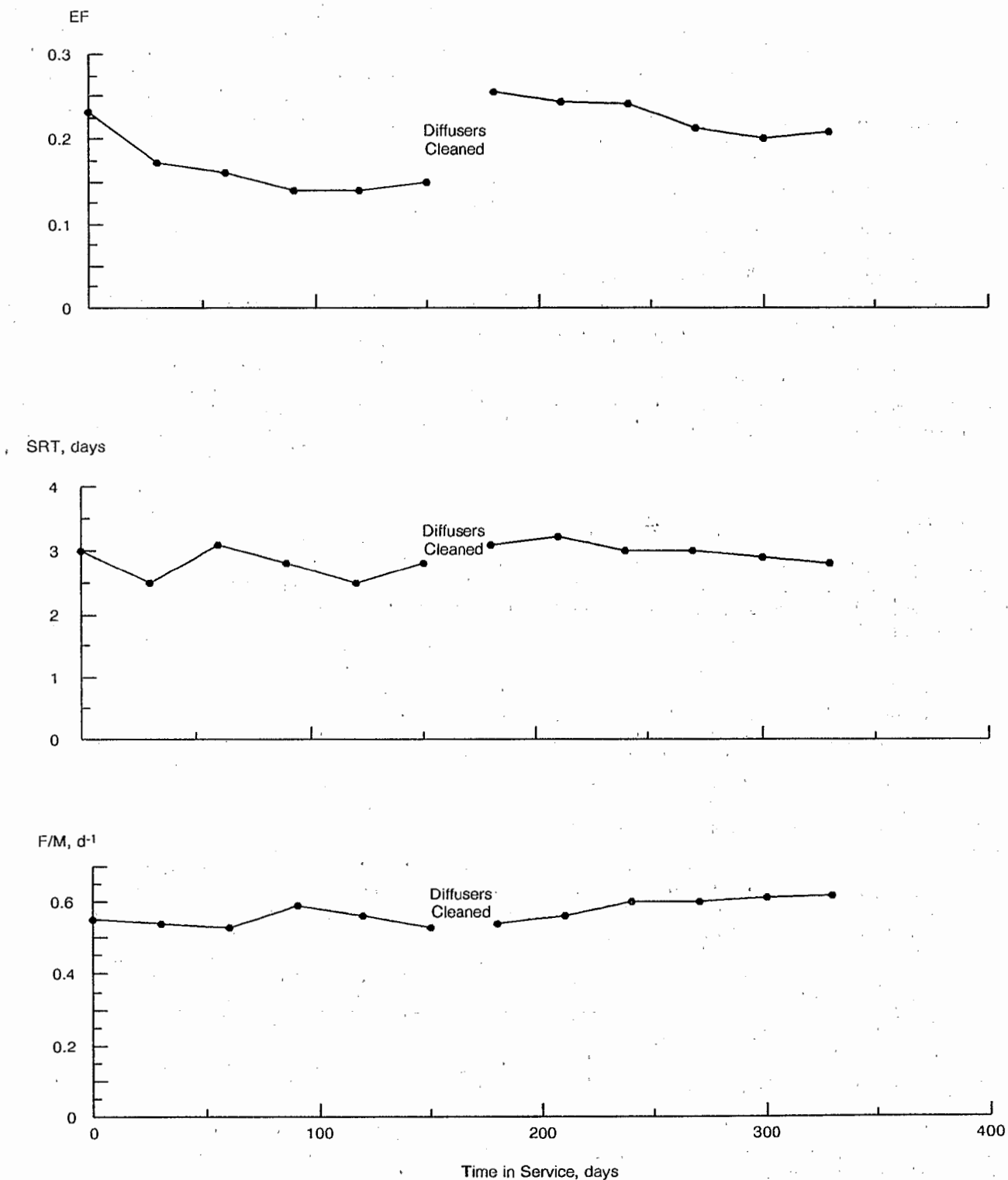
Although EF is only roughly proportional to OTE_f , it should provide a reasonable indication of how OTE_f is changing provided reasonable care is exercised in collecting the pertinent data. The operating DO concentration is the greatest source of error. The basin average DO concentration should take into account spatial and temporal variations. Airflow meters should be properly calibrated and regularly checked.

A second ratio that can be used to estimate aeration system efficiency is the oxygen demand removed per unit of electrical power consumed. Since electrical power consumption is normally measured as the input to the motor, this second ratio includes the efficiencies of the motor and blower and air distribution system losses. Once again, the mixed liquor DO concentration correction must be made.

If a decreasing trend is observed in either EF or oxygen demand removed/unit electrical power consumed, the oxygen requirement per unit mass of oxygen demand satisfied has increased or OTE_f has decreased. Factors that can affect the oxygen requirement per unit mass of BOD_5 satisfied include the characteristics of the incoming wastewater and operating parameters such as SRT and F/M loading. Since these factors and equipment operating parameters can also affect OTE_f , more data are required to determine the cause when a decreasing trend is observed. The operating data should be scrutinized to see if any significant changes have occurred in SRT, F/M loading, BOD loading, or degree of nitrification. If no significant changes are found, diffuser fouling is suspected and the operator should obtain diffusers for evaluation either from removable headers, if available, or by draining the basin.

For the data shown in Figure 4-1, no significant changes in either SRT or F/M loading with time were noted. Therefore, diffuser fouling with attendant losses in OTE_f would be suspected as the cause of decreasing EF values with time. These data depict typical results where diffuser fouling over time adversely affects OTE_f and OTE_f (or EF) is subsequently restored by diffuser cleaning. Methods

Figure 4-1. Trend charts for aeration system monitoring.



for evaluating diffuser fouling and cleaning are presented in the maintenance section of this chapter.

c. Visual Inspection

Visual observation of the system aeration pattern can provide useful information. For diffused aeration systems with a grid layout, the surface pattern should be free of localized turbulence and boiling. Boiling can indicate leaks in the submerged air supply piping, i.e., leaking gaskets, faulty joints, or broken pipes/diffusers. A significant amount of energy can be wasted by allowing air to leak to the atmosphere rather than being delivered to the process. Leaks should be repaired as quickly as possible, both because of the decrease in OTE_f that will occur due to poor distribution of air along with the release of coarse bubbles and the possibility of further damage to the diffuser system.

Nonuniformity of the surface pattern can indicate that portions of the diffusion system are becoming plugged. For example, an unusually low degree of surface turbulence in one segment of the aeration basin may indicate restriction of airflow to that portion of the basin resulting from fouled diffusers. Cleaning of the affected diffusers may be required.

The size of the air bubbles evident on the aeration basin surface can also provide an indication of fouling. Loosely adherent biomass on fine pore diffuser media causes the formation of large bubbles. Some degree of coarse bubbling is normally observed at feed points along the aeration basin, and the degree of coarse bubbling may vary throughout the day. It is believed this phenomenon may be caused by surfactants contained in the influent wastewater and not fouling. These surfactant materials are quickly adsorbed or degraded by the activated sludge, which restricts the size of the coarse bubble zone.

On the other hand, if biofouling occurs, the coarse bubble zone can expand until, in the worst cases, it covers the entire surface of the aeration basin. When an aeration system is initially placed in service, but after equilibrium has been established (usually several days), the surface of the aeration basin should be inspected and photographed to become familiar with and to record the size and appearance of the bubbles at the inlet and outlet ends of the basin. Bubble patterns should be photographed at various airflow rates and the flow rate and time of day when taken should be marked on each photograph. This documentation will provide a basis for recognizing more extreme coarse bubbling should it occur later.

Once problems are identified qualitatively by visual observation, quantitative measurements should be made to confirm the type and extent of fouling and the type of diffuser cleaning required. Experience indicates that qualitative observations can be a

valuable tool when used in conjunction with quantitative measures of DWP and OTE_f .

d. Condensate Removal

The air piping condensate blowoff system should be operated on a set schedule. A record of airflow, humidity, and mixed liquor temperature can provide a reliable means of calculating the condensation to be expected over any period of time. Since the amount of condensate depends on the season and weather conditions, plant operating experience will determine the frequency needed. Initially, weekly checks should be made. When removing condensate, the liquid removed should be observed. The liquid should be clear. If it contains appreciable quantities of solids, there may be a leak in the submerged portions of the air piping. The piping should be inspected and repaired as soon as practical.

4.2.3.3 Recordkeeping

The following operations data should be collected and recorded on a regular basis. Daily collection and recording are recommended at least initially. A change in the frequency to more or less often can be made once operating experience is gained.

- Weather conditions. Temperature, barometric pressure, humidity, wind direction, and precipitation.
- Aeration basins. Visual observations of the mixed liquor, especially the surface pattern and bubble size. Look for boils, and listen for air leaks in the distribution piping. OTE_f measurements periodically if appropriate equipment is available and if efficiency ratios warrant them.
- Process operation. Note any changes in operation such as shutdowns, solids wasting rates, unusual wastewater characteristics, etc.
- Blower operation. Discharge airflow rate, pressure and temperature, time in service, oil pressures, vibration, bearing temperatures, and power consumption. The power drawn should be measured using a multi-phase wattmeter. When using multiple blowers, power factors should also be measured.
- Air filter conditions. Time in service and differential pressure.
- Air distribution system. Total airflow rate, airflow rate to each basin and/or grid, and line pressures at the aeration basins and other key points in the system. DWP should be monitored if appropriate equipment is installed.
- Condensate blowoffs. Date operated, estimate of volume removed, and clarity.

- Process records. Wastewater, return sludge, and waste sludge flow rates. Influent and effluent BOD₅ concentrations. Mixed liquor, return sludge, and waste sludge SS concentrations. Mixed liquor DO concentration at several locations in the aeration basin and mixed liquor temperature. Special events such as power outages and their duration should be documented.

- Record of cleaning frequencies and methods.

In addition to recording operations data, all maintenance work should be documented. Suggested maintenance records are detailed in Manual of Practice OM-3 (6).

The results of all special studies such as wastewater characterizations, diffuser cleaning tests, and oxygen transfer tests should always be documented in a concise report and filed for future reference. The report should include the purpose of the study, methods used, results, and conclusions. All raw data and calculations should be appended to the report.

4.3 Maintenance

There are two kinds of maintenance, preventive and corrective. Preventive maintenance is performed to keep equipment operating at an acceptable level of performance, prolong equipment life, and avoid emergency situations. When equipment no longer operates at an acceptable level of performance or a breakdown occurs, corrective maintenance is performed. This chapter only addresses preventive maintenance since corrective action is usually equipment specific and is more appropriately covered by the equipment manufacturer's literature.

Preventive maintenance is necessary to keep a fine pore aeration system in proper working order and maintain an optimum level of performance, as well as minimize the need for emergency corrective maintenance due to system failure. Proper maintenance procedures will also decrease the frequency of interruptions in the air supply that can lead to the flow of solids into the air distribution system. The deposition of solids on the wastewater side of the diffusers and subsequent penetration into the upper pores will also decrease with a decrease in air supply interruptions. Operation at airflow rates per diffuser equal to or greater than the minimum recommended value will help prevent deposition of solids on diffuser media (7).

A major finding of a survey (7) on dome diffuser plants in the United Kingdom and Holland was that the historically excellent O&M performance of these grid systems was due to diligent care exercised by knowledgeable treatment plant operators. Routine draining, basin and grid washdown, and hardware inspection were standard operating procedures at all

plants surveyed. Operators were also aware of the symptoms of problems in the diffuser system and were quick to respond.

4.3.1 Blowers

The manufacturer's recommended maintenance requirements should be followed to minimize blower problems.

4.3.2 Air Systems

Air systems include filtration equipment, air distribution piping, and airflow measuring instrumentation. Filtration equipment maintenance consists of cleaning and changing filter media and cleaning of ionizer elements in electrostatic filtration units. The manufacturer's recommendation for maximum headloss or hours of operation should be used to gauge when filter elements should be cleaned or replaced. Preventive maintenance on the air filtration and supply systems can virtually eliminate air-side dust and particulate fouling of fixed fine pore diffusers.

Air distribution piping normally requires very little maintenance. Inspection and repair of protective coatings and joint gaskets are usually all that are required. The entire system should be checked for leaks at least annually. A significant deterioration in aeration efficiency can result from leaks that rob air from the process.

Since accurate airflow and DO measurements are essential for monitoring aeration systems, calibration and/or zeroing of meters is an important maintenance task (see Chapter 6).

The airflow calibration data provided by the manufacturer should be reviewed after start-up to ensure that the specified base conditions for the flowing air temperature and pressure are appropriate. If the actual airflow conditions are other than the specified values, the meter will not read in the units shown on the meter, usually scfm. Although the temperature of the flowing air will undergo seasonal changes, reasonable accuracy will be achieved by using the annual average airflow temperature.

4.3.3 Diffusers

4.3.3.1 Cleaning Methods

A variety of fine pore diffuser cleaning techniques are available. They can be broadly classified as process interruptive or process noninterruptive. Process interruptive cleaning techniques require that the aeration basin be taken out of service to provide access to the diffusers, while process noninterruptive techniques do not require such access. A further distinction in cleaning techniques can be made between those that do not require removal of the diffusers from the basin (in situ) and those that do (ex situ). All ex-situ techniques are process interruptive, while only some in-situ techniques are process

interruptive. Ex-situ cleaning techniques are generally not cost effective compared with in-situ techniques because the time and effort required to remove and replace the diffusers are substantial.

a. Ceramic Diffusers

Some of the cleaning procedures that have been developed, identified, and applied to cleaning ceramic fine pore diffusers include (8-10):

Ex Situ

- Refiring
- Silicate-phosphorus washing
- Alkaline washing
- Acid washing
- Detergent washing
- High-pressure water jetting

In Situ - Process Interruptive

- Acid washing
- Flaming
- High- and low-pressure water hosing
- Withholding influent (creating endogenous conditions)
- Sandblasting
- Chlorine washing
- Steam cleaning
- Gasoline washing
- Drying
- Ultrasonic

In Situ - Process Noninterruptive

- Acid injection
- Air bumping (air turned off and on)

Refiring is an expensive cleaning technique. It involves removal of the diffuser from the aeration basin, placing it in a kiln, and heating it in the same fashion originally used in its manufacture. The result is removal of most foulants from, or incorporated in, the diffuser element and restoration of the element to essentially its original condition. Other ex-situ methods are usually less expensive because costs for transporting the diffusers to a kiln are eliminated. The jet washing technique has also been used for cleaning ceramic tube diffusers. Labor costs are reduced by using an automatic feed/jetting machine (11).

Among the important in-situ process interruptive cleaning methods in use today are water hosing, steam cleaning, and liquid acid cleaning. Hosing with either high-pressure [>415 kPa (60 psia)] or low-pressure water sprays and/or steam cleaning will effectively dislodge loosely adherent, wastewater-side biological growths. The application of 14-percent HCl (a 50-percent solution of 18 Baume inhibited muriatic acid) with a portable spray applicator to each ceramic diffuser following hosing or steam cleaning and then rehosing the spent acid is effective in removing both organic and inorganic foulants (12-14).

The in-situ process noninterruptive acid gas injection method is accomplished by injecting an aggressive gas (HCl or formic acid) into the air feed to the fouled diffusers (15,16). Gas cleaning requires that operations personnel understand the hazardous properties associated with exposure to such gases and become fully trained in the methods available for their safe use. With gas cleaning systems, the cleaning agent is transported to the diffuser by the air stream where it may dislodge most foulants. Specifically, the gas injection procedure includes increasing the airflow rate per diffuser to near the maximum design value to provide good distribution and to get as many pores operating as possible. The cleaning agent can then be injected into the air stream, usually until DWP stops decreasing. With the HCl cleaning system, the gas reacts with the water entrained in the diffuser element to form liquid HCl. The acid, which can reach a concentration of about 28 percent, dissolves acid soluble deposits. A system is normally cleaned one grid at a time, each grid taking about 30 minutes. This procedure is covered by a U.S. patent (17).

Acid injection systems are most effective on Type I fouling (see Section 3.3.2.1) involving inorganic acid soluble foulants, such as iron hydroxides, and calcium and magnesium carbonates. Acid injection for controlling Type II fouling (see Section 3.3.2.2) has been demonstrated to be effective in a laboratory study (18) but not completely effective in full-scale evaluations (5,19). Acid injection will not remove atmospheric dust deposited on the air side of the diffuser or granular material such as silica deposited on, or incorporated in, Type II foulants adhering to the wastewater side of the diffuser.

Air bumping of ceramic diffusers is accomplished by increasing the airflow rate per diffuser to a value recommended by the manufacturer for about 15 minutes, then returning to the normal operating range. This can be accomplished when the blowers are rotated by starting the blower being placed in service before the blower being taken out of service is shut down. Caution must be exercised to avoid incurring costly electrical demand charges. Some success has been reported when air bumping of ceramic disc diffusers was combined with HCl gas injection (20).

b. Rigid Porous Plastic Diffusers

Most of the procedures used for cleaning ceramic diffusers have also been applied to rigid porous plastic diffusers. The exceptions are kilning, flaming, and sandblasting.

c. Perforated Membrane Diffusers

The use of ex-situ techniques to clean perforated membrane diffusers is generally not cost effective compared to in-situ techniques because the time and

effort required to remove and replace the diffusers are substantial.

An in-situ, process interruptive method comprising hosing with a 415-kPa (60-psia) water spray, scrubbing with a stiff bristled brush, and rehosing was effective in cleaning membrane tube diffusers in Green Bay, WI (5).

The air bumping procedure has been recommended by the manufacturers of perforated membrane diffusers as a method for preventing or minimizing the effects of fouling. The air bumping procedure, also called flexing, varies depending on the style of diffuser. It is usually accomplished by shutting off the air to the diffusers allowing them to collapse onto the frame. The air is then reintroduced and the airflow rate increased to 2-3 times normal for several minutes before returning to the desired operating condition. Under no circumstances, however, should the manufacturer's recommended maximum airflow rate be exceeded. The procedure is performed on a grid-by-grid basis to minimize the air required. The manufacturers' recommended flexing frequency is normally 1-4 weeks. Documented improvement in diffuser performance due to flexing, either by decreasing DWP or increasing oxygen demand, is limited. In one study (5), flexing did not remove loosely attached foulant from the membranes. Additional experience is necessary to adequately characterize the effects of flexing on maintaining oxygen transfer performance under conditions that promote fouling.

4.3.3.2 Cleaning Method Selection

Since fouling of fine pore diffusers is site specific and all the variables that affect fouling are not understood, selection of a cleaning method requires appropriate experimentation and analysis. Therefore, the aeration system should be designed to allow evaluation of the most likely procedures and frequencies after initial start-up. The effectiveness of a diffuser cleaning program should be judged on its ability to control increases in DWP and losses in OTE, as both factors affect overall aeration efficiency. Because wastewater characteristics usually change with time, the preventive maintenance program should be reevaluated every few years or as specific plant experiences dictate.

The effectiveness of in-situ process noninterruptive cleaning methods can be determined in several ways. Full-scale testing can be conducted if more than one basin is in service. The preventive maintenance technique can be applied to the diffusers in one basin while a second basin is used as a control, or different cleaning frequencies can be applied to the diffusers in two or more basins. The oxygen transfer performance of the two basins can then be compared by monitoring the air volume used per basin provided the two basins are operated in parallel with equal

loadings, SRTs, and DO concentrations. Process water OTEs of the two basins can provide the comparative performance directly, but at somewhat higher cost. The test period should be long enough to separate real long-term trends from short-term fluctuations. If the fouling rate is rapid, 1-2 months should be sufficient. If the fouling rate is slow, 6 months to a year may be necessary.

Laboratory testing can be conducted whenever diffusers are available from removable headers (i.e., those mounted on swing arms), removable test headers, or fixed grid systems when a basin is drained (see Section 2.5). The advantage of laboratory testing is that DWP and OTE can be measured under controlled conditions, allowing the generation of more precise data than is normally possible in the field. Disadvantages are that only a small number of diffusers can be economically tested and special care must be exercised in handling and transporting the diffusers to ensure that their condition remains essentially the same as those remaining in the aeration basin. Laboratory tests recommended for the examination of diffusers are DWP, bubble release vacuum (BRV) (porous diffusers only), OTE, and foulant analysis. Air-side fouling can and should be tested by checking the BRV of the air-side of several diffusers.

Small-scale clean water OTE tests can also be conducted to evaluate the relative difference in OTE between two diffuser elements (see Section 2.5.10 for details of test method). The following procedure can be used to evaluate fouled diffuser cleaning methods:

- Obtain a representative sample of new and used diffusers.
- Characterize the diffusers to determine what effect the foulant has had on DWP, BRV, and OTE.
- Analyze the foulant.
- Evaluate cleaning methods using DWP, BRV, and OTE as indicators of effectiveness.

A staged laboratory testing process, employing several fouled diffusers, can be used to test the effectiveness of various cleaning methods. In each stage, a method is tested, and, if visual observations indicate the method was effective, the effectiveness is quantified by measuring DWP, BRV, and clean water OTE. The simplest cleaning methods should be tested first. More involved methods can be tested later, if necessary. Biological slimes can usually be removed by mechanical means such as hosing with a low-pressure [<415 kPa (60 psia)] or high-pressure [>415 kPa (60 psia)] water spray, steam cleaning, or brushing. Inorganic precipitates firmly attached to the diffuser element may yield to chemical treatment.

If time or process constraints will not allow such a rigorous diffuser testing program but system monitoring indicates that cleaning is necessary, a staged approach can be applied to the full-scale system. A portion of the grid can be used to test various cleaning methods. Cleaning using one or more of the following steps, in the order presented, has been effective in several installations (5,13,14).

- Hosing to remove loosely attached materials
- Brushing to loosen residual materials and rehosing
- Acid treatment to remove scale deposits and rehosing

Between each step, the treated units should be evaluated to determine if more cleaning is needed. The evaluation can take the form of visual observations or a selected test to determine quantitatively the effectiveness of the cleaning procedure. On rigid fine pore diffusers such as ceramics and porous plastics, the BRV test can be performed on in-situ units. If the initial hosing effectively removes all the foulant except scale, the second step can be skipped. Before treating any diffuser element with acid, it should be ascertained that the materials of construction will not be adversely affected.

It is clear that every fine pore installation will require some form of diffuser cleaning on a periodic basis. The need for, type of, and frequency of cleaning for fine pore installations are highly equipment- and site-specific. As such, no one approach can be recommended. Manual of Practice FD-13 (10) is a good reference on experiences with cleaning fine pore diffusers. Additional diffuser cleaning data generated during the EPA/ASCE Fine Pore Aeration Project are summarized in Table 4-1 and Chapter 7.

4.3.3.3 Estimating Cleaning Frequency

Diffuser cleaning may be accomplished according to a regular preventive maintenance schedule that balances the cost of diffuser cleaning against the power cost savings resulting from lower system pressure or higher system OTE_f. The relationship between O&M costs and cleaning frequency is illustrated in Figure 4-2. With infrequent cleaning, cleaning costs are low but power costs are substantially higher than those associated with a cleaner diffuser system. As cleaning frequency is increased, power costs decrease but cleaning costs increase. Usually, the total of the power and cleaning costs will decrease initially as cleaning frequency is increased. The optimum cleaning frequency occurs where the total cost reaches a minimum value.

Although Figure 4-2 is an idealized plot, it presumes, among other things, that the fouling rate and its effects remain constant with time and that cleaning

can restore OTE_f and DWP to like-new conditions. The concept is useful for estimating optimum cleaning frequency. The following examples show how fouling rate data can be used to determine the optimum cleaning frequency for Type I and Type II fouling.

Chapter 7 (Section 7.3) presents a detailed method for determining an optimal diffuser cleaning frequency based on fouling rate, power cost, and cleaning cost. Section 7.4 gives an example using this method; Section 7.5 describes a Lotus spreadsheet based on this method. The following examples are consistent with the method described in Section 7.3. However, these examples compare equivalent annual costs for various cleaning frequencies, whereas the Chapter 7 example compares present worth costs. Other differences are that the Chapter 7 example includes initial cost, uses different power and cleaning cost data, and allows for a higher fouling rate at the head end of the aeration basin.

a. Example 4-2 (Type I Fouling)

This example is hypothetical and is presented to illustrate Type I fouling, which adversely affects DWP but not OTE. The operating conditions and costs, which are similar to those for Example 4-3 for comparative purposes, are as follows:

Operating Conditions:

1. Field atmospheric pressure = 14.7 psia
2. Blower discharge pressure = 21.7 psia
3. Blower inlet air temperature = 20°C (528°R)
4. Rate of DWP increase = 1.0 in w.g./mo
= 0.036 psia/mo
5. Combined blower/motor efficiency = 0.7
6. Field standardized volumetric airflow rate = 16,775 scfm
7. Power cost = \$0.04/kWh

In this case, fouling causes the operating pressure to increase, which results in higher blower discharge pressure. The blower wire power consumption can be related to the discharge pressure using the equation for adiabatic compression of air (4):

$$WP = AP/\epsilon \\ = \{(wRT_a/eK)[(P_d/P_b)^K - 1]\}/2.655 \times 10^6 \quad (4-11)$$

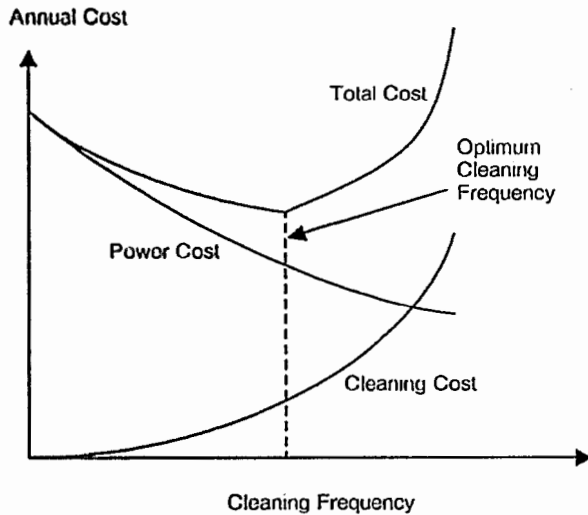
where,

WP = wire power consumption, kW
AP = adiabatic power consumption, kW
w = mass rate of air, lb/hr [= 0.0750 lb/cu
ft × 60 min/hr × q_s = 4.5 q_s]

Table 4-1. Cleaning Experiences with Fine Pore Diffusers

Diffuser Type/Plant/Location	Cleaning Procedure	Results and Observations
Ceramic domes and discs Whittier Narrows Plant Los Angeles County, CA	1. Acid (HCl) gas injection about every 3 months during study. 2. Modified Milwaukee Method (low-pressure hose from basin top, hose from 6-in range, apply 14-% HCl acid, soak for 30 minutes, re hose as above). 3. Hose in a laboratory test. 4. Milwaukee Method in a laboratory test.	1. DWP and BRV were less for gassed diffusers but higher than for new units. Less effective on domes due to numerous gasket leaks. 2. DWP and BRV were reduced substantially, but like-new conditions were not achieved. Less effective on domes, probably due to gasket leakage problems. 3. DWP and BRV were reduced substantially, but like-new conditions were not achieved. 4. Restored DWP and BRV on disc diffusers to near-new conditions late in the study. Earlier laboratory tests were not as successful.
Ceramic domes and discs Nine Springs Plant Madison, WI	1. Milwaukee Method (hose @ 120 psig for about 1 minute from 2-ft range while feeding air @ 1 scfm/diffuser, apply 50-mL 18° Baume-inhibited muriatic acid [14-% HCl], soak for 30 minutes, re hose as above). 2. High-pressure hose (120 psig from 2-ft range).	1. Restored DWP and BRV of dome diffusers to like-new conditions. 2. Reduced BRV of ceramic disc diffusers from 15 in w.g. to < 10 in w.g., but still above like-new conditions. DWP reduced only slightly.
Ceramic disc diffusers (specific permeabilities of 14, 26, 38, and 50 @ 2-in w.g.; BRV ₀ of 9, 6, 4, and 3) Monroe, WI	1. Milwaukee Method (hose @ 60 psig while feeding air @ 3 scfm/diffuser, turn off air and apply 50-mL 20° Baume-inhibited muriatic acid diluted 1:1 with water, soak for 20-30 minutes, re hose as above). 2. Milwaukee Method (same as above).	1. Diffusers having various BRV₀ values were obtained from test headers and evaluated after 4, 12, and 16 months of operation. Based on DWP and BRV measurements, all diffusers were restored to like-new conditions. No air-side fouling occurred. 2. Diffusers having BRV₀ values of 6 and 4 in w.g. were field cleaned after 24 months in operation. Moderately-fouled diffusers were restored to like-new conditions based on DWP, BRV, and OTE measurements.
Ceramic disc diffusers Green Bay MSD Plant Green Bay, WI	1. Hose from basin top, fill with service water to 3 ft above diffusers, inject HCl gas into airflow to dose diffusers @ 0.1 lb each, drain basin, re hose as above.	1. Restored DWP and BRV to like-new conditions. OTE restored to 95% of new conditions.
PVC Perforated membrane tube diffusers Green Bay MSD Plant Green Bay, WI	1. High-pressure hose from basin floor, scrub with stiff brush, re hose as above.	1. DWP reduced to less than new conditions. OTE not restored (membrane material properties were changed).
Ceramic dome diffusers Hartford, CT	1. Milwaukee Method (hose from basin top while feeding air @ 1 scfm/diffuser, apply 50-mL of "Zep" [22-% HCl plus surfactants], soak for 30 minutes, scrub with brush as necessary, re hose as above).	1. Dirty diffusers were severely fouled with some areas completely plugged. Cleaning greatly improved airflow uniformity. BRV was reduced substantially, but not to like-new conditions.
Ceramic dome diffusers Ridgewood, NJ	1. Hose from basin top or brush with 10-% HCl.	1. Individual diffusers were not tested. Visual inspection of OTE_i data suggested regular cleaning would maintain efficiency of the aeration system.
Ceramic plate diffusers Jones Island East Plant Milwaukee, WI	1. Milwaukee Method (high-pressure hose from basin floor, apply liquid HCl, soak for 20-30 minutes, start airflow and re hose as above)	1. Off-gas testing of full-scale aeration system indicated improved OTE_i after cleaning.

Figure 4-2. Idealized plot of optimum cleaning frequency to minimize power and cleaning costs.



q_s = field standardized volumetric airflow rate, scfm
 R = ideal gas constant = 53.3 ft-lb/lb-°R
 T_a = blower inlet air temperature, °R
 P_d = blower discharge pressure, psia
 P_b = field atmospheric pressure, psia
 $K = (k - 1)/k = 0.283$ for air
 k = ratio of specific heats for air, $C_p/C_v = 1.4$
 e = combined blower/motor efficiency, fraction
 and 2.655×10^6 is in units of ft-lb/hr-kW.

Assuming DWP increases at a constant rate, the average power consumption for operating the blowers between cleaning events is given by:

$$WP' = (WP_0 + WP_1)/2 \quad (4-12)$$

$$WP' = WP_0 (1 + WP_1/WP_0)/2 \quad (4-13)$$

where,

WP' = average wire power consumption, kW

WP_0 = wire power consumption for the aeration system when operating with clean diffusers, kW

WP_1 = wire power consumption for the aeration system when operating with fouled diffusers just before cleaning, kW

and WP_1/WP_0 is termed the power ratio.

The cost of power for an operating period of any length in months is:

$$Z_p = 720 (WP') (n_m) (E_p) \quad (4-14)$$

where,

Z_p = period power cost, \$/operating period

n_m = number of months between cleanings

E_p = unit power cost, \$/kWh

720 = conversion factor, hr/month

The period power cost can be put on an annual basis:

$$EAC_p = 12 Z_p / n_m \quad (4-15)$$

where,

EAC_p = equivalent annual power cost, \$/yr

12 = conversion factor, months/yr

Likewise, the period diffuser cleaning cost can also be put on an annual basis:

$$EAC_c = 12 Z_c / n_m \quad (4-16)$$

where,

EAC_p = equivalent annual diffuser cleaning cost, \$/yr

Z_c = period diffuser cleaning cost, \$/operating period

Figure 4-3 illustrates how wire power in terms of power ratio (WP_1/WP_0) changes with time for operating periods of 1, 2, 3, 4, 6, and 12 months. Table 4-2 lists annualized costs as a function of operating period length and cleaning frequency. For the conditions listed above, the optimum time of operation between cleaning of the diffusers is 9 months. However, the annualized total cost curve near the optimum point is relatively flat and extending the operating period to 12 months only increases the cost by \$227.

b. Example 4-3 (Type II Fouling)

This example is based on fouling rate data collected at the Green Bay wastewater treatment facility between May 1986 and October 1987 (5). This plant is comprised of four pairs of contact and return sludge reaeration basins (Figure 4-4). Quadrant 2 was retrofitted with ceramic disc fine pore diffusers in early 1986. The contact basin was outfitted with 6,128 diffusers, and the reaeration basin received 2,148 diffusers. The quadrant treated approximately 1.5 million lb BOD₅/month during the test period.

Fouling at the Green Bay plant was severe and resulted in relatively rapid and substantial losses in OTE_r without significant changes in DWP (Type II fouling). The cost of power to operate the system with clean diffusers was about \$9/1,000 lb BOD₅ treated, or \$13,500/month to treat 1.5 million lb BOD₅.

Figure 4-3. Power ratio vs. time for $\Delta DWP = +2.5$ in w.g./month.

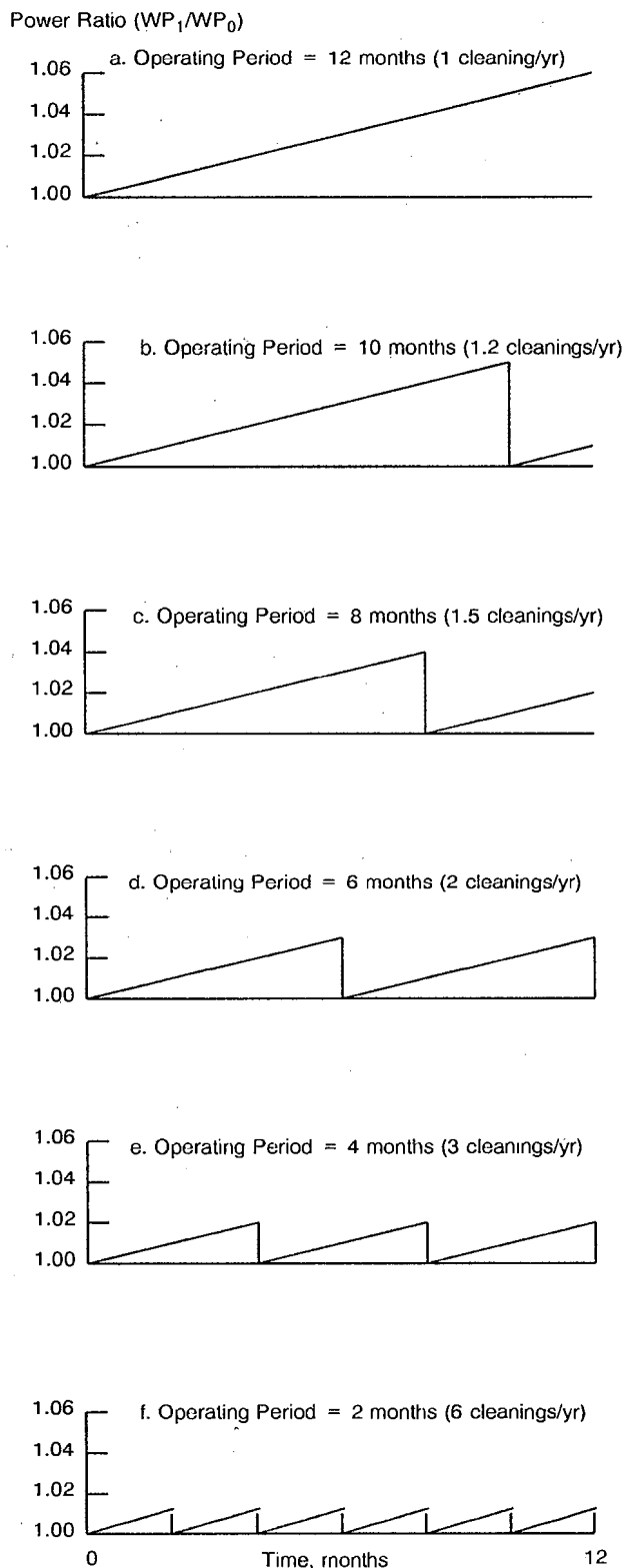


Table 4-2. Annualized Costs for a Fine Pore Aeration System Experiencing a DWP Increase of 1.0 in w.g./month (see Example 4-2)

Operating Period ¹ , months	Cleaning Frequency ² , times/yr	Annualized Cost, \$/yr		
		Power ³	Cleaning ⁴	Total
1	12.0	162,370	31,200	193,570
2	6.0	162,730	15,600	178,330
3	4.0	163,090	10,400	173,490
4	3.0	163,460	7,800	171,260
5	2.4	163,280	6,240	170,060
6	2.0	164,190	5,200	169,390
7	1.7	164,550	4,460	169,010
8	1.5	164,920	3,900	168,820
9	1.3	165,280	3,470	168,750
10	1.2	165,650	3,120	168,770
11	1.1	165,010	2,840	168,850
12	1.0	166,370	2,600	168,970

¹ Time of operation between cleanings.

² Cleaning frequency = $12 \div$ operating period.

³ Based on power cost = \$0.04/kWh.

⁴ Based on cleaning cost = \$2,600/cleaning.

Figure 4-5 shows EF (see Equation 4-6) as a function of time in service for the Green Bay ceramic disc diffusers. Since EF is roughly proportional to OTE_f , the rate of decrease in EF can be interpreted as a fouling rate. Over the first 2 months of record shown in Figure 4-5, EF decreased by about 15 percent per month. This is indicative of an extremely high fouling rate (see Tables 3-8 and 3-9). However, no further loss in EF was observed after the first 2 months. Laboratory testing showed that a three-step cleaning procedure of hosing the diffusers from the basin walkway, followed by treatment with HCl gas and rehosing was effective in restoring OTE_f to a near-new condition. Approximately 0.1 lb HCl/diffuser was used. The diffusers were cleaned by the three-step procedure after being in service for 6 months. OTE_f then decreased at a relatively constant rate of about 5 percent/month.

The associated power costs are depicted in Figure 4-6. The cost of electrical power over the course of the study (May 1986 through October 1987) was constant at \$0.04/kWh.

The costs associated with cleaning the diffusers include the labor for hosing the diffusers and performing the acid gas treatment and the HCl gas itself. Hosing of the 6,128 contact basin diffusers took two operators about 8 hours (5-10 sec/diffuser) - 16 labor-hr. The reaeration basin diffusers could be hosed off by two operators in about 4 hours - 8 labor-hr. The labor required for the acid gas cleaning step was about 2 hr/grid; there are 10 grids in the contact basin and 6 in the reaeration basin - 32 labor-hr. At a labor cost of \$30/hr, the labor cost for cleaning was

Figure 4-4. Schematic of Green Bay wastewater treatment plant.

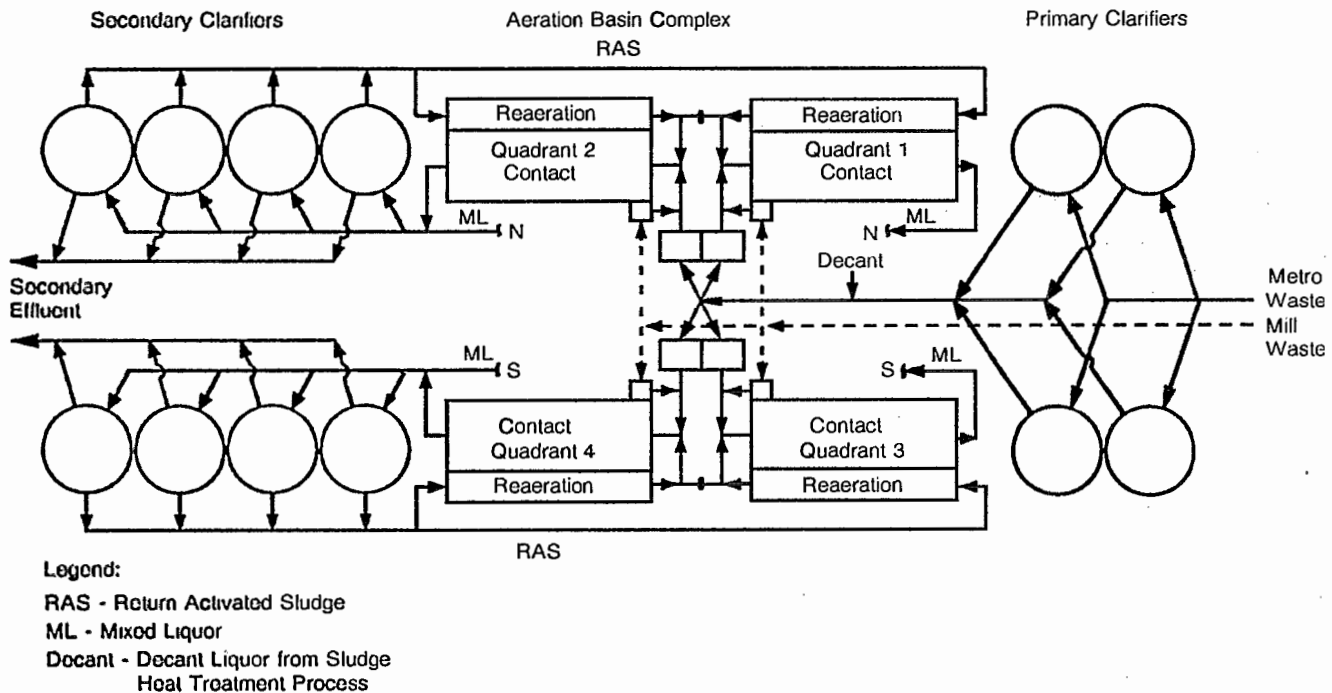
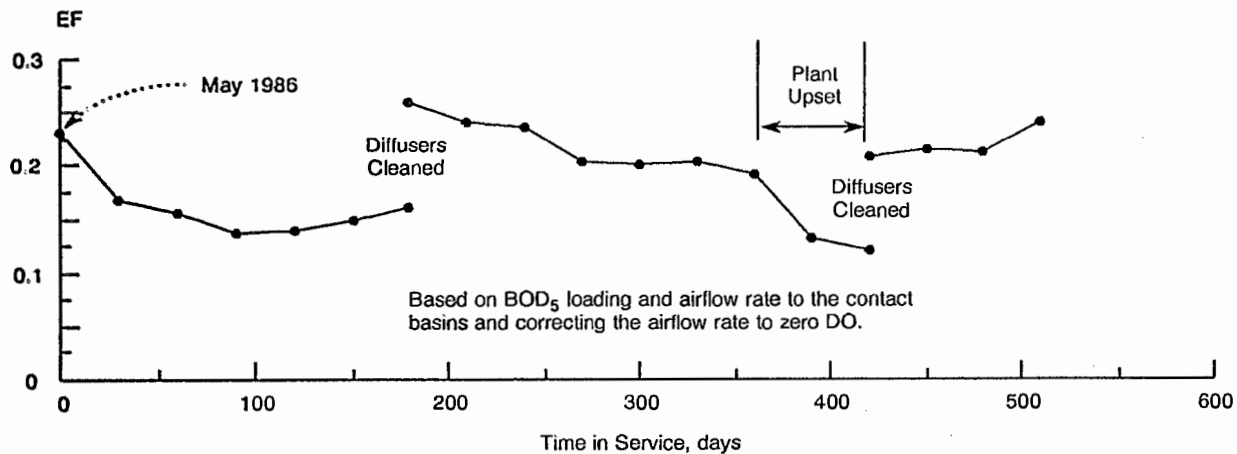


Figure 4-5. EF vs. time in service for ceramic disc diffusers - Green Bay, WI.



\$1,680. The chemical cost of acid gas cleaning was 8,276 diffusers x 0.1 lb HCl/diffuser x \$2.00/lb HCl = \$1,655. The total cost was about \$3,300, or approximately \$0.40/diffuser.

It should be emphasized that the study performed at Green Bay was designed to compare two different diffuser systems. During the study, every effort was made to maintain performance, perhaps to the point where cleaning costs may not represent the more average case that would occur at another plant.

Figure 4-7 illustrates the relationship between F and time for the case of severe fouling where OTE_f was reduced by 15 percent/month to a maximum loss of 30 percent ($F = 0.70$), similar to the first 2 months at Green Bay. Fouling factors for six cleaning frequencies between 1 and 12 times/yr are plotted. Annual average F values range from 0.725 for annual cleaning to 0.925 for monthly cleaning.

The annual cost of electrical power is equal to the clean diffuser power cost (\$162,000/yr) divided by the annual average fouling factor. Figure 4-8 plots annual

Figure 4-6. Power cost vs. time in service for ceramic disc diffusers - Green Bay, WI.

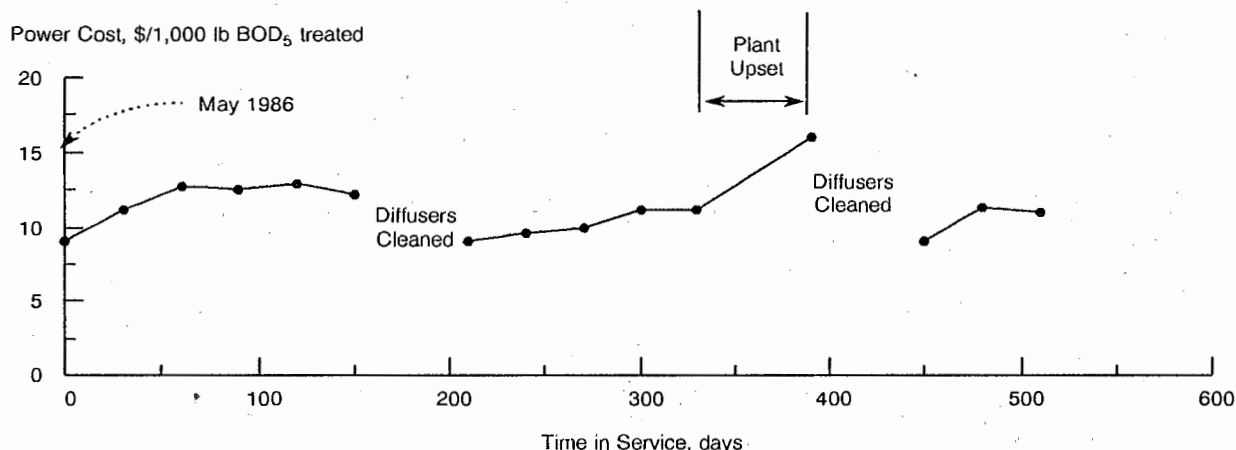
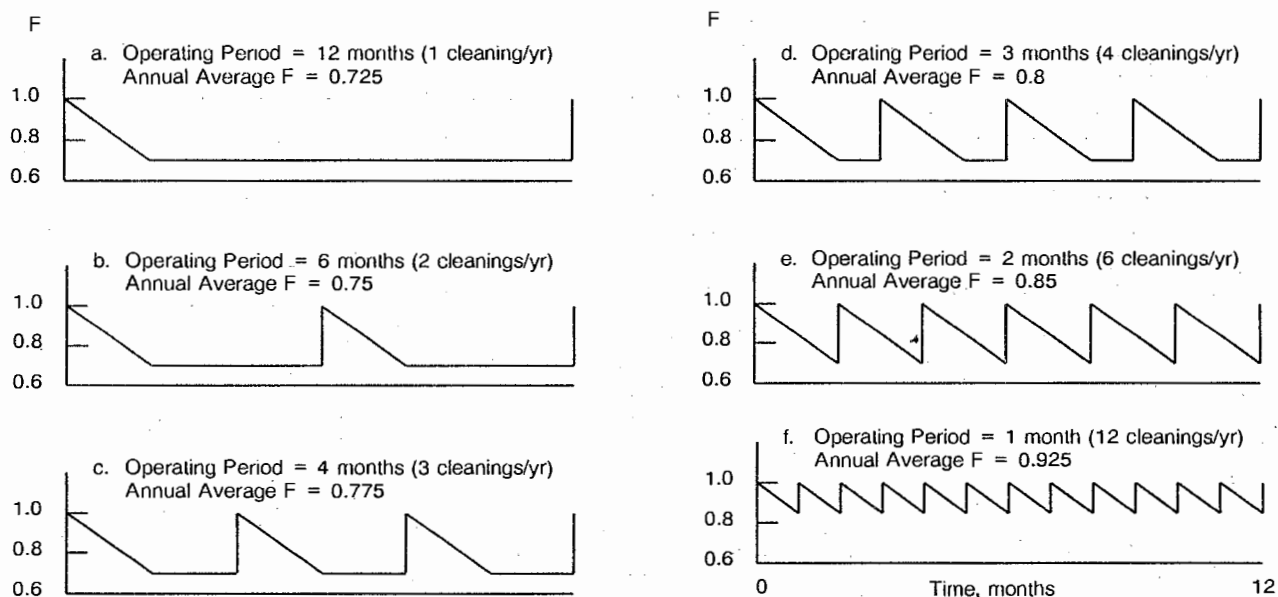


Figure 4-7. Effects of cleaning frequency on annual average F ($f_F = 15$ percent/month).



O&M cost (electrical power plus cleaning) and annual average F as a function of cleaning frequency. For this case of severe fouling, cleaning 6 times/yr (every 2 months) would have been cost effective.

For comparison, the cost trade-off analyses for a moderate and a low fouling rate (both hypothetical linear rates - the higher of which is similar to that observed during a portion of the test period at Green Bay) are shown in Figure 4-9. For the moderate fouling rate of 5 percent loss in OTE_f /month (to a maximum loss of 30 percent), the optimum cleaning frequency would be 4 times/yr (every 3 months) but very little extra cost would be incurred by decreasing the frequency to 3 times/yr (every 4 months). For the

low fouling rate of 1 percent loss in OTE_f per month, the optimum cleaning frequency would be 1 to 2 times/yr. These results are comparable to those of the example presented in Section 7.4

These two examples demonstrate the merit of investigating the fouling tendencies of installed diffusers. In the first example, Type I fouling affected DWP but not OTE and the effect on power consumption was small and could be controlled with a minimal cleaning frequency. In the second example, Type II fouling significantly affected OTE and considerable power savings were achieved with frequent cleaning under severely fouling conditions. A cost-effective analysis showed that moderate to low

Figure 4-8. Cost tradeoff analysis for determining cleaning frequency based on fouling patterns shown in Figure 4-7.

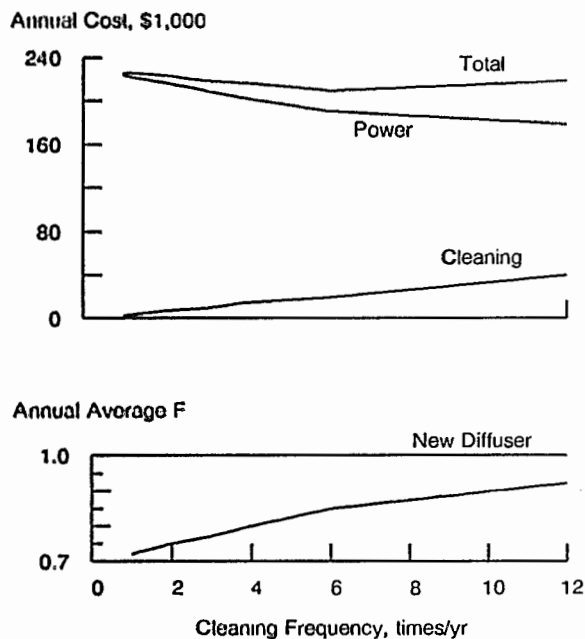


Figure 4-9. Cost tradeoff analysis for $f_F = 1$ percent and 5 percent/month.

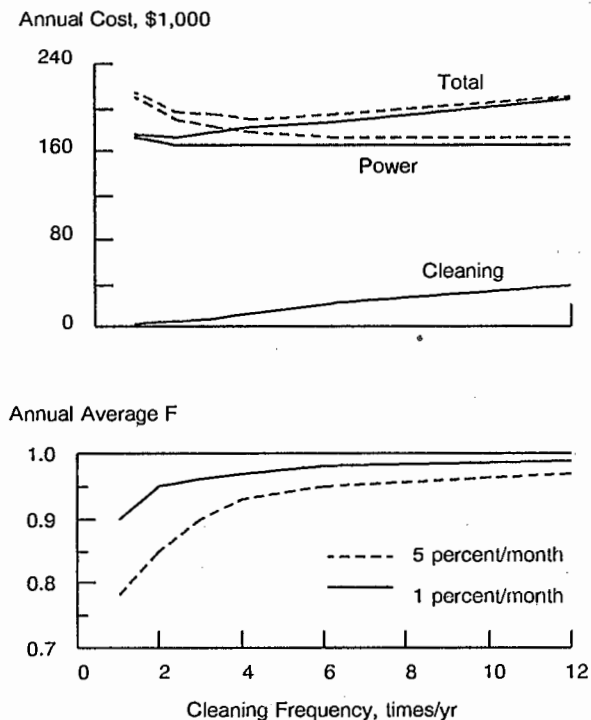


Table 4-3. Fine Pore Aeration System Troubleshooting Guide

Problem	Probable Cause	Action
Blower discharge pressure increase at constant volume	Fouled diffusers	Evaluate condition of diffusers (see Section 4.2.3.2); clean diffusers if necessary
	Automatic flow control valve not operating properly	Check operation of automatic valves in the main air distribution system
	Clogged air filter downstream of blower	Check pressure drop across filter medium; clean or replace filter elements per manufacturer's recommendation
Air usage increase but BOD loading remains constant	Residual DO may be increasing	Check calibration of DO probes
	Air leaking from distribution system	Check air distribution piping for leaks; repair as necessary
	Change in air requirement/mass BOD treated	System may be running at longer SRT; reevaluate operating parameters; adjust sludge wasting rates if appropriate
	Fouled diffusers	Evaluate condition of diffusers (see Section 4.2.3.2); clean diffusers if necessary
Continuous large bubbles or clumps of bubbles	Diffusers partially clogged	Inspect and clean diffusers
	Increase in surfactant concentration	Evaluate oxygen transfer capacity; adjust basin loadings if necessary
Dead spots	Not enough airflow	Check that airflow is above manufacturer's minimum; check calibration of airflow meters
	Diffusers completely clogged	Evaluate condition of diffusers (see Section 4.2.3.2); clean diffusers if necessary
	High airflow/diffuser	Decrease airflow or install additional diffusers
Continuous boils	Broken diffuser or air distribution pipe	Drain basin; inspect diffusers and piping; make repairs as necessary

levels of fouling could be controlled with a much reduced cleaning frequency.

4.3.4 Troubleshooting

Some of the more common operating problems, causes of trouble, and corrective actions associated with fine pore aeration systems are tabulated in Table 4-3. Equipment-specific mechanical problems are not included because they should be covered in the manufacturer's literature.

4.4 References

When an NTIS number is cited in a reference, that reference is available from:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650

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Chapter 5

System Design and Installation

5.1 Introduction

A typical fine pore aeration system is illustrated schematically in Figure 5-1. The air supply system consists of air filters, blowers, air piping, and airflow control equipment (flow meters and flow control valves). The diffusion system consists of a series of headers and lateral piping placed in the aeration basin, to which fine pore diffusers are attached. The system is usually arranged as a series of "grids" (or zones) to allow for proper airflow distribution and accommodate oxygen transfer rate variations within the aeration basin.

This chapter presents the procedures required to design and install a fine pore aeration system. The chapter is divided into five major sections. Process and operation and maintenance (O&M) considerations affecting aeration basin and aeration system design are addressed in Section 5.2. The determination of process oxygen and mixing requirements is discussed in Section 5.3. Procedures for estimating process oxygen requirements, including both average values and their temporal and spatial variations, are presented. Major design and installation considerations related to the in-basin equipment are discussed in Section 5.4. Diffuser selection, system layout, airflow distribution, diffuser cleaning and maintenance, system installation, contract specifications, and retrofit considerations are discussed. The remaining components of the system are considered in Section 5.5. These include air filters, blowers, and air piping. Again, installation and retrofit considerations are discussed. Section 5.6 provides a consistent and logical approach to the integrated design of a fine pore aeration system.

Extensive use of examples is made throughout Sections 5.3, 5.4, and 5.5. These examples are not intended to provide a "cookbook" set of design procedures that can be followed in every instance to arrive at the "right" answer. While component sizing of a fine pore aeration system is based on a specific set of calculations, many assumptions must be made and form the basis for those calculations. These assumptions are dependent on the specific situation and the knowledge and experience of the system designer. The examples illustrate the types of calculations required to design a fine pore aeration

system. More importantly, they also illustrate the interplay of experience-based assumptions and specific design calculations during the design process.

5.2 Process and O&M Considerations

Several process- and O&M-related considerations affect fine pore aeration system design and basin configuration. These considerations include wastewater characteristics and organic loading, nutrient control requirements, hydraulic flow regime, mixing requirements, diffuser fouling and cleaning, and personnel qualifications, among others. They must be addressed in the overall design concept of the system before initiating detailed design of oxygen dissolution and supply components.

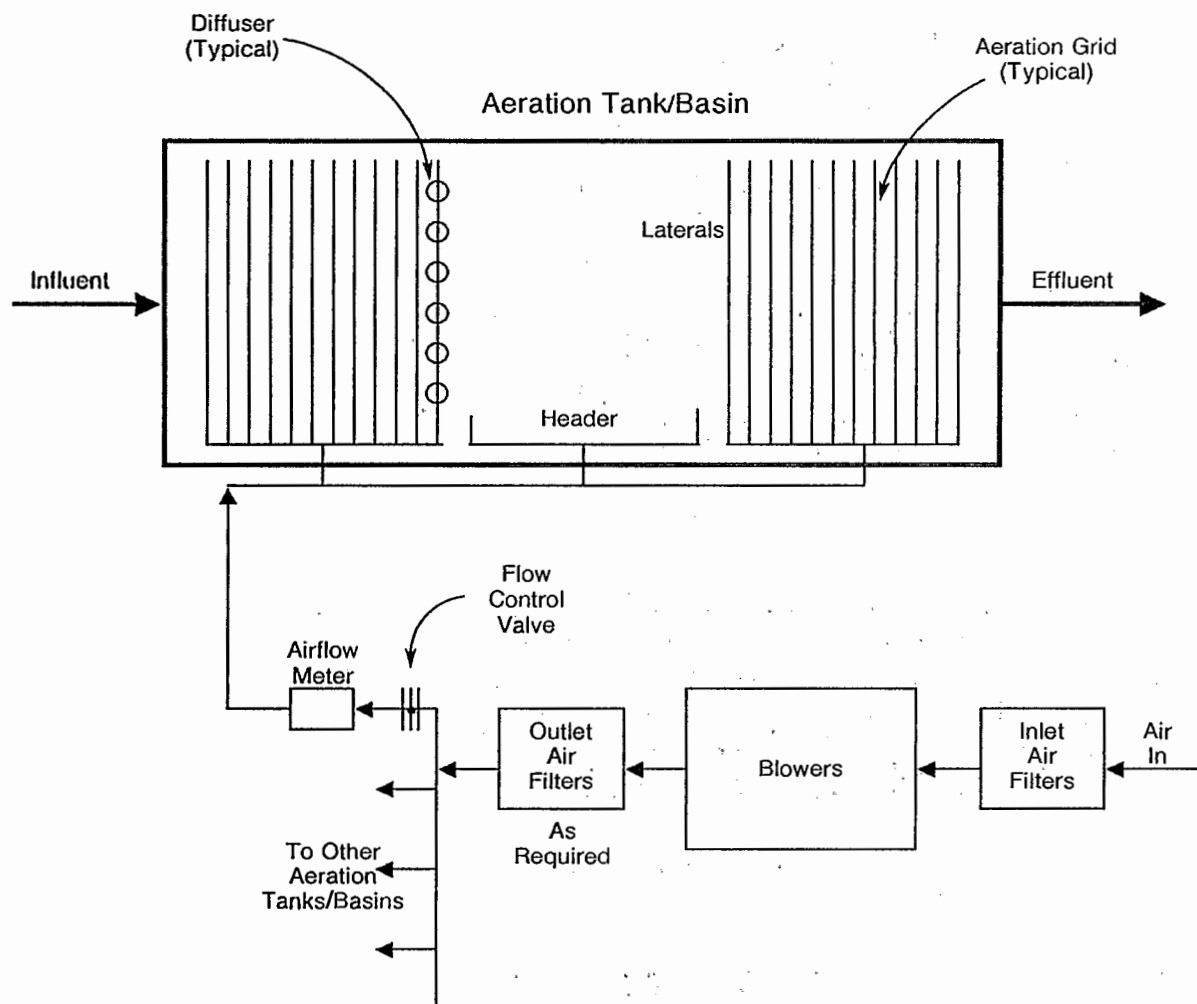
5.2.1 Process-Related Considerations

Process-related considerations that affect fine pore aeration system design include the type (or degree) of wastewater treatment, hydraulic flow pattern desired for the biological reactor, and degree of flexibility required for the aeration system. Four biological reactors configured to provide different degrees of wastewater treatment and satisfy different effluent requirements are illustrated in Figure 5-2.

Biological treatment is used primarily to remove organics (usually quantified as 5-day biochemical oxygen demand [BOD₅]) from wastewater, as typified by conventional secondary treatment (Figure 5-2a). Fine pore aeration systems have been used successfully in biological treatment systems designed to meet this objective. Their primary advantage in this application is their relatively low energy requirements compared with other oxygen transfer systems available, which can result in significant operating cost advantages. One disadvantage in this application is the potential for diffuser fouling in certain wastewaters, such as industrial wastes containing high strength, readily biodegradable materials or fine colloidal solids.

As discussed in Chapter 3, the designer should select conservative process water oxygen transfer efficiencies (OTEs) for fine pore diffusers used in secondary treatment systems with high organic loading rates due to the adverse effects of these high loadings on OTE. It can be difficult to physically place

Figure 5-1. Schematic of a fine pore aeration system.



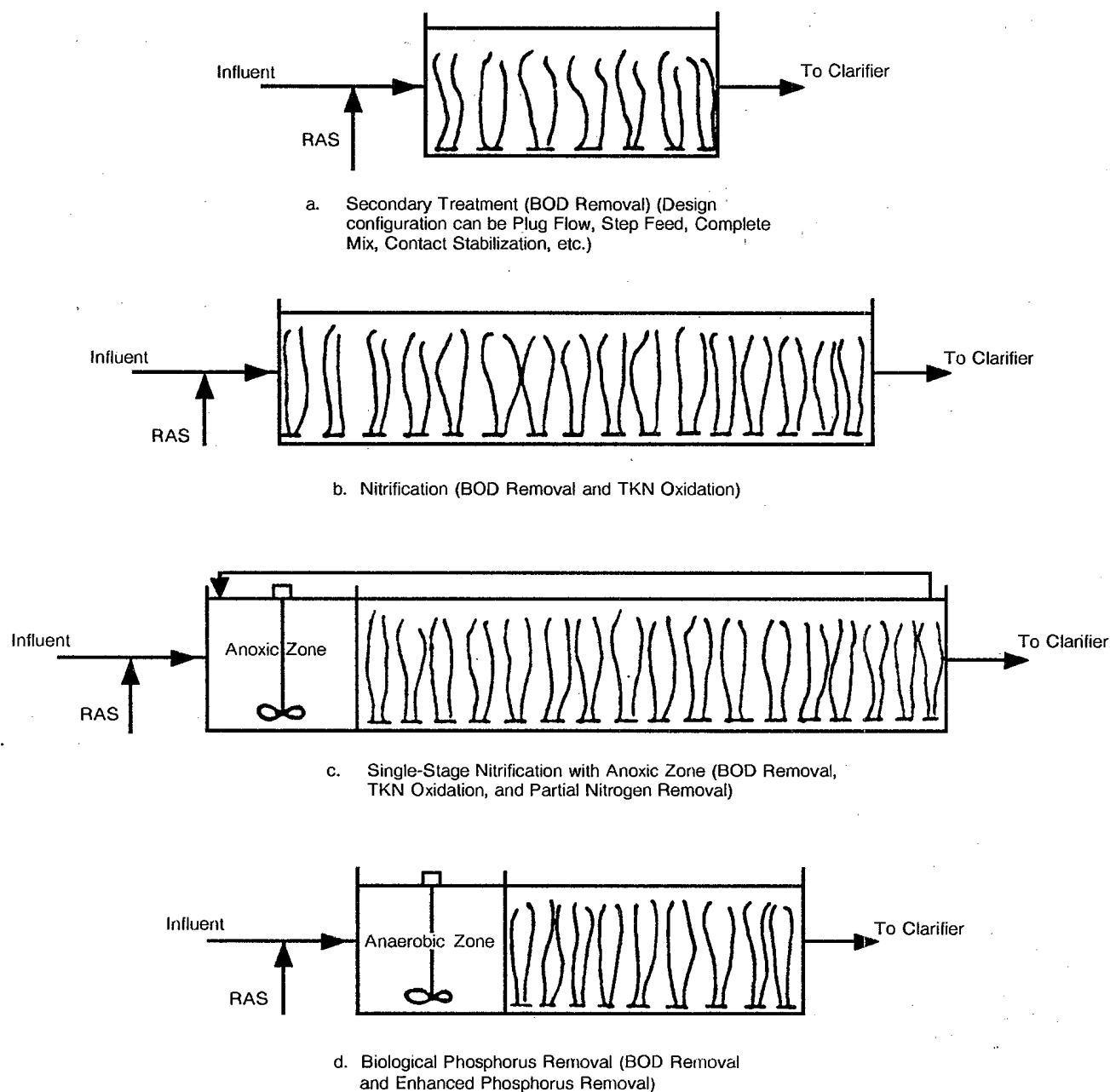
all the diffusers required to meet the volumetric oxygen demands occurring within the influent end of plug flow basins, where low process water OTEs are anticipated. This may limit the sizing and configuration of the basin.

Ammonia and organic nitrogen may also be removed from wastewater through their conversion to nitrate nitrogen via the process of nitrification (Figure 5-2b). Fine pore aeration systems have also been used successfully in this application. Relatively long solids retention times (SRTs) are generally required to achieve reliable and consistent nitrification. Reference 1 describes the process conditions required to achieve reliable nitrification and can be used as a general design resource. Because of their longer SRTs, process organic loadings for nitrification systems will be relatively low and OTEs will be higher than those observed in conventional secondary

treatment systems (as discussed in Chapter 3). Therefore, the energy cost advantage of fine pore aeration is often greater in nitrification applications than for conventional secondary treatment alone.

Nitrogen removal may be accomplished by the addition of an anoxic zone to the head end of a single-stage nitrification system (Figure 5-2c). An anoxic zone is a section of the biological reactor that is mixed but not aerated and within which nitrate nitrogen (not molecular oxygen) serves as the principal terminal electron acceptor. Fine pore aeration systems have been used quite successfully in the aerobic sections of biological nitrogen removal facilities. In fact, significant operational advantages are possible with the incorporation of anoxic zones into nitrification systems using fine pore aeration (2). These advantages include reduced energy requirements resulting from the use of recycled nitrate as a terminal

Figure 5-2. Representative (commonly-used) biological wastewater treatment systems using fine pore aeration.



RAS = Return Activated Sludge

electron acceptor and improved α_F values due to the metabolism of some organic matter in the anoxic zone. In addition, anoxic zones can effectively control some types of sludge bulking (3).

Phosphorus can also be removed from wastewater using a variety of biological phosphorus removal processes. One option, illustrated in Figure 5-2d, uses anaerobic and aerobic sequencing (4). Biological phosphorus removal is discussed in detail elsewhere

(5). Considerations for applying fine pore aeration to biological phosphorus removal are similar to those for conventional secondary treatment. The presence of the upstream anaerobic zone may lead to improved α_F values, similar to the effect seen with anoxic zones; however, data confirming this hypothesis are not currently available.

The hydraulic flow pattern produced within the aerobic section of a biological reactor must be compatible with

the design of the aeration system. Hydraulic flow patterns can range from the extreme cases of complete mix to plug flow, with intermediate conditions characterized as the equivalent number of basins-in-series for the reactor (6). During the late 1960s and early 1970s, the trend was toward the use of complete mix aerobic reactors. This was due largely to the greater potential for such systems to handle toxics and other materials that require dilution of the incoming wastewater. However, experience indicated that complete mix designs can lead to excessive growths of filamentous organisms that adversely affect the thickening characteristics of activated sludge mixed liquor (7).

Plug flow systems, on the other hand, discourage the growth of filamentous organisms and encourage the growth of desirable floc-forming bacteria. Plug flow conditions also improve the nitrification efficiency of single sludge systems (1,8). As discussed in Chapters 3 and 4, plug flow conditions affect the performance characteristics of fine pore diffusers. α values vary through a plug flow reactor, being lowest at the influent end and highest at the effluent end of the reactor.

Diffuser fouling rates also vary in step feed systems, usually being more significant at the influent end of the reactor. Switching to a step feed flow regime during periods of high loading can minimize this variability by spreading out the organic load over the full basin length. Since coarse bubble diffusers are less susceptible to fouling than fine pore systems, another alternative is to use a hybrid aeration system consisting of coarse bubble diffusers at the influent end and fine bubble diffusers elsewhere in the reactor. The impact of variations in α and fouling factor (F) on fine pore aeration system design is illustrated in Section 5.4.8.

The range of volumetric oxygen transfer rates that must be accommodated also affects aeration system evaluation and selection. For many fine pore systems, the airflow rate per diffuser must be maintained within a given range. Ideally, the lower limit is the rate that still produces uniform air distribution across the entire diffuser surface. Failure to maintain this rate results in an increased potential for diffuser fouling since foulant deposits will accumulate on the unused portion of the diffuser surface. Continued accumulation will eventually decrease diffuser performance (9,10).

Upper limit airflow rates per diffuser are those that cause diminishing improvements in oxygen transfer rate. To illustrate the principle of constraint on airflow range, consider typical ceramic diffusers. For these diffusers, the allowable ratio of maximum to minimum airflow rates is about 5:1, resulting in a ratio of maximum to minimum oxygen transfer rates of about 4:1; see Chapters 2 and 3 (11). If a greater range of volumetric oxygen transfer rates is required, the

designer should consider another diffuser type. Mixing requirements should also be checked to confirm that there is adequate energy input for mixing at the minimum airflow rate required to satisfy the lowest oxygen transfer needs. Airflow and volumetric oxygen transfer ranges vary with fine pore diffuser type. As a result, process requirements may sometimes dictate the type of fine pore diffuser that can be used.

5.2.2 O&M-Related Considerations

O&M-related considerations that affect the selection and design of a fine pore aeration system include the degree of treatment provided ahead of the biological system, nature of the wastewater, overall O&M concept of the facility, physical design characteristics of the system, and level of expertise of the plant operating staff.

As discussed in Chapter 3, fouling rates for fine pore aeration systems may be more rapid in plants with no primary treatment or with poor grit removal prior to the biological reactor. It appears that coarse solids not removed in such systems contribute to accelerated fouling of fine pore diffusers. This effect has been observed with both porous ceramic and perforated membrane fine pore diffusers (10). As a result, fine pore diffuser cleaning might need to be more frequent in systems incorporating little or no preliminary treatment of the wastewater than in systems with better pretreatment. If this is not acceptable, then another oxygen transfer system should be considered. If fine pore diffusers are used under these circumstances, the design of the system must accommodate the potential for frequent diffuser maintenance.

In most cases, regardless of the degree of prior treatment provided, periodic drainage of the biological reactor will be required to inspect, clean, repair, and/or replace diffusers. Multiple basins designed to facilitate easy drainage and cleaning are therefore required. Sufficient treatment capacity must also be available to allow periodic drainage of individual basins without adversely affecting system performance.

Also, as discussed in Chapter 3, wastewater type can significantly affect fine pore diffuser fouling rates and required cleaning. The presence of high-strength, readily-biodegradable wastewaters can significantly increase diffuser fouling rates caused by biological growths on the diffusers. Fine colloidal solids can accumulate on the diffusers, again contributing to increased fouling rates. The presence of a high concentration of readily settleable solids may also interfere with fine pore aeration system cleaning operations. Unfavorable water chemistry can result in the formation of precipitates within the diffusers. This effect can be accelerated by the addition of wastewater treatment chemicals such as ferrous or ferric iron used for phosphorus removal. Cleaning methods, which should be evaluated and selected in

the facility design phase, will be dictated by the nature of the foulant (refer to Chapter 4 for more information).

Experience suggests that some fine pore aeration systems are more fragile than other aeration systems now available (12). Many of the problems encountered with early fine pore systems can be avoided by careful attention to physical design details, material selection, and equipment specifications. Necessary steps include proper design of the header and lateral system for expansion/contraction, proper manufacturing techniques, use of stainless steel for piping supports, and proper selection of header and lateral piping material.

Because the potential for fouling of fine pore diffusers is greater than for other systems, such as coarse bubble aeration, a higher degree of attention may be required to operate fine pore diffusion systems within adequate control ranges and provide necessary maintenance. The expertise and motivation of existing plant personnel must be assessed when selecting fine pore aeration system. In some cases, the qualifications of plant personnel may not be appropriate for installation of a fine pore system. If possible, the designer should discuss the advantages and disadvantages of using a fine pore aeration system with plant personnel. The purpose of this discussion is to confirm that plant personnel are aware of the O&M requirements of fine pore aeration technology and are willing to devote the effort necessary to operate and maintain their system in a manner that minimizes operational problems and maximizes process performance and energy-savings potential.

5.3 Process Oxygen and Mixing Requirements

The first step in designing a fine pore aeration system is to determine the range and spatial distribution of the process oxygen requirements that must be met with the system. Sufficient energy must also be imparted into the basin to maintain biological solids in suspension (mixing requirements). This section describes the procedures commonly used to determine process oxygen and mixing requirements.

5.3.1 Process Oxygen Requirements

A suggested list of loading conditions that should be considered in estimating process oxygen requirements is illustrated as a worksheet in Table 5-1. Process loadings vary over the life of the facility, normally being lower in initial years of operation, increasing to design conditions often projected to occur 15-20 years in the future. Process oxygen requirements also vary significantly during any year. Daily values vary significantly, as represented in Table 5-1 by the minimum, average, and maximum daily values occurring throughout the year in question. Diurnal

fluctuations occur each day, as illustrated by the minimum 4-hr, average, and maximum 4-hr values shown for these three loading conditions. Process loadings also vary on a sustained basis, as represented by the minimum and maximum monthly values shown in Table 5-1. Diurnal fluctuations also occur during these sustained loading periods, as illustrated by the minimum 4-hr, average, and maximum 4-hr values for each of these two loading conditions. These represent "typical" diurnal ranges during the subject sustained loading period.

Table 5-1. Suggested Worksheet for List of Process Oxygen Requirements

Loading Condition	AOR (kg/d)		
	Initial Year	Mid-Point	20-yr Design
Minimum Day			
Minimum 4-hr	_____	_____	_____
Average	_____	_____	_____
Maximum 4-hr	_____	_____	_____
Minimum Month			
Minimum 4-hr	_____	_____	_____
Average	_____	_____	_____
Maximum 4-hr	_____	_____	_____
Average Day			
Minimum 4-hr	_____	_____	_____
Average	_____	_____	_____
Maximum 4-hr	_____	_____	_____
Maximum month			
Minimum 4-hr	_____	_____	_____
Average	_____	_____	_____
Maximum 4-hr	_____	_____	_____
Maximum day			
Minimum 4-hr	_____	_____	_____
Average	_____	_____	_____
Maximum 4-hr	_____	_____	_____

It is not necessary to estimate process oxygen requirements corresponding to each loading condition identified in Table 5-1. The range of conditions that must be considered depends on the process design objectives of the biological wastewater treatment system, the potential impacts of periodic low mixed liquor dissolved oxygen (DO) on process performance and operating characteristics, and economics. In general, the objective is to meet the range of process oxygen requirements that occur "most" of the time. However, it is generally not necessary to meet the entire range of process oxygen requirements that can occur under all circumstances.

Several examples of the calculation of process oxygen requirements for various biological treatment systems are presented in this chapter. Oxygen demands are calculated for a variety of process loading conditions,

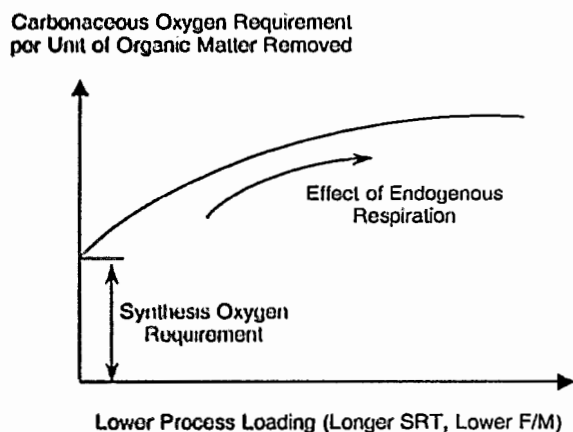
as appropriate for the particular system. An overall aeration system design problem is also presented, beginning as Example 5-8. The philosophy used to select process loading conditions in this example is discussed in detail to illustrate the thought process.

5.3.1.1 Types of Process Oxygen Requirements

Oxygen must be provided in biological wastewater treatment systems to satisfy several types of demands. One demand (associated with the oxidation of organic matter or carbonaceous materials) is called carbonaceous oxygen demand. Carbonaceous oxygen demand is generated by two cellular functions: cell synthesis and endogenous respiration.

Cell synthesis carbonaceous oxygen demand occurs when organic matter is first metabolized by microorganisms contained in the mixed liquor. It is related to the oxygen required to oxidize a portion of the organic matter to provide the energy necessary for cell synthesis. Endogenous respiration carbonaceous oxygen demand occurs as the synthesized organisms are retained in the treatment system. It represents the oxygen demand exerted as the organisms oxidize internal storage reserves to maintain essential life processes. The net result is that increasing amounts of oxygen are required as lower process organic loadings are used. Lower process organic loadings are characterized by operation at longer SRTs and lower food-to-microorganism (F/M) loadings. This concept is illustrated in Figure 5-3. References 13-16 provide a detailed discussion of this topic.

Figure 5-3. Effect of process loading on carbonaceous oxygen requirement.



Oxygen is also required to oxidize inorganic materials present in the influent wastewater. A good example is hydrogen sulfide, which is oxidized chemically when brought in contact with DO in the biological reactor. Other examples are listed in Section 5.3.1.2d. Reactions of this type can be quite rapid and can proceed to complete oxidation according to well established stoichiometry.

In some cases, inorganic chemical oxygen demand is quantified by direct measurement of the chemical in the influent wastewater. In other cases, it is quantified by measurement of the resulting oxygen demand, traditionally by use of the immediate oxygen demand (IOD) test. This test has been eliminated from the most recent edition of Standard Methods (17) because of limitations on its accuracy. However, the concept behind the test is appropriate for understanding the nature of inorganic chemical oxygen demand as described above. Basically, the oxygen consumption of a diluted sample of waste is measured over a period of time (15 minutes in the old test) short enough to exclude biological oxidation but long enough for chemical oxidation of all readily oxidizable chemicals in the wastewater sample.

In addition, oxygen is required for biological nitrification of ammonia nitrogen to nitrate nitrogen. If the process is designed and operated in a nitrification mode, the oxygen demand due to nitrification must be included in the calculation of oxygen requirements for the system. However, nitrification may also occur in systems where only carbonaceous BOD removal is required. When the wastewater is warm, say 20°C (68°F) or above, it may not be possible to operate the treatment system at a high enough organic loading to prevent nitrification from occurring. Under these circumstances, oxygen transfer capacity to meet this additional demand must be provided.

Process oxygen requirements will be reduced if denitrification occurs in the aeration system. Denitrification can occur under controlled conditions if the system is specifically designed with an anoxic zone for nitrogen removal (see Section 5.2.1). It also occurs in some systems with relatively poor mixing or in nitrifying systems where oxygen demand exceeds the oxygen supplied. These circumstances result in the development of unintentional "anoxic zones" in the poorly mixed region of the reactor.

5.3.1.2 Calculation of Process Oxygen Requirements

Several approaches are available to calculate process oxygen requirements for a biological wastewater treatment system. This section presents the general types of procedures available and discusses the differences between them.

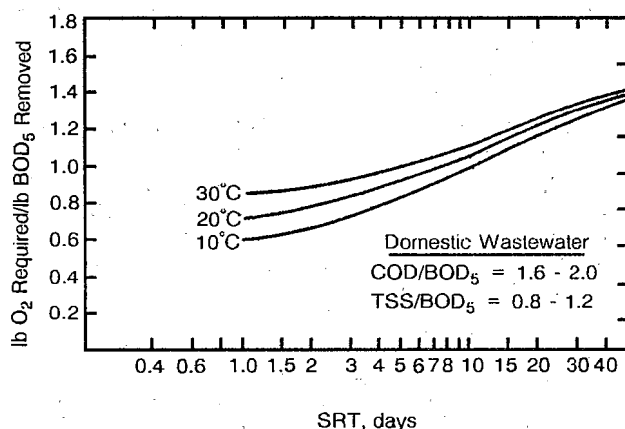
Several factors are important in determining the appropriate procedure for a particular situation. The most important factor is the confidence the designer has in the accuracy of the design data base. Common sense suggests that little is gained in the use of a highly sophisticated procedure when process loading and operating conditions are known only on an approximate basis. However, the use of a sophisticated procedure may be highly desirable if relatively accurate data are available. The designer must also consider that an oxygen transfer system is

designed to meet a range of process oxygen requirements. In certain cases, when the actual range of process oxygen requirements is not well known, it may be appropriate to use a conservative approach. If a conservative value for the maximum oxygen transfer requirement is used, sufficient flexibility should be incorporated in the system design to accommodate much lower process oxygen requirements efficiently.

a. Carbonaceous Process Oxygen Requirements

Four different approaches are reviewed to calculate carbonaceous process oxygen requirements. The first approach is empirical in nature and is referred to here as the oxygen consumption ratio approach. With this approach, a factor relating oxygen demand to organic loading is selected and used for design. Most often the organic loading is expressed as the BOD₅ loading in units of mass per time, while the oxygen consumption ratio factor is expressed as mass of oxygen required per mass of BOD₅ applied to (or removed by) the system. The regulations employed by many states to govern the design of wastewater treatment facilities use this approach. In other cases, this approach is incorporated into state regulations by reference to Ten States Standards (18). For carbonaceous process oxygen requirements, Ten States Standards states: "In the absence of experimentally determined values, the design oxygen requirements for all activated sludge processes shall be 1.1 lb O₂/lb peak BOD₅ applied to the aeration basins (1.1 kg O₂/kg peak BOD₅), with the exception of the extended aeration process, for which the value shall be 1.8."

Figure 5-4. Example oxygen consumption ratios for carbonaceous oxygen demand.



A more sophisticated version of this approach is to use the curves presented in Manual of Practice 8 (13), as illustrated in Figure 5-4.

To use these curves, the appropriate oxygen consumption ratio is selected considering the

anticipated operating conditions (i.e., SRT and temperature) for the system. This ratio is then multiplied by the organic loading to calculate the process oxygen requirement. The use of this technique is illustrated in Example 5-1 below.

The oxygen consumption ratio method implicitly considers the effects of endogenous respiration on carbonaceous process oxygen requirements by using a ratio that increases as SRT increases, as illustrated in Figures 5-3 and 5-4.

The second procedure specifically considers the separate effects of cell synthesis and endogenous respiration on carbonaceous oxygen requirements. Synthesis oxygen requirements are calculated directly from the applied BOD₅ loading, while the endogenous respiration demand is calculated from the inventory of activated sludge solids maintained in the system. This method usually requires knowledge of the anticipated loading and operating conditions for the biological wastewater treatment system, as well as knowledge of the appropriate coefficients for a particular design. The calculations are similar to those used with the oxygen demand method described below.

The third technique calculates oxygen demand based on an oxygen demand mass balance. The basic concept (19) assumes that oxygen demand applied to a biological system is either satisfied by oxidation of the applied organics or leaves the system in the effluent or waste sludge. The oxygen demand balance procedure requires knowledge of system loadings, operating conditions, and kinetic factors. Example 5-2 illustrates the procedure.

The fourth method for estimating carbonaceous process oxygen requirements uses more sophisticated process models that subdivide the wastewater and mixed liquor into several components. This approach is typified by the comprehensive model developed by a task group of the International Association on Water Pollution Research and Control (IAWPRC) (20). In this model, organics contained in the influent wastewater are divided into rapidly biodegradable, slowly biodegradable, nonbiodegradable soluble, and nonbiodegradable particulate fractions. Mixed liquor components include active bacteria, inactive bacteria, and inert influent solids. Carbonaceous process oxygen requirements are calculated using an oxygen demand mass balance similar in concept to that illustrated in Example 5-2. The adequacy of this model in predicting total carbonaceous process oxygen requirements is probably no better than that of the other methods reviewed above. However, the more sophisticated structure of models such as the IAWPRC model allows them to more accurately estimate temporal and spatial variations in carbonaceous process oxygen requirements. Because of this, the use of models will be discussed in more detail in Section 5.3.1.3.

Example 5-1. Oxygen Consumption Ratio Approach

Consider an activated sludge system with the following process loadings:

	BOD ₅ Loading (lb/d)	Wastewater Temp. (°C)
Minimum month	5,500	10
Average month	6,600	15
Maximum month	7,700	25
Peak day	12,800	25

The operating SRT is 4 days under all conditions. From Figure 5-4, the oxygen consumption ratio at a 4-day SRT and 10°C (50°F) is 0.65 lb O₂/lb BOD₅ removed, increasing to 0.82 at 15°C (59°F) and 0.95 at 25°C (77°F). Using these factors, and neglecting the soluble BOD₅ in the process effluent, carbonaceous process oxygen requirements are calculated:

Minimum month:

$$(5,500 \text{ lb BOD}_5/\text{d})(0.65 \text{ lb O}_2/\text{lb BOD}_5) = 3,575 \text{ lb O}_2/\text{d}$$

Annual average:

$$(6,600 \text{ lb BOD}_5/\text{d})(0.82 \text{ lb O}_2/\text{lb BOD}_5) = 5,412 \text{ lb O}_2/\text{d}$$

Maximum month:

$$(7,700 \text{ lb BOD}_5/\text{d})(0.95 \text{ lb O}_2/\text{lb BOD}_5) = 7,315 \text{ lb O}_2/\text{d}$$

Peak day:

$$(12,800 \text{ lb BOD}_5/\text{d})(0.95 \text{ lb O}_2/\text{lb BOD}_5) = 12,160 \text{ lb O}_2/\text{d}$$

b. Nitrification Process Oxygen Requirements

Nitrification process oxygen requirements are generally estimated on a stoichiometric basis. Theoretically, 4.57 lb O₂ are required per lb nitrate nitrogen produced in the nitrification process (1,21). Accurate estimation of the amount of nitrate nitrogen that can be generated through nitrification is critical to accurate use of this procedure.

Reduced nitrogen is generally present in an influent wastewater in two primary forms: ammonia nitrogen (NH₃-N) and organic nitrogen. Together, the two components constitute the total Kjeldahl nitrogen (TKN) of the influent wastewater. Figure 5-5 illustrates the fate of nitrogen in a typical nitrifying activated sludge system. Influent organic nitrogen consists of both biodegradable and nonbiodegradable fractions. The nonbiodegradable organic nitrogen can be further subdivided into soluble and particulate forms. The soluble nonbiodegradable organic nitrogen will simply pass through the biological treatment system. The particulate nonbiodegradable organic nitrogen will accumulate in the mixed liquor in the biological reactor and will be removed from the system in the waste

sludge. Biodegradable organic nitrogen will be converted into ammonia nitrogen. This, combined with the ammonia nitrogen present in the influent wastewater, constitutes the nitrogen in the system available to the biomass.

Some of the available nitrogen will be used for cell synthesis by the carbonaceous and nitrifying bacteria produced in the treatment system. The remainder is available to be converted to nitrate nitrogen by the nitrifying organisms. An example of the fate of nitrogen in a typical wastewater treatment system is presented in Example 5-3.

More detailed discussions of this topic (1,13,14,16,20,21) are presented elsewhere. The IAWPRC and many similar models, as discussed in Section 5.3.1.2a, incorporate the nitrogen cycle in the procedures used to calculate nitrification process oxygen requirements.

As with carbonaceous process oxygen requirements, simplifying assumptions can be made in calculating nitrogenous oxygen demand for those situations

Example 5-2. Oxygen Demand Mass Balance Approach

Consider the process loadings and operating conditions used in Example 5-1. Assume the following:

The ratio of ultimate oxygen demand (BOD_{ult}) to BOD_5 is 1.5.

Y_g = yield coefficient = 0.5 lb VSS/lb BOD_5 removed

b = decay coefficient = 0.06 d^{-1}

The oxygen demand of cell material is 1.42 lb/lb VSS.

Effluent soluble BOD_5 and VSS are negligible.

For maximum month conditions, BOD_{ult} applied to the system is:

$$(7,700 \text{ lb } BOD_5/d)(1.5 \text{ lb } BOD_{ult}/\text{lb } BOD_5) = 11,550 \text{ lb } BOD_{ult}/d$$

The biomass produced (P_x) is calculated using the following equation (19):

$$P_x = (BOD_5)(Y_g)/[(1 + b(SRT))] \quad (5-1)$$

$$\begin{aligned} P_x &= (7,700 \text{ lb } BOD_5/d)(0.5 \text{ lb VSS/lb } BOD_5)/[1 + 0.06 \text{ d}^{-1}(4 \text{ d})] \\ &= 3,105 \text{ lb VSS/d} \end{aligned}$$

Expressed as ultimate oxygen demand, this becomes:

$$(3,105 \text{ lb VSS/d})(1.42 \text{ lb } O_2 \text{ demand/lb VSS}) = 4,409 \text{ lb } O_2 \text{ demand/d}$$

The process oxygen requirement of the system is the difference between the oxygen demand applied and the oxygen demand contained in the waste sludge. That value is:

$$\begin{aligned} \text{Process } O_2 \text{ Requirement} &= O_2 \text{ Demand Applied} - O_2 \text{ Demand of Waste Sludge} \\ &= 11,550 \text{ lb } BOD_{ult}/d - 4,409 \text{ lb } O_2 \text{ demand/d} \\ &= 7,141 \text{ lb } O_2/d \end{aligned}$$

The maximum month process oxygen requirement estimated using the oxygen consumption ratio approach (Example 5-1) was 7,315 lb O_2 /d. The close agreement between the two methods indicates that appropriate coefficients were assumed in the oxygen demand mass balance approach.

where precise information is not available. For example, estimates of the particulate nonbiodegradable organic nitrogen and available nitrogen incorporated into biomass can be combined and expressed in terms of the total nitrogen in the waste sludge. For municipal wastewater that has been subjected to primary treatment (i.e., municipal primary effluents), it can be assumed that biologically inert volatile matter that enters an activated sludge system (including particulate nonbiodegradable organic nitrogen) normally contributes about 0.1 lb VSS/lb BOD_5 applied to the mass of waste sludge produced. The total process yield (biomass produced plus biologically inert volatile matter that passes through the process) for Example 5-3 would be about 0.6 lb VSS produced/lb BOD_5 applied to the biological reactor using this assumption. The nitrogen content of biologically inert volatile matter will generally be less than that of biomass. Assuming that the nitrogen content of the waste sludge is decreased from 10 to 9 percent by this inert material, the mass of nitrogen contained in the waste sludge can be calculated as:

$$\begin{aligned} (150 \text{ mg/L } BOD_5)(0.6 \text{ lb VSS/lb } BOD_5)(0.09 \text{ lb N/lb VSS}) \\ = 8.1 \text{ mg N/L} \end{aligned}$$

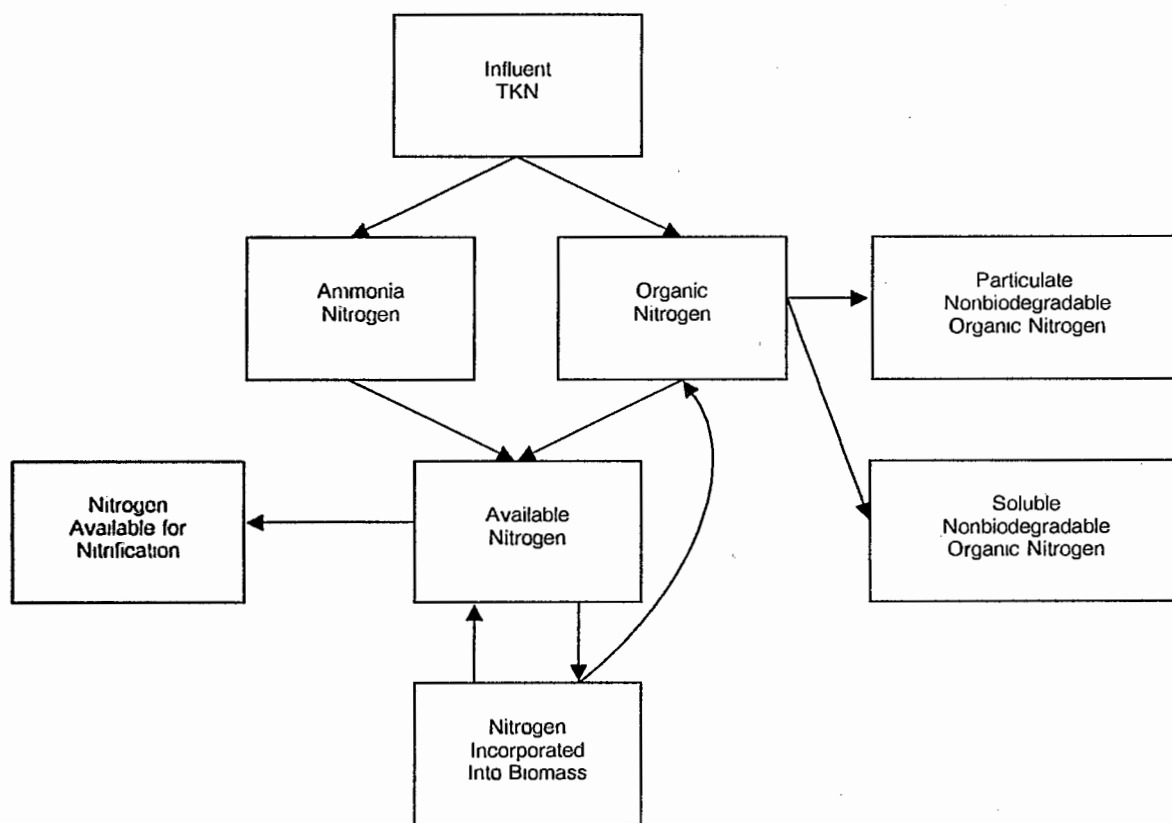
In other cases it may be appropriate to assume that the influent ammonia nitrogen is equal to the nitrogen available to be nitrified. This would have been appropriate for the conditions described in Example 5-3 (21.2 mg N/L influent ammonia nitrogen vs. 21.0 mg N/L nitrogen available to be nitrified). The assumption inherent with the use of influent ammonia nitrogen to represent the amount of nitrogen available to be nitrified is that the organic nitrogen concentration equals the nitrogen synthesized by the waste sludge. This assumption is often appropriate for municipal wastewaters with minimal industrial components.

It is also sometimes assumed that all the nitrogen present in the influent wastewater (i.e., the influent TKN) is available to be nitrified. This is conservative and results in overestimation of the nitrification process oxygen requirement. However, it is sometimes appropriate to use this assumption, particularly when influent nitrogen concentrations are not well characterized.

c. Denitrification Process Oxygen Credit

The occurrence of denitrification in an aeration system reduces total process oxygen requirements. This

Figure 5-5. Nitrogen metabolism in nitrifying activated sludge systems.



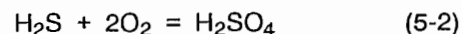
occurs because a portion of the carbonaceous oxygen demand is satisfied by reduction of nitrate nitrogen to nitrogen gas during the denitrification process. Theoretically, 2.86 lb O₂ demand is satisfied per lb nitrate nitrogen reduced to nitrogen gas (1,21). Thus, the denitrification process oxygen credit is calculated by multiplying the mass of nitrogen denitrified by 2.86.

Denitrification occurs in a biological wastewater treatment system when nitrate is added to an anoxic zone (see Figure 5-2c). The extent of denitrification can be limited by either of two factors: 1) the mass of nitrate nitrogen added to the anoxic zone, or 2) the denitrification capability of the anoxic zone. Assuming that sufficient capability is present in the anoxic zone to denitrify the nitrate nitrogen loading, the mass of nitrate nitrogen denitrified can be calculated directly from a mass balance on the zone. Procedures used to size anoxic zones are presented elsewhere (5,21).

d. Inorganic Chemical Process Oxygen Requirements
A variety of reduced materials can be present in a wastewater stream that will be oxidized when brought in contact with DO. Examples include reduced forms of sulfur such as sulfide, sulfite, and thiosulfite; ferrous iron; and reduced manganese. For many wastewaters, the process oxygen requirements associated with oxidation of these materials are

insignificant in comparison to those associated with oxidation of organic material and ammonia nitrogen. This occurs because wastewater collection systems are ideally designed to maintain the wastewater in an aerobic condition. Therefore, DO is available in the wastewater as it flows through the collection system and any reduced inorganic materials are normally oxidized there before they reach the wastewater treatment plant. Under certain conditions, however, significant quantities of reduced inorganic materials can be present. These conditions include: 1) the development of anaerobic conditions in the collection system due to the use of shallow slopes or force mains, 2) the presence of an industrial waste that contains significant quantities of reduced inorganic materials, and 3) the addition of reduced chemicals as part of the treatment process, such as the use of ferrous chloride for phosphorus removal.

Inorganic chemical process oxygen requirements can be calculated directly on a stoichiometric basis. For example, consider the oxidation of hydrogen sulfide:



For this reaction, 2 moles of O₂ are required to oxidize 1 mole of hydrogen sulfide (H₂S) to sulfuric acid (H₂SO₄). This corresponds to approximately 2 lb

Example 5-3. Oxygen Demand Mass Balance Approach

Consider a wastewater influent to a biological wastewater treatment system with the following characteristics:

Flow = 5.3 mgd
Ammonia nitrogen = 21.2 mg N/L
Organic nitrogen = 8.8 mg N/L

[TKN of this wastewater is 21.2 mg N/L ammonia nitrogen plus 8.8 mg N/L organic nitrogen, or 30 mg N/L.]

The nonbiodegradable components of the organic nitrogen are:

Particulate nonbiodegradable organic nitrogen = 3.0 mg N/L
Soluble nonbiodegradable organic nitrogen = 1.0 mg N/L

The available nitrogen is the influent TKN less the nonbiodegradable nitrogen components:

Available nitrogen = $21.2 + 8.8 - 3.0 - 1.0 = 26.0$ mg N/L

A portion of this nitrogen is used for cell synthesis. Cell synthesis is a function of influent BOD_5 concentration, process loading conditions, and process kinetics. For this example, these parameters are assumed to be:

Influent $BOD_5 = 150$ mg/L
 $Y_g = 0.5$ lb VSS/lb BOD_5 removed
 $b = 0.06$ d⁻¹
Nitrogen content of biomass = 0.1 lb N/lb VSS
Process SRT = 8 d

Then, from Equation 5-1, the nitrogen used for synthesis of heterotrophic organisms is:

$$(0.1 \text{ lb N/lb VSS})(150 \text{ mg/L } BOD_5)(0.5 \text{ lb VSS/lb } BOD_5)/[1 + 0.06d^{-1}(8d)] = 5.0 \text{ mg N/L}$$

Theoretically, some nitrogen is also used for synthesis of the nitrifying organisms. However, this quantity can be neglected for most practical applications and the nitrogen to be nitrified is the difference between the available nitrogen and the nitrogen incorporated in the biomass:

$$\text{Nitrogen to be nitrified} = 26.0 - 5.0 = 21.0 \text{ mg N/L}$$

[This calculation assumes either that nitrogen is not returned to the liquid process stream from solids processing or that this nitrogen is included in the influent concentration. Nitrogen recycles from solids processing can be substantial.]

Assuming complete nitrification, the nitrification process oxygen requirement is:

$$(5.3 \text{ mgd}) (21 \text{ mg/L } NO_3\text{-N generated}) (4.57 \text{ lb } O_2/\text{lb } NO_3\text{-N generated}) (8.34 \text{ lb/mil gal/mg/L}) \\ = 4,242 \text{ lb } O_2/d$$

O_2 /lb H_2S . Similar stoichiometric calculations should be used to estimate process oxygen requirements for other reduced inorganic materials.

Another approach is used to calculate inorganic chemical process oxygen requirements when the IOD procedure is employed to quantify the concentration of reduced inorganic chemicals present in a wastewater stream. In this case, since the concentration of reduced inorganic materials is measured directly as its oxygen equivalent, the measured IOD is used directly as the associated process oxygen requirement. Caution should be

exercised when using the IOD procedure to ensure that all inorganic chemicals are oxidized within the time frame of the IOD procedure. Caution is also required to ensure that none of the reduced inorganic materials are oxidized because of unintentional aeration during sample collection or handling before performing the analysis.

e. Total Process Oxygen Requirements

The total process oxygen requirement (also called the actual oxygen requirement, or AOR) for a biological wastewater treatment system is the sum of the process oxygen requirements described above:

AOR = Carbonaceous Process Oxygen Requirement
+ Inorganic Chemical Process Oxygen Req.
+ Nitrification Process Oxygen Requirement
- Denitrification Process Oxygen Credit (5-3)

Examples 5-4 through 5-7 illustrate the calculation of AORs for several situations.

5.3.1.3 Variations in Process Oxygen Requirements

Process oxygen requirements vary both spatially (i.e., from point to point) and temporally (i.e., from time to time) in biological wastewater treatment systems. Spatial variations occur because the various components of the total process oxygen requirement are not uniformly distributed throughout the biological reactor. Temporal variations occur because of variations in process loadings and operating conditions. Sufficient capacity and flexibility must be designed into fine pore aeration systems to accommodate these variations.

Inadequate capacity in the highly-loaded section of a biological reactor can adversely affect process performance due to sustained low process DO concentrations. However, in some cases, the oxygen demand will be transferred down the basin and be satisfied without affecting effluent quality. Poor distribution of oxygen transfer capacity or inadequate aeration rate turndown capability can result in overaeration and inefficient operation during periods of lower process loading.

The magnitude of temporal and spatial variations, along with procedures for quantifying them, are discussed in the following sections.

a. Temporal Variations

The concept of temporal variations in process oxygen requirements was introduced in Section 5.3.1, using Table 5-1 to illustrate the types of variations that can occur. Temporal variations occur because of both short- and long-term variations in process loadings and operating conditions. Short-term variations include both day-to-day variations in process loadings and operating conditions, as well as variations during the day (i.e., diurnal variations). Figure 5-6 presents a typical diurnal BOD₅ loading for wastewater treatment plants. The peak 4-hr:average BOD₅ loading values reported for four full-scale treatment plants were 1.17, 1.30, 1.38, and 1.50 (22).

Importantly, short-term variations in process oxygen requirements are smaller than corresponding short-term variations in process loadings. This occurs for three reasons: 1) the process does not fully adapt to short-term loading extremes (either high or low), 2) storage of organic matter occurs at peak loadings, resulting in attenuation of peak process oxygen requirements, and 3) the aeration basin volume has an equalization effect on process loadings. For

example, a 3:1 diurnal range in process BOD₅ loadings may result in only about a 2:1 diurnal range in carbonaceous process oxygen requirements.

Long-term variations in process loadings and operating conditions have a more pronounced effect on process oxygen requirements because the process fully acclimates to these changes. Long-term variations include weekly, monthly, and seasonal variations. In reality, the impacts of short- and long-term variations in process loadings and operating conditions on process oxygen requirements are additive. Long-term variations result in changes in "average" process oxygen requirements. Superimposed on these are short-term changes in process oxygen requirements resulting from diurnal variations in process loadings and operating conditions.

Judgment must be exercised in selecting the range of process oxygen requirements to be accommodated by a particular design. According to Manual of Practice 8 (13), it is not unusual for the peak organic loading to be 5-10 times the minimum hourly load in a conventional wastewater treatment plant. It is generally not necessary, however, to satisfy the entire range of process oxygen requirements. Periodic occurrences of low process DO can generally be tolerated without compromising process integrity or significantly affecting process performance. However, frequent or prolonged periods of suppressed process DO should be avoided.

Thus, it is not necessary to install sufficient oxygen transfer capacity to meet the peak diurnal process oxygen requirement occurring on the peak day. Rather, the normal design approach would be to install sufficient oxygen transfer capacity to meet the typical or average diurnal process oxygen requirement occurring during the sustained loading condition selected as the basis for the process design. Since process designs are often based on maximum month loading, the oxygen transfer system would be designed to meet both the peak day demands and the typical diurnal process oxygen requirements occurring in the maximum month. Maximum diurnal demands during peak days could be handled with the standby blower capacity in the system.

Estimation of temporal variations in total process oxygen requirements is illustrated in Example 5-8.

b. Spatial Variations

Figure 5-8 illustrates an idealized spatial distribution of process oxygen requirements along the length of a plug flow reactor when not limited by the process DO concentration. In this illustration, the carbonaceous process oxygen requirement is divided into its two components, synthesis and endogenous respiration. Endogenous process oxygen requirements are associated with the biomass and tend to be distributed

Example 5-4. Conventional Secondary Treatment with Seasonal Nitrification

Consider the activated sludge system from Example 5-1. Although not required, it is likely that nitrification will occur during the summer when wastewater temperatures are higher. It is assumed that wastewater temperatures average 20°C (68°F) during the summer months when nitrification is occurring. Without adequate oxygen, the onset of nitrification can lead to septic conditions and process upsets. Sufficient oxygen transfer capability must be provided to satisfy these periods of nitrification and to preserve acceptable effluent quality. However, periodic low DO episodes can be tolerated, indicating that nitrification process oxygen demand need not be satisfied during peak day events.

The average ammonia nitrogen loading to the facility is about 935 lb NH₃-N/d. Assume that the nitrogen available to be nitrified is equal to the ammonia nitrogen loading. As a result, the nitrification process oxygen requirement is 4.57 lb O₂/lb NO₃-N generated x 935 lb NO₃-N generated/d = 4,273 lb O₂/d. Tabulate AOR for both nitrifying and non-nitrifying conditions. For non-nitrifying conditions, AOR is the carbonaceous process oxygen requirement as calculated in Example 5-1. For nitrifying conditions, nitrification process oxygen requirement of 4,273 lb O₂/d must be added to the average and maximum month carbonaceous process oxygen requirements. The results are:

Loading Condition	AOR (lb/d)	
	Non-nitrifying	Nitrifying
Minimum month	3,575	Not Applicable
Average month	5,412	9,685
Maximum month	7,315	11,588
Peak day	12,160	Not Applicable

Example 5-5. Effect of Inorganic Chemical Oxygen Demand

Consider the activated sludge system from Example 5-4, and evaluate the effect of wastewater septicity on AOR. Assume for this evaluation that the H₂S concentration of the influent wastewater approaches 10 mg/L. From Section 5.3.1.2d, 2 lb O₂ are required to oxidize 1 lb H₂S. Therefore, the inorganic chemical oxygen requirement associated with the H₂S in the influent wastewater is:

$$(5.3 \text{ mgd})(10 \text{ mg/L H}_2\text{S})(2 \text{ lb O}_2/\text{lb H}_2\text{S})(8.34 \text{ lb/mil gal/mg/L}) = 884 \text{ lb/d}$$

Referring to the AORs listed in Example 5-4, wastewater septicity (i.e., the presence of hydrogen sulfide) would increase the average month AOR by 9 percent under nitrifying conditions and by 16 percent under non-nitrifying conditions.

uniformly throughout the length of the reactor. Synthesis process oxygen requirements are highest in the more highly-loaded portion of the reactor (i.e., the initial section). Nitrification process oxygen requirements are exerted uniformly along the length of the reactor until they become limited by the depletion of ammonia nitrogen (23).

Use of the more sophisticated procedures for predicting spatial variations in process oxygen requirements necessitates an understanding of the hydraulic flow pattern within the biological reactor. Very often, flow patterns are characterized in terms of the equivalent number of basins-in-series that the basin represents (6). Hydraulic flow patterns for existing reactors may be characterized using standard tracer techniques. In other situations, experience or

correlations from the literature can be used. For example, the Water Research Centre in the United Kingdom has developed the following empirical relationship to estimate the number of equivalent basins-in-series for a diffused air aeration basin:

$$N = 7.4 LQ(1 + r_r) \div (WH) \quad (5-4)$$

where,

N = equivalent number of basins-in-series

L = aeration basin length, m

Q = wastewater flow, m³/s

r_r = return activated sludge recycle ratio (dimensionless)

W = aeration basin width, m

H = water depth, m

Example 5-6. Nitrifying Activated Sludge

Consider the activated sludge system from Example 5-1. The system is to be expanded to provide year-round nitrification. A design SRT of 12 days is selected to allow nitrification to occur during cold weather operation. Process BOD₅ loadings are as listed in Example 5-1. An analysis of the mass of ammonia nitrogen, nitrite nitrogen, and nitrate nitrogen in the process effluent was completed and indicated the following masses of nitrogen were available to be nitrified:

770 lb/d	-	Minimum month
935 lb/d	-	Average month
1,080 lb/d	-	Maximum month
1,500 lb/d	-	Peak day

Process AOR is calculated as the sum of the carbonaceous process oxygen requirements and the nitrification process oxygen requirements. Carbonaceous process oxygen requirements are calculated using Figure 5-4:

Loading Condition	SRT (d)	Temp. (°C)	Ratio (lb O ₂ /lb BOD ₅)	BOD ₅ Loading (lb/d)	Carbonaceous Oxygen Req. (lb/d)
Minimum month	12	10	1.00	5,500	5,500
Average month	12	15	1.05	6,600	6,930
Maximum month	12	25	1.15	7,700	8,855
Peak day	9	25	1.05	12,800	13,440

It should be noted that an "effective SRT" of 9 days was selected to calculate process oxygen requirements for peak day operating conditions to account for the lower unit oxygen consumption ratio that will occur during relative short-duration, high-loading conditions. In these situations, a higher proportion of organics will be stored rather than oxidized by the microorganisms. Thus, even though SRTs will not change instantaneously in the field, use of an effective SRT of 9 instead of 12 days in this example is assumed to approximate the lower oxygen demands under these circumstances.

Nitrification process oxygen requirements are calculated directly from the mass of nitrogen available to be nitrified:

Loading Condition	N Loading (lb/d)	Ratio (lb O ₂ /lb N)	Nitrification Oxygen Req. (lb/d)
Minimum month	770	4.57	3,519
Average month	935	4.57	4,273
Maximum month	1,080	4.57	4,936
Peak day	1,500	4.57	6,855

The AOR is the sum of the carbonaceous and nitrification process oxygen requirements:

Loading Condition	Process Oxygen Requirement (lb/d)		
	Carbonaceous Demand	Nitrification Demand	AOR
Minimum month	5,500	3,519	9,019
Average month	6,930	4,273	11,203
Maximum month	8,855	4,936	13,791
Peak day	13,440	6,855	20,295

The impact of designing for complete, as opposed to partial, nitrification on process oxygen requirements can be observed by comparing these results with those of Example 5-4. In this case, average month design AORs are increased by only 16 percent, but peak day AORs are increased by about 67 percent.

Example 5-7. Impact of Anoxic Zone

Consider the nitrifying activated sludge system from Example 5-6, and evaluate the impact of the addition of an upfront anoxic zone on AOR. For the evaluation, assume that the anoxic zone size and mixed liquor recirculation rate (see Figure 5-2c) are adequate to allow denitrification of 60 percent of the nitrate nitrogen generated in the process (see References 5 and 21 for information on the design of anoxic zones). Denitrification satisfies 2.86 lb O₂ demand/lb NO₃-N denitrified. The denitrification process oxygen credit is:

Loading Condition	NO ₃ -N Generated ¹ (lb/d)	NO ₃ -N Denitrified ² (lb/d)	Oxygen Credit ³ (lb/d)
Minimum month	770	462	1,321
Average month	935	561	1,604
Maximum month	1,080	648	1,853
Peak day	1,500	900	2,574

¹ From Example 5-6.

² 60 percent of NO₃-N generated.

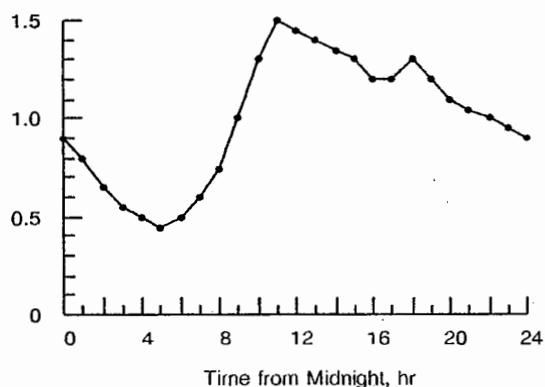
³ 2.86 x NO₃-N denitrified.

Comparing these values to the AORs tabulated for Example 5-6, addition of an anoxic zone will reduce AOR for the nitrifying activated sludge system by 13-15 percent. The design AORs would then be:

Loading Condition	Process Oxygen Requirement (lb/d)			AOR
	Carbonaceous Demand	Nitrification Demand	Denitrification Credit	
Minimum month	5,500	3,519	1,321	7,698
Average month	6,930	4,273	1,604	9,599
Maximum month	8,855	4,936	1,853	11,938
Peak day	13,440	6,855	2,574	17,721

Figure 5-6. Example diurnal BOD₅ loading for a municipal wastewater treatment plant.

Relative BOD₅ Loading



Several procedures can be used to estimate spatial variations of total process oxygen requirements in biological wastewater treatment systems. In some cases, simple rules-of-thumb based on experience with similar treatment systems are used. For example, oxygen transfer capacity in a conventional activated sludge reactor is often tapered as follows:

45-55 percent of total process air in the first one-third;
25-35 percent of total process air in the second one-third;
and
15-25 percent of total process air in the last one-third.

Another approach involves construction of diagrams, such as Figure 5-8, that quantitatively distribute the various components of the total process oxygen requirement. A numerical example of this approach is presented below.

For existing biological wastewater treatment systems, temporal and spatial variations in process oxygen requirements can be measured directly. Hourly, daily, and seasonal variations can be measured in various portions of the reactor and used to establish ranges that must be accounted for in the design. This approach is limited to the wastewater type and operating conditions encountered during testing. If an existing system is to be retrofitted, the possibility of a change in overall reactor mixing patterns must also be considered.

When sufficient information is available, process models such as the IAWPRC model described above can be used to estimate spatial and temporal variations in total process oxygen requirements. Recent work (24) suggests that the IAWPRC model

Example 5-8. Temporal Variations in Total Process Oxygen Requirements

A fine pore aeration system is being designed to serve the wastewater treatment needs of a community. Wastewater flows were projected 20 years into the future and are estimated to average 5.3 mgd at that design condition. Current flows average 2.6 mgd, and wastewater flows and loadings are anticipated to increase in an approximate linear fashion from current levels up to their 20-yr design values.

Secondary treatment is to be provided to meet discharge requirements. The average hydraulic retention time (HRT) in the aeration basin is 6 hours. The average operating SRT is estimated to be 4 days to limit nitrification and its associated process oxygen requirements. However, nitrification is expected to occur to some degree during the 5 warmest months of the year. The design process loadings are as listed for Examples 5-1, 5-2, and 5-4.

The selected activated sludge system consists of four aeration basins, each 23 ft wide by 130 ft long with a sidewater depth (SWD) of 15 ft. Diffuser submergence is 14 ft. Four basins may be considered an unusually large number for a 5.3-mgd facility; some designs would provide only two. However, four basins were chosen in this case considering the wide variation in process loadings from initial operation to the 20-yr design values. Selection of the number of aeration basins is an economic issue that must be considered for each installation. Construction of more basins increases initial costs but is normally needed for diffuser maintenance. In addition, operating costs are reduced since only the number of basins necessary to satisfy maximum process oxygen requirements need be in service at any point in the life of the facility. The trade-off between these two factors must be considered for each design. Figure 5-7 presents a schematic of the proposed facility.

The range of total process oxygen requirements that form the design basis for this facility are estimated in the following discussion. For design purposes, total process oxygen requirements will be estimated for five process loading conditions:

1. Minimum month
2. Average non-nitrifying (winter) month
3. Average nitrifying (summer) month
4. Maximum month (including nitrification)
5. Peak day (non-nitrifying)

Conditions 1 through 4 represent sustained loading conditions, while condition 5 represents a short-term peak. Short-term periods with minimum total process oxygen requirements less than the minimum month requirement will occur within this system. However, it is not judged cost effective to design for anything less than the minimum month because of the low frequency of occurrence of these periods. The option is simply to waste some energy during those infrequent periods when process demands are less than the minimum month value. Designing for the peak day not only accommodates this peak loading, but also provides an allowance for diurnal variations during more typical average loading conditions.

Total process oxygen requirements have already been calculated in Example 5-4 for the specified design loading conditions. Using the format of Table 5-1, AOR design values are:

Loading Condition	AOR (lb/d)		
	Initial Year	Midpoint	20-yr Design
Minimum month	1,788	2,681	3,575
Average non-nitrifying month	2,706	4,059	5,412
Average nitrifying month	4,843	7,264	9,685
Maximum month	5,794	8,691	11,588
Peak day (non-nitrifying)	6,080	9,120	12,160

(continued)

Example 5-8. Temporal Variations in Total Process Oxygen Requirements (continued)

The 20-yr design values are taken directly from Example 5-4, while the initial year and midpoint values were calculated simply as being proportional to process loadings (i.e., the initial-year values are one-half of the 20-yr design values, and the midpoint values are three-quarters of the 20-yr design values). This approach can be used because a sufficient number of aeration basins is available to approximately match design process loadings over the design life of the facility (i.e., two basins will be operated in the initial years, three at the midpoint, and all four at the 20-yr design value). Note that the use of peak day non-nitrifying conditions for sizing purposes will accommodate significant variations in diurnal process oxygen requirements under average loading conditions. Approximate allowable diurnal peaking factors are 12,160:5,412, or 2.25:1, for non-nitrifying conditions and 12,160:9,685, or 1.25:1, for nitrifying conditions.

Figure 5-7. Activated sludge system for Example 5-8.

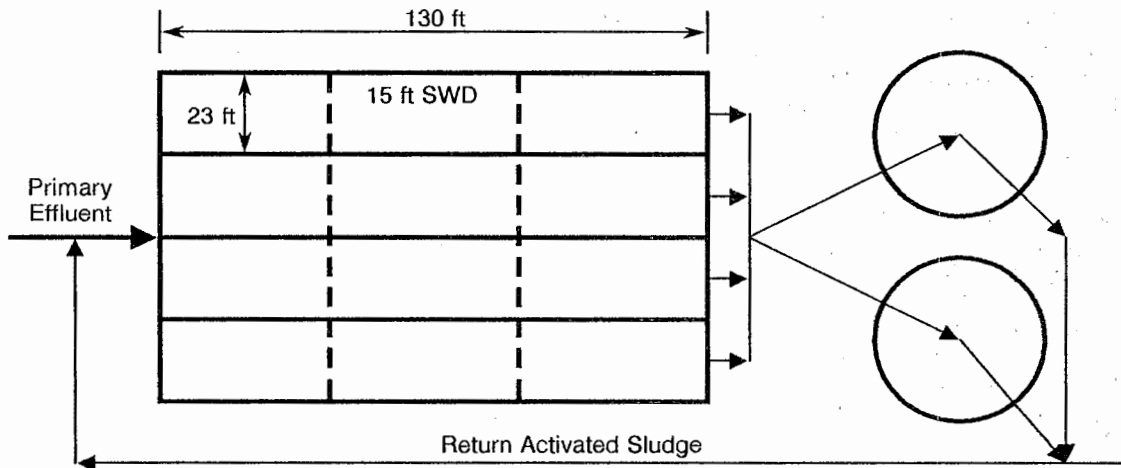
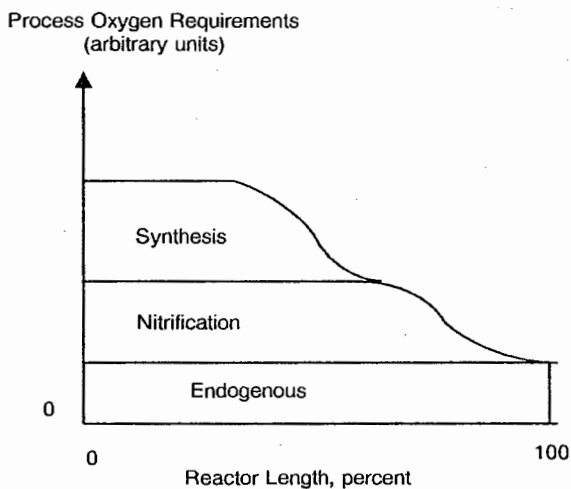


Figure 5-8. Spatial variation in process oxygen requirements along the length of a biological reactor.



can be readily calibrated to existing wastewater treatment facilities. Adjustments in only two or three key parameters were required (while keeping 17 other model parameters at their default values) to calibrate the model to six full-scale wastewater treatment plants.

The Water Research Centre has also developed a biological process model that it uses to predict spatial and temporal variations in total process oxygen requirements (25). The use of process models to estimate variations in process oxygen requirements is not standard practice in North America today.

Spatial variations in total process oxygen requirements are estimated for a hypothetical activated sludge system in Example 5-9.

5.3.2 Process Mixing Requirements

Sufficient aeration must be provided to prevent deposition of suspended matter. In evaluating process mixing requirements, different diffuser configurations exhibit very different mixing characteristics. Limited information has been published, however, on minimum mixing requirements. One document (15) indicates that the airflow rate required to ensure good

Example 5-9. Spatial Variations in Total Process Oxygen Requirements

Consider the activated sludge system from Example 5-8. Experience indicates that the hydraulic flow pattern within each of the basins in this example can be approximated as three equivalent basins-in-series (note that Equation 5-4 would predict between three and four equivalent basins-in-series, depending on r). As a result, the diffusion system in each reactor will consist of three equal size aeration zones, as illustrated in Figure 5-7. The number of diffusers in each zone will be varied in proportion to the estimated fraction of the average total process oxygen requirement that can be satisfied in each zone. Using this information, estimates of the spatial distributions in total process oxygen requirements for the 20-yr design conditions can be made.

First, subdivide the carbonaceous process oxygen requirement into its synthesis and endogenous components. Assume that the oxygen consumption ratio of the synthesis component is about 0.5 lb O_2 /lb BOD_5 applied. At the average BOD_5 loading of 6,600 lb/d:

$$\begin{aligned} \text{Synthesis Process Oxygen Requirement} \\ = (6,600 \text{ lb } BOD_5/d)(0.5 \text{ lb } O_2/\text{lb } BOD_5) = 3,300 \text{ lb } O_2/d \end{aligned}$$

The total carbonaceous process oxygen requirement is 5,412 lb O_2 /d, so the endogenous component can be calculated by subtraction:

$$\text{Endogenous Process Oxygen Requirement} = 5,412 - 3,300 = 2,112 \text{ lb } O_2/d.$$

Experience indicates that two-thirds of the synthesis process oxygen requirement will occur in the first one-third of the reactor, while the remainder will occur in the middle one-third (26). If sufficient oxygen transfer capacity is not provided in the initial and middle thirds of the reactor to satisfy these requirements, resulting low process DOs will shift a portion of the oxygen demand load further down the reactor.

Based on the above assumptions, the distribution in the carbonaceous process oxygen requirement among the three zones is:

Zone	Average Carbonaceous Process Oxygen Requirement (lb O_2 /d)		
	Synthesis	Endogenous	Carbonaceous
1	2,200 ¹	704 ³	2,904
2	1,100 ²	704	1,804
3	—	704	704

¹ $2/3 \times 3,300 \text{ lb } O_2/d$.

² $1/3 \times 3,300 \text{ lb } O_2/d$.

³ 2,112 lb O_2 /d divided equally into three zones.

This is the spatial distribution under non-nitrifying conditions. When nitrification occurs, an additional oxygen requirement of 4,273 lb O_2 /d must be satisfied. Since a 4-day SRT is about the lowest SRT at which reliable nitrification can be expected to occur, nitrification process oxygen requirements should occur fairly uniformly throughout the reactor until the nitrogen concentration becomes substrate limiting (23,26). Assume, therefore, that 40 percent occurs in the first one-third of the reactor, 40 percent in the second one-third of the reactor, and the remainder (20 percent) in the last one-third of the reactor (23). This distribution pattern will vary from plant to plant. For this example, the nitrification process oxygen requirement will be distributed as follows:

$$\begin{aligned} \text{For the first and second zones, nitrification process oxygen requirement} \\ = 0.4(4,273 \text{ lb } O_2/d) = 1,709 \text{ lb } O_2/d \text{ each} \end{aligned}$$

$$\begin{aligned} \text{For the last zone, nitrification process oxygen requirement} \\ = 0.2(4,273 \text{ lb } O_2/d) = 855 \text{ lb } O_2/d \end{aligned}$$

(continued)

Example 5-9. Spatial Variations in Total Process Oxygen Requirements (continued)

These are added to the carbonaceous process oxygen requirement in each zone. A summary of calculations made for each condition yields the following spatial distribution of total process oxygen requirements:

Zone	Peak Day	Max. Month	AOR (lb/d)		
			Average Month Nitrifying	Average Month Non-Nitrifying	Min. Month
1	6,187	5,430	4,613	2,904	2,109
2	4,053	4,147	3,513	1,804	1,191
3	1,920	2,010	1,559	704	275
Total	12,160	11,588	9,685	5,412	3,575

mixing in diffused air systems is 0.33-0.50 L/s-m³ (20-30 scfm/1,000 cu ft). The diffuser type and layout are not delineated in this document. Manual of Practice 8 (13) recommends a minimum mixing requirement of 0.6 L/s-m² (0.12 scfm/sq ft) be used for ceramic dome diffusers operating in a grid configuration and 0.33 L/s-m³ (20 scfm/1,000 cu ft) for a coarse bubble spiral roll configuration. Mixing evaluations performed on a ceramic dome diffuser grid configuration (diffusers 61 cm [24 in] off the floor) at the Los Angeles - Glendale, CA Water Reclamation Plant (27) revealed no solids settling problems (MLSS = 1,500 mg/L) after 2 weeks of testing at airflow rates as low as 0.25 L/s-m² (0.05 scfm/sq ft).

5.4 Air Diffusion System

The air diffusion system transfers oxygen to the aeration basin. The transfer should occur in such a way that the microorganisms are not "stressed." A stressed situation can occur if either the overall rate of oxygen transfer to the basin or the distribution of oxygen within the basin is not adequate. This section discusses key considerations in the design of the air diffusion system, including diffuser selection, arrangement of the diffusers within the basin, airflow distribution, diffuser cleaning and maintenance, diffuser installation, and retrofit applications. Following the discussion of these items, an example is presented that illustrates a typical air diffusion system design.

5.4.1 Diffuser Selection

Several factors should be considered in selecting the specific fine pore diffusion device to be used in a particular application. Cost considerations include initial cost of the total diffusion system, O&M costs, and life-cycle cost. Often the major concern is the initial cost of the system. However, this cost usually represents a small fraction (15-25 percent) of the life-cycle cost of the system. The major part of the life-cycle system cost is determined by O&M costs. OTE plays a major role in establishing system O&M costs. Other factors that affect O&M costs, but that are more

difficult to quantify, include operational flexibility, system reliability, and maintenance requirements.

5.4.1.1 Oxygen Transfer Efficiency

One important diffuser selection criterion is its clean water OTE. Performance and oxygen transfer characteristics of fine pore diffusers in clean water are discussed in Chapter 2. As indicated in that chapter, factors that affect clean water transfer efficiencies include diffuser type (material, shape, and size), diffuser configuration and density (number per 100 sq ft), airflow rate per diffuser, diffuser submergence, and air flux uniformity.

While clean water OTE is an important selection criterion, it is not an accurate indicator of diffuser performance under process conditions. OTEs are usually substantially lower under process conditions than in clean water. Chapter 3 discusses factors that affect oxygen transfer under process conditions. Factors over which the designer has control include process type, flow regime, basin geometry, and diffuser placement (including depth, configuration, and density).

Selections of the process type, flow regime, and basin geometry partially determine the average wastewater characteristics to which the diffuser will be exposed. These selections have a direct effect on α and F profiles throughout the basin. Low-rate systems (low F/M loadings or high SRTs), complete mix systems, and the effluent end of plug flow basins will normally have higher average α values than high-rate systems and the influent end of plug flow basins. Diffusers operated in systems or areas within a basin with low α values also will usually exhibit higher rates of biological fouling than diffusers operated under high α value conditions.

Increasing the plug flow characteristics of the basin by baffling or increasing the length-to-width ratio will cause α to decrease and the rate of biological fouling to increase at the influent end of the basin. At the same time, the specific oxygen demand (oxygen

demand per unit volume) will increase at the influent end of the basin.

Chapter 2 discusses the effects of diffuser depth and density of placement on oxygen transfer characteristics. Increasing diffuser depth usually increases OTE (as a percent of the oxygen content of the air delivered to the basin). However, wire aeration efficiency (measured as kg [lb] oxygen transferred per kWh [wire hp-hr]) does not appear to vary significantly with diffuser depth over diffuser depths of 4-8 m (12-25 ft) (see Figure 2-22). For a given airflow per diffuser, both OTE and wire aeration efficiency generally increase as the diffuser arrangement moves from a spiral roll to a full floor coverage configuration.

As part of making final decisions regarding features of the design described above, the designer should evaluate oxygen transfer characteristics of the diffusers and process requirements under various conditions. For example, influent zones of plug flow basins may exhibit α values of 0.3 and, after several months of operation, F may be reduced to 0.8. Thus, the diffusers in these zones might only be transferring a maximum of 25 percent of their clean water capabilities at that time. Further, the extremes of peak process loadings with fouled diffusers and minimum process loadings with clean diffusers (turndown/turnup) must be considered.

5.4.1.2 Operational Flexibility

A variety of activated sludge reactor configurations (i.e., flow regimes) can be designed. Most of these fall into one of three groups: complete mix, plug flow, or step feed. A step feed regime can also be used with a plug flow configuration to offer greater operational flexibility. Each of these configurations has advantages and disadvantages. As a result, treatment facilities are sometimes designed to allow operation using more than one flow regime (for example, both plug flow and complete mix configurations or an interchangeable combination of step feed and plug flow configurations could be used). Further, each of these configurations can be designed to operate under high-rate (high F/M) loading conditions, low-rate (low F/M) loading conditions, or somewhere between these two extremes. Wastewater treatment plants are normally designed anticipating growth in the service area, so a facility designed to operate as a high-rate system may initially operate as a low-rate system. Process operational flexibility increases as the number of reactor configurations and the range of loading conditions the operator can use increase.

Nearly all designers of wastewater treatment plants attempt to provide some process operational flexibility. Sufficient operational flexibility should be included in any aeration system to meet the variable oxygen demand requirements that different reactor configurations and loading conditions impose.

Methods for calculating oxygen requirements are discussed in Section 5.3.1.2. The designer needs to estimate oxygen requirements for the entire range of operating conditions likely to be encountered in the treatment facility. As indicated previously, oxygen requirements vary both temporally and spatially. Variations with time may include changes that occur diurnally, by day of the week, by season, and between plant start-up and when design loading conditions are reached. Oxygen demands will be higher at the inlet end of a plug flow basin than at the outlet end, and will be highest at the feed points in a step feed basin.

Having calculated the range of oxygen demand conditions expected, the engineer must design the various components of the aeration system to meet these conditions. These components include the blowers, air piping and appurtenances, and diffusers. The first two components are discussed later in this chapter.

All fine pore diffusers have an allowable range of unit airflow rates that can be applied to the diffuser. These allowable airflow rates depend on diffuser size, as discussed in Chapter 2. For example, allowable airflow rates for perforated membrane tube diffusers are generally 0.5-4.7 L/s (1-10 scfm)/diffuser. Similarly, for ceramic discs (nominal 23-cm [9-in] diameter) and domes (nominal 18-cm [7-in] diameter), the allowable rates are generally 0.2-1.2 L/s (0.5-2.5 scfm)/diffuser. These allowable ranges of airflow rates offer turndown operational flexibility of 4:1 to 10:1. For many systems, these will be adequate to cover the anticipated range in oxygen demand. For systems where significant growth is anticipated, the diffusion system should be designed to meet initial diurnal and seasonal variations but may or may not satisfy ultimate design oxygen demands. In such cases, provisions should be made for adding diffusers or additional basins in the future as plant loadings increase.

Careful consideration should be given to the desired airflow range during design. Testing has shown that OTE is dependent on airflow rate per diffuser, increasing as the flow rate decreases (see Sections 2.6 and 3.4). This performance characteristic may tempt engineers to design fine pore systems to operate at very low unit airflow rates. Although favorable in terms of oxygen transfer, this practice can lead to operational problems.

At low airflow rates, uniform air distribution across the entire diffuser surface may be difficult to obtain. Also, at low diffuser airflow rates, the headloss across the control orifice could be <25 mm (1 in) w.g., requiring a change to different size orifices to balance airflow throughout the system. In any case, if either the entire surface or portions of individual diffusers are not discharging air, foulant deposition can begin, which

could then lead to premature fouling of the entire system.

Both the type and arrangement of diffusers should be selected based on anticipated operating conditions. Generally, the most cost-effective designs approximately match the numbers of diffusers to the required oxygen transfer rates in the basin. For example, more diffusers are usually provided at the upstream end of a plug flow basin than at the downstream end. Diffuser arrangement is discussed in more detail later in this chapter.

5.4.1.3 Reliability

The reliability of fine pore diffusion systems is determined by several factors, including maintenance requirements and mechanical integrity. Maintenance requirements are discussed in the next section. Mechanical integrity is best determined by the performance record of equipment in full-scale service.

Many types of fine pore diffusers are currently available. However, relatively few have received widespread use in North America, so obtaining full-scale reliability information on some of these units is difficult at present. Some of these units have been used in other countries for several years. Transferring this experience to North American designs should be done with caution, however. Different design practices, wastewater characteristics, and plant operating methods must be considered in evaluating true equipment performance.

In reviewing a diffusion system for mechanical integrity, each of the components should be considered. Critical components are the diffuser material, diffuser supports, diffuser connections, piping supports, and submerged air piping. Considerations for the diffuser material include physical and chemical resistance to the wastewater (including, for perforated membranes, the potential for loss of flexibility). Designers should incorporate mounting details that minimize buildup of stringy material on diffuser piping. The diffuser supports and connections should be able to withstand the range of stresses that will occur both during installation and operation. For example, tube-type diffusers will be subject to bending and relatively high stresses at the point of connection to the air piping during normal operation. The supports and air piping must be able to resist the dead weight of the equipment during installation as well as the buoyant forces of the system in normal operation (as well as keep the diffusers nearly level).

The designer should anticipate that some parts of the system will eventually fail because of damage or normal deterioration. The design, therefore, should permit portions of the system to be isolated for repairs with minimal disruption in normal plant operation.

5.4.1.4 Maintenance Requirements

O&M requirements and procedures for fine pore diffusion systems are covered in Chapter 4. This section summarizes O&M considerations that the designer should be aware of in selecting diffusers for a specific application.

All fine pore diffusion systems require maintenance. The amount of routine maintenance required will vary, depending on wastewater characteristics, type of treatment process, and characteristics of the specific diffuser. Maintenance is required for two primary reasons: to control diffuser fouling (and thus maximize OTE), and to replace diffuser components when they deteriorate. Maintenance requirements are generally greater in high-rate systems than in low-rate systems. Maintenance requirements can increase as the fraction of industrial waste increases.

To maximize OTE and minimize costs, fouling must be controlled. As fouling progresses, headloss across the diffuser pores may gradually increase, thereby increasing blower energy requirements. Gradual fouling of fine pore diffusers is not uncommon and should be considered in designing the aeration system by allowing for a moderate increase in headloss across the diffusers. Typical designs allow for a headloss increase across fouled diffusers prior to cleaning of 3.4-10.3 kPa (0.5-1.5 psi). Headloss increases beyond the design allowance indicate excessive fouling, and periodic maintenance to control this condition should also be anticipated by the designer.

Provisions can be made by the designer to manage fine pore diffuser fouling. Good preliminary treatment to remove most of the fibrous material and/or high-density suspended solids in the influent wastewater is appropriate when fine pore diffusion systems are used. This would usually include screening (maximum of 12.7-mm [0.5-in] openings) and grit removal. Providing a system that allows routine monitoring of fouling should be considered. Since fouling normally results in increased headloss across the diffuser, the ability to monitor changes in air pressure in the air distribution piping can aid in indicating the degree of fouling that has occurred (see Section 4.2.3.2). Systems that directly monitor headloss across the diffusers have also been used (see Figure 2-9).

Short-term increases in airflow through the diffuser (air bumping) can remove some deposits. Should the designer elect to incorporate provisions for air bumping, the aeration system should be designed to allow increased airflow to be applied independently to each aeration zone. The aeration basins should be arranged to allow isolation and rapid dewatering of each basin to permit the diffusers to be physically cleaned in place. Access to a source of plant water that can deliver a high flow at reasonable pressure (i.e., approximately 415 kPa [60 psig]) should be

provided so that the diffusers can be periodically sprayed to remove surface deposits. Other in-basin cleaning methods include periodic acid gas cleaning, acid washing, and chlorine washing. Aeration system materials of construction that have adequate chemical resistance to these cleaners should be selected and specified by the designer.

Fine pore diffusers may be subject to gradual deterioration, and eventual replacement or rehabilitation should be anticipated. This deterioration may be due to buildup of inorganic materials within the diffuser that cannot be removed by moderate cleaning procedures or to breakdown of the diffuser material itself. The rate of diffuser deterioration depends on wastewater characteristics and the type of diffuser (see Section 3.3.3.6). The useful service life of a diffuser is generally considered to have been reached when the diffuser has deteriorated to a point that the cost of replacing the diffuser will be offset by the reduced operating cost brought about by new diffuser performance.

Present worth cost analyses are appropriate for both selecting diffusers and evaluating the cost effectiveness of diffuser replacement. Economic analysis of fine pore aeration systems is discussed in Chapter 7.

5.4.2 Basin Arrangement

Proper arrangement of the aeration basins and the diffusers within the basins are important to provide the degree of wastewater treatment intended, maximize OTE, and facilitate system maintenance. Important design considerations include basin inlet conditions, wastewater and airflow patterns within the basin, ability to isolate and dewater individual basins, access to the diffusers within the basins, and availability of plant water.

The arrangement/configuration of the diffusers within the basin affects wastewater flow patterns. Diffusers should be arranged to provide adequate mixing throughout the basin. Typical basin and diffuser arrangements are shown in Figure 2-8.

The distribution of influent wastewater and return sludge flows to the inlet end of the aeration basin(s) should be considered carefully. Depending on basin size and configuration, it may be advisable to distribute these flows, possibly through baffling, across the entire width of the basin. Such distribution may minimize localized high velocity gradients and poor initial mixing in this zone of the aeration basin.

Provisions should be made for partially filling the basin without allowing the incoming flow to cascade directly onto the diffusers and in-basin piping. Both the piping and diffusers can be damaged if a large volume of water is allowed to drop directly onto them.

Dry isolation of each basin will be necessary periodically to allow maintenance of the in-basin piping and diffusers. A drain system that permits each basin to be dewatered in a reasonable period of time (normally 8-24 hr) should be provided. The basin floor should be sloped adequately to allow complete drainage to occur without ponding and to facilitate easy removal of residual solids. One arrangement that has been used effectively is to construct a drain trough along one wall of the basin, with the basin floor sloped to drain to the trough and the trough sloped to drain to a sump or dewatering manhole.

Diffusers should be arranged within the basins to allow space for walking and access to them. Access to the diffusers is necessary both for installation and maintenance. Spacing between diffusers on adjacent laterals, between grids, and between each basin wall and adjacent diffusers should be examined. A minimum clear walkway space of 51 cm (20 in) is usually adequate.

Basin and diffuser cleaning require water at moderate pressure (approximately 410-690 kPa [60-100 psi]) at the nozzles. Hydrants with 38-mm (1.5-in) hose connections are usually adequate. These hydrants should be placed at frequent intervals and easily-accessible points around the basins; 61 m (200 ft) between hydrants is generally adequate. Either tap water or secondary effluent can be used.

5.4.3 Airflow Distribution

5.4.3.1 Control

Oxygen demands vary in the aeration basin both temporally and spatially, as previously discussed. Well designed systems provide sufficient flexibility to reasonably match aeration rates to system oxygen requirements. This permits the system to be operated without stressing the microorganisms and without excessive aeration (and the associated energy cost).

Aeration control systems can be fully manual or highly automated, or have both manual and automatic features. Until recently, fully manual control systems were more common, primarily because of the lack of reliable DO monitoring instrumentation. With continuing improvements in this area, reasonably reliable instrumentation is now available and automatic control of aeration systems is feasible.

With a manual control system, operators make periodic measurements of DO concentrations in the aeration basins and adjust airflow rates accordingly. In contrast, automatic control systems monitor aeration rates and DO concentrations using primary sensing elements and automatically adjust air delivery rates based on the signals received. Aeration control methods are discussed in detail in Chapter 6.

Even with automated DO control, temporal and spatial variations in oxygen demand cannot be exactly matched. Further, moderate variations in DO within the basin (± 0.3 - 0.5 mg/L) can be tolerated without either adverse effects on the treatment process or undue increases in operating costs. Arranging the diffusers in grids, as described earlier in this chapter, and making periodic automatic adjustments in airflow rates to these grids (at 5- to 30-minute intervals) based on DO concentrations at one or two locations in the aeration basin normally results in a cost-effective control system. The designer must find a reasonable compromise between controlling the aeration rate throughout the basin to minimize power costs and maintain the biomass in a healthy condition, and minimizing the complexity, cost, and maintenance of the control system.

Regardless of the method of control used, the aeration system should be arranged to allow aeration zones to be isolated and airflow to be increased to specific zones to facilitate air bumping if deemed necessary (particularly for perforated membrane systems). The designer should consider the number of valves to be manually operated and other changes that will have to be made by the operator to allow air bumping of a particular aeration zone.

5.4.3.2 Airflow Measurement

The numbers and locations of airflow measurement points depend on process control requirements and energy conservation objectives. For most facilities, instrumentation should be provided to allow the total airflow to the aeration basins to be monitored continuously. Provisions should also be made to allow the airflow to specific aeration basins and to aeration zones within each basin to be monitored. This may include permanent flow meters, access points for connecting portable flow meters, or a combination of both. Where automatic DO control is used, instrumentation is usually installed to permit airflow to individual basins to be monitored continuously, with access points to allow manual measurement and adjustment of airflow to individual aeration grids. Even for systems that will not have automated DO control, it is good practice to provide access points in the air piping where a portable airflow measurement device can be attached.

As with other mechanical components of the aeration system, flow meters should be sized to allow accurate measurement of airflows over the entire range of design conditions (including minimum flow at plant start-up and maximum flow at design conditions). If the range of flows is such that a single flow meter cannot handle the entire range of flows, provisions should be made to enable system components (or the entire system) to be replaced in the future.

Airflow can be measured with several types of devices. The most commonly used devices are based

on either differential pressure across a control element or mass flow. General features of each device are described in Table 5-2.

Table 5-2. Properties of Airflow Measurement Devices

Device	Description and Principles of Operation	Range-ability	Accuracy
Differential Pressure			
Averaging Pitot Tube	Insertion probe with multiple upstream ports and one downstream port; difference between upstream and downstream pressures proportional to square root of flows; low headloss	3:1	2-5% of full scale
Venturi Tube	Flow-through device with converging and throat sections; constriction causes increase in velocity and pressure drop proportional to square root of flow; moderate headloss	3:1	1% of actual flow
Flow Tube	Similar to Venturi tube, but smaller in size and lower headloss; moderate headloss	3:1	1% of actual flow
Orifice Plate	Thin plate with opening placed perpendicular to flow; orifice causes increase in velocity and pressure drop proportional to square root of flow; moderate headloss	3:1	2-5% of full scale
Turbine Meter	Multi-blade rotor placed with axis of rotation perpendicular to flow; rotational velocity proportional to flow; high headloss	10:1	0.5% of actual flow
Thermal Mass Flow Meter	Heated element and unheated element; temperature differential proportional to log of flow; low headloss	10:1	1% of full scale

In designing the air piping system, the designer should consider the installation and operating requirements of the specific airflow measurement devices to be used. In particular, sufficient straight lengths of piping must be provided upstream and downstream of the permanent device or portable device connection point to allow accurate measurements to be made. A minimum upstream length equal to 10 pipe diameters and a minimum downstream length equal to 5 pipe diameters should be provided.

5.4.4 Diffuser Cleaning and Maintenance

Chapter 4 discusses diffuser O&M requirements in detail. This subsection discusses provisions that should be made by the designer to facilitate diffuser cleaning and maintenance.

Because diffusers require periodic cleaning and maintenance, the system should be designed to facilitate these functions without major interruptions in plant operation. Appropriate design provisions depend on the cleaning methods to be used. Types of cleaning methods include those that are process noninterruptive, process interruptive with diffusers in place, and process interruptive with diffusers removed.

Noninterruptive cleaning methods require the ability to isolate a portion of the air piping system to introduce the cleaning material (usually either a high volume of air or acid gas). If the diffusers are to be chemically cleaned, materials of construction must be selected to be chemically resistant. Materials selection is discussed later in this chapter. The acid gas cleaning method involves proprietary technology, and special appurtenances are required (28,29).

For the process noninterruptive methods, special considerations include the provision of local airflow control valves and flow meters for flexing of perforated membrane diffusers. Ceramic and plastic diffuser systems should be designed to be compatible with acid gas injection. To facilitate in-situ gas cleaning, a tap, with shutoff valve, is provided on the drop pipe to each grid. Portable acid feed systems can be provided for testing. A portable rig consisting of gas cylinders, regulators, flow meters, and other appurtenances is then moved throughout the system and temporarily connected to the tap on each grid. A permanent feed system can be provided later if the process proves to be functionally and economically attractive. In some cases, the tap consists of a nozzle that vaporizes the gas as it enters the air manifold.

Process interruptive cleaning methods require the ability to isolate aeration basins. Generally, dry isolation is required so that the basin can be dewatered and the diffusers either cleaned in place or removed from the basin for cleaning. Basin design features to facilitate dry isolation were discussed earlier in this chapter. Methods for cleaning the diffusers in place include acid washing, steam cleaning, and low-pressure hosing. If the diffusers are to be chemically cleaned, chemically resistant materials of construction must be selected. Guidelines for placement of hydrants for low-pressure hosing of diffusers were given earlier in this chapter.

Facilities can be provided to simplify monitoring of the condition of the diffusers by plant operators. Diffuser fouling will result in an increase in headloss within the aeration system. This increase in headloss may result in an increase in system pressure of 3-5 kPa (0.4-0.7 psi). This change may be imperceptible on typical blower discharge pressure meters. Systems that directly monitor the headloss across the diffusers (i.e., DWP), however, will provide the operator with a more sensitive measure of the degree of diffuser fouling.

As discussed in Chapter 2, systems for monitoring the condition of the diffusers include pressure taps for measuring DWP and pilot headers. Pressure taps allow monitoring of the headloss across the diffuser, which can help the operator determine when cleaning is required. Figure 2-9 provides a sketch of the various components of a typical headloss monitoring system. The individual pressure taps are usually connected to lengths of flexible tubing that run to the surface. Common practice is to place several flexible lines inside a section of rigid pipe that serves as a means of support. The individual lines are then fixed to a board or panel attached to the railing or basin wall. All lines under pressure should include a shutoff valve. Multiple units are usually provided so that the headloss at various points throughout the system can be monitored. Chapter 2 discusses operational features of these systems.

A fine pore aeration system should include provisions for removing liquid that may accumulate inside the pipe. This liquid can enter during periods when the air is turned off or during normal operation when moisture in the incoming air condenses. Accumulation of liquid within the piping may increase headloss through the piping and cause system performance to deteriorate.

Another approach is to provide a separate condensate removal system. This system usually consists of a short section of pipe or tubing extending down near the bottom of the air distribution pipe at a low point in the system. In some cases, a collection sump is provided in one corner of the grid to aid in accumulating the liquid. The tubing is attached to a section of rigid piping extending to the basin surface where a shutoff valve is placed.

5.4.5 Diffuser Installation

Installation of fine pore diffusers requires special precautions. These precautions include ensuring that: 1) the air supply system is properly prepared before the diffusers are installed, 2) the diffuser components were not damaged during shipping, and 3) they are not damaged during installation.

To minimize the potential for air-side fouling of the diffusers, the air header system should be carefully cleaned to remove construction debris (dust, metal shavings, oil, etc.) before the diffusers are installed. The same considerations apply whenever modifications are made to any part of the air supply system after the diffusers are in place.

Most diffusers have relatively fragile components that can be damaged during handling, and they should be handled accordingly. When installing the diffusers on the header system, the manufacturer's recommendations should be carefully followed. Overtightening of certain components, particularly plastics, can lead to failure of these components. Overtightening or undertightening can result in air

leaks and maldistribution of air, thereby reducing system OTE.

The diffusers must be accurately leveled after installation on the header system. Differences in vertical placement of the diffusers will lead to uneven air distribution and reduced OTE. Provisions must be made in the design of the header system to allow leveling, including adjustable pipe supports and flexible or adjustable pipe joints.

A manufacturer's representative and the design engineer should be on site during initial installation. Both should inspect the work as it progresses to ensure that proper procedures are followed, including connecting the diffusers to the air piping and final leveling of the air piping and diffusers (for flat plates). In addition, the manufacturer's representative should certify that the completed facility was constructed, and the equipment installed, in accordance with the manufacturer's recommendations.

5.4.6 Specifications

For a completed system to meet the design intent, the specifications included in the contract documents must be thorough and comprehensive. Some of the items that should normally be addressed include the following:

- Component design and quality assurance/quality control (including diffusers, connectors for attaching diffusers to air piping, and pipe supports)
- Nature of wastewater and its constituents, particularly the percentage of industrial wastewater (by loading and flow) and specific types of industrial wastes
- Materials of construction (including diffusers, connectors, piping, and pipe supports)
- Shop testing (including component sampling during manufacture [see Chapter 2] and clean water performance testing)
- Installation (including preparation of the air supply system prior to diffuser installation, assembling of components to avoid damage, and requirements for leveling of diffusers)
- Representation of manufacturer during installation (including requirements to inspect, provide quality control, and certify the completed installation)
- Operating conditions (including estimated values of α and F , maximum MLSS concentration, range of wastewater and air temperatures, atmospheric pressure, and diffuser submergence)

- Performance requirements (including range of required SOTRs by aeration zone, range of allowable airflow rates by aeration zone, and minimum allowable number of diffusers by zone)
- Physical testing of completed installation (including leak testing, uniformity of air release, and verification of level installation)
- Performance testing of completed installation (including test and data analysis, interpretation, and reporting methods to be followed that are consistent with the ASCE Standard (30), and penalties if performance requirements are not met.) Normally, only clean water performance testing is required because of the potential variability in wastewater characteristics and the significant impact this can have on diffuser performance. In addition, the designer should consider the costs of requiring extensive compliance testing in relation to the initial cost of the aeration system and present worth of future operating costs.

The above specification items focus on clean water performance. However, the designer must be aware that fine pore diffuser performance in process water is normally significantly lower than in clean water. The specific diffuser, wastewater characteristics, and treatment system configuration all have significant impact on α and F , which together can reduce performance under process operating conditions to a fraction of clean water transfer efficiencies. The designer should provide sufficient operational flexibility to enable the system to be operated efficiently over a range of conditions, including ranges of α and F .

5.4.7 Retrofit Considerations

An existing diffused air aeration system must be carefully evaluated when considering replacement of that system with an alternative fine pore diffusion system. Many of the considerations discussed previously for diffuser selection also apply to retrofit situations. In addition, the designer may be limited by the existing blower and air piping system and basin geometry.

Pressure requirements for the new fine pore system may differ from those of the existing diffusers. Again, diffuser fouling will increase headloss through the diffusers. The designer should verify that the existing blower system has adequate capacity to deliver the required volume of air to the diffusers under worst-case pressure loss conditions.

The potential for air-side diffuser fouling may increase in retrofit situations. Deterioration of metal air piping may have resulted in a substantial amount of corrosion products in the piping. The potential effects

of this material on diffuser performance should be considered.

Both diffuser and process performance can be significantly affected by basin geometry and basin flow patterns. Both wastewater flow patterns and airflow patterns should be considered. Fine pore diffuser OTEs are usually substantially higher for systems with high diffuser densities and low airflow rates per diffuser than for systems with low diffuser densities and high airflow rates per diffuser. However, there are likely to be optimum densities that are diffuser specific.

OTE performance testing under typical process water operating conditions should be conducted on the existing installed aeration equipment to establish an accurate baseline against which the need for a fine pore retrofit and the eventual performance of the retrofit system can be judged. Further, the opportunity also exists for evaluating process water OTEs for candidate fine pore diffusers in a portion of the existing facility or using the test header apparatus described in Chapter 2 (see Figure 2-10).

5.4.8 Air Diffusion System Design Example

Example 5-10 presents an approach to the design of a fine pore air diffusion system. This example illustrates some of the design considerations discussed in Sections 5.4.1 through 5.4.7. In an actual design, it is likely that several unique features and site-specific factors (including control system requirements, O&M staff expertise, owner preferences, etc.) will have to be considered. These types of factors are not considered in this example.

5.4.9 Flexibility of Design

The preceding example was based on oxygen transfer requirements in the design year (20 years in the future). As discussed in Example 5-8, the design must have sufficient flexibility to handle temporal variations in loading and oxygen demand, including hour-to-hour, day-to-day, and year-to-year variations.

Providing the flexibility necessary to handle year-to-year variations can be accomplished in several ways. Where the design period is relatively long and steady growth is anticipated (as in the preceding example), the designer/owner could choose to build the facility in phases. In this example, two basins could be provided in the first construction phase, with either one or two additional construction phases, as necessary, in the future. Another option is to construct all facilities in the first phase, with provisions for operating only two of the four basins during the early life of the facility. A third option is to construct all the basins, buildings, and major yard piping in the first phase, and stage construction of the mechanical equipment (blowers, in-basin piping, and diffusers), as necessary. This may be the more practical option of the last two methods

because the mechanical equipment would not be exposed to the weather while not in use.

The specific approach taken depends on several factors, including funding, projected growth patterns, and owner preference. A cost-effectiveness analysis of several alternatives will be helpful in choosing an acceptable plan. In completing this analysis, it is important to take into account the higher capital cost of facilities that are constructed in separate phases as compared with single-stage construction.

Regardless of the approach selected for constructing the facilities necessary to accommodate year-to-year variations in loading and oxygen requirements, flexibility to allow economical operation throughout the design life of the plant must be provided. For example, if more basins and blowers are installed than are required to handle initial loads and oxygen demands, capability should be provided to operate only as many basins and blowers as needed while keeping the remaining ones out of service.

In some situations, substantial variations in loading may occur on a seasonal basis. Again, the designer should consider providing the ability to change the number of basins and blowers in service on a seasonal basis to handle these types of variations. Providing the capability to operate in more than one mode, e.g., plug flow or step feed, is desirable.

Flexibility for handling hour-to-hour and day-to-day variations in loading and oxygen demand should be accommodated by providing the capability to adjust airflows to various basins and zones in response to these changes. Factors that should be considered in selecting and designing DO control systems are discussed in Section 5.4.3.1 and Chapter 6.

5.5 Air Supply System

The air supply system delivers atmospheric air or high purity oxygen to the air diffusion system. While selection and design of the diffusion system often receive more attention, care is necessary in designing the air supply system to ensure that overall process objectives are met and power consumption is minimized.

This section discusses some of the key considerations for design of the air supply system. It is not a detailed guide for the mechanical design of the various components. Rather, it presents an overview of the important elements of the system.

The air supply system consists of three basic components: air piping, blowers, and air filters and other conditioning equipment (including gas injection diffuser cleaning systems). The air piping conveys air from the blowers to the diffusers. The blowers are designed to develop sufficient pressure to overcome

Example 5-10. Design of Fine Pore Aeration System

Consider the activated sludge system from Examples 5-4, 5-8, and 5-9. Design an air diffusion system to meet the oxygen transfer requirements developed in these examples.

Example 5-8 addressed variations in process oxygen requirements from plant start-up through ultimate design loading. This example presents calculations for the ultimate condition only. Design considerations to facilitate operation during initial operating years were introduced in Example 5-8 and are further discussed later in this chapter.

A plant schematic was presented in Figure 5-7. The basic design data for the plant are as follows:

	BOD ₅ Loading lb/d	Wastewater Temperature °C
Minimum month	5,500	10
Average month	6,600	15
Maximum month	7,700	25
Peak day	12,800	25

Design Dimensions: 4 aeration basins, each 130 ft long by 23 ft wide

SWD = 15 ft (diffuser submergence = 14 ft)

Wastewater Flow = 5.3 mgd

SRT = 4 days; HRT = 6 hr

Plant Elevation = 1,000 ft

Minimum Air Temperature = -9°C (15°F)

Maximum Air Temperature = 40°C (105°F)

A 4-step approach will be used to design the fine pore aeration system.

Step 1: Determine field oxygen transfer rates (OTR_fs) by aeration zone and operating condition. Set these OTR_fs equal to their corresponding AORs (i.e., OTR_fs must satisfy corresponding AORs).

System OTR_fs were calculated by operating condition and aeration zone (or grid) in Example 5-9 and are summarized below:

Zone	System OTR _f (lb/d)				
	Peak Day	Max. Month	Avg. Month Nitrifying	Avg. Month Non-nitrifying	Min. Month
1	6,187	5,430	4,613	2,904	2,109
2	4,053	4,147	3,513	1,804	1,191
3	4,920	2,010	1,559	704	275
Total	12,160	11,588	9,685	5,412	3,575

These same OTR_fs for one basin are as follows (these will be carried through the next phase of the design):

Zone	Basin OTR _f (lb/d)				
	Peak Day	Max. Month	Avg. Month Nitrifying	Avg. Month Non-nitrifying	Min. Month
1	1,547	1,358	1,153	726	527
2	1,013	1,037	878	451	298
3	480	503	390	176	69
Total	3,040	2,898	2,421	1,353	894

(continued)

Example 5-10. Design of Fine Pore Aeration System (continued)

Step 2: Convert OTR_f values to standard oxygen transfer rate (SOTR) values to account for the effects of process operating conditions.

OTR_f is related to SOTR as follows (see Reference 31 for a more detailed discussion of the development of this equation and precise estimation of the various coefficients):

$$OTR_f = \alpha F (SOTR) \theta^{T-20} (\Omega \cdot \beta C_{\infty 20} - C) / C_{\infty 20} \quad (5-5)$$

where,

OTR_f = oxygen transfer rate under process conditions, lb/hr

α = (process water $K_L a$ of a new diffuser)/(clean water $K_L a$ of a new diffuser)

F = (process water $K_L a$ of a diffuser after a given time in service)/($K_L a$ of a new diffuser in the same process water)

αF = used as a product for this design example with design ranges for each aeration zone (see detailed discussion in Chapters 3 and 4).

SOTR = oxygen transfer rate under standard conditions (20°C, 1 atm, $C = 0$ mg/L), lb/hr

θ = 1.024

T = process water temperature, °C

θ^{T-20} = $K_L a / K_L a_{20}$

$K_L a$ = apparent volumetric mass transfer coefficient in clean water at temperature T , 1/hr

Ω = pressure correction for $C_{\infty} \sim P_b / P_s$ (approximation that excludes effect of d_e at relatively low water depths)

P_b = field atmospheric pressure, psia

P_s = standard atmospheric pressure (14.7 psia or 1.0 atm at 100 percent relative humidity), psia

ι = temperature correction for $C_{\infty} = C_{\infty}^* / C_{\infty 20}^* = C_{\infty}^* / C_{\infty 20}^*$

β = (process water C_{∞}^*)/(clean water C_{∞}^*)

$C_{\infty 20}^*$ = steady-state DO saturation concentration attained at infinite time for a given diffuser at 20°C and 1 atm, mg/L

C = process water DO concentration, mg/L

Before converting OTR_f values to SOTR values, a preliminary selection of the fine pore diffuser should be made. Information specific to that diffuser can then be obtained, including values for certain of the coefficients in Equation 5-5. Operating conditions are:

T_{min} = 10°C

T_{avg} = 15°C (non-nitrifying months)

T_{avg} = 20°C (nitrifying months)

T_{max} = 25°C

β = 0.98 (from clean water testing; typical values for municipal wastewater are 0.95-1.0)

Zone	αF Range
1	0.2-0.3
2	0.3-0.5
3	0.6-0.8

[The values for αF and β were selected based on designer experience. Data from other plants with similar system configurations and wastewater loadings may be helpful in selecting appropriate αF values for design. These characteristics are highly plant specific and must be carefully evaluated before selecting design values. Refer to Chapter 3.]

(continued)

Example 5-10. Design of Fine Pore Aeration System (continued)

$$C_{\infty 20} = 10.5 \text{ mg/L (from clean water testing)}$$

$$C = 2.0 \text{ mg/L for average month nitrifying condition and minimum month; 1.0 mg/L for average month non-nitrifying condition and maximum month; and 0.5 mg/L for peak day}$$

For an elevation of 1,000 ft, the atmospheric pressure, P_b , is 14.3 psi (from Appendix C, Figure C-1). Thus:

$$\Omega = 14.3/14.7 = 0.97$$

From Table C-1, the values of τ are:

$$@10^\circ\text{C}, \tau = C_{s10}/C_{s20} = 11.29/9.09 = 1.24$$

$$@15^\circ\text{C}, \tau = C_{s15}/C_{s20} = 10.08/9.09 = 1.11$$

$$@20^\circ\text{C}, \tau = 1 \text{ (by definition)}$$

$$@25^\circ\text{C}, \tau = C_{s25}/C_{s20} = 8.26/9.09 = 0.91$$

For this example, Equation 5-5 becomes:

$$(\text{OTR}_t/\text{SOTR}) = \alpha F (9.98\tau - C)(1.024^{T-20})/10.5$$

The following values were selected for the design:

	T (°C)	τ	C (mg/L)
Peak day	25	0.91	0.5
Maximum month	25	0.91	1.0
Average month, nitrifying	20	1.00	2.0
Average month, non-nitrifying	15	1.11	1.0
Minimum month	10	1.24	2.0

Assume the design operating DOs are equal in all three zones. Lower operating DO values are sometimes used in the first zone to reduce operating costs. However, this practice can lead to sludge bulking problems (7). Therefore, relatively conservative values were selected. Even at these DO levels, bulking due to low DO may occur (7).

Using the above coefficient values, Equation 5-5 can be further simplified:

Peak day	$\text{OTR}_t/\text{SOTR} = \alpha F (0.920)$
Maximum month	$\text{OTR}_t/\text{SOTR} = \alpha F (0.867)$
Average month, nitrifying	$\text{OTR}_t/\text{SOTR} = \alpha F (0.760)$
Average month, non-nitrifying	$\text{OTR}_t/\text{SOTR} = \alpha F (0.852)$
Minimum month	$\text{OTR}_t/\text{SOTR} = \alpha F (0.780)$

(continued)

Example 5-10. Design of Fine Pore Aeration System (continued)

Values of $OTR_i/SOTR$ can then be computed for each zone:

	Zone 1	Zone 2	Zone 3
Peak day			
αF	0.20	0.30	0.60
$OTR_i/SOTR$	0.18	0.27	0.55
Maximum month			
αF	0.20	0.30	0.60
$OTR_i/SOTR$	0.17	0.26	0.52
Average month, nitrifying			
αF	0.25	0.40	0.70
$OTR_i/SOTR$	0.19	0.31	0.54
Average month, non-nitrifying			
αF	0.25	0.40	0.70
$OTR_i/SOTR$	0.21	0.34	0.60
Minimum month			
αF	0.30	0.50	0.80
$OTR_i/SOTR$	0.23	0.39	0.62

Using the above values of $OTR_i/SOTR$, the following SOTRs for each aeration zone and process condition can be generated:

Zone	Basin SOTR (lb/d)				
	Peak Day	Max. Month	Avg. Month Nitrifying	Avg. Month Non-nitrifying	Min. Month
1	8,594	7,988	6,068	3,457	2,291
2	3,752	3,988	2,832	1,326	764
3	873	967	722	293	111
Total	13,219	12,943	9,622	5,076	3,166

Step 3: Calculate required field standardized volumetric airflow rates (q_s) by zone and the numbers of diffusers necessary to handle these rates.

At this point, the designer needs to determine the performance characteristics of the fine pore aeration device that was selected preliminarily. For this example, data shown in Figure 5-9 will be used for design purposes. Figure 5-9 presents transfer performance (SOTR) as a function of both diffuser density (number/100 sq ft) and unit airflow rate (scfm/diffuser). These data are applicable to full floor coverage, ceramic disc/dome grid combinations. In actual practice, such data should be obtained from the manufacturer of the specific commercial fine pore diffuser selected for the design.

Final selection of the fine pore diffuser should be based on evaluation of several alternative devices and designs. Characteristics of these devices and designs affect both system performance and cost. Accordingly, during this evaluation the designer should usually consider equipment costs, equipment compatibility/suitability, maintenance requirements, and equipment reliability over the useful life of the treatment system.

The following equation relates q_s to SOTE and SOTR:

$$q_s = (0.04 \text{ scfm/lb } O_2/d) (SOTR)/(SOTE) \quad (5-6)$$

(continued)

Example 5-10. Design of Fine Pore Aeration System (continued)

Zone 1:

The first zone will need to satisfy the highest oxygen demands; therefore, it will necessarily have the highest diffuser densities and likely use the highest unit airflow rates. Thus, as an initial attempt (this will be an iterative process), the clean water performance for a diffuser density of 45 diffusers/100 sq ft was used (from top curve, Figure 5-9). An airflow rate of 2.5 scfm/diffuser is selected, which is higher than typical but considered acceptable for this application. From Figure 5-9, an SOTE of 28 percent is estimated for Zone 1.

1. Peak Day SOTR Requirements Control the Design

$$q_s = 0.04 (8,594)/(0.28) = 1,228 \text{ scfm}$$
$$(1,228 \text{ scfm})/(2.5 \text{ scfm/diffuser}) = 491 \text{ diffusers}$$

2. Check Diffuser Density

$$\begin{aligned} \text{Diffuser Density} &= (100)(491)/(43.3 \text{ ft})(23 \text{ ft}) \\ &= 49.3 \text{ diffusers/100 sq ft} \end{aligned}$$

[Assumed density of 45 diffusers/100 sq ft yields slightly lower efficiency than will occur at 49.3 diffusers/100 sq ft. Use 491 diffusers for conservative design.]

3. Check SOTR at Minimum Airflow of 0.5 scfm/diffuser

From Figure 5-9, SOTE = 37 percent at this airflow rate; therefore:

$$\text{SOTR}_{\text{min air}} = 491 \text{ diffusers}(0.5 \text{ scfm/diffuser})(0.37)/(0.04) = 2,271 \text{ lb/d}$$

This calculated minimum SOTR is nearly equal to the minimum month oxygen requirement of 2,291 lb/d for this zone. Therefore, diffuser turndown should not control the aeration rate in Zone 1 (however, if all of the diffusers are installed initially, during early years of plant operation, allowable diffuser turndown is likely to determine the minimum aeration rate. Often, only a portion of the diffusers are installed initially with others being installed on a staged basis as needed.).

4. Check Minimum Mixing Requirements

Adequate air must be provided to maintain thorough mixing within the basin. The minimum air requirements for mixing depend on several factors (including basin geometry, diffuser arrangement, MLSS concentration, settling characteristics of the sludge, and basin inlet conditions). Experience indicates airflows that satisfy process oxygen requirements will provide adequate mixing through most of the aeration basin. However, in some instances, such as towards the end of plug flow basins, mixing requirements rather than process oxygen requirements may dictate minimum acceptable aeration rates. Accordingly, mixing requirements should be considered during the design.

Airflows to maintain adequate mixing in activated sludge aeration basins are usually established from "rule-of-thumb" criteria, as discussed in Section 5.3.2. A typical value is 0.1 scfm/sq ft of basin area (i.e., approximately 7 scfm/1,000 cu ft of basin volume).

Determine mixing requirement:

$$\text{Area per zone} = 996 \text{ sq ft}$$

$$\text{Mixing airflow} = (0.1 \text{ scfm/sq ft})(996 \text{ sq ft}) = 100 \text{ scfm/zone}$$

Since the minimum allowable airflow rate for Zone 1 is 491 diffusers x 0.5 scfm/diffuser (manufacturer's recommended minimum) = 245 scfm, this value and not the mixing requirement is the limiting design factor in Zone 1.

(continued)

Example 5-10. Design of Fine Pore Aeration System (continued)

Zone 2:

1. Maximum Month SOTR Requirements Control the Design

Assume a diffuser density of 30 diffusers/100 sq ft and an airflow rate of 2.0 scfm/diffuser for Zone 2. Then, from Figure 5-9 (second curve from top), SOTE = 27 percent.

$$q_s = 0.04 (3,988)/(0.27) = 591 \text{ scfm}$$
$$(591 \text{ scfm})/(2.0 \text{ scfm/diffuser}) = 296 \text{ diffusers}$$

2. Check Diffuser Density

$$\begin{aligned} \text{Diffuser Density} &= (100)(296)/(43.3 \text{ ft})(23 \text{ ft}) \\ &= 29.7 \text{ diffusers/100 sq ft} \\ &\quad [\text{approximately equal to assumed density}] \end{aligned}$$

3. Check SOTR at Minimum Airflow of 0.5 scfm/diffuser

SOTE = 33 percent (from Figure 5-9)

$$\begin{aligned} \text{SOTR}_{\text{min air}} &= 296 \text{ diffusers}(0.5 \text{ scfm/diffuser})(0.33)/(0.04) \\ &= 1,221 \text{ lb/d} \end{aligned}$$

Since this is higher than the minimum month oxygen requirement of 764 lb/d for this zone, the minimum month oxygen requirement will not control minimum airflow to Zone 2.

4. Check Minimum Mixing Requirements

Since the minimum allowable airflow rate for Zone 2 is 296 diffusers x 0.5 scfm/diffuser (manufacturer's recommended minimum) = 148 scfm, this value and not the mixing requirement (100 scfm) is the limiting design factor in Zone 2.

Zone 3:

1. Maximum Month SOTR Requirements Control the Design

Assume a diffuser density of 18 diffusers/100 sq ft and an airflow rate of 1.0 scfm/diffuser for Zone 3. Then, from Figure 5-9 (bottom curve), SOTE = 27 percent.

$$q_s = 0.04 (967)/(0.27) = 143 \text{ scfm}$$
$$(143 \text{ scfm})/(1.0 \text{ scfm/diffuser}) = 143 \text{ diffusers}$$

2. Check Diffuser Density

$$\begin{aligned} \text{Diffuser Density} &= (100)(143)/(43.3 \text{ ft})(23 \text{ ft}) \\ &= 14.4 \text{ diffusers/100 sq ft} \\ &\quad [\text{less than assumed density of 18 diffusers/100 sq ft; by extrapolation in Figure 5-9, actual SOTE is approximately 26 percent}] \end{aligned}$$

Recalculate the number of diffusers and diffuser density using SOTE = 26 percent:

$$\begin{aligned} \text{Actual Number of Diffusers Required} &= 149 \\ \text{Diffuser Density} &= 15.0 \text{ diffusers/100 sq ft} \end{aligned}$$

(continued)

Example 5-10. Design of Fine Pore Aeration System (continued)

3. Check SOTR at Minimum Airflow of 0.5 scfm/diffuser

By extrapolation in Figure 5-9, SOTE = 28 percent (approximately) at the actual diffuser density; therefore:

$$\begin{aligned} \text{SOTR}_{\text{min air}} &= 149 \text{ diffusers}(0.5 \text{ scfm/diffuser})(0.28)/(0.04) \\ &= 522 \text{ lb/d} \end{aligned}$$

This is higher than the minimum month oxygen requirement of 111 lb/d for this zone. Therefore, the minimum month oxygen requirement will not control minimum airflow to Zone 2.

4. Check Minimum Mixing Requirements

Since the minimum allowable airflow rate for Zone 3 is 149 diffusers x 0.5 scfm/diffuser (manufacturer's recommended minimum) = 75 scfm, the mixing requirement of 100 scfm is the limiting design factor in Zone 3. This equates to approximately 0.7 scfm/diffuser.

Summary:

Aeration rates were calculated for each zone based on the required number of diffusers determined above. These aeration rates and the number and densities of diffusers required for each zone and individual basin and the total aeration system are summarized below for all process conditions:

Zone	Required Airflow (scfm)				Approximate No. Diffusers	Unit Airflow Rate* (scfm/diffuser)	Approx. Diffuser Density (No./100 sq ft)
	Min.	Average Non-nitrifying	Average Nitrifying	Max.			
1	245	432	867	1,228	491	1.8	49.3
2	148	166	405	591	296	1.4	29.7
3 ^{**}	100	100	111	149	149	0.7	15.0
Basin	493	698	1,383	1,968	936	—	—
System	1,972	2,792	5,532	7,872	3,744	—	—

* For average nitrifying condition.

** This zone is mixing limited under all operating conditions.

At this point, the engineer should review the preliminary system design to identify any potential drawbacks in terms of probable constructability and operability. Three features of this example design that the engineer should consider are the high diffuser density in Zone 1, the fact that Zone 3 will be mixing limited under all operating conditions, and the wide range of unit airflow rates (scfm/diffuser) in the three zones. Since it is desirable for the unit airflow rate (calculated above for the average nitrifying condition) to be about the same in each zone to minimize headloss and airflow control difficulties, the designer may want to reevaluate the number of diffusers in each zone. The designer should also consider how the system will be operated from start-up through ultimate capacity.

The area per diffuser in Zone 1 (2.0 sq ft) is near the minimum acceptable for 7-in diameter diffusers. The clear walkway between diffusers is only about 18 in. If this is considered inadequate by the owner or designer, the design will need to be modified.

Operating Zone 3 under mixing-limited conditions means that the aeration rate will exceed that necessary to meet process requirements for a large percentage of time. This results in higher operating costs than would occur if all zones in the basin were operated to avoid mixing limitations.

(continued)

Example 5-10. Design of Fine Pore Aeration System (continued)

Several options are available to address these concerns. One design option is to place fewer diffusers in Zone 1 without changing the allowable airflow rates per diffuser. This would allow a larger diffuser spacing in Zone 1. It would also result in more of the system oxygen demand being passed to Zones 2 and 3. The design could be modified so that Zone 3 could be operated to avoid mixing-limiting conditions some, or all, of the time. A drawback to this approach is that low operating DO levels would occur in Zone 1, which could lead to sludge bulking problems as discussed earlier.

A second design option is to provide the capability to operate the basins in a step feed mode. This would allow part of the influent load to be introduced into the basin in Zone 2 and/or Zone 3 as well as Zone 1. In this case, the designer would need to reevaluate the αF distribution down the length of the basin. An additional advantage of a step feed operating mode is an improved capability to avoid solids washout during extreme flow events. One potential disadvantage may be lower treatment efficiency during these periods.

If the relatively high diffuser density in Zone 1 is acceptable, a third option for avoiding mixing-limiting conditions in Zone 3 is to allow Zone 1 and/or Zone 2 to be operated at low DOs. For example, suppose that during average nitrifying conditions the airflow to Zone 1 is reduced by 40 percent. This would result in an airflow rate of 1.1 scfm/diffuser and an SOTE of approximately 30 percent in Zone 1. Zone 1 SOTR would drop from 6,068 lb/d to 4,185 lb/d. This would result in a transfer of 1,883 lb/d oxygen demand (SOTR) to Zone 3, assuming no change in the operation of Zone 2. The AOR transferred to Zone 3 would be $0.19 \times 1,883$ [i.e., $(0.768\alpha F)(SOTR)$] = 358 lb O₂/d. The SOTR required to meet this additional demand in Zone 3 would be $358 / [(0.768)(0.7)] = 663$ lb O₂/d. The required total SOTR in Zone 3 would be 1,385 lb/d. The required airflow in Zone 3 to meet this demand would be about 1.4 scfm/diffuser, and process oxygen requirements (rather than mixing) would control minimum airflow to this zone. The load shift would require a reduction in airflow of approximately 350 scfm in Zone 1. This reduction would cause depression of DO levels in Zone 1 and could lead to bulking problems, as discussed previously.

For the purposes of this example, the design as presented in the summary of required airflow rates is assumed to be acceptable. The next step is to configure the diffuser system.

Step 4: Configure the diffuser system.

Assume the following for the arrangement of the diffusers for full floor coverage of the basins:

Number of drop legs/zone = 1

Number of extra diffuser attachments for contingency = 20 percent

Floor area/zone = (23 ft)(43.3 ft) = 996 sq ft

Arrange the diffusers approximately evenly within each zone. The following approximate spacings apply:

First zone = 996 sq ft/491 diffusers = 2.03 sq ft/diffuser
= 1.4-ft spacing, center-to-center

Second zone = 996 sq ft/296 diffusers = 3.36 sq ft/diffuser
= 1.8-ft spacing, center-to-center

Third zone = 996 sq ft/149 diffusers = 6.68 sq ft/diffuser
= 2.5-ft spacing, center-to-center

Assume main headers will be placed across the basin width in the center of each zone, with laterals fed from that main header (half on each side of the header). Determine the number and spacing of laterals and number and spacing of diffuser connectors on each lateral. Zone size is 23 ft x 43.3 ft.

(continued)

Example 5-10. Design of Fine Pore Aeration System (continued)

First Zone:

$$(23 \text{ ft}) / (1.4 \text{ ft/diffuser}) = 16.4, \text{ say } 16 \text{ spaces}$$

Use 16 laterals on each side of the main header (32 total). Arrange the laterals in pairs. Place the laterals in each pair 0.75 ft apart, center-to-center. Place adjacent pairs 1.9 ft apart, center-to-center, to maximize walking space between alternating rows of diffusers. Place the outside laterals 1.85 ft from center to basin wall. Even with the staggered spacing between laterals, the clear space between 7-in diameter diffusers on the wide-spaced laterals is only 1.32 ft (15.8 in), which is less than ideal.

$$(491 \text{ diffusers})(1.2) / 32 \text{ laterals} = 18.4, \text{ say } 18 \text{ diffusers/lateral (15 installed)}$$

[Note that this results in $(15)(32) = 480$ diffusers initially in Zone 1.]

Allow 2 ft for header in center of zone, 2 ft at basin wall, and 1 ft at end of zone. A total of 18 diffuser baseplates will be installed per lateral, although 3 of them will be plugged initially. There are 17 equal-size spaces between the 18 baseplates.

$$(43.3 - 5) / [(17)(2)] = 1.13 \text{ ft spacings between diffusers, center-to-center}$$

Use 1.13-ft nominal diffuser spacing, 2.0 ft from end wall, and 1.0 ft from end of zone. Arrange the diffusers on each pair of laterals so that they are not directly across from each other (i.e., stagger diffuser placement).

Second Zone:

$$(23 \text{ ft}) / (1.8 \text{ ft/diffuser}) = 12.8, \text{ say } 12 \text{ spaces}$$

Use 12 laterals on each side of the main header (24 total). Arrange the laterals in pairs. Place the laterals in each pair 1.25 ft apart, center-to-center. Place adjacent pairs 2.2 ft apart, center-to-center, again to maximize walking space. Place the outside laterals 2.25 ft from center to basin wall.

$$(296 \text{ diffusers})(1.2) / 24 \text{ laterals} = 14.8, \text{ say } 15 \text{ diffusers/lateral (12 installed)}$$

[Note that this results in $(12)(24) = 288$ diffusers initially in Zone 2.]

Allow 2 ft for header in center of zone and 1 ft at each end of zone.

$$(43.3 - 4) / [(14)(2)] = 1.40\text{-ft spacings between diffusers, center-to-center}$$

Use 1.40-ft nominal diffuser spacing, 1.0 ft from each end of zone.

Third Zone:

$$(23 \text{ ft}) / (2.5 \text{ ft/diffuser}) = 9.2, \text{ say } 9 \text{ spaces}$$

Use 9 laterals on each side of the main header (18 total). Space laterals evenly at 2.25 ft apart, center-to-center. Place the outside laterals 2.5 ft from center to basin wall.

$$(149 \text{ diffusers})(1.2) / 18 \text{ laterals} = 9.9, \text{ say } 10 \text{ diffusers/lateral (8 installed)}$$

[Note that this results in $(8)(18) = 144$ diffusers initially in Zone 3.]

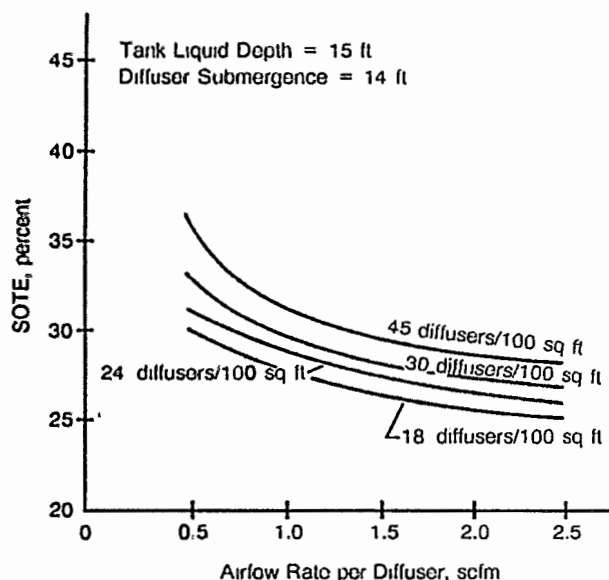
Allow 2 ft for header in center of zone, 1 ft at beginning of zone, and 2 ft at end wall.

$$(43.3 - 5) / [(9)(2)] = 2.13\text{-ft spacings between diffusers, center-to-center}$$

Use 2.13-ft diffuser spacing, 1.0 ft from beginning of zone, and 2.0 ft from basin wall.

Figure 5-10 illustrates the diffuser arrangement described above.

Figure 5-9. Manufacturer's SOTE data for Design Example 5-10.



the static head and line losses and deliver the required airflow to the diffusion system. The air filters remove particulates, such as dust and dirt, from the blower inlet air to protect the blowers from mechanical damage. These filters may also be necessary to protect fine pore diffusers from air-side fouling. Additional blower inlet air treatment may be necessary in certain applications (for example, when part of the air is taken from the plant headworks or primary treatment areas to help in odor control). Also, blower outlet filters are sometimes installed to provide additional air-side protection for the diffusers. Figure 5-11 is a schematic of a typical air supply system.

5.5.1 Air Piping

5.5.1.1 Materials

The air piping takes air from the blowers through the droplegs and into the aeration basin. The major considerations in selecting materials are strength, potential for deterioration due to corrosion, attack by HCl or other oxidants used for cleaning, other environmental factors, and thermal effects.

Piping materials commonly used in air supply systems include carbon steel, stainless steel, ductile iron, fiberglass reinforced plastic (FRP), high density polyethylene (HDPE), and polyvinyl chloride (PVC). Carbon steel, ductile iron, and FRP are the materials most commonly used for delivering air from the blowers to the basins because of their strength and durability. Piping within the basin may be stainless steel, PVC, or HDPE because of the resistance of such materials to corrosion.

Temperatures $>90^{\circ}\text{C}$ (200°F) are not uncommon in the blower discharge piping. It is important, therefore, that the pipe and accessories (pipe supports, valves, and gaskets) be designed to withstand these high temperatures. Provisions for pipe expansion and contraction are usually needed since thermal stresses can be significant. The blower discharge piping is often insulated to protect workers from burns. Heat from the supply air usually dissipates within a few feet of the point where the piping goes underground or becomes submerged, and thermal stresses under these conditions are normally small. However, during transient conditions when basins are down for repair/inspection in winter or summer, these stresses can be significant and should be evaluated.

Because of the potential for corrosion at the interface between the atmosphere and the liquid, a change in piping material from carbon steel or ductile iron to stainless steel or PVC is usually made at the droplegs into the basins. Since blower discharge pressures are normally <100 kPa (15 psi), thin-walled stainless steel pipe is often used to reduce cost. The use of thin-walled pipe requires that the pipe be adequately protected from physical damage. The loads the pipe must withstand should be considered in selecting the material and wall thickness.

Once inside the basin, the piping branches into a system of headers and manifolds. The choice between stainless steel and PVC pipe is usually dependent on the structural requirements of the diffuser connection and on whether a gas cleaning system is being used.

Stainless steel piping is often selected for systems that use tube diffusers because of the cantilever load applied to the lateral pipes by the diffusers. However, PVC piping has also been used successfully with tube diffusers when the connections between the lateral pipes and diffusers have been designed to withstand the cantilever loads.

PVC piping is commonly specified when disc or dome diffusers are used. These types of diffusers are usually mounted on top of the laterals and the forces transmitted through the connection to the laterals are minimal. Appropriate PVC pipe specifications are described in Section 2.4.3

When a gas cleaning system is provided, it is essential that the piping material and the gas used for cleaning be compatible. PVC is often the material of choice when an acid gas cleaning system is provided because of its high chemical resistance.

It is not uncommon for basins to be drained and left empty for extended periods of time. Thus, piping systems designed to be submerged will be exposed, a situation that must be considered when selecting materials of construction. For example, in areas where

Figure 5-10. General arrangement of diffusers in in-tank air piping for Design Example 5-10.

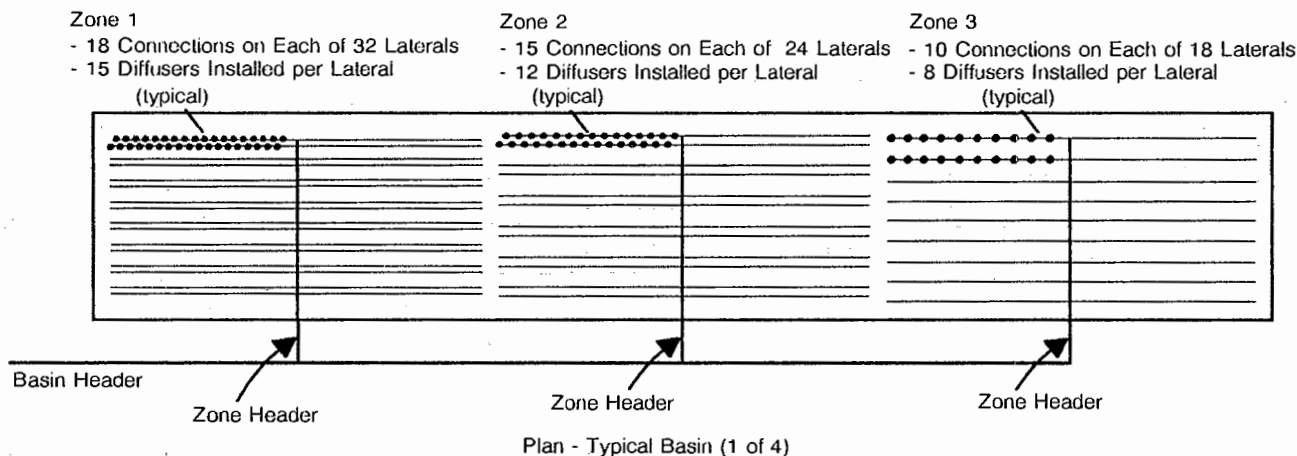
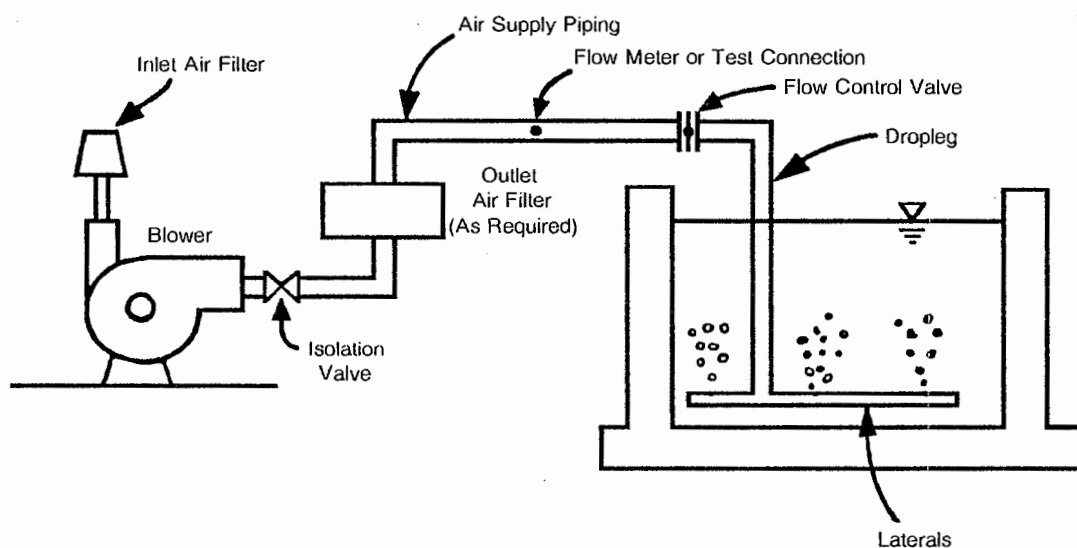


Figure 5-11. Air supply system schematic.



freezing occurs, the materials need to be able to withstand the effects of freezing and thawing. If the header and lateral piping material is PVC, it is important that it be formulated to be resistant to the ultraviolet rays of sunlight. Titanium dioxide (minimum TiO_2 of 2 percent) is the compound most commonly used in PVC piping to provide protection against ultraviolet radiation.

5.5.1.2 Design

As discussed in previous sections, both the air piping and aeration basins should be designed to allow for the basins to be drained and left empty for extended periods of time. In cold climates, the effects of freezing and thawing should be considered and provisions for protecting the system from damage associated with cold weather should be made. These provisions should include, as a minimum, designing

the piping system to allow for expansion and contraction, providing the capability to drain the system fully, and designing the basin to avoid frost heave. Operational considerations for protecting air supply piping when aeration basins are out of service are discussed in Chapter 4.

Air piping should be sized so that the headloss in the supply, header, and lateral piping is small compared with the headloss across the diffusers. Generally, if losses in the air piping between the last positive flow split (valve or other control device) and the farthest diffuser are less than 10 percent of the headloss across the diffusers, good air distribution throughout the basin can be maintained. A control valve is usually provided at the top of each dropleg into the basin. Since the headloss through a fine pore diffuser is normally 23-38 cm (9-15 in) w.g., including the control

orifices, headloss through the dropleg and air distribution piping within the basin should be less than about 4 cm (1.5 in). Higher headlosses in the air distribution piping can result in uneven air distribution within the basin.

Considerations in air piping design to accommodate flow measurement devices are discussed in Section 5.4.3.2. In general, a straight piping length equal to 10 pipe diameters should be provided upstream of the device, and a straight length equal to 5 pipe diameters should be provided downstream.

Basic principles of fluid mechanics can be used to determine headloss in air piping systems. At the rates of flow and velocities found in these systems, air can be treated as an incompressible fluid within the pipe and the Darcy-Weisbach equation can be used to determine headloss:

$$h_f = f (l/D) (H_v) \quad (5-7)$$

where,

- h_f = headloss, psia
- f = friction factor, from the Moody diagram (see Appendix C, Figure C-2)
- l = length of pipe, ft
- D = inside diameter of pipe, ft
- $H_v = 1.93 \times 10^{-6} (y_a) (v^2/2g)$
- = velocity head in pipe, psi
- y_a = specific weight of air in pipe, lb/cu ft
- v = airflow velocity in pipe, ft/min
- g = acceleration due to gravity = 32.2 ft/sec²

Headloss calculations for straight pipe segments can be simplified by using Equation 5-7 to develop headloss charts. Headloss for valves, bends, and other pipe system components can be calculated as a multiple of the velocity head:

$$h_f = K_h H_v \quad (5-8)$$

where,

- K_h = headloss coefficient (see Appendix C, Table C-2 to obtain coefficients for common appurtenances)

5.5.2 Air Filtration

5.5.2.1 Degree of Cleaning Required

The degree of cleaning or air filtration required is dependent on both the supply air quality and the particular diffusers in place. Filtration is required to protect blowers from abrasion and may be needed to control air-side fouling of fine pore diffusers. Typical minimum requirements for blower inlet air filtration to protect the blowers are 95 percent removal of particles 10 microns and larger (31,32).

Standard practice in designs using fine pore aeration devices is to provide blower inlet air filtration to remove 90 percent of all particles 1 micron and larger (31). However, perforated membrane diffuser manufacturers now indicate that filters designed to protect the blowers will also provide adequate protection for their diffusers (11,31). There is also evidence, based on recent studies (10,33), that this same degree of filtration may be adequate for ceramic diffusers in new installations. However, because air-side fouling is much more difficult to remove than water-side fouling, designers should be cautious in providing less efficient air filtration than is current standard practice.

5.5.2.2 Types of Filters

Air filters are commonly grouped into three broad groups: fibrous media filters, renewable media filters, and electronic air cleaners (34). Fibrous media filters, which include viscous impingement filters and dry-type filters, are the types most commonly used for wastewater aeration.

Dry-type filters are composed of random mats of fibers. The size and type of fiber used dictates the degree of filtration achieved. Dry-type filters are often pleated to obtain a greater media surface for a given face area, which results in a more reasonable pressure drop across the filter.

Viscous impingement filters use a high porosity media made up of coarse fibers coated with a viscous substance, such as oil. The viscous substance acts as an adhesive to trap particles trying to pass through the media. These types of filters are often used in series with dry-type filters to minimize the possibility of oil-laden air entering the system.

5.5.2.3 Filter Selection

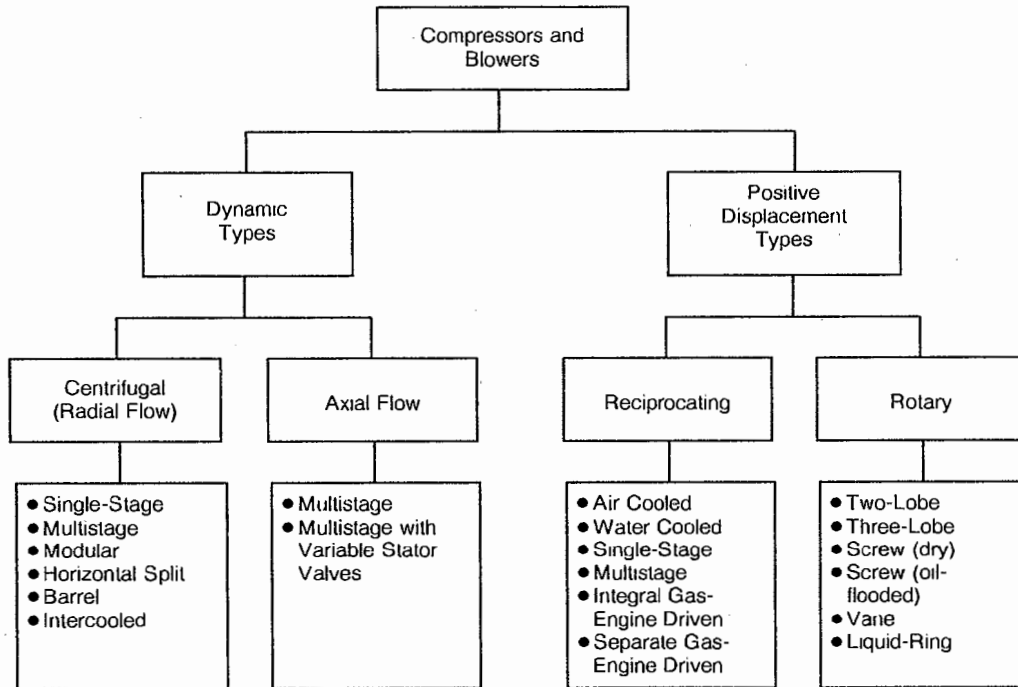
Selecting the proper filter for a particular application should include the following considerations: efficiency, cost, and expected filter life. The required efficiency is usually designated by the diffuser manufacturer. As stated previously, the degree of filtration required is dependent on the type of diffuser selected and the individual diffuser manufacturer. As would be expected, the cost of air filters increases as their efficiency increases. Since filters should be cleaned or replaced periodically, it is important that they be readily accessible.

5.5.3 Blowers

5.5.3.1 Description

As illustrated in Figure 5-12, many different types of blowers are available (35). The term "blower" generally applies to units that deliver pressures up to approximately 100 kPa (15 psi). The term "fan" is commonly applied to units that deliver pressures up to only about 14 kPa (2 psi). "Compressors" are units that deliver discharge pressures >100 kPa (15 psi).

Figure 5-12. Types of compressors and blowers.



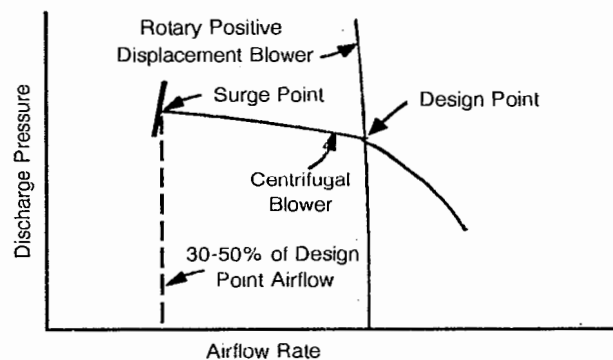
Since most aeration applications in wastewater treatment require air pressures of 70-100 kPa (10-15 psi), blowers are used. The two types of blowers normally used for wastewater aeration are rotary positive displacement units and centrifugal units (both single and multiple stage).

Blower capacity may be given in several ways but, for proper selection, the capacity must be referenced to inlet (or actual) conditions. Therefore, the most useful measure of capacity is inlet (or actual) volume per unit time, L/s (cu ft/min; icfm or acfm). Commercially available rotary positive displacement blowers have capacities of 2-23,600 L/s (5-50,000 acfm). Centrifugal blowers are usually available in capacities of 240-70,800 L/s (500-150,000 acfm). The impellers of a centrifugal unit can be arranged singly or in multiple stages for higher discharge pressures.

Figure 5-13 illustrates the general operating characteristics of a rotary positive displacement unit and a centrifugal unit. As seen in the figure, the rotary positive displacement unit will deliver a relatively constant airflow rate over a range of discharge pressures. In contrast, the centrifugal unit is capable of delivering a range of airflow rates at a relatively constant discharge pressure.

High efficiency and the ability to operate over a range of discharge pressures are two of the principal advantages of positive displacement blowers. The main disadvantages of these units, compared with centrifugal blowers, are the inability to effectively throttle airflow rate (however, the blowers can be

Figure 5-13. General operating characteristics of blowers.



speed controlled), the usual requirement for a more substantial foundation to dampen and resist vibration, and generally noisier operation.

Advantages of centrifugal blowers include quieter operation and smaller foundation requirements. Their disadvantages include a limited operating pressure range and a reduced volume of air delivered with any backpressure buildup due to clogged diffusers.

5.5.3.2 Turndown Considerations

If the selected blowers are to operate in an economic range over the entire life of the project, they must be capable of supplying appropriate volumes of air to meet the varying oxygen demands of the wastewater. Oxygen demand variations result from both diurnal fluctuations and the differences between start-up and design loads. Therefore, blower selection should take

into account minimum air requirements at plant start-up (which may be limited by mixing requirements) and peak air requirements at design conditions. It is essential that appropriate aeration control strategies and equipment be incorporated in the overall air delivery design. This will ensure full realization of the potential operating benefits of reduced power consumption of fine pore diffusion systems compared with coarse bubble and mechanical aeration systems. This aspect of blower design assumes even greater importance in retrofit situations. Detailed information on aeration control is provided in Chapter 6.

5.5.3.3 Blower Selection

Because different types of blowers have different operating characteristics, it is important to select a blower that is compatible with the normal operating mode of the basins. Other factors, such as efficiency, noise, maintenance, and operator preference, must also be considered in blower selection.

As discussed previously, centrifugal blowers are capable of supplying a range of air volumes at a nearly constant discharge pressure, whereas rotary positive displacement blowers are capable of supplying a nearly constant air volume over a range of discharge pressures. Therefore, if the aeration system is to be operated with a fairly constant water depth, as is typical in activated sludge aeration basins, a centrifugal blower is often an appropriate selection. Conversely, if it is to be operated over a wide range of depths, such as with a sequencing batch reactor, a positive displacement blower may be a better selection.

Both discharge pressure and the volumetric flow of air necessary to meet a given process oxygen requirement vary with inlet air temperature, since both the pressure and volume of air are functions of its density. As a result, blower capacity (in inlet L/s [icfm]) should be based on supplying the required air volume at maximum inlet temperatures when the volumetric flow required to provide a given mass flow will be greatest. Blower motor sizing should be based on blower operation at full capacity under minimum inlet temperature conditions when the density of air will be highest.

5.5.3.4 Control Considerations

Chapter 6 provides a detailed discussion of blower control methods. This section summarizes some of the key considerations.

Control of the air volume using a rotary positive displacement blower is normally accomplished by using variable speed controls. Inlet vanes or throttling valves may be used for control of air volume delivered by a centrifugal blower. Surge limits for centrifugal blowers can be lowered to nearly 30 percent of the rated capacity using inlet guide vanes (31,35). Inlet throttling valves can lower the surge limit to about 45

percent of rated capacity (31,35). The use of multiple blower units is another potential air volume control option. In all cases, blower manufacturers' recommendations should be sought. Table 5-3 compares these three control methods relative to efficiency, cost, and complexity.

Table 5-3. Control Methods for Blowers

	Positive Displacement	Centrifugal	
	Speed Control	Inlet Vane Adjustment	Inlet Valve Throttling
Efficiency	High	Medium	Low
O&M Costs	Low	Medium	High
Capital Costs	High	Medium	Low
Complexity	High	Medium	Low

Inlet valve throttling is often used to control the output of a centrifugal blower because it is the least complex method of control. Throttling the inlet valve will allow the air volume to be increased or decreased. This type of control can be accomplished using either a manually-operated valve or a motorized valve that operates based on some other measured parameter in the system, such as DO. Airflow and discharge pressure can also be throttled using a valve downstream of the blower. However, this method of control usually requires more horsepower than if the inlet valve is used to throttle airflow and pressure.

When varying the air volume delivered by a centrifugal blower, care must be taken not to decrease the airflow rate to a point where surge occurs. Surge is an unstable condition where rapid pulsations in discharge pressure and airflow occur, producing high-frequency reversals in the axial thrust on the blower shaft (36). This condition can become severe enough to damage the blower. To minimize the possibility of reaching the surge point, the design point on the blower curve should be selected so that the surge point occurs at approximately 30-50 percent of the design airflow rate. It is also good practice to specify a blower with a slightly higher surge pressure than the maximum system pressure under minimum airflow conditions. The surge point of a typical centrifugal compressor is shown in Figure 5-13.

5.5.4 Design and Installation

Proper installation of the air supply system is necessary to maximize system efficiency and minimize maintenance requirements. To help achieve proper installation, several items that should be considered during the design of the system are listed below:

- Provide an adequate number of isolation valves. This will permit routine maintenance without sacrificing the operation of the entire air supply system.

- Avoid low spots in the air piping. Moisture may collect at these low points causing a decrease in efficiency of the air supply system. If low points are unavoidable, provide manual or automatic drains.
- Provide for expansion and contraction in the air piping system due to temperature changes. Provisions should include an adequate number of expansion fittings and pipe supports that allow movement in the piping system.
- Select proper materials for the high temperatures that will occur in the piping system. Materials used for gaskets, supports, valve seats, and other miscellaneous appurtenances must be considered.
- Provide adequate airflow and pressure measurement devices throughout the system. These devices aid the operator in properly controlling the distribution of air in the system.
- Locate and size airflow and pressure indicators so they are easy to read from the points at which the operator adjusts system airflow.
- Provide sufficient space around the blowers to facilitate maintenance of these units.
- Include provisions for removing the blowers from their pads for maintenance. Depending on the sizes and locations of the blowers, these provisions may include overhead hatches, monorail beams, mechanical hoists, access for a front end loader, and others.
- Locate the blower intake filters where it is easy for operators to inspect and replace them when necessary.

5.5.5 Retrofit Considerations

The retrofit of an existing aeration system is site specific. Many of the same considerations that apply to design of new aeration systems apply to design of retrofit installations. These considerations include process oxygen requirements, diffuser selection, and configuration of the air diffusion system within the basins. There are some factors, however, over which the designer generally has little control, such as the configuration of the basins. In some cases, for example when replacing a diffusion system of another type, the designer must make decisions regarding the use, refurbishing, or replacement of other components of the system. The following sections address some of these decisions.

5.5.5.1 Air Piping

The sizes of existing air distribution pipes are generally adequate for a retrofitted fine pore aeration system. Because required airflow rates decrease as a result of the improved OTE achieved by retrofitting to fine pore diffusers, the size of the existing blower

discharge headers and air mains that deliver air to the basins will usually be sufficient. Depending on the type and arrangement of fine pore diffusion equipment selected, the individual drop pipes into the basins may also be large enough. The piping arrangement must be checked to determine if the air piping is properly located to provide the air distribution and flow control capabilities required. In addition, replacement and/or recalibration of airflow measuring devices should be considered at this time. It is important that the flow measuring devices are operable and accurate over the new airflow range.

The air distribution piping should be inspected to determine the condition of the various components. Connections, particularly flexible connections, should be checked for leaks. Areas subject to corrosion (such as basin drop pipes) need careful inspection. Existing swing arms are often unusable due to corrosion and wear. Use of these arms may require the addition of weights if relatively heavy coarse bubble diffusers are being replaced with light fine pore diffusers.

As with the design of a new air piping system, control of airflow and distribution of air within the aeration basins are the keys to a successful retrofit. Control of airflow usually requires a positive control device (usually a valve) on each dropleg and each basin supply air main. Considerations for designing air diffusion systems to provide adequate air distribution within the basins, discussed earlier in this chapter, apply to retrofit installations.

5.5.5.2 Air Filtration

Blower inlet filters will effectively remove contaminants from the outside air, but will not protect the diffusers from dirt, rust, scale, or other debris already in the downstream piping. This debris may be the result of internal pipe corrosion, leaks in submerged piping, physical damage to the nonsubmerged piping, or other causes. Thorough cleaning of the air piping system prior to diffuser replacement may be required to remove this debris.

In addition to cleaning the air piping, installing air filters on the discharge side of the blowers should be considered. In some cases, it may be advantageous to locate filters at the top of the drop pipes leading into the aeration basins. New piping can then be installed in the basins, and the filters will minimize the potential for air-side fouling of the diffusers due to debris from the existing upstream air supply piping.

Existing piping systems composed of stainless, galvanized, or coated steel normally present little danger of diffuser fouling from rust or scale. Existing painted or uncoated steel or iron pipe, however, should be reused only with extreme caution unless downstream in-line filters are installed.

5.5.5.3 Blowers

If the aeration system to be replaced is either a diffused air or sparged mechanical aeration system, air blowers and distribution piping will already be present. Replacement blowers may sometimes be required due to age or lack of flexibility. Blower capacity should be evaluated to determine if it is sufficient for the retrofitted system (keeping in mind that replacement of coarse bubble diffusers with fine pore diffusers reduces airflow requirements). Turndown capabilities should also be evaluated to determine whether the blowers can be operated at the lower airflow rates normally used with fine pore diffusers and whether the revised operating mode will reduce energy costs. Obviously, a plant with mechanical surface aerators will require installation of new blowers and air piping to use fine pore diffusers.

The energy savings available with fine pore diffusers result from a reduction in the volume of air required to transfer required DO to the process. These savings may be partially offset by the increased operating pressure required for fine pore diffusion systems. The reduction in airflow, if achieved, will result in operating fewer blowers or operating the same number of blowers at different points on their performance curves.

As the operating point of a centrifugal blower moves away from its maximum capacity, the efficiency of the machine decreases. As a result, the potential reduction in energy requirements associated with use of a fine pore diffusion system may be partially offset by lower blower efficiency if existing blowers operate further from their maximum efficiency points. It is important to confirm that the existing combination of blowers can operate over the required airflow range of the retrofitted air diffusion system prior to replacing the system.

Control strategies available for both centrifugal and positive displacement blowers, discussed earlier in this chapter, apply to retrofit situations. Centrifugal blowers not equipped with inlet guide vanes should be throttled on the inlet side rather than on the discharge side. Discharge throttling does not achieve energy savings, while inlet throttling results in significant power savings at any operating point. Airflow from positive displacement blowers can be varied by operating more or fewer units, adjusting the speed of the units, or "blowing off" air to the atmosphere. The last method is the least preferred, because it does not reduce energy requirements. As with centrifugal blowers, it is important to confirm that existing positive displacement blowers can operate over the required airflow range of the retrofitted air diffusion system prior to installing that system.

The capability of the blowers to deliver the required air volume at peak air temperatures should be checked. The capacity of the blower motors under minimum air

temperature conditions should also be checked. The overall blower system integrity should be evaluated in terms of its turndown capability and flexibility of operation.

5.5.6 Air Supply System Design Example

Consider the activated sludge air diffusion system design presented in Example 5-10. A corresponding appropriate air supply system is designed in Example 5-11.

Several modifications to the designs presented in Examples 5-10 and 5-11 could be considered to improve operability and reduce operating costs. Possible modifications of the system construction schedule to economically satisfy temporal variations in process oxygen requirements between plant start-up and the time when design plant loadings are reached have been discussed. Another modification that could be considered is to install a separate main air header to supply each basin. This would increase the capital cost of the aeration system but would provide the opportunity to reduce operating costs by more accurately controlling the airflow to each basin. Airflow control is discussed in more detail in Chapter 6. A third possible modification is to supply one blower with a capacity of one-half the blowers selected for the ultimate plant loadings (i.e., 1,400 scfm) to provide better airflow turndown capability during the initial years of plant operation.

Normally, several control alternatives will be evaluated in arriving at a final system configuration that meets the objectives of the designer and owner. Considerations in meeting these objectives may include ease of operation, reliability, capital cost, and O&M cost.

5.6 Summary of Aeration System Design Procedure

The design of a fine pore aeration system for an activated sludge process involves a series of steps. Design examples that illustrate each of these steps were presented through the earlier sections of this chapter. These examples illustrate the general approach to design. Design of an actual system requires consideration of several site- and system-specific factors, not all of which were fully discussed in these examples.

This section briefly summarizes the overall approach to the design of fine pore diffusion systems, highlighting some of the key design considerations. A summary list of steps is presented, followed by a discussion of each of these steps.

Example 5-11. Design of Air Supply System

Step 1: Design the blower system.

Determine the range of aeration rates required.

Maximum = (1,968 scfm/basin) (4 basins) = 7,872 scfm
Average nitrifying = (1,383 scfm/basin) (4 basins) = 5,532 scfm
Average nonnitrifying = (698 scfm/basin) (4 basins) = 2,792 scfm
Minimum = (493 scfm/basin) (4 basins) = 1,972 scfm

Set number and approximate capacity of blowers.

Assume the following criteria for the system:

3 blowers to provide 100 percent capacity
4 blowers installed
1 blower to meet minimum requirements

Provide four 2,800-scfm capacity blowers.

Determine discharge pressure requirements.

The following piping losses were calculated using the Darcy-Weibach equation:

Diffuser submergence = 14 ft
Diffuser headloss = 0.70 psi
Piping headloss = 0.15 psi
Inlet valve and filter headloss = 0.3 psi
Atmospheric pressure at 1,000 ft elevation = 14.3 psia

Static head = (14 ft) (0.43 psi/ft) = 6.02 psi
System head = 6.02 + 0.70 + 0.15 + 0.3 = 7.17 psig
Discharge pressure = 14.3 + 7.17 = 21.5 psia

Estimate blower horsepower.

The expression for blower wire power consumption was given in Equation 4-11. Combining the values of w , R , and K with the conversion factor 2.655×10^6 yields the following working equation:

$$WP = (4.28 \times 10^{-4} q_s T_a / e) [(P_d / P_b)^{0.283} - 1] \quad (5-9)$$

where,

WP = wire power consumption (approximately equal to brake horsepower), hp
 T_a = blower inlet air temperature, °F
 e = combined blower/motor efficiency
 P_d = blower discharge pressure, psia
 P_b = field atmospheric pressure, psia
and 4.26×10^{-4} is in units of hp-min/cu ft-°R.

Using this relationship, and assuming a blower inlet air temperature of 68°F and an overall blower/motor efficiency of 70 percent:

$$WP = [(4.28 \times 10^{-4}) (2,800) (460 + 68)/0.70] \{[(14.3 + 7.2)/(14.3)]^{0.283} - 1\} = 111 \text{ hp}$$

(continued)

Example 5-11. Design of Air Supply System (continued)

Check the motor horsepower under minimum temperature conditions.

This requires determining the relationship between actual airflow (q_a) and standard airflow under field conditions (q_s):

$$(q_a/q_s) = [(T_a + 460)/(68 + 460)] (14.7/P_b) \quad (5-10)$$

Substituting the appropriate values for T_a and P_b yields:

$$\begin{aligned}(q_a/q_s) &= 0.925 \text{ at } T_{\min} = 15^\circ\text{F} \\ (q_a/q_s) &= 1.10 \text{ at } T_{\max} = 105^\circ\text{F}\end{aligned}$$

Each blower must be sized to deliver the required q_a under maximum temperature conditions:

$$(q_a/2,800) = 1.1; \text{ therefore, } q_a = 3,080 \text{ icfm}$$

To size the blower motor, assume the blower is operating at maximum capacity (q_a) under minimum temperature conditions:

$$(3,080/q_s) = 0.925; \text{ therefore, } q_s = 3,330 \text{ scfm}$$

Check WP requirements at maximum airflow:

$$\text{WP} = (4.28 \times 10^{-4}) (3,330) (460 + 15)/0.70 \{ [(14.3 + 7.2)/(14.3)]^{0.283} - 1 \} = 117 \text{ hp}$$

Use a 140-hp motor for a 2,800-scfm blower.

Published centrifugal blower curves are applicable to operation at standard conditions (68°F inlet temperature, 14.7 psia inlet pressure, and 36 percent relative humidity). Where different inlet conditions apply (as in this example), an equivalent air pressure (EAP) must be calculated to allow the blower curves to be used. Figure C-3 (Appendix C) can be utilized to make this correction.

Use:

Blower discharge pressure = 7.2 psig
Blower inlet airflow = 3,100 icfm
Plant elevation = 1,000 ft
Blower inlet temperature = 105°F

From Appendix C, Figure C-3, EAP = 7.9 psig

A blower with an operating point from a published performance curve that shows 3,100 icfm airflow at a discharge pressure of 7.9 psig will deliver 2,800 scfm at a discharge pressure of 7.2 psig at the inlet conditions shown.

Select 3,100-icfm (at 7.9 psig) blowers (4 each) with 140-hp motors.

Step 2: Design the air piping system.

The general piping arrangement will be established based on site constraints, layout of other facilities, and other considerations. The general arrangement assumed for the four aeration basins in this example is shown in Figure 5-14.

Air piping can be preliminarily sized using the general guidelines for velocities given in Appendix C, Table C-3. Accurate headloss calculations must be made, and the pipe sizes (or blower discharge pressure) must be refined as necessary to match blower capacity and system headlosses.

(continued)

Example 5-11. Design of Air Supply System (continued)

Using the velocity guidelines given in Appendix C, Table C-3, the following preliminary pipe sizing estimates were made:

	Approximate Peak Airflow, scfm	Pipe Diameter, in	Approximate Airflow Velocity, fpm
<i>Header Segment</i>			
1	8,000	20	3,700
2	4,000	14	3,700
3	4,000	14	3,700
4	1,600	10	2,900
5	440	6	2,000
6	1,200	10	2,200
7	600	6	3,100
8	220	6	1,000
<i>Laterals</i>			
Zone 1	40	4	460
Zone 2	25	4	290
Zone 3	12	4	140

Headlosses are calculated most accurately using the Darcy-Weisbach equation (Equation 5-7), as discussed in Section 5.5.1.2. To use the Darcy-Weisbach equation, corrections must be made for the specific weight of air and air temperature under actual conditions in the air piping. The equation can be conveniently applied in the following form:

$$(h_f/100) = (f/D) (v^2/2g) (1.93 \times 10^{-4} \gamma_a)(1/36) \quad (5-11)$$

where,

$h_f/100$ = headloss per 100 ft of pipe, psia

The specific weight of air can be determined by treating air as an ideal gas (which is nearly correct at typical centrifugal blower air temperatures and pressures):

$$\gamma_a = 144 P_d / (R T_p) \quad (5-12)$$

where,

R = ideal gas constant = 53.3 ft-lb/lb-°R for air

T_p = air temperature in pipe, ft/°R

The temperature rise through the blower can be estimated by assuming that compression is adiabatic:

$$\Delta T = (T_a/e) [(P_d/P_b)^{0.283} - 1] \quad (5-13)$$

where,

ΔT = temperature rise through blower, °R

(continued)

Example 5-11. Design of Air Supply System (continued)

Heat will dissipate in the air piping, so the calculated air temperature rise through the blower will not be the temperature rise throughout the air piping system. As an approximation, it can be assumed that the air temperature in the piping is the average of the blower inlet and discharge temperatures. Then:

$$T_p = T_a + (\Delta T/2) \quad (5-14)$$

Combining Equations 5-13 and 5-14 yields:

$$T_p = T_a \{1 + (1/2e)[(P_d/P_b)^{0.283} - 1]\} \quad (5-15)$$

Actual velocity in the pipe is determined by correcting for pressure, temperature, and relative humidity of the air after compression:

$$q_a = q_s (T_p/T_s) [(P_s - H_s P_{vs})/(P_d - H_d P_{vd})] \quad (5-16)$$

where,

T_s = air temperature at standard conditions = 528°R

H_s = relative humidity at standard conditions, fraction

P_{vs} = vapor pressure of water at standard conditions = 0.34 psia

P_s = atmospheric pressure at standard conditions = 14.7 psia or 1 atm at 100 percent relative humidity

H_d = relative humidity of blower discharge air, fraction

P_{vd} = vapor pressure of water in blower discharge air, psia

Normally, the vapor pressure correction terms are small and can be neglected. The velocity in the pipe is then:

$$v = (4q_s/\pi D^2) (T_p/T_s) (P_s/P_d) \quad (5-17)$$

Substituting the expressions for q_a , ΔT , T_p , and v into Equation 5-11 and using the appropriate values of the constants in these expressions yields:

$$h_f/100 = (f/D^5)(q_s^2/P_d)T_a\{1 + (1/2e)[(P_d/P_b)^{0.283} - 1]\}(1.02 \times 10^{-8}) \quad (5-18)$$

To use this equation to determine headloss, f must be determined. This can be accomplished by calculating the Reynolds number (R_e) and using Appendix C, Figure C-2..

$$R_e = 2.37 q_s/D\mu \quad (5-19)$$

where,

μ = viscosity, centipoises

For temperatures encountered in aeration, μ can be estimated from:

$$\mu = (32.2 + 0.28T_p) \times 10^{-4} \quad (5-20)$$

(continued)

Example 5-11. Design of Air Supply System (continued)

Preliminary headloss estimates can be made using a headloss chart. However, estimates determined using such a chart may be overly conservative. More accurate estimates can be made by using the Darcy-Weisbach equation.

Table 5-4 presents preliminary headloss calculations for this example. In these calculations, the pipe length for each segment (from Figure 5-10) was increased by 20 percent to allow for losses through fittings, valves, and other appurtenances. More accurate calculations that include estimates of losses through each of these elements should normally be part of the final design. Losses through these components can be estimated using the Darcy-Weisbach equation and Appendix C, Table C-2, as discussed earlier.

Using the data from Table 5-4, headlosses to each zone can be determined. The values obtained are:

	Headloss, psia	
	Total	Dropleg to Diffuser
Zone 1	0.079	0.014
Zone 2	0.134	0.054
Zone 3	0.107	0.008

While these values are acceptable (<0.07 psi headloss after the last positive flow split [10 percent of the headloss through the diffuser orifice]; < 0.15 psi headloss between blower and diffuser), it is prudent to make changes in two segments: 1 and 7. Increasing the pipe diameter to 24-in in Segment 1 and 8-in in Segment 7 results in the revised headloss estimates shown in Table 5-5. These headlosses are conservative. The design could be refined by calculating the headlosses through all the piping appurtenances (such as fittings and valves) and then reducing the air piping sizes accordingly. This refinement is beyond the scope of the example.

5.6.1 Outline of Approach

1. Determine flows and loads
2. Establish process design criteria
3. Size basins
4. Configure basins
5. Determine oxygen transfer requirements
6. Select diffusers
7. Determine aeration rates
8. Configure diffuser system
9. Design blower system
10. Review system flexibility
11. Design air piping system

5.6.2 Steps in Design

5.6.2.1 Determine Flows and Loads

Design wastewater flows and loadings should be established for the entire range of operating conditions anticipated. From these, system oxygen requirements can be estimated. Accordingly, loading parameters that describe carbonaceous oxygen demand (BOD or COD), nitrogenous oxygen demand (TKN and $\text{NH}_4\text{-N}$), and inorganic oxygen demand (IOD) are usually required (see Section 5.3.1.2 for calculation procedures). Waste streams include both the main plant flow and all sidestreams (such as sludge

thickening and dewatering flows). Loading conditions to be considered generally include:

1. minimum month, to establish blower and diffuser turndown requirements (normally occurs at plant start-up),
2. average conditions (nitrifying and nonnitrifying), to establish the normal operating condition for the blowers and other system components,
3. maximum month, to determine the maximum condition under which process oxygen requirements must be met without stressing the microorganisms (that is, for which the design average DO must be maintained), and
4. peak day/4-hr peak (considering diurnal fluctuations), to establish the maximum operating point for all system components, including diffusers, air supply piping, and blowers.

5.6.2.2 Establish Process Design Criteria

Several factors are important in determining system oxygen requirements (both under standard and actual

Figure 5-14. General arrangement of process air piping for Design Example 5-11.

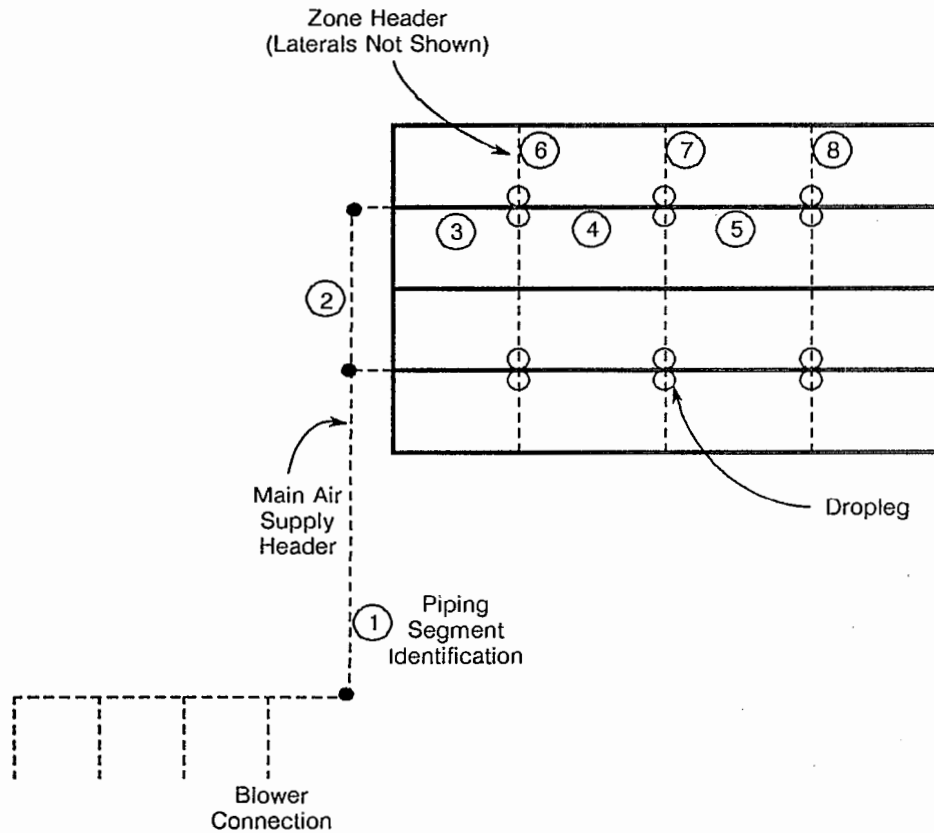


Table 5-4. Air Piping Headloss Calculations for Example 5-10 – First Iteration

Pipe Seg.	Length, ft	D, in	k_s , ft	k_s/D	Airflow, scfm	Air Temp., °F	Reynolds No.	Friction Factor	Headloss, psi
1	160	20	0.00015	0.00009	8,000	154.9	5.57E + 05	0.014	0.0325
2	50	14	0.00015	0.000128	4,000	154.9	3.98E + 05	0.015	0.0162
3	40	14	0.00015	0.000128	4,000	154.9	3.98E + 05	0.015	0.0130
4	50	10	0.00015	0.00018	1,600	154.9	2.23E + 05	0.017	0.0158
5	50	6	0.00015	0.0003	440	154.9	1.02E + 05	0.020	0.0181
6	80	10	0.00015	0.00018	1,200	154.9	1.67E + 05	0.016	0.0134
7	80	6	0.00015	0.0003	600	154.9	1.39E + 05	0.020	0.0538
8	80	6	0.00015	0.0003	220	154.9	5.10E + 04	0.022	0.0080
L1	25	4	0.00015	0.00045	40	154.9	1.39E + 04	0.032	0.0009
L2	25	4	0.00015	0.00045	25	154.9	8.70E + 03	0.034	0.0004
L3	25	4	0.00015	0.00045	12	154.9	4.17E + 03	0.039	0.0001

k_s = absolute roughness factor

Field atmospheric pressure = 14.3 psia

Blower discharge pressure = 21.5 psia

Blower inlet temperature = 105°F

Blower efficiency = 70 percent

Table 5-5. Air Piping Headloss Calculations for Example 5-10 – Second Iteration

Pipe Seg.	Length ,ft	D, in	k_s , ft	k_s/D	Airflow, scfm	Air Temp, °F	Reynolds No.	Friction Factor	Headloss, psi
1	160	24	0.00015	0.000075	8,000	154.9	4.64E + 05	0.014	0.0131
2	50	14	0.00015	0.000128	4,000	154.9	3.98E + 05	0.015	0.0162
3	40	14	0.00015	0.000128	4,000	154.9	3.98E + 05	0.015	0.0130
4	50	10	0.00015	0.00018	1,600	154.9	2.23E + 05	0.017	0.0158
5	50	6	0.00015	0.0003	440	154.9	1.02E + 05	0.020	0.0181
6	80	10	0.00015	0.00018	1,200	154.9	1.67E + 05	0.016	0.0134
7	80	8	0.00015	0.000225	600	154.9	1.04E + 05	0.020	0.0128
8	80	6	0.00015	0.0003	220	154.9	5.10E + 04	0.022	0.0080
L1	25	4	0.00015	0.00045	40	154.9	1.39E + 04	0.032	0.0009
L2	25	4	0.00015	0.00045	25	154.9	8.70E + 03	0.034	0.0004
L3	25	4	0.00015	0.00045	12	154.9	4.17E + 03	0.039	0.0001

conditions) and the spatial and temporal variations in these requirements. These include:

1. maximum wastewater temperature and the corresponding maximum SRT, used to determine the maximum carbonaceous oxygen consumption ratio and whether nitrification is likely to occur under these conditions (see Section 5.3.1.2),
2. minimum wastewater temperature and the corresponding minimum SRT, used to determine the minimum carbonaceous oxygen consumption ratio (see Figure 5-4) and whether nitrification is likely to occur under these conditions (see Section 5.3.2.2),
3. extent of denitrification (if the system is designed to denitrify), used to refine the system oxygen demand estimates (see Section 5.3.1.2), and
4. basin configuration, used to establish the distribution of oxygen demand within the basin (see Section 5.3.1.3)

Other criteria that are important in designing the aeration system include:

5. control of airflow (including process modes available and control provided) and wastewater flow distribution (e.g., step feed flexibility) to meet system process oxygen demand variations, and
6. design life and process loading growth patterns.

5.6.2.3 Size Basins

After establishing process design criteria, the aeration basins can be sized. Basin sizing is beyond the scope of this manual.

5.6.2.4 Select Diffusers

Considerations for selecting diffusers are discussed in detail in previous sections of this chapter. Key considerations include OTE, O&M requirements, initial

cost, O&M cost, and compatibility with existing facilities (for retrofits).

5.6.2.5 Configure Basins

Basin configuration involves converting the required aeration basin volume into physical dimensions. The depth of diffuser submergence is important because it determines OTE and the static pressure that the blowers must overcome. Length-to-width ratio is important because it establishes spatial distribution of oxygen demands and constrains how the air diffusion system can be arranged. Typical diffuser arrangements are illustrated in Figure 2-8.

5.6.2.6 Determine Oxygen Transfer Requirements

Determination of system oxygen transfer requirements is addressed in Example 5-10. Variations with both time and position in the aeration basin should be considered.

5.6.2.7 Determine Aeration Rates

Oxygen transfer requirements (from Section 5.6.2.6) are used to determine aeration rates. The procedure for converting standard oxygen transfer rates to required aeration rates is illustrated in Example 5-10.

5.6.2.8 Configure Diffuser System

After determining required aeration rates, the diffuser system can be configured. Several iterations will normally be required to ensure that the entire range of oxygen transfer requirements can be met without exceeding the recommended limits on airflow rate per diffuser. The basin and diffuser system also need to be arranged to allow space for installation and to facilitate operation (including adequate space for maintenance of the in-basin piping and diffusers and providing for isolation of portions of the system for maintenance).

5.6.2.9 Design Blower System

Temporal variations in oxygen demands should be considered in selecting an appropriate number of blowers. Typically, the blowers are sized to allow one

blower to meet minimum oxygen requirements, one or more blowers operating at full capacity to meet annual average requirements, and two or more blowers operating at full capacity to meet peak hour requirements.

5.6.2.10 Review System Flexibility

Sufficient flexibility should be provided to enable the system to be operated cost effectively over the entire life of the facility. This review should consider how the system will be operated at start-up and at design loading. Considerations should include the number of basins constructed and operated at various points in the design life of the system, flexibility to operate in the step feed mode, diffuser layout and ability to accommodate changing system oxygen requirements, DO and airflow control, and the number and capacity of blowers installed and operating at various points in the design life.

5.6.2.11 Design Air Piping System

The air piping system should be designed to permit cost-effective installation and operation. Piping materials should be selected to provide the degree of durability (including resistance to mechanical damage, corrosion, and sunlight degradation) appropriate for the facility. Both permanent flow meters and flow points for portable meter installation need to be properly located to allow accurate airflow measurements. This includes providing sufficient straight lengths of piping upstream and downstream (normally, a minimum of 10 and 5 pipe diameters, respectively). An adequate number of flow points where portable flow measurement devices can be inserted should be provided. As a minimum, a flow meter for measuring total system airflow and flow points for measuring total airflow to each basin and each zone should be included. Piping should be sized to provide acceptable headlosses at maximum airflows, including a headloss between the last positive flow split and the farthest diffuser of less than 10 percent of the loss through the diffusers. Losses through the blower inlet filter, control valves, check valves, basin control valves, and fittings all need to be considered in establishing total blower discharge pressure requirements.

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National Technical Information Service

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Springfield, VA 22161
(703) 487-4650

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Chapter 6

Aeration Control

6.1 Introduction

The major objectives of aeration control are to: 1) ensure that the supply of oxygen meets the dynamic spatial and temporal variations in process biomass oxygen demand discussed in Chapter 5, and 2) effectively control air delivery and oxygen transfer to minimize aeration energy costs.

This chapter specifically addresses automated aeration control in the activated sludge process. Automated aeration control is the manipulation of the aeration rate by computer or controller to match the dynamic oxygen demand and maintain a desired residual or set-point mixed liquor dissolved oxygen (DO) concentration. Benefits of control, control strategies, instrumentation, and final control element hardware considerations are examined. The information presented will facilitate effective communication between designers, control specialists, and operations personnel to ensure incorporation of control considerations in the design of the aeration system.

6.2 Benefits of Aeration Control

The benefits of implementing an aeration control strategy in a wastewater treatment facility are: 1) assured integrity and uninterrupted operation of the process, 2) increased reliability in meeting plant discharge requirements, and 3) reduced process costs. If properly applied, aeration control offers the potential for significant cost savings.

6.2.1 Process Implications

Maintenance of an inadequate residual mixed liquor DO concentration can inhibit biological activity and contribute to problems such as sludge bulking (1,2) and inhibition or loss of nitrification (3). Conversely, excessive aeration can shear the activated sludge floc and result in settleability problems (4,5). Improved process reliability, organic nitrogen removal efficiency, sludge settleability, and effluent quality have been attributed to automated DO control (6,7).

6.2.2 Economic Considerations

Aeration energy consumption usually represents 50-90 percent of the total energy demand (8) and up to 30 percent of the total operating cost (9) for activated

sludge plants. The incorporation of effective automated control of the aeration process can result in considerable energy savings (10-13). However, as the complexity of a control system increases, labor costs can increase. The design goal is to select the optimal control system, i.e., one that achieves satisfactory treatment at minimal total cost.

6.2.2.1 Manual Control

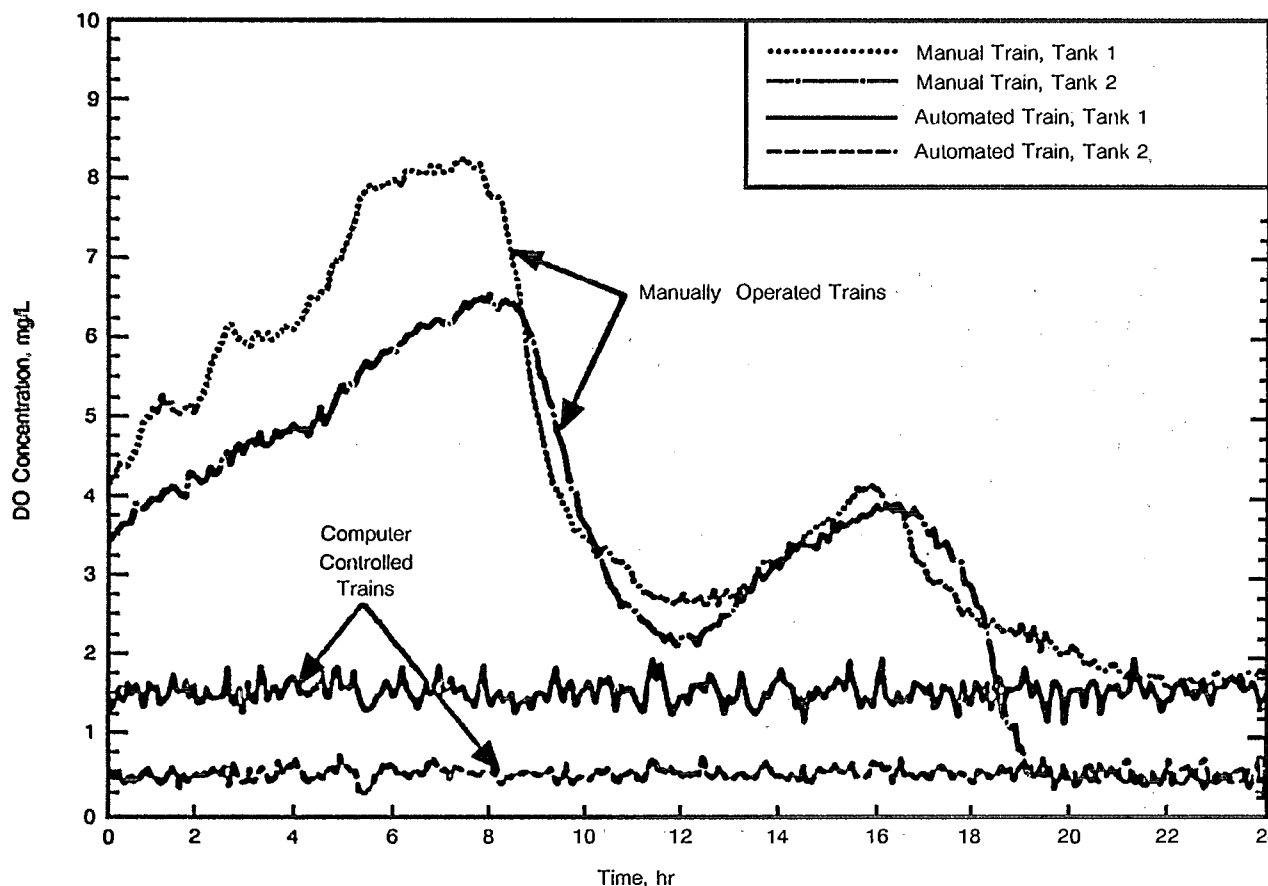
As indicated in previous chapters, wastewater treatment plants rarely, if ever, operate under steady-state conditions. Temporal and spatial variations in oxygen demand make it very difficult, if not impossible, for an operator to manually manipulate airflow rates and air distribution to maintain desired mixed liquor DO concentrations throughout a sustained operating period. This is true even for plants with well-designed, flexible aeration systems. Therefore, manually-adjusted aeration systems are usually operated at a fixed airflow rate and distribution. Changes are initiated once or twice daily, at best, and often on a weekly or seasonal basis only. Airflow is manually fixed at a rate high enough to satisfy the oxygen demand anticipated during peak loading periods. This practice results in unnecessary and costly excess aeration during extended periods of reduced loading.

6.2.2.2 Automated Control

Automated DO control is the only practical way a well-designed aeration system can be effectively manipulated to satisfy biomass oxygen demand, minimize operational problems associated with inadequate or excessive aeration, and minimize aeration energy consumption. Generally, the potential aeration energy savings achievable by automatic aeration or DO control is 25-40 percent (10,11), but can be as high as 50 percent (12,13). Potential savings are plant specific and depend on plant loading characteristics, plant configuration and process hardware design, and the existing level of manual control.

An example of the results achievable with automated control vs. manual operation is given in Figures 6-1 and 6-2 (14). The DO profiles of two parallel, "completely mixed" basins-in-series aeration trains are shown in Figure 6-1. For the manually-controlled

Figure 6-1. Comparative DO profiles for automated control vs. manual operation.



aeration train, the airflow rate was fixed and the DO profiles are, therefore, a reflection of plant loading dynamics. Automated control of DO concentration in the other aeration train was achieved through continuous manipulation of: 1) aeration capacity using speed regulation of rotary lobe positive displacement blowers with a variable-frequency a.c. drive, and 2) air distribution using automated control valves. Figure 6-2 shows the energy savings achieved through continuous control of the airflow rate in the automated train compared with the fixed aeration rate operation of the manual train.

As indicated in Chapters 2 through 4, as the airflow rate applied to a fine pore diffuser increases, oxygen transfer efficiency (OTE) usually decreases and aeration efficiency drops because of increased pressure losses. Therefore, continuously minimizing the airflow rate while satisfying the dynamic oxygen demand through set-point DO control maximizes OTE and aeration efficiency and minimizes aeration energy consumption. The DO set-point chosen for the controller also has an impact on aeration energy expended. In respiring systems, the dynamics of

reaeration are well known and identified by the simplified model:

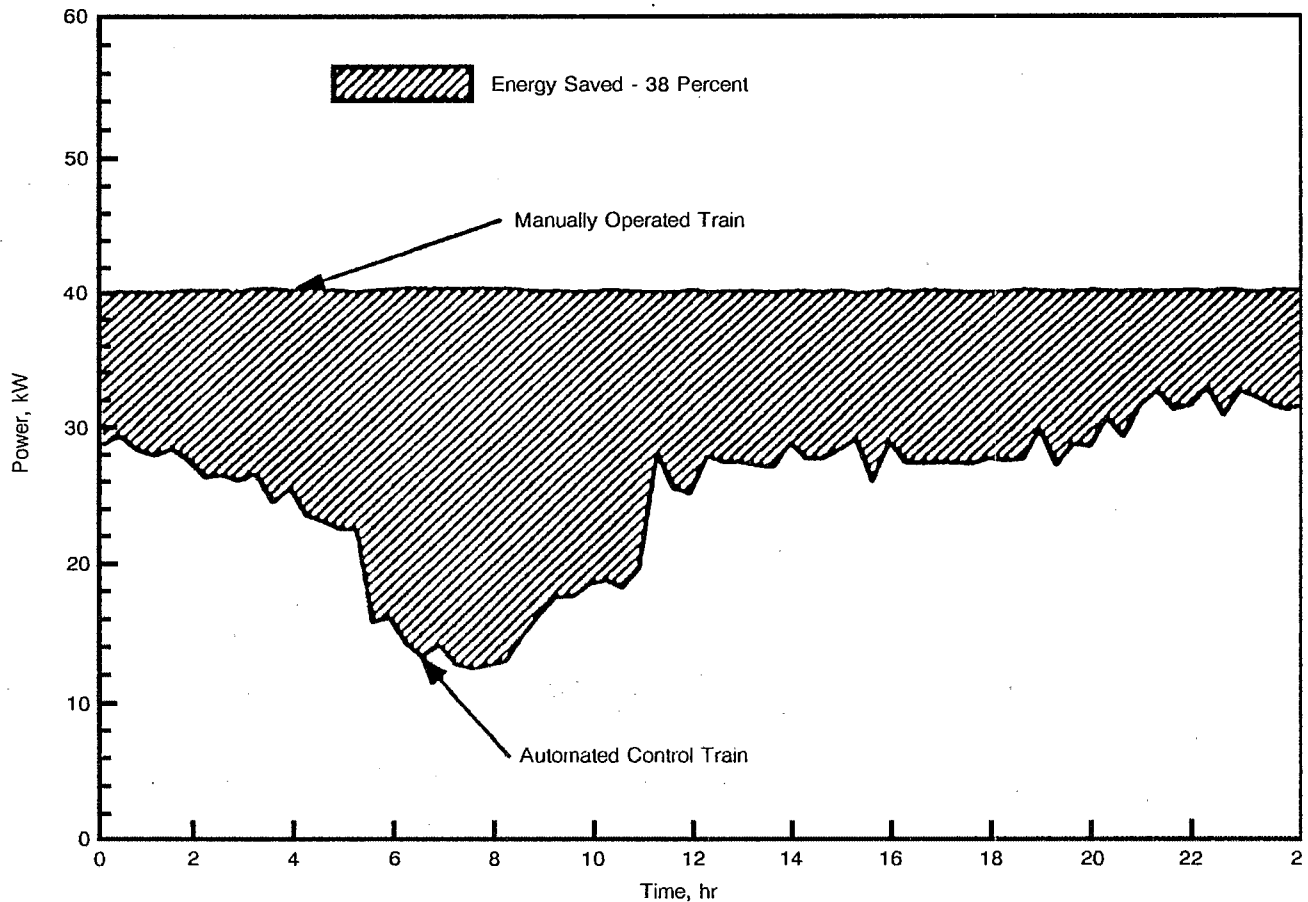
$$dC/dt = \alpha F(K_{La}) (C^*_{\infty} - C) - r \quad (6-1)$$

where,

- C = process water DO concentration, mg/L
- t = time, hr
- α = (process water K_{La} of a new diffuser) $\div$ (clean water K_{La} of a new diffuser)
- F = (process water K_{La} of a diffuser after a given time in service) $\div$ (K_{La} of a new diffuser in the same process water)
- K_{La} = apparent volumetric mass transfer coefficient in clean water at temperature T , 1/hr
- C^*_{∞} = steady-state DO saturation concentration attained at infinite time at water temperature T and field atmospheric pressure P_b , mg/L
- r = volumetric respiration rate, mg O_2 /L/hr

As outlined in Sections 3.1 and 4.2.3.1d, the residual DO concentration affects the OTE under process

Figure 6-2. Comparative energy consumption for automated control vs. manual operation.



conditions (OTE_f) by changing the oxygen transfer driving force ($C^*_\infty - C$). The maximum OTE_f is realized when the driving force is greatest, i.e., at a residual mixed liquor DO control set-point of zero. The positive DO residual set-point usually maintained for process performance reduces the driving force, lowers OTE_f , and requires a greater amount of airflow to meet the oxygen demand. This can represent a significant increase in aeration energy consumption. It is important, therefore, to maintain the DO residual at the lowest level possible without adversely affecting treatment. A detailed example is given in Section 4.2.3.1d.

6.3 Control Strategy Development

6.3.1 Degree of Control

How much aeration control is required or desired and can be achieved at an activated sludge plant is site specific. The degree of aeration control implemented can range from the extremes of very infrequent manual manipulation based on manual measurements (virtually no control) to comprehensive automated

control of the aeration delivery and distribution hardware to maintain on-line measured DO concentration at desired set-points throughout the aeration trains under dynamic loading conditions.

6.3.1.1 New Treatment Facility

For a new treatment plant, the decision to incorporate aeration control is straightforward. The capital cost of implementing even a high degree of automated control as an incremental cost above that required to provide open loop, on-line monitoring is a small percentage of the total initial cost of plant, generally 1-5 percent, depending on the size of the facility. As outlined in Chapter 4, the decision is based on the desired process configuration and operational control goals. Successful implementation of automated control of airflow and DO in a new facility requires that the plant be designed from the outset with the intent of incorporating efficient automated control.

Careful attention to process and hardware flexibility is necessary to realize the maximum benefits from a well-designed aeration control system throughout the

plant design life. The various components of the aeration system must be designed to allow for operational flexibility to meet the dynamic oxygen requirements of the system (see Sections 5.3.1.3 and 5.4.3). Of greatest importance in this respect are: 1) operational constraints and turndown capacity of the blowers, 2) air distribution control hardware, and 3) diffuser allowable airflow range.

6.3.1.2 Retrofit Facility

For an existing, manually-controlled plant, the decision to retrofit for automated aeration control must be based on one or both of the following objectives: 1) provision of more effective control of the aeration process to minimize operational problems, or 2) optimization of the aeration process to achieve energy consumption savings.

In either case, the level or degree of control implemented should be based on an incremental cost-benefit analysis. The economic analysis should consider the cost of retrofitting the plant for various levels of control, training requirements and personnel changes, the potential for energy savings, O&M costs, and the intangible benefits of improved operation and plant reliability. Automated control may also result in more efficient use of existing tankage and optimization of plant capacity. This might permit postponement of expected plant expansions and the associated capital financing expenditure. While this possibility is a less obvious benefit of improved aeration and process control, it may outweigh the cost savings that are achievable through operating cost reduction alone.

The economics for adding automated DO control also depend on whether the control system is being incorporated as part of an overall aeration system upgrade or on a stand-alone basis. The economics of upgrading the aeration system of a hypothetical 219-L/s (5-mgd) plant with higher efficiency aeration equipment and automatic DO control has been evaluated (15). It was estimated that the simple payback period for the entire retrofit project would be 5-7 years depending on the economic assumptions made. It was also determined that the capital cost associated with adding automatic control would be small compared with the cost of the retrofitted aeration equipment. Yet, the anticipated savings resulting from this addition would account for nearly 70 percent of the expected energy savings of the entire retrofitted aeration system. Additional economic analysis considerations and procedures are presented in Chapter 7.

6.3.2 Control Systems

The principles of control theory used in the control systems examined in this section are available in standard control textbooks (16-18). In addition, an EPA report (10) describes in detail several control strategies and basic techniques used for DO control in the activated sludge process.

The automated control of mixed liquor DO concentration to a set-point value does not itself require any in-depth knowledge of biological metabolism or activity. Simply stated, the DO concentration is measured using on-line instrumentation and the airflow rate is controlled in the zone of the basin where the measurement is being made. The manipulatable variable in this case is adjusted, if necessary, by a controller directing final control elements accordingly.

6.3.2.1 Control Theory

The most common DO control strategies involve conventional feedback or feedforward-feedback controllers. A feedback control loop is shown schematically in Figure 6-3. The DO sensor signal is fed to the comparator where it is compared to a desired set-point value, and the error is determined. The controller calculates a control signal based on this error using an established algorithm or control function. It then sends an output signal to adjust a final control element, such as a blower or air distribution valve, to achieve a change in the manipulatable variable.

If feedforward action is added to the controller, as illustrated in Figure 6-4, an incoming process disturbance (a change in influent flow rate, for example) is detected directly through additional instrumentation. The controller initiates control of the manipulatable variable immediately rather than waiting until the disturbance is reflected in a change in the controlled variable. Usually, the two controllers are coupled so that the feedforward portion of the controller paces the action and the feedback portion serves to "fine tune" or "trim" the feedforward control action. The process DO response to changing input is normally slow and can be adequately handled by control systems using feedback control only.

6.3.2.2 Control Functions

The control signal is derived from the measured variable error according to a control law or algorithm. This can be as simple as on/off control of the final control element to adjust the manipulatable variable. For DO control, this could involve bringing on-line or taking off-line one or more blowers in a multiple blower system to change the aeration rate whenever the DO was below or above the set-point, respectively. In cases where the resulting response of the process DO concentration to this type of air delivery control is fast, excessive starting and stopping of blowers can result. This is undesirable from the standpoint of both hardware O&M and energy demand and consumption.

These problems can be minimized by modifying the controller to take no control action within a user-selectable band about the set-point. For example, where the desired DO concentration is 1.5 mg/L, the controller could be set to start up a blower at 1.0 mg/L

Figure 6-3. Block diagram for feedback control loop.

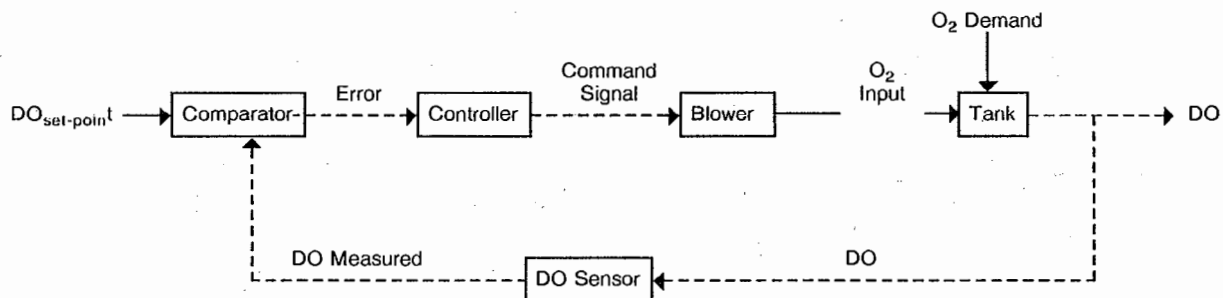
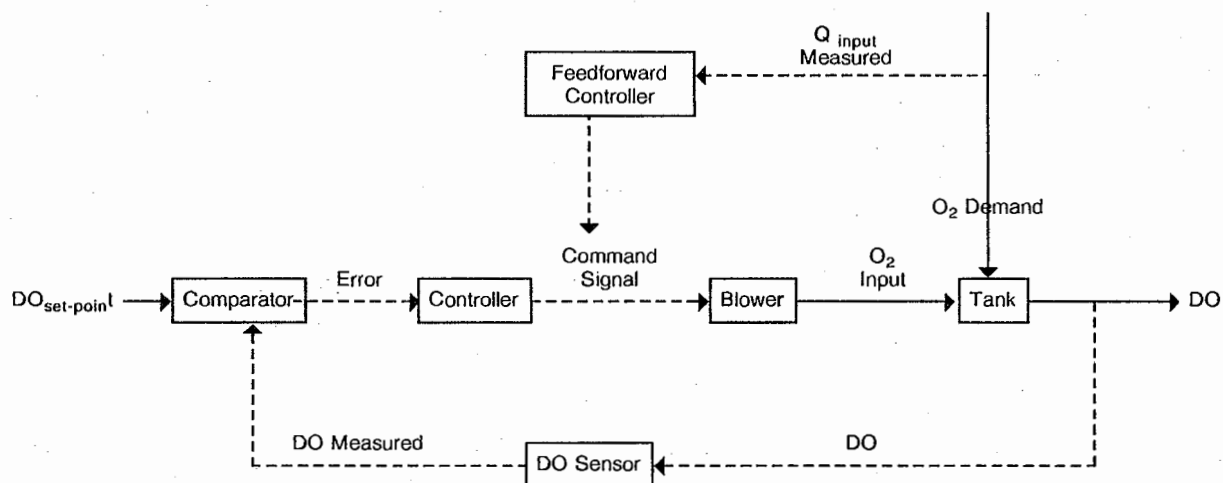


Figure 6-4. Block diagram for feedforward-feedback control loop.



and to shut off the blower at 2.0 mg/L. Thus, the DO concentration would be allowed to fluctuate within a "band" about the set-point. This type of controller is called a "dead band" controller and results in a longer cycle time for blower starting and stopping. There is, however, a corresponding decrease in the degree of control.

Usually, however, the control signal is derived from a continuous controller such as a proportional-integral controller. For this controller, the control signal is made up of two components: one proportional to the error and one proportional to the integral of the error. Proportional control alone can result in an offset or steady-state error. The addition of the integral action term (reset) compensates for this error. The mathematical function describing this control signal is:

Change in Control Signal =

$$K_p \text{DO}_{\text{dif}} + \frac{1}{K_I} \int_0^t \text{DO}_{\text{dif}} dt \quad (6-2)$$

where,

DO_{dif} = $\text{DO}_{\text{set-point}} - \text{DO}_{\text{measured}}$
 t = time
 K_p = proportional gain
 K_I = integral time constant

In some control applications where very rapid response is required, a third parameter, the time derivative of the error, $K_D(d\text{DO}_{\text{dif}}/dt)$ (where K_D = derivative time), is added to the above equation. This is then termed a proportional-integral-derivative controller. Usually proportional-integral control is adequate for aeration control schemes.

The "tuning" of the controller involves selecting the controller constants of proportional gain and integral time to obtain the desired corrective action of the controller. Mathematical models and tuning rules as outlined in general control theory references (16-18) can be used to obtain an initial set of constants. However, once the plant is operational, step testing of the system is usually used to refine the estimates for the process gain and reset time. Sometimes, more thorough process identification experimentation may be required to develop a process and disturbance model that can be used to design and optimize the control algorithm.

Generally, for a given set of operating conditions, there is an optimum set of controller parameters. However, for DO concentration control, where the dynamics are nonlinear and time varying, the tuning parameters that are optimum for maintaining control under peak diurnal loading periods may not sustain

that level of control over an extended operating range. A compromise between ideal control and the maintenance of controller stability often results in the controller being "detuned" to a degree to achieve adequate control over a wide range of operating conditions. The controller is then periodically retuned, as necessary, to accommodate gross changes in DO dynamics that can occur on a seasonal basis.

6.3.3 DO Control Strategies

6.3.3.1 Conventional Control

In aeration basins designed to be completely mixed, the oxygen demand is relatively uniform. Therefore, automated control of DO concentration in the basin is based only on feedback from the DO sensor. In many other cases, however, multiple control loops are required to control DO concentration effectively.

As indicated in Section 5.3.1.3b, the spatially-varying oxygen demand along a plug flow reactor requires a nonuniform rate of oxygen transfer to accomplish uniform DO control. For a steady-state condition, this can be achieved by tapering the diffuser density in grids down the length of the basin. Automated air distribution control valves can be installed to regulate the airflow rate to, and maintain the DO concentration in, each grid at a desired set-point. If this is not practical, the air distribution profile can be established with manually-adjusted air distribution valves and the total airflow to the basin automatically regulated to maintain the desired DO profile down the length of the basin (19).

Figure 6-5 shows a typical DO control system for a tapered diffused air delivery, compartmentalized, plug flow aeration basin. A proportional-integral controller determines the required change in airflow needed to restore the DO set-point and "cascades" a set-point for airflow rate to a separate airflow control loop. Because the control loops for each basin operate independently, an increase in airflow to Basin 1 will result in decreased airflow to and decreased DO concentration in Basin 2. The system will attempt to compensate for this at the next control interval. This can result in the controllers continually "hunting" and perhaps even cause instability in the control system.

The addition of a pressure control loop minimizes "hunting." This loop ensures the existence of adequate airflow for both basins and system operating pressure set-point is minimized to achieve maximum energy savings by always maintaining one of the valves in its "most open" position. The control algorithm usually incorporates a minimum allowable airflow set-point to maintain minimum mixing requirements in the reactor.

For modern digital controllers, the timing of the control loop action (control interval) is critical. It must be matched to the time constants of the variables being

controlled to accommodate process dynamics, process dead time, if any, and disturbance or noise in the process or primary measurement signal that should be ignored or rejected. For the case above, the DO controller is the slowest loop in the system. This is because the aeration process dynamics are relatively slow, and it can take up to 30 minutes for the DO to reach a new equilibrium value after a change in airflow has been initiated, even under steady-state conditions. There is little point, therefore, to run the DO control loop more often than once every few minutes.

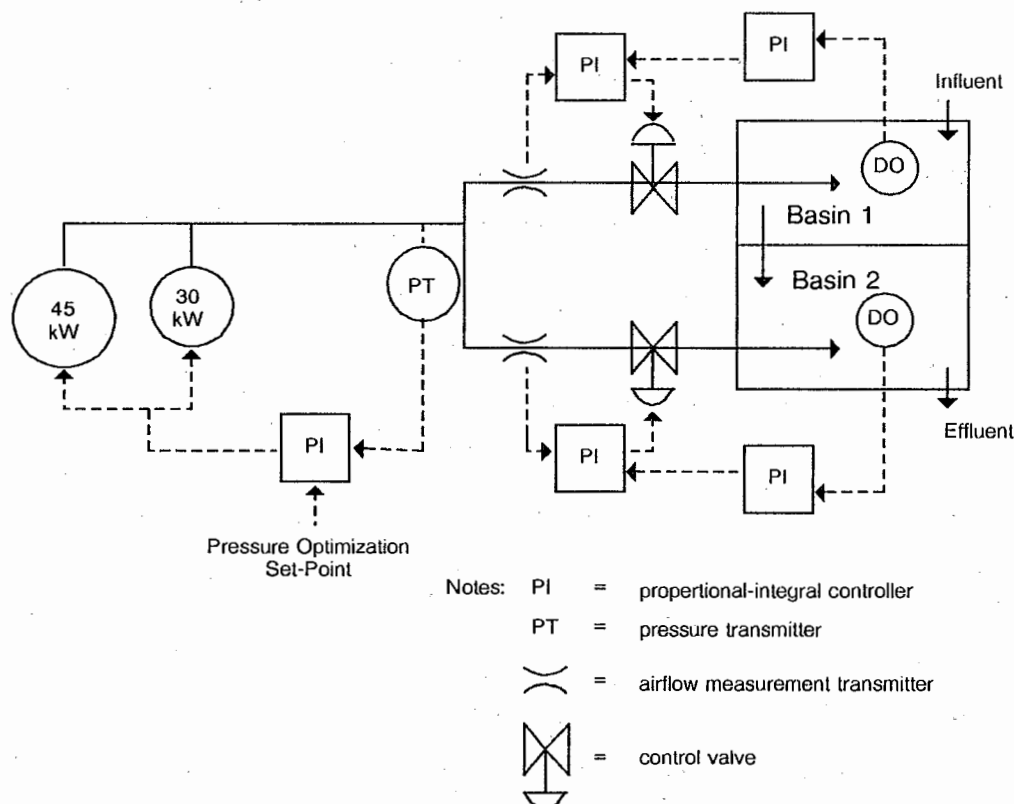
The individual air distribution control loops have a much faster response time, and the control interval may be on the order of several seconds. A pressure optimization control loop will adjust the final control elements on the blowers to regulate the total airflow to the system and maintain the desired system pressure. This controller must account for the disturbances generated by the control valve. The control interval will, therefore, be slower (about 1-2 minutes) than the air distribution control loops, but not as slow as the DO control loop. The proper tuning of these several control loops is necessary to obtain desired system response. This task can become quite tedious because of the various process and controller interactions involved.

6.3.3.2 Advanced Control

Programmable digital controllers have much more flexibility than traditional analog controllers and are widely used today (18). These controllers can readily compensate for the considerable dead time that usually delays the response of the control variable to disturbance or control action. They also facilitate the implementation of more advanced controllers that can extend the empirical engineering solutions exemplified by proportional-integral control. Digital filtering of raw signals from process instruments can eliminate or minimize controller disruption due to signal noise.

The computing power of the digital processor can be used to obtain important additional information about the process from on-line measurements. For example, from the DO mass balance identified above as Equation 6-1, if the relationship between αF ($K_L a$) and airflow rate (see Section 3.4.2.2) was known and the DO controlled, the oxygen uptake rate (r) could be estimated directly from the airflow rate. This would yield valuable process information to the operator on a continuous basis. The accuracy of this estimation depends on the assumption that the parameters in the established αF ($K_L a$)-airflow rate relationship have remained constant over time. In reality, however, the αF ($K_L a$)-airflow rate function may change with time due to changes in α and F , especially for fine pore systems. Therefore, the change in airflow rate may be reflecting a change in αF ($K_L a$) rather than a change in r .

Figure 6-5. Two-stage DO control system for a compartmentalized plug flow aeration train.



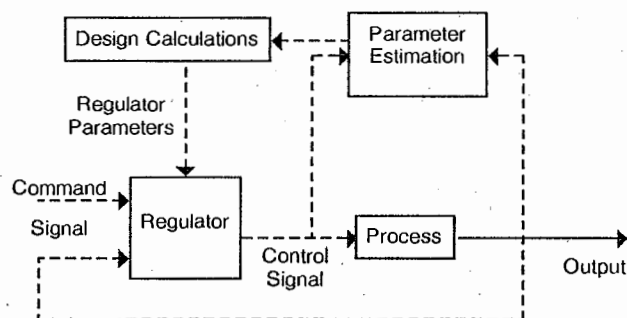
As a result, the $\alpha F(K_L a)$ -airflow relationship must be checked and updated, if necessary, on a continual basis. This information would also be very useful in determining the need for diffuser or air delivery system maintenance. These determinations can be made off-line by monitoring the dynamic response in DO to a change in airflow rate under conditions where r is assumed constant and independent of DO concentration. This can also be conducted on-line by temporarily suspending DO control, "bumping" the airflow rate, monitoring the DO response dynamics, and calculating $\alpha F(K_L a)$ directly. Again, this requires that the respiration rate be constant. The determinations should therefore be made during off-peak loading periods when respiration is assumed to be largely endogenous and relatively constant.

These assumptions, however, may not be entirely correct. A means to distinguish and simultaneously estimate both $\alpha F(K_L a)$ and r is necessary to minimize the errors and maximize the potential of this technique. This has been successfully achieved using advanced control techniques described below.

Advances in industrial process control have led to the development and commercial application of adaptive controllers otherwise known as self-tuning or auto-tuning controllers. With these controllers, the controller tuning parameters can be calculated from measurements of process response to control action

and updated recursively as process conditions and DO dynamics change. The two interacting loops of a self-tuning controller are shown schematically in Figure 6-6. The updated tuning parameters of the conventional controller are obtained either directly or determined from process parameters that have been estimated recursively from the process response (18). This minimizes the effects of time-varying disturbances such as seasonal temperature changes, changes in the oxygen transfer coefficient due to diffuser clogging (F effects), or wastewater composition variation (α effects) on the controller.

Figure 6-6. Block diagram of a self-tuning regulator.



The adaptive controller can be implemented for feedforward-feedback situations and also where the sequential changes in the manipulated variable must

be constrained. This serves to minimize wear due to excessive control action on mechanical components such as motor drives and valves. Self-tuning or adaptive control of DO concentration has been successfully implemented at the Kappala sewage works in Stockholm (20).

Through special handling of an adaptive controller, the need identified above has been addressed and a means developed to estimate simultaneously the process parameters $\alpha F(K_L a)$ and r while maintaining effective DO control (21). Estimation of time-varying parameters requires a high degree of excitation of the system. This contradicts the regulation purpose of the controller, and a compromise must be reached to ensure that the oscillations of the controller are large enough to provide the estimator with parameter information, but small enough to allow for effective DO regulation. The airflow rate is disturbed in every sampling interval, which causes the DO concentration to deviate from its set-point, but yields enough information for the estimator to identify both $\alpha F(K_L a)$ and r .

This successful adaptation has important implications for advanced aeration control. It provides not only an on-line determination of the oxygen uptake rate from measurements of DO concentration and airflow rate, which is useful for process control, but also serves as an on-line monitor of aeration system performance [$\alpha F(K_L a)$]. Changes in the value of $\alpha F(K_L a)$, determined on-line, can indicate both wastewater composition variations (α effects) and diffuser clogging (F effects). These indications could potentially be used to identify plant O&M needs such as diffuser cleaning.

6.4 Control System Components

6.4.1 Instrumentation

The successful operation of installed on-line instrumentation is critical to the successful application of automated aeration control. Incorrectly applied, installed, or maintained instruments can render an otherwise well-designed process control system useless. Not only will the objectives of the control system not be met, but serious and costly operational problems can result. As such, sensors are often considered the weakest link in the control system.

The control strategies discussed in Section 6.3.3 above require DO and, in some cases, airflow rate instrumentation. Other process instrumentation requirements for this application generally include air pressure, air temperature, and air distribution valve actuator position monitors. Instrumentation required to monitor and control blower operation depends on the specific requirements of the blower control system. Functions monitored may include speed, blower inlet

vane or valve position, current or power draw, and suction and discharge temperature and pressure.

The above instruments are all, with the possible exception of DO monitoring, considered standards in the chemical and industrial process control industry. A large body of literature exists concerning the application, installation, calibration, and maintenance of this instrumentation. Some of these references (22-25) are considered "standards" in the industry, and this information should be reviewed in detail before specifying or procuring any of this instrumentation. It is essential that the definitions used to describe instrument characteristics and performance — such as range, span, accuracy, hysteresis, repeatability, sensitivity, dead band, resolution, response time, and drift — be understood to appropriately specify and apply these instruments. Considerations crucial to successful application of the major groups of instrumentation are reviewed briefly below.

6.4.1.1 Dissolved Oxygen

Without doubt, DO monitoring equipment is the most notorious of all on-line sensors used in wastewater treatment. It is most often cited as the main reason for DO control system failure. While system failure may be due to faulty equipment in some cases, it is at least as likely to be due to improper application, poor installation, lack of attention and maintenance by plant personnel, or a combination thereof. These problems usually have at their root a lack of understanding of the instrumentation, insufficient attention to details during the design phase, or lack of commitment to keeping instrumentation operating properly.

a. Principles of Operation

Virtually all DO probes available today are electrochemical cells that contact the fluid through an oxygen-permeable membrane. The oxygen concentration in the cell electrolyte reaches equilibrium with that in the bulk fluid, and a chemical reaction induces a change in voltage across the electrodes. The subsequent current flow across the electrodes produces an electrical signal in proportion to the oxygen content of the fluid. One device has no membrane, and the probe uses the bulk fluid as its electrolyte.

b. Selection and Installation

Instrument selection should only be undertaken after application constraints such as environmental conditions, operating ranges, and design requirements have been identified. Existing comparative instrument test data and the experience of other users under both bench and field conditions should be taken into account (26,27). The user-based, nonprofit North American Water and Wastewater Instrument Testing Association (ITA) conducts structured evaluations in accordance with strict peer-reviewed test protocols. In 1988, ITA completed a comparative test of seven DO

measurement systems. Results are available to members directly from ITA (28).

A field protocol for selecting, locating, and maintaining DO sensors has been developed and, based on a 60-day test of equipment from several manufacturers, specific recommendations regarding probe location, calibration, and maintenance have been offered (27). The manufacturer usually stipulates installation conditions; however, in general, DO sensors should be installed in the aeration basin in a "dip" mode, i.e., directly in contact with the mixed liquor and easily removed and serviced by operations personnel. This minimizes time delays and the maintenance of ancillary equipment associated with flow-through cell configurations. The mounting hardware should be accessible and of a quick-release type to allow for maintenance (27). It is also important to provide flexibility in mounting hardware and signal cabling to permit relocation of the sensor in the basin (10).

c. Field Verification, Calibration, and Maintenance

Each manufacturer has a specific recommended calibration procedure. Usually, it is a simple one- or two-point calibration. As part of the field verification procedure for the installed instrument, accurate output should be verified over the entire expected operating range. Other performance checks, such as response time, hysteresis, and repeatability should also be made.

In the environment of the bioreactor, the tendency for fouling of the membrane is of substantial concern as foulants affect membrane permeability and, hence, the accuracy of the DO measurement. Biofouling in the form of a slimy biofilm is usually the most significant problem. It can usually be effectively removed from the membrane surface by careful wiping with a wet tissue or soaking in a 10-percent HCl solution, thereby restoring probe performance. Mineral deposits or oil can change the permeability of the membrane and are not easily removed by cleaning.

Frequency of cleaning will vary depending on process loading characteristics and operating configuration. To minimize maintenance requirements, it is important to clean the probes only when necessary. Checking the process probe for conformance with a reference probe can indicate when probe servicing is required. The reference probe must be accurately calibrated and have a time response similar to the process probe, and the linearity of both meters must be known.

The frequency for carrying out the conformance procedure can be optimized with experience. Generally, the process probe should not be touched until successive conformance checks show a significant deviation - often taken to be 0.4-0.5 mg/L. The criteria ultimately selected is site specific. Cleaning will normally restore probe performance. If it

does not, intensive recalibration or even replacement of the electrochemical cell may be necessary.

Total annual labor requirements for conformance checks, cleanings, and calibrations for four on-line DO probes are 80-120 labor-hr at one site (29).

6.4.1.2 Airflow Measurement

Airflow monitoring equipment is an important component of most aeration control schemes. Effective distribution of airflow to several points in the aeration basin requires accurate airflow measurement. Determination of mass airflow rate is necessary to ensure the correct quantity of oxygen is being delivered. The importance of this measurement demands that the required instrumentation be carefully selected and installed to maximize the probability that performance expectations will be met.

a. Principles of Operation

The various airflow metering systems widely used today are based either on differential pressure across a control element or mass flow. Differential pressure meters all use the same basic relationship to measure flow rate:

$$\text{Flow Rate} = (\text{Velocity}) (\text{Area}) (\text{Factor}) \quad (6-3)$$

The differences between differential flow meters is largely a function of how the velocity term is determined. Plate orifice and Venturi meters use a constriction to produce a measurable differential head or pressure. This differential pressure is then converted to velocity using fundamentals of mass and energy conservation. To obtain a measurement of mass flow, temperature and pressure corrections must be applied.

Mass flow meters generally operate on the principle of a hot wire anemometer. A wire is placed in the flow stream with an electric current applied to maintain the wire at a preset temperature. The rate of cooling of the wire, based on the current required to maintain it at the preset temperature, is proportional to the mass flow rate of air.

b. Selection and Installation

A large number of airflow instruments are available, each with its own advantages and disadvantages. These are discussed in detail in the references previously cited (22-25). Care must be taken in selecting the airflow meter to not unnecessarily constrain the air delivery system in terms of headloss or turndown requirements. It is also very important that the meter be sized to accommodate only the immediate future expected ranges in airflow. Oversizing and attendant poor flow measurement will occur if the range used to size the meter is based too far into the future.

Careful installation is needed to avoid jeopardizing the performance of an appropriately applied and sized meter. This includes closely following the manufacturer's recommendations for approach and downstream conditions to ensure the accuracy of the velocity determination.

c. Field Verification, Calibration, and Maintenance

The fundamental principles outlined for commissioning and maintaining DO sensors also apply to airflow monitoring equipment. The meter usually comes calibrated to the user's specification from the factory. Once the meter is installed in the system, a conformance check should be made, if possible. Even an approximation of conformance using blower performance curves is worthwhile and can likely be done for the entire range of the meter (30).

Since the sensors are not in contact with wastewater, much less maintenance is required, once their performance is verified, than for DO probes. Periodic conformance checks are recommended, however.

6.4.1.3 Pressure and Temperature

Pressure and temperature measurements are used in the aeration control system to monitor blower suction and discharge conditions. They also provide on-line information for converting volumetric field flow rates to standard flow rates. These instruments are standard throughout the process control industry and are not discussed in detail here. The same fundamentals described for DO and airflow rate measurements concerning selection, verification, calibration, and maintenance apply to these instruments. It is most important to incorporate instruments that are suitable for the environment encountered at a wastewater treatment plant and able to meet the objectives of the application in terms of operating range and performance.

6.4.2 Final Control Elements

The final control elements in any control system are required to carry out the desired control action. For a DO control system, this means adjusting the delivery and distribution of air through manipulation of blowers and air control valves.

6.4.2.1 Air Delivery Blowers

The two major classifications of blowers normally used in aeration control systems are rotary lobe positive displacement (PD) blowers and centrifugal blowers. The operating and performance characteristics of each have been identified in Section 5.5.3. Additional details are available elsewhere (10,19,31,32).

The effective and efficient control of the blower or blowers in an aeration control system is almost totally dependent on good design. The blowers must be sized such that an operating map of the air delivery system not only meets the expected variations in process air requirements, but also maximizes blower

efficiency throughout the delivery range (see Sections 5.5.3, 5.5.5.3, and 6.5). The control system must be designed to not only minimize unnecessary disturbances in airflow rate and DO concentration, but also to maximize the energy savings extracted from variable air delivery. The control strategies for the two different classes of blowers are different because of their principles of operation.

a. Positive Displacement Blowers

As indicated in Chapter 5, the PD blower is essentially a constant-volume, variable-pressure machine. The pressure the blower runs at is dictated by system requirements. Historically, changing the number of blowers in service and controlling blowers with multiple-speed motors were the only options for controlling PD blowers. Today, use of a variable-frequency a.c. drive also allows the PD blower to run as a variable-volume, variable-pressure machine. Controlling and saving airflow, however, must translate into energy savings. Variable-frequency drives can consume up to 10 percent of the energy applied as heat. This premium must be considered carefully as, sometimes, it can quickly effect the economic incentive for automated DO control.

From an operations viewpoint, the variable-frequency drive should not be permitted to lower the blower speed below the manufacturers recommended limit. Less heat dissipation at lower-than-recommended speed could result in overheating of and damage to the blower. At the other end of the speed scale, most a.c. variable-frequency drives can operate at 110 percent of normal frequency, thereby increasing motor speed and, hence, blower speed by 10 percent overall. While this places a greater load on the motor and consumes additional energy, it is one way to increase the capacity and operational flexibility of the PD blower.

It is very important that the blower and drive manufacturers understand, in detail, the application, control strategy, and anticipated operating conditions of the air delivery system. This ensures proper integration of appropriately sized motors, drives, and monitoring instrumentation.

b. Centrifugal Blowers

Usually, the volume output from centrifugal blowers is manipulated by adjusting speed or inlet guide vanes, or throttling either the inlet or outlet valves. These approaches vary in terms of difficulty, energy efficiency, reliability, and effect on stability (see Table 5-3). The control of these blowers is also complicated by the need to stay between the low output operating limit or surge point and the maximum blower hydraulic limit. Often, large, complex blower packages come with built-in controls to prevent surge conditions. Detailed explanations of various types of centrifugal blower control schemes are available elsewhere (10,19,31,33).

The same degree of involvement of the manufacturer with the designer and instrumentation and control specialist as for a PD blower application is also essential for centrifugal blowers.

6.4.2.2 Air Distribution

Control valves are used to distribute air to aeration basins, headers, and grids. Control valves are designed to maintain a relationship between airflow rate through the valve and valve travel as it is varied from 0 to 100 percent of its "most open" position. Valves are thus characterized to provide relatively uniform control loop stability over the expected operating range.

A valve with a linear flow characteristic yields an airflow rate that is directly proportional to valve travel. For an equal-percentage valve, equal increments of valve travel produce equal percentage changes in the existing flow. Equal-percentage valves are typically used on pressure control applications where a large percentage of the pressure drop is normally absorbed by the system itself, with only a small amount available at the valve.

The sizing of valves, not unlike airflow meters, is critical for good air distribution control. The valve should be sized to control over the immediately foreseeable operating range. In some cases, valves with replaceable "trim" are available, which provides the flexibility to handle different ranges of flows.

A valve and actuator may have a degree of hysteresis associated with their response to a control signal. Hysteresis is a measure of the difference in the valve response for a particular input signal, depending on whether the new position was approached from a more open or more closed position. If such a condition exists, it must be accommodated in the control algorithm to obtain good control.

It is also important to note that, while the valves should always be maintained as open as possible to minimize overall system pressure and aeration energy expenditure, it is necessary to sacrifice some headloss to have control. This trade-off requires constant balancing. Energy losses due to increased headloss can be minimized with properly sized and applied valves. The air distribution designer should work with the valve supplier applications engineer in selecting and specifying these valves and their operating characteristics.

6.4.3 Controller

Control hardware changes so rapidly it is difficult to stay current with available equipment options. In the past, real-time minicomputers were the only realistic option for on-line process control of a treatment plant. Now, desktop microcomputers are capable of the same if not a better level of control when coupled with industrial programmable logic controllers in a

distributed network. Industrial programmable logic controllers are much more sophisticated in terms of digital control than they were just 2 or 3 years ago. As a result, the distributed system offers a high degree of reliability and control capability.

An in-depth discussion and evolution of control hardware is beyond the scope of this manual. Manual of Practice SM-5 (34) is an excellent reference for details on the types of control system options now available.

6.4.4 Software

A detailed discussion of the software required for an effective automated aeration control system is beyond the scope of this document. Manual of Practice SM-5 (34) is a good primer on software categories and the important characteristics of each. Generally, software is classified as "system" software and "application" software. System software controls and directs operation of the computer and supports operation of the application software. It includes the computer operating system software, programming languages, and utility programs.

Application software performs specific tasks required by the user. This includes process control tasks ranging from simple pump scheduling to more complex tasks such as on-line, sensor-based DO control, solids retention time (SRT) or solids inventory control, and energy optimization. Generic control packages, off-the-shelf packages for data base management, spreadsheets, word processors, and preventive maintenance packages are also types of application software.

The desired control strategy cannot be effectively implemented if the application software designed to achieve real-time control of process operations such as aeration is faulty. Careful attention to the following general considerations will ensure successful implementation and effective use of the control system by the plant operating staff.

Requirements for the application software should be clearly stated and understood by the designer, control and instrumentation specialists, O&M personnel, and computer specialists and programmers. Employing a team approach to define and design process control goals and strategies, operator interface with the data acquisition and control system, and reporting systems is recommended. The team should also select and specify appropriate computer/controller hardware, system software, and on-line instrumentation. The software must be designed to be flexible and "user-friendly." Wherever possible, the software should also be designed to be modular, menu- or graphics-driven, and easily modified. This requires the continual involvement of the users in the design and implementation of software.

Software documentation must be accurate, complete, and readily understood. The "Operations Manual" and "Computer Control System Manual" should be compatible and include, for each application, "readable" process and control narratives; control loop block diagrams that identify the specific instrumentation and control hardware to be used; technical guidelines for data acquisition, manipulation, and storage; interlink maps and diagrams of various computers, controllers, and system software; and examples of the graphics interfaces and report templates. Finally, extensive user/operator-interface documentation is required to illustrate how to: 1) change set-points, scales or ranges of instrumentation inputs, and control loop and controller parameters, and 2) use the control system in general.

It is important that the control system be designed to permit override or suspension of automated control and allow manual operation. Further, the control system should default to a safe operating condition that maintains process integrity in the event of control system failure. For example, air distribution valve positioners should default to open the air valves if the system fails, with the valves then being operated manually until the problem is corrected.

6.5 Aeration Control Example

The example design presented in Chapter 5 for the air diffusion and supply system of a plug flow activated sludge plant will be expanded to illustrate the design considerations necessary for the successful incorporation of an effective aeration control system.

The general layout of the process air piping for this example is presented in Figure 5-14. For this design, the diffusers in each plug flow reactor are arranged in three grids or zones to allow for adjustment of airflow down the length of the reactor to more closely match the anticipated spatial oxygen demands. As stated previously, the degree of aeration control implemented can generally range from the extremes of very infrequent manual manipulation based on manual measurements to comprehensive, automated, set-point DO concentration control. These options also exist for this example.

Ideally, a set-point DO concentration would be maintained under dynamic loading conditions in each of the 12 aeration zones shown in Figure 5-14 by automatically configuring the blower system to efficiently meet total air requirements and manipulating the air distribution control valves to vary the air delivery rate to each aeration zone. This would result in a rather complex control system. The least complex control system for this example would automatically manipulate the blower configuration and total air output to the four aeration trains based on maintaining a desired DO set-point at one point in one of the reactors. The desired DO concentration profile along

the length of each reactor would be maintained by periodically manually adjusting air delivery to each zone.

For this example design, several control options lie between these extremes, each representing a compromise between the level of control achievable and the complexity and cost of the control system. These options are outlined in further detail below.

6.5.1 Air Delivery Control

For this example, the basic air delivery control hardware requirements are similar for virtually all anticipated control options. The four 1,320-L/s (2,800-scfm) blowers selected in Chapter 5 were sized to accommodate the diurnal, seasonal, and yearly variations in total air requirements expected when the plant reaches its design loading. The air delivery control strategy for any option considered would continually optimize the number of blowers in service and their operating points to efficiently deliver the total air required at any time in the design life of the facility. This strategy is essential to achieve the goal of maximized energy savings through effective airflow control. Often, a well-designed control system maintains DO concentration set-points as desired, but, because of inefficient operation of the blowers, does not realize its full potential aeration energy savings.

6.5.1.1 Blower Operating Map

Manufacturer blower curves should be used to develop a detailed operating map for configuring the number of blowers in service and their individual or collective operating points to achieve the most efficient air delivery possible at all times. This map should incorporate the effects of environmental conditions such as temperature and humidity. Once the blowers are installed, it is possible to fine tune this operating map and determine any site-specific operating limitations through measurements of temperature, humidity, pressure rise, power draw, speed, and overall airflow.

Mathematical and empirical relationships incorporating these parameters can be used to optimize the on-line configuring of the air delivery system. The blower manufacturer application engineer should be requested to confirm the most efficient operating configurations to meet any operating set-point. Any operating limits or restrictions identified by the application engineer should be strictly observed.

6.5.1.2 Start/Stop Control

For any aeration system, careful attention must be given to blower start/stop control. A well-designed automated control system is able to use the maximum range of a blower, or combination of blowers, to minimize the necessity of bringing on-line or taking off-line additional blowers. Implementation of automatic start/stop of blowers is straightforward. In some control systems, however, operator approval is

a required additional judgement step prior to start-up or nonemergency shutdown of any blower to minimize starting and stopping of blowers. In other cases, the control system only flags the need for bringing additional blowers on-line or taking some off-line and the actual operation is carried out manually.

To minimize operational problems, a blower (whether automatically or manually initiated and controlled) is usually started off-line and brought up to operating conditions by delivering air through either a recycle loop or vent valve. Only then are the appropriate isolation valves manipulated to allow the blower to discharge into the common header and be integrated into the control loop. Under certain operating and start-up conditions, the main header operating pressure may have to be reduced to permit the blower to open its check valve and come on-line. In addition, to minimize energy demand charges, it is often necessary to reduce air delivery, and thereby power consumption, of the running blowers prior to bringing a new blower on-line. Finally, the control strategy must respect any restrictions on minimum run time and time between starts.

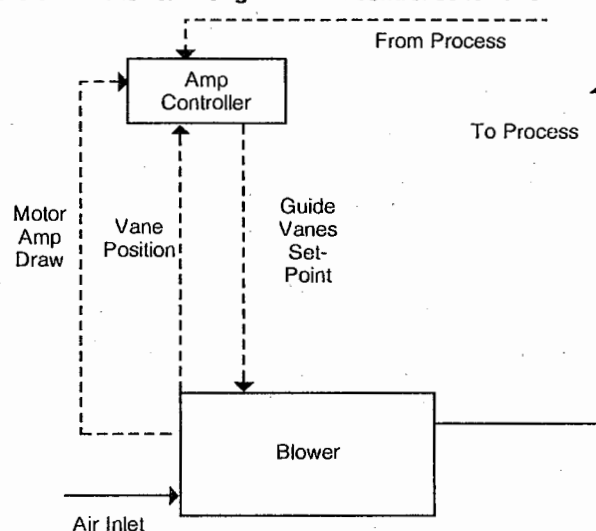
The above considerations are machine and facility specific. For the design example, specific operating requirements for the selected blowers would be incorporated in the initial control software design. They would be fine tuned following system start-up and after a modest level of operating experience had been obtained.

6.5.1.3 Variable Capacity Control

For this example, the variable delivery capacity of the operating blowers will be controlled by adjusting the blower inlet guide vanes. The selected aeration system is designed to operate at relatively constant system pressure, which results in a nonlinear relationship between guide vane position and blower throughput. However, blower power draw or motor amperage vs. throughput is nearly a linear relationship and will be used to control the inlet guide vanes as shown generically in Figure 6-7 for one of the four blowers.

Where multiple air valves are manipulated by independent automatic DO controllers, generally in more complex control systems, a main header pressure controller is added to minimize the disturbance of air distribution control on the blower controller. The pressure controller cascades the amperage or power draw set-point to the amp controller as shown in Figure 6-8 for one of the four blowers. The addition of a variable pressure set-point optimization routine to further maximize aeration energy savings by always minimizing the header operating pressure may be justified in this case. However, because of the relatively small size of the blowers in this example, this refinement would most likely be justifiable only after the design capacity of

Figure 6-7. Blower inlet guide vane control schematic.



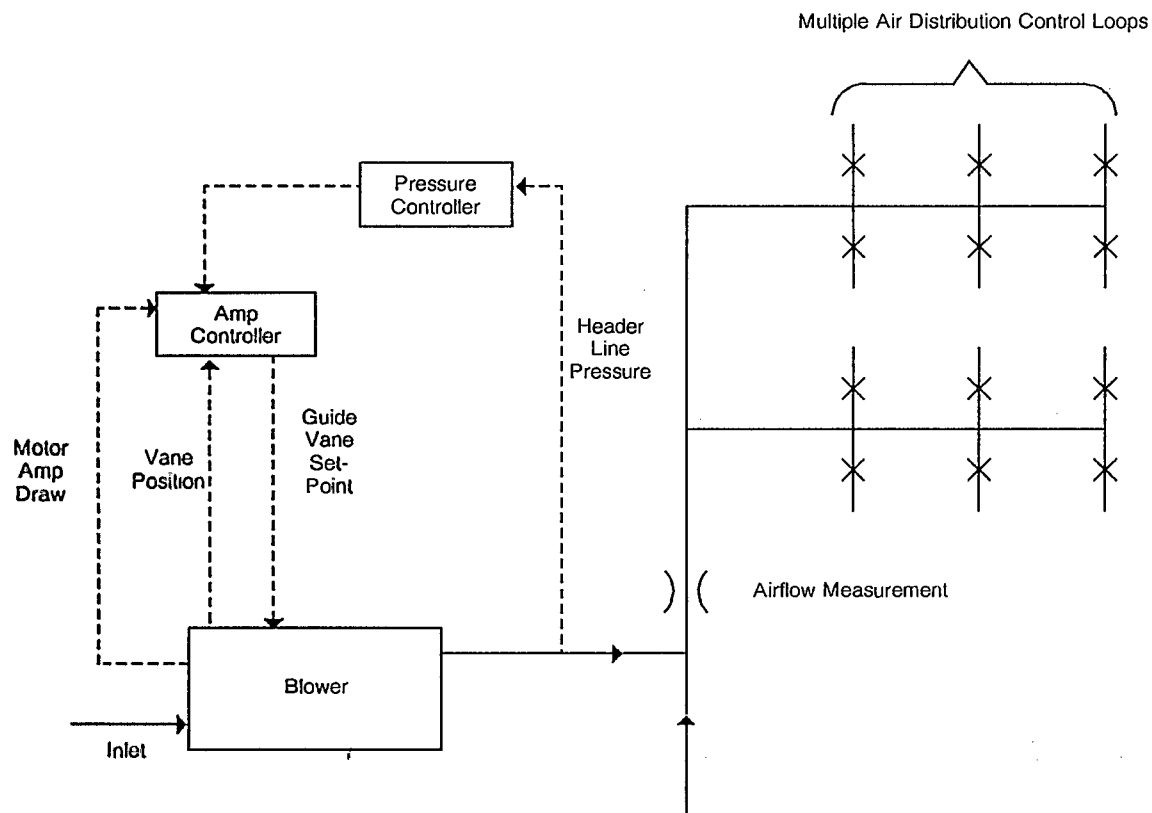
the plant was being approached and operation of three blowers was required to meet the normal oxygen demand.

6.5.1.4 Surge Protection

When a centrifugal blower cannot develop enough pressure to overcome the downstream process pressure, the blower can begin to surge - a condition in which momentary reversible pulsing of air occurs inside the compressor. Since this condition can be particularly destructive to centrifugal blowers, surge protection is essential. Most blower manufacturers provide independent surge protection control systems; however, additional levels of surge protection can, and should, be incorporated in the overall blower control algorithm. Surge can occur at certain high-pressure or low-throughput conditions. Therefore, careful attention to the interaction between air distribution and air delivery controllers is necessary to minimize line pressure.

A minimum blower amperage limitation that corresponds to the above critical operating conditions is often used for surge protection. However, when inlet guide vanes are manipulated to control centrifugal blower delivery, as in this example, the surge point varies with each guide vane setting. Typically, when guide vanes are manipulated to reduce blower throughput, the motor amperage draw corresponding to the surge point is also reduced. Care must be taken, therefore, not to set the absolute minimum amperage too high, thereby reducing effective blower turndown under normal operating conditions. The relationship between guide vane position and surge point amperage draw is often nonlinear over the range of guide vane operation. Once established, it can be used with on-line measurements of blower differential pressure or

Figure 6-8. Blower control schematic.



individual blower discharge airflow to predict and appropriately update safe operating limits.

6.5.1.5 Blower Performance Evaluation

Provisions necessary to periodically evaluate the performance of the blower control system should be incorporated in the initial design. This is particularly important in this case where multiple blowers operate in parallel. At various periods in the plant design life, the operating objective may be to either balance the load among blowers or maximize air delivery overall efficiency in accordance with the operating map. To confirm that these objectives are being achieved, provisions for measuring individual blower operating parameters must be made. This requires inclusion of appropriately located standard pipe taps in the suction and discharge piping of individual blowers to facilitate temporary installation of instrumentation for measuring such variables as temperature, pressure, and airflow rate. These data provide a means for assessing individual machine as well as overall system performance.

6.5.2 Air Distribution Control

Control valves are required for effective distribution of air to the individual zones in each aeration train and,

depending on the control system, to the aeration trains themselves. Whether automatically or manually adjusted, the valves must be properly sized and of a type suitable to minimize pressure headloss, yet maintain controllability over their anticipated ranges of airflow. The manufacturer applications engineer should be consulted to ensure that type, size, and flow control characteristics are compatible with control objectives over the anticipated design life of the plant. For automated control, electric or pneumatic valve actuators, complete with positioners, where necessary, are used in place of manual hand operators.

To illustrate how the design of the air distribution control system can be incorporated into the overall aeration system design (see Figure 5-14 for air delivery system layout), two control options are outlined below for the design example. The first represents a low-complexity option, and the second a moderate-complexity control option. A third control scheme, not recommended for this size plant, is also presented to show a high-complexity control strategy that could be considered for large plants. These options are presented to illustrate the various degrees to which aeration control can be implemented. The specific features of any option could be integrated to

generate a modified, i.e., a more- or less-complex control scheme, as appropriate.

6.5.2.1 Low-Complexity Control Strategy

The least-complex control strategy for this example involves manipulating the blower configuration and total aeration output to the four reactors to maintain a desired set-point DO concentration at one location in one aeration basin. Initially, Zone 2 is selected for the DO probe location for this control measurement. Zone 3 is not selected because load changes and changes in system oxygen demand may not always be detected in this zone or will be detected too late to respond to changes in DO concentration in Zones 1 and 2. Zone 1 is not selected because DO changes typically occur more rapidly here than further down the tank and may result in unnecessary or erroneous corrections to airflow in Zones 2 and 3. This is discussed further in Section 6.5.3.

A proportional-integral DO controller cascades the airflow set-point to the air demand controller, which regulates the blower output through the manipulation of inlet guide vanes to maintain an amperage set-point as outlined in Section 6.5.1.3. The operator would strive to maintain an acceptable DO concentration profile along the length of the reactors by periodically manipulating the aeration grid distribution valves manually to adjust air delivery to other aeration zones. In this option, careful operator attention is required to maintain the distribution valves in their collective "most open" positions to minimize air header pressure.

The control loops for this option are shown schematically in Figure 6-9. The blowers are operated by the control system to respond to variable oxygen demands. The number of on-line blowers depends on the load to the plant. Bringing blowers on-line or taking them off-line is carried out automatically upon receiving an on/off signal from the air demand controller.

The blower system operating map would be used to determine control of the on-line blowers to achieve optimum energy efficiency. This may be accomplished most effectively by controlling all on-line blowers with the same signal from the air demand controller. This strategy controls all on-line blowers at the same operating point while matching the variable total airflow demand.

Alternatively, one blower could be operated by the control system to respond to variable oxygen demands and one or more of the other blowers operated at constant output to provide a "base supply" of air. Periodic substitution of a different blower to serve as the variable delivery blower allows for load balancing and accommodates maintenance requirements. The blower manufacturer application engineer should be consulted to ensure that the

envisioned control strategy achieves the control objectives.

It may be desirable to initially override part of the automated control of the blowers and allow the operating staff to manually control certain aspects of the blower system operation. This could be accomplished by providing the controller output information to the operator who would in turn make the required adjustments to guide vanes and the bringing on-line or taking off-line of blowers. As the level of comfort with the control system increases, fully automated control could be implemented on a staged basis.

This control strategy assumes the four parallel aeration basins are operated to achieve uniform spatial and temporal oxygen demand profiles and that by similarly adjusting the air distribution valves in the parallel zones, an acceptable DO profile can be obtained in each aeration basin. However, even though the aeration basins are operated in parallel, it is unlikely they will perform identically.

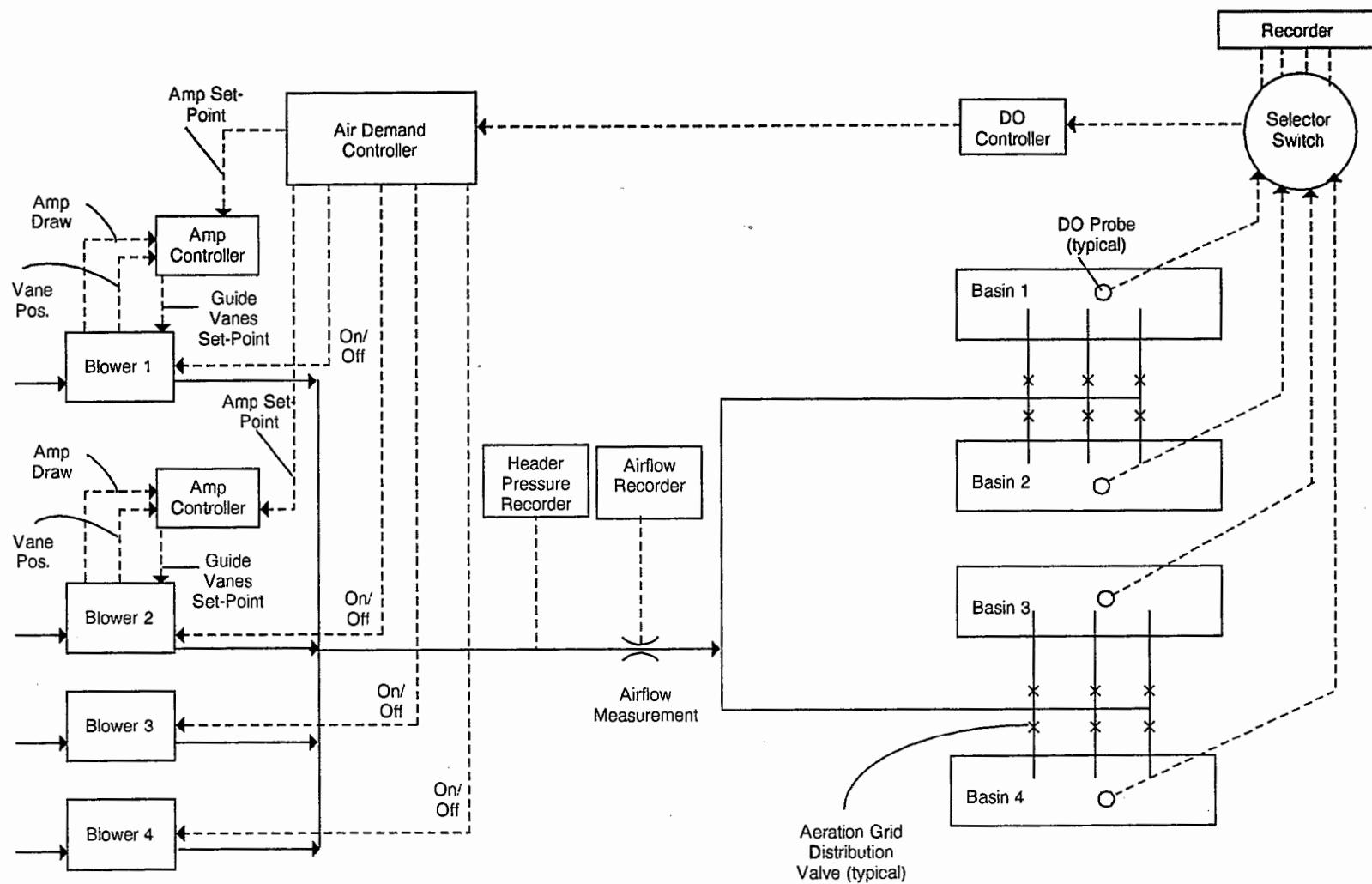
An important assumption inherent in this strategy is that the system hydraulic design results in equal wastewater flow distribution and that air system headlosses are very close, if not equal, for each aeration basin. Since the diffusers may have different operating and cleaning schedules, DWPs could vary from basin to basin. Different levels of fouling of the diffusers in each zone would also result in different OTEs and affect DO dynamics between basins. This may make it difficult for the operator to continuously maintain a uniform DO concentration profile in all aeration basins and emphasizes the importance of monitoring DO in all basins.

Ideally, an on-line DO sensor would be provided for each aeration zone (a total of 12 sensors) to optimize monitoring of system DO concentration dynamics. However, for reasons outlined in Section 6.4.1, it may be appropriate to reduce, at least initially, on-line probes to a number with which O&M personnel are comfortable.

DO monitoring can be accomplished by placing DO probes with a continuous readout in the other three basins at the same location as the DO probe in the control basin. This design permits any of the four readout probes and their respective basins to serve as the DO control system depending on which basins are out of service for cleaning. This arrangement also allows any of the basins to be removed from service during low-loading periods.

A calibrated portable DO probe can be used by the operator to monitor and maintain desired DO levels in those sections of the system not served by on-line meters. As acceptance of the on-line instrumentation and the comfort level of the plant staff increases,

Figure 6-9. Low-complexity control schematic.



additional on-line probes could be added. It is important that hardware and software provisions for easily accommodating expanded monitoring capability be incorporated in the control system design.

The tuning of the rather coarse aeration controller recommended for this low-complexity strategy would be carried out as identified in Section 6.3.2.2. Selection of the final DO feedback location and set-point would be adjusted following system start-up and after process response was known.

6.5.2.2 Moderate-Complexity Control Strategy

A moderate-complexity control strategy is described here as an alternative to the low-complexity control system to provide more exact DO control in each basin. This system also facilitates more accurate control of airflow to each basin by using individual DO set-points, controllers, airflow control valves, and air headers for each basin.

The basic controller design is shown schematically in Figure 6-10. The major difference between this design and the low-complexity control system is that each aeration basin is provided with its own separately controlled air distribution header. Thus, the air control systems for the four basins are independent of each other, and the need to assume, or dictate, that adjacent aeration basins are operated identically is eliminated. The control of the DO concentration profile in each aeration basin would be similar to that described in the low-complexity example.

One measurement of DO concentration initially in Zone 2 of each aeration basin would provide feedback to the airflow controller for that basin. Again, as indicated in the low-complexity example, it would be ideal to monitor the DO concentration in each of the other zones with on-line probes. However, the DO concentration could, initially at least, be monitored with a portable DO probe and meter in the other zones. Periodic manual adjustment of the air distribution valves in the individual aeration zones maintains the desired DO concentration profile. This would be easier to achieve than in the previous case outlined because of the greater independence of the four aeration control systems. As before, the operator would strive to keep the air distribution valves as collectively open as possible to minimize header pressure.

Automated valves located in the four individual headers distribute the total blower output to the four aeration basins. At least one of these valves is always maintained in its "most open" position to minimize the main air header pressure. A pressure controller located in the main header regulates blower output by manipulating the inlet guide vanes as described above. The same considerations regarding blower

control options for achieving optimum system efficiency apply to this control strategy as well.

For this strategy, implementation of fully-automated air distribution control could also be staged to build operator confidence. Initially, the control strategy would be simplified. The operator would designate the basin with the highest oxygen demand as the "control basin" and use the output from the DO controller in that basin to manually set its air header distribution valve in its "most open" position. The DO controllers for the other three basins would automatically adjust their respective air distribution header control valves to maintain the desired DO set-point in their respective basins.

Implementation of the four airflow controllers shown in Figure 6-10 could be postponed and the DO controllers used to manipulate the air distribution control valves directly. As before, the manual aeration grid distribution valves in each basin would be adjusted by the operator to achieve the desired profile. The output from the DO controller with the manually-controlled header valve would be used to control the blowers by providing the set-point for an air demand controller, as shown in Figure 6-9. Installation of the pressure controller shown in Figure 6-10 would also be postponed. Once experience is gained with, and the operating staff has accepted automated control of, the air header distribution control valves, full automated control of the air distribution system can be implemented, if desired.

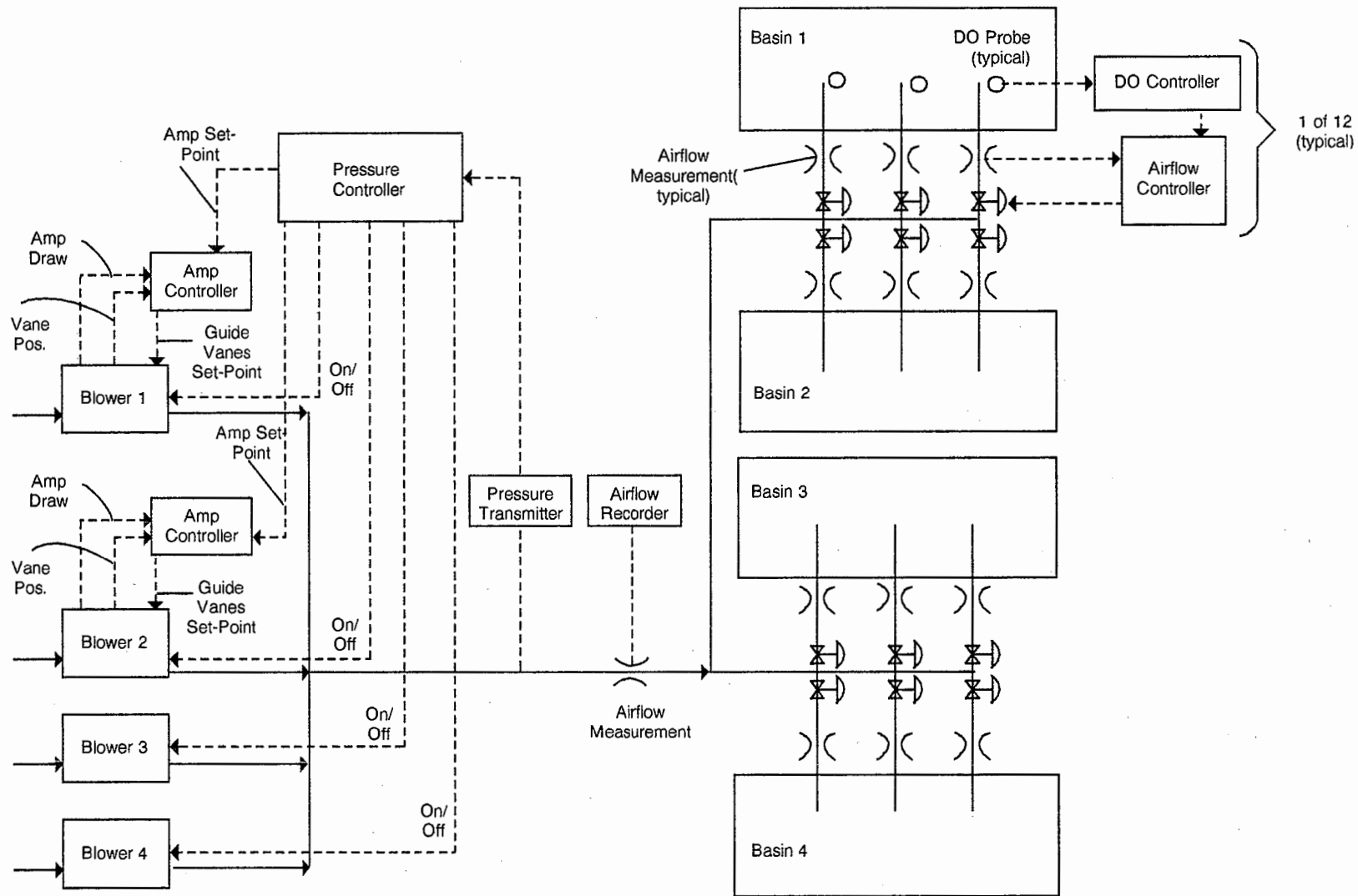
6.5.2.3 High-Complexity Control Strategy

A more complex controller design option for an aeration system configuration similar to the one used in this example provides independent set-point control of DO concentration in each zone or grid of each of the four parallel aeration basins. This control strategy would normally be considered only for a much larger plant (>890 L/s [20 mgd]) as it is probably not cost effective for the plant size used in this design example. This system uses: 1) 12 cascaded DO concentration/airflow control loops to control the air to each zone, and 2) a main air header pressure controller to regulate blower output through manipulation of inlet guide vanes to maintain an amperage set-point (as outlined in Section 6.5.1.3), and the number of on-line blowers. The control system is shown schematically in Figure 6-11.

The complexity of this control scheme requires that additional instrumentation and final control elements be provided. Besides the 12 DO sensors, airflow measurement (standard conditions) is required for each zone. An automated actuator/positioner is also required for each aeration grid distribution control valve. These valves must be appropriately selected, sized, and located to achieve the necessary control action.



Figure 6-11. High-complexity control schematic.



In each of the control strategies described above, tuning of control parameters and selection of control loop intervals are critical. The control intervals will be on the order of those identified in Section 6.3.3.1 (e.g., 20 minutes for the DO control loop, 30 seconds for the airflow control loop, and 3 minutes for the pressure control loop). Fine tuning of overall control performance will be required once the process is on-line and operating at desired DO concentration set-points.

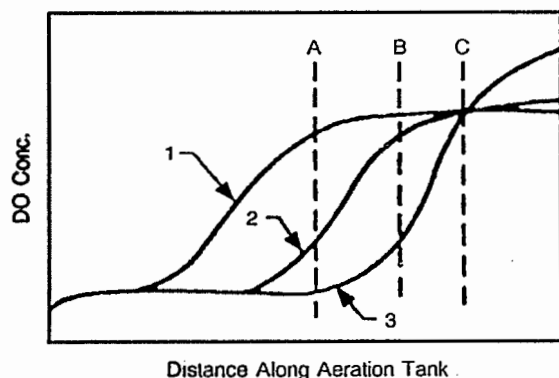
6.5.3 DO Probe Location and DO Set-Point

The selection of DO concentration control points and set-points is a major consideration in the successful operation of any DO/airflow control system. As outlined previously in this chapter and in Chapters 3 and 4, selection of the operating DO concentration affects process performance and aeration efficiency.

In two of the cases outlined above, DO concentration is set and controlled at only one point in the plug flow reactor and airflow distribution is manually adjusted to maintain an acceptable DO concentration profile. The DO profile is dynamic, changing in response to influent concentration and hydraulic load variations throughout the day.

The limitations of having only one DO concentration reading in a plug flow reactor are illustrated in Figure 6-12 (35). In this example, three different shapes of the profile could exist if DO is measured only at Point C. If Profile 2 is the desired profile for optimum process performance, Profile 1 suggests the biological reactions have been completed too soon, with a corresponding wastage of air. Conversely, Profile 3 suggests the reactions have not been completed in the desired time. The use of three on-line DO measurements (i.e., Point C plus Points A and B) provides valuable additional information, particularly near the area of the inflection point in the DO profile.

Figure 6-12. Significance of additional DO measuring probes on interpolation of DO profile.



For Profile 1, the early completion of the reactions and corresponding wastage of energy are confirmed by the high value of DO at Point A. Point A on Profile 2 suggests partial completion of the biological reactions with neither underaeration or overaeration at this location in the basin, while Points B and C indicate the reactions have been substantially completed for a long enough period to achieve both good process removals and sludge settleability. On the other hand, the DO readings on Profile 3 would seem to indicate either excessive process loading or underaeration, or both, in the critical middle segment of the reactor.

This analysis (35) illustrates the considerations that must be taken into account when trying to maintain an acceptable residual DO profile in a plug flow reactor. Further, the profiles in Figure 6-12 show that an estimate of the profile slope, based on two or three DO probes placed near the outlet end of the aeration basin, would be a better feedback variable than a measurement from a single DO probe. This could be easily implemented using modern microprocessor-based controllers and the reliable DO monitoring instrumentation available today.

For this example, if 12 probes are provided initially, the three probes in each basin should be used in the early phase of operation to adequately define the location and profile of the DO inflection curve. These data can then be used to adjust process operating parameters as required. The DO set-point should be high enough to ensure that variations in DO in other parts of the basin (primarily in Zone 1), which result from this relatively high variance control strategy, do not become rate limiting for extended periods of time. Once the process has been fine tuned and is performing satisfactorily on a consistent basis, the optimum location of the probes can be determined. Subsequent significant changes in process operating conditions may require reestablishment of optimum probe locations.

In the more complex control strategy, the controller is designed to maintain a DO concentration set-point in each zone. The DO set-point values are selected to maintain the lowest possible DO concentration residuals without adversely affecting treatment performance. To achieve nitrification, higher set-points may be required than would be necessary to meet nonnitrifying requirements. In this case, the reduced variance of the controller permits tighter DO set-points to be maintained without adversely affecting performance. The traditional assumption that DO set-points should always remain constant may not be valid (20,36). Site-specific operating experience is necessary to determine the most appropriate DO set-point values.

6.6 Experiences with Automated Aeration Control

Incorporation of automated aeration control systems in wastewater treatment plants has been reported for a number of cases (6,7,10,12-14,19,29,33,37). The DO concentration control schemes employed at 12 wastewater treatment facilities, in sizes of 44-7,000 L/s (1-160 mgd), have been described and reviewed in detail (10). The results achieved at these 12 facilities have been further summarized (38). In this summary, and in almost all other cases cited where the aeration control systems were well-designed, properly implemented, and well maintained, significant aeration energy savings and improved process efficiency resulted.

Where automated control systems were inappropriately designed, improperly implemented, or poorly maintained, problems occurred that often led to the abandonment of the system. These problems included inability to control DO because of low plant loadings, limitations in blower turnaround capacity, oversized air distribution control valves accompanied by ineffective air distribution control, inadequate mixing, operator indifference, system complexity, instrumentation failure, and high instrumentation maintenance.

Many of these experiences occurred 10-15 years ago when microprocessor-based control technology was in its infancy and on-line instrumentation was less reliable. The more recent successful applications have resulted from advances in control hardware technology and control strategy development, improved on-line instrumentation reliability, a greater understanding of the control process, and greater interaction between design and control specialists and end users. Several recent examples of successful implementation of automated airflow/DO control are described below.

6.6.1 Piscataway, MD

A computer-based process control system at the Washington Suburban Sanitary Commission (WSSC) activated sludge plant in Piscataway, MD, has been operating successfully since 1981 (39). The plant has a design capacity of 1,315 L/s (30 mgd) and an average flow of approximately 50 percent of design. The process includes primary clarification followed by first-stage activated sludge treatment for carbonaceous BOD₅ removal and second-stage activated sludge treatment for nitrification and phosphorus removal. The computer control system is capable of continuous and sequential control of all major unit processes and equipment in the second-stage (nitrification) treatment train.

Operating experience has shown that computer-based control of the nitrification aeration system is economical. The system functions without major

problems. Nitrification aeration energy costs have been reduced by 34 percent as compared with manual control. No adverse effects on the treatment process have been reported.

The nitrification aeration system consists of two four-pass, plug flow (or step feed) aeration basins. Air is supplied by four 10-m³/s (21,190-scfm), 500-kW (670-hp) centrifugal blowers discharging into a common header from where it is distributed into the aeration basins through coarse bubble diffusers. The control system and strategy are very similar to those outlined for the design example in Section 6.5. The blower control strategy is virtually identical to that described in Section 6.5.1. Inlet throttling valves are employed to control blower capacity using the control strategy illustrated in Figure 6-8. The computerized blower controller, which provides surge protection and automatic start-up, has resulted in continuous, safe aeration system operation.

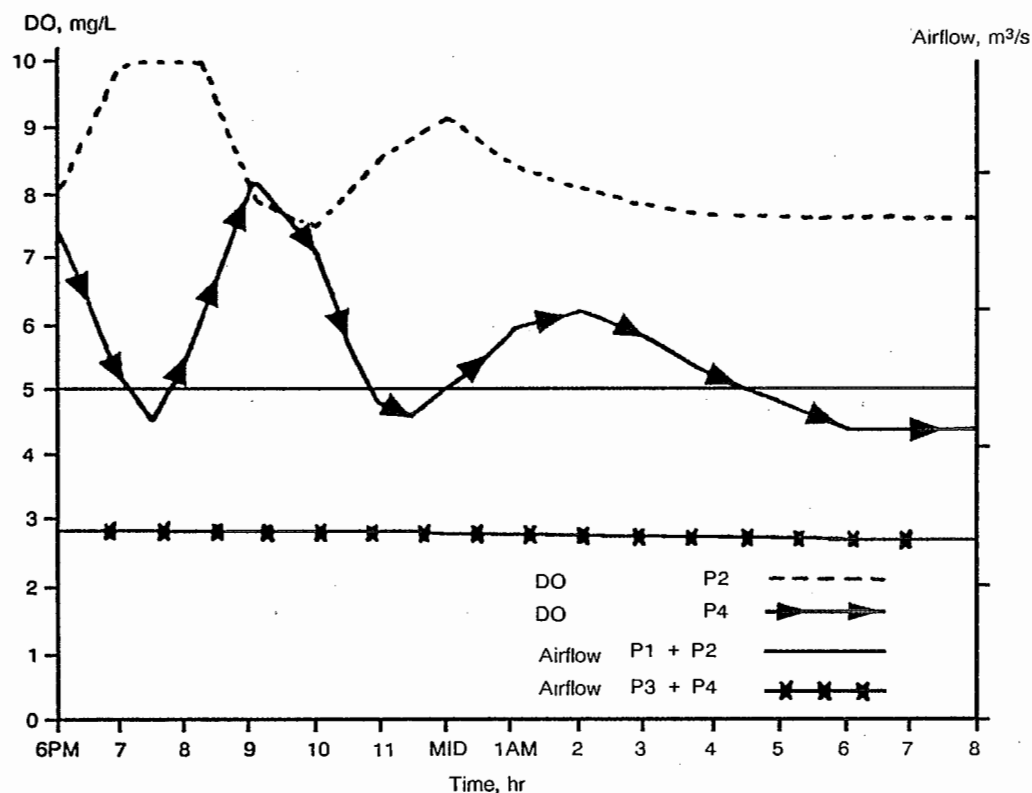
The basic design of the air distribution controller utilized to maintain DO set-points is similar to that shown in Figure 6-10. However, in this case Basins 1 and 2 (Figure 6-10) are actually equivalent to the first two and last two passes, respectively, of one 4-pass aeration basin. Each pair of passes is supplied with air through a separate air distribution header. DO probes are located in the second and fourth passes in each aeration basin. The controller incorporates a minimum airflow set-point to maintain adequate mixing. The controller successfully maintains DO at the desired set-points (± 0.1 mg/L).

The system was initially commissioned with manual control and full computer monitoring. During this period, plant staff became familiar with the on-line instrumentation and process operation. This was followed by full computer control during the day shift of the normal work week and finally with 24-hr automated control. The plant is run by 33 operators, 13 electromechanical maintenance personnel, and 2 instrument technicians. An instrument service company provides assistance, as required, under contract to WSSC. The computer system is maintained by two data processing personnel. The instrumentation technicians and data processing personnel are considered essential to the successful operation of the automated control system.

During the period of manual control, airflows to Passes 1 and 2 and Passes 3 and 4 were periodically manually adjusted and the resulting DO concentration profiles monitored. High DO concentrations are evident in both Passes 2 and 4 during the evening and morning hours (Figure 6-13).

The on-line instrumentation for measuring airflow took longer to commission than expected. The airflow sensors were downsized to achieve more accurate measurement at low airflows. This emphasizes the

Figure 6-13. Manual control of DO at Piscataway.



careful attention necessary in selecting and specifying instrumentation to ensure proper operation during all stages of the anticipated plant design life. Following extensive staff training on the control system, automated operation of the nitrification train was phased in. Initially, the plant was run in the automated mode during the day shift, Monday to Friday only. This staged approach resulted in a confident transition by the operators from manual operation to continuous, fully automated control. Twenty-four hour automated operation was initiated once the O&M staff was confident and comfortable with the system.

The performance of the system has been excellent. The overaeration problem encountered during manual control has been nearly eliminated. DO concentration profiles under fully automated operation are plotted in Figure 6-14. It is evident that, except for periods of minimum airflow limitations in the fourth pass, DO concentration was effectively controlled at the set-points of 0.8 mg/L and 1.0 mg/L in the second and fourth passes, respectively. Adjustments to set-points were made to optimize process and aeration efficiencies as experience with the system was gained. The DO set-points were gradually lowered from 4.5 mg/L to 0.6-1.0 mg/L with no adverse effects on the process. In addition, the minimum airflow set-

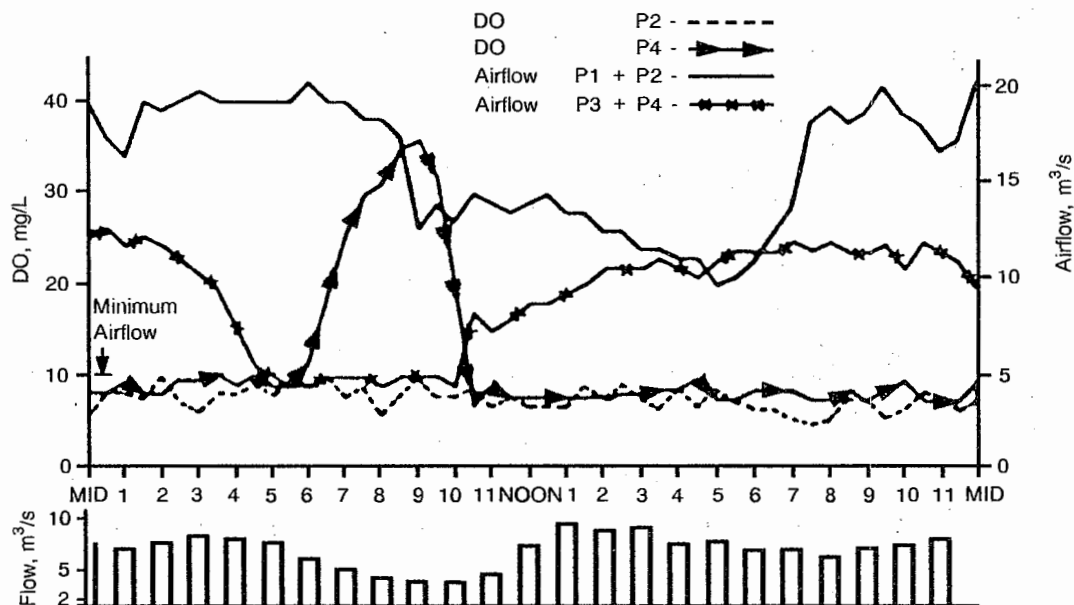
point for each pair of aeration passes was lowered from 0.71 to 0.47 m³/s (1,500 to 1,000 scfm), also without adverse process effects. The individual air diffuser valves were manually adjusted to obtain an even mixing pattern throughout the basins.

Automated control to lower DO concentrations has resulted in a corresponding reduction in average blower power per unit loading of 34 percent in the nitrification system. It is expected these aeration energy savings will further increase as process optimization continues.

The nitrification aeration system has been operated with automated control more than 90 percent of the time. The main interruptions have been because of routine sensor maintenance. The plant staff clean and calibrate the DO probes weekly. The other instrumentation associated with the aeration system (airflow, pressure, and temperature measurements) is checked every 3 months.

Early involvement of the operations staff at the Piscataway plant, and their continuing commitment to maintaining and optimizing the system, was reported to be critical in achieving successful operation of the plant's automated aeration control system (39).

Figure 6-14. Automated control of DO at Piscataway.



6.6.2 Madison, WI

A distributed control system was incorporated as part of a recent plant expansion and aeration system upgrade at the Madison, WI Metropolitan Sewerage District Nine Springs Wastewater Pollution Control Plant. The expansion and upgrade were undertaken to achieve nitrification in a single-stage activated sludge process. Fine pore diffusers were incorporated in all aeration basins. The control system was installed to save energy, estimated to be about 10 percent, and minimize the need for additional staff to operate the expanded plant. The automated system controls a variety of processes and unit operations. These include influent flow splitting, primary effluent flow splitting, waste activated sludge pumping, recycle sludge pumping, UV disinfection, effluent pumping, digester sequencing, and DO and blower control.

Details regarding the background and history of the upgrade and the control system design have been presented elsewhere (40-42) and are further summarized in Chapter 8. Experience with operating the automated aeration and DO control system is of interest here.

The treatment plant has a design capacity of 2,190 L/s (50 mgd) and now operates at an average flow of 1,665 L/s (38 mgd). As a result of various expansions, there are two plants on site designated as the East (Old) plant and the West (New) plant. The East plant consists of six three-pass aeration basins, while the West plant is comprised of four three-pass aeration

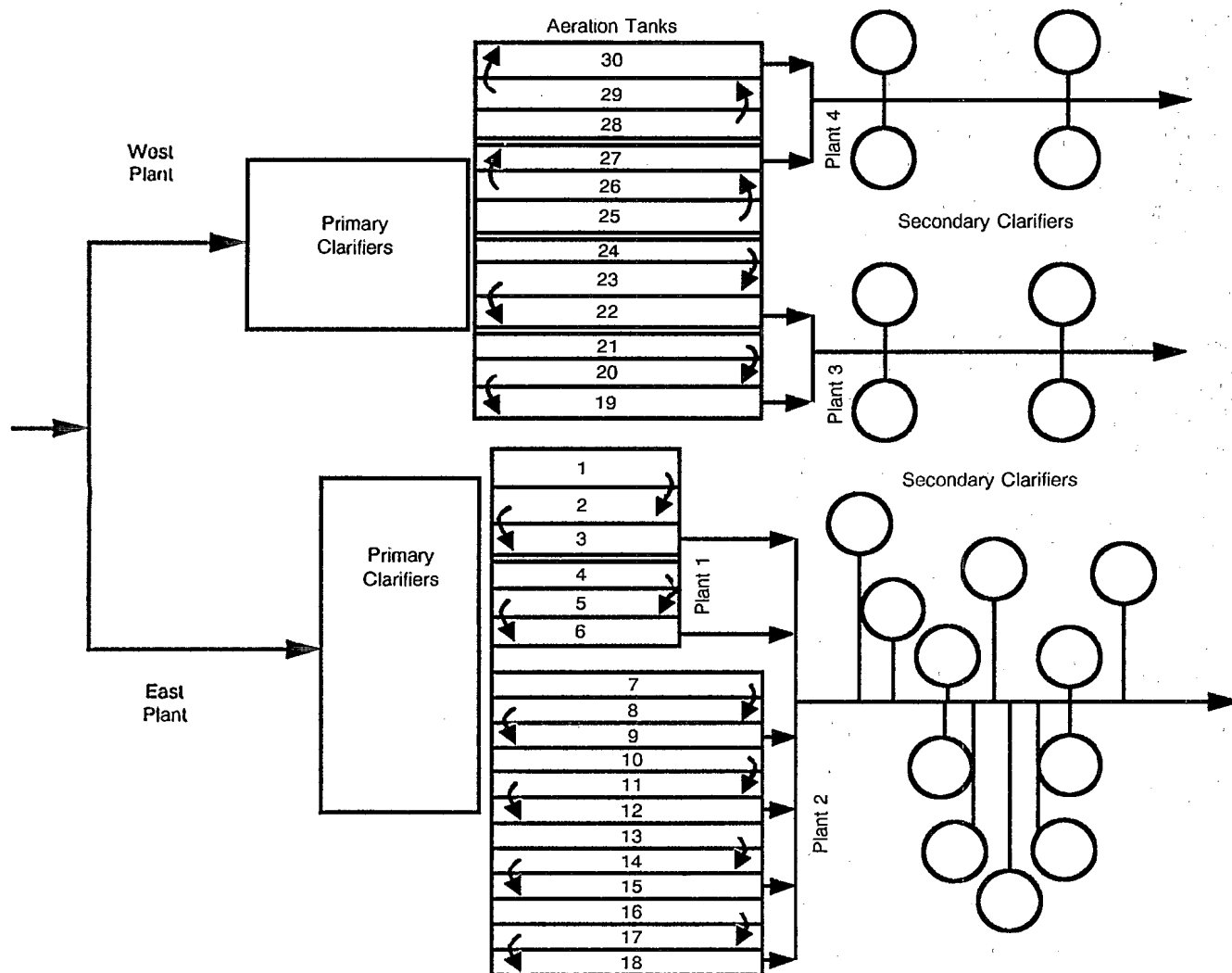
basins. The East plant is further split into Plants 1 and 2 and the West plant into Plants 3 and 4. There are, therefore, effectively four treatment plants on site that can be operated independently from one another. An overall flow schematic is presented in Figure 6-15.

The aeration systems for the East and West plants are completely separate. For each of the three-pass aeration basins, a DO probe located at the end of each pass is used to manipulate an air distribution control valve for that pass. The DO controller cascades the airflow set-point to the air control algorithm for that pass. A minimum airflow requirement limits the total airflow turndown to the pass. Air is further distributed to each of the three aeration grids in each pass by manual adjustment of butterfly valves.

The inlet guide vanes on the centrifugal blowers are adjusted to vary air delivery to maintain a constant header pressure, plus or minus a deadband - much as previously described in Section 6.5.2.3. For the West plant, it was anticipated that only one of three single-stage centrifugal blowers would be needed to satisfy air requirements. The East plant has one gas engine driven blower, two 2-stage centrifugal blowers, and two PD blowers available. It was initially assumed that one PD blower plus one of the 2-stage centrifugal blowers would be used on a routine basis.

On system start-up, problems were encountered in operating the West plant blowers. They had been

Figure 6-15. Plant schematic for Nine Springs wastewater treatment plant – Madison, WI.



supplied with a rated capacity of 24 m³/s (50,000 scfm) each, even though they had been specified to have an operating range of 6-12 m³/s (12,500-25,000 scfm). Motors capable of driving the blowers to the 12-m³/s (25,000-cfm) delivery point had been supplied with hardwired lockouts to the guide vane controllers to prevent the motors from being overloaded if the guide vanes opened too far. The lockouts were not tied to the control system initially. As a result, when air demand subsequently dropped and the airflow distribution valves began to close, the blower(s) would go into a surge condition before the operator could react.

Individual watt transducers were installed on the blowers and interfaced to the control system. The control system could then control the blower guide vanes between motor operating limits, and the hardware lockouts were subsequently removed. In

addition, changes were made to the blower control algorithm to facilitate blower rotation. The operator manually overrides the blower control system and throttles the inlet guide vanes to cause the air distribution control valves to open and reduce the main header pressure, thereby enabling a second blower to be brought on line. The valves are then "frozen" for 10 minutes while the first blower is shut down. This prevents pressure rise in the system due to closing of distribution valves and eliminates the possibility of blower surge. The solution to this problem is one example of effective use of process control computer communication to minimize adverse impacts on plant equipment and prevent process upsets. The blowers for the East plant are handled similarly.

Reduced loading to the Nine Springs plant initially caused some problems with tuning the air delivery

controller to work effectively at low airflows. At the lowest guide vane settings, a small percentage change in guide vane position resulted in a much larger percentage change in airflow. A wide pressure set-point band was therefore incorporated to minimize this problem and facilitate effective tuning of the control algorithms. To minimize energy requirements, a "lookup table" of pressure set-points vs. total system airflow demands was incorporated in the process control computer to automatically minimize the pressure set-point, yet maintain effective control.

To achieve some degree of airflow reduction and energy savings while operating in an overall reduced loading condition, one-half of the East plant was shut down and the corresponding flow routed to the West plant. This flow adjustment allowed the gas engine driven blower to supply total air requirements for the East plant. Even though this blower could not be automatically controlled, the utilization of digester gas resulted in reduced cost. The West plant had been unable to realize the full benefits of DO concentration and airflow control because of limitations in blower turndown capacity. Increased OTE and the low loadings resulted in overaeration much of the time. The increased loading achieved by diversion of East plant flow allowed the West plant to maintain typical set-points of 1.2, 1.6, and 2.0 mg/L, respectively, in the three successive passes. This resulted in more efficient air delivery and stable process performance.

Options for increasing overall aeration system flexibility are currently being examined at Madison. One option being considered is connecting the East and West plant main headers together. This would provide substantially increased flexibility in blower turndown capacity and an improved ability to configure the size and number of blowers in operation to achieve maximum efficiency.

The DO probes have required the greatest amount of control system maintenance at Madison. Probe cleaning is required every 3-4 days in the first passes when plant loadings are high and the plant is operating at lower sludge ages. Lower loadings and operating at higher sludge ages reduce probe maintenance requirements. The probes are usually cleaned and calibrated every 2 weeks. Operators handle the cleanings, calibrations, and simple maintenance such as membrane replacement. Electronics technicians are called in for more serious problems. Careful monitoring of maintenance requirements and probe performance has shown that the probes are not performing as well as expected. Efforts to determine whether this is an equipment or procedural problem are proceeding.

The fine tuning of the process control system has involved changing several control algorithms. In many instances, this was caused by changes in plant operating conditions. In other instances, it was caused

by overdesign and the inability to control hardware optimally. However, it is to the credit of the Nine Springs plant staff that they have made the system work under these conditions. Although the expected energy savings have not yet been realized, effective utilization of the automated process control system for sludge age and aeration/DO control has resulted in exceptionally stable operation of the treatment process. Active efforts to optimize the control system and plant hardware will result in energy savings and more operational flexibility as plant loadings increase.

6.7 Summary

The benefits associated with automated aeration control have been known for many years. Many systems have been successfully implemented and have generated the expected benefits of aeration energy savings and improved process control. Yet, in many situations where the potential benefits are evident and far outweigh the associated costs, the user community is very reluctant to implement an on-line, sensor-based automated control system.

This reluctance is often due to perceived problems with the technology. In some cases, such an attitude is justified based on past experiences. In most instances, however, these problems could have been avoided with careful attention to system constraints and process requirements.

Instrumentation, long cited as the cause of most problems, can no longer be used as a scapegoat. Reliable instruments are available, but they are not black boxes. They require continual maintenance that, if properly applied, is usually not excessive.

The amount of energy used for aeration, and the potential for saving a portion of that energy with effective control, must be weighed against the life-cycle cost of the control system, including hardware and software. The aeration system designer, process control engineer, and operating staff should review each aeration system design option and determine the associated cost of the various control options. During this iterative process, it is important to consider the flexibility and expansion potential of each option to accommodate all variations in loading anticipated over the design life of the plant. This time-consuming task is vital to the selection of an automated control strategy that will be compatible with the final aeration system design and maintain process integrity at the least possible cost.

The intent of this chapter has been to identify the major benefits of automated aeration control and the most important factors to consider in the design and implementation of automated control systems. Where automated control has been successfully incorporated in the operation of activated sludge wastewater treatment plants, a major contributing factor has been

comprehensive interaction between the design consultant, plant O&M staff, process control personnel, and instrumentation and control hardware manufacturers. The successful application of an automated control system begins at the design phase of the aeration system. The operational success of a well-designed control system depends on the commitment of the plant staff.

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National Technical Information Service
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Chapter 7

Economic Analysis

7.1 Introduction

The principal reason for installing fine pore aeration systems is the savings in aeration energy costs made possible through the higher oxygen transfer efficiencies (OTEs) of fine pore devices. Any decision to employ fine pore diffusers should be justified by an economic analysis that confirms these savings are large enough to offset any additional equipment, installation, and maintenance expenditures that may be required compared to more energy-intensive aeration alternatives. This chapter presents a summary of those factors that need to be considered in performing such an analysis.

This chapter is organized as follows. First, the significant components of aeration costs are summarized. Next, a technique for performing an economic analysis is discussed. This method is applied to the design example introduced in Chapter 5 to illustrate the economic impact of different fouling rates for a fine pore aeration system compared to a traditional, nonfouling coarse bubble aeration system. Examples of desktop and computer-based spreadsheet implementation of this method are provided. Finally, a compendium of actual component cost data obtained from various fine pore installations is presented.

7.2 Cost Components

Fine pore aeration systems may be retrofitted to existing aeration basins or installed in new aeration basins. The following cost items need to be considered when developing cost estimates for these aeration systems:

- Aeration basin dewatering, cleaning, and degritting
- Old equipment removal, disposal, and salvage
- Installation of new diffuser system and associated below-water air piping
- Installation or rehabilitation of above-water air piping, including valves
- Installation of a new or upgrading the existing air filtration system

- Installation of airflow and pressure monitoring/control equipment
- Installation of a dissolved oxygen (DO) monitoring/control system
- Upgrading or replacing the existing blower system
- Upgrading or replacing the existing blower prime movers
- Installation of variable frequency drives, inlet guide vanes (centrifugal), or alternative equipment for blower control
- Installation of acid (liquid or gas) cleaning system
- Installation of other cleaning systems or components, such as high-pressure pumps

Initial costs include all construction activities, equipment purchases and installation. Items such as mobilization, bonding, insurance, engineering, and legal and administrative fees represent additional initial cost items depending on the particular project in question.

Ongoing operations and maintenance (O&M) costs over the evaluation period must also be taken into consideration. These include all energy, labor, and materials costs. Particular attention must be paid to the cost of cleaning or replacing diffusers on a periodic basis.

Replacement costs are expenditures made to purchase and install equipment whose useful life is less than the period of analysis. Diffusers, blowers, air filters, and monitoring devices are examples of items that may have to be replaced on a periodic basis.

7.3 Economic Analysis Procedure

This section presents a method for estimating and evaluating the cost of diffused aeration systems. This method is applicable to both coarse bubble and fine pore diffuser systems for either existing, new, or retrofit projects. It computes total system costs as the present worth of initial expenditures and future

equipment replacement costs, monthly energy and equipment maintenance costs, and periodic diffuser cleaning costs.

The method can be used to judge the cost effectiveness of alternative aeration system designs. Typical issues that can be addressed include:

- choosing between coarse bubble and fine pore aeration,
- finding the optimal cleaning frequency for fine pore diffusers,
- determining the least-cost choice of such design variables as number of diffusers and blowers, and
- examining the sensitivity of results to uncertainties in oxygen demands, OTEs, fouling rates, power pricing, etc.

Because different aeration system costs are incurred at different points in time, a consistent method is needed to express the value of future dollar outlays against current ones. Present worth analyses recognize that future expenditures do not have the same value to society as an equal level of expenditures made today. Interest factors are used to place the two types of costs on an equal footing. The well-known compound interest formula can be used to relate a present worth to a future worth in terms of a number of time intervals, and the decimal interest rate per time interval:

$$F_w = P_w (1 + i)^n \quad (7-1)$$

where,

P_w = present worth cost, \$
 F_w = future expenditure, \$
 i = periodic discount rate, decimal
 n = total number of time periods

The ratio of P_w to F_w , termed the single payment present worth factor, PWF, is given by:

$$PWF = (P_w/F_w) = 1 \div (1 + i)^n \quad (7-2)$$

Consider, for example, a \$1,000 expenditure made 5 years into the future with the time value of money taken as 8 percent/yr ($i = 0.08$):

$$PWF = 1 \div (1 + 0.08)^5 = 0.6806$$

The present worth cost is $0.6806(1,000) = \$680.60$. This means that it is cost effective to spend \$680.60 or less now to avoid the \$1,000 expenditure 5 years hence.

Likewise, a uniform series of end-of-period payments, each of magnitude A and made at the end of each

one of n periods, may be related to a present worth, P_w , using the capital recovery factor, CRF:

$$CRF = (A/P_w) = i(1 + i)^n \div [(1 + i)^n - 1] \quad (7-3)$$

or its reciprocal, the uniform series present worth factor, SPWF:

$$SPWF = (P_w/A) = [(1 + i)^n - 1] \div [i(1 + i)^n] \quad (7-4)$$

The present worth of an annual savings in power costs may be calculated by multiplying the annual savings by the uniform series present worth factor. Consider, for example, annual savings in power costs over a 10-yr life of an aeration system when $i = 0.08$:

$$SPWF = [(1 + 0.08)^{10} - 1] \div [0.08(1 + 0.08)^{10}] = 6.71$$

This means that \$1 of annual savings in each of 10 years is equivalent to \$6.71 of present worth. Put another way, it is cost effective in this example to spend up to \$6,710 in initial investment to save \$1,000/yr in power costs.

A fourth factor, useful for calculating the present worth of diffuser cleaning expenses, is the periodic series present worth factor, PSPWF:

$$PSPWF = (P_w/Z_c) \quad (7-5)$$

$$= [PWF(i_m, n_m)] [SPWF(i_m, n_m M)] \div [SPWF(i_m, n_m)]$$

where,

Z_c = period diffuser cleaning cost
 i_m = monthly interest rate = annual interest rate $\div 12$
 n_m = number of months between cleanings
 M = number of cleanings over the life of the system

The present worth of the cleaning expenses can be calculated by multiplying the cost of an individual cleaning by the periodic series present worth factor. Consider a situation in which diffusers are cleaned at 5-month intervals over a 10-yr (120-month) life of a system. The cost of each cleaning is \$1,000.

For this example:

i = 8 percent/yr = 0.08
 i_m = $0.08/12 = 0.0067/\text{month}$
 n_m = 5 months
 M = $120 \text{ months} / 5 \text{ months} = 24 \text{ cleanings}$
 (round to nearest whole number)

$$PWF(i_m, n_m) = PWF(0.0067, 5)$$

$$= 1 \div (1 + 0.0067)^5 = 0.967$$

$$SPWF(i_m, n_m M) = SPWF[0.0067, 120]$$

$$= [(1 + 0.0067)^{120} - 1] \div [0.0067(1 + 0.0067)^{120}]$$

$$= 82.28$$

$$\begin{aligned} \text{SPWF}(i_m, n_m) &= \text{SPWF}(0.0067, 5) \\ &= [(1 + 0.0067)^5 - 1] \div [0.0067(1 + 0.0067)^5] \\ &= 4.90 \end{aligned}$$

$$\begin{aligned} \text{PSPWF} &= [\text{PWF}(i_m, n_m)] [\text{SPWF}(i_m, n_m M)] \div [\text{SPWF}(i_m, n_m)] \\ &= (0.967)(82.28) \div 4.90 = 16.23 \end{aligned}$$

Thus, the present worth of the diffuser cleaning costs is $16.23(1,000) = \$16,230$. This means that, for this example, it is cost effective to spend up to \$16,230 in initial costs to lower cleaning costs by \$1,000 per cleaning event.

The discount rate i used in these factors reflects the degree to which society is willing to postpone current expenses and pay more at a later point in time. It is only partially reflected by the current rate of return on investment obtainable in financial markets. The choice of a proper discount rate to use for present worth analyses, especially for public sector projects, is an arguable point and no specific rate will be recommended here.

Another issue that arises in considering future expenditures is inflation. Two approaches are available. The first inflates future expenditures as they occur and then discounts them back to time zero using the above equations. The second uses a discount rate that has been adjusted for inflation and keeps all future costs inflation free. If the same inflation rate applies to all expenditures, the two methods provide identical results.

The material that follows assumes that an inflation-adjusted discount rate i will be used and that no future cost increases due to inflation need be made. Also, it is convenient to use a month as the basic time period. Therefore, if the discount i is stated as an annual rate, i_m should be used in the above equations when n and m are given in months.

The total present worth of the project is the sum of initial costs plus the present worth of all future expenditures discounted using one of the above equations. A desktop approach for calculating the various present worth elements of a project is presented in Sections 7.3.1 through 7.3.6. The information required to perform the calculations that follow is identified in Table 7-1. A sample desktop analysis is presented in Section 7.4. An alternative, computer-based spreadsheet approach is presented in Section 7.5.

7.3.1 Calculate Initial Costs

Initial costs include expenditures for equipment, construction, and installation of the items listed in Section 7.2. Empirical cost data are presented for general guidance in Section 7.6. By definition, the actual cost of these items is equal to the present worth.

Table 7-1. Information Needed to Perform Desktop Economic Analysis of Diffused Aeration Systems

Component Cost Data

Initial costs
Equipment replacement intervals and costs
Unit cost of power
Monthly routine maintenance cost
Cost per diffuser for major cleaning
Time interval between major diffuser cleanings
Length of analysis period
Discount Rate

Aeration Zone Data

Number of diffusers
Average oxygen demand*
Average ratio of field to standard OTE*
Rate of loss of OTE due to fouling
Maximum percentage loss of OTE possible
Pressure drop across clean and fouled diffuser
Orifice pressure drop at 1 scfm of airflow
Airflow required for mixing
Minimum and maximum airflows per diffuser
Relation between SOTE and diffuser airflow

Air Delivery System Data

Barometric pressure
Headloss due to depth of submergence and line losses
Overall blower efficiency

* Annual average values; monthly values are used for computer-based spreadsheet method.

7.3.2 Calculate Energy Costs

Energy costs embody the blower motor horsepower required to deliver sufficient air to the diffusers to meet process oxygen demands. These costs will vary from day to day over the analysis period as oxygen demands change and OTE decreases because of diffuser fouling. When a major diffuser cleaning effort occurs, OTE will be substantially restored and a new time pattern of energy consumption will begin. For desktop analysis, it is not practical to track these effects over each discrete time period (hour, week or month) of the analysis period. Instead, energy consumption is computed using annual average oxygen demands and the average degree of fouling that exists between major diffuser cleanings. A major cleaning is one that restores a diffuser's OTE to its original unfouled condition.

As was done for the design example in Chapter 5, the cost analysis divides the aeration basin into one or more aeration zones, where the oxygen demands, OTEs, and fouling rates vary by zone. The following simplifying assumptions are made for each zone:

1. Oxygen demand equals the annual average demand (lb/d).
2. The ratio of the field OTR (OTR_f) to standard OTR (SOTR) for a clean diffuser equals the annual average value of that ratio.

3. The fouling factor, F , decreases from 1.0 at a linear rate with time down to some lower limit.
4. The pressure drop across a fine pore diffuser increases in direct proportion to the degree of fouling.
5. A major cleaning restores F to 1.0.

With these assumptions, total present worth energy costs can be estimated using the following five-step procedure:

Step 1. Assume a diffuser cleaning interval and perform the following for each aeration zone:

- 1a. Find the average F , F_a , that exists over this cleaning interval.
- 1b. Determine the airflow per diffuser needed to meet the oxygen demand in the aeration zone:

$$q = 0.04(\text{AOR}) \div [(\text{SOTE})(\text{OTR}_i/\text{SOTR})(F_a)(N_d)] \quad (7-6)$$

where,

q = airflow rate rate, scfm/diffuser
 AOR = actual oxygen requirement, lb/d
 SOTE = standard OTE
 F_a = average fouling factor
 N_d = number of diffusers in the zone
 0.04 = conversion factor to obtain scfm of air from lb/d of oxygen

Note: If SOTE is a function of q , then an iterative solution of the above equation is necessary. Begin with any feasible value of SOTE and solve the above equation for q . If at this q the diffuser's SOTE is close to the previous SOTE value then stop. Otherwise, repeat the process using the new SOTE value until a convergence is achieved.

- 1c. Adjust q to reflect constraints on minimum airflow and mixing:

$$q_d = \text{MAX}\{q, q_{\min}, q_{\text{mix}}\} \quad (7-7)$$

where,

q_d = design airflow rate, scfm/diffuser
 $q_{\min}$ = manufacturer's recommended minimum airflow rate, scfm/diffuser
 q_{mix} = minimum airflow rate required for solids suspension, scfm/diffuser

Adjust q_d to reflect constraints on maximum airflow:

$$q_d = \text{MIN}\{q_d, q_{\max}\} \quad (7-8)$$

where,

$q_{\max}$ = manufacturer's recommended maximum airflow rate, scfm/diffuser

- 1d. Find the pressure drop across the diffuser and its orifice where the former is proportional to the degree of fouling and the latter to the square of the airflow through the diffuser:

$$dP = dP_{d1} + (dP_{d2} - dP_{d1})(1-F) \div (1-F_{\min}) + (dP_{o1})(q_d^2) \quad (7-9)$$

where,

dP = pressure drop, psig
 dP_{d1} = pressure drop across a clean diffuser, psig
 dP_{d2} = pressure drop across fouled diffuser, psig
 $F_{\min}$ = minimum value for F
 dP_{o1} = orifice drop at airflow of 1 scfm/diffuser, psig

Step 2. Find the average total airflow for the system during the interval between cleanings:

$$q_s = \sum q_{di} N_i \quad (7-10)$$

where,

q_s = field standardized volumetric airflow rate, scfm
 q_{di} = design airflow rate for Zone i (found in Step 1c), scfm/diffuser
 N_i = number of diffusers in Zone i

Step 3. Find the average pressure drop through the aeration system during the interval between cleanings:

$$P_d = dP_{\text{line}} + dP_{\text{sub}} + \text{MAX}\{dP_1, dP_2, \dots, dP_i\} \quad (7-11)$$

where,

P_d = blower discharge pressure, psig
 dP_{line} = pressure drop in air piping, psig
 dP_{sub} = head of water above diffusers, psig [= (0.433) (submergence, ft)]
 dP_i = diffuser pressure drop in zone i (found in Step 1d), psig

Step 4. Estimate the monthly power consumption needed by the blowers to deliver airflow q_s at a pressure rise of P_d .

Normally, this will depend on the number of blowers available, their operating characteristics, and the type of guide vane or speed control available. If this type of information is not available or is too difficult to use for desktop analysis, power consumption can be

estimated from the theoretical adiabatic work expression (Equation 4-11):

The expression for the universal gas law is:

$$P_b V_s = RT_a / 144 \quad (7-12)$$

where,

- P_b = field atmospheric pressure, psia
- V_s = specific volume, cu ft/lb
- R = ideal gas constant = 53.3 ft-lb/lb-°R
- T_a = blower inlet air temperature, °R

Further, mass rate of air is related to volumetric airflow rate and specific volume by:

$$w = 60 q_s / V_s \quad (7-13)$$

where,

- w = mass rate of air, lb/hr
- q_s = field standardized volumetric airflow rate, scfm

By substituting the above terms in Equation 4-11 and using $K = 0.283$, the following working equation can be developed:

$$WP = (0.0115 q_s P_b / e) \{ [(P_b + P_d) / P_b]^{0.283} - 1 \} \quad (7-14)$$

where,

- WP = wire power consumption, kW
- e = combined blower/motor efficiency, fraction (using a constant blower efficiency simplifies this calculation; however, efficiency will change under varying operating conditions)
- P_b = field atmospheric pressure, psia
- P_d = blower discharge pressure, psig and 0.0115 is in units of kW-sq in-min/(ft-lb)-sq ft.

The average monthly energy consumption (WE_M) in kWh can be calculated by multiplying Equation 7-14 by 720 hr/month to yield:

$$WE_M = (8.268 q_s P_b / e) \{ [(P_b + P_d) / P_b]^{0.283} - 1 \} \quad (7-15)$$

Step 5. Compute the present worth cost of the monthly average energy consumption over the entire analysis period:

$$Z_e = WE_M (E_p) (SPWF) \quad (7-16)$$

where,

- Z_e = present worth power cost, \$
- E_p = unit cost of power, \$/kWh

7.3.3 Calculate Maintenance Costs

Maintenance costs are expenditures made on a regular basis for labor and materials needed to keep the aeration system functioning properly. They cover normal maintenance functions for such equipment as blowers and instrumentation and might also include the continuing costs of using a noninterruptive method of diffuser cleaning, such as gas cleaning. The present worth of maintenance costs is calculated by multiplying the monthly maintenance cost by SPWF (Equation 7-4).

7.3.4 Calculate Diffuser Cleaning Costs

The analysis assumes that process interruptive diffuser cleaning occurs on a regularly scheduled basis every n_m months. The total number of cleanings over the analysis period is M . The present worth of cleaning costs is calculated by multiplying the cost of an individual cleaning by PSPWF (Equation 7-5).

7.3.5 Calculate Replacement Costs

Calculation of equipment costs is similar to diffuser cleaning costs. Assume a specific piece of equipment must be replaced every n_m months and that the total number of replacements over the analysis period is M . Then the present worth replacement cost of this item is its installed cost times the periodic series present worth factor calculated by Equation 7-5. Repeating this calculation for each replacement item and adding the results together produces the total present worth replacement costs.

7.3.6 Calculate Total Present Worth Cost

Add the initial, energy, maintenance, cleaning, and replacement present worth costs to obtain total present worth cost for the cleaning interval selected.

7.3.7 Determine Lowest Total Present Worth Cost

If the lowest present worth cost is desired for various alternatives, repeat the calculations in Sections 7.3.1 through 7.3.5 using different conditions (e.g., cleaning intervals) to determine the lowest total present worth.

7.4 Sample Desktop Economic Analysis

A desktop economic analysis is performed below for the fine pore aeration system design presented in Example 5-10. The cost of this system is compared with that of a coarse bubble aeration system. The analysis demonstrates the sensitivity of aeration costs to different assumptions concerning fouling rates, cleaning frequencies and prices, and power prices.

As in Example 5-10, each of the four aeration basins is divided into three aeration zones. The average nitrifying month and average nonnitrifying month OTR_s used in that example are assumed to be based on the following distribution of monthly average OTR_s :

Month	Total System OTR _f , lb/d		
	Zone 1	Zone 2	Zone 3
Jan.	2,108	1,192	275
Feb.	2,497	1,551	605
March	3,047	1,903	737
April	3,410	2,097	821
May	3,722	2,438	1,155
June	4,290	3,300	1,408
July	4,730	3,586	1,562
Aug.	5,445	4,134	2,009
Sept.	4,400	3,322	1,434
Oct.	4,202	3,223	1,375
Nov.	3,047	1,903	737
Dec.	2,497	1,551	605
Average month, nitrifying	4,613	3,513	1,559
Average month, nonnitrifying	2,904	1,804	704
Overall Average	3,619	2,517	1,060

The nitrification period for this example plant is June-October.

Oxygen transfer rates, even for clean diffusers, vary with time of year due to changes in wastewater temperature and target DO levels in the aeration basin. The relationship of OTR_f to SOTR for a new or clean diffuser ($F = 1.0$) is:

$$\text{OTR}_f/\text{SOTR} = \alpha B_{C,T} \quad (7-17)$$

where,

α = (process water K_{La} of a new diffuser) ÷ (clean water K_{La} of a new diffuser)

K_{La} = apparent volumetric mass transfer coefficient in clean water at temperature T , 1/hr

C = process water DO concentration, mg/L

T = process water temperature, °C

$B_{C,T} = 0T^{20} (\Omega \cdot \beta^\circ C^{\omega_{20}} - C) \div C^{\omega_{20}}$, as described in Equation 5-5.

For fixed DO concentrations, $B_{C,T}$ varies only slightly within the temperature range of 10-25°C, having values of about 0.86 and 0.77 at DOs of 1.0 and 2.0, respectively. Since target DOs in the example problem were assumed to vary by month, the corresponding ratios of OTR_f to SOTR are shown at the top of the next column.

Note that Zone 2 DO in August is allowed to drop to 1 mg/L in response to the highest oxygen demand of the year. Otherwise, Zone 2 DO is maintained at 2 mg/L during the nitrifying months and 1 mg/L during the nonnitrifying months.

Months	Target DO, mg/L			OTR _f /SOTR		
	Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3
Jan.-May	1	1	2	0.86a	0.86a	0.77a
June-July	1	2	2	0.86a	0.77a	0.77a
Aug.	1	1	2	0.86a	0.86a	0.77a
Sept.-Oct.	1	2	2	0.86a	0.77a	0.77a
Nov.-Dec.	1	1	2	0.86a	0.86a	0.77a
Average				0.86a	0.83a	0.77a

Baseline conditions for the economic analysis assume that this is new construction using an annual net discount rate of 8 percent, a 20-yr analysis period, a power price of \$0.05/kWh, and a diffuser cleaning cost of \$1.00/diffuser. No equipment replacement costs are considered. Blowers are assumed to be wired to an automated DO control system and capable of having their output adjusted to keep pace with the airflows and pressures demanded.

7.4.1 Fine Pore System Design

Table 7-2 summarizes the information used to perform a cost analysis of the example fine pore aeration system. Initial costs of the system are \$927,000 and are itemized in Table 7-3. In this example, annual maintenance costs are taken as 2 percent of the installed blower costs. The assumed average α values of 0.4, 0.6, and 0.9 in Zones 1, 2, and 3 result in average OTR_f/SOTR values of 0.344, 0.498, and 0.693, respectively (for new diffusers, $F = 1.0$).

The number of diffusers in each zone for all four aeration basins (from Example 5-10, Step 4) and their respective densities are:

The SOTE values used in this analysis for the above diffuser densities were estimated by linear regression of curves presented in Figure 5-9. This was done to simplify the analysis. Therefore, the calculated values used in this chapter are slightly different than those used in Example 5-10.

For this example, it is assumed the OTR_f of a fully fouled fine pore diffuser is 40 percent lower than for a clean diffuser. Thus, the lowest possible F is 0.6. The rate at which fine pore diffusers will foul is one of the most difficult operating parameters to predict. In this example, four different fouling rates are considered, as shown in Table 7-2. They are based on the range of values observed at actual installations as summarized in Chapter 3. For all cases, Zone 2 fouls 1.4 times faster than Zone 3, while Zone 1 fouls twice

Zone	Number of Diffusers	Diffuser Density, Number/100 sq ft
1	1,920	48.2
2	1,152	28.9
3	576	14.5

Table 7-2. Design Information for Example Fine Pore Aeration System

Initial Costs, \$ (from Table 7-3)	927,000		
Replacement Costs, \$	0		
Monthly Maintenance Costs, \$	400		
Unit Cost of Energy, \$/kWh	0.05		
Cost of Diffuser Cleaning, \$/diffuser	1.00		
Cleaning Interval, months	(variable—see text)		
Discount Rate, percent	8		
Analysis Period, months	240		
Barometric Pressure, psia	14.3		
Headloss from Submergence and Line Losses, psig	6.2		
Overall Blower Efficiency	0.7		

	Zone 1	Zone 2	Zone 3
Number of Diffusers	1,920	1,152	576
Average OTR _f , lb/d	3,617	2,517	1,060
α	0.4	0.6	0.9
Average OTR _f /SOTR	0.344	0.498	0.693
Rate of Fouling, percent loss of OTE/month (i.e., F x 100):			
°Case 1	0.5	0.35	0.25
°Case 2	1.0	0.7	0.5
°Case 3	3.0	2.1	1.5
°Case 4	5.0	3.5	2.5
Maximum Percent Loss of OTE Possible	40	40	40
Pressure Drop Across Diffuser, in:			
Clean	5	5	5
Fully Fouled	24	24	24
Orifice Pressure Drop at 1 scfm, in	2.67	2.67	2.67
Mixing Requirement, scfm	400	400	400
Minimum Airflow/Diffuser, scfm	0.5	0.5	0.5
Maximum Airflow/Diffuser, scfm	2.5	2.5	2.5
SOTE at Minimum Airflow, percent	36.5	30.3	28.4
SOTE at Maximum Airflow, percent	26.4	24.9	23.2

Table 7-3. Initial Costs of Design Example Fine Pore and Coarse Bubble Aeration Systems

Category	Fine Pore System, \$	Coarse Bubble System, \$
Piping	51,000	42,000
Diffusers	131,000	24,000
Blowers	240,000	320,000
Instrumentation & Control	150,000	150,000
Contingency	143,000	134,000
Mobilization, Bonding, Insurance	57,000	54,000
Total Estimated Construction Cost	772,000	724,000
Engineering @ 15 percent	116,000	109,000
Legal & Administrative @ 5 percent	39,000	36,000
Total Estimated Initial Cost	927,000	869,000

as fast as Zone 3. Overall, the four sets of fouling rates increase in relative proportions of 1:2:6:10.

7.4.2 Coarse Bubble System Design

Table 7-4 lists the information needed to perform a cost analysis of a new, equally-sized coarse bubble aeration system to provide the same OTR_fs and DO levels as in the fine pore system design. The initial cost of \$869,000 is broken down as shown in Table 7-3. Higher capacity blowers are needed for the coarse bubble system than for the fine pore system, increasing the blower initial cost by 33 percent. A total of 600 diffusers is used. The assumed average α values in Zones 1, 2, and 3 of 0.6, 0.7, and 0.9, respectively, result in average OTR_f/SOTR values of 0.516, 0.581, and 0.693. SOTE values are assumed to be 10 percent at all airflows in all aeration zones. Since coarse bubble diffusers do not foul, there is no need to prescribe a fouling rate, a cleaning cost, or minimum and maximum diffuser pressure drops.

Table 7-4. Design Information for Example Coarse Bubble Aeration System

Initial Costs, \$ (from Table 7-3)	869,000		
Replacement Costs, \$	0		
Monthly Maintenance Costs, \$	535		
Unit Cost of Energy, \$/kWh	0.05		
Cost of Diffuser Cleaning, \$/diffuser	0		
Cleaning Interval, months	None		
Discount Rate, percent	8		
Analysis Period, months	240		
Barometric Pressure, psia	14.3		
Headloss from Submergence and Line Losses, psig	6.2		
Overall Blower Efficiency	0.7		

	Zone 1	Zone 2	Zone 3
Number of Diffusers	300	200	100
Average OTR _f , lb/d	3,617	2,517	1,060
α	0.6	0.7	0.9
Average OTR _f /SOTR	0.516	0.581	0.693
Rate of Fouling, percent loss of OTE/month	0	0	0
Maximum Percent Loss of OTE Possible	0	0	0
Pressure Drop Across Diffuser, in:			
Clean	0	0	0
Fully Fouled	0	0	0
Orifice Pressure Drop at 1 scfm, in	0.1	0.1	0.031*
Mixing Requirement, scfm	400	400	400
Minimum Airflow/Diffuser, scfm	2	2	2
Maximum Airflow/Diffuser, scfm	15	15	15
SOTE at Minimum Airflow, percent	10	10	10
SOTE at Maximum Airflow, percent	10	10	10

* Limited mixing condition in Zone 3 permits the use of a larger orifice with corresponding lower pressure drop.

7.4.3 Comparison of Present Worth Costs

The desktop method was used in conjunction with Table 7-2 to determine the present worth cost of this system under each fouling rate case for several different diffuser cleaning frequencies. Tables 7-5 and 7-6 include the calculations made for a cleaning interval of 18 months and Case 3 fouling to illustrate the steps involved. These calculations were repeated for several other cleaning intervals to produce Table 7-7 and Figure 7-1, which plots total present worth of the energy, cleaning, and maintenance costs as a function of cleaning interval. The optimum cleaning interval for Case 3 fouling is seen to be 9 months with a present worth energy, cleaning, and maintenance cost of \$394,000. Adding the initial cost of \$927,000 yields a total present worth cost of \$1,320,000 for Case 3 fouling.

The results of the calculations for all four fouling rates are summarized in Table 7-8. Figure 7-2 plots the optimal cleaning interval, the percentage of operating costs devoted to cleaning, and the present worth cost per diffuser for cleaning against the fouling rate (as measured relative to Case 1, the lowest rate used). The optimal cleaning intervals range from 7 to 27 months. Even under the most severe fouling rate, cleaning is less than 15 percent of the total operating costs.

As indicated in Table 7-7, cleaning costs represent a small fraction of either initial or energy costs for Case 3 fouling. Further, the trade-off between cleaning costs and energy costs as a function of cleaning frequency is relatively constant. Therefore, for similar situations where operators are faced with a Zone 1 fouling rate of approximately 3 percent/month, a wide choice of cleaning frequencies is available and a decision to clean on an annual basis would be consistent with the analysis shown.

Tables 7-9 and 7-10 summarize the desktop cost computations for the coarse bubble aeration system. Total present worth costs are \$1,513,270, of which \$580,500 (38 percent) are for energy. These costs are compared with fine pore aeration system costs in Table 7-8. The fine pore system is more cost effective than the coarse bubble system under all assumed fouling rates.

7.4.4 Sensitivity Analysis

Additional computations were made to determine the sensitivity of these economic results to changes in the discount rate and the unit costs of energy and diffuser cleaning. Using a 4 percent discount rate instead of an 8 percent rate resulted in no change in the optimal cleaning intervals. Operating costs increased by a factor of 1.38. This is exactly the increase in the uniform series present worth factor between discount rates of 8 and 4 percent.

Table 7-11 illustrates the effect on total present worth operating costs (energy, cleaning, and maintenance) as the unit costs of power and diffuser cleaning are changed. As the power price increases and the cleaning price decreases, it pays to clean more often. When both prices rise in the same proportion, there is no change in the optimal cleaning interval. Total operating costs are many times more sensitive to changes in power pricing than to equal relative changes in diffuser cleaning costs.

7.4.5 Retrofit Comparison

The previous analysis compared fine pore vs. coarse bubble aeration for a new treatment plant. This section includes a similar analysis assuming that a coarse bubble aeration system already exists and that replacement with a fine pore aeration system is being considered. Operating costs for the two systems are the same as calculated before. No capital costs are incurred for the existing coarse bubble system. The new fine pore system can use the existing blowers, instrumentation and control equipment, and above-water air piping. Capital costs for diffusers, below-water air piping, and basin cleanup/modification are assumed to be \$65/diffuser. For 3,648 diffusers, this totals \$237,120.

The costs of the fine pore aeration retrofit for the four fouling rates used previously are compared to the cost of the existing coarse bubble aeration system in Table 7-12. The retrofit is uneconomic only at the highest fouling rate using an 8 percent discount rate.

7.5 Lotus Spreadsheet

A Lotus 1-2-3 (Version 2) spreadsheet calculation approach is presented in Appendix D. The user can input varying diffuser fouling rates, diffuser cleaning intervals, and monthly variations in OTR_f . The spreadsheet outputs present worth costs for the fine pore aeration system and provides graphical display of costs and airflow requirements.

Tables 7-13 through 7-16 display the spreadsheet data input forms for the fine pore aeration Case 3 fouling rate problem analyzed earlier in this chapter. Table 7-17 lists the total present worth costs of this system calculated based on the input design data and using the optimum cleaning interval of 9 months. Figures 7-3 through 7-5 display the plots generated by the spreadsheet. (The monthly cost and airflow graphs were generated with an analysis period of 5 years to maintain sufficient detail in the plots.)

Table 7-8 also displays the present worth costs of both the fine pore and coarse bubble aeration systems calculated with the computer-based spreadsheet method. This method is identical to the desktop method except that OTR_f , $OTR_f/SOTR$, and F values can vary by month. Because of this, the results will be somewhat sensitive to the month of the year

Table 7-5. Sample Desktop Calculations: Case 3 Fouling Rate for Fine Pore Aeration Design Example (18-month Cleaning Interval)

A. Present Worth Initial Costs

From Table 7-3, P_w (initial costs) = \$927,000

B. Present Worth Energy Costs

1. Average airflows and pressure drops within each aeration zone (see Table 7-6 for detailed calculations in each zone):

	<u>Zone 1</u>	<u>Zone 2</u>	<u>Zone 3</u>
Average airflow/diffuser, scfm	0.882	0.729	0.694
Average pressure drop, psig	0.69	0.57	0.46
Number of diffusers	1,920	1,152	576

2. Total system airflow (q_s):
From Equation 7-10, $q_s = 0.882(1,920) + 0.729(1,152) + 0.694(576) = 2,934$ scfm

3. Total system pressure drop (P_d):
Submergence + line loss = 6.2 psig
Maximum drop in aeration zones = 0.69 psig
From Equation 7-11, $P_d = 6.2 + 0.69 = 6.89$ psig

4. Monthly energy consumption (WE_M):
Barometric pressure = 14.3 psia
Blower efficiency = 0.7
Compressibility factor = $[(14.3 + 6.89)/14.3]^{0.283} - 1 = 0.118$
From Equation 7-15, $WE_M = 8.268(2,934)(14.3)(0.118)/(0.7) = 58,475$ kWh

5. Present worth cost of energy:
Unit cost of power = \$0.05/kWh
Discount rate = (8 percent/yr)/100/12 = 0.0067/month
Analysis period = 240 months
Monthly power cost = $0.05(58,475) = \$2,924$
From Equation 7-4, $SPWF = [(1 + 0.0067)^{240} - 1]/[0.0067(1 + 0.0067)^{240}] = 119.2$
 P_w (energy costs) = $\$2,924(119.2) = \$348,540$

C. Present Worth Cost of Maintenance

Discount rate = 0.0067/month
Analysis period = 240 months
Monthly maintenance cost = \$400
 P_w (maintenance costs) = $\$400(119.2) = \$47,680$

D. Present Worth Cleaning Costs

Cost to clean a diffuser = \$1.00
Total number of diffusers = 3,648
Interval between cleanings = 18 months
Total number of cleanings = $240/18 = 13$
Cost per cleaning = \$3,648

From Equation 7-2,
 $PWF(0.0067, 18) = 1/(1 + 0.0067)^{18} = 0.887$

From Equation 7-4,
 $SPWF(0.0067, 234) = [(1 + 0.0067)^{234} - 1]/[0.0067(1 + 0.0067)^{234}] = 118$
and
 $SPWF(0.0067, 18) = [(1 + 0.0067)^{18} - 1]/[0.0067(1 + 0.0067)^{18}] = 16.9$

From Equation 7-5,
 $PSPWF = 0.887(118)/16.9 = 6.19$
 P_w (cleaning costs) = $3,648(6.19) = \$22,580$

E. Total Present Worth Cost

P_w (total cost) = $\$927,000 + \$348,540 + \$47,680 + \$22,580 = \$1,345,800$

Table 7-6a. Sample Desktop Calculations (Case 3 Fouling Rate): Zone 1 of Fine Pore Aeration Design Example (18-month Cleaning Interval)

- a. Find average F:
 - Cleaning Interval = 18 months
 - Rate of OTR loss = 3 percent/month
 - Maximum loss of OTR = 40 percent
 - Time to reach 40 percent loss = $(40)/(3) = 13$ months
 - Average F for months 1 to 13 = $(1 + 0.6)/2 = 0.8$
 - Average F for months 14 to 18 = $1 - (40)/(100) = 0.6$
 - Overall average F = $(0.8)(13)/(18) + (0.6)(5)/(18) = 0.744$
- b. Determine airflow per diffuser (q):
 - Average OTR_f = 3,617 lb/d
 - Average OTR_f/SOTR = 0.344
 - Average F = 0.744
 - Number of diffusers = 1,920
 - From Equation 7-6, $q = 0.04(3,617)/[(0.344)(0.744)(1,920)(SOTE)] = 0.294/SOTE$ (7-18)
 - From Table 7-2 (assuming linear relation between q and SOTE):
 - SOTE = 0.348 for q = 0.5, and SOTE = 0.264 for q = 2.5, giving
 - SOTE = $0.369 - 0.042(q)$ (7-19)
 - From Equations 7-18 and 7-19, $q_d = 0.882$ scfm/diffuser
- c. Check constraints on q:
 - Minimum airflow = 0.5 scfm/diffuser
 - Mixing requirement = $(400)/(1,920) = 0.208$ scfm/diffuser
 - $q_d = \text{MAX } \{0.882, 0.5, 0.208\} = 0.882$ scfm/diffuser
 - Maximum airflow = 2.5 scfm/diffuser
 - $q_d = \text{MIN } \{0.882, 2.5\} = 0.882$ scfm/diffuser
- d. Find pressure drop across diffuser and orifice:
 - Pressure drop across clean diffuser = 5 in
 - Pressure drop across fouled diffuser = 24 in
 - Average degree of fouling = $(1 - F)/(40/100) = 0.63$
 - Average diffuser pressure drop = $5 + 0.63(24 - 5) = 16.97$ in
 - Average orifice pressure drop = $(2.67)(0.882)^2 = 2.08$ in
 - Total average pressure drop = $(16.97 + 2.08)(0.036 \text{ psig/in}) = 0.69$ psig

chosen to begin the analysis. For this example, June was taken as the start-up month. A comparison of the results in Table 7-8 shows that the optimal cleaning intervals arrived at by the two methods are virtually identical. The energy costs resulting from use of the spreadsheet method average 6.4 percent higher than from the desktop method, while the total present worth costs vary by no more than 2 percent.

7.6 Compendium of Empirical Cost Data

The actual cost of any fine pore aeration system will be highly dependent on site-specific factors. Although empirical cost data have been obtained from many sources, the application of these data to the evaluation of any specific installation must be performed with caution. Where cost information was obtained from Canadian installations, a constant conversion rate of \$0.80 U.S. = \$1.00 Canadian was used.

7.6.1 Basin Cleaning and Preparation Costs

Costs for basin cleaning and old equipment removal are too site specific for general estimates. At the Terminal Island treatment plant in Los Angeles, CA (1), only 40 labor-hr were required for a 91.4 m x 9.1 m x 4.6 m sidewater depth (SWD) (300 ft x 30 ft x 15 ft) basin. At Monroe, WI (2), 20 labor-hr were required

for each 31.1 m x 15.2 m x 4.6 m SWD (102 ft x 50 ft x 15 ft) basin for initial cleaning and degritting plus an additional 12 labor-hr for removal of air lift knee joints. At Green Bay, WI (3), it was estimated that 120 labor-hr were required to dewater and clean each set of contact (74.4 m x 11.1 m x 6.8 m SWD [244 ft x 36.3 ft x 22.3 ft]) and reaeration (74.4 m x 22.3 m x 6.2 m SWD [244 ft x 73.3 ft x 20.5 ft]) basins.

Labor for dewatering and cleaning and degritting at these three locations can be summarized as follows:

Location	Labor-hr/1,000 sq ft floor area
Terminal Island	4.4
Monroe	3.9
Green Bay	4.5

7.6.2 Diffuser Costs

The variety of fine pore diffuser types, materials, sizes, and throughput capacities described in Chapter 2 is matched by an equally extensive variety of unit costs for installation of these systems. Initial cost information reported by various participants in the EPA/ASCE Fine Pore Aeration Project and others is summarized in Table 7-18. As far as practical, these data represent just the cost of the diffusers, the below-water air piping, and their installation. However, reference to the comments in the table is essential for

Table 7-6b. Sample Desktop Calculations (Case 3 Fouling Rate): Zone 2 of Fine Pore Aeration Design Example (18-month Cleaning Interval)

- a. Find average F:
 Cleaning Interval = 18 months
 Rate of OTR loss = 2.1 percent/month
 Maximum loss of OTR = 40 percent
 Time to reach 40 percent loss = $(40)/(2.1) = 19$ months
 Average F for months 1 to 18 = $1 - [0.05(18)(2.1)/100] = 0.811$
 Overall average F = 0.8
- b. Determine airflow per diffuser (q):
 Average $OTR_1 = 2,517$ lb/d
 Average $OTR_1/SOTR = 0.498$
 Average F = 0.811
 Number of diffusers = 1,152
 From Equation 7-6, $q = 0.04(2,517)/[(0.498)(0.811)(1,152)(SOTE)] = 0.216/SOTE$ (7-20)
 From Table 7-2 (assuming linear relation between q and SOTE):
 SOTE = 0.303 for q = 0.5, and SOTE = 0.249 for q = 2.5, giving
 SOTE = $0.316 - 0.027(q)$ (7-21)
 From Equations 7-20 and 7-21, $q_d = 0.729$ scfm/diffuser
- c. Check constraints on q:
 Minimum airflow = 0.5 scfm/diffuser
 Mixing requirement = $(400)/(1,152) = 0.347$ scfm/diffuser
 $q_d = \text{MAX } \{0.729, 0.5, 0.347\} = 0.729$ scfm/diffuser
 Maximum airflow = 2.5 scfm/diffuser
 $q_d = \text{MIN } \{0.729, 2.5\} = 0.729$ scfm/diffuser
- d. Find pressure drop across diffuser and orifice:
 Pressure drop across clean diffuser = 5 in
 Pressure drop across fouled diffuser = 24 in
 Average degree of fouling = $(1 - F)/(40/100) = 0.473$
 Average diffuser pressure drop = $5 + 0.473(24 - 5) = 13.98$ in
 Average orifice pressure drop = $(2.67)(0.729)^2 = 1.42$ in
 Total average pressure drop = $(13.98 + 1.42)(0.036 \text{ psig/in}) = 0.57$ psig

a proper interpretation of the costs. As indicated, it was not always possible to isolate costs to this level. Also, as noted in the comments, some costs include a gas cleaning system as part of a ceramic fine pore aeration system package.

Oxygen transfer testing is an additional capital cost item. Normally, the cost of a field test is not closely related to the number of diffusers in an aeration basin. Such testing can add several dollars per diffuser to the total cost of the system, depending on specification requirements. Shop tests also add to initial costs, but not to the extent of field tests.

7.6.3 Air Filtration Costs

As discussed in Section 5.5.2, a new or upgraded air filtration system may be needed. At Madison, WI (10), the \$31,000 cost of the new air filtration system (static filters plus rotating fiberglass filters for three centrifugal blowers each with a capacity of 11,800 L/s [25,000 scfm]) was equivalent to \$1.99/installed diffuser. This system was estimated to require 10 labor-hr/yr for maintenance and \$200/yr for materials. Green Bay, WI (3) selected an in-line, 12,980-L/s (27,500-scfm) capacity canister filter for their ceramic disc quadrant. The \$30,000 installed cost (\$3.62/diffuser) achieves 90 percent removal of

particles /1 micron, and an estimated 18 labor-hr/yr are required for maintenance.

The air filtration system at Monroe, WI (2) - air supply capacity of 3,825 L/s (8,100 scfm) - is an American Airfilter UF-H unit consisting of a disposable glass fiber prefilter and a Biocel DH final filter. Maintenance is estimated to require 30 labor-hr/yr and \$200/yr for materials. The 525-L/s (12-mgd) Whittier Narrows treatment plant in Los Angeles County, CA (1) installed an air filtration system in 1980 at a cost of \$13,000 for three centrifugal blowers with a nominal total output of 13,925 L/s (29,500 scfm). They replace the glass fiber prefilters four times per year and the high-efficiency pleated paper filters once per year. Estimated annual filter replacement costs are \$2,000.

San Mateo, CA (21) has a double dry coarse and fine air filtration system for an installed blower capacity of 8,310 L/s (17,600 cfm) that requires 96 labor-hr/yr for maintenance and \$2,000/yr for the replacement elements. Durango, CO (22) uses a 3-stage air filtration system for a 2,125-L/s (4,500-cfm) total installed blower capacity to achieve 95 percent removal of 0.5-micron particles. Filters are changed annually (2 labor-hr/yr), and materials costs are estimated at \$600/yr.

Table 7-6c. Sample Desktop Calculations (Case 3 Fouling Rate): Zone 3 of Fine Pore Aeration Design Example (18-month Cleaning Interval)

- a. Find average F:
 Cleaning Interval = 18 months
 Rate of OTR loss = 1.5 percent/month
 Maximum loss of OTR = 40 percent
 Time to reach 40 percent loss = $(40)/(1.5) = 27$ months
 Average F for months 1 to 18 = $1 - [0.5(18)(1.5)/100] = 0.865$
 Overall average F = 0.865
- b. Determine airflow per diffuser (q):
 Average $OTR_1 = 1,060$ lb/d
 Average $OTR_1/SOTR = 0.693$
 Average F = 0.865
 Number of diffusers = 576
 From Equation 7-6, $q = 0.04(1,060)/[(0.693)(0.865)(576)(SOTE)] = 0.123/SOTE$ (7-22)
 From Table 7-2 (assuming linear relation between q and SOTE):
 SOTE = 0.284 for q = 0.5, and SOTE = 0.232 for q = 2.5, giving
 SOTE = $0.297 - 0.026(q)$ (7-23)
 From Equations 7-22 and 7-23, $q_d = 0.430$ scfm
- c. Check constraints on q:
 Minimum airflow = 0.5 scfm/diffuser
 Mixing requirement = $(400)/(576) = 0.694$ scfm/diffuser
 $q_d = \text{MAX } \{0.430, 0.5, 0.694\} = 0.694$ scfm/diffuser
 Maximum airflow = 2.5 scfm/diffuser
 $q_d = \text{MIN } \{0.694, 2.5\} = 0.694$ scfm/diffuser
- d. Find pressure drop across diffuser and orifice:
 Pressure drop across clean diffuser = 5 in
 Pressure drop across fouled diffuser = 24 in
 Average degree of fouling = $(1 - F)/(40/100) = 0.338$
 Average diffuser pressure drop = $5 + 0.338(24 - 5) = 11.42$ in
 Average orifice pressure drop = $(2.67)(0.694)^2 = 1.29$ in
 Total average pressure drop = $(11.42 + 1.29)(0.036 \text{ psig/in}) = 0.46$ psig

Table 7-7. Present Worth Costs as a Function of Cleaning Interval for Case 3 Fouling Rate

Cleaning Interval, months	Present Worth Costs, \$1,000				
	Maintenance	Cleaning	Energy	Initial	Total
3	48	144	270	927	1,389
4	48	108	274	927	1,357
6	48	72	284	927	1,331
8	48	53	294	927	1,322
9	48	47	299	927	1,320
10	48	42	304	927	1,321
11	48	38	310	927	1,323
12	48	35	316	927	1,326
13	48	32	322	927	1,329
15	48	28	334	927	1,337
18	48	23	349	927	1,346
24	48	17	371	927	1,363

7.6.4 Blower Costs

Figure 7-6 summarizes blower costs updated to 1988 (Marshall & Swift ECI = 847) obtained from a variety of sources. The data from EPA's CAPDET cost estimating program (24) are for a 1,415-L/s (3,000-scfm) rotary positive displacement blower; a vertically split, multistage 5,665-L/s (12,000-scfm) centrifugal blower; and a pedestal-type, single-stage 23,600-L/s (50,000-scfm) centrifugal blower. Also shown in Figure

7-6 are uninstalled blower costs for several Canadian installations (20). These costs are for individual blowers of the indicated capacity. Increasing these costs by 40-60 percent may be a reasonable estimate of installation costs for retrofits where a blower building already exists (20). For totally new construction, purchased blower costs can be increased by 200-300 percent to estimate final installed costs (20).

Figure 7-1. Present worth operating costs of example fine pore aeration system for Case 3 fouling rate.

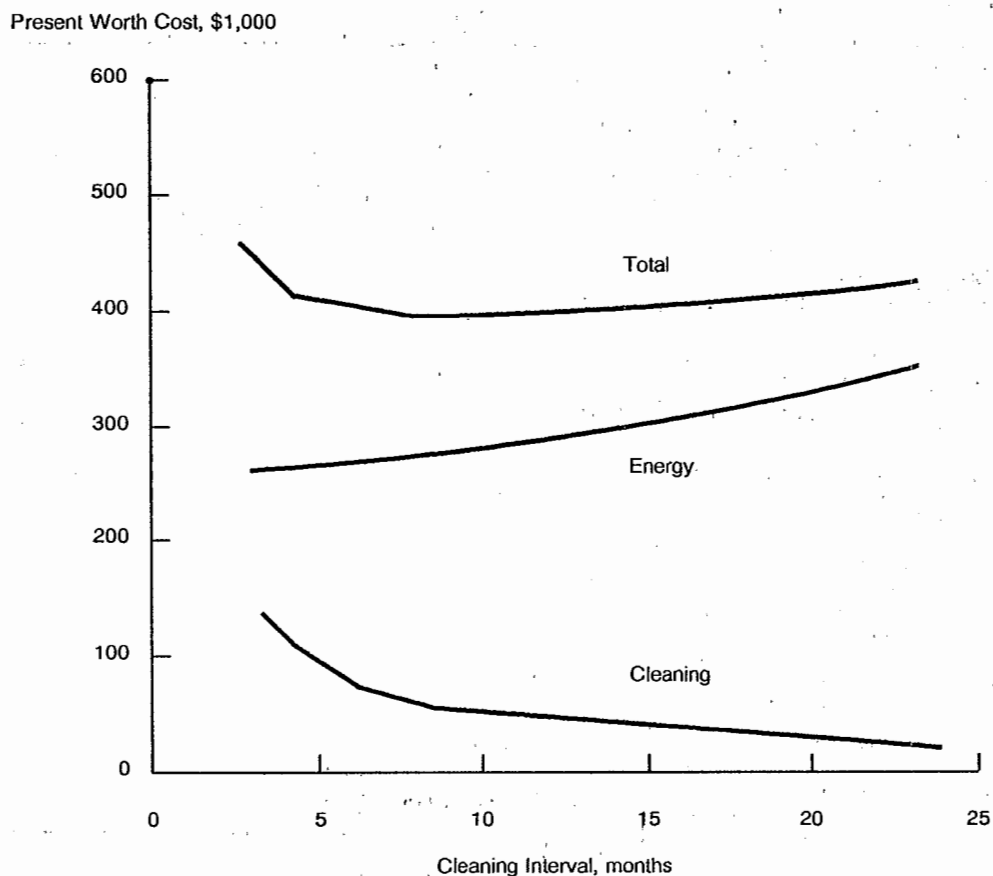


Table 7-8. Economic Comparison of Newly Constructed Fine Pore and Coarse Bubble Aeration Systems

Fouling Rate	Optimal Cleaning Interval, months	Lowest Present Worth Costs, \$1,000				
		Maintenance	Cleaning	Energy	Initial	Total
<u>Results of Desk-Top Computations</u>						
Case 1	27	48	14	277	927	1,265
Case 2	18	48	23	284	927	1,281
Case 3	9	48	47	299	927	1,320
Case 4	7	48	61	314	927	1,349
Coarse Bubble		64	0	580	869	1,513
<u>Results of Spreadsheet Computations</u>						
Case 1	24	48	17	293	927	1,284
Case 2	19	48	21	305	927	1,301
Case 3	9	48	47	320	927	1,341
Case 4	7	48	61	337	927	1,372
Coarse Bubble		64	0	610	869	1,543

Figure 7-2. Optimal cleaning intervals and costs for example fine pore aeration system for alternative fouling rates.

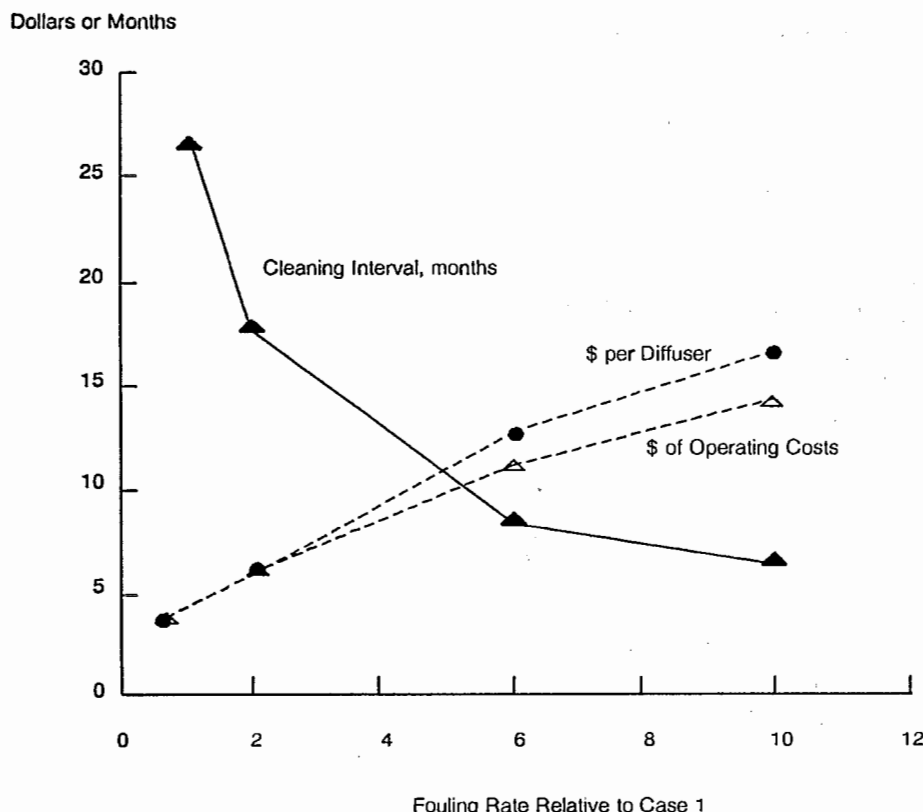


Figure 7-6 also shows uninstalled blower and piping costs to the aeration basin for five facilities plotted as a function of total installed blower capacity rather than as a function of individual blower sizes (22). For these five facilities, total blower costs (including buildings, blowers, piping to basins, electrical work, and all related construction costs) averaged 300 percent of the uninstalled blower and piping costs.

Many small facilities use rotary, positive displacement blowers. For small to intermediate size (<220 L/s [5 mgd]) plants, the capital cost of the blowers (uninstalled) is usually about 70-80 percent of the capital cost of the aeration equipment itself (19). This cost estimate applies to blowers <75 kW (100 hp).

In 1985, Madison, WI (10) installed three new 900-kW (1,200-hp) centrifugal blowers, each with a capacity of 5,900-11,800 L/s (12,500-25,000 cfm). Installed blower costs excluding the blower building were \$663,000 (\$18.73/L/s [\$8.84/scfm] capacity) with an additional \$254,000 for an automated control system. The installed cost per individual blower (adjusted to 1988) is shown in Figure 7-6. For 1986, DO sensor maintenance associated with the control system required 180 labor-hr and \$90 for materials. In

comparison, the new blowers required 40 labor-hr and \$200 for materials in 1986.

The blower system at the Terminal Island treatment plant in Los Angeles, CA (1) was not upgraded when fine pore diffusers were added. Three existing 1,120-kW (1,500-hp) centrifugal Roots blowers are capable of delivering 18,400 L/s (39,000 acfm) each. The plant aeration system is automated, requiring 500 labor-hr/yr for DO sensor maintenance. The blowers, originally installed in 1976, required an estimated 500 labor-hr for maintenance and an estimated \$12,000/yr for materials in 1987.

Monroe, WI (2) installed four new 956-L/s (2,025-scfm) positive displacement blowers in their existing blower building in 1985. Installed costs, including the air f 1,120-kW (1,500-hp) centrifugal Roots blowers are capable of delivering 18,400 L/s (39,000 acfm) each. The plant aeration system is automated, requiring 500 labor-hr/yr for DO sensor maintenance. The blowers, originally installed in 1976, required an estimated 500 labor-hr for maintenance and an estimated \$12,000/yr for materials in 1987.

Table 7-9. Sample Desktop Calculations for Coarse Bubble Aeration Design Example

A. Present Worth Initial Costs

From Table 7-3, P_w (initial costs) = \$869,000

B. Present Worth Energy Costs

1. Average airflows and pressure drops within each aeration zone (see Table 7-10 for detailed calculations for Zone 1):

	<u>Zone 1</u>	<u>Zone 2</u>	<u>Zone 3</u>
Average airflow/diffuser, scfm	9.35	8.66	6.12
Average pressure drop, psig	0.315	0.270	0.042
Number of diffusers	300	200	100

2. Total system airflow (q_s):

From Equation 7-10, $q_s = 9.35(300) + 8.66(200) + 6.12(100) = 5,149$ scfm

3. Total system pressure drop (P_d):

Submergence + line loss = 6.2 psig

Maximum drop in aeration zones = 0.315 psig

From Equation 7-11, $P_d = 6.2 + 0.315 = 6.52$ psig

4. Monthly energy consumption (WE_M):

Barometric pressure = 14.3 psia

Blower efficiency = 0.7

Compressibility factor = $[14.3 + 6.52]/14.3 \cdot 0.283 - 1 = 0.112$

From Equation 7-15, $WE_M = 8.268(5,149)(14.3)(0.112)/(0.7) = 97,400$ kWh

5. Present worth cost of energy:

Unit cost of power = \$0.05/kWh

Discount rate = (8 percent/yr)/100/12 = 0.0067/month

Analysis period = 240 months

Monthly power cost = $\$0.05(97,400) = \$4,870$

From Equation 7-4, $SPWF = [(1 + 0.0067)^{240} - 1]/[0.0067(1 + 0.0067)^{240}] = 119.2$

P_w (energy costs) = $\$4,870(119.2) = \$580,500$

C. Present Worth Cost of Maintenance

Discount rate = 0.0067/month

Analysis period = 240 months

Monthly maintenance cost = \$535

From Equation 7-4, $SPWF = 119.2$

P_w (maintenance costs) = $\$535(119.2) = \$63,770$

D. Present Worth Cleaning Costs

Diffuser cleaning costs = 0

E. Total Present Worth Cost

P_w (total cost) = $\$869,000 + \$580,500 + \$63,770 + \$0 = \$1,513,270$

Table 7-10. Sample Desktop Calculations for Zone 1 of Coarse Bubble Aeration Design Example

- a. Average $F = 1.0$

- b. Determine airflow per diffuser, q :

Average oxygen demand = 3,617 lb/d

Average $OTR/SOTR = 0.516$

Average $F = 1.0$

$SOTE = 10/100 = 0.1$

Number of diffusers = 300

From Equation 7-6, $q = 0.04(3,617) \div [(0.516)(1.0)(300)(0.1)] = 9.35$ scfm/diffuser

- c. Check constraints on q :

Minimum airflow = 2 scfm/diffuser

Mixing requirement = $(400)/(300) = 1.33$ scfm/diffuser

$q_d = \text{MAX} \{9.35, 2, 1.33\} = 9.35$ scfm/diffuser

Maximum airflow = 15 scfm/diffuser

$q_d = \text{MIN} \{9.35, 15\} = 9.35$ scfm/diffuser

- d. Find pressure drop:

Average orifice pressure drop = $(0.1)(9.35)^2 = 8.74$ in

Total average pressure drop = $(8.74)(0.036 \text{ psig/in}) = 0.315$ psig

Table 7-11. Sensitivity of Fine Pore Aeration Costs to Changes in Price of Power and Diffuser Cleaning

Power Price, \$/kWh	Cleaning Price, \$/diffuser	Optimal Cleaning Interval, months	Present Worth Cost, \$1,000			
			Maint.	Clean.	Energy	Tot. Operating
<u>Fouling Rate</u>						
0.05	1.00	27	48	14	277	339
0.05	0.50	19	48	11	271	330
0.10	1.00	19	48	21	541	610
0.10	0.50	13	48	16	532	596
<u>Fouling Rate</u>						
0.05	1.00	9	48	47	299	394
0.05	0.50	7	48	30	288	366
0.10	1.00	7	48	61	577	686
0.10	0.50	5	48	43	558	649

Table 7-12. Economic Comparison of Retrofit Fine Pore and Existing Coarse Bubble Aeration Systems

Fouling Rate	Lowest Present Worth Costs, \$1,000		
	Operating	Initial	Total
8-percent Discount Rate			
Case 1	338	237	576
Case 2	354	237	591
Case 3	397	237	634
Case 4	422	237	659
Coarse Bubble	647	0	647
4-percent Discount Rate			
Case 1	468	237	705
Case 2	489	237	726
Case 3	543	237	780
Case 4	584	237	821
Coarse Bubble	893	0	893

Table 7-13. Input Data Form for Oxygen Requirements for Economic Analysis Spreadsheet - Case 3 Fouling Rate

Month	Total System OTR _i , lb/d			OTR _i /SOTR		
	Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3
Jan.	2,108	1,192	275	0.344	0.516	0.693
Feb.	2,497	1,551	605	0.344	0.516	0.693
Mar.	3,047	1,903	737	0.344	0.516	0.693
April	3,410	2,097	821	0.344	0.516	0.693
May	3,722	2,438	1,155	0.344	0.516	0.693
June	4,290	3,300	1,408	0.344	0.462	0.693
July	4,730	3,586	1,562	0.344	0.462	0.693
Aug.	5,445	4,134	2,009	0.344	0.516	0.693
Sep.	4,400	3,322	1,434	0.344	0.462	0.693
Oct.	4,202	3,223	1,375	0.344	0.462	0.693
Nov.	3,047	1,903	737	0.344	0.516	0.693
Dec.	2,497	1,551	605	0.344	0.516	0.693

Press <Alt-M> to return to Main Menu
Press <Alt-D> to return to Data Menu

Monroe, WI (2) installed four new 956-L/s (2,025-scfm) positive displacement blowers in their existing blower building in 1985. Installed costs, including the air loperation/hr of maintenance. DO sensor maintenance at this plant requires 35 labor-hr/yr and \$100 for materials.

San Mateo, CA (21) operates two 112-kW (150-hp) and five 93-kW (125-hp) blowers that require about 200 labor-hr/yr for routine repair and maintenance and an additional \$20,000/yr in materials costs.

The capital cost of two new 1,220-L/s (2,590-icfm) centrifugal blowers purchased by Frankenmuth, MI (12) was estimated in 1985 as \$22,000, or \$9.01/L/s (\$4.25/scfm) capacity. The uninstalled cost per blower, adjusted to 1988, is also given in Figure 7-6.

In the absence of specific blower maintenance cost information, estimates of annual maintenance requirements of 3 percent of the uninstalled mechanical equipment cost for centrifugal blowers and 5 percent for positive displacement blowers (20), and 5 percent for either type of blower (25) have been recommended.

7.6.5 Ceramic Diffuser Gas Cleaning Costs

Sanitaire markets a proprietary gas cleaning process (U.S. Patent No. 4,382,867) that normally uses HCl gas. Over 60 systems had been installed as of November 1988. The 1988 installed cost for the gas delivery hardware and license fee was reported (26) to average \$10/diffuser with a typical range of \$8-12/diffuser, depending on system size. Of this total, the royalty or license fee is \$6/diffuser. For large

Table 7-14. Input Data Form for Diffuser Characteristics for Economic Analysis Spreadsheet - Case 3 Fouling Rate

	Zone 1	Zone 2	Zone 3
Minimum Airflow, scfm/diffuser	0.5	0.5	0.5
Maximum Airflow, scfm/diffuser	2.5	2.5	2.5
SOTE at Min. Airflow, percent	34.8	30.3	28.4
SOTE at Max. Airflow, percent	26.4	24.9	23.2
OTE loss rate, percent/month	3	2.1	1.5
Maximum percent OTE Loss	40	40	40
Minimum (Clean) DWP, in	5	5	5
Maximum (Fouled) DWP, in	24	24	24
Orifice P-drop at 1 scfm, in	2.67	2.67	2.67
Mixing Requirement, scfm	400	400	400
Number of Diffusers	1,920	1,152	576

Press <Alt-M> to return to Main Menu
Press <Alt-D> to return to Data Menu

Table 7-15. Input Data Form for Economic Factors for Economic Analysis Spreadsheet - Case 3 Fouling Rate (9-month Cleaning Interval)

Factor	Value
Discount Rate, percent	8
Diffuser Installation Cost, \$/unit	0
Other Initial Costs, \$	927,000
Electricity Rate, \$/kWh	0.05
Diffuser Cleaning Cost, \$/unit	1
Cleaning Interval, months	9
Routine Maintenance, \$/yr	4,800
Analysis Period, months	240
Start-up Month (Jan = 1, etc.)	6

Press <Alt-M> to return to Main Menu
Press <Alt-D> to return to Data Menu

Table 7-16. Input Data Form for Blower Characteristics for Economic Analysis Spreadsheet - Case 3 Fouling Rate

Item	Value
Barometric Pressure, psia	14.3
Pressure Head w/o Diffusers, psig	6.2
Overall Blower Efficiency, percent	70

Press <Alt-M> to return to Main Menu
Press <Alt-D> to return to Data Menu

sanitary authorities with many plants, it may be possible to obtain a "blanket license" for as low as \$2-3/diffuser. The gas dosage per cleaning is usually 90-100 g (0.02-0.2 lb) HCl/diffuser (27). Gas cleaning costs are summarized in Table 7-19 for nine treatment plants.

The estimated installed cost of a Sanitaire gas cleaning system at Frankenmuth, WI (12), including

Table 7-17. Output Display from Economic Analysis Spreadsheet - Case 3 Fouling Rate (9-month Cleaning Interval)

Operating Period, months	240
Present Worth Costs, \$1,000:	
Initial	927.0
Energy	319.5
Cleaning	46.7
Maintenance	47.8
Total	1,341.0

fees, was \$25,000, or \$10.42/diffuser. At this plant, dynamic wet pressure (DWP) is monitored on a weekly schedule (3 diffusers) requiring about 50 labor-hr/yr. Cleaning is normally performed at 38-46 cm (15-18 in) DWP. The average HCl cost for 1987 was \$3.42/kg (\$1.55/lb). From April 1986 through August 1987, an average 32 kg (71 lb) HCl/month were used, with the average dose per diffuser varying during the period. Ignoring the very high dosages during the first 2 months of start-up, the average monthly dose was 9 g (0.02 lb)/installed diffuser. Average labor requirements for gas cleaning were 0.1 labor-hr/kg (0.045 labor-hr/lb) HCl delivered.

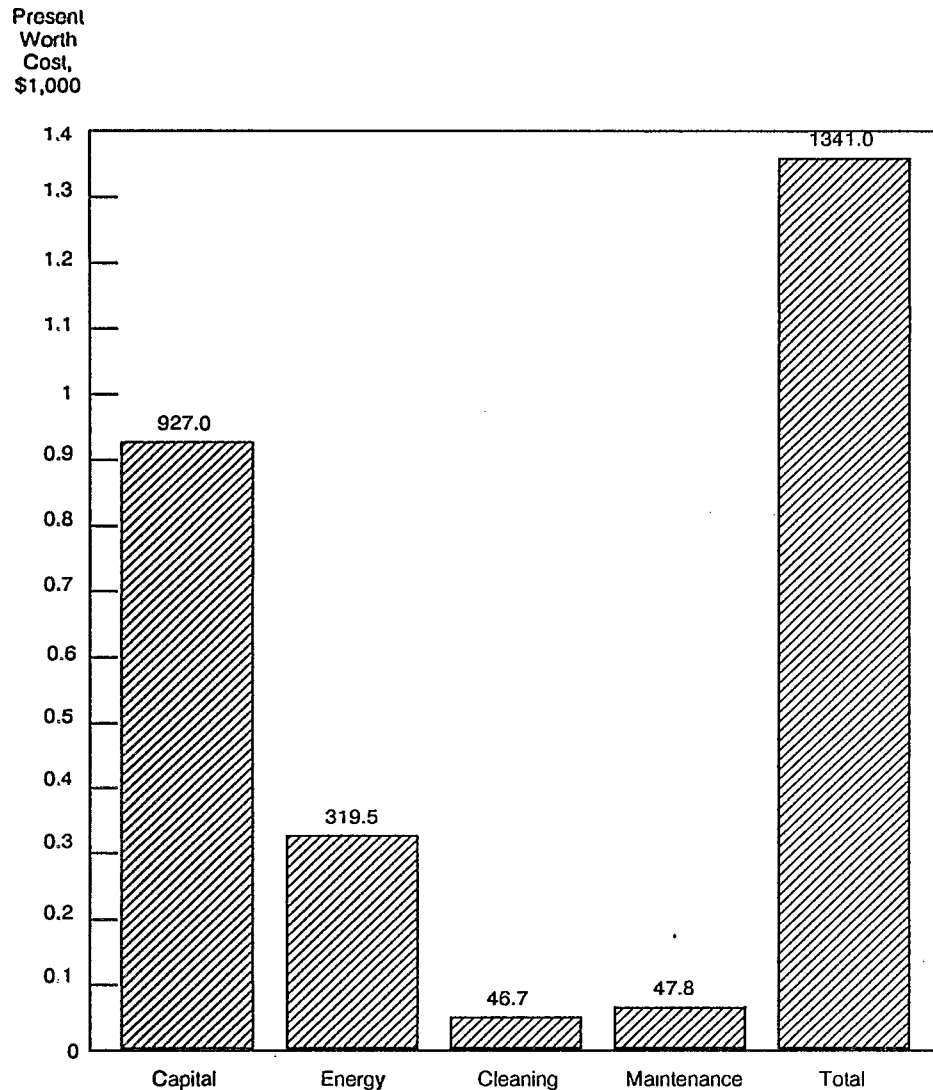
The total installed cost of a gas cleaning system at Green Bay, WI (3), consisting of the building (\$59,100), royalty, and feed system, was \$128,334, or \$15.50/diffuser in 1986. The normal gas dose was 45 g (0.1 lb) HCl/diffuser at an average HCl cost of \$1.48/kg (\$0.67/lb). Thus far, 5 of the 10 installed grids have been cleaned with a labor expenditure of 14 labor-hr/cleaning, which is equivalent to 0.075 labor-hr/kg (0.034 labor-hr/lb) HCl or 4.6 labor-hr/1,000 diffusers, for changing cylinders and monitoring the gas cleaning system during the procedure.

A gas cleaning system at the Whittier Narrows treatment plant in Los Angeles County, CA (1) was installed at a nominal cost for research purposes. HCl costs (1987) were \$2.58/kg (\$1.17/lb) using 272-kg (600-lb) cylinders, plus \$500/cylinder for shipping. Additional costs are incurred for demurrage and loading and unloading cylinders. Gas dosages have averaged 23 g (0.05 lb)/diffuser. The estimated time required for a cleaning is:

Setup time	2.0 hr
HCl cleaning time:	
1,000 units per grid	2.5 hr
500 units per grid	1.5 hr
Cleanup time	1.5 hr

Setup and cleanup times include moving cylinders, attaching hoses, and loading and unloading needed equipment.

Figure 7-3. Present worth costs generated by economic analysis spreadsheet – example fine pore aeration system: Case 3 fouling rate.



7.6.6 Other Diffuser Cleaning Methods and O&M Costs

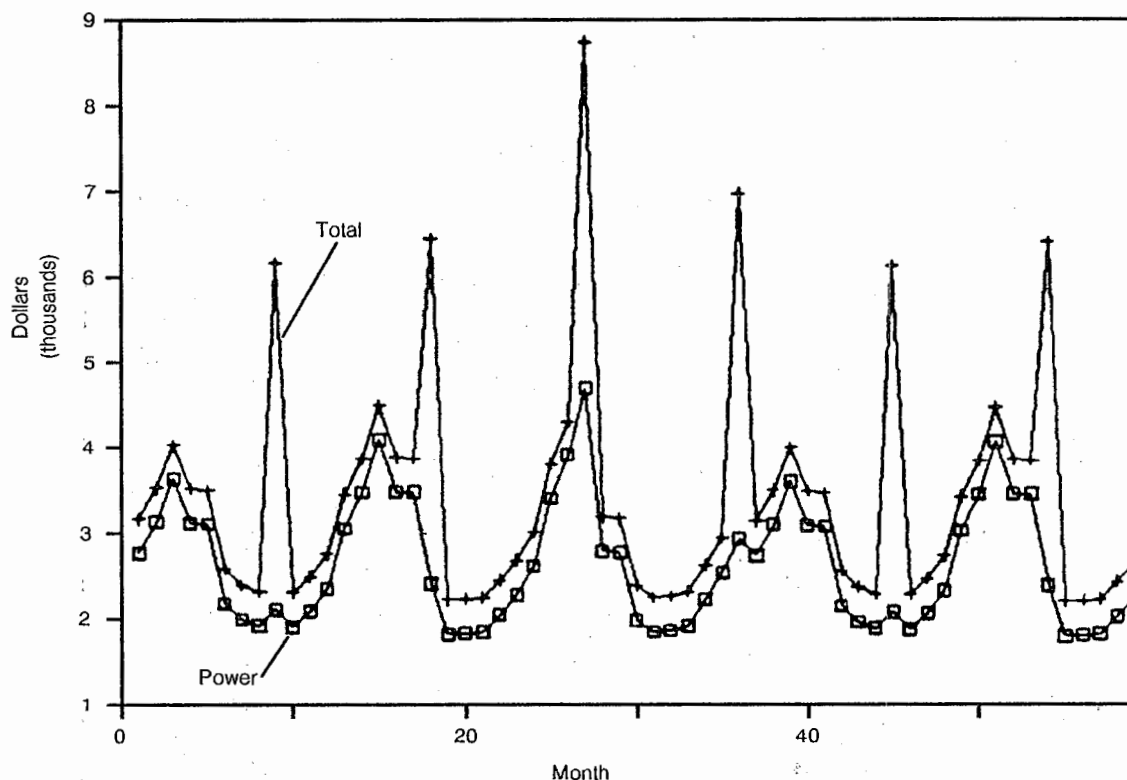
A variety of O&M activities are associated with the use of fine pore aeration systems, including:

- monitoring for diffuser fouling,
- basin drainage for visual inspection,
- cleaning diffusers by high-pressure hosing,
- cleaning diffusers by brushing,
- cleaning diffusers by chemical treatment/hosing (Milwaukee method),

- other less frequently used diffuser cleaning methods,
- diffuser membrane replacement, and
- repair of cracks, leaks, etc.

The cost of ceramic dome diffuser cleaning was significantly influenced by the work rules and procedures employed at a particular plant (28). This analysis of the unit operations associated with basin and diffuser cleaning led to the generalized time

Figure 7-4. Monthly operating costs generated by economic analysis spreadsheet during first 5 years of operation – example fine pore aeration system: Case 3 fouling rate.



estimates for various unit operations summarized in Table 7-20.

At Madison, WI (10), a combination of off-gas testing and DWP monitoring requires 40 labor-hr/yr. Annual inspections require just 4 labor-hr for basin drainage and gross cleaning of each 10,200-m³ (2.7-mil gal) basin. High-pressure hosing and acid application were each estimated to require 0.03 labor-hr/diffuser with a chemical cost for acid application of \$0.014/diffuser.

By the end of 1986, Ridgewood, NJ (6) had 3-3/4 years of experience with their ceramic dome diffuser system. Diffusers were cleaned with a high-pressure fire hose or acid cleaned with 20 percent HCl diluted 1:1 with tap water and scrubbed into each diffuser. Hose cleaning required 0.012 labor-hr/diffuser and acid cleaning 0.025 labor-hr/diffuser. A summary of diffuser cleaning and repair costs for Ridgewood is given in Table 7-21.

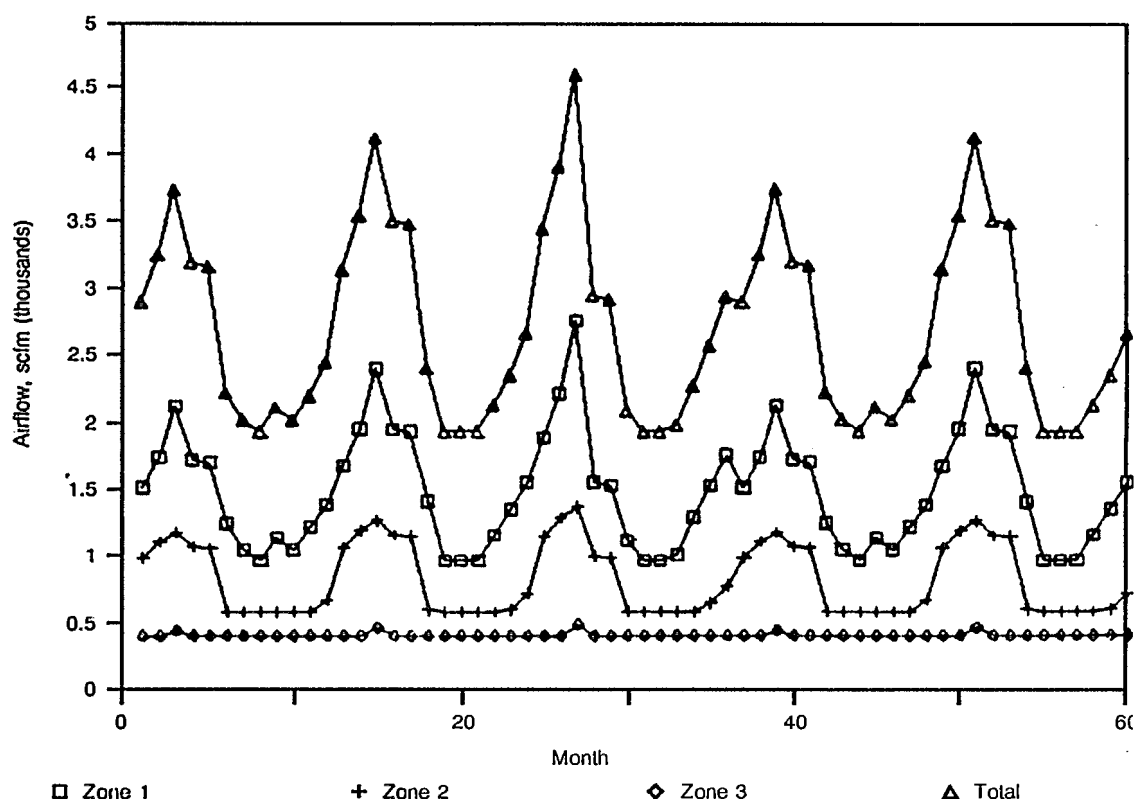
Repairs included tightening bolts, sealing cracks, and adjusting and replacing domes and bolts. Ridgewood now uses only fire hose cleaning in early Spring and late Fall for each basin (8).

The modified Milwaukee diffuser cleaning method was applied at the Whittier Narrows treatment plant (29).

The method consists of: 1) low-pressure hosing for approximately 7.5 seconds/diffuser, 2) application of 50-percent muriatic acid solution to the media surface of each diffuser, 3) air/acid agitation for approximately 10 minutes, and 4) another 7.5 seconds/diffuser of low-pressure hosing. Cleaning 2,026 ceramic disc diffusers required 42 labor-hr, or 0.021 labor-hr/diffuser. Of this total, 12 labor-hr were for the top man connected with a safety line to the bottom men because the basins were considered as confined spaces. Cleaning costs for acid, air, water and capitalized equipment costs (spray equipment, protective clothing, etc.) amounted to \$145/cleaning, or \$0.071/diffuser. The \$20/hr labor cost increased the total unit cleaning cost to \$0.49/diffuser.

Ceramic dome diffusers at the San Mateo, CA treatment plant (21) are cleaned every 6 months because of the development of coarse bubbling and increased blower discharge pressures. Dewatering the aeration basins (3,785 m³ [1.0 mil gal] capacity) by pumping and gross cleaning require about 24 hours or 0.008 labor-hr/diffuser. Several cleaning methods, including acid cleaning, have been evaluated but the combination of high-pressure hosing and brushing yields satisfactory results and has become the method of choice. Brushing and high-pressure hosing require

Figure 7-5. Monthly airflow generated by economic analysis spreadsheet during first 5 years of operation – example fine pore aeration system: Case 3 fouling rate.



a total of 0.016 labor-hr/diffuser. Checking bolt tension and leak checking the system after cleaning adds another 0.014 labor-hr/diffuser, resulting in a total cost of \$0.57/diffuser (\$15.00/hr labor) for a complete cleaning cycle. The diffuser failure rate is only 1-2 units/1,000 diffusers/cycle. This rate has been steady over the 4 years since system installation.

Hartford, CT (15,16) cleans according to the Milwaukee method as follows: dewater (air on), high-pressure hose (air on), apply 50 mL acid/diffuser (air off), brush diffusers (air off), and re hose (air on). The acid solution is a commercial product (ZEP) containing 22 percent HCl and surfactants. Estimated costs for the Milwaukee method as applied at Hartford are summarized in Table 7-22.

With a labor rate of \$20/hr, the cost per cleaning at Hartford, including leak repair, was \$1.35/diffuser. Excluding the costs for spare parts and leak repair, the average cleaning cost was \$0.70-\$0.75/diffuser. These cleaning costs do not include grit removal.

Monroe, WI (2) has three 2-pass basins, each containing 900 ceramic disc diffusers. Aeration basin dewatering requires pumping and consumes 0.009 labor-hr/diffuser. Cleaning is by high-pressure hosing,

acid spray/soak, brushing, and rehosing. Both hosings require a total of 0.006 labor-hr/diffuser, acid application 0.005 labor-hr/diffuser, and brushing 0.007 labor-hr/diffuser. An additional 0.004 labor-hr/diffuser is spent checking bolt tension and for leaks. No failures were observed in the first year of operation. At Monroe's \$12/hr labor rate, cleaning costs for labor total \$0.37/diffuser, of which \$0.11/diffuser is for basin dewatering.

The cost of a kiln, electrical hookup, and accessories installed at Bozeman, MT (30,31) in 1982 was about \$3,000. The ceramic disc diffusers in a given basin (682/basin) are changed every 1-2 years and the removed diffuser stones fired 50 at a time at temperatures of 1,540-1,760C (2,800-3,200F). The diffuser stones are placed in the blower room to dry for about 1 month before firing since firing wet stones led to problems with breakage. Careful placement of stones in the kiln is required, representing about 1 hr/load (0.02 hr/diffuser). Removal time is about 30 minutes/load. In 1978, labor for removing the diffuser stones from the basins (remove screw caps and O-rings, take to kiln) was reported as 0.035 labor-hr/stone and reinstallation was also reported as 0.035 labor-hr/stone. Stone removal time has been reduced

Table 7-18. Initial Cost Information for Selected Fine Pore Aeration Systems

Plant	Date Installed	Diffuser Type	No. Diffusers Installed	Installation Cost			Notes	Ref.
				Material, \$/diffuser	Labor, hr/diffuser	Total, \$/diffuser		
Green Bay, WI	May 1986	Sanitaire Ceramic Discs	8,276	33.83		44.87	C,R,a	3-5
Green Bay, WI	Jan. 1986	Parkson Perf. Membrane Tubes	6,018	55.33		68.18	C,R,a	3-5
Ridgewood, NJ	April 1983	Gray Ceramic Domes	1,080			201.85	C,R,b	6-8
Madison, WI	1985	Sanitaire Ceramic Discs	15,576			28.44	C,N,c	9,10
Frankenmuth, MI	Dec. 1985	Sanitaire Ceramic Discs	2,400	47.08	0.33	53.75	P,R,d	11,12
Valencia, CA	Sept. 1986	Nokia Rigid Porous Plastic Discs	5,490	24.42		59.20	C,R,e	1,13
Terminal Island, CA	June 1987	AERTEC Nonrigid Porous Plastic Discs	770	32.47	0.125	36.21	P,R,f	1,13
Terminal Island, CA	April 1987	Parkson Perf. Membrane Tubes	1,000	60.00	0.96	89.00	P,R,g	1,13
Trinity River Auth., TX	Oct. 1987	Sanitaire Ceramic Discs	40,250			34.75	R,h	14
Newark, OH	Spring 1985	Parkson Perf. Membrane Tubes	4,000			75.00	C,R,i	14
Hartford, CT	Fall 1982	Norton Ceramic Discs	13,316	~25		~45	C,R,j	15,16
Glastonbury, CT	Summer 1984	FMC Rigid Porous Plastic Tubes	320	~38	0.75	~53	P,R,k	16,17
Whittier Narrows, CA	1980	Sanitaire Ceramic Discs	2,026			62.98	C,R,l	1,13
		Norton Ceramic Domes	5,064					
Monroe, WI	1985	Sanitaire Ceramic Discs	2,700			31.85	C,R + N,m	2,18
Richardson, TX	Nov. 1987	EDI Ceramic Plates	112	288.40	0.5	~303	P,R,n	19
Amsterdam, NY	Sept. 1986	EDI Ceramic Plates	160	237.50	0.5	~253	n	19
Sycamore Creek, OH	Under Const.	EDI Ceramic Plates	427	278.69	0.5	~294	n	19
Piqua, OH	March 1988	EDI Ceramic Plates	170	296.18	0.5	~311	n	19
Guelph No. 1, Canada	1986	Sanitaire Ceramic Discs	4,000	44.27			o	20
Guelph Nos. 2 and 3, Canada	1988	Sanitaire Ceramic Discs	6,704	47.36			p	20
Mid Halton, Canada	1988	Sanitaire Ceramic Discs	1,428			61.92	q	20
Georgetown, Canada	1987	Sanitaire Ceramic Discs	6,082	50.64			r	20
Oakville, Canada	1987	Sanitaire Ceramic Discs	3,391			73.60		20
Celdonia, Canada	1988	Envirex Perf. Membrane Discs	232			92.80		20
San Mateo, CA	1985-1986	Norton Ceramic Domes	11,800			50.00	C,R,s	21
Broomfield, CO	1987	Gray Ceramic Domes	3,792			35.60	C,n,t	22,23
Yakima, WA	1988	Sanitaire Ceramic Discs	7,400			46.22	C,R,u	22,23
Serra, CA	1989	Statiflo Ceramic Domes	9,170			46.67	C,R,v	22,23
Littleton, CO	1985	Gray Ceramic Domes	4,800			58.33	w	22,23
Edmonds, WA	Planned	Sanitaire Ceramic Discs	5,000			60.00	x	22,23

Table 7-18 Notes:

- C Installation by contractor.
- P Installation by plant personnel.
- N New installation.
- R Retrofit installation.
- a Basin degritting/cleaning by plant personnel. Total cost includes bond, mobilization, concrete (\$18,400), demolition (\$10,000), equipment, labor, and miscellaneous.
- b Payment for installation made annually based on energy savings for that year. Installed cost is sum of all payments to be made until a total of \$201.85/diffuser is reached.
- c Cost is 17.1 percent of total cost of blowers, blower building, automated controls, above-water air piping, air filtration system, and diffuser installation.
- d Does not include gas cleaning system cost. Includes 6 new airflow isolation/control valves. Total cost based on plant superintendent estimate of average labor cost.
- e Cost includes basin cleaning, old equipment removal, and new air filtration system.
- f Tube diffusers retrofitted directly to existing swing arms; labor does not include basin cleaning and old equipment removal.
- g Does not include labor for basin cleaning and old equipment removal; capital cost includes diffusers at \$30.00 each plus piping and pipe supports.
- h Not including basin cleaning costs.
- i All new air piping from outside blower building to diffusers; cost includes basin preparation.
- j Includes removal of coarse bubble system, installation of new drop pipes and diffuser system, and installation of "biocell" air filters in inlet blower plenums. Air filtration cost was about \$25,000. Component costs estimated from lump sum bid.
- k Retrofit to existing reconditioned swing arm assemblies; \$30.00/diffuser unassembled; \$7.80/diffuser miscellaneous pipe fittings/hardware; \$15.00/diffuser installation.
- l Total cost including air filtration estimated at \$446,500; cost of \$62.98/diffuser is average for both ceramic diffuser types. Total price includes 350 spare Sanitaire diffusers, 876 spare Norton diffusers, and installation of plugged baseplates on the laterals to accept the spare diffusers, if needed.
- m Does not include costs for basin cleaning, old equipment removal, and installation of stainless steel leveling rods for new system.
- n 4 sq ft ceramic plate diffuser; capital cost is bid price; installed cost estimated by vendor and includes concrete in diffuser base and below-water piping.
- o Materials cost for diffusers, piping to headers, supports, etc., delivered to site was \$30.95; gas cleaning system cost including license fee was \$13.32/diffuser.
- p Materials cost includes diffusers, piping to headers, supports, etc., delivered to site plus gas cleaning system including license fee.
- q Installed cost for diffusers, piping and supports was \$39.20/diffuser; \$22.72/diffuser was for gas cleaning system.
- r Materials cost for diffusers, piping to headers, supports, etc., delivered to site was \$34.2/diffuser; gas cleaning system cost including license fee was \$16.44/diffuser.
- s Cost represents two separate contracts, one for \$550,000 in 1985 and another for \$40,000 in 1986.
- t Cost based on October 1985 bid data. Addition of new stainless steel header piping increased installed cost to \$87.02/diffuser.
- u Cost based on January 1988 bid data.
- v Cost based on contractor bid. Addition of new stainless steel header piping plus 500 spare domes increased installed cost to \$86.68/diffuser.
- w Cost based on contractor breakout in March 1985.
- x Cost based on contractor 1988 bid data. Installation planned in 1990.

to 5 hr/basin (0.007 hr/diffuser) as the operators have gained more experience with this operation. Power for the kiln firing averages \$0.02/stone.

7.6.7 Power Charges

Electric energy charges are highly specific to the utility providing the service. The following types of monthly charges may be contained in a utilities rate structure:

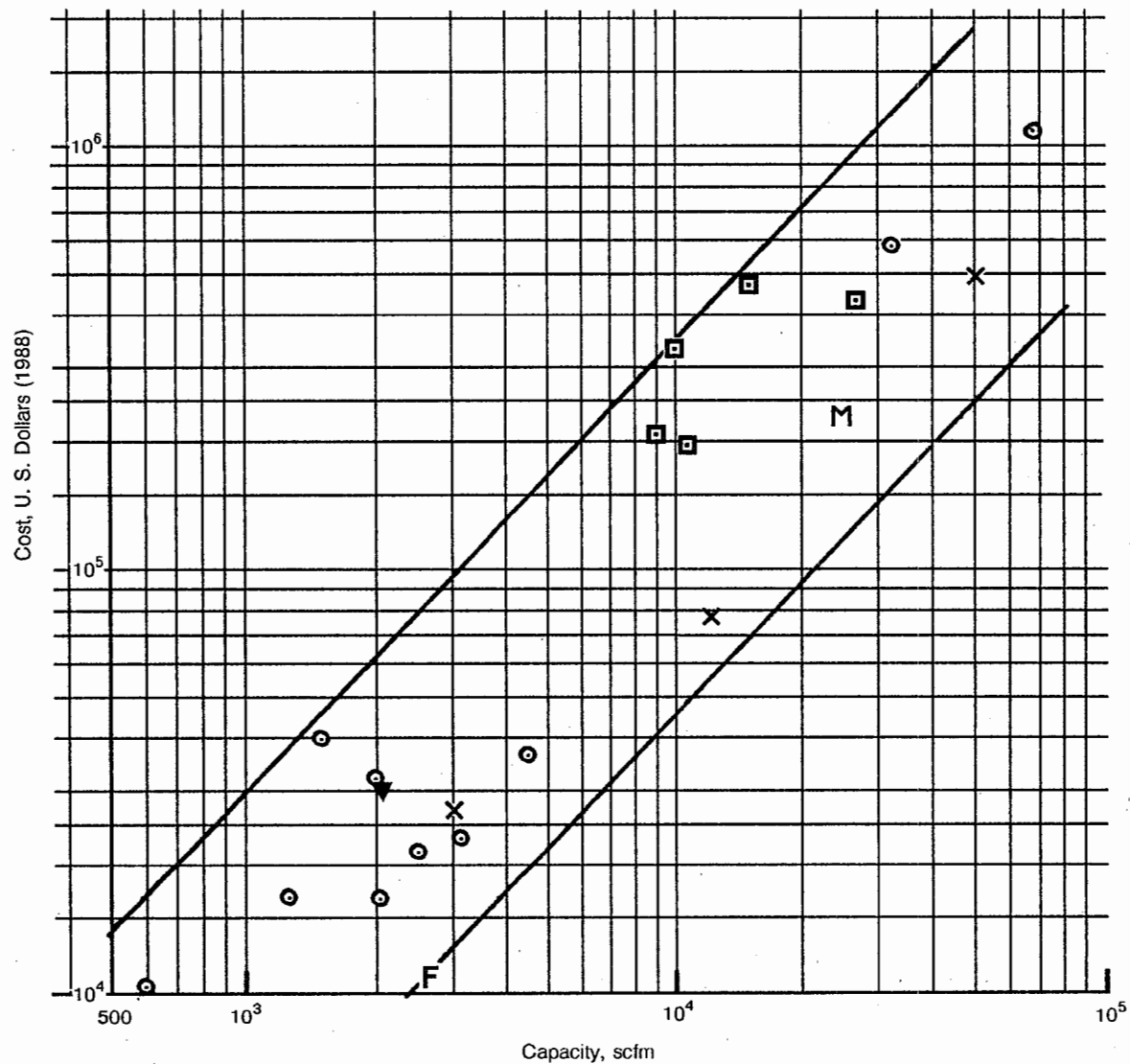
- Flat customer charge
- Demand charge (\$ per maximum kW demand in past)
- Energy charge (\$ per kWh used in current month)
- Power factor clause

These charges may also vary with time of day, day of week, or season of the year. An example rate schedule for the Wisconsin Public Service Corporation is shown in Table 7-23.

Rate schedules of this type make it difficult to estimate aeration energy costs accurately. Use of a flat average \$/kWh energy price in the analysis may produce misleading results unless it represents a composite number that somehow reflects the relative contributions of all demand charges and peak/off-peak pricing.

There can be a significant cost disadvantage to the use of large blowers with substantial excess capacity to satisfy an occasional peak demand. Consider a hypothetical situation using the rate schedule in Table 7-23 in which a 750-kW (1,000-hp) blower motor drawing 70 percent of its rated load is turned on to satisfy peak load requirements during a period of peak plant demand. The incremental cost to operate this blower for various time periods is shown in Table 7-24. The cost of an occasional blower start-up is evident. Even though the on-peak energy charge is only \$0.0369/kWh, the actual incremental cost to operate this blower can be several dollars per kWh once the demand charges are included. Use of the appropriate rate schedule is an essential part of a cost-effectiveness analysis.

Figure 7-6. Blower costs as a function of capacity.



- X Uninstalled Individual Blower Costs (24)
- ⊙ Uninstalled Individual Blower Costs (20)
- ◻ Uninstalled Total Capacity plus Piping (22)
- M Installed Individual Blower Cost - Madison, WI (8)
- F Uninstalled Individual Blower Cost - Frankenmuth, MI (10)
- ▼ Installed Individual Blower plus Filter Cost - Monroe, WI (18)

Table 7-19. Costs Associated with Gas Cleaning

Plant	No. Diff.	HCL Usage Per Diffuser Per Cleaning		Labor Per Cleaning		Ref.
		lb	\$	hr/1,000 diff.	hr/lb HCL sol.	
Albuquerque, NM	25,000	0.24	0.24	6.3	0.026	26
Soymour, WI	1,240	0.10	0.21	3.2	0.033	26
Plymouth, WI ^a	1,350	0.13	0.31	2.2	0.017	26
Ripon, WI ^a	1,092	0.22	0.51	9.2	0.042	26
Sturgeon Bay, WI ^a	1,374	0.22	0.51	5.8	0.027	26
Miller/Fulton, NY	11,250	0.05	0.05	3.6	0.067	26
Frankenmuth, WI	2,400	0.02	0.03	1.0	0.045	12
Green Bay, WI	8,276	0.10	0.07	4.6	0.034	3
Whittier Narrows, CA	1,000	0.05	0.06 ^b	6.0	0.12	1
Whittier Narrows, CA	500	0.05	0.06 ^b	10.0	0.20	1

^a Cleaning on contract basis using 60-lb HCL cylinders at \$140 each.

^b \$0.10 if cylinder shipping is included.

Table 7-20. Estimated Time Requirements for Basin and Diffuser Cleaning

Operation	Time Required	
	labor-hr/tank	labor-hr/diffuser
Basin Dewatering	4 to 6	0.02
Basin Cleaning		0.02
Low-Pressure Hosing		0.025
High-Pressure Hosing		0.06
Acid Washing		0.085
Dome Removal and Replacement		

Table 7-21. Diffuser Cleaning and Repair Costs – Ridgewood, NJ

Year	Type of Cleaning	No. Cleanings per Year	Cleaning ^a Cost, \$/yr	Repair Cost, \$/yr
4/83-12/83	None		0	0
1984	Hose	2	350	700 ^{**}
1985	Hose	8	1,400	350
	Acid	3	1,125	
1986	Hose	3	525	0
	Acid	1	375	

^a Average labor cost is \$21.80/hr.

^{**} Includes installation of 220 new diffusers on existing blanks.

Table 7-22. Milwaukee Method Diffuser Cleaning Costs – Hartford, CT

Labor for hosing, acid cleaning, and leak repair [*]	0.03 labor-hr/diffuser
Cleaning chemical	\$0.075/diffuser
Spare parts (gaskets, bolts, supports, domes) ^{**}	\$0.45/diffuser
Equipment and protective clothing	\$0.22/diffuser

^{*} Leak repair required 0.01 labor-hr/diffuser.

^{**} 5-10 percent of the diffusers required leak repair in the first two cleanings. At the 5-yr cleaning point (October 1988), repair of bolts and gaskets was required for 35-40 percent of the diffusers.

Table 7-23. Wisconsin Public Service Corporation Rate Schedule

AVAILABILITY

The schedule is applicable to customers whose monthly demand is $\geq 1,000$ kW.

MONTHLY RATE

Customer Charge: \$300.00/month

Demand Charge

1. Customer Demand: \$1.00/kW per kW of maximum demand during the current or preceding 11 months, plus:
2. System Demand:
 - Peak Load \$6.32/kW
 - Intermediate Load \$4.55/kW
 - Base Load \$0.00
3. Energy Charge:
 - On Peak \$0.0369/kWh
 - Off Peak \$0.0261/kWh

MINIMUM CHARGE

The minimum monthly charge is the customer charge plus the demand charges. The sum of the system demand charges for the annual period, including the current and the succeeding 11 months, shall not be less than \$41/kW of maximum peak load demand during the current month.

Table 7-24. Cost of Operating a 750-kW (1000-hp) Motor at 70 percent of Rated Load for Various Periods Over a Year (Demand = 522 kW)

Period of on-Peak Use	Power Consumed, kWh/yr	Annual Cost, \$			Total Cost	
		Demand Charge		Energy Charge	\$/yr	\$/kWh
		Customer	System			
1 hr/yr [*]	522	6,264	3,299	19	9,582	18.36
1 hr/month [*]	6,264	6,264	39,588	231	46,083	7.36
6 hr/month [*]	6,264	6,264	39,588	1,387	47,239	1.26
100 hr/month ^{**}	626,400	6,264	39,588	23,114	68,966	0.11
300 hr/month ^{**}	1,879,200	6,264	39,588	69,342	115,194	0.06

^{*} On-peak use occurs at peak plant demand.

^{**} On-peak use occurs at peak plant demand at least once per month.

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Chapter 8

Case Histories

8.1 Introduction

Case histories provide essential information about the progression of a new technology that can not be totally incorporated in the categorical approach used in this manual. Case histories illustrate how engineers and wastewater treatment plant authorities apply such technologies to solve specific problems. Although these problems arise from site-specific situations, valuable general guidance can often be gained from a study of such installations by others contemplating use of the same technology. It is with this objective in mind that the following summaries have been prepared.

Case histories have been developed for several fine pore diffuser systems evaluated by contractors retained on the EPA/ASCE Fine Pore Aeration Project. Substantial in-process oxygen transfer testing was conducted in these field studies, and the data generated are summarized in the respective case histories reported herein. In addition, to provide a broader perspective of fine pore diffuser applications, advertisements were placed in the professional newsletters of ASCE and WPCF to solicit information on other potential case histories. Several case histories have been developed from these sources and are also included here. For the most part, no field oxygen transfer data are available for these additional case histories. Performance of these systems must be judged on overall power consumption, operation and maintenance (O&M) requirements, and effluent quality.

In general, each case history is organized to provide information on: 1) the reason why fine pore diffusers were selected, 2) the type of plant and wastewater involved, 3) the fine pore diffusion system selected and some detail on its installation, 4) how the system performed during the 12 months or more of operation following its installation, and 5) the benefits derived as a result of employing the new system. An effort has been made to provide summaries that are as complete as possible to direct potential users of this technology to situations that most closely resemble their own.

As might be expected, many of the case histories involved retrofitting plants previously equipped with

coarse bubble diffused aeration systems. These retrofit examples generally reflect the economic power savings possible with fine pore aeration. In a few cases, however, predicted economics were not realized in actual operation. In several other cases, problems were encountered that were not envisioned beforehand. Conversely, diffuser fouling problems anticipated at several plants never materialized.

When judging the success or failure of a particular retrofit, readers are cautioned against making a strict economic judgement for the following reasons. First, many of the fine pore systems described in this chapter are just beginning their useful life and full life-cycle costs are not available. Second, it is not always equitable to directly compare operating data from before a retrofit to after because of a variety of other changes that may have occurred during either period for which documentation is either unavailable or incomplete. Obviously, such changes could bias the comparison. Third, plants retrofitted with fine pore aeration often achieve nitrification as an added benefit. Finally, retrofitted systems are frequently operated at different dissolved oxygen (DO) levels than prior to the retrofit. Where possible, these different before and after conditions have been reported but have not necessarily been factored into cost differentials.

Case histories, as a whole, permit the formation of generic conclusions regarding the claims for a new technology and the likelihood that a real advancement has been achieved. Two such conclusions may be drawn from the case histories presented herein concerning the increasing trend toward employing fine pore diffusers in treating municipal wastewater. First, the projected greater oxygen transfer rates for similar energy inputs have generally been realized, although complete life-cycle costs are not yet available and, in some cases, cost savings are marginal. Second, although diffuser fouling has not always accompanied the changeover to fine pore diffusers, many plants are periodically cleaning their diffusers by a variety of methods in the belief that such efforts will prevent fouling from developing.

The case histories that follow offer the reader a number of diverse situations. They should be useful to

Table 8-1. Summary of Case Histories

Facility	Design Flow, mgd	Fine Pore Aeration System
Performance Evaluation by Off-Gas Testing		
Frankenmuth, MI	1.8	Ceramic Discs
Glastonbury, CT	3.6	Rigid Porous Plastic Tubes
Groon Bay, WI	52.5	Ceramic Discs and Perforated Membrane Tubes
Hartford, CT	60.0	Ceramic Domes
Jones Island, WI	200.0	Ceramic Plates
Madison, WI	38.0	Ceramic Discs and Ceramic Domes
Ridgewood, NJ	3.0	Ceramic Domes
Whittier Narrows, CA	15.0	Ceramic Discs and Ceramic Domes
Performance Evaluation by Means Other Than Off-Gas Testing		
Cleveland, WI	0.2	Rigid Porous Plastic Plates
Plymouth, WI	1.3	Ceramic Discs
Renton, WA	72.0	Perforated Membrane Tubes
Ripon, WI	2.0	Ceramic Discs
Saukville, WI	0.5	Ceramic Discs

those considering fine pore diffusers for new or existing plants. Table 8-1 lists the plants that are described in this chapter. The plants are divided into two groups depending on how the plant's performance was evaluated. Section 8.2 includes plants that were evaluated by off-gas testing data; Section 8.3 includes plants that had to be evaluated by means other than off-gas testing, including treatment performance, energy used, and quantity of air supplied per unit of BOD₅ removed. Section 8.4 summarizes the various sources of information used to assemble these case histories.

8.2 Performance Evaluation by Off-Gas Testing

8.2.1 Frankenmuth Wastewater Treatment Plant

LOCATION: Frankenmuth, Michigan

OPERATING AGENCY: City of Frankenmuth

DESIGN FLOW: 79 L/s (1.8 mgd)

WASTEWATER: Domestic Plus Brewery

ORIGINAL AERATION SYSTEM: Broad Band Coarse Bubble Tube Diffusers

FINE PORE AERATION SYSTEM: Sanitaire Ceramic Disc Diffusers

YEAR FINE PORE SYSTEM PLACED IN OPERATION: 1986

BASIS OF PERFORMANCE EVALUATION: Off-Gas Testing
Overall Process Performance

CLEANING METHOD: In-Situ HCl Gas Cleaning

I. INTRODUCTION

Frankenmuth is a small community of about 4,000 people in central Michigan. It is also the home of a brewery that produces beer and other products. The brewery wastewater accounts for about 25-30 percent of the flow and 50-70 percent of the BOD load to the wastewater treatment facility.

In January 1986, conversion from a stainless steel broad band coarse bubble diffuser system to fine pore aeration was completed in all of the six existing aeration tanks. Two smaller centrifugal blowers with inlet filters capable of removing particles ≥ 20 microns in size were installed as well as an in-situ HCl gas cleaning system. Plant energy consumption per unit of BOD removed was measured and recorded before and after the fine pore aeration conversion. Oxygen transfer efficiencies (OTEs) were measured by off-gas testing on 13 different days between April 1987 and May 1988. Some of the off-gas tests were done on successive days before and after gas cleaning of the diffusers to observe the effect of cleaning on OTE.

In addition, an attempt was made to monitor the condition of fine pore aeration diffusers by measuring dynamic wet pressure (DWP) and pressure drop across air distribution orifices in test diffuser assemblies. Four diffusers were placed in one of the six activated sludge aeration cells, and measurements were generally obtained at 1-2 week intervals after equipment installation.

Summary details are presented below on the original aeration system, the basis for changing to fine pore aeration, and the design, performance, and evaluation of the new system.

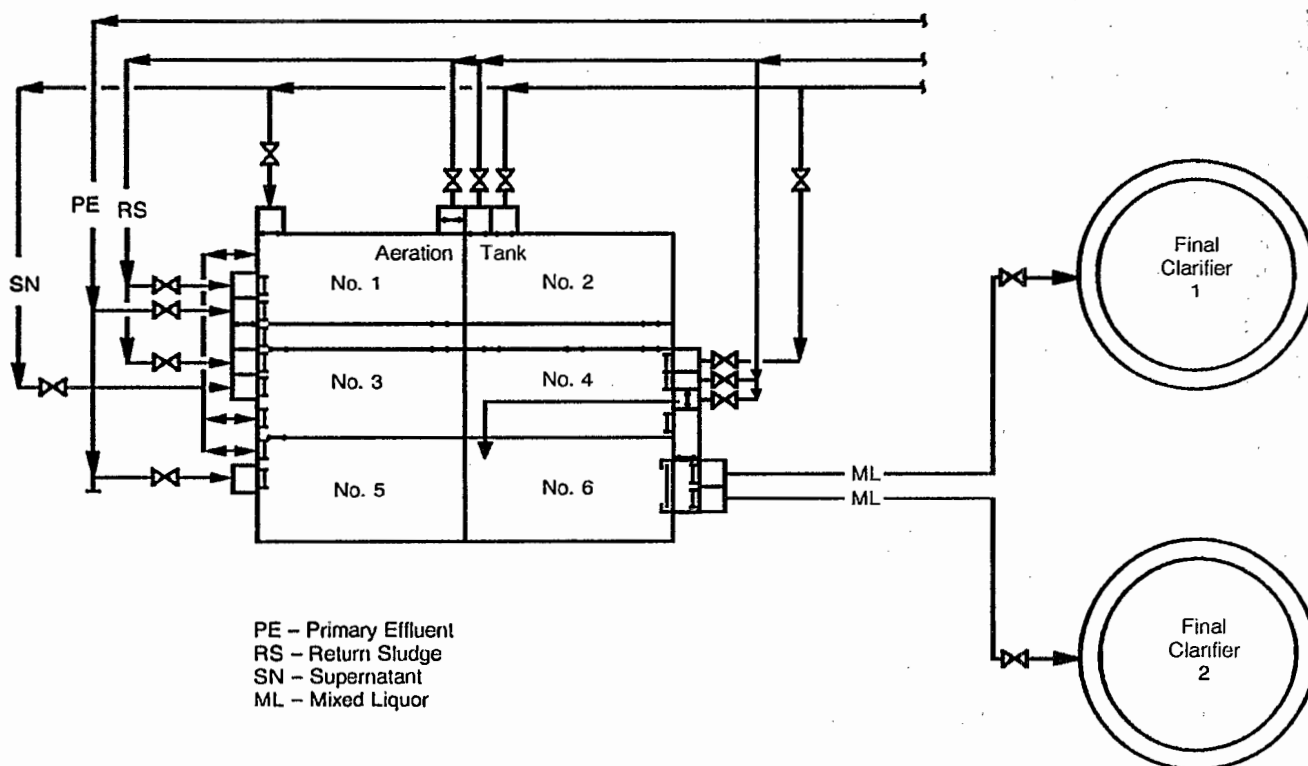
II. ORIGINAL TREATMENT FACILITY

The process flow scheme for the plant consists of a manual bar screen, raw wastewater pumping, a square aerated grit tank, two rectangular primary clarifiers, aeration tanks, two 15-m (50-ft) diameter final clarifiers, and a chlorine disinfection system. Primary and waste activated sludge are combined prior to anaerobic digestion. The digested sludge is dewatered with vacuum filtration and hauled for disposal off site. In-plant recycle streams are returned to the raw wastewater pumping station.

The aeration tank layout, shown in Figure 8-1, consists of six individual aeration cells. Each cell is 13.4 m by 6.7 m (44 ft by 22 ft) with a 4.6-m (15-ft) sidewater depth (SWD), resulting in a total aeration volume of 2,465 m³ (651,000 gal). The hydraulic design for the aeration cells allows a variety of process flow regimes ranging from modified contact stabilization to conventional plug flow activated sludge by operating the six cells in series. Contact stabilization can be varied by using 2-4 of the six cells in series for return sludge aeration followed by the remainder of the cells (2-4) in series for wastewater aeration, with primary effluent added to the first cell after return sludge aeration. One modified contact stabilization operating mode has been to operate with Cells 1-3 for return sludge aeration, followed by Cells 4-6 in series for wastewater aeration with primary effluent added to Cell 4. Normal operation, however, is to use Cells 1 and 2 (and possibly 3) for return sludge aeration and Cells 4 and 3, and 5 and 6 as two parallel, two-tanks in series activated sludge trains.

The air diffusion equipment initially installed was stainless steel broad band coarse bubble diffusers

Figure 8-1. Aeration tank arrangement - Frankenmuth, MI.



mounted on galvanized steel headers. Four multi-stage blowers were provided, each with a nominal capacity of 3,070 L/s (6,500 scfm).

The plant's NPDES permit requires that 30-day average effluent BOD₅ and SS concentrations each be less than 30 mg/L. There is no effluent ammonia nitrogen discharge requirement.

III. FINE PORE AERATION MODIFICATION EVALUATION

Basis for Change

The retrofit to fine pore aeration was not predicated solely on the desire to reduce operating costs because of higher OTEs associated with fine pore aeration. Rather, it was motivated by the need to replace a significant number of coarse bubble diffusers that had broken off due to corrosion, and the inability of the system to always supply the required oxygen demand.

A pre-design analysis indicated that the initial cost for the retrofit to fine pore aeration was approximately \$160,000, the same as replacing the existing system with new coarse bubble aeration equipment. Initial cost estimates for the fine pore aeration system included new diffusers and diffuser grid piping, new air

drop pipes in each cell, in-situ gas cleaning, two new small blowers, and new air inlet filters. Initial costs for the coarse bubble system included new diffusers and in-tank piping and new stainless steel drop pipes. The estimates were based on using 2,400 ceramic disc diffusers and 2,000 stainless steel broad band coarse bubble units.

Before initiating the final design, a test header with four ceramic disc diffusers was installed near the inlet end of Cell 5 to monitor the potential for plugging and fouling with this relatively high-strength wastewater application. The DWP and orifice pressure drop were monitored daily for about 10 weeks to ascertain the possible level of plugging and fouling. At the end of that period, the test header diffusers were cleaned by injecting HCl gas into the air supply to the header.

Initial DWP readings were approximately 15 cm (6 in) w.g. Within the first week, the DWP increased to 38 cm (15 in) w.g. During the fifth week, the air supply was increased in an attempt to "air bump" the diffusers to reduce fouling. The DWP decreased from about 43 cm (17 in) w.g. to 30 cm (12 in) w.g. the following week, but this was within the range of other DWP fluctuations so no conclusions could be made with regard to the benefits of air bumping. After gas cleaning, the DWP decreased from about 35 cm (14

in) w.g. to 24 cm (9.5 in) w.g., the lowest observed level since the first week of the test, so it was concluded that fouling and plugging of fine pore diffusers could be controlled in this application by the use of gas cleaning. Thus, the final design of the fine pore aeration system was continued with plans to use gas cleaning.

Existing System Evaluation

The anticipated range of airflow rates for the fine pore aeration system was 378-1,888 L/s (800-4,000) scfm to satisfy minimum mixing requirements and peak oxygen demands. The estimated average airflow rate was approximately 1,038 L/s (2,200 scfm). This was near the minimum operating level or surge point of the existing blowers. An evaluation of blower operating efficiencies at this airflow rate from the blower performance curve found that blower efficiency would be very low, especially compared to what is possible using smaller size blowers.

To ensure that anticipated energy savings for fine pore aeration could be achieved and to operate above the blower surge point, new blowers were selected for the retrofit system. Two multi-stage 149-kW (200-hp) centrifugal blowers with a nominal capacity of 1,038 L/s (2,200 scfm) each were selected. Only the blowers were replaced. The existing blower bases, motor starters, valves, flexible connectors, and piping were used with the new equipment. Two of the existing 187-kW (250-hp) blowers were left in place to provide standby capacity.

The inside lining of the existing air piping was determined to be in excellent condition; the only new piping required was for the air header drop pipes and the diffuser grid system. Due to the age of the existing piping system, the design engineers recommended in-line air filters be placed immediately upstream of the air header drop pipes to each cell. Specifications for these filters required 97 percent removal of particles ≥ 0.3 micron in size to protect the diffuser equipment from air side fouling. After finding the existing piping was in good condition, the City elected not to install the in-line filters. New elements for existing blower inlet air filters capable of removing particles ≥ 20 microns in size were installed instead.

Cost-Effectiveness Evaluation

Table 8-2 summarizes the assumptions and calculations for the pre-design aeration energy comparison between fine pore and coarse bubble aeration alternatives. The estimated O&M cost for the fine pore system was based on periodic HCl gas cleaning of the fine pore diffusers. The average annual aeration operating cost for fine pore aeration was estimated to be about one-half of the coarse bubble aeration cost. Based on this evaluation, even if the coarse bubble system didn't need replacing, replacement could be considered with the annual energy savings providing a simple replacement

payback within 6 years based on an initial cost estimate of \$160,000.

Table 8-2. Comparison of Fine Pore and Coarse Bubble Aeration Energy Requirements: Pre-design Estimates - Frankenmuth, MI

Parameter	Ceramic Fine Pore	Stainless Steel Coarse Bubble
Average Primary Effluent Flow, mgd ¹	1.4	1.4
Average Primary Effluent BOD ₅ ¹ , mg/L	512	512
lb/d	5,977	5,977
Required Oxygen Transfer Rate (AOR) ² , lb/d	6,575	6,575
Assumed Actual OTE ³ , percent	11	7.2
Average Airflow Required ³ , scfm	2,214	3,641
Average Horsepower, hp	88	180
Estimated Annual Energy Cost ⁴ , \$	26,140	58,815
Estimated Annual O&M Cost ⁴ , \$	3,000	
Total Estimated Annual Cost, \$	29,140	58,815
Estimated Annual Savings, \$	29,675	

¹ Flows and loads based on averages for November 1983-October 1984.

² Assumes 1.1 lb O₂ required/lb BOD applied.

³ At average mixed liquor DO of 2.0 mg/L.

⁴ Assumes power cost of \$0.045/kWh.

IV. FINE PORE AERATION RETROFIT DESIGN DESCRIPTION

The new aeration system consisted of ceramic disc diffusers installed in a full-floor coverage grid pattern and in-situ HCl gas cleaning. Installation was begun in December 1985 by the treatment plant staff with technical assistance provided by the equipment manufacturer. The new equipment was fully in service by January 1986. The total equipment cost was \$160,000, and the plant staff invested approximately 800 labor-hr in installation and start-up. The total project cost, including equipment, installation, and engineering, was approximately \$190,000.

A total of 2,400 diffusers were installed with 400 diffusers evenly spaced in each of the six aeration cells. The diffuser density was thus one diffuser/0.22 m² (2.42 sq ft) of tank floor area. The anticipated maximum airflow rate at peak load was approximately 0.8 L/s (1.7 scfm)/diffuser. The minimum airflow rate was estimated to be 0.3 L/s (0.7 scfm)/diffuser. Airflow rates to each cell are controlled by manually operated butterfly valves.

V. OPERATIONAL PERFORMANCE AND EVALUATION

Treatment Performance

The wastewater treatment facility consistently met its NPDES permit for effluent BOD after the retrofit in spite of the high primary effluent BOD concentration

Table 8-3. 1986 Performance Summary - Frankenmuth, MI.

Date	Flow, mgd	Primary Effluent				Volumetric Load, lb BOD ₅ /d/1,000 cu ft	Final Effluent			
		BOD ₅		SS			BOD ₅		SS	
		mg/L	lb/d	mg/L	lb/d		mg/L	lb/d	mg/L	lb/d
January 1986	1.46	539	6,720	283	3,553	83.3	15	183	23	293
February	1.20	729	7,545	430	4,459	79.9	22	233	21	220
March	1.77	587	8,129	288	4,267	86.1	29	452	23	354
April	1.47	838	10,605	378	4,788	112.3	51	658	32	395
May	1.35	866	10,172	479	5,812	107.8	29	339	24	276
June	1.52	621	7,947	231	2,836	84.2	24	316	18	239
July	1.39	769	9,111	422	5,034	96.5	22	262	12	1,411
August	1.27	723	7,959	248	2,658	84.3	17	174	20	207
September	1.90	474	6,724	220	3,523	71.2	16	220	27	405
October	1.72	490	6,830	232	3,474	72.4	9	125	22	314
November	1.20	673	7,185	289	2,931	76.1	14	137	32	310
December	1.39	520	6,655	222	2,642	71.6	29	349	24	278

due to the brewery wastewater contribution. Table 8-3 summarizes monthly average plant loadings and treatment performance for 1986. The mean solids retention time (SRT) was typically 5-10 days. The hydraulic retention time (HRT) was 10-12 hours, and typical aeration tank mixed liquor suspended solids (MLSS) levels were in the range of 3500-7000 mg/L.

Aeration System Oxygen Transfer Efficiency

Off-gas testing was performed on selected aeration cells on 13 different days from April 1987 to May 1988. The purpose was to measure OTEs of the fine pore aeration system in the various operating cells and to observe the effect of diffuser gas cleaning on diffuser performance. The standard off-gas testing procedure was followed using a 61-cm by 305-cm (2-ft by 10-ft) fiberglass off-gas collection hood. The hood was typically located at a total of four locations near the center of the aeration cell. There were two locations on each side of the transverse center line. These two locations were end-to-end to provide almost complete coverage of the aeration cell width.

During testing in May 1988, two additional pairs of hood locations were used to sample near the aeration cell inlet and outlet. The measured OTEs many times varied by 20-30 percent for the different hood locations in a given aeration cell. This may have been due to cell mixing characteristics. The OTE values were averaged to allow a comparison of aeration performance between cells and for different test days.

Two operating modes were used during off-gas testing. The most common mode was the use of Cells 1-3 for return sludge aeration followed by primary effluent addition to Cell 4 and operation of Cells 4-6 in series. During off-gas testing in April 1987 and May 1988, Cells 1 and 2 were used for return sludge aeration, followed by two parallel trains with primary

effluent addition to Cells 4 and 5. Mixed liquor then flowed from Cell 4 to Cell 3 and from Cell 5 to Cell 6.

Table 8-4 summarizes the average off-gas testing results from June 1987 through March 1988 for the series operating mode. Cell 3 was used for return sludge aeration as well as Cells 1 and 2, and primary effluent was added to Cell 4. The airflow rate in each cell averaged about 0.9 L/s (2.0 scfm)/diffuser. The results illustrate the effect of the degree of wastewater stabilization on the average $\alpha F(SOTE)$. $\alpha F(SOTE)$ values were in the 7-8 percent range in Cells 4 and 5, but following substantial soluble BOD removal, $\alpha F(SOTE)$ values averaged 12.1 and 13.2 percent in Cells 6 and 3, respectively. The weighted average $\alpha F(SOTE)$ was 10.0 percent for all four cells at an average airflow rate of about 0.9 L/s (2.0 scfm)/diffuser. Using a reasonable assumption that $\alpha F(SOTE)$ values for Cells 1 and 2 were between those for Cells 3 and 6, the weighted average $\alpha F(SOTE)$ for the system was estimated to be about 10.9 percent. This compares to the value of 11.9 percent used in the pre-design analysis to evaluate potential energy savings of fine pore aeration.

Table 8-4. Off-Gas Test Results - Frankenmuth, MI

	Aeration Cell No.			
	3	4	5	6
Airflow, scfm/diffuser	1.9	2.0	1.9	2.1
Avg. $\alpha F(SOTE)$, %	13.2	7.1	7.8	12.1
$\alpha F(SOTE)$ Range, %	10.0-16.3	6.8-7.4	7.0-9.6	10.3-16.2
No. Test Days	5	2	8	9

Effect of Cleaning on Performance

HCl gas cleaning was initiated to control DWP below 41-46 cm (16-18 in) w.g. This occurred at various

Table 8-5. Estimated Energy Cost Savings - Frankenmuth, MI

	Year			
	1985 - Coarse Bubble	1986 - Fine Pore	1987 - Fine Pore	1988 - Fine Pore
Average BOD ₅ treated, lb/mo	295,939	295,939	295,939	295,939
Average kWh used/lb BOD ₅ removed	0.83	0.59	0.68	0.88
Average monthly power cost ¹ , \$	12,281	8,730	10,062	13,021
Average monthly savings, \$	-	3,551	2,219	-740
Annual savings, \$	-	42,612	26,628	-8,880

¹ @ \$0.05/kWh.

intervals that were typically about once per month during the first 2 years of operation. After September 1987, the amount of HCl gas used during cleaning was reduced and, in 1988, cleaning was performed only 3 out of the first 7 months. The actual gas used averaged about 150 g (0.33 lb)/diffuser/yr compared to an estimated consumption of 450 g (1.0 lb)/diffuser/yr in the pre-design evaluation stage. The cost of gas cleaning, including labor and gas, ranged from approximately \$2,400 during the first year of operation to approximately \$400/yr when cleaning frequency and gas dosage were decreased.

Off-gas testing was performed on days immediately before and after gas cleaning on five different occasions between June 1987 and May 1988 in Cells 5 and 6. No increase in OTE was found on the day following gas cleaning. This may have been due to variations in wastewater characteristics, poor mixing of primary effluent with recycle sludge in Cells 4 and 5, and possible variations in the test results.

Gas cleaning was found to effectively control the DWP of the diffusers. The DWP level of 14-15 cm (5.5-6.0 in) w.g. typically measured on new diffusers was not always achieved, but DWPs were usually decreased to 15-25 cm (6-10 in) after cleaning. Although no direct OTE benefits could be seen for cleaning, long-term control of DWP may be helpful in minimizing operating pressures at the blower discharge and energy requirements.

VI. ECONOMIC CONSIDERATIONS

Table 8-5 summarizes total energy consumed per unit of BOD₅ removed for operating periods before 1985 and after the retrofit. Average monthly savings were calculated by comparing the average observed kWh/lb BOD₅ removed ratio to that before the retrofit and multiplying that value by the average monthly BOD₅ removal rate. The average monthly BOD₅ removal rate for 1985 was used for the subsequent year in Table 8-5 to provide an equal basis for comparing the energy demands between fine pore and coarse bubble aeration. The average annual energy savings calculated for 1986 and 1987 is \$34,620, which is above the value of \$29,140 used in the pre-design fine pore aeration economic evaluation. The energy consumption ratio was much higher in 1988 because plant personnel maintained high aeration rates even though the BOD loading to the plant had significantly decreased. Thus, the potential energy savings benefit of fine pore aeration was not realized during this period.

8.2.2 Glastonbury Water Pollution Control Plant

LOCATION: Glastonbury, Connecticut

OPERATING AGENCY: Town of Glastonbury

DESIGN FLOW: 158 L/s (3.6 mgd)

WASTEWATER: Domestic

ORIGINAL AERATION SYSTEM: Delrin Coarse Bubble Diffusers

FINE PORE AERATION SYSTEM: FMC Pearlcomb Rigid Porous Plastic Tube Diffusers

YEAR FINE PORE SYSTEM PLACED IN OPERATION: 1984

BASIS OF PERFORMANCE EVALUATION: Off-Gas Testing

CLEANING METHOD: Detergent Washing

I. INTRODUCTION

A secondary wastewater treatment facility with an average design flow of 158 L/s (3.6 mgd) was placed into operation at Glastonbury, CT in 1972. The original aeration system consisted of coarse bubble spargers on swing-arm assemblies. As electricity costs increased from the mid- to late-1970s, Glastonbury became interested in converting the aeration system to fine pore diffusers to reduce plant operating costs.

Alternative fine pore diffuser systems were investigated by obtaining manufacturers' product information and by making site visits to other facilities that had been retrofitted from coarse bubble to fine pore aeration. Continued use of the existing swing-arm assemblies was desired because they were still in good condition and the need to drain an aeration tank during cleaning of full-floor coverage fine pore diffusers was not an attractive operational feature for this small plant. Bids were received for new fine pore diffusers in October 1983, and the Pearlcomb rigid porous plastic tube diffuser was selected for the retrofit. Air filtration equipment was also purchased.

The new aeration equipment was installed by the Town public works employees and placed in service during the Fall 1984. A smaller, more efficient 75-kW (100-hp) blower was installed in 1985 to better match the airflow rate requirements of the new system.

An extensive aeration system performance evaluation involving six separate site visits was undertaken during the period November 1985-September 1988. Over 160 individual off-gas tests were performed across the aeration tank to determine OTEs as a function of diffuser location and age.

Summary details are presented herein for the original system and retrofit designs, the performance evaluation of the fine pore aeration system, and the

estimated economic benefits of the aeration modification.

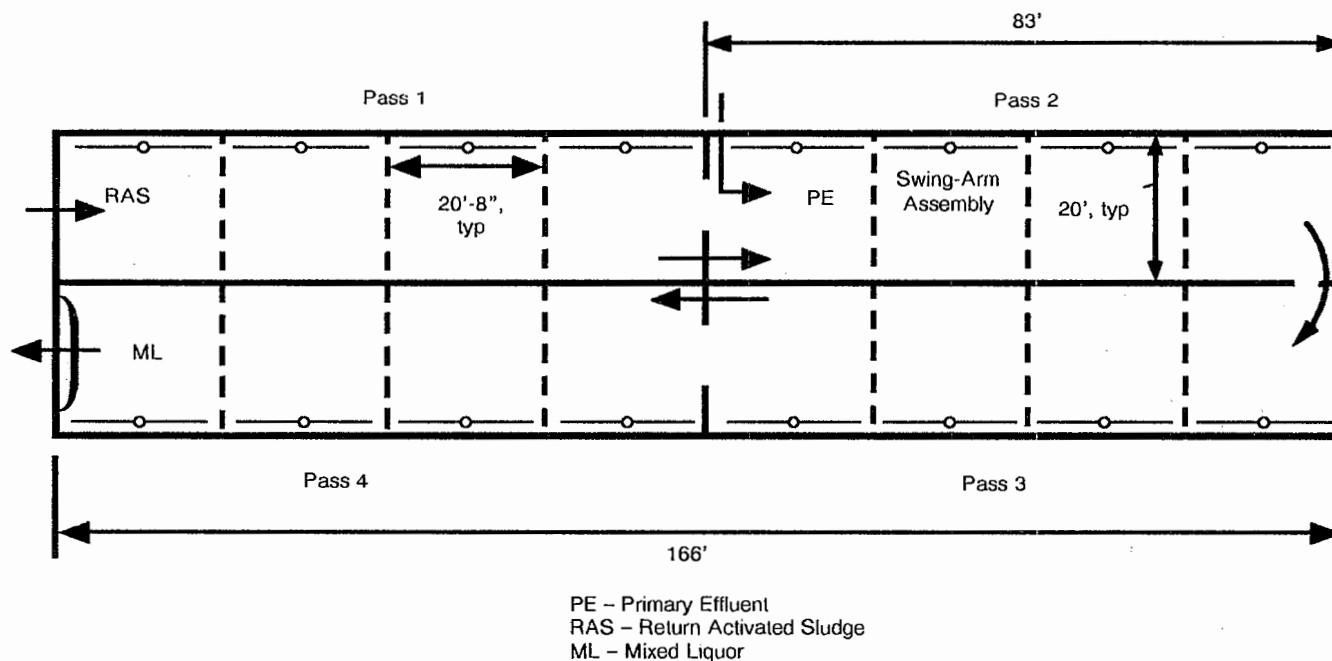
II. ORIGINAL WASTEWATER TREATMENT FACILITY

The original wastewater treatment facility was designed for a 1990 average daily flow of 158 L/s (3.6 mgd) and a peak flow of 355 L/s (8.1 mgd). Population growth and industrial flow projections used for design did not develop as anticipated. During the aeration system evaluation period, the average and maximum daily flows were about 66 L/s (1.5 mgd) and 88 L/s (2.0 mgd), respectively. The wastewater treatment facility consists of preliminary treatment, two primary clarifiers, activated sludge aeration tanks, two 19.8-m (65-ft) circular secondary clarifiers, and chlorine disinfection. Thickened waste sludge from the plant is trucked to the Hartford treatment facility for final treatment and disposal.

The secondary treatment system contains two identical aeration tanks, but only one has been used since actual flows have been less than design. Each aeration tank is 50.6 m (166 ft) long and 12.2 m (40 ft) wide with an SWD of 4.6-4.7 m (15.0-15.5 ft) and is divided into four equal-size passes. Each pass is 25.3 m (83 ft) long and 6.1 m (20 ft) wide. Total tank volume is 2,890 m³ (764,000 gal). Figure 8-2 is a schematic of the aeration tanks. Return sludge is directed to the head of Pass 1 at an average rate equal to about 34 percent of the plant flow. Primary effluent is normally introduced at the head of Pass 2. However, during the aeration evaluation site visits in 1988, primary effluent was fed to the head of Pass 1.

The original aeration equipment installed in 1972 consisted of Walker Process Jackknife Sparger-Header Diffuser assemblies with Delrin coarse bubble spargers installed on the air manifolds at the end of each jackknife. The coarse bubble spargers contained

Figure 8-2 Aeration tank schematic - Glastonbury, CT.



four 6-mm (1/4-in) diameter air orifices at 90 degrees to one another. The total airflow capacity was 6.2 L/s (13.1 scfm)/diffuser at 28 cm (11 in) w.g. headloss. A total of 320 spargers was installed in each tank, with 20 spargers installed on each swing-arm assembly. There are four swing-arm assemblies in each of the four aeration tank passes. The spargers were uniformly spaced along the air manifolds at 61-cm (2-ft) intervals, and no aeration tapering was possible.

The centerline of the horizontal air manifold of each swing-arm assembly was positioned 76-91 cm (2.5-3.0 ft) above the aeration tank floor and 76 cm (2.5 ft) from the tank sidewall. Sparger submergence was 3.7-3.8 m (12.0-12.5 ft). The spargers were located between the drop-leg of the swing-arm and the tank sidewall. A spiral roll aeration and mixing pattern was created by this diffuser placement. $\alpha F(SOTE)$ of this coarse bubble diffuser system was estimated to be 4-5 percent.

Air for the original aeration system was supplied by three 149-kW (200-hp) Hoffman multi-stage centrifugal blowers, each with an airflow capacity of 945-2,125 L/s (2,000-4,500 scfm) and an average discharge pressure of 150 kPa (7.0 psig). Operation of only one blower was required at any given time, and the airflow rate was adjusted by throttling the blower inlet valve.

Mixed liquor DO and air supply control were carried out with manual measurement of DO and manual adjustment of airflow to Passes 1 and 2 and Passes 3

and 4 using in-line valves. In addition, each swing-arm assembly contained an isolation valve that could be used to throttle airflow to that assembly.

III. FINE PORE AERATION SYSTEM MODIFICATION

Retrofitting the plant to fine pore aeration was based on the desire to reduce electrical power costs, although several other considerations were identified as part of the retrofit evaluation. These were;

1. Achieve a short initial cost payback period based on power savings, hopefully about 24 months.
2. Minimize any additional O&M costs over the existing aeration equipment.
3. Use the existing swing-arm assemblies so that tank draining for diffuser cleaning would not be necessary.
4. Provide the same operational flexibility as afforded by the existing equipment.
5. Maintain the same process treatment performance as before the retrofit.
6. Avoid the need to use multiple blower units to keep electrical demand charges acceptably low.

Prior to the retrofit feasibility study, one of the original blowers was modified to provide lower airflow rates

and power draw. The modification allowed airflow turndown from the original surge point of 895 L/s (1,900 scfm) to under 755 L/s (1,600 scfm).

Glastonbury solicited bids from various fine pore aeration suppliers. Several were from fine pore tube manufacturers, including perforated membranes and various rigid media types. At least one bid was received from a fine pore dome diffuser manufacturer. Evaluation parameters used by the Town to compare the various bids included:

1. energy savings over the current aeration process,
2. expected equipment life,
3. operating energy costs over the system life,
4. O&M costs over the system life,
5. initial cost,
6. equipment flexibility within the system life to accommodate varying flows and loadings, and
7. location of systems currently using the proposed new aeration equipment.

For the evaluation, the system life was set at 10 years, or the actual proposed life of the equipment, if less than 10 years.

The successful bid called for 320 Pearlcomb tube diffusers, Model SP-35, to be installed in one of the aeration tanks. Each tube diffuser consisted of:

- one tube adapter manufactured from an ABS polymer provided with a stainless steel insert suitable for connection to a 19-mm (3/4-in) NPT thread and control orifice,
- one diffuser tube,
- one end cap manufactured from an ABS polymer,
- one stainless steel rod threaded at both ends with PVC nuts, and
- one set of Neoprene gaskets and polyethylene washers.

They were shipped unassembled, requiring assembly at the job site during installation.

Similar to the previous system, 20 diffusers were installed on each of the existing swing-arm assemblies at 61-cm (2-ft) intervals. Although two coarse bubble diffusers had been positioned between the sidewall and air manifold at each interval location, only one tube was located between the sidewall and air manifold, and the other was located on the inboard

side of the manifold due to space limitations. The airflow rate recommended by the manufacturer for adequate tank mixing was 1.9-2.4 L/s (4-5 scfm)/diffuser, compared to an airflow rate of 3.3 L/s (7 scfm)/diffuser used for the coarse bubble system prior to the retrofit. Thus, the anticipated airflow was 605-755 L/s (1,280-1,600 scfm)/tank.

One of the three existing 149-kW (200-hp) blowers was replaced with a 75-kW (100-hp) Hoffman multistage centrifugal blower. This blower has an airflow rate operating range of 470-1,415 L/s (1,000-3,000 scfm) at a discharge pressure of 149 kPa (6.85 psig).

Mixed liquor DO concentrations are controlled by manual DO measurements in the basin and throttling the blower inlet valve. DO concentrations were 1.5-4.5 mg/L in the winter and 0.5-1.2 mg/L during summer operation.

IV. OPERATIONAL PERFORMANCE AND EVALUATION

After a few weeks of operation, several diffusers appeared to be clogged or plugged and the airflow patterns did not appear to be uniform. Investigation of the problem revealed that mixed liquor was backflowing into the blow-down holes in the air manifolds on each swing-arm assembly and plugging the inside of the diffusers. Steps were taken to correct this problem by plugging the holes, and the diffusers were thoroughly cleaned.

During the aeration system evaluation period, average plant influent BOD₅ was approximately 240 mg/L and average primary effluent BOD₅ approximately 120 mg/L. Operating MLSS levels were 1,500-3,000 mg/L. Average HRT and SRT were about 11 hours and 12 days, respectively. Effluent BOD₅ and SS concentrations were usually below 10 mg/L.

For the aeration performance evaluation, six off-gas tests were performed at the following times:

November 21 and 22, 1985
March 26 and 28, 1986
September 17, 1987
January 11, 1988
May 17, 1988
September 7, 1988

The sampling plan for off-gas tests in November 1985 and March 1986 consisted of two sets of replicate tests in the influent and effluent quadrants of each aeration pass. Each replicate test consisted of two individual off-gas tests, one taken with the hood positioned across that half of the aeration pass width nearest the swing-arm assembly and one taken with the hood placed at the half-width position furthest from the swing-arm assembly. The off-gas airflow was

much higher in the first hood position than in the second position.

For the remaining four off-gas test visits, the sampling plan was modified to use a larger hood and one replicate per run at each sample point. Three consecutive test runs were conducted during each site visit with this plan. The larger collection hood extended across the full width of the aeration pass. This sample plan reduced the time necessary to test the total aeration tank on a once-through basis and was more representative of overall performance conditions in the aeration tank. Another advantage for using the full-width hood was the elimination of the need to calculate airflow weighted average OTEs at the sampling locations.

The lowest off-gas OTEs were observed during the first series of tests in November 1985. $\alpha F(SOTE)$ values were about 3 percent compared to 7 percent for later tests. Also, at that time, significant coarse bubbling was observed at the liquid surface directly above the diffusers. This was found to be due to air leaking around the gaskets at the ends of the tube media for several diffusers. Tightening of the retaining nuts on the diffusers eliminated the leaking problem.

There was no obvious trend in changes in overall OTE as a function of the length of service for the fine pore tube diffusers. The overall efficiencies were similar for the March 1986-September 1988 testing period. It should be noted that the diffusers were not cleaned during this period. The only cleaning occurred before the November 1985 testing, after observation of air-side fouling due to backflowing mixed liquor.

Table 8-6 summarizes the average $\alpha F(SOTE)$ values for the entire tank and for each pass. These data are based on the five off-gas testing events after November 1985. All the averages shown are airflow weighted averages using the individual sample location measured airflows and off-gas results. $\alpha F(SOTE)$ was consistently lower in the first pass than the other three passes by 10-15 percent. This may have been due to leakage around the diffuser gaskets, indicated by more coarse bubbling in Pass 1.

Table 8-6. Summary of $\alpha F(SOTE)$ Determinations Glastonbury, CT

Basis*	$\alpha F(SOTE)$, percent			Average Estimated αF
	Average	Minimum	Maximum	
Entire Tank Avg.	7.2	6.6	7.6	0.61
Pass 1 Avg.	6.7	6.1	7.3	0.56
Pass 2 Avg.	7.3	4.7	8.4	0.61
Pass 3 Avg.	7.8	7.3	8.3	0.66
Pass 4 Avg.	7.5	7.3	7.7	0.63

* All efficiencies are airflow weighted averages. Does not include November 1985 test.

αF values shown in Table 8-6 were determined using clean water oxygen transfer data obtained from the manufacturer and during an EPA-sponsored oxygen transfer test project conducted by Los Angeles County Sanitation Districts. The estimated average SOTE for the Glastonbury fine pore tubes is 11.9 percent. αF values ranged from 0.56 to 0.66 with an average of 0.61 for the entire aeration tank.

Power Consumption and Airflow Rate

Although no long-term baseline information exists for pre-retrofit blower electrical power usage, measured power reduction, on a spot-check basis, after the retrofit and installation of the new 75-kW (100-hp) blower was approximately 50 kW (67 hp), a reduction of about 40 percent. Although most of the power reduction is due to in-tank equipment improvements, there was a significant improvement in air compression efficiency due to the installation of the new blower. This power reduction compares reasonably well to the observed reduction in airflow to the retrofitted aeration tank. Before the retrofit the airflow rate ranged from 1,040 L/s (2,200) to 1,180 L/s (2,500 scfm), and after the retrofit it ranged from below 470 L/s (1,000 scfm) to about 895 L/s (1,900 scfm).

Diffuser Cleaning

The fine pore tube diffusers have been cleaned only once, which was a few weeks after start-up when internal fouling of the diffusers was discovered. No routine cleaning program has been performed since. During the cleaning, the diffusers were disassembled and a detergent wash used. The diffusers were disassembled and the diffuser tubes soaked for about 30 minutes in a solution of warm water and commercial grade detergent. A firm bristle brush was then used to wash the inner and outer surfaces to loosen deposits. Finally, a thorough clean water rinse was applied before reassembling and placing the diffusers back into service.

V. ECONOMIC CONSIDERATIONS

$\alpha F(SOTE)$ averaged 6.5-7.0 percent for the fine pore tube diffusers, compared to an estimated 4.0-4.5 percent for the original coarse bubble diffusers. The post-retrofit $\alpha F(SOTE)$ is thus 150-160 percent of the original $\alpha F(SOTE)$.

Based on the observed blower reduction of about 50 kWh, the estimated electricity cost savings is about \$50/d, or \$15,000-\$18,000/yr, depending on blower usage and maintenance performed.

The approximate total initial cost for the retrofit project was \$28,000. The price of the diffusers was about \$30 each, unassembled, for a total cost of \$9,600. The time required for Town employees to remove the old diffusers, recondition the swing-arm assemblies, and install the new diffusers was about 0.75 labor-hr/diffuser. At a rate of \$20/labor-hr, the installation

cost was approximately \$6,500. Miscellaneous pipe fittings and hardware cost about \$2,000. The estimated total cost of the new blower was \$10,000, including air filtration equipment and installation.

The actual payback period is affected by the diffuser cleaning method used and frequency of cleaning. The effort required for the detergent cleaning operation was much greater than routine in-situ cleaning of the exterior surface of diffusers. The time required to disassemble and clean each diffuser was 20-30 minutes with a cost of \$5.00-\$7.50/diffuser (or an actual cost of \$1,600-\$2,400).

Cleaning of diffuser exterior surfaces was not performed at Glastonbury, but hosing and brushing should take no more than 2-3 minutes/diffuser. Annual maintenance should include at least one exterior cleaning of the diffusers with an inspection and

tightening of retaining nuts and gaskets to prevent coarse bubbling due to air leaks. The estimated cost for annual diffuser exterior surface cleaning is about \$500 for the Glastonbury system.

Based on the estimated total initial cost and electrical power savings, the simple payback period is 18-21 months. Simple payback periods of less than 2 years may thus be possible for replacement of spiral roll coarse bubble aeration equipment with spiral roll fine pore tube diffuser aeration equipment. The actual payback period will be a function of the total initial cost and the ability to reduce blower power usage through turndown and/or shutdown of blower units after retrofitting with new equipment. For the Glastonbury type of retrofit, in-tank equipment modifications are generally inexpensive if air piping and swing-arm assemblies are in good working condition. The cost of blower modifications can vary depending on the site.

8.2.3 Green Bay Wastewater Treatment Plant

LOCATION: Green Bay, Wisconsin

OPERATING AGENCY: Green Bay Metropolitan Sewerage District

DESIGN FLOW: 2,300 L/s (52.5 mgd)

WASTEWATER: Domestic Plus Pulp and Paper

ORIGINAL AERATION SYSTEM: Sparged Turbines

FINE PORE AERATION SYSTEM: Sanitaire Ceramic Disc and Parkson Perforated (Flexible) Membrane Tube Diffusers

YEAR FINE PORE SYSTEM PLACED IN OPERATION: 1986

BASIS OF PERFORMANCE EVALUATION: Off-Gas Testing

CLEANING METHOD: Ceramic Discs; Hosing-In-Situ HCl Gas Cleaning-Hosing
Perforated Membrane Tubes; Hosing-Brushing-Hosing

I. INTRODUCTION

Based on pilot-plant studies conducted in 1983, the Green Bay Metropolitan Sewerage District (GBMSD) decided to investigate the use of fine pore aeration as an alternative to existing sparged turbine aerators to reduce plant operating costs. Both ceramic disc and perforated membrane tube diffusers were considered viable alternatives, but long-term testing was undertaken to determine the possibility and effects of diffuser fouling on OTE under actual wastewater treatment conditions.

After installation of the two types of fine pore aeration systems in individual activated sludge treatment quadrants, an 18-month field testing program was initiated in May 1986 to evaluate their long-term performance. Initially, the two fine pore aeration quadrants treated the entire plant flow until a decrease in OTE required directing some of the influent flow to one of the two remaining sparged turbine aeration quadrants. The diffuser performance evaluation included an extensive field off-gas testing program to observe changes in OTE vs. operating time and the effects of diffuser cleaning on oxygen transfer performance. A pilot program was also carried out concurrently to evaluate characteristics of diffuser fouling, changes in diffuser performance after fouling, changes in diffuser operating characteristics such as DWP and bubble release vacuum (BRV), and the effects of different cleaning methods on restroing diffuser performance.

Summary details are presented herein on the Green Bay retrofit design, the performance and evaluation of the two types of fine pore diffusers, the results of the diffuser cleaning evaluation program, and the results

of an economic analysis on the conversion to fine pore aeration.

II. HISTORICAL BACKGROUND

GBMSD uses a modified contact stabilization activated sludge facility for secondary treatment. Sparged turbine aeration was used in the original facility, and aeration energy costs typically accounted for about one-half of the total plant's electrical energy costs.

With an objective of reducing plant operating costs, recommendations were made in 1983 (based on field test work in Summer 1983) to consider fine pore ceramic diffusion as a possible replacement for the existing mechanical aeration system. However, a major concern with fine pore diffusers was potential media fouling and the effects that such fouling could have on overall system economics by increasing operating pressure, decreasing OTE, and increasing maintenance costs for diffuser cleaning. It was recommended, therefore, that fine pore diffused aeration be tested initially by installing a full-scale ceramic diffuser system in only one of four quadrants of the activated sludge system complex.

Since the 1983 field tests showed that a substantial portion of the foulant materials was soluble in acid, the recommended ceramic installation was to include an in-situ HCl gas injection system. Preliminary calculations indicated that, to operate the fine pore system in a mode equivalent to design year loadings, approximately 40 percent of the influent flow would have to be fed to the fine pore system and 60 percent to one or more of the existing sparged turbine systems.

In the fall of 1984, GBMSD considered perforated membrane tube diffusers as an additional alternate fine pore system. The manufacturer claimed that these diffusers normally do not foul and, if fouling occurs, it can be controlled by flexing the units. Based on the data available at the time, the ceramic diffusers were expected to have a higher OTE than the membrane diffusers when the systems were clean. However, since fouling was expected to adversely affect OTE of the ceramic diffusers, the perforated membrane units could possibly produce better OTEs in the long run if, in fact, the membrane diffusers did not foul.

Because the cost effectiveness of ceramic disc and perforated membrane tube diffusers was believed to be similar, and fouling characteristics and maintenance procedures were potentially different, it was decided to install and test both types of fine pore diffusers. Testing two fine pore diffuser systems also provided the opportunity to try to treat all of the wastewater in the two test quadrants and achieve substantial energy savings during the test period. The membrane diffuser system was installed first and placed in service in January 1986. By April 1986 the ceramic diffuser system installation was completed. To provide a clean start for both systems, the basins containing the membrane diffusers were drained and a cleaning procedure recommended by the manufacturer followed. This involved hosing the membranes, scrubbing them with a stiff bristle brush, and rehousing. Both systems were placed in service in May 1986.

III. FINE PORE AERATION RETROFIT DESIGN DESCRIPTION

The GBMSD activated sludge facility treats a mixture of metropolitan (Metro) and pulp and paper mill (mill) wastewaters. The Metro wastewaters are comprised of municipal and industrial wastes including a seasonal contribution from vegetable canning industries. The Metro wastewaters receive preliminary and primary treatment before entering the activated sludge system. The mill wastewaters receive primary treatment at the mills before they enter the plant through separate interceptor sewers and are pumped directly to the activated sludge system. Plant recycle streams, which include decant liquor from a Zimpro sludge heat treatment process, are returned to the primary effluent channels.

The GBMSD activated sludge facility is a contact stabilization system consisting of four quadrants (Figure 8-3). Each quadrant includes a 22.3-m x 74.4-m x 6.2-m (73.3-ft x 244-ft x 20.5-ft) SWD contact basin (10,370-m³ [2.74-mil gal] volume) and a 11.1-m x 74.4-m x 6.9-m (36.3-ft x 244-ft x 22.5-ft) SWD reaeration basin (5,680 m³ [1.5-mil gal] volume). Inlet flumes were added to the contact basins to distribute

the incoming wastewater across the entire width of the basin. Each contact basin was originally equipped with 12 93-kW (125-hp) sparged turbine aerators. The reaeration basins had six 56-kW (75-hp) sparged turbine aerators. The process air is supplied by four 1,864-kW (2,500-hp) centrifugal blowers, each having a capacity of 21,000 L/s (44,500 scfm) at a discharge pressure of 184 kPa (12-psig). The centrifugal blowers did not need modification because the 184-kPa (12-psig) discharge pressure was more than adequate for the 5.8-m (19.1-ft) submergence of the diffusers.

Quadrant 2 was retrofitted with Sanitaire ceramic disc diffusers, while Quadrant 4 received Parkson perforated membrane tube diffusers. The design criteria for selecting the number and distribution of fine pore diffusers in the aeration basins are presented in Table 8-7. The design criteria were based on the results of the field studies conducted in 1983, operating experience with the sparged turbines, and information supplied by the manufacturers of the fine pore aeration systems. The α values used for design, 0.68 in the contact basins and 0.90 in the reaeration basins, were selected based on the results of the 1983 field work and with consideration given to other design constraints such as maximizing power savings during the test period by treating the entire plant flow in the two fine pore diffuser equipped quadrants. However, this design strategy was only viable if the actual α values were equal to or greater than the values used for design. In the event that α values were lower or plant loadings higher than expected, additional aeration capacity could be added by placing one or both of the remaining sparged turbine quadrants in service.

The contact basins were divided into three zones and subdivided into ten grids each. The number of diffusers per grid was the highest in the tank inlet zone and lowest in the tank outlet zone. The reaeration basins were divided into six grids each. Since oxygen demand was expected to be relatively uniform in these basins, the number of diffusers per grid was constant.

The number of diffusers installed in each grid and the design airflow rates per diffuser are summarized in Table 8-8. The design average airflow rates used for the ceramic diffusers, 1 L/s (2.1 scfm)/diffuser in the contact basin and 0.9 L/s (1.9 scfm)/diffuser in the reaeration basin, were relatively high compared to the normal practice of designing for about 0.6 L/s (1.25 scfm)/diffuser. This was due to the high organic loading applied to the activated sludge system. The airflow rates in the contact basin are a result of providing the maximum number of diffusers that would physically fit in the basin inlet grids and then using the same diffuser airflow rate for all grids in the basin. This relatively high average airflow rate per diffuser was possible because the mill waste discharge resulted in minimal diurnal load variations.

Figure 8-3. Treatment plant schematic - Green Bay, WI.

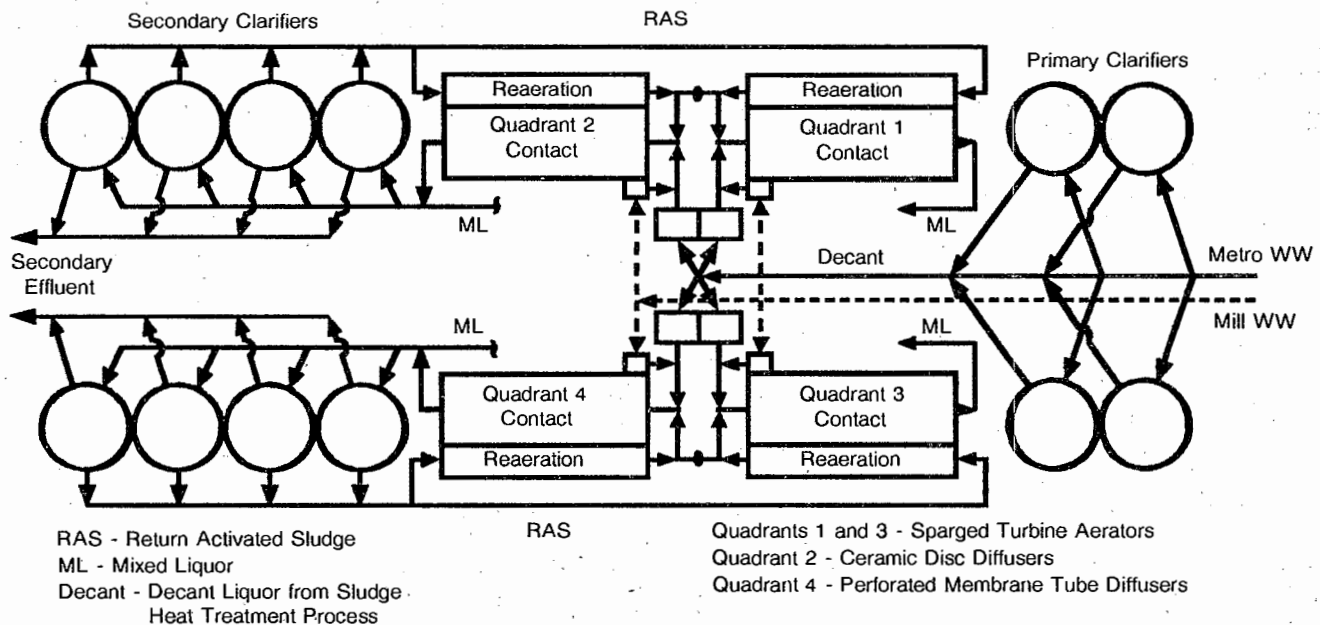


Table 8-7. Fine Pore Aeration System Design Criteria - Green Bay, WI

Parameter	Criteria
BOD ₅ ¹ , lb/d	
Average day (50th percentile)	161,000
Maximum month	202,000
Maximum day	239,000
O ₂ Requirement ²	1.0 lb O ₂ /lb BOD ₅ applied
Contact Basins	
Size	73.3 ft x 244 ft x 20.5 ft deep
Number	4
Volume, gal per quadrant	2,740,000
O ₂ demand	75 % of quadrant total
O ₂ demand profile, %:	
Zone 1	55
Zone 2	30
Zone 3	15
α	0.68
β	0.95
Diffuser submergence, ft	19.1
Reaeration Basins	
Size	36.3 ft x 244 ft x 22.5 ft deep
Number	4
Volume, gal per quadrant	1,540,000
O ₂ demand	25 % of quadrant total
O ₂ demand profile	Uniformly Distributed
α	0.90
β	0.95
Diffuser submergence, ft	19.1

¹ Calculated from data reported for January 1982-April 1983. A total of 478 values were used.

² Based on 1983 off-gas results.

The membrane system was designed for an airflow rate of 1.4 L/s (2.9 scfm)/diffuser in the contact basin and 1.2 L/s (2.6 scfm)/diffuser in the reaeration basin. The manufacturer's recommended design range for these diffusers was between 0.9 and 2.4 L/s (2.0 and 5.0 scfm)/diffuser.

Before the aeration equipment was approved for installation, manufacturer shop tests were conducted to determine clean water OTE. The tests were conducted in accordance with the ASCE Standard procedure. The Sanitaire ceramic discs met or exceeded the specified SOTE values for each contact basin zone and for the sludge reaeration basin with the respective diffuser densities and diffuser airflow rates shown in Table 8-8. These SOTEs were 31.0, 35.7, 38.3, and 36.2 percent for contact basin Zones 1, 2, and 3 and the reaeration basin, respectively. The Parkson membrane diffusers achieved a much higher SOTE than the specified value of 27.5 percent. The SOTEs were 31.3, 33.8, 31.7, and 34.9 for contact basin Zones 1, 2 and 3 and the reaeration basin, respectively. Since the number of membrane diffusers was not reduced to account for the higher SOTEs, the projected design airflow rates per membrane diffuser were reduced to about 0.9 L/s (2.0 scfm)/diffuser in the reaeration basin and 1.2 L/s (2.5 scfm)/diffuser in the contact basin.

Five removable pilot headers were provided in each contact basin, and two were provided in each

Table 8-8. Fine Pore Diffuser Configuration Summary - Green Bay, WI

	Zone	No. Grids	Diffusers/Grid	Diffusers/Zone	Diffuser Density, sq ft floor area/diffuser	Design Airflow, scfm/diffuser
Contact Basin 2 - Ceramic Disc Diffusers	1	4	805	3,220	1.85	2.1
	2	4	490	1,960	3.03	2.1
	3	2	474	948	6.25	2.1
	Total			6,128		
Reaeration Basin 2 - Ceramic Disc Diffusers	1	6	358	2,148	4.17	1.9
Contact Basin 4 - Perforated Membrane Tube Diffusers	1	4	616	2,464	2.44	2.9
	2	4	350	1,400	4.35	2.9
	3	2	378	756	7.69	2.9
	Total			4,620		
Reaeration Basin 4 - Perforated Membrane Tube Diffusers	1	6	233	1,398	6.25	2.6

reaeration basin to obtain diffusers for visual observation and testing without having to drain the basins. Each removable header was equipped with four diffusers at a submergence of about 5.2 m (17 ft). The headers were placed at the inlet, middle, and outlet of the contact basins and at the inlet and outlet of the reaeration basins. The diffusers on the removable headers and two diffusers per fixed grid were provided with pressure taps for monitoring DWP.

A two-stage, in-line air filter was provided on the main header to the ceramic disc quadrant. The air filter was originally designed to remove more than 99.9 percent of all particles ≥ 0.3 micron in size. After start-up, problems were encountered with excessive headloss across the filter so the second-stage elements were changed to a coarser medium. The filtration efficiency of the modified filter was 98 percent of all particles ≥ 1.0 micron in size.

IV. OPERATIONAL PERFORMANCE AND EVALUATION

Operation and Testing Procedures

The main goals of the evaluation program were to operate each fine pore diffuser quadrant at equal organic loadings, follow recommended diffuser cleaning methods, and monitor OTE performance of the diffusers with the standard off-gas testing procedure. Table 8-9 summarizes the monthly average operating conditions for the two systems for the duration of the test program. A low operating SRT was used to prevent nitrification. The average operating DO concentrations and SRTs were essentially equal for the two systems. The membrane diffuser system had a slightly higher average organic loading, which was due to the inability to divert an exactly equal distribution of influent to each quadrant.

For the first 6 months of operation before a major diffuser cleaning effort was carried out, half of the ceramic grids were treated with HCl gas at 1-3 month intervals and half of the membrane grids were flexed every 3 weeks. Normally, the HCl gas dose is added

in sufficient quantities during cleaning until the DWP decreases to a predetermined level. Since DWP did not increase appreciably during plant operation, a fixed HCl gas dose of approximately 45 g (0.1 lb)/diffuser was used.

The membrane flexing procedure was done according to the membrane diffuser manufacturer's instructions. One grid was flexed at a time by closing the downcomer air valve, bleeding off the air in the header system so the membranes would collapse completely onto the frame, increasing the airflow rate to about 3.8 L/s (8 scfm)/diffuser for 2-5 minutes, and returning the airflow rate to the previous operating level.

The first of the nine off-gas tests was conducted on May 13, 1986 (just after the start of the test program), and five more tests were performed before a major diffuser cleaning in November 1986. An off-gas test was conducted just after cleaning in December 1986, and the other three off-gas tests were conducted in June, August, and October 1987. The August 1987 test followed another major diffuser cleaning in July 1987.

A typical off-gas test was conducted over 2 days. One day was used to survey 24 positions in each of the contact basins. The second day was used to survey 12 positions in each of the reaeration basins. Corresponding positions in each basin were alternately sampled and analyzed at about the same time during the sampling day. The results of the off-gas testing were summarized by calculating a weighted α F(SOTE) value for each contact and reaeration basin. The weighted average is based on the measured off-gas flow and OTE.

Based on pilot tests, the rigorous diffuser cleaning methods used in November 1986 and July 1987 were modified from the original procedures. The cleaning procedure selected for use on the ceramic diffusers was hosing from the tank top with fire hoses, partially filling the basin with service water, gas cleaning with 45 g (0.1 lb) HCl/diffuser, draining off the service

Table 8-9. Operating Data - Green Bay, WI

Month	Quadrant 2 - Ceramic Disc Diffusers			Quadrant 4 - Membrane Tube Diffusers		
	BOD ₅ Loading, 1,000 lb/d	SRT, days	DO, mg/L	BOD ₅ Loading, 1,000 lb/d	SRT, days	DO, mg/L
May 1986	56.5	3.00	2.4	54.7	3.02	2.3
June	55.5	2.36	1.6	65.2	2.36	1.6
July	57.0	3.23	1.8	59.4	3.03	1.8
August	58.8	2.65	1.2	62.8	2.86	1.4
September	56.0	2.52	1.3	58.7	2.86	1.6
October	58.1	2.66	1.5	62.1	2.87	1.6
November	49.7	3.14	2.3	55.3	3.37	1.8
December	51.2	3.21	2.5	53.8	3.64	2.5
January 1987	52.9	2.90	2.5	54.2	3.42	2.4
February	64.7	2.89	1.6	64.8	3.26	2.1
March	55.3	2.82	1.7	58.1	3.09	2.0
April	54.1	2.73	2.1	59.1	2.92	2.0
May	31.0	4.26	2.4	38.2	3.67	2.2
June	36.7	2.96	2.2	39.5	2.74	2.0
July	35.4	4.72	2.0	38.3	4.91	1.8
August	52.6	3.24	1.6	46.0	3.55	1.8
September	44.1	3.50	2.0	45.2	3.98	2.0
October	43.2	3.91	2.4	44.1	4.11	2.3
Average	50.7	3.15	2.0	55.3	3.31	2.0

water, and rehousing from the tank top. All of the membranes were cleaned by hosing from the basin floor, scrubbing with a stiff-bristled brush, and rehousing.

Aeration Performance

Table 8-10 summarizes weighted $\alpha F(SOTE)$ values determined from off-gas testing of the ceramic and membrane diffuser systems. A comparison of performance between the two types of diffusers is shown chronologically in Figure 8-4. The two systems started out at nearly equal $\alpha F(SOTE)$ s. $\alpha F(SOTE)$ then decreased substantially for both systems such that, after 3 months of operation, values were about 75 percent of their respective initial values. In October 1986, the fifth off-gas test was conducted and the $\alpha F(SOTE)$ s were still substantially below the values measured in May 1986. There was also a problem with maintaining acceptable DO concentrations at the inlet end of the contact basins, so it was decided to drain the basins for inspection and rigorous cleaning of the diffusers. Once the cleaning was complete, the systems were put back into service and a follow up off-gas test was conducted. The increased $\alpha F(SOTE)$ of the ceramic system indicated that the discs were essentially restored to their original condition in both the contact and reaeration basins. A smaller increase in $\alpha F(SOTE)$ was observed in the membrane-equipped basins.

The next off-gas test was conducted in June 1987. Measured $\alpha F(SOTE)$ s were similar to those measured in October 1986 before the systems had been cleaned. Based on the off-gas test results, a decision was made to drain, inspect, and clean the two test quadrants. After cleaning, the systems were put back into service and off-gas tested. The $\alpha F(SOTE)$ of the ceramic system showed an increase to above its

original level. The membranes showed little if any improvement.

The last off-gas test was conducted during the last week of October 1987. The $\alpha F(SOTE)$ of the contact basin ceramic disc system decreased from nearly 25 percent to about 17 percent. A similar reduction was experienced in the reaeration basin ceramic disc system. The membrane systems remained relatively constant at about 12 percent in the contact basin and 13 percent in the reaeration basin.

In summary, off-gas testing before and after rigorous cleaning indicated the ceramic diffusers could achieve higher $\alpha F(SOTE)$ s with cleaning, but that membrane system $\alpha F(SOTE)$ s were relatively unaffected by cleaning. This is further illustrated in Table 8-11, which also shows the αF values calculated for the systems using the earlier determined clean water SOTE values. The αF values approached similar values in the range of 0.34-0.44 for both diffusers after fouling increased. Clean ceramic diffusers in either basin yielded αF values in the range of 0.5-0.65.

αF values were also not greatly different for the contact and reaeration basins. Contrary to some other studies, αF values were not depressed at the wastewater addition points. Tank geometry may have influenced this observation, since GBMSD tanks have a length-to-width ratio of 4:1, which is lower than for many plug flow type systems that exhibit a more significant reduction in αF at the influent introduction zone.

Cleaning and Diffuser Evaluations

Diffusers were tested at various times during the study to observe changes in diffuser characteristics

Figure 8-4. OTE (off-gas method) vs. time - Green Bay, WI.

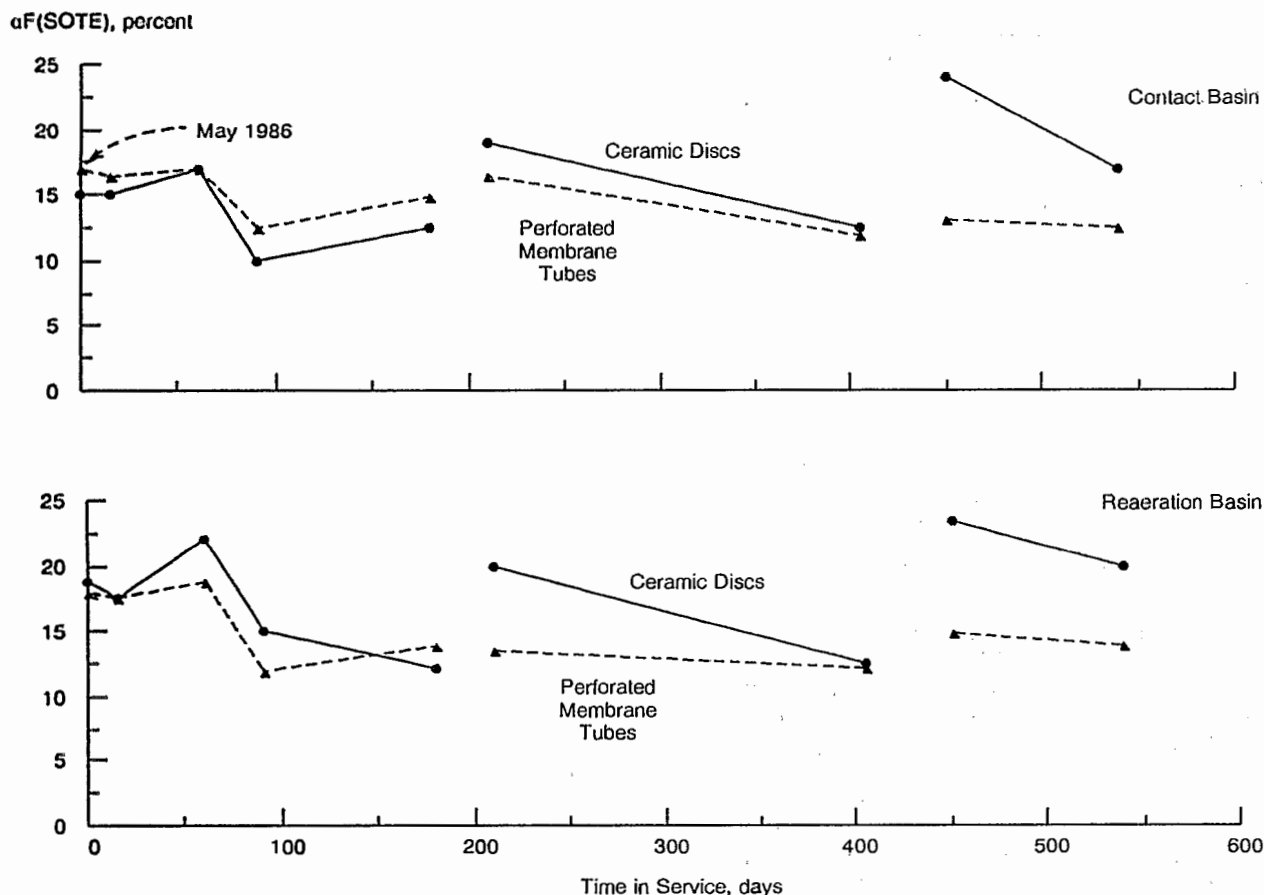


Table 8-10. αF(SOTE) Values from Off-Gas Testing - Green Bay, WI

Basin	Test Date	αF(SOTE)	
		Ceramic Diffusers	Membrane Diffusers
Contact	5/13/86	14.8	16.5
	5/15/86	14.7	16.2
	7/2/86	17.1	17.0
	7/30/86	9.7	12.1
	10/30/86	12.2	14.3
	12/3/86	19.1	16.3
	6/18/87	11.8	11.4
	8/5/87	20.2	12.1
	10/28/87	16.5	11.5
Reaeration	5/12/86	18.2	17.6
	5/16/86	17.0	17.0
	7/1/86	21.2	18.4
	7/29/86	14.3	11.2
	10/29/86	11.6	13.4
	12/2/86	19.6	13.1
	6/17/87	11.8	11.1
	8/4/87	23.2	13.7
	10/27/87	19.5	12.7

caused by fouling or aging and to evaluate the effectiveness of preventive maintenance and cleaning procedures. Both types of diffusers were characterized by DWP and steady-state clean water OTE tests. The ceramic diffusers were further evaluated using the BRV test. Ceramic disc thickness and strength and perforated membrane size, weight, hardness, and modulus of elasticity were measured to quantify any changes caused by aging. Steady-state clean water OTE tests were run in the laboratory in a 76-cm (30-in) diameter by 3-m (10-ft) water depth tank to characterize diffuser OTE. Steady-state conditions were established by feeding a constant rate of sodium sulfite solution to maintain a DO concentration of 1-3 mg/L. OTE was measured using the off-gas method. Diffusers for testing were obtained from the removable pilot headers or from the in-basin grids when the basins were drained for inspection and cleaning.

Ceramic diffusers removed from the reaeration basin had different fouling characteristics than those removed from the contact basin. They both had an

Table 8-11. αF as a Function of Time in Service - Green Bay, WI

Basin	Time in Service, months					
	Total		Since Cleaning		αF	
	Ceramic	Membrane	Ceramic	Membrane	Ceramic	Membrane
Contact	< 1	4	< 1	< 1	0.46	0.49
Reaeration	< 1	4	< 1	< 1	0.50	0.53
Contact	2	6	2	2	0.57	0.53
Reaeration	2	6	2	2	0.65	0.57
Contact	3	7	3	3	0.32	0.40
Reaeration	3	7	3	3	0.42	0.35
Contact	6	10	6	6	0.39	0.44
Reaeration	6	10	6	6	0.34	0.41
Contact	7	11	< 1	< 1	0.57	0.46
Reaeration	7	11	< 1	< 1	0.55	0.38
Contact	13	17	7	7	0.37	0.36
Reaeration	13	17	7	7	0.36	0.35
Contact	15	19	< 1	1	0.64	0.39
Reaeration	15	19	< 1	1	0.66	0.43
Contact	18	22	3.5	4	0.51	0.37
Reaeration	18	22	3.5	4	0.57	0.38

outer slimy layer, which was about 6-mm (1/4-in) thick, that could be hosed off with water at a pressure of about 309 kPa (30 psig). The ceramic diffusers from the reaeration basin also had a second bottom layer that was black, hard, and firmly attached to the diffuser surface. The black layer was soluble in 14 percent HCl, but only slowly. The membrane diffusers exhibited the same type of fouling for each of the basins. The outer layer appeared to be comprised of a biological slime into which a gritty sand-like material was incorporated. The major constituents of the inner black layer on membrane diffusers from the reaeration basin was found to be iron (18.5 percent) and calcium (3.2 percent). Results of clean water oxygen transfer tests on test diffusers indicated that hosing was most effective in increasing the OTE of the ceramic diffusers. Thus, the outer slime layer was felt to be responsible for most of the loss in OTE.

Evaluation of cleaning methods for ceramic diffusers from the contact basin showed that hosing alone was effective in restoring the clean water OTE to a like-new condition. Acid gas treatment did not further affect OTE, but did slightly lower DWP. Acid gas was much more effective in improving OTE of ceramic diffusers from the reaeration basin and further lowering DWP readings. Regular gas treatment may also have helped control DWP for ceramic diffusers in both basins.

Cleaning studies using fouled perforated membrane diffusers showed that flexing was not an effective cleaning method. The hosing-brushing-hosing (H-B-H) sequence did effectively clean the membranes, but the clean water OTE could not be improved compared to the fouled diffusers. Contrary to what was expected, DWP decreased to below values of a new

membrane diffuser after the H-B-H cleaning procedure.

Physical observations were made on the membrane diffusers to explain the DWP and performance characteristics of cleaned used diffusers relative to new ones. The membrane material was found to be stiffer, and changes in the diffuser slits were documented. The slits were wider than when new and did not close completely. This very likely explains the depressed OTEs after cleaning and the decreased DWP values. Causes of the changes in the membrane material are not known. The plasticizer in the PVC membrane may have been affected by environmental conditions, including the temperature of the mixed liquor, which averaged above 29°C (85°F) in the summer months.

V. ECONOMIC CONSIDERATIONS FOR FINE PORE AERATION

An economic analysis was done to compare the initial, operating, and total present worth costs of retrofitting the entire plant to either ceramic or membrane diffusers. For ease of comparison, a hypothetical situation was used where all four quadrants of the aeration system were converted to fine pore aeration irrespective of the existing situation. This cost analysis includes a comparison of the retrofitting cost to the operational costs of the existing sparged turbine system. The BOD₅ loading used for the analysis was the average plant loading from 1983 through 1985, which was 25 million kg (55 million lb)/yr. Table 8-12 summarizes the cost items and compares the costs of the aeration alterations.

The 1985 construction costs determined by competitive bidding were used to develop the initial cost estimates for the two fine pore diffuser systems.

Table 8-12. Cost Summary Comparison for Alternative Aeration Systems - Green Bay, WI

Cost	Sparged Turbines	Ceramic Discs	Perforated Membrane Tubes	
			New	Used
Capital, \$	0	2,221,600	1,998,200	1,998,200
Annual O&M, \$/yr				
Electrical Power ^a	1,020,800 ^b	550,000 ^c	550,000 ^c	847,000 ^d
Mechanical Maintenance	57,000	5,400	5,400	8,100
Diffuser Cleaning	0	45,900	8,600	8,600
Total	1,077,800	601,300	564,000	863,700
O&M Present Worth ^e , \$	9,927,500	5,538,000	5,194,400	7,954,700
Total Present Worth, \$	9,927,500	7,759,600	7,192,600	9,952,900

^a Based on treating 55,000,000 lb/BOD₅/yr.

^b Based on power cost of \$18.56/1,000 lb BOD₅ applied.

^c Based on power cost of \$10.00/1,000 lb BOD₅ applied.

^d Based on power cost of \$15.40/1,000 lb BOD₅ applied.

^e Based on 20 years at 8-7/8 percent interest, PWF = 9.21.

The acid gas storage and feed building and acid feed equipment were included in the ceramic diffuser cost estimate. A royalty payment of \$236,800 was also included in the ceramic diffuser system initial cost estimate for use of the in-situ acid gas cleaning procedure.

The costs for operating the two fine pore aeration systems and the sparged turbine aeration system would typically include labor for process monitoring and adjustment of activated sludge control parameters, and the electrical power to run the air supply blowers and turbine mixers. However, since all three aeration systems would require an equivalent amount of effort for monitoring the activated sludge process and adjusting the airflow rate to the basins, these estimated costs were not included in the comparison.

Estimated aeration energy costs were calculated by first determining the actual average energy required per unit of BOD₅ applied for the three systems. A value was determined for the sparged turbine system by averaging energy consumption and BOD₅ applied data for 1983-1985. Using a historical electrical cost of \$0.04/kWh, the unit power cost for the sparged turbine system was \$40.92/1,000 kg (\$18.56/1,000 lb) BOD₅ applied. The fine pore diffuser performance results for the last 4 months of the study were used to obtain the unit power cost of these aeration systems. These data reflect the higher OTE of the ceramic diffuser due to its favorable response to cleaning. The unit power costs used for the ceramic and membrane diffusers were \$22.04 and \$33.95/1,000 kg (\$10.00 and \$15.40/1,000 lb) BOD₅ applied, respectively.

Diffuser cleaning costs for the ceramic system assumed draining the basins twice annually for inspection and cleaning with hosing followed by in-situ HCl gas treatment and rehosing. Monthly in-situ acid gas treatment is assumed for the reaeration basins to prevent a buildup of the inner black foulant layer. A minimal cleaning effort was included for the membrane diffusers, which consists of draining the basins once per year for inspection and H-B-H cleaning. The sparged turbine system is shown in Table 8-12 to have the highest total maintenance cost followed by used perforated membrane tube diffusers, then ceramic disc diffusers, and, finally, new perforated membrane tube diffusers.

A comparison of electrical power costs and O&M costs between the ceramic disc diffuser and sparged turbine aeration system (Table 8-12) shows a savings of about \$471,000/yr in electrical power costs and \$476,500/yr in total O&M costs for the ceramic disc system. The simple payback period on the initial investment would be about 4.5 years.

The membrane tube diffusers would have shown similar economics had they not lost their initial high OTE. Based on the performance of new diffusers, the annual savings in total O&M costs are estimated at \$514,000, which would have provided a simple payback period of about 4 years. However, the lost transfer efficiency resulted in a substantial increase in the electrical power requirements and an actual O&M savings of only \$214,000/yr. The simple payback period under these circumstances would be more than 9 years. Based on a 20-yr life of the equipment and an interest rate of 8-7/8 percent, retrofitting with the membrane tube diffusers would not be economical because the total present worth of the retrofit is greater than the cost of continuing to operate the sparged turbines.

8.2.4 Hartford Water Pollution Control Plant

LOCATION: Hartford, Connecticut

OPERATING AGENCY: Hartford Metropolitan District Commission

DESIGN FLOW: 2,630 L/s (60 mgd)

WASTEWATER: City of Hartford Plus Six Area Towns

ORIGINAL AERATION SYSTEM: Chicago Pump "Deflectofuser" Coarse Bubble Diffusers

FINE PORE AERATION SYSTEM: Ceramic Dome Diffusers

YEAR FINE PORE SYSTEM PLACED IN OPERATION: 1982

BASIS OF PERFORMANCE EVALUATION: Off-Gas Testing

CLEANING METHOD: Hosing/Acid Application/Hosing ("Milwaukee Method")

I. INTRODUCTION

In November 1982, the Hartford Water Pollution Control Plant in South Meadows, CT went on-line with a retrofit from a coarse bubble to a fine pore aeration system. Four of the six aeration tanks were retrofitted with diffusers, air-line valves and controls were modified, and air filters were installed on the inlets to all three existing blowers. Extensive aeration studies were conducted on the fine pore system in 1985-1987 to evaluate OTE over time and the effectiveness of diffuser cleaning. Information is presented on the original aeration system, the basis for changing to fine pore diffusers, retrofit design and performance, and an economic evaluation of the new system.

II. HISTORICAL BACKGROUND

The Hartford plant treats wastewater from six greater Hartford area towns. The secondary activated sludge treatment facility processes an average daily flow of about 1,970 L/s (45 mgd); design is based on an average daily flow of 2,630 L/s (60 mgd) and a peak hydraulic flow of 4,775 L/s (109 mgd).

Faced with the need for additional aeration capacity (greater oxygen transfer), steadily increasing electrical rates, and the demand charge for placing a second 2,240-kW (3,000-hp) blower on line, Hartford Metropolitan District Commission (MDC) staff engineers initiated a retrofit evaluation project in 1978 for the purpose of examining ways of reducing future power costs.

In addition to the objective of significant electrical savings, other objectives of the retrofit were: 1) simple payback of initial cost in approximately 3 years, 2) adding minimum O&M costs over the existing aeration system, 3) providing operational flexibility, 4) increasing OTE to avoid having to use two large

blowers simultaneously, and 5) maintaining process performance and effluent water quality.

Original Aeration System

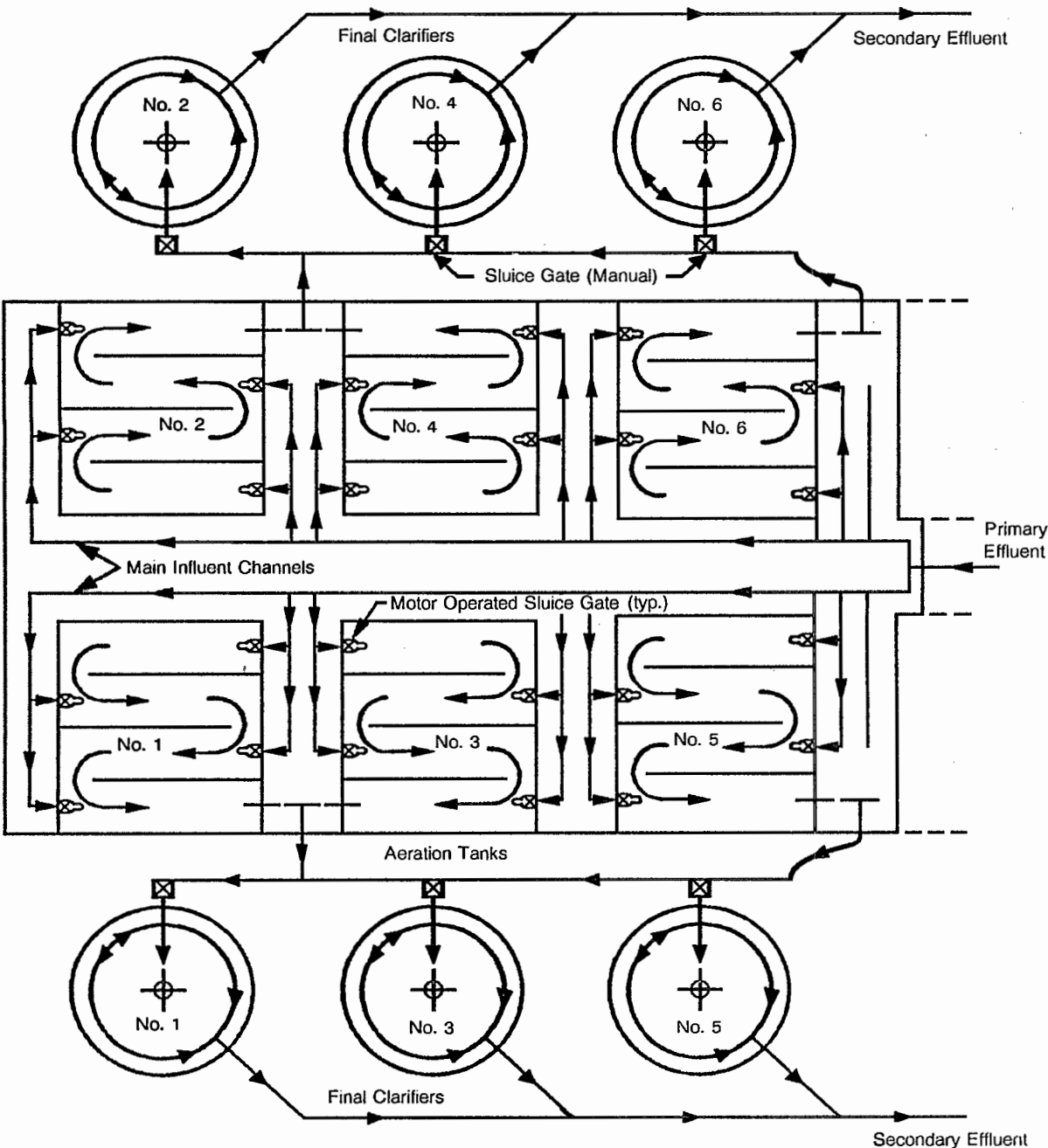
In November 1972, the new secondary wastewater treatment facility began operation. The activated sludge aeration system consisted of six identical four-pass aeration tanks, each 24.4 m wide x 59.2 m long (80 ft x 194 ft) with a nominal operating liquid depth of 4.7 m (15.5 ft) (Figure 8-5).

Primary effluent is pumped to the secondary facilities and split among four of the six aeration tanks (Aeration Tanks 5 and 6 have never been in operation). Each 6,815-m³ (1.8-mil gal) aeration tank is divided into four passes of equal size. The normal mode of operation is step feed. Return activated sludge is fed into the head end of Pass 1 of each aeration tank, and primary effluent is normally split equally among Passes 2, 3, and 4 (Figure 8-5).

The air supply for the activated sludge process is furnished by one (or more) of three identical rotary vane blowers. Each blower is rated at a maximum output of 28,320 L/s (60,000 scfm) at 153 kPa (7.5 psig). Each blower is driven by a 2,240-kW (3,000-hp) motor. The airflow rate generated by the blowers is adjusted by the positioning of the inlet guide vanes on the suction side of each blower.

The original aeration equipment consisted of Chicago Pump "Deflectofuser" coarse bubble diffusers with large 1-cm (3/8-in) diameter orifices on the periphery of the diffuser. Approximately 250 of these diffusers were installed on each of seven drop pipe/manifold assemblies per pass. A spiral roll aeration and mixing pattern was established by this design geometry. The SOTE of the "Deflectofuser" system at Hartford was estimated to be 6-7 percent.

Figure 8-5. Secondary treatment process schematic - Hartford, CT.



The air supply control system is designed with flow control and flow indicators for each pass of each aeration tank. A DO probe senses the DO concentration in the pass. The signal is fed to an analyzer and then to an electronic controller where the DO is manually set. The output signal from the controller modulates the 30-cm (12-in) motor-operated butterfly valves that meter the correct amount of air to match the set-point DO that has been manually set.

From start-up in 1972, one blower always operated at full capacity. Yet DO demand in the aeration system, particularly at the inlet points, was not met during the summer months. The only operational solution was to turn on a second 2,240-kW (3,000-hp) blower. This was a costly proposition for providing a small amount of additional air.

Basis for Changing to Fine Pore Aeration

Total plant power costs had increased steadily from about \$300,000/yr in 1973 to over \$900,000/yr in 1979. Between 1979 and 1982, a large decrease in energy usage was realized by the upgrading of sludge handling and treatment equipment from coil filters to belt filter presses and the initiation of a new incinerator operating mode. Despite these electrical cost reduction improvements, total plant electrical costs continued to rise at an alarming rate. Energy efficient aeration equipment needed to be considered since this equipment accounted for about 60 percent of the energy used at the plant.

Over a 5-yr period beginning in 1978, MDC engineers, with the assistance of equipment manufacturers and consultants, developed a system that was compatible with existing facilities and was believed cost effective and efficient. Ceramic domes and discs were chosen for pilot testing because they appeared to have the greatest OTE and satisfied the compatibility requirements of tank geometry and the air supply system.

The pilot tests indicated the possibility of a 50-60 percent reduction in total air supply requirements for aeration. Total estimated air supply requirements were set at 8,495-10,385 L/s (18,000-22,000 scfm), which included air to suspend solids in the influent channel.

With one blower normally operating at maximum capacity of 28,320 L/s (60,000 scfm) for the existing aeration system, the next concern was to investigate the turndown capability of the existing blower equipment. It was determined that each blower could be turned down to below 4,720 L/s (10,000 scfm) without surging; however, operating efficiency would diminish as airflow was reduced.

The original air piping system at the Hartford plant was constructed of spiral welded steel and wrought iron pipe. Inspection revealed: 1) the bituminous epoxy coating in the air mains and suction lines was

in excellent condition and would be suitable for the fine pore system without repair, 2) the coating in the 30-cm (12-in) air pipes in Aeration Tanks 1, 2, 3, and 4 was in good condition (paradoxically, the coating in the same air pipes in Aeration Tanks 5 and 6 (never operated) was damaged and contained rust and scale), and 3) the 15-cm (6-in) drop pipes and manifolds to which the "Deflectofusers" were connected were rusted, and the drop pipes could not be used with the fine pore aeration system.

Fine pore ceramic domes would require removal of 95 percent of all particles ≥ 0.3 micron in size in the air supply. The existing automatic oil bath filters were capable of removing only 25-30 percent of the particles and, therefore, were not usable alone for the fine pore system. "Biocell" filters, which could be installed inside the existing inlet plenums, were selected.

Oxygen transfer projections and energy requirements for coarse and fine pore diffuser systems over a 20-yr period were examined. Minimum air requirements for the proposed fine pore dome system would be dictated by the air needed to keep the MLSS in suspension. Peak air demand for the domes could be supplied by one existing blower throughout the planning period, while peak air demands for the existing coarse bubble system would require simultaneous operation of two blowers during summer months. The total system head on the blowers with the new system was expected to be well within the capacity of the existing equipment, and blower surging would not be expected to occur for the expected air demand.

In 1981, the estimated initial cost of all recommended improvements to retrofit to fine pore domes was between \$1,115,000 and \$1,830,000 with an estimated simple payback period of 3-6 years.

III. FINE PORE AERATION RETROFIT DESIGN DESCRIPTION

The cost-effectiveness study for Hartford included a complete design review for sizing the fine pore aeration system to meet process needs through the year 2001. The projected food-to-microorganism (F/M) loading of the retrofit was 0.2-0.3 d⁻¹, which resulted in a ratio of oxygen required:BOD₅ removed of about 1.0 kg O₂/kg BOD₅ based on design criteria in WPCF MOP No. 8.

Average daily oxygen requirements at field conditions (OTR_f) were projected to be 33,115 kg (73,000 lb)/d in the year 2001 during the period May-October, and 21,230 kg (46,800 lb)/d the rest of the year. For 1982 conditions, the expectation was for OTR_f values of 22,635 and 13,700 kg (49,900 and 30,200 lb)/d for May-October and the remainder of the year, respectively. The standard oxygen transfer rate (SOTR) was calculated using: 1) $\alpha = 0.75$ for the

ceramic fine pore domes (0.85 was used for the existing coarse bubble diffusers), 2) $\beta = 0.95$, 3) operating DO of 2.0 mg/L, and 4) average mixed liquor temperature of 15°C (59°F). α was selected from literature information. Average SOTEs were selected as 29 percent for the fine pore discs and 6 percent for the existing coarse bubble diffusers.

The resulting projected air requirements for 1982 conditions including nitrification were 32,145 L/s (68,100 scfm) using the existing system and 12,270 L/s (26,000 scfm) using the fine pore dome system. Airflows without nitrification were estimated to be 21,665 L/s (45,900 scfm) for the existing system and 9,675 L/s (20,500 scfm) for the fine pore dome system. An additional 5,665 L/s (12,000 scfm) was also allocated for mixing in the influent channel.

Four of six aeration tanks originally placed in service in 1972 would continue to be used after the retrofit. No modifications to the tanks or to the process liquid piping would be necessary. Only in-tank air piping would be changed. The mode of operation both before and after retrofit is step feed. Pass 1 of each aeration tank is used for reaeration of the return activated sludge. Normally, one-third of the primary effluent is fed into the head end of each of the remaining three passes.

The layout and design of the fine pore dome diffuser system was planned so that most of the existing air piping could be utilized without modification. The new submerged air distribution piping and diffuser grid piping was designed to facilitate an easy and economical installation.

The acceptable fine pore diffuser system had to have a guaranteed SOTE of 28 percent at 0.24 L/s (0.5 scfm)/diffuser, 26 percent SOTE at 0.47 L/s (1.0 scfm)/diffuser, and 23 percent SOTE at 0.94 L/s (2.0 scfm)/diffuser when operated at the average design diffuser density in 4.7 m (15.5 ft) of clean water. In addition, a minimum airflow of 0.24 L/s (0.5 scfm)/diffuser was established to prevent water-side fouling. Further, a minimum mixing requirement of 0.61 L/s/m² (0.12 scfm/sq ft) of tank bottom was established together with a minimum diffuser spacing of 61 cm (2 ft) on center. Certified oxygen transfer and mixing test results were required as part of the bid documents of each manufacturer submitting a bid. Diffuser performance data are presented as part of Figure 8-6.

It was planned that Aeration Tanks 1 and 2 be retrofitted first and then placed on-line before completion of the retrofits in Aeration Tanks 3 and 4. Tanks 1 and 2 would then be field tested and additional diffuser density modifications incorporated into Tanks 3 and 4, as needed.

DO measurements were taken in Aeration Tanks 1 and 2 soon after being placed in operation. The DO profiles indicated that more diffusers were needed at the influent end of the passes. Redistribution of the diffusers was easily accomplished in Aeration Tanks 3 and 4 by use of the spare saddles specified in the design. Final diffuser density and quantity information by grid and pass are contained in Figure 8-7 for one aeration tank.

No blower air handling capacity modifications were planned as part of the aeration system retrofit. The existing 28,320-L/s (60,000-scfm) rotary vane blowers were found to be suitable for use with the new fine pore diffuser system. Although preretrofit airflow from a single blower had been at the 28,320-L/s (60,000-scfm) level, the new fine pore aeration system would require less than 14,160 L/s (30,000 scfm). By inlet guide vane adjustment, turndown of the blowers was possible to a surge point of approximately 3,775 L/s (8,000 scfm). The only cost of turndown was in the reduced efficiency of the blower at lower airflow output rates.

Norton dome diffuser equipment was installed in Aeration Tanks 1-4. Each diffuser is an 18-cm (7-in) diameter porous ceramic dome secured to a PVC plastic pipe saddle by a dome orifice bolt. Air emerges from the 10-cm (4-in) grid piping network at each saddle location up through a hollow plastic dome bolt that contains a 5-mm (13/64-in) diameter orifice in the bolt sidewall.

IV. OPERATIONAL PERFORMANCE AND EVALUATION

By November 1982, installation of the entire project was complete. With all four aeration tanks on-line with the new fine pore aeration equipment, air usage dropped to 1,020,000 m³ (36,000,000 cu ft)/d, down from 1,810,000 m³ (64,000,000 cu ft)/d prior to the retrofit, and power fell to a level of 22,000 kWh/d, down from 31,000 kWh/d. For the remainder of 1982, the system was operated at this level.

The automatic control system did not perform as planned. Blower discharge pressure was too large to deliver air to all passes, and air supply to some passes was reduced to levels lower than the minimum recommended values required for solids suspension and estimated to be necessary to prevent water-side fouling of the ceramic diffusers.

The blower discharge pressure was 151-153 kPa (7.1-7.4 psig) in the automatic air control mode. Airflow control was switched to manual operation to alleviate the high discharge pressure. The blower discharge pressure was adjusted to 149 kPa (6.8 psig).

Foaming of the aeration tanks worsened after start-up of the fine pore system. It was determined that high SRTs (>3-5 days) caused foaming to increase above

Figure 8-6. OTE characteristics - Hartford, CT.

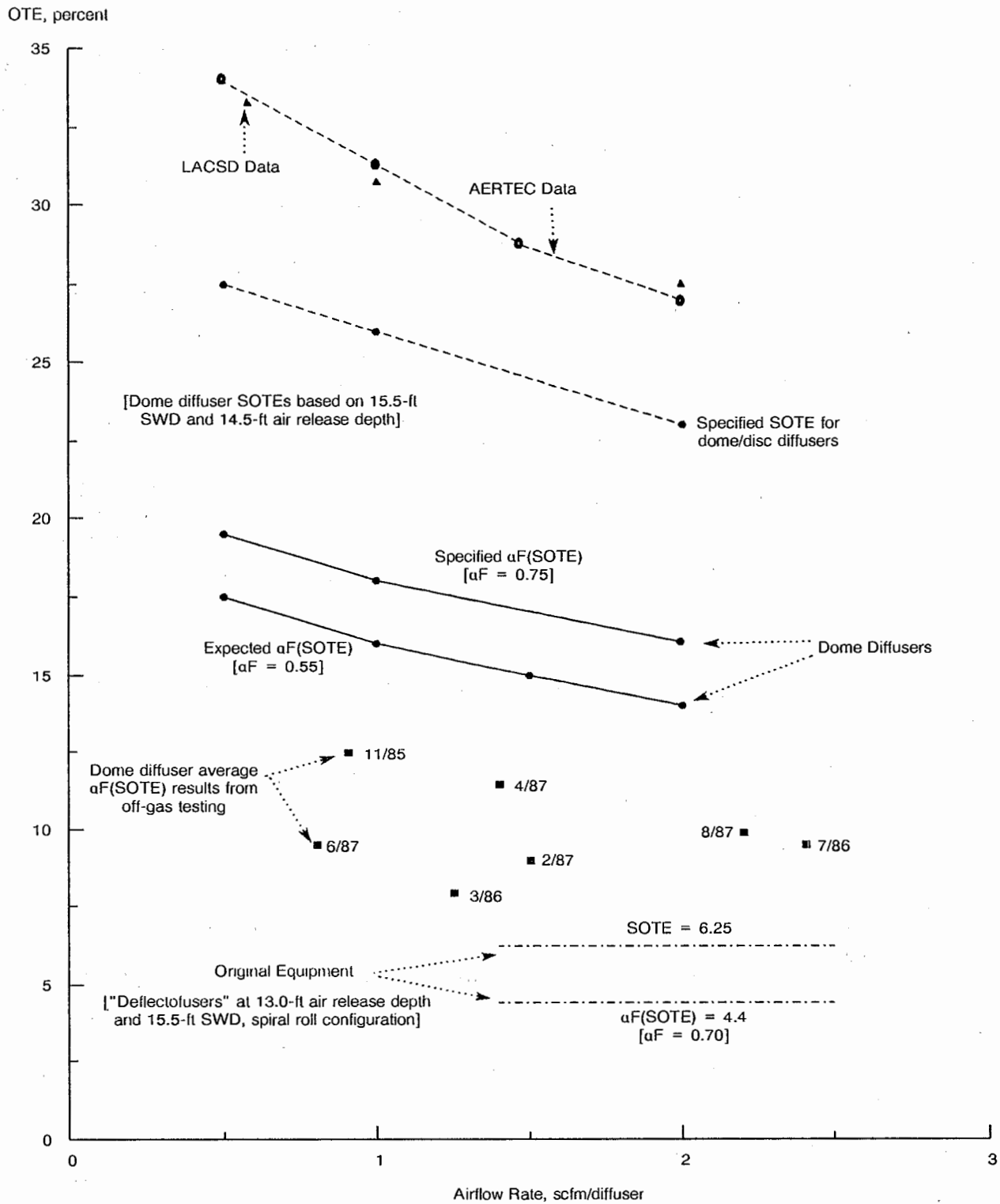
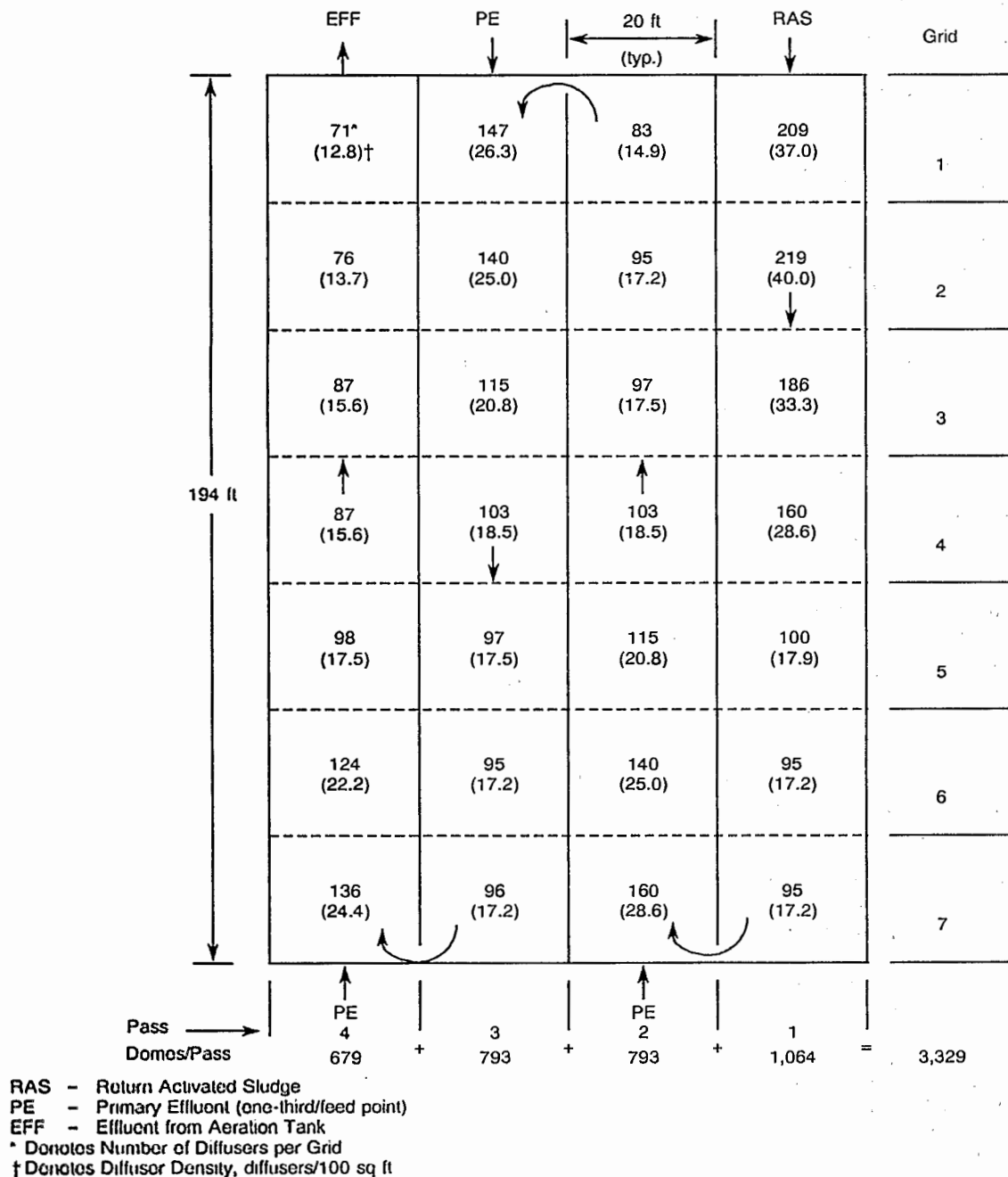


Figure 8-7. Typical diffuser layout for one aeration tank - Hartford, CT.



an acceptable level. Short-term remedial action to reduce foam consisted of reducing the mixed liquor DO concentration to near zero or zero. Foaming had been noticed in the 1979 pilot tests of the fine pore diffusers.

MLSS concentration, with a design design range of 2,000-2,500 mg/L, varied widely after retrofit implementation through the period of off-gas testing. Concentrations as high as 6,000 mg/L were

measured, and the average MLSS level was much greater than the upper limit design value of 2,500 mg/L. The elevated mixed liquor solids inventory resulted in increased oxygen demand and energy consumption. The foaming problem brought on by the higher MLSS values and resulting higher SRTs also appeared to adversely affect OTE.

Following the change to manual airflow control, the established mode of operation was to leave all

aeration pass control values fully open, allowing all diffusers to operate at approximately equal rates throughout the system. If DO concentrations increased in some aeration passes or tanks, air supply throttling was initiated at the individual aeration pass or passes having the greater DO concentration. Throttling was not continued to a point below which airflow to a pass would be less than the minimum airflow to achieve mixing and solids suspension (approximately 0.16 L/s/m³ [1.3 scfm/1,000 gal]) or less than 0.24 L/s (0.5 scfm)/dome. Plant effluent quality remained consistently high after implementation of fine pore aeration. Effluent BOD₅ and TSS concentrations nearly always remained below 10 mg/L.

Aeration Performance Evaluation

Table 8-13 summarizes aeration performance data by site visit for Aeration Tank 2. From 36 to 48 individual off-gas tests were conducted during each site visit. The whole tank average values are based on seven site visits from November 1985 to August 1987 and represent the summary of over 340 individual tests. During each site visit, each aeration pass was tested at the influent, middle, and effluent grids.

These data are plotted in Figure 8-8 for the average whole tank test results by site visit. The average expected SOTE for the Hartford design was 27.5 percent, and the average whole tank $\alpha F(SOTE)$, as measured by off-gas testing, was 10.0 percent.

Average αF for the whole tank was 0.37 with a range of 0.29-0.45. Usually, the very low values were measured at the influent feed point sample locations in any of the aeration passes.

The SOTE of the original coarse bubble spiral roll aeration system was estimated to be 6.25 percent. The efficiency of this aeration equipment is reduced to 4.4 percent [$\alpha F(SOTE)$] when an αF of 0.7 is assumed. The resulting OTE in mixed liquor with a DO concentration of 2.0 mg/L is 3.2 percent for the coarse bubble system.

The average $\alpha F(SOTE)$ for all whole-tank tests conducted over the 2-yr study period on the fine pore aeration system in Aeration Tank No. 2 was 9.97 percent, with a range of 8.2-12.6 percent. This represents 2.25 times the transfer efficiency of the original equipment. The ratio of 2.25 is in general agreement with the ratio of airflows before and after retrofit.

Effect of Cleaning on Performance

Prior to the beginning of off-gas testing in Aeration Tank 2 in the fall of 1985, the tank was dewatered and the diffusers cleaned. The other three aeration tanks were also cleaned in the fall of 1985 for the first time. Only Aeration Tank 2 was cleaned a second

time - in May 1987. There was no performance basis used to initiate cleaning in May 1987.

The cleaning method used both times is known as the "Milwaukee Method" (see Table 4-1), which uses hosing and acid application. A high pressure water jet is applied to the diffuser surface (air on) followed by acid spraying (air off) with ZEP, a commercially available cleaning compound with an HCl content of 22 percent, and brush scrubbing after letting the acid soak for 30 minutes. A second hosing is then performed (air on) to remove any solubilized foulant and residual acid.

Immediately after cleaning the diffusers, air distribution and leak testing was conducted prior to placing the aeration tank back on-line. Plant effluent was introduced to the aeration tank until the diffuser grid was submerged by 51-76 mm (2-3) inches of liquid. Airflow was adjusted to approximately 0.24 L/s (0.5 scfm)/diffuser, and observations were made for proper air distribution and leaks. All gasket, dome bolt, and other air leaks were repaired throughout the tank, and any leveling of, or repairs to, pipe supports was accomplished at this time.

Off-gas test results in Aeration Tank 2 before and after the May 1987 cleaning are summarized in Table 8-14. Although $\alpha F(SOTE)$ values were higher in Pass 2 after cleaning than before, lower OTEs were observed in Passes 1, 3, and 4 after cleaning. As a result, total tank average performance results for the after-cleaning tests were actually lower than those recorded before cleaning. The before-cleaning results were the highest $\alpha F(SOTE)$ values measured during the entire test period since the initial tests conducted in November 1985.

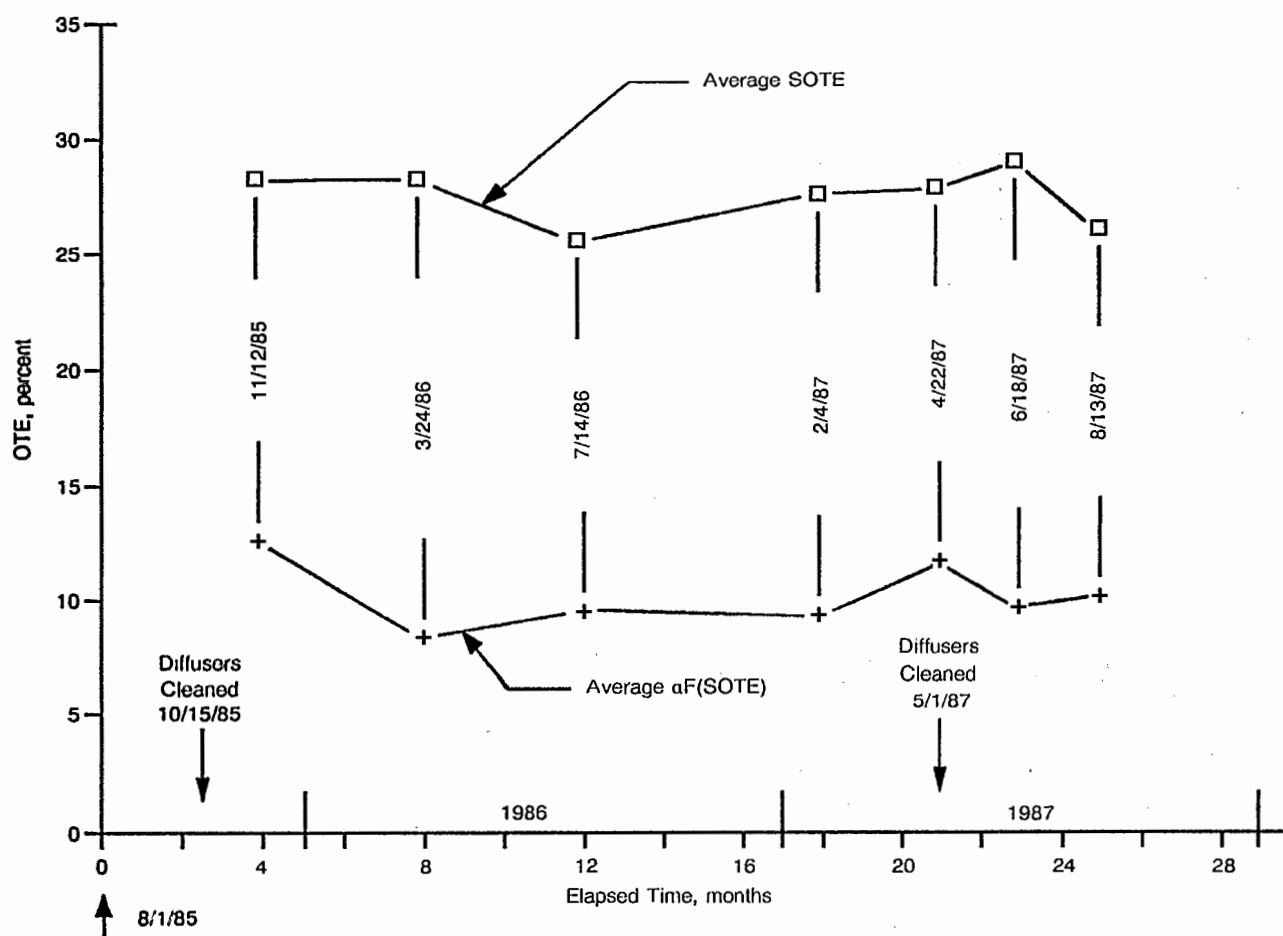
Although diffuser cleaning may have little effect on OTE at Hartford, the cleaning of diffusers on a routine basis is beneficial. It removes built-up deposits of both inorganic and organic materials that cause increased backpressure. Additionally, diffuser cleaning facilitates an inspection of the aeration equipment and the undertaking of air distribution and leak tests. Any necessary repairs to limit gasket and other leaks and the performance of any other repairs constitutes good maintenance practice at the time of tank cleaning.

The average downtime required to clean each aeration tank was 1 week, including tank draining and filling time. No adverse effects on plant effluent quality occurred during cleaning. However, if peak loading had occurred during cleaning, effluent quality could have been reduced due to reduced retention time in the aeration process and possible diffuser air capacity limitations.

V. ECONOMIC CONSIDERATIONS

The estimated initial cost of the retrofit based on the consultant's estimate was between \$1,115,000 and

Figure 8-8. Oxygen transfer performance for Aeration Tank 2 - Hartford, CT.



\$1,830,000. The actual total initial cost was less than \$600,000, completely installed.

The installed cost was less than \$50/diffuser, including modifications to the instrumentation and additional air filtration. In-tank diffuser equipment and piping costs, alone, probably represented about half of the total cost of the project.

Annual operating savings were over \$200,000 for the first year of operation, yielding a simple payback period of less than 3 years. A daily power reduction of about 12,000 kWh was realized, and the electrical rate in 1983 was about \$0.05/kWh. Similar savings in the cost of electricity have been observed for succeeding years.

Annual maintenance costs for the fine pore system have not increased significantly over maintenance costs for the coarse bubble system. The ceramic dome diffusers in all four aeration tanks were cleaned in late 1985. Up until that time, no cleaning or other maintenance had been performed on the fine pore system. The cost to clean each aeration tank in 1985

was approximately \$4,500, or \$18,000 for all four tanks. The breakdown for cleaning the diffusers in each tank is presented in Table 8-15.

The cost of replacing domes, gaskets, and bolts with new equipment would be approximately \$35,000 per aeration tank. In addition, removal of grit, debris, and sludge could cost an additional \$15,000 per tank. Total rehabilitation of the fine pore diffuser system should not be required more often than every 5 to 8 years. However, gaskets and plastic bolts may require replacement as often as every 3 years.

Reductions in blower power consumption achieved by replacing spiral roll coarse bubble aeration equipment with full floor coverage fine pore dome/disc aeration equipment, such as at Hartford, are predicated on the ability to turn down and/or shut down blower units after retrofitting with the new equipment. Historical blower power consumption for the ceramic dome diffuser system in Aeration Tank 2 is plotted in Figure 8-9 for over 6 years of operation, along with airflow and BOD₅ removed (BOD_R), all normalized for plant flow.

Table 8-13. Tank Average Off-Gas Results (Aeration Tank 2) - Hartford, CT

Date	Test No. ¹	Mixed Liquor Temp., °C	αF(SOTE), percent	Airflow, scfm		New SOTE, percent	αF	αF(SOTR), lb O ₂ /hr	New SOTR, lb O ₂ /hr
				per dome	total				
11/12/85	1A	18.9	12.60	0.96	3,195	28.2	0.45	417	932
3/24/86	2A	13.9	8.18	1.28	4,261	28.2	0.29	361	1,248
7/14/86	3B	22.5	9.40	2.40	7,994	25.4	0.37	778	2,107
2/4/87	4B	13.1	9.00	1.49	4,953	27.3	0.33	462	1,401
4/22/87	5B	14.7	11.36	1.41	4,674	27.5	0.41	550	1,332
6/18/87	6B	21.6	9.35	0.85	2,819	28.6	0.33	273	836
8/13/87	7B	24.7	9.88	2.20	7,309	25.6	0.39	748	1,942

¹ "A" tests designate 4 replicate tests per sample location and 1 pass through the aeration tank.

"B" tests designate 1 replicate tests per sample location and 3 passes through the aeration tank.

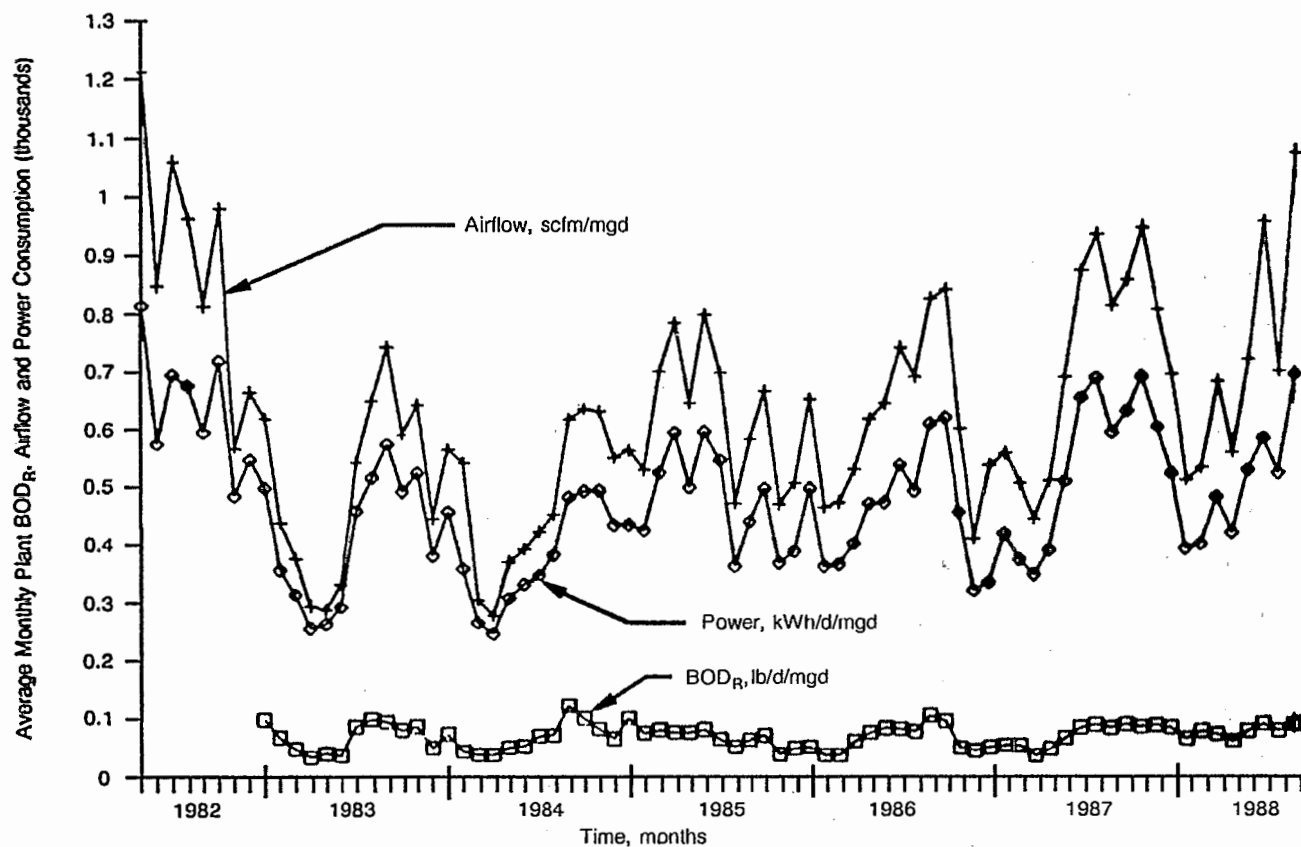
Table 8-14. Average Off-Gas Test Results Before and After May 1987 Cleaning (Aeration Tank 2) - Hartford, CT

	Before Cleaning (4/22/87)	After Cleaning (6/18/87)
Primary effluent BOD ₅ , mg/L	49	112
Final effluent BOD ₅ , mg/L	4	9
Plant flow, mgd	62.3	47.2
MLSS, mg/L	3,200	4,500
SRT, days	7.9	9.7
Entire Tank, Average αF(SOTE), percent	11.36	9.35
Entire Tank, Average αF	0.41	0.33
Pass 1, Average αF(SOTE), percent	11.43	8.66
Pass 1, Average αF	0.40	0.30
Pass 2, Average αF(SOTE), percent	9.80	11.65
Pass 2, Average αF	0.36	0.40
Pass 3, Average αF(SOTE), percent	11.63	10.40
Pass 3, Average αF	0.43	0.36
Pass 4, Average αF(SOTE), percent	10.87	7.55
Pass 4, Average αF	0.41	0.27

Table 8-15. Diffuser Cleaning Costs - Hartford, CT

Item	Cost, \$
Labor (100 man-hr, incl. overtime)	2,000
Chemicals (ZEP cleaner)	250
Cleaning equipment and protective clothing	750
Spare parts (domes, bolts, gaskets, pipe hangars, etc.)	1,500
Total Tank	4,500

Figure 8-9. Power consumption profile for Aeration Tank 2 - Hartford, CT.



8.2.5 Jones Island Wastewater Treatment Plant

LOCATION: Milwaukee, Wisconsin

OPERATING AGENCY: Milwaukee Metropolitan Sewerage District

DESIGN FLOW: 8,765 L/s (200 mgd)

WASTEWATER: Domestic Plus Industrial

ORIGINAL AERATION SYSTEM: Ceramic Plate Diffusers

FINE PORE AERATION SYSTEM: Ceramic Plate Diffusers

YEAR FINE PORE SYSTEM PLACED IN OPERATION: 1925

BASIS OF PERFORMANCE EVALUATION: Air Usage; Off-Gas Testing

CLEANING METHOD: Various Methods, Including Water Hosing, Sand Blasting, and Acid Washing

I. HISTORICAL BACKGROUND

The Milwaukee Jones Island wastewater treatment plant has a long history of using fine pore ceramic plates in its activated sludge facilities. The West plant, with an initial design capacity of 3,725 L/s (85 mgd), was placed in operation in 1925 and consisted of 24 aeration tanks 71.9 m long by 13.4 m wide (236 ft x 44 ft) with a 4.6-m (15-ft) SWD. The aeration tanks are operated as a two-pass system. Ceramic plate diffusers in a ridge-and-furrow configuration were selected for the original design. Containers that hold nine 30-cm (1-ft) square porous ceramic diffuser plates were placed across the width of the aeration tanks between the ridge separators. One row of containers also ran the length of each tank and held seven diffusers per section. The ratio of floor area to diffuser area was 4:1, yielding a 25-percent coverage of the floor surface with plate diffusers.

The original ceramic plates used in the West plant were Filtros fused silica 38-mm (1.5-in) thick plates. Norton Alundum 25-mm (1-in) thick plates replaced the Filtros plates in several West plant aeration tanks (North battery) shortly after the plant was placed in operation. Eventually, these Alundum plates were all replaced with Filtros fused silica plates. The original Filtros fused silica plates installed in 1925 in the entire South battery of the West plant were still in service as of February 1989.

The East plant was constructed in stages as an addition to the West plant, with the first addition in 1935. Final additions in 1952 brought the total nominal treatment capacity for the Jones Island plant to 8,765 L/s (200 mgd). The first 12 of 20 East plant aeration basins installed in 1935 contained a plate diffuser layout along one side of the aeration tank to provide a spiral roll mixing pattern. Each aeration tank was 112.8 m long by 13.4 m wide (370 ft x 44 ft) with a 4.6-m (15-ft) SWD. These basins were also operated

initially in a two-pass flow mode so that each channel was 6.7 m (22 ft) wide. The diffuser design consisted of two rows of Norton Carborundum square alumina plates 46 cm (18 in) apart with 1,296 plates in each aeration pass. In 1942 and 1943, an additional row of plates was added to each of the 24 aeration passes, increasing the number of diffusers per pass to 1,944. The permeability rating of these plates was 32-36.

An additional expansion completed in 1952 added eight aeration tanks to the East plant with four rows of plate diffusers along one side of the tank. These were all Filtros fused silica plates with permeabilities of 19.5-24. At this time, the total flowsheet consisted of bar screening, grit removal, and fine screening prior to activated sludge treatment. The West plant contained 15 secondary clarifiers with 4.6-m (15-ft) SWDs. The diameter was 29.9 m (98 ft) for 11 of the clarifiers and 13.0 m (42.5 ft) for the other four clarifiers. The East plant contained a total of 10 secondary clarifiers 25.6 m wide by 49.2 m long (84 ft x 161.5 ft) with a 4.3-m (14-ft) SWD.

In 1957, the East plant aeration system was modified by replacing the spiral roll, ceramic plate diffuser system with a tapered aeration, ceramic tube diffuser system. Prior to this, in 1956, saran-wrapped diffusers on fixed headers were installed on an experimental basis. Due to a greater clogging problem with the saran-wrapped diffusers, ceramic tubes were selected for the tapered aeration modification. Forty-two headers at 5.3-m (17.5-ft) intervals were installed in the two-pass aeration tanks. The number of tubes per header decreased incrementally from 33 to 12 in the first 21 headers. The next eight headers had 12 tubes each, the next had 11 tubes each, and the final two headers contained 15 tubes each, for a total of 711 tubes per tank. Approximately equal quantities of air were applied to the two plants, averaging 10.2 m³ air/m³ wastewater flow (1.36 cu ft/gal).

At the time of the 1957 diffuser system modification, East plant return sludge was separated from that of the West plant. Both plants were operated with independent return sludge systems after July 1958. However, East plant waste sludge was directed to the West plant return sludge line for ultimate sludge wasting via the West plant.

As the conversion to the tapered aeration ceramic tube diffuser system progressed in 1958-1960, East plant performance decreased. Annual average effluent BOD₅ increased from 19.6 mg/L in 1958 to 30.7 mg/L in 1960 to 59.8 mg/L in 1963.

A plant-scale research project was initiated in 1961 to study the effect of various plate diffuser placement patterns. This ultimately led to conversion of all 20 East plant aeration tanks to a five-row longitudinal diffuser placement pattern utilizing nine diffusers/container with a total of 10 containers, or 90 diffuser plates on each downcomer. A total of 3,150 plates was installed in each aeration tank. The tanks continued to operate in the double-pass mode. The ratio of theoretical tank surface to plate surface was 5.17:1 compared to 4:1 provided in the original ridge-and-furrow design of the West plant. By 1965, all East plant aeration basins had been converted to this ceramic plate design. The effluent BOD₅ concentration decreased to 10-20 mg/L as the conversion progressed.

In 1983, the East plant basins were rehabilitated with new diffuser plates and air piping. The fine pore longitudinal diffuser arrangement was retained. A trench was also provided along one side of the tank to collect flushed solids during cleanup operations.

The new diffusers were Norton ceramic plates, 30 cm x 30 cm x 25 mm thick (12 in x 12 in x 1 in). The permeabilities of these plates is 17-23. The plates are grouped by permeabilities in ranges of 17-19, 20-21, and 22-23. Each downcomer is fitted with plates of only one range. The plates are grouted into concrete containers placed flush with the bottom of the tank. Each container has nine plates and is connected at one end to a 25-mm (1-in) diameter air pipe. The containers are placed end-to-end in the direction of the tank length, 32 containers in a row and five rows across the basin width, yielding 1,450 plates per pass and 2,900 per two-pass basin.

Air is supplied from downcomers to three separate zones in each pass. The total number of plates is 558 in Zone 1 at the pass inlet, 450 in Zone 2, and 446 in Zone 3. The ratio of tank floor area to diffuser plate surface area is 5.62:1, i.e., the plates cover 17.8 percent of the tank floor area. Airflow to each zone is set manually by a butterfly valve, but, within each zone, there are no orifices for control of air distribution. Each downcomer is equipped with an orifice meter, and the airflow corresponding to the

pressure drop is read from a portable flow indicator. A permanently-mounted orifice meter and flow indicator for each pair of passes (six zones) provides a check on the sum of the readings taken at the separate zones.

Although the number of diffuser plates in each of the three zones is different, diffuser density is uniform down the length of each pass because the length of each zone is different. Airflow can be varied to each zone to achieve a tapered aeration pattern. Both tapered and uniform aeration patterns have been utilized.

In June 1985, the East plant basins were converted from two-pass to single-pass operation. An off-gas testing program was carried out from June 1985 to June 1988 in the North and South passes of Basin 6, each operated as a single-stage system. Prior to initiating the testing program, the diffusers were hosed.

II. PLANT PERFORMANCE

From 1961 through 1964, oxygen transfer tests were conducted for a variety of diffuser configurations in the East and West plants. The test method was an early version of the off-gas testing procedure. A hood was used to collect gas leaving the liquid surface, the oxygen content of the gas was measured by the Orsat method, and gas flow was measured as the rate that it displaced water in a gas accumulation tank.

A summary of measured $\alpha F(SOTE)$ values for Jones Island is presented in Table 8-16. From 1961 to 1963, the efficiency of the tube diffusers in the East plant decreased. After a program of cleaning and refurbishing, the spiral roll tube diffuser $\alpha F(SOTE)$ increased to 7.6 percent in 1964. The ridge-and-furrow plate diffuser system in the West plant produced a 20.9-percent $\alpha F(SOTE)$ in 1964 after a program of cleaning was carried out. This was the first cleaning of these diffusers in 10 years. The West plant longitudinal plate configuration produced $\alpha F(SOTE)$ s within the same range as the ridge-and-furrow system. In 1985 and 1988, after more than 60 years of operation and scheduled to be decommissioned, the ridge-and-furrow West plant diffusers were performing comparably to their efficiency prior to cleaning in 1964. The refurbished East plant continues to demonstrate the overall performance of plate diffuser plants. Table 8-17 summarizes East plant average annual performance from 1970 to 1986. Similar effluent BOD₅ concentrations were also observed for the West plant.

After single-pass operation began in the East plant and after cleaning the diffusers, periodic off-gas testing was conducted in Basin 6 over a 30-month period from 1985 to 1988. The gas collection hood used had dimensions of 61 cm (2 ft) by 5 m (16.5 ft). Twelve test stations were located equal distances

Table 8-16. Summary of Oxygen Transfer Tests - (Jones Island) Milwaukee, WI

Location	No. Tests	Average ¹ $\alpha F(SOTE)$, percent
East Plant, Spiral Flow, Tubes		
1961	6	7.9
1962	7	5.4
1963	7	4.8
1964	6	7.6
West Plant, Ridge and Furrow, Plates		
1961	4	15.8
1962	5	11.7
1963	6	12.9
1964	6	20.9
East Plant, Transverse Plates		
1964	20	13.8
West Plant, Longitudinal Plates		
1964	21	15.8
West Plant, Ridge and Furrow, Plates		
1985 and 1987	21	11.9
East Plant, Tapered Full Floor, Plates		
1985 and 1988	30	16.4

¹ $\alpha F(SOTE)$ based on effective clean water DO saturation of 10.5 mg/L.

along the tank length, yielding a gas sampling area of 5 percent of the basin surface area. The North and South pass sample locations in Basin 6 were alternately tested to obtain data under similar conditions for each pass. The hood was positioned across the width at about the center of the basins. The total test time to complete sampling of both passes was about 6 hours.

Table 8-18 contains a summary of the East plant operating conditions and average $\alpha F(SOTE)$ values obtained for both passes in Basin 6. The average SRT reported for the aeration test days for the East plant was 3.8 days and ranged from 0.3 to 5.3 days. The F/M loading averaged 0.65 d⁻¹.

III. DIFFUSER CLEANING

A variety of cleaning methods have been used at the Jones Island plant, including high-pressure hosing, sand blasting, and acid washing. At the Milwaukee South Shore plant, these cleaning methods were evaluated in more detail from 1981 to 1985 and an additional method was tried. This is called the scarifying method and involves cleaning the diffuser plates with a powered wire brush. Muriatic acid treatment cleaning followed by a water wash has been shown to be effective at the South Shore plant, and this is known as the "Milwaukee Method" of diffuser cleaning.

Cleaning frequency at the East plant was variable and ranged from one to eight times over a 16-yr period. Acid washing was done in some tanks in 1980 and 1981. For the West plant, no tanks have been cleaned

more than five times in a 22-yr period and the average number is 3.3 cleanings in 22 years.

The diffusers in East plant Basin 6 received the "Milwaukee Method" cleaning procedure before and after the 30-month off-gas test program. After the diffuser cleaning in June 1988, the measured $\alpha F(SOTE)$ values were 17 and 19 percent for the North and South passes, respectively. While these are higher than the typical $\alpha F(SOTE)$ s observed over the entire course of the testing, it is difficult to conclude with just this one set of data that cleaning alone caused such a pronounced increase in $\alpha F(SOTE)$.

Table 8-17. East Plant Operating and Performance Data (Annual Averages) - (Jones Island) Milwaukee, WI

Year	Flow, mgd	Screened Wastewater BOD ₅ , mg/L	Effluent BOD ₅ , mg/L	No. Aeration Tanks in Service	Air Usage, cu ft/gal	Volumetric Loading, lb BOD ₅ /1,000 cu ft/d
1970	94.2	208	16.5	19.2	1.27	38.3
1971	100.0	220	19.0	20	1.28	41.0
1972	96.0	218	18.0	20	1.36	39.3
1973	92.2	261	17.0	19	1.36	46.0
1974	85.4	302	18.0	19	1.53	50.9
1975	78.0	347	22.0	16	1.57	60.4
1976	81.6	326	21.0	16	1.51	60.4
1977	78.0	329	18.0	16	1.55	58.0
1978	79.8	313	21.0	17	1.46	55.8
1979	79.0	290	20.0	17	1.57	51.9
1980	73.0	291	14.8	16	1.58	48.0
1981	74.0	273	14.9	15	1.51	47.3
1982	68.0	263	15.8	13	1.60	50.0
1983	80.0	304	14.7	15	1.36	65.1
1984	73.5	291	13.4	13	1.51	62.4
1985	81.7	278	12.8	15	1.49	58.8
1986	85.4	254	9.3	14	1.26	58.0

Table 8-18. Oxygen Transfer Performance (1985-1988) for Tapered, Full-Floor Plate Configuration (Jones Island East Plant, Basin 6) - Milwaukee, WI

Time in Service, mo	aF(SOTE), percent	Airflow Rate, scfm/diffuser	Influent BOD ₅ , mg/L	HRT, hr	MLVSS, mg/L
3	16	1.2	360	3.5	1,680
4	15	1.5	300	3.8	1,270
16	15	1.2	210	4.1	1,220
17	16	1.1	140	4.0	1,000
24	16	0.9	220	4.1	1,310
24	17	1.0	370	4.1	1,610
26	15	1.2	320	5.3	1,100
30	14	1.0	380	4.9	1,460

8.2.6 Nine Springs Wastewater Treatment Plant

LOCATION: Madison, Wisconsin

OPERATING AGENCY: Madison Metropolitan Sewerage District

DESIGN FLOW: 1,665 L/s (38 mgd)

WASTEWATER: 85 percent Municipal, 15 percent Industrial (food processing)

ORIGINAL AERATION SYSTEM: Walker Sparjer and Sanitaire D-24 Coarse Bubble Diffusers

FINE PORE AERATION SYSTEM: Norton Ceramic Dome and Sanitaire Ceramic Disc Diffusers

YEAR FINE PORE SYSTEM PLACED IN OPERATION: 1977 and 1984, respectively

BASIS OF PERFORMANCE EVALUATION: Off-Gas Testing

CLEANING METHOD: At high loading, dome plant was cleaned with high-pressure hosing or steam applied routinely. Dome system with this cleaning pattern delivers high OTE after 12 years of service. At low loading, need for cleaning has decreased - one cleaning after 630 days of service with high-pressure hosing did not produce significant change in OTE.

I. INTRODUCTION

The Madison, WI Metropolitan Sewerage District (MMSD) began upgrading its Nine Springs plant to fine pore diffused aeration in 1977. Additional aeration system upgrading was implemented from 1984 to 1986. In addition to aeration system changes, SRT was increased from less than 6 days to more than 9 days, DO control was installed, and nitrification was accomplished in single-stage tanks. Extensive aeration studies were performed on the fine pore aeration system to: 1) evaluate various diffuser cleaning methods, and 2) determine the effects of plant operation on fine pore OTE. When it was discovered that serious fouling was no longer occurring at the MMSD plant, the studies on diffuser cleaning methods were de-emphasized.

Summary details are presented on the economics of the system as currently operating, the cost of installing the new aeration system, the OTEs being achieved as compared to those envisioned, and the effects of plant operating variables, such as F/M loading and SRT, on oxygen transfer.

II. HISTORICAL BACKGROUND

The Nine Springs wastewater treatment facility, located on the south side of Madison, serves the cities of Madison, Monona, Middleton, and Fitchburg; six villages; and portions of several townships within Dane County. Approximately 15 percent of the flow to the plant is industrial, consisting mainly of food processing wastes. Current average flow is approximately 1,665 L/s (38 mgd); the design flow is 2,190 L/s (50 mgd.)

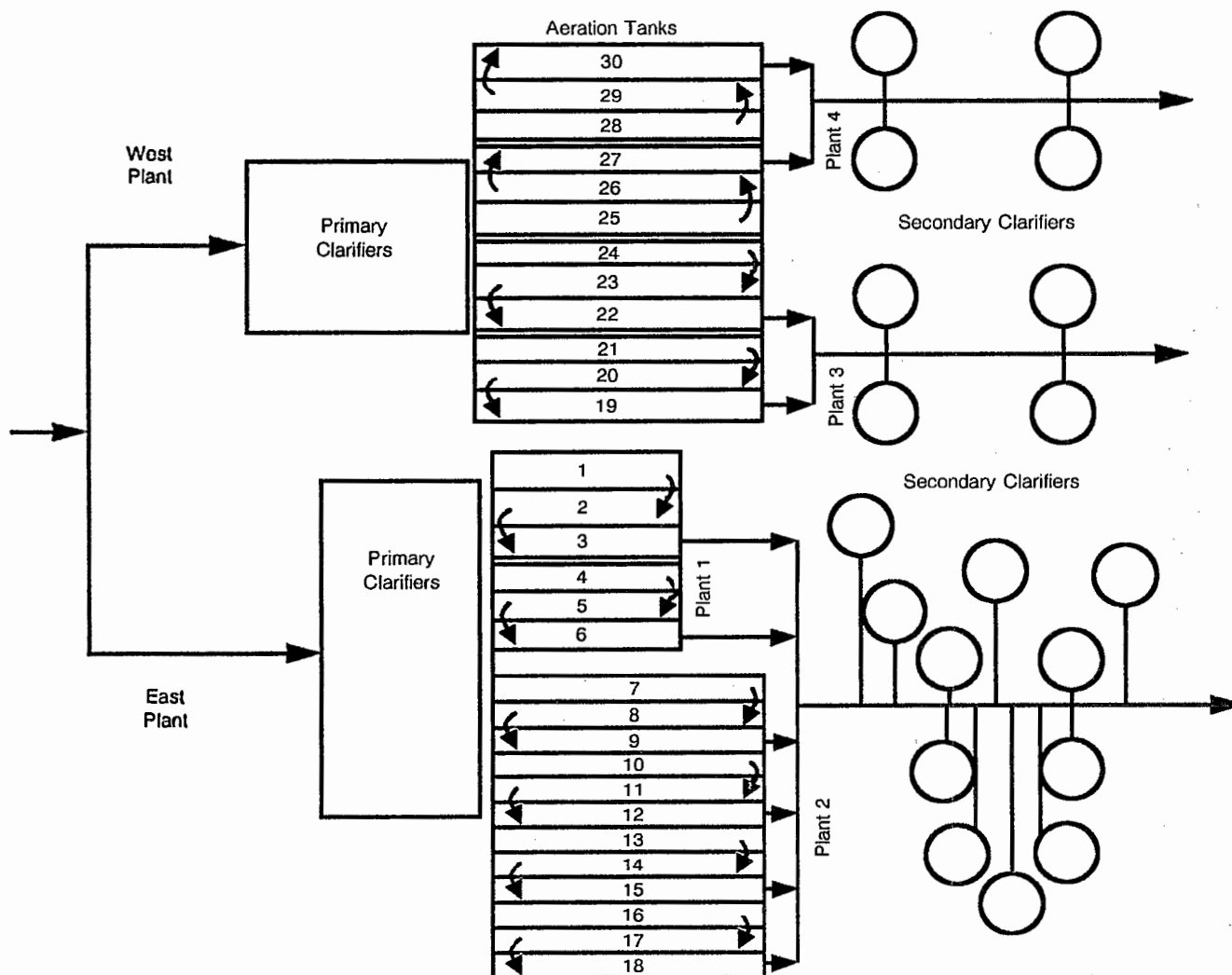
Raw wastewater is brought to the treatment plant through 113 miles of interceptor sewers and force mains with the help of 84 pumping stations. Degritted wastewater is subsequently split between East and West plant sections where it is settled prior to activated sludge treatment. The plant is currently operated to nitrify in a single-stage activated sludge process. Secondary effluent receives UV irradiation prior to being pumped back into the Yahara River watershed downstream of the chain of lakes in the Madison area.

The Nine Springs facility consists of a number of activated sludge process additions undertaken since its initial construction in 1934. Figure 8-10 shows the current configuration of the East and West plant sections.

Norton dome diffusers were installed in Tanks 1-6 (East plant) in 1977. Original plans called for installation of Sanitaire coarse bubble diffusers in these six tanks to replace Walker Sparjers in a spiral roll configuration. It was estimated that installation of Norton domes could raise the overall $\alpha F(SOTE)$ of these tanks from 5.75 to 11.25 percent, providing a net annual savings of \$9,000/yr at \$0.03/kWh. The cost for retrofitting Tanks 1-6 with 6,364 domes was estimated at \$281,000, \$98,000 more than retrofitting with coarse bubble diffusers.

Tanks 7-15 of the East plant, which contained Sanitaire D-24 coarse bubble diffusers, were retrofitted with Sanitaire disc diffusers, and new Tanks 16-18 were constructed with Sanitaire disc diffusers in 1984 and 1985. For an estimated contract price of

Figure 8-10. Plant layout - Madison, WI.



\$451,000, 11,472 Sanitaire discs were installed in these 12 tanks.

The new West plant (Tanks 19-30) was constructed with 15,576 Sanitaire discs in 1984-1985 for an estimated \$443,000. These prices were the mechanical contractor's contract payment prices and included grid piping, labor, and diffusers. It was estimated in the facilities plan that, at an overall $\alpha F(SOTE)$ of 12 percent for each 3-pass tank, the fine bubble diffuser installations would be cost effective.

Prior to 1985, the East plant was operated most of the time as a non-nitrifying or partially nitrifying secondary plant. The modes of operation included step feed, contact stabilization, and plug flow. Filamentous bulking incidents were encountered regularly prior to 1985. The reason for such incidents was likely operation of the plant as a high-rate activated sludge plant with poor DO control. One probe on one of the

15 tanks was used to manually change blower output for the whole plant.

III. FINE PORE AERATION RETROFIT DESIGN DESCRIPTION

From 1983 to 1985, the plant was converted from a 2,190-L/s (50-mgd) secondary plant to a 2,190-L/s (50-mgd) nitrification facility. By January 1985, the plant was completely nitrifying. Table 8-19 summarizes the estimated oxygen requirements for the expanded plant.

The East plant in Madison consists of two different sets of aeration tanks and clarifiers referred to as Plant 1 (Tanks 1-9) and Plant 2 (Tanks 10-18) (see Figure 8-10). Tanks 1-6 have Norton ceramic domes and Tanks 7-18 have Sanitaire ceramic discs. The West plant consists of two sets of aeration tanks and clarifiers designated as Plants 3 and 4. All tanks in Plants 3 and 4 contain Sanitaire discs. The East blower building serves Plants 1 and 2, and the West

Table 8-19. Oxygen Requirements - Madison, WI

Plant influent flow, mgd	50
Thickener recycle flow, mgd	4
Total flow, mgd	54
BOD ₅ removed, lb/d [(202 mg/L - 19 mg/L)(8.34)(54)]	82,400
Ammonia nitrogen removed, lb/d [(32 mg/L)(8.34)(54)]	14,400
Oxygen demand based on planning data	
lb O ₂ /lb BOD ₅	1.25
lb O ₂ /lb NH ₃ -N	4.6
O ₂ safety factor, percent	33
Total oxygen demand, lb/d	
BOD ₅ [(82,400)(1.25)]	103,000
NH ₃ -N [(14,400)(4.6)]	66,200
Subtotal	159,200
Safety factor	55,800
Total	225,000
Total air required @ 9-percent αF(SOTE), scfm	100,000

Table 8-20. Blower Capacities - Madison, WI

Blower No.	Capacity, scfm each
East (Plants 1 and 2)	
1 (gas engine)	7,875 (600 rpm)
	10,500 (800 rpm)
2 and 3 (2-stage centrifugal)	5,500-12,500
4 (positive displacement)	7,760 (low)
	10,850 (high)
5 (positive displacement)	5,840 (low)
	9,070 (high)
West (Plants 3 and 4)	
1, 2, and 3 (single-stage centrifugal)	12,500-25,000

blower building serves Plants 3 and 4. The actual blower capacities are given in Table 8-20.

As previously mentioned, the installation of fine pore diffusers took place in several phases. The maximum possible airflow rate, based on blower system design, was 14.2 L/s/m² (2.8 scfm/sq ft) tank area on the East side and 16.3 L/s/m² (3.2 scfm/sq ft) tank area on the West. Minimum airflow rates, which have occurred frequently, are blower-limited rather than diffuser-limited. Design minimum airflow rates for both the Sanitaire discs and Norton Domes were 0.24 L/s (0.5 scfm)/diffuser, but minimum airflow rates have been set somewhat higher because of minimum blower turndown capability. Minimum mixing rates that have been used in operation are approximately 0.46 L/s/m² (0.09 scfm/sq ft).

Aeration system control was significantly upgraded and is briefly discussed here (Chapter 6 contains a more detailed description of Nine Spring's control system). Basically, a DO probe, located at the effluent end of each aeration tank pass, controls an air valve for that pass. A cascade control loop is used for each pass of a three-pass tank to control the DO and an airflow set-point is output to an airflow controller. An airflow tube measures the total airflow to each pass. The airflow controller controls a single butterfly valve

in the air supply line for that pass. A minimum airflow is defined for each pass to maintain mixing requirements. DO set-points are typically 1.2, 1.6, and 2.0 mg/L for the three consecutive passes.

For a given total airflow to the aeration tank passes, air header pressure changes the butterfly valve settings for each individual aeration tank pass. Centrifugal blowers equipped with inlet guide vanes are used for controlling the main air header pressure at a predetermined set-point, plus or minus a deadband.

All DO probes are calibrated by operators against an air-calibrated YSI probe every week unless problems are noticed before scheduled calibrating. Membrane replacement is handled by the operators. Other problems are turned over to the electronics staff. At first, probes were calibrated every 2 weeks, but too many problems with calibration were being encountered. Now, first-pass probes are cleaned every week prior to calibration, as growth may easily coat the membrane within a 1-week period. Second- and third-pass probes may be cleaned only once every 2 or 3 weeks.

IV. OPERATIONAL PERFORMANCE AND EVALUATION

Following the 1985 conversion of the plant to single-stage nitrification with a plug flow operating mode and with automatic DO control, plant performance has been consistently good and filamentous bulking incidents rare. Plant performance for 2 years between November 1986 and September 1988 was excellent. The raw wastewater flow during that period was 1,550 L/s (35.4 mgd) with an average daily influent BOD₅ of 178 mg/L (σ=8.9), TSS of 176 mg/L (σ=18.2), and TKN of 26.7 mg/L (σ=1.6). Final effluent average concentrations for the same period were: BOD₅ = 2.9 mg/L (σ=1.5), TSS = 4.5 mg/L (σ=1.5), and NH₃-N = 0.2 mg/L (σ=0.2).

In the spring of 1985, studies included monitoring of OTEs of Tanks 1-6 with the off-gas method, along with studying the effect of operational parameters on OTE in parallel aeration tanks in the new West plant. Oxygen transfer studies using off-gas procedures in the East plant began in May 1984 and continued through the summer of 1987.

Shown in Figure 8-11 are oxygen transfer test results for aeration Tanks 1-3 of the East plant. Data for two periods of operation are summarized: May 1984-August 1985 when the plant was run as a high-rate system (SRT=1.4-5.8 days), and November 1986-July 1987 when the plant was run as a single-stage nitrification system (SRT=10-16 days). αF values are presented in Table 8-21. These estimates of αF were derived from clean water tests performed by the Los Angeles County Sanitation Districts on ceramic domes for a variety of gas flows and diffuser densities.

Figure 8-11. $\alpha F(\text{SOTE})$ profile for East plant Tanks 1-3 - Madison, WI.

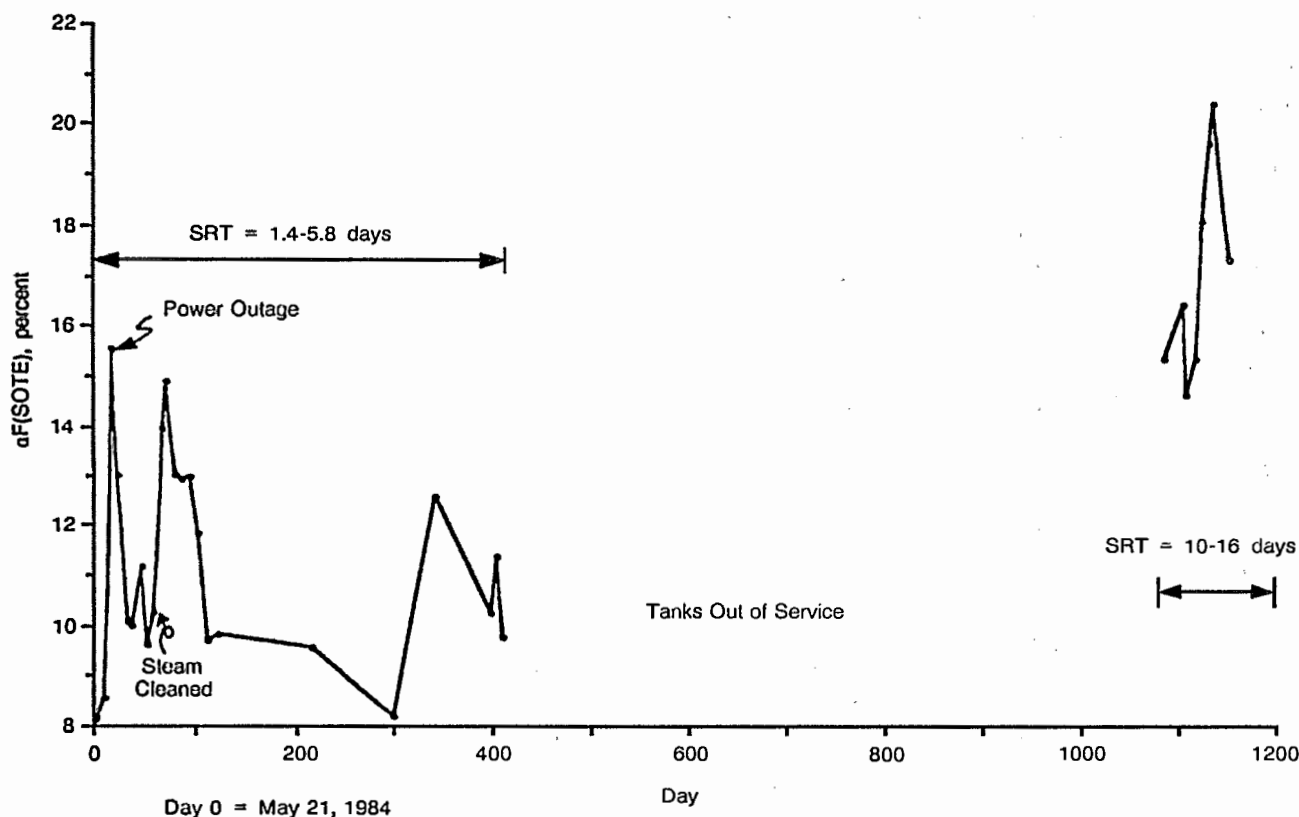


Figure 8-11 indicates overall system $\alpha F(\text{SOTE})$ values were higher when the plant was run as a low-loaded, single-stage nitrification facility than when the plant was run as a high-rate system. Wastewater characteristics were virtually identical during both periods. It could be speculated that a decrease in load, as measured by high SRT (low F/M loading), resulted in higher αF values due, in part, to biological degradation of surfactants that were typically present in the final effluents when SRT was lower and nitrification occurred only sporadically. Lower loadings also seemed to eliminate slime growth and fouling on diffusers further downstream from the inlet. This observation is based on viewing diffusers when the tanks were emptied as well as examining BRV and DWP for diffusers that were removed and taken to the laboratory for testing. Furthermore, the high-SRT operation appeared to extend the period before diffuser fouling would significantly influence OTE.

In 1984, a power interruption and follow-up steam cleaning of the dome diffusers significantly affected transfer efficiencies as shown by the increase in αF in Table 8-21. During the power outage and subsequent startup, clogged pores may have been opened due to the forces created in the diffusers by the flow of mixed liquor. This benefit lasted only 2-3 weeks, however. Steam cleaning, on the other hand, created

an increase in αF values that lasted about 7 weeks according to the data presented in Table 8-21. Operations personnel believe the mixed liquor flooding and purging of the diffusers affected a small number of pores but that the effect was felt through the full depth of the diffuser. Steam cleaning, on the other hand, affected a greater number of pores, but the effect was largely superficial, i.e., the cleaning was mainly on the surface.

Diffuser performance at the tank inlets was greatly influenced by wastewater characteristics. Coarse bubbling was always observed on the liquid surface at inlet zones both during periods after cleaning and in 1987, when the plant was run in the low-loaded nitrification mode.

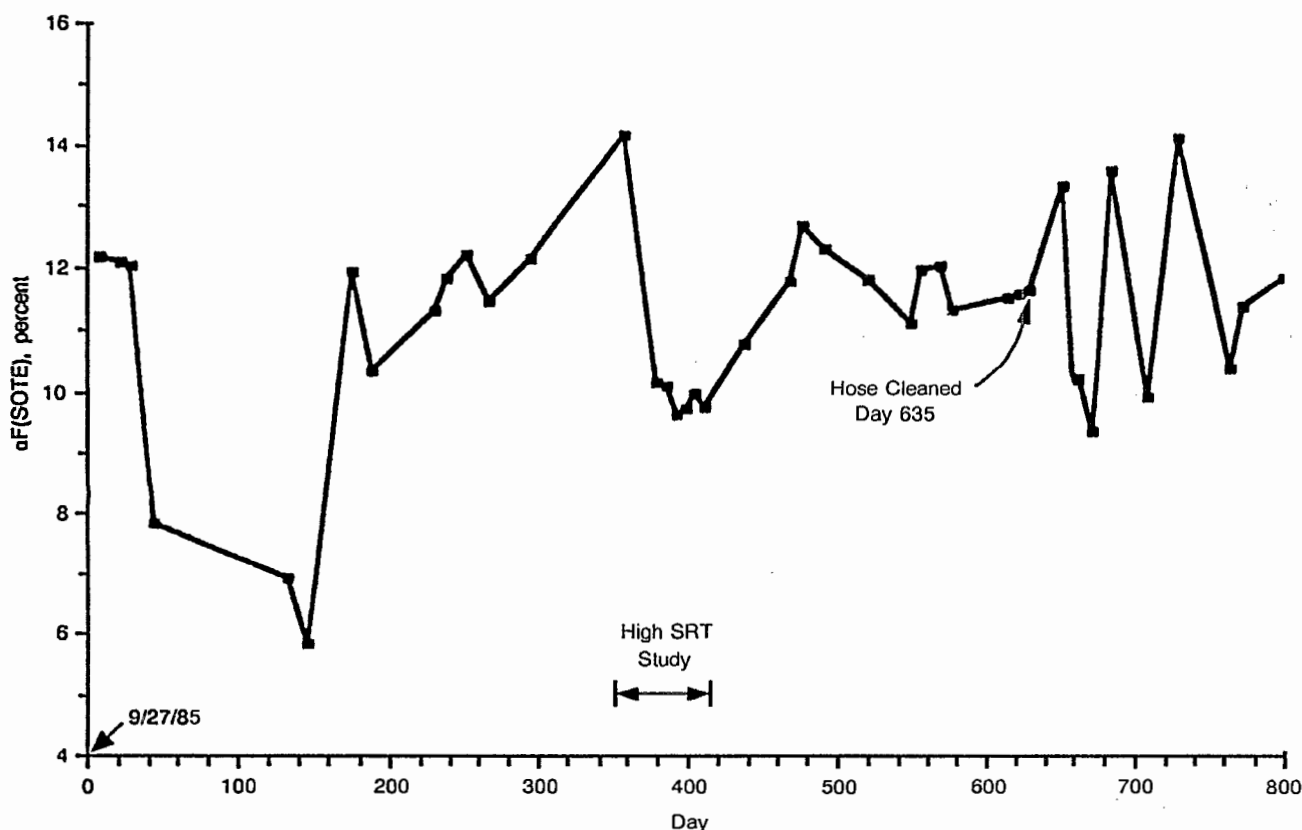
Figures 8-12 and 8-13 present the results of off-gas testing of two parallel first-pass tanks in Plants 3 and 4 of the West plant, respectively. These two plants were operated in parallel throughout much of the time between start-up (9/25/85, day 0) and the end of the study (12/5/87, day 800). Over this period of time, no perceptible decrease in diffuser performance was observed in the first-pass tanks based on $\alpha F(\text{SOTE})$ measurements. The mean first-stage $\alpha F(\text{SOTE})$ over the 800 days was 11.5 percent. The mean weighted $\alpha F(\text{SOTE})$ for all three passes ranged from 12.1 to

Table 8-21. East Plant α F Values - Madison, WI

Date	Day	Tank 1		Tank 2		Tank 3	
		scfm/diffuser	α F	scfm/diffuser	α F	scfm/diffuser	α F
5/21/84	1	0.50	0.26	0.96	0.35	0.84	0.43
5/23/84	3	0.77	0.25	1.04	0.29	0.95	0.38
5/30/84	10	0.95	0.24	1.30	0.36	0.87	0.42
6/7/84	POWER OUT						
6/8/84	19	0.52	0.44	0.56	0.60	0.49	0.56
6/12/84	23	0.49	0.38	0.61	0.49	0.61	0.51
6/21/84	32	0.76	0.33	1.03	0.38	0.92	0.40
6/26/84	37	0.83	0.34	1.09	0.40	1.15	0.36
7/6/84	47	0.78	0.33	1.04	0.44	1.12	0.51
7/12/84	53	0.90	0.31	0.69	0.33	0.86	0.40
7/20/84	59	0.43	0.32	0.69	0.37	0.64	0.41
	STEAM CLEANED						
7/27/84	68	1.05	0.43	1.08	0.56	0.84	0.64
8/1/84	73	0.65	0.38	0.61	0.61	0.46	0.71
8/7/84	81	0.93	0.30	0.60	0.62	0.70	0.76
8/13/84	87	0.62	0.30	0.40	0.49	0.67	0.68
8/20/84	94	0.42	0.33	0.40	0.44	0.54	0.56
8/29/84	103	0.63	0.34	0.82	0.43	0.62	0.54
9/7/84	112	1.10	0.31	1.40	0.36	0.81	0.59
9/18/84	123	0.80	0.29	1.04	0.38	1.00	0.45
6/20/85	398	0.93	0.28	1.15	0.39	1.13	0.57
6/26/85	404	0.95	0.31	1.15	0.48	0.92	0.61
7/3/85	411	0.97	0.24	1.28	0.38	1.16	0.60 ^a
7/17/85	425	0.52	0.47	0.63	0.57	0.72	0.71 ^a
8/14/85	OUT OF SERVICE						
7/17/85	STEAM CLEANED						
11/18/85	IN SERVICE						
5/8/87	1,086	0.73	0.33	0.90	0.64	0.79	0.86
5/11/87	1,089	0.73	0.34	0.86	0.63	-	-
5/27/87	1,105	0.72	0.40	0.86	0.65	0.61	0.91
5/29/87	1,107	0.59	0.36	0.51	0.54	0.61	0.77
6/3/87	1,111	0.62	0.38	0.41	0.54	-	-
6/9/87	1,117	0.62	0.38	0.81	0.55	0.63	0.85
6/17/87	1,125	0.59	0.42	0.68	0.67	0.73	0.97
6/25/87	1,133	0.61	0.44	0.84	0.78	0.76	1.01
6/29/87	1,137	0.62	0.47	0.80	0.74	0.14	1.15
7/15/87	1,154	0.61	0.43	0.85	0.68	0.74	0.85

^a Nocardia scum.

Figure 8-12. $\alpha F(\text{SOTE})$ profile for Tank 21 (showing influence of high SRT and cleaning) - Madison, WI.



15.3 percent, based on six analyses of all three passes.

As shown in Figures 8-12 and 8-13, during a 60-day period in Fall 1986, Plant 3 was operated at a higher SRT (approximately 11 days) than Plant 4 (SRT=approximately 7 days) to evaluate the effect of process loading on $\alpha F(\text{SOTE})$. Results of this trial are described more fully in Section 3.4.2.4.

The diffusers in Tanks 19-21 (operated as a three-pass, series flow system - see Figure 8-10) were cleaned by high-pressure hosing within the tank 635 days after being placed in service (6/23/87). Inspection of the diffusers in those tanks indicated moderate fouling in the first pass and little or no fouling in the other two. A series of off-gas tests were conducted on Tanks 19-24 between June 1, 1987 and November 6, 1987. Results of these tests are in Table 8-22. (Note that these data are for the two sets of aeration basins in Plant 3 operated under the same conditions. αF was determined by extrapolating clean water test data supplied by the manufacturer to the actual tank dimensions and densities at Madison.) Review of Table 8-22 indicates that cleaning diffusers in Tanks 19-21 did not appreciably affect the performance of that system over the parallel one

(Tanks 22-24) that was not cleaned. The data suggest that immediately after cleaning there may have been some improvement in Tank 21. This was short-lived, however, and both parallel basins produced similar $\alpha F(\text{SOTE})$ s 3 weeks after cleaning. In fact, it was not possible to determine whether the elevated $\alpha F(\text{SOTE})$ for Tank 21 on July 9 was due to diffuser cleaning or the wastewater characteristics that day. No significant improvement was seen in the downstream tanks.

The successful long-term performance of the West plant basins, as contrasted to the East plant basins (prior to nitrification), strongly implicates plant loading as a critical factor in fine pore ceramic diffuser fouling.

V. ECONOMIC CONSIDERATIONS

The fine pore diffuser installation at Madison is proving to be very cost effective, especially since the need for diffuser cleaning is very infrequent when the plant is run as a low-loaded, single-stage nitrification facility. Only one set of three tanks has been cleaned since 1985, and there were no demonstrated benefits from cleaning. When tanks are cleaned, it has been estimated that the cost of steam cleaning one set of three tanks is about \$0.61/diffuser. If only hosing is performed, this cost is reduced.

Figure 8-13. $\alpha F(\text{SOTE})$ profile for Tank 25 (showing influence of low SRT) - Madison, WI..

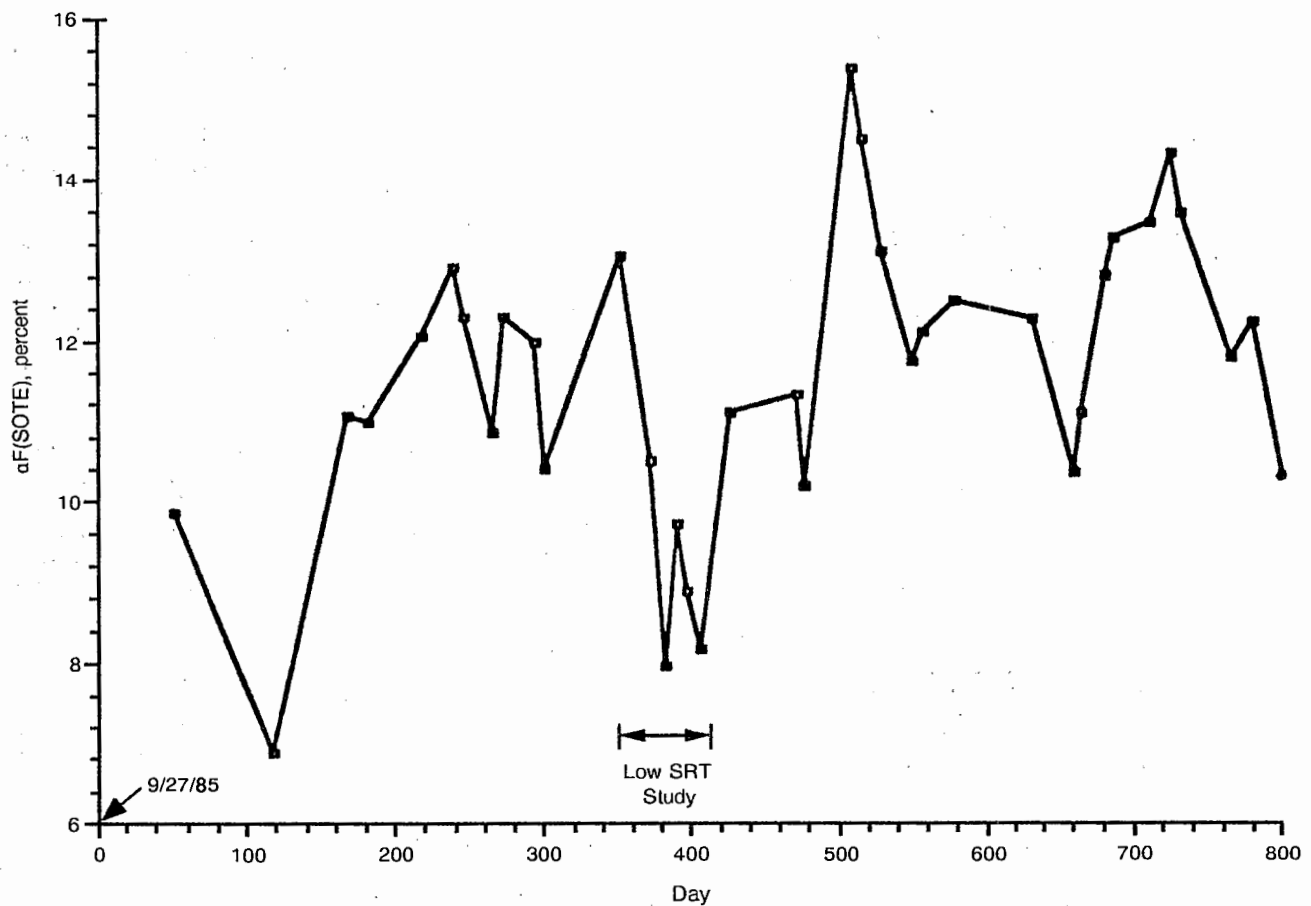


Table 8-22. Off-Gas Test Results: West Plant (Plant 3) - Madison, WI

Date	Tanks 21 or 24			Tanks 20 or 23			Tanks 19 or 22			Mean Weighted $\alpha F(\text{SOTE})$
	scfm/diffuser	$\alpha F(\text{SOTE})$	αF	scfm/diffuser	$\alpha F(\text{SOTE})$	αF	scfm/diffuser	$\alpha F(\text{SOTE})$	αF	
6/1/87	1.32	10.27	0.31 (24)	1.32	16.81	0.57 (23)	1.19	18.93	0.63 (22)	13.85
6/10/87	1.32	11.57	0.35(21)	1.29	16.11	0.54 (20)	1.24	17.49	0.59 (19)	14.05
6/11/87	1.27	10.13	0.30 (24)	1.53	15.77	0.55 (23)	1.36	15.70	0.53 (22)	13.08
6/23/87	Steam	Clean	Diffusers	in	Tanks	19,20,21				
7/9/87	1.26	13.31	0.40 (21)	1.04	16.89	0.55 (20)	1.06	17.12	0.56 (19)	14.96
7/10/87	1.22	8.55	0.25 (24)	1.15	16.14	0.53 (23)	0.94	16.78	0.54 (22)	12.13
8/6/87	1.02	11.36	0.33 (21)	1.30	17.76	0.60 (20)	1.29	19.47	0.66 (19)	15.32

() = tank number.

Note: Tanks 21 and 24, 20 and 23, and 19 and 22 are parallel 1st, 2nd, and 3rd pass aeration tanks, respectively (see Figure 8-10).

Air usage since 1986 for Plants 3 and 4 is shown in Table 8-23 along with total plant power consumption. Air usage in both plants has actually dropped since 1986, as has total plant power consumption. This is because one of the more significant problems associated with plant start-up was an inability to effectively turn down the aeration system because of the excellent OTEs of the fine pore diffusers and the

fact that loadings were only 60 percent of design. Minimum airflows for each aeration tank and minimum blower capacities did not enable turning down the air far enough to match demand. Further, the air headers for the East and West plants were not tied together, preventing excess air on one side of the plant from being transferred to the other.

Table 8-23. Air Usage - Madison, WI

Date	Plant 3		Plant 4		Total Plant Power Use, avg. kW/mo
	cu ft Air/lb BOD ₅ Removed	cu ft Air/lb O ₂ Demand Removed	cu ft Air/lb BOD ₅ Removed	cu ft Air/lb O ₂ Demand Removed	
November 1986	1,513	803	1,418	755	2,538
December	1,384	691	1,359	680	2,517
January 1987	1,200	639	1,273	678	2,504
February	1,076	607	1,107	625	2,633
March	1,239	692	1,196	670	2,537
April	1,145	673	1,122	659	2,516
May	1,161	668	1,148	659	2,490
June	1,090	655	1,091	655	2,401
July	1,240	759	1,133	693	2,417
August	1,174	702	1,002	599	2,433
September	1,036	574	1,066	588	2,443
October	1,031	565	1,061	581	2,368
November	910	514	959	555	2,427
December	1,061	550	1,151	597	2,425
January 1988	1,000	532	1,023	544	2,459
February	1,062	563	1,067	566	2,490
March	905	512	908	513	2,305
April	985	558	914	520	2,124
May	1,053	595	857	484	2,101
June	884	524	799	474	2,049
July	897	506	841	473	2,035
August	822	519	790	492	2,106
September	1,021	606	884	525	2,125

In March 1988, this problem was solved, in part, by taking nine aeration tanks out of service in the East plant, turning off all electric blowers on the East side, and reducing the flow split to the East plant. This allowed operation with a methane gas engine blower only in the East plant. DO control is poor since the gas engine speed is varied manually within a narrow range, but no operational problems have occurred. The West plant is being loaded more heavily and is using air more efficiently. Experience at Madison has shown that blower and diffuser design for present loadings requires careful consideration to take full advantage of high fine pore diffuser efficiencies.

Economic analyses are not presented for Madison because of the step-wise nature of the retrofit and because of changes in the control and operational methods used at the plant before and after the retrofit. One potential cost savings not explored was the consideration of leaving coarse bubble diffusers in the head end of tanks while employing fine bubble diffusers in the remainder of the tanks. Mixing would be more complete, and fouling might be eliminated, or dramatically reduced, under high loading conditions.

8.2.5 Ridgewood Wastewater Treatment Plant

LOCATION: Ridgewood, New Jersey

OPERATING AGENCY: Village of Ridgewood

DESIGN FLOW: 131 L/s (3 mgd)

WASTEWATER: Domestic

ORIGINAL AERATION SYSTEM: Walker Sparjer Coarse Bubble Diffusers

FINE PORE AERATION SYSTEM: Gray "Fine Air" Dome Diffusers

YEAR FINE PORE SYSTEM PLACED IN OPERATION: 1983

BASIS OF PERFORMANCE EVALUATION: In-Process Nonsteady-State and Steady-State Oxygen Transfer Testing and Off-Gas Testing

CLEANING METHOD: Hosing; Acid Brushing

I. INTRODUCTION

In 1983, the Ridgewood, NJ Wastewater Treatment Plant underwent a retrofit from a coarse bubble to a fine pore diffused aeration system. Also, the process was changed from contact stabilization to tapered aeration activated sludge. The purpose of the plant retrofit was to reduce energy consumption and minimize power costs. Extensive aeration studies were conducted on the fine pore system in 1985 and 1986 to examine changing OTEs with time and evaluate the effects of different diffuser cleaning methods and frequencies on OTE.

Information is presented on the original aeration system, including oxygen transfer test results, the basis for changing to fine pore diffusers, the retrofit design, and the performance and evaluation of the new system including cleaning methods. An economic evaluation of the fine pore aeration system, including bid prices, maintenance costs, and simple payback period based on power savings, is also included.

II. HISTORICAL BACKGROUND

The Ridgewood contact stabilization activated sludge plant was constructed in 1959 with a capacity of 131-L/s (3-mgd).

Original Aeration System

The original plant flow diagram (coarse bubble aeration system) is shown in Figure 8-14. Influent was screened before passing through grit chambers and primary clarifiers. Stabilized return sludge was combined with primary effluent in the influent channel and flowed by gravity to Aeration Tank 1. From this contact tank, flow was discharged to both secondary clarifiers.

Sludge was returned to Aeration Tank 2 for stabilization prior to combining with the primary

effluent. Aeration Tank 3 was used to stabilize sludge supernatant. Aeration Tank 4 was not utilized in the original plant.

The original aeration system (Table 8-24) consisted of coarse bubble Walker spargers in a wide-band, spiral roll configuration and two blowers. Blower discharge temperature, pressure and flow data were available. For Aeration Tanks 1 and 2, both flow tube and orifice plate data were available. During summer months, blower capacity was often unable to maintain measurable DO in the aeration tanks resulting in periodic odors.

Basis for Changing to Fine Pore Aeration

The average $\alpha F(SOTE)$ of the coarse bubble diffusers in batch and flowing systems in the contact and stabilization tanks was 4.8 percent. Using an anticipated αF value of 0.4 and a clean water SOTE of 28 percent for dome diffusers, an $\alpha F(SOTE)$ of 11.1 percent was projected for the fine pore system. This would allow one blower to be used instead of two to satisfy the same oxygen utilization rate as the coarse bubble system.

Table 8-25 summarizes the economic advantages that were anticipated from the upgrade. A simple payback period of 6.1 years was estimated for the retrofit, and odors from the aeration tanks were expected to be eliminated. Lower sludge production was projected as a result of the new system's ability to supply the sludge endogenous respiration requirement.

III. FINE PORE AERATION RETROFIT DESIGN DESCRIPTION

In 1982, a full-floor coverage fine pore diffuser (Gray "Fine Air") system was installed in Aeration Tanks 3 and 4. The system was also converted from contact stabilization to the conventional plug flow mode

Figure 8-14. Plant flow diagram (original coarse bubble aeration system) - Ridgewood, NJ.

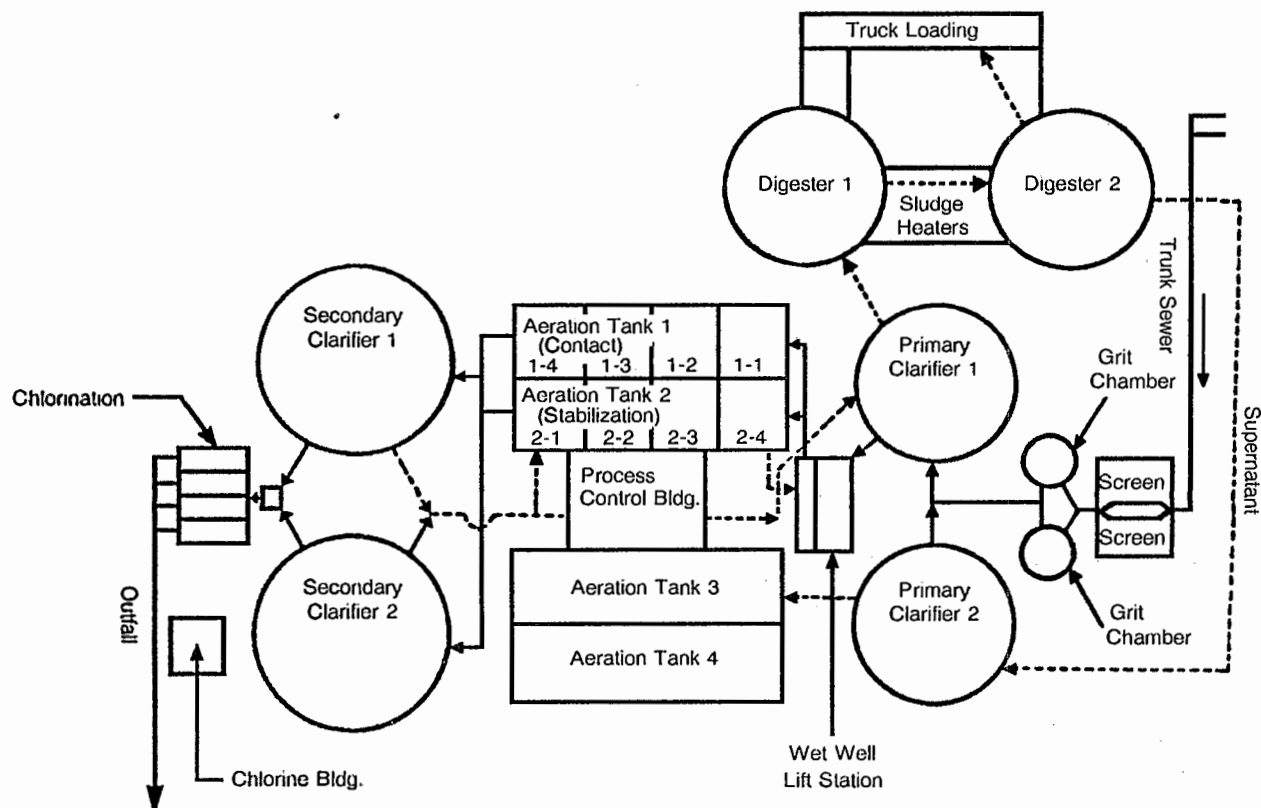


Table 8-24. Physical Characteristics of Original Coarse Bubble Aeration System (Tanks 1 and 2) - Ridgewood, NJ

	Aeration Tank	
	Tank 1 (Contact)	Tank 2 (Stabilization)
Diffusers (Walker Sparjers)		
No. compartments	4	4
Surface area/compartment, sq ft	678	678
No. diffusers/compartment	40	28
No. diffusers/tank	160	112
Density, sq ft/diffuser	17.0	24.2
Height off tank bottom, ft	2	2
Tank water depth, ft	14.5-15.5	14.5-15.5
Blowers (Spencer Turbine - Turbo-Compressor Model 362)		
Type	Centrifugal	
Nominal rating, hp	75	
Total number	5	
Number in use at any time	2	
Typical efficiency, percent	43	

(Figure 8-15), with primary effluent now flowing to both aeration tanks in parallel.

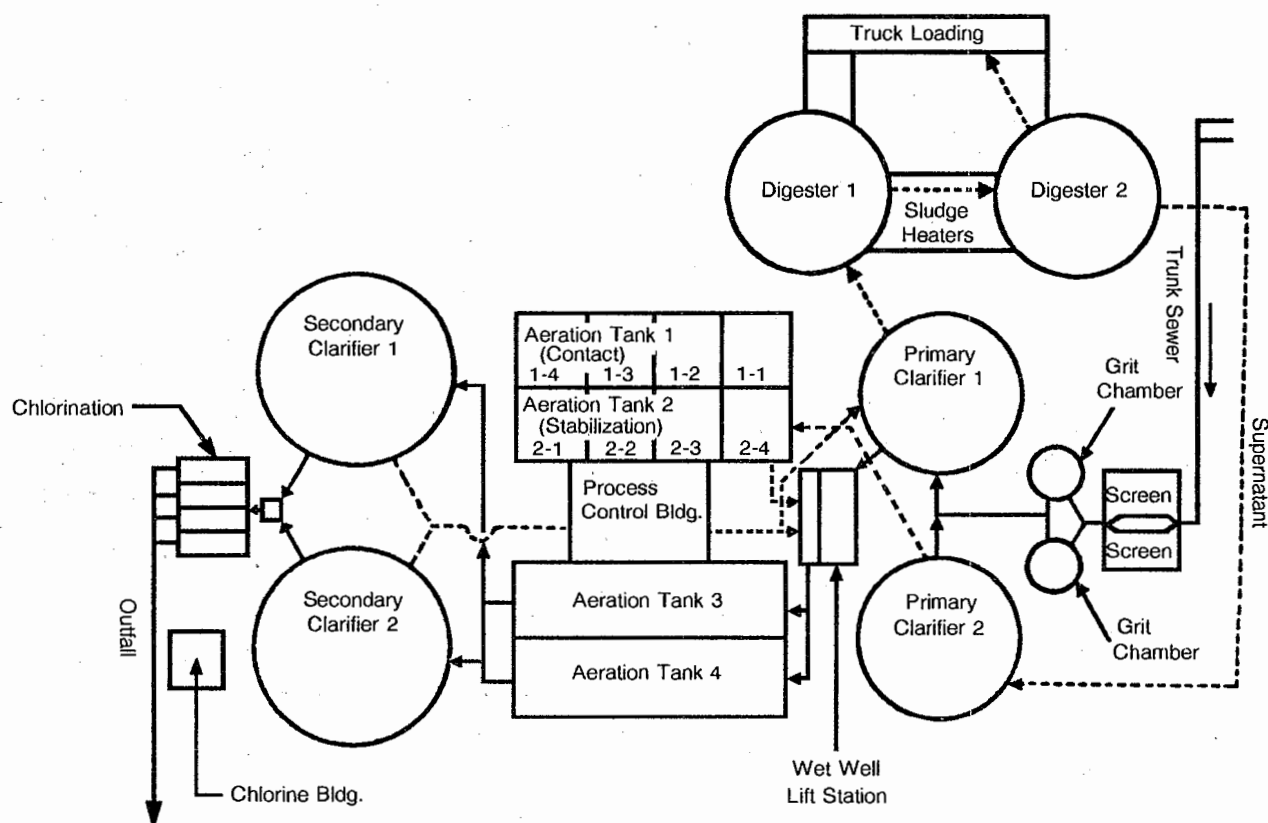
At the influent and effluent ends of both aeration tanks, wooden baffles were installed to distribute and

Table 8-25. Projected Energy Savings - Ridgewood, NJ

	Aeration System	
	Coarse Bubble	Fine Pore
SOTE, percent	8.6	28.0
Temperature, °C	20	20
α_F	0.55	0.40
β	0.99	0.99
C, mg/L	0	0
$\alpha_F(SOTE)_t$, percent	4.8	11.1
Airflow, scfm	2,100	1,100
No. blowers in use	2	1
Power draw, kWh/d	3,000	1,500
Power cost (@\$0.065/kWh), \$/yr	71,200	35,600
Bid price for retrofit, \$	-	218,000
Simple payback period, yr	-	6.1

collect the flow across the total tank width. Four grids were used in each tank with a decreasing number of domes from inlet to effluent end, as summarized in Table 8-26. All domes are 17.8-cm (7-in) diameter Carborundum (Aloxite) diffusers that were initially connected to the saddles approximately 25 cm (10 in) off the bottom using plastic (acetal) bolts. After 1-1/2 years of operation, all plastic bolts were replaced with

Figure 8-15. Plant flow diagram (retrofitted fine pore aeration system) - Ridgewood, NJ.



brass bolts due to numerous failures. The fine pore aeration system was started up in April 1983.

IV. OPERATIONAL PERFORMANCE AND EVALUATION

In March 1983, four clean water oxygen transfer studies were conducted on the newly-installed dome diffuser system. The results of these tests are summarized in Figure 8-16 (see plot labeled "Original Equation"). Unlike the previous coarse bubble diffuser system, increased airflows resulted in now significantly decreased SOTEs. Therefore, Aeration Tanks 3 and 4 were modified by increasing the average dome density from 2.1/m² (19.4/100 sq ft) to 2.5/m² (23.4/100 sq ft). The dome configuration for the modified density is presented in Table 8-26. No clean water studies were conducted after the modification. The equation used to calculate SOTE as a function of airflow for Ridgewood was modified based on modeling concepts as follows (see Figure 8-16):

$$\begin{aligned} \text{SOTE} &= 31.6 - 5.38 (\text{Airflow}) && \text{(original)} \\ \text{SOTE} &= 32.1 - 5.47 (\text{Airflow}) && \text{(modified)} \end{aligned}$$

where airflow is in scfm/diffuser.

Often during summer months, sludge accumulation in the plant was significant due to abandonment of the

sludge lagoons and Aeration Tanks 1 and 2 were used periodically for waste sludge storage. Digester sludge supernatant quality during this time was generally poor with a significant quantity of digested solids probably recycling through the aeration system. Also, with the retrofit, a significant amount of "Nocardia" growth appeared in late spring and early summer months and remained until winter. This resulted in a thick surface foam layer that periodically overflowed the tanks.

Aeration Performance Evaluation

Two oxygen transfer studies were conducted on the coarse bubble aeration system, while the remaining studies were performed on the fine pore aeration system. Estimated annual averages for $\alpha F(\text{SOTE})$ and αF are indicated in Table 8-27 for the two systems under both low and high airflow rates.

A nonsteady-state analysis technique was employed to evaluate the coarse bubble system. Testing was initiated on October 21, 1981 with five batch wastewater, two flowing wastewater, and three clean water tests conducted. In July 1982, 18 nonsteady-state flowing wastewater tests were conducted. For each of the flowing wastewater tests, the primary effluent and return sludge flows were reduced to provide reduced load conditions and positive DO concentrations for testing. $\alpha F(\text{SOTE})$ results for the

Table 8-26. Physical Characteristics of Fine Pore Retrofit System (Tanks 3 and 4) - Ridgewood, NJ

	Each Tank	Grid			
		A	B	C	D
Diffusor type	7-in Gray Domes	696	696	696	696
Tank surface area, sq ft	2,784				
No. grids	4				
Tank water depth, ft	14.5-15.5				
Diffusor height off tank bottom, ft	2				
<u>Initial Operation (4/83-9/84)</u>					
No. diffusers	340	180	160	100	100
Dome density, sq ft/dome	5.15	3.87	4.35	6.96	6.96
<u>Final Operation (9/84-present)</u>					
No. diffusers	650	234	208	104	104
Dome density, sq ft/dome	4.28	2.97	3.35	6.60	6.69

Figure 8-16. SOTE vs. airflow rate (fine pore system) - Ridgewood, NJ.

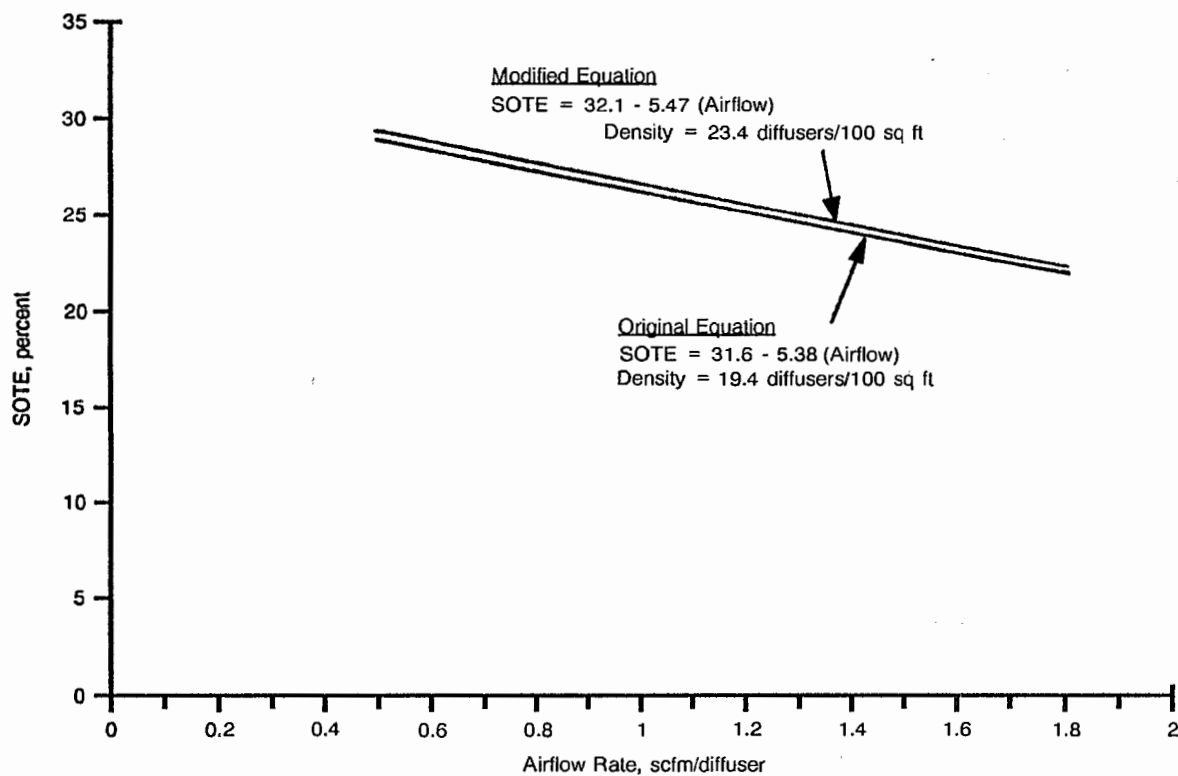


Table 8-27. Estimated Yearly Average $\alpha F(SOTE)$ and αF - Ridgewood, NJ

System	Test Period	No. Tests	Airflow Rate	$\alpha F(SOTE)$, percent	αF
Coarse Bubble	1981-1983	25	High & Low	4.8	0.55
Fine Pore	1985	21	High	7.5	0.36
		7	Low	8.9	0.36
Fine Pore	1986	20	High	9.6	0.41
		4	Low	12.6	0.48

coarse bubble system varied from 3.6 to 6.5 percent under wastewater conditions, while clean water SOTE was 8.6 percent. The coarse bubble system had an estimated annual yearly average $\alpha F(SOTE)$ of 4.8 percent and an average αF of 0.55.

From June 1985 to September 1986, 66 flowing wastewater tests and one batch wastewater test were conducted on the fine pore ceramic dome system. The off-gas and nonsteady-state techniques were employed during the early stages of the study, with off-gas and steady-state test procedures emphasized in the middle and latter stages. Measured $\alpha F(SOTE)$ values exhibited a large degree of variability during the study with results ranging from 5.2 to 15.2 percent. In 1985, the fine pore system had an average $\alpha F(SOTE)$ of 7.5 percent and an average αF of 0.36 under high airflows. Under low airflows, average $\alpha F(SOTE)$ and αF were 8.9 percent and 0.36, respectively.

Potential wastewater effects on αF were minimized by conducting low and high airflow testing at approximately the same time of the day. For 1986, the estimated average $\alpha F(SOTE)$ was 9.6 percent with an average αF of 0.41 under high airflows. Under low airflows conducted in the morning hours during low loading periods, average $\alpha F(SOTE)$ and αF were 12.6 percent and 0.48, respectively. *Nocardia* foam was a problem during the studies and tended to affect OTE results.

In summary, the Ridgewood, NJ coarse bubble system, tested over 2-3 years near the end of its 25-yr life, had an average $\alpha F(SOTE)$ of 4.8 percent with an average αF of 0.55. In contrast, the fine pore system, in operation for almost 4 years, had an average $\alpha F(SOTE)$ of about 9.5 percent with an average αF of 0.40 during normal daytime high-load operation and with two tanks in service.

Effect of Cleaning on Performance

Two methods of cleaning were utilized on the dome diffusers, acid brushing and water hosing. To acid clean the domes, a solution made from 1/2 carboy of 20 percent HCl, diluted 1:1, was used to brush each dome. Water hose cleaning used a high pressure stream of water from a fire hose sprayed from the top of the aeration tank. Typically, an aeration tank was out of service for less than 15 days during a cleaning.

It was difficult to evaluate an immediate effect of diffuser cleaning on OTE due to changing wastewater characteristics and the limited amount of data for the periods both before and after cleaning. An immediate increase in OTE was observed after the July 17th and July 28th, 1985 cleanings on Aeration Tank 3. The low-airflow $\alpha F(SOTE)$, measured at 9.1 percent before the cleanings, increased to 9.9 percent after the hose cleaning (July 17th). After a second cleaning by acid brushing (July 28th), the low-airflow $\alpha F(SOTE)$ increased to 11.5 percent. However, primary effluent BOD_5 for the above tests decreased from 159 mg/L to

141 and 97 mg/L, respectively. Thus, it is not clear what immediate impact, if any, cleaning had on OTE.

V. ECONOMIC CONSIDERATIONS

Preliminary assessment indicated that fine pore aeration retrofit would enable Ridgewood to reduce blower power consumption by 50 percent. Actual power reduction averaged approximately 28 percent for 1984-1986, as shown in Table 8-28. Table 8-29 summarizes the maintenance costs incurred with the fine pore system. Maintenance costs from April 1983 through 1986 averaged \$2,780/yr for the fine pore system; by comparison, minimal maintenance was required for the coarse bubble system. These fine pore maintenance costs include experiments in diffuser cleaning and control of *Nocardia* foam, neither of which may be transferable costs to other systems.

Figure 8-17 illustrates the savings in power consumption obtained with the ceramic dome aeration system. Two-blower operation requires 89,700 kWh/mo, while average actual power consumption is about 63,400 kWh/mo. The projected cost for the coarse bubble system is based on continuous two-blower operation. Approximately 40 percent of the initial cost was paid off from April 1983 to December 1986. The bid price for retrofitting the plant with fine pore diffusers was \$218,000. The initial cost was to be recovered from the power savings incurred with the new aeration system. Based on a 50-percent power consumption reduction and 1982 power costs, the simple payback period was projected to be 6.1 years. Based on actual payments, the predicted simple payback period is approximately 9.7 years. If the increased dome maintenance cost is included as computed, the projected simple payback period is 11.1 years as shown in Table 8-30.

Installation of the fine pore dome system has resulted in a significant improvement in effluent quality with respect to nitrification. Beginning in May 1987, Ridgewood was required to provide seasonal nitrification. Consequently, greater oxygen demand has been incurred by the fine pore aeration system in recent summers than experienced by the coarse bubble aeration system. Although BOD and TSS removals have deteriorated slightly during the last several years, the high degree of nitrification achieved in the summer months has significantly reduced overall oxygen demand on the Ho-Ho-Kus Brook receiving stream. This reduced oxygen demand is not taken into account in the above economic analysis.

The original purchase agreement specified that Ridgewood would pay back the initial cost of the retrofitted aeration system incrementally based on actual energy savings realized from yearly reductions in blower power consumption. This procedure was followed for several years. Because of the lowered oxygen demand of their treatment plant's effluent, however, the Village decided to pay off the remainder of the initial cost in a lump sum.

Table 8-28. Average Blower Power Reduction – Ridgewood, NJ

Parameter ¹	Blower		Total	Reduction
	1	2		
On-time, hr/mo	730	313	1,043	417
Power cost, \$/kWh	0.0746	0.0746		
Power usage, kWh/mo	44,840	19,583	63,423	26,257
Power cost, \$/yr	39,950	17,550	57,550	22,400

¹ Based on average values for 1984-1986. Yearly power reduction = $100(22,400)/(2)(39,950) = 28$ percent.

Table 8-29. Dome Diffuser System Maintenance Costs – Ridgewood, NJ

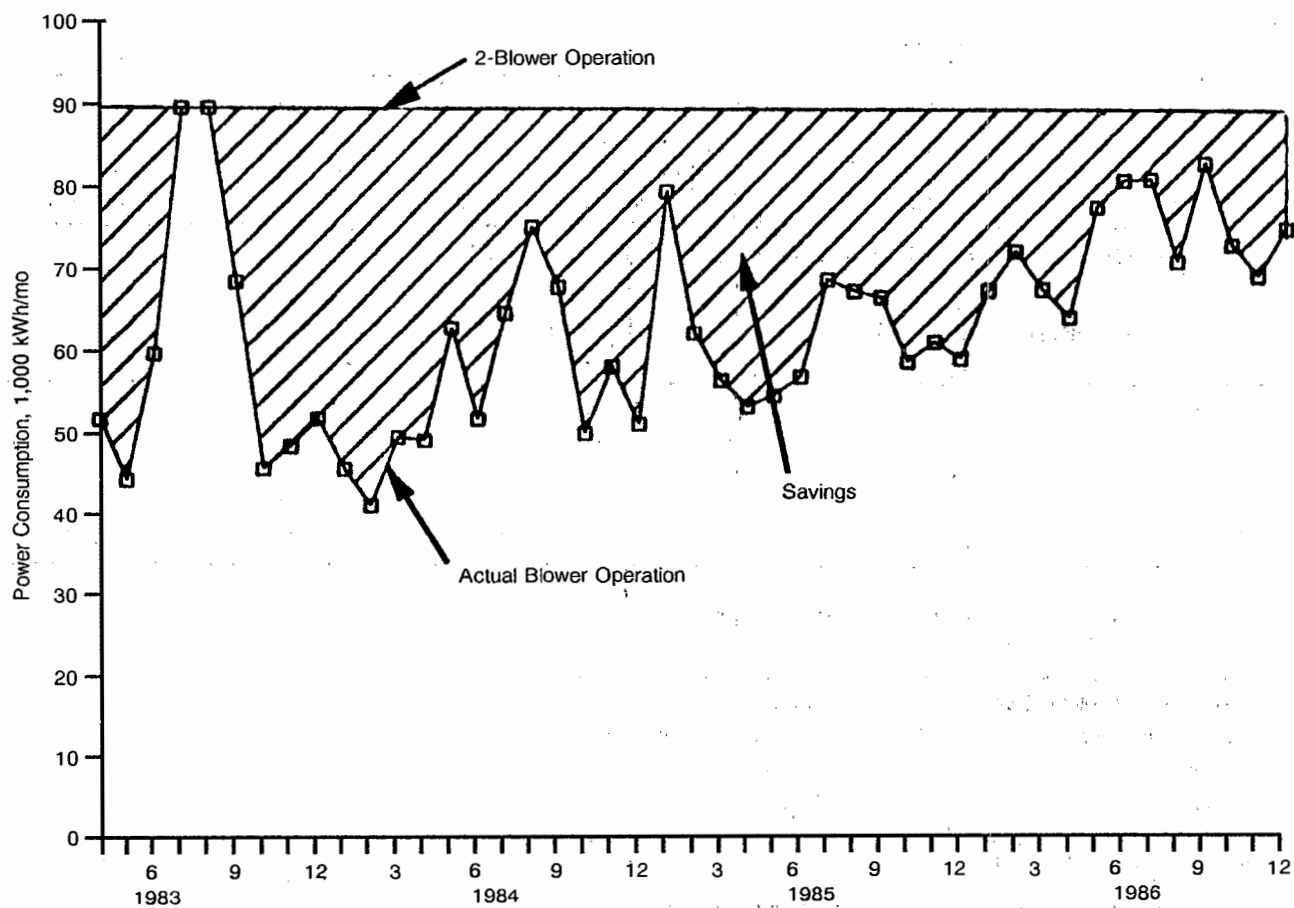
Year	Diffuser Cleaning, \$	Repairs, \$	Foam Chlorination, \$	Foam Cleanup, \$	Total, \$
4/83-12/83	0	0	0	0	0
1984	250	700	0	0	1,080
1985	2,525	350	1,825	2,275	8,975
1986	900	0	875	630	2,405
Average	1,005	280	720	775	2,780

Table 8-30. Dome System Economic Summary – Ridgewood, NJ (1983-1986)

Power savings from retrofit, \$/yr	22,400
Increased maintenance, \$/yr	2,780
Net savings from retrofit, \$/yr	19,620
Fine pore system bid price ¹ , \$	218,000
Projected simple payback period, yr	
Based on average power savings only	9.7
Based on average net savings	11.1

¹ Initial cost plus interest expenses (7 yr @ 9 percent).

Figure 8-17. Savings in power consumption - Ridgewood, NJ.



8.2.8 Whittier Narrows Water Reclamation Plant

LOCATION: El Monte, Los Angeles County, California

OPERATING AGENCY: Los Angeles County Sanitation Districts

DESIGN FLOW: 657 L/s (15 mgd)

WASTEWATER: Domestic

ORIGINAL AERATION SYSTEM: Coarse Bubble Diffusers

FINE PORE AERATION SYSTEM: Sanitaire Ceramic Disc and Norton Ceramic Dome Diffusers

YEAR FINE PORE SYSTEM PLACED IN OPERATION: Ceramic Discs, 1980
Ceramic Domes, 1982

BASIS OF PERFORMANCE EVALUATION: Off-Gas Testing

CLEANING METHOD: In-Situ HCl Gas Cleaning

I. INTRODUCTION

The Whittier Narrows Water Reclamation Plant is one of the older secondary treatment plants in the Los Angeles County Sanitation Districts (LACSD) system. It is considered a water reclamation facility since it also provides treated effluent for groundwater recharge to the San Gabriel groundwater basins. Industrial discharge to the plant is closely monitored and limited. The plant is operated with relatively constant flows with diurnal fluctuations bypassed to the downstream Joint Water Pollution Control Plant (JWPCP) in Carson, California.

In the 1970's, LACSD conducted clean water tests at the JWPCP in an attempt to determine the relative performance of various aeration systems, including coarse bubble diffusers, static aerators, jet aerators, and fine pore diffusers (rigid porous plastic tubes and ceramic domes). As a result of these tests, LACSD decided to evaluate fine pore ceramic and rigid porous plastic diffusers and jet aerators under process conditions in the aeration tanks at the Whittier Narrows plant. Specifications were developed and, based on the bids received, the three field systems installed were Sanitaire ceramic discs, Nokia rigid porous plastic tubes, and Cleave-Pac jet aerators. After 1 year of evaluation, the jet and tube systems were decommissioned in favor of ceramic domes/discs. In March and May 1982, Norton dome diffusers were installed in two of the three basins. The third basin continued to operate with the Sanitaire disc diffusers. The three aeration systems have remained in operation since, with the only modification being the replacement of the original dome diffusers with new ones in September and October 1987.

An aeration system evaluation program was carried out from April 1986 to July 1988. The objective was to evaluate the presence and effect of long-term diffuser

fouling and the effectiveness of in-situ HCl gas cleaning in preventing or retarding the rate of diffuser fouling. In-situ gas cleaning was performed periodically in the tank with the disc diffuser system and in one of the tanks containing the dome diffusers. The second dome tank served as a control, and these diffusers were not cleaned. At the start of the evaluation program, the diffusers were cleaned in all tanks by a liquid acid cleaning procedure. After starting the test program, 33 site visits were made for off-gas testing over a 28-month period.

Summary information is presented to describe the secondary treatment and fine pore aeration systems, diffuser cleaning and off-gas testing programs, results of the long-term aeration performance evaluation, and an estimate of the economic benefits of using fine pore aeration at this site.

II. DESCRIPTION OF WASTEWATER TREATMENT FACILITY

The Whittier Narrows plant is one of eight plants operated by LACSD. The plant is uniquely located so that the flow to the plant can be maintained at a relatively constant rate by directing other flows downstream in the gravity flow sewerage system to the JWPCP in Carson. The waste sludge is also directed downstream; as a result, the Whittier Narrows plant has no sludge handling facilities and associated recycle flows. As with all LACSD plants, industrial flows to the plant are monitored and limited. Thus, the plant has ideal operating conditions with regard to sludge recycle streams, flow variations, and toxic loads.

Whittier Narrows is a conventional primary-secondary treatment system consisting of three rectangular primary clarifiers, three activated sludge aeration basins, and six rectangular secondary clarifiers. These

are followed by sand/anthracite filtration, chlorination, and dechlorination prior to groundwater recharge or discharge to the San Gabriel River. One of the secondary clarifiers has been converted for use as a filter backwash storage tank. The primary clarifiers are 91.4 m (300 ft) long by 6.1 m (20 ft) wide with a 3.7-m (12-ft) SWD. The secondary clarifiers are 45.7 m (150 ft) long by 6.1 m (20 ft) wide with a 3.0-m (10-ft) SWD. The secondary clarifier overflow rate, using five units, is 41 m³/m²/d (1,000 gpd/sq ft) at the average design flow of 657 L/s (15 mgd). The three parallel aeration basins are 91.4 m (300 ft) long, 9.1 m (30 ft) wide and have a nominal 4.6-m (15-ft) SWD, resulting in a nominal 4.8-hr detention time at the average design flow. Y-walls in the aeration basins reduce the surface width to about 7.6 m (25 ft). The aeration basins can be operated in series with serpentine flow or in parallel as conventional plug flow systems. In either mode, step feeding of the influent is possible. The conventional plug flow operating mode was used during most of this ceramic diffuser field evaluation study, with the exception of step feeding from November 1987-January 1988.

The facility is normally operated at a low enough SRT to avoid nitrification. The lack of industrial toxics and the warm wastewater temperature (yearly average 24°C [75°F]) provide ideal conditions for nitrification. Nitrification reduces the effectiveness of the chlorination facility. Better chlorination is provided when a combined residual chlorine can be maintained. Disinfection is very important because the effluent coliform standard is the same as for drinking water (<2.2 MPN). Virus destruction is also of concern. This is addressed by the State of California through the effluent turbidity standard, which is <2 NTU.

During the ceramic diffuser fine pore aeration study period, the average operating SRT was 2.7 days. This was calculated using the aeration tank solids inventory and does not include solids inventory in the secondary clarifier. A 3-day running average of SRT was 1.8-8.3 days during the study. During this period, the average F/M loading, MLSS and MLVSS concentrations, and influent flow rate were 0.59 d⁻¹, 1,047 mg/L and 771 mg/L, and 574 L/s (13.1 mgd), respectively. Primary effluent TSS, BOD₅, and COD concentrations averaged 91, 102, and 231 mg/L, respectively. Treatment efficiency was generally excellent, with an average effluent BOD₅ concentration after filtration and disinfection of 5.2 mg/L. SVI averaged 171 mL/g and ranged from 97 to 654 mL/g. A low-SRT operation from August to October 1986 produced high SVI sludge. On occasion, organic polymer was added in the channel between the secondary clarifier and aeration basin to improve solids settling in the clarifier.

III. DESCRIPTION OF FINE PORE AERATION SYSTEMS

Figure 8-18 is a schematic of the Whittier Narrows aeration basin. Each tank has three aeration grids with

a downcomer to each that has one control valve and flow measuring tube. There are two main air headers, with one of them shared between Basins 2 and 3, which contain the dome diffusers. The main air header piping was kept in service when the system was converted to fine pore aeration. The diffuser submergence for all basins is 3.7 m (12.3 ft), i.e., 0.8 m (2.7 ft) above the floor, which is required due to limited available blower pressure.

Basin 1 contains the Sanitaire 23-cm (9-in) ceramic discs of the old design that have a 25-mm (1-in) thickness. Basins 2 and 3 are equipped with 18-mm (7-in) Norton domes of the old design, which are high-fire, tan-colored stone compared to the low-fire, gray-colored stones of the new design. Each diffuser in these systems is equipped with an individual removable inlet orifice. The Norton system is unusual in that fiber-reinforced ABS bolts and "spongy" gaskets were used, as opposed to PVC bolts and hard rubber gaskets. The ABS bolts were used because PVC bolts have poor resistance to HCl acid application. The spongy gaskets were standard issue at the time. When the domes were replaced in September and October 1987, several domes were equipped with hard rubber gaskets. The ABS bolts failed in that application, confirming the need to use spongy gaskets with ABS bolts.

Table 8-31 summarizes diffuser layout and density in each basin and grid. The design includes tapered aeration to provide for reduced air application to the third grid at the end of each aeration basin. The diffuser density is about 23-26 percent greater for the domes than for the discs. The relative density is based on the assumption that the media surface area of 1 disc is approximately equivalent to that of 1.25 domes.

The aeration system has three centrifugal blowers remaining from the original spiral roll coarse bubble aeration operation. Two are 298-kW (400-hp) units, each rated at 5,760 L/s (12,200 scfm) at 146 kPa (6.5 psig). The other blower is a 149-kW (200-hp) unit, rated at 2,830 L/s (6,000 scfm) at 146 kPa (6.5 psig). Normally one of the large blowers is operated. Flow meters are available for each blower, aeration tank header, and aeration grid downcomer. A two-stage air filtration system was installed in the blower suction air line but was not used for most of the aeration evaluation period because of corrosion problems in the piping.

Automatic DO control is used for this plant. A probe is mounted at the effluent end of each tank, and blower flow rate is increased or decreased as needed. The air distribution between Basin 1 and Basins 2 and 3 is manually set by the two header valves. The relative flows to each grid are set by the downcomer valves. Adjusting the airflow distribution usually requires several valve adjustment iterations.

Figure 8-18. Aeration basin schematic - Whittier Narrows, CA.

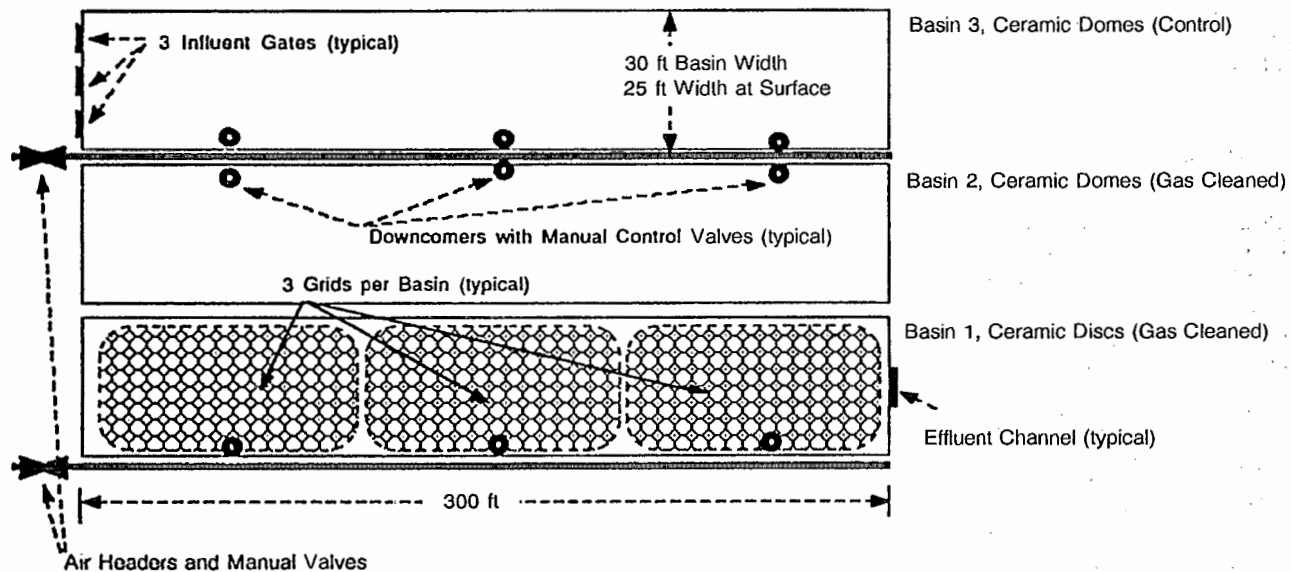


Table 8-31. Diffuser Layout Summary - Whittier Narrows, CA

Basin	Grid	Diffusers (submergence = 15 ft)	
		Number	Density, No./100 sq ft
1 Discs	1	792	26
	2	774	26
	3	460	15
2 and 3 Domes	1	988/836 ^a	33/28 ^a
	2	968	32
	3	574/728 ^a	19/24 ^a

^a Before and after August 21, 1987.

Over the period of this study, the DO control operational strategy changed several times. Generally the DO is maintained at 0.3 mg/L or less in Grid 1 and is increased to 1-2 mg/L at the effluent end of the tank.

IV. OPERATIONAL PERFORMANCE AND EVALUATION

Table 8-32 summarizes the off-gas testing and diffuser cleaning program schedule. In May and June 1986, after operating for about 18 months without cleaning, the diffusers were rigorously cleaned using a liquid acid surface application method. Off-gas testing was conducted prior to this cleaning to determine dirty diffuser OTE. Off-gas testing was performed at least once per month thereafter to follow diffuser fouling and performance with time both before and after cleaning events.

The times between gas cleanings were selected on a somewhat arbitrary basis. Initially, it was hoped the rate of increase of diffuser pressure loss, as indicated by an increase in DWP or a loss in OTE as measured by off-gas testing, would dictate the need for acid gas

cleaning. Variations in OTE due to day-to-day fluctuations in wastewater characteristics and poor precision in the DWP measurements made this strategy impractical. In addition, during the planning phase of the project, a change in the gas cleaning philosophy was introduced by Sanitaire. Cleaning was no longer felt to be a method to restore fouled diffusers, but was felt to be an effective method to prevent diffuser fouling when applied periodically. The experimental design called for cleaning of Grid 1 in Basins 1 and 2 every 3 months. Grid 2 was cleaned every 6 months, and Grid 3 was cleaned every 9 months.

During cleaning, the HCl gas was introduced into the downcomer feeding each diffuser grid. One grid at a time was cleaned. The airflow to the grid being cleaned was increased to a desired level of 1.4 L/s (3 scfm)/diffuser, or as close to that as possible. Generally, the airflow achieved was about 1.2 L/s (2.5 scfm)/diffuser. The increased airflow rate ensures that HCl gas permeates through the entire diffuser area. The HCl gas rate was approximately 9.4 L/s (20 scfm)/grid. A small decrease in DWP and increased in air flow rate was usually observed within 30 seconds of introducing the gas. The original Sanitaire protocol required that 45 g (0.1 lb) HCl/diffuser be used. This quantity of gas per cleaning event was reduced based on DWP observations. Gas addition was curtailed when DWP readings decreased to a plateau. Consequently, the gas dosage was 10-25 g HCl/diffuser.

On two occasions, air leakage was noted for the dome diffusers in Basins 2 and 3 based on the air bubble pattern on the surface. For the first instance in September 1987, the leaks were occurring around the

Table 8-32. Project Chronology - Whittier Narrows, CA

Date	Event	Comments
4/28/86	Off-gas testing	Background testing performed to determine dirty diffuser efficiency
5/12/86	Off-gas testing	Background testing
5/13-6/19-86	Liquid acid cleaning of all 3 basins	Diffusers collected for analysis; dome gasket leakage noted
6/20/86	Off-gas testing	
7/02/86	Off-gas testing	
7/22/86	Off-gas testing	Hoods not moved in order to determine diurnal fluctuations in $\alpha F(SOTE)$
8/01/86	Off-gas testing	
8/86	Process operation changed	MLSS reduced in all three basins
8/21/86	Off-gas testing	
8/26-8/27/86	First HCl gas cleaning	Grids 1, 2, & 3 cleaned in Basins 1 & 2
9/04/86	Off-gas testing	
9/17/86	Off-gas testing	
10/17/86	Off-gas testing	
10/31/86	Off-gas testing	
11/17/86	Off-gas testing	
12/9/86	HCl gas cleaning	Grid 1 of Basins 1 & 2 cleaned
1/16/87	Off-gas testing	
1/30/87	Off-gas testing	
2/13/87	Off-gas testing	
2/27/87	Off-gas testing	
3/13/87	Off-gas testing	
3/26-3/27/87	HCl gas cleaning	Grids 1, 2, & 3 of Basins 1 & 2 cleaned. Simultaneous off-gas testing performed.
4/03/87	Off-gas testing	
4/17/87	Off-gas testing	
5/22/87	Off-gas testing	
6/05/87	Off-gas testing	
6/15-16/87	HCl gas cleaning	Grid 1 of Basins 1 & 2 cleaned
6/19/87	Off-gas testing	
7/10/87	Off-gas testing	
7/31/87	Off-gas testing	
8/31/87	Off-gas testing	
9/9/87	Domes replaced in Basin 3	Some gasket leakage noted afterwards
9/30/87	Domes replaced in Basin 2	Some gasket leakage noted afterwards
9/30/87	HCl gas cleaning	Grid 1 of Basin 1 cleaned
10/9/87	Off-gas testing	
11/13/87	Off-gas testing	
12/04/87	Off-gas testing	
12/24/87	Off-gas testing	
1/15/88	Off-gas testing	Grids 1, 2, & 3 of Basin 1 cleaned
1/26/88	HCl gas cleaning	Grid 1 of Basin 2 cleaned
1/29/88	Off-gas testing	
2/19/88	Off-gas testing	
3/11/88	Off-gas testing	
5/88; 6/88	Basins 2 & 3 manually cleaned using tank top hosing	Gas leakage noted. Broken bolts noted
6/16/88	Off-gas testing	
8/7/88	Basin 1 manually cleaned using tank-top hosing	
8/12/88	Off-gas testing	

Basin 1 - Disc Diffusers
Basins 2 and 3 - Dome Diffusers

diffuser gaskets. It was determined that the diffusers were fouled to the extent that they had to be replaced. In May 1988, the observed air leakage was due to broken bolts that were repaired.

At selected periods, diffusers were collected from each grid and sent to the University of Wisconsin for observation and analysis. The diffusers were analyzed for DWP, BRV, foulant material mass and composition, and air distribution profiles. Diffusers were collected prior to cleaning at the start of the test program to determine their characteristics after 18 months of operation without cleaning by tank top hosing.

The standard off-gas testing procedure was followed, and the gas hoods used in the basins were in the size range of 3 m long by 61 cm wide (10 ft by 2 ft). The hood was situated at two locations across the basin width and two down the length of a grid to produce a total of four measuring points per grid. The location along the grid length was at about the 1/3 and 2/3 points. At these locations, the hood was placed against one wall and then in the center of the basin. Both the dome and disc diffuser basins were tested on the same day. To obtain comparative test results under as similar wastewater conditions as possible, the grids were tested alternately. When grid testing was finished at one hood location, testing would take place in the other basin while the hood in the first basin was moved to the next location.

Evaluation of the removed diffuser samples indicated that DWP could be controlled by HCl gas cleaning. However, DWP after cleaning was usually about twice that of a new diffuser. BRV measurements seemed to increase with time of service, but were also reduced after gas cleaning. The amount of fouling material found on the sampled diffusers was about twice as high in Grid 1 as in Grid 3, with Grid 2 diffuser fouling in between these.

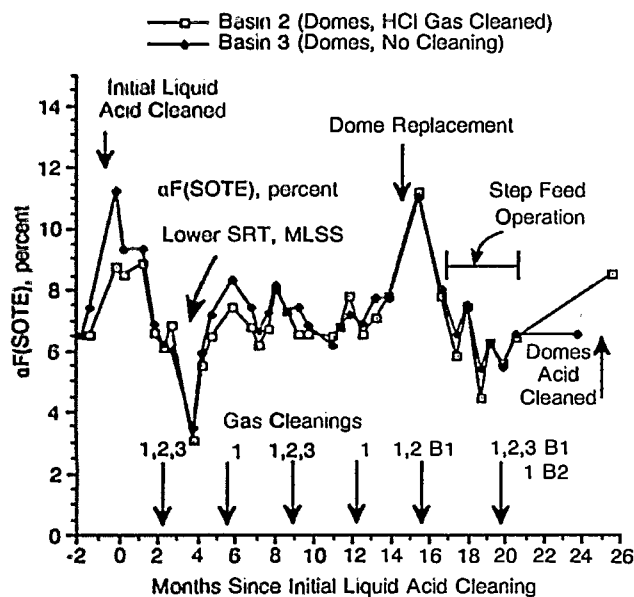
Lab diffuser cleaning studies compared the effectiveness of cleaning by hosing and liquid acid application methods. Based on DWP and BRV measurements, liquid acid cleaning was superior to hosing in reducing DWP and BRV. In many instances, hosing decreased BRV but not DWP.

Off-Gas Testing Results

Figure 8-19 compares $\alpha F(SOTE)$ over the duration of the study for the dome diffusers in Basins 2 and 3. The only difference between the two basins is that gas cleaning was performed on the diffusers in Basin 2 but not in Basin 3. It is apparent from Figure 8-19 that gas cleaning did not affect OTE for the dome diffusers, quite possibly because of diffuser gasket leakage problems.

Two significant dips in the $\alpha F(SOTE)$ curves at approximately the 3rd and 17th months were due to

Figure 8-19. $\alpha F(\text{SOTE})$ vs. time (ceramic dome diffusers) - Whittier Narrows, CA.



plant operational changes. Around the 3rd month, the operating SRT and MLSS concentration decreased from 2.0 to 1.7 and from about 1,000 mg/L to 700 mg/L, respectively. The lowest $\alpha F(\text{SOTE})$ (about 3 percent) occurred on October 17, 1986, when the MLVSS concentration was 409 mg/L and the SRT was 1.2 days. The second operational change that resulted in a lower overall $\alpha F(\text{SOTE})$ was when step feeding was temporarily implemented at around the 17th month of the study.

Figure 8-20 compares disc diffuser performance in basin 1 with gas cleaning to dome diffuser performance in Basin 3 without gas cleaning. Contrary to the comparison between Basins 2 and 3, gas cleaning the discs resulted in improved OTEs.

The effects on OTE of lowering the MLSS concentration and using a step feed mode of operation also noted for the disc diffusers. Figure 8-20 shows that when new domes were installed the OTEs were very similar between the discs and domes. With time, the dome OTE decreased to below that of the discs. Because of the variability in the day-to-day characteristics and off-gas results, the effect of HCl gas cleaning on OTE is not obvious when only the disc diffuser data are observed. However, comparing these results to the uncleaned dome diffuser results shows a long-term benefit of higher OTEs when gas cleaning is applied on a routine basis.

The disc diffuser system was operating with an $\alpha F(\text{SOTE})$ of 8.5-9.0 percent before initial cleaning with the modified Milwaukee method. The domes were operating at 6.5-7.5 percent. Since the two types

of diffusers exhibited similar clean water OTEs and the discs had been operated under process conditions 16 months longer than the domes, it is very likely that much of the difference in OTE may have been due to gasket leakage with the dome diffusers.

Overall $\alpha F(\text{SOTE})$ just after the liquid acid cleaning, was 10.2 percent for Basin 1 (discs) and averaged 10 percent for the two basins with dome diffusers. Between the 5th and 13th months of operation, after the low MLSS operating condition and before the dome replacement, the average $\alpha F(\text{SOTE})$ s of the disc and dome diffuser systems were 9.8 percent and 7.0 percent, respectively. This results in average αF values of 0.34 and 0.24, respectively.

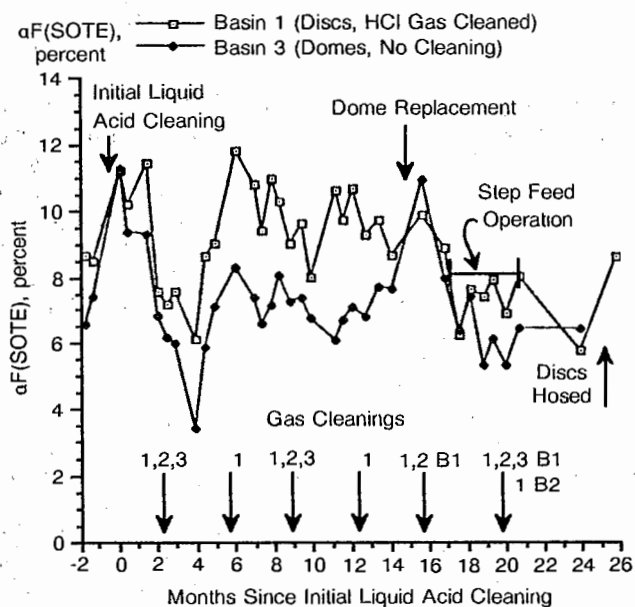
V. ECONOMIC BENEFIT

The total initial cost of the in-basin aeration equipment installation was about \$420,000. Additional costs of \$13,000 for air filtration equipment and \$13,500 for air take-off piping resulted in a total retrofit expenditure of \$446,500. However, this did not include the royalty payment for the gas cleaning system. The average air application rate observed during the study was 3,923 L/s (8,312 scfm) at 574 L/s (13.1 mgd). Based on prior experience with coarse bubble diffusers at this plant, the OTE with disc diffusers was about twice that of coarse bubble aeration. Thus, the required air application rate was decreased by approximately one-half using fine pore aeration. Based on a blower transfer capacity of 16.5 L/s/kW (26.1 scfm/hp), this results in a daily power savings of 5,700 kWh. With an actual electricity cost of \$0.085/kWh, the daily electrical cost savings is \$484, or \$176,964/yr.

Diffuser cleaning costs must be considered in the overall cost analysis. For these diffusers, the cleaning cost was based on employing HCl gas cleaning once every 3 months and the modified Milwaukee method on the average of once every 2 years. (LACSD's normal practice is tank top hosing every 6 months and the modified Milwaukee method every 2 years). Gas cleaning costs were based on conservative estimates of 45 g (0.1 lb) HCl/diffuser and the need for 12 labor-hr/tank at \$20/hr. The gas cost including delivery was estimated to be \$1.36/kg (\$3/lb). The modified Milwaukee method was estimated to require 4 labor-days/tank. The above cleaning costs amount to \$16,680/yr. The estimated net O&M savings are therefore \$160,284/yr.

The energy savings resulting from conversion to fine pore aeration from coarse bubble aeration, when combined with gas cleaning costs, yields a simple payback period of 2.8 years. The relatively high cost of energy in Los Angeles is a significant factor in the cost evaluation. Diffuser cleaning has a relatively small impact on the cost evaluation.

Figure 8-20. Comparison of ceramic dome and disc diffuser performance - Whittier Narrows, CA.



8.3 Performance Evaluation by Means Other Than Off-Gas Testing

8.3.1 Cleveland Wastewater Treatment Plant

LOCATION: Cleveland, Wisconsin

OPERATING AGENCY: Village of Cleveland

DESIGN FLOW: 7.9 L/s (0.18 mgd)

WASTEWATER: Domestic Plus Community College

ORIGINAL AERATION SYSTEM: Coarse Bubble Diffusers

FINE PORE AERATION SYSTEM: EDI Reef IV Rigid Porous Plastic Plate Diffusers

YEAR FINE PORE SYSTEM PLACED IN OPERATION: 1986

BASIS OF PERFORMANCE EVALUATION: Overall Process Performance

CLEANING METHOD: No Cleaning Necessary to Date

I. HISTORICAL BACKGROUND

The Village of Cleveland, WI, population 1,425, operates a wastewater treatment plant that receives wastewater from its residents and 2,000 community college students. The plant was first operated in the contact stabilization mode. When the mode of operation was changed to extended aeration to achieve improved BOD removal and nitrification, sufficient DO could not be maintained in the aeration tank.

To improve oxygen transfer performance, the pipe mounted coarse bubble diffusers were removed and replaced with porous plastic plate fine pore diffusers. The 20-yr old blowers and motors were also replaced with positive displacement units.

The activated sludge system consists of an 11-m (36-ft) diameter package plant with a 5.5-m (18-ft) clarifier in the center. The volume of the aeration bays is 345 m³ (91,000 gal), divided into three sections of 129, 144, and 72 m³ (34,000, 38,000, and 19,000 gal) each. The aerobic sludge digestion tank volume is 95 m³ (25,000 gal). Flow to the plant averages 7.9 L/s (0.18 mgd). Influent BOD₅, TSS, and NH₃-N concentrations average 173, 165, and 30 mg/L, respectively. Prior to the retrofit, effluent BOD₅ was 30-40 mg/L. Operating parameters in the contact stabilization mode were an MLSS inventory of about 1,590 kg (3,500 lb) and a target mixed liquor DO of 2.0 mg/L. Two 11.2-kW (15-hp) centrifugal blowers, one a standby, could each deliver 142 L/s (300 scfm) air.

II. FINE PORE AERATION SYSTEM DESIGN DESCRIPTION

The new rigid porous plastic plate diffusers, each 1.2 m long x 46 cm wide x 6.4 mm thick (48 in x 18 in x

1/4 in) housed on top of a thin plastic box to which air is fed by a flexible hose, were installed in January 1986. Piping used for the coarse bubble aeration system was reused in part for the new system. Ten new diffusers were installed on the bottom inside periphery of the aeration tank, and two were installed in the aerobic digester, a 4.9-m x 4.9-m (16-ft x 16-ft) tank butting against the circular package plant. Equal water depth over the diffusers is maintained in the aeration and digestion tanks. The two diffusers in the hopper-bottom digestion tank were placed on stilts to achieve the equitable depth. A cross roll aeration pattern is achieved with the fine pore diffuser configuration. The retrofitted plant is operated as an extended aeration system with 10-14 hr HRT, an MLSS concentration of 1,800 mg/L, and DO levels of 1.5-2.5 mg/L in the aeration tank and 1.0-1.5 mg/L in the digestion tank.

The installed cost of the retrofit system was \$11,500, including design, equipment, and labor. Plant personnel designed and installed the system. Hardware expenditures totaled \$8,060, including retrofitting the piping and purchasing the new diffusers, blowers, and motors.

III. PERFORMANCE

The new system is reported to be performing effectively with no maintenance problems in over 2 years of operation. Average effluent characteristics are as follows: BOD₅ = 6.4 mg/L, CBOD₅ = 2.8 mg/L, TSS = 5.1 mg/L, and NH₃-N = trace amounts. Diffusers are inspected periodically, and only a slight growth on 3-5 percent of the media surface has been observed. Experiments have shown that, if desired, the growth can be easily removed with a 10-percent solution of sulfuric acid.

IV. COST SAVINGS

Savings in electricity are reported to be \$2,400/yr, which equates to a simple payback period of just under 5 years. Normally, one blower is operated at 130 L/s (275 scfm) and 55 kPa (8 psi). According to operating personnel, the old coarse bubble aeration system, including blowers and motors, had expended its useful life and was in need of replacement at the time the fine pore system was installed.

8.3.2 Plymouth Wastewater Treatment Plant

LOCATION: Plymouth, Wisconsin

OPERATING AGENCY: Plymouth Utilities

DESIGN FLOW: 72 L/s (1.65 mgd)

WASTEWATER: Municipal Plus Significant Cheese Manufacturing Wastes

ORIGINAL AERATION SYSTEM: Surface Aerators

FINE PORE AERATION SYSTEM: Sanitaire Ceramic Disc Diffusers

YEAR FINE PORE SYSTEM PLACED IN OPERATION: 1986

BASIS OF PERFORMANCE EVALUATION: Overall Process Performance; Power Savings

CLEANING METHOD: In-Situ HCl Gas Cleaning System Provided

I. HISTORICAL BACKGROUND

The Plymouth, WI activated sludge plant operated from 1978 through 1985 using three aeration basins, each equipped with one 30-kW (40-hp) mechanical surface aerator. The plant receives wastewater from the City, population 7,000, plus industrial wastes from three cheese manufacturers. The domestic/industry organic loading split is about 1:1.

Energy use was not the major factor in Plymouth's decision to retrofit their plant with fine pore ceramic discs. The reasons included: a) the need in 1980 to provide nitrification in a system designed only for carbonaceous BOD removal, b) the inability of the surface aeration system to consistently maintain solids in suspension, which resulted in varying MLSS levels and effluent quality, and c) mechanical problems and high repair costs associated with the surface aerators.

The plant consists of grit removal, primary clarification, activated sludge treatment, secondary clarification, tertiary filtration, and disinfection. Pickle liquor (ferrous chloride) is added to the aeration basin for phosphorus removal. Sludge is anaerobically digested, and digester supernatant and tertiary filter backwash are returned to the primary clarifiers. Effluent standards (summer/winter) are as follows: 10/20 mg/L BOD₅, 10/20 mg/L TSS, 1/9 mg/L NH₃-N, and 1/1 mg/L TP. The plant received average loadings in 1986 of 57 L/s (1.3 mgd) flow, 990 kg (2,182 lb) BOD₅/d, 689 kg (1,518 lb) TSS/d, 50 kg (111 lb) NH₃-N/d, and 29 (64 lb) TP/d. The system is normally operated at an MLSS of 3,000-3,500 mg/L and an F/M loading of 0.11-0.13 d⁻¹.

The three aeration basins, each 12.2 m x 12.2 m x 4.6 m (40 ft x 40 ft x 15 ft) SWD, were designed to operate as a contact stabilization system in either the complete mix or plug flow mode. The system was designed to treat 1,051 kg (2,317 lb) BOD₅/d from primary clarification plus 340 kg (750 lb) BOD₅/d from

digester supernatant. Annual power costs for aeration were estimated at \$37,200 based on 45 amps current draw/surface aerator, 191 days with two aerators operating, 174 days with three aerators operating, and a power cost of \$0.0526/kWh.

Annual energy savings from installing fine pore diffusers was estimated at \$28,200. These savings were based on anticipated lower BOD₅ loads than included in the original design plus an average NH₃-N load of 60 kg (133 lb)/d. Average mixed liquor DO for the retrofitted system was assumed to be 2.5 mg/L, with aF estimated at 0.6.

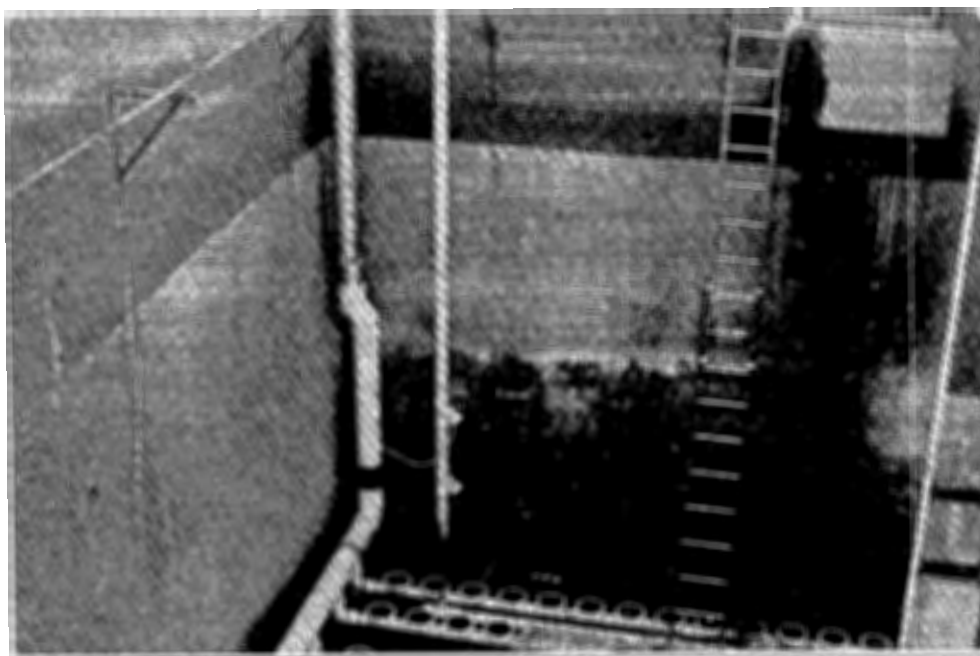
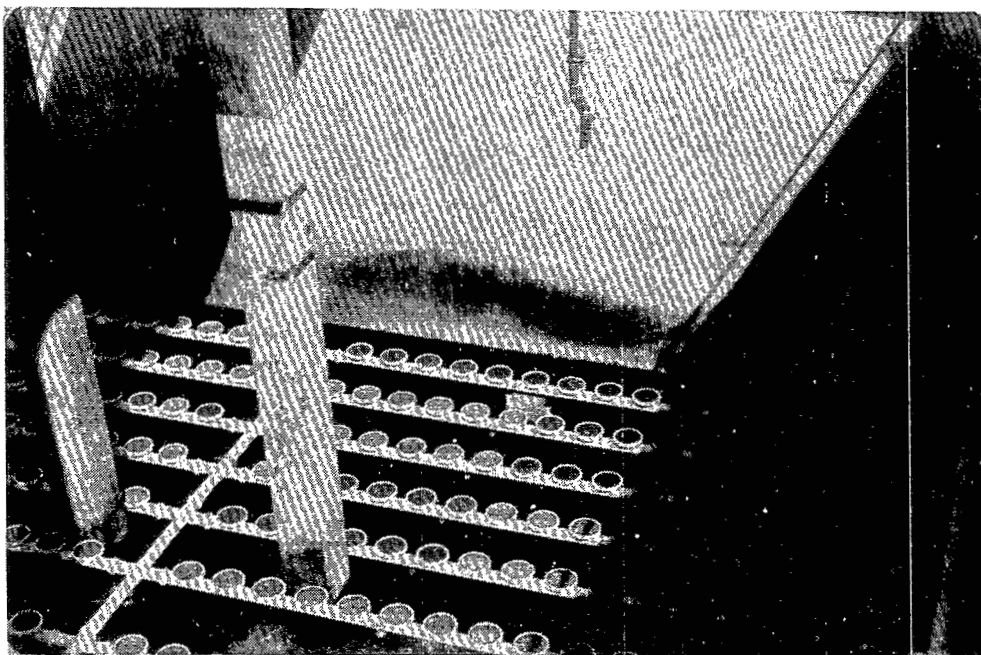
II. FINE PORE AERATION SYSTEM DESIGN DESCRIPTION

The new aeration system consisted of 1,350 23-cm (9-in) diameter ceramic fine pore discs with a ratio of tank floor area to diffuser surface area of 8.6 and a new aeration building containing three 37-kW (50-hp) positive displacement blowers, each capable of delivering 400 L/s (850 scfm) air. The design criteria were: flow = 72 L/s (1.65 mgd), BOD₅ = 615 kg (1,356 lb)/d, NH₃-N = 136 kg (300 lb)/d, total oxygen requirement = 1.15 kg O₂/kg BOD₅ applied + 4.6 kg O₂/kg NH₃-N applied, and airflow rate = 0.63 L/s (1.33 scfm)/diffuser. Each blower was expandable to 802 L/s (1,700 scfm) by upgrading the motor to 56 kW (75 hp). Each aeration basin received 450 ceramic disc diffusers, equally spaced at 66 cm (26 in) o.c. In-situ gas cleaning capability and pressure monitoring systems were also provided. Figure 8-21 shows the Plymouth fine pore aeration system.

III. SYSTEM PERFORMANCE

Following the retrofit, average effluent BOD₅ and TSS concentrations for 1986 were 3 mg/L each. MLSS were consistently maintained between 3,000 and 3,500 mg/L. Aeration tank temperatures have averaged about 5°F higher than before the retrofit,

Figure 8-21. Air header distribution system used to retrofit fine pore ceramic discs into a tank formerly equipped with surface aeration - Plymouth, WI.



and mixed liquor DO has been maintained between 5 and 6 mg/L. BOD₅ and NH₃-N loadings were 6.5 and 8.2 percent higher for the 12 months prior to the retrofit than during the 12 months following the retrofit.

IV. COST SAVINGS

The capital cost of the system included a 6.1-m x 11-m (20-ft x 36-ft) building (\$89,628), labor for installation of blowers and diffusers (\$36,702), labor for removing old aerators (\$2,370), diffusers (\$46,720), blowers (\$33,294), engineering, and a change order credit for a total cost of \$224,207.

Power savings were based on operating two blowers 5 days each week drawing 55 amps and one blower on weekends drawing 35 amps. This resulted in an annual savings of 383,240 kWh compared with the previous year. The annual power savings under these conditions were \$20,160, or about 20 percent less than the estimated \$28,200. Based on a continued energy savings of \$20,160/yr, the system has a simple payback period of 11.1 years.

8.3.3 Renton Wastewater Treatment Plant

LOCATION: Renton, Washington

OPERATING AGENCY: Seattle Metro

DESIGN FLOW: 3,155 L/s (72 mgd)

WASTEWATER: Domestic

ORIGINAL AERATION SYSTEM: Coarse Bubble Diffusers

FINE PORE AERATION SYSTEM: Wyss Perforated (Flexible) Membrane Tube Diffusers

YEAR FINE PORE SYSTEM PLACED IN OPERATION: 1983

BASIS OF PERFORMANCE EVALUATION: Overall Process Performance and Air Usage

CLEANING METHOD: Occasional Hosing

I. HISTORICAL BACKGROUND

The Renton, WA Wastewater Treatment Plant was placed in operation in 1965 to serve the urban and suburban areas lying to the east, south and north of Lake Washington, just east of Seattle. The plant was originally designed in anticipation of future incremental expansion. The capacity of the original facility was 1,052 L/s (24 mgd). This was expanded to 1,578 L/s (36 mgd) during 1972-1974 and was doubled to 3,155 L/s (72 mgd) in late 1987.

Rising power costs led to an evaluation of possible modifications of the existing coarse bubble diffused aeration system in 1982. 45-50 percent of the plant's energy usage could be attributed to the aeration blowers. Plant power costs increased from approximately \$10,000/mo in 1979 to \$46,000/mo in 1981. Based on projected increases in anticipated flow and power rates, annual power costs were expected to increase from approximately \$550,000 in 1981 to \$1,150,000 by 1986. Consequently, a significant cost savings could be realized by conversion to a more efficient aeration system.

The Renton plant is a conventional activated sludge plant designed to meet an effluent TSS limit of <30 mg/L. SRT is controlled at 2-3 days to prevent nitrification and minimize energy needs. Plant influent is screened before passing to preaeration, grit removal, and primary sedimentation.

The plant's three aeration tanks each contain four passes 9 m (30 ft) wide by 111 m (317.5 ft) long with an SWD of 4.6 m (15 ft). HRT at average wet weather flow (December-April) is 4.3 hr. The original coarse bubble diffusers were mounted as sidewall diffusers on swing arms. The aeration system is equipped with six single-stage centrifugal blowers that discharge into a common air header at a discharge pressure of 153 kPa (7.5 psig). Two of the blowers have a nominal

capacity of 5,665 L/s (12,000 scfm) each, while the other four have a capacity of 6,610 L/s (14,000 scfm) each. An automatic DO control system is used to adjust the airflow to each aeration tank. The blower inlet vanes are also throttled in response to pressure fluctuations in the air supply system.

The plant is equipped with four peripheral-feed secondary clarifiers, each with a diameter of 30 m (100 ft) and an SWD of 4.3 m (14.2 ft), in addition to 12 30-m (100-ft) diameter center-feed secondary clarifiers. The secondary clarifier overflow rate at the 3,155-L/s (72-mgd) average wet weather flow is 23.3 m³/m²/d (572 gpd/sq ft). Effluent is discharged to Puget Sound.

Prior to October 1987, waste primary and secondary sludges were discharged to a trunk line to the main Seattle Metro 6,570-L/s (150-mgd) plant. Since October 1987, sludge handling facilities have been placed in operation and consist of diffused air flotation thickening, anaerobic digestion, and belt filter press dewatering of primary and secondary sludges.

II. FINE PORE AERATION SYSTEM RETROFIT

Wyss perforated membrane tube diffusers were selected for in-plant evaluation in 1982. They were installed in the first two passes of one aeration tank. This tank was operated under identical influent feed rates and DO levels as the first two passes of another aeration tank containing coarse bubble diffusers. The performance of the two systems was compared by measuring the airflow rates needed to control DO to 2 mg/L and indirectly determining OTEs. OTEs were determined by comparing oxygen consumption rates, calculated from measured basin oxygen uptake rates, to air application rates. These tests indicated the perforated membrane diffuser system requires 30-40 percent less air than the coarse bubble diffuser system to maintain comparable DO levels.

Table 8-33. Monthly Average Performance - Renton, WA

Month	Flow, mgd	Influent BOD ₅ ¹ , mg/L	MLSS ² , mg/L	SRT, days	Effluent, mg/L		cu ft Air/lb BOD ₅	Estimated OTE ³ , percent
					BOD ₅	TSS		
January 1987	61.6	145	798	3.1	11.6	8.7	693	8.3
February	59.4	145	674	2.5	10.4	7.7	631	9.1
March	57.3	145	758	2.6	11.6	7.6	642	9.0
April	46.6	163	730	2.4	12.6	11.0	747	7.7
May	45.4	150	655	2.2	14.2	11.4	849	6.8
June	45.7	169	751	2.1	14.0	10.7	761	7.6
July	43.6	170	840	2.4	14.3	8.9	893	6.4
August	43.0	161	831	2.4	9.0	8.7	842	6.8
September	41.2	147	823	2.4	10.9	7.4	1,018	5.7
October	45.3	143	824	2.3	12.3	9.8	856	6.7
November	43.0	160	703	2.2	19.0	16.6	844	6.8
December	51.0	138	795	3.8	16.2	9.8	974	5.9
Average	48.6	158	803	2.5	13.3	10.0	813	7.2

¹ BOD₅ to secondary system.

² From Tank 2.

³ Assumes 0.0272 lb O₂/cu ft air and 1.0 lb O₂/lb BOD_R.

Based on the actual retrofit cost of approximately \$380,000, a simple payback period of <5 years was expected. By early 1983, the entire system had been converted to sidewall mounted perforated membrane tube diffusers with swing arms for expedient diffuser removal and cleaning. The existing blowers and air piping system were acceptable. Approximately 1,000 diffusers were installed in each pass. The airflow rate/diffuser at average loads was estimated to be 0.9-1.4 L/s (2-3 scfm), with a peak rate of 2.4 L/s (5 scfm).

III. PERFORMANCE

Power consumption at the Renton facility has been carefully monitored. Efforts were made from 1979 to 1982 to reduce plant power consumption by operational changes. Total plant power use was decreased from 390 to 355 kW/1,000 m³ after installation of the fine pore aeration system. Assuming an average annual flow of 2,130 L/s (48.6 mgd) and a power cost of \$0.04/kWh results in an annual energy savings of about \$92,500/yr and a simple payback period of slightly more than 4 years.

Table 8-33 summarizes plant performance for 1987. The annual average SRT was about 2.5 days, and secondary clarifier effluent BOD₅ and TSS concentrations averaged 13.3 and 10.0 mg/L, respectively. Based on the reported air supplied per unit of BOD₅ removed in the secondary system, OTEs were estimated at 5.7-9.1 percent, with an average of 7.2 percent. These estimates assume an oxygen consumption of 1.0 kg O₂/kg BOD₅ removed.

8.3.4 Ripon Wastewater Treatment Plant

LOCATION: Ripon, Wisconsin

OPERATING AGENCY: City of Ripon

DESIGN FLOW: 87.7 L/s (2.0 mgd)

WASTEWATER: 80 percent Municipal, 15 percent Industrial (Food Processing)

ORIGINAL AERATION SYSTEM: Coarse Bubble Diffusers

FINE PORE AERATION SYSTEM: Sanitaire Ceramic Disc Diffusers

YEAR FINE PORE SYSTEM PLACED IN OPERATION: 1986

BASIS OF PERFORMANCE EVALUATION: Overall Process Performance

CLEANING METHOD: Preventive Maintenance; In-Situ HCl Gas Cleaning

I. HISTORICAL BACKGROUND

Prior to 1986, the City of Ripon, WI operated two 31-m (101-ft) diameter Walker Process Package Plants constructed in 1974-76. Ripon, population 7,200, treats municipal wastewater and industrial wastes from an appliance manufacturer and four food processing plants. The industrial waste represents 15 percent of the flow and 50 percent of the organic loading received by the plant.

In an effort to improve energy efficiency and replace aging equipment, the original coarse bubble diffuser system was replaced with fine pore ceramic disc diffusers capable of being cleaned with HCL gas. The installation was completed in 2 weeks and placed on-line January 1, 1986. It was estimated in 1985 that the aeration retrofit (including new coarse bubble units in the aerobic digester) would save \$30,700/yr; these savings would result from reduced blower operation.

Prior to the retrofit, two blowers were used 8 months of the year and 1-1/2 blowers were used 4 months of the year. With the blower inlet throttle open 100 percent, each blower consumed 140 amps or 105.6 kW (141.6 hp). At an average power cost of \$0.04/kWh, annual costs for power for both aeration and aerobic digestion were estimated to be \$64,000. The new diffusers were estimated to require one blower year round at 150 amps. Maintenance of the new diffusers was estimated at \$2,400/yr (two gas cleanings/yr). The project was estimated to cost \$60,000, and the estimated simple payback period was 2.1 years. Both ceramic disc and tube fine pore diffusers were compared for operating cost, maintenance, initial cost, and life expectancy, with discs being chosen.

The treatment facility contains grit removal, secondary aeration and denitrification, aerobic digestion, phosphorus removal using pickle liquor addition,

filtration, and chlorination. Effluent standards are 10 mg/L BOD₅, 10 mg/L TSS, 5 mg/L NH₃-N, and 1 mg/L P. In 1986, the plant received loadings of 83.2 L/s (1.9 mgd) flow, 1,199 kg (2,643 lb)/d BOD₅, 1,309 kg (2,885 lb)/d TSS, and 30 kg (66 lb)/d TP. Plant effluent concentrations in 1986 averaged 6 mg/L BOD₅, 7 mg/L TSS, and less than 1 mg/L NH₃-N. An F/M loading of 0.15 d⁻¹ and a MLSS level of 3,500-4,000 mg/L were reported as normal operating conditions.

II. FINE PORE AERATION SYSTEM DESIGN DESCRIPTION

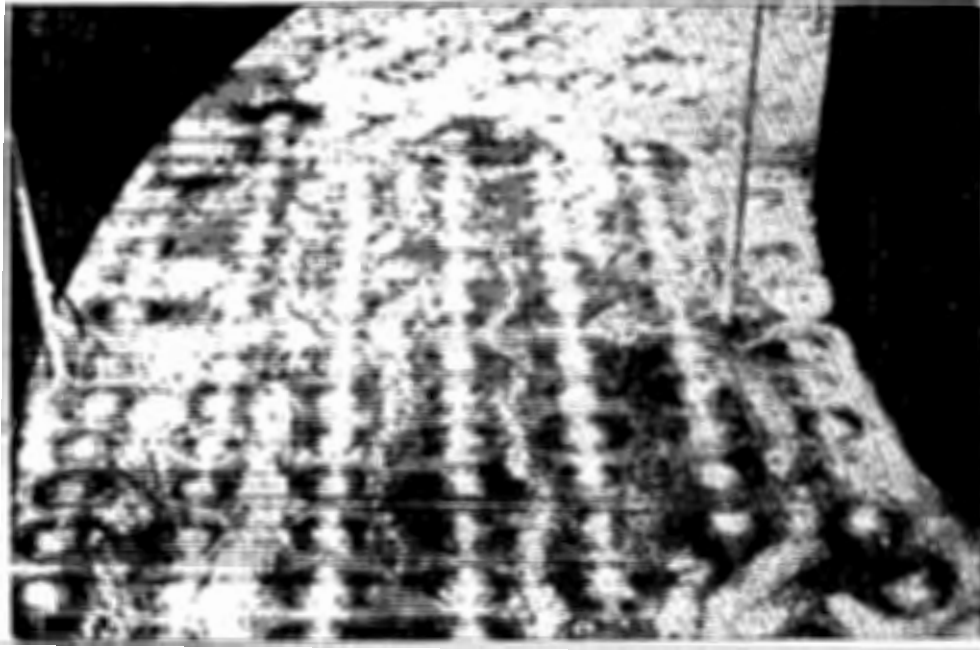
The new aeration system for each package plant consisted of 540 23-cm (9-in) diameter ceramic fine pore disc diffusers equally spaced in six grids. The new system for the aerobic digester consisted of stainless steel drop pipes and stainless steel coarse bubble diffusers. The digester diffusers were set 30 cm (12 in) above the tank floor, and the ceramic diffusers in the aeration tank were set 23 cm (9 in) above the tank floor. Equivalent headlosses in the two systems were achieved by placing an orifice in the line feeding air to the coarse bubble system. Figure 8-22 shows the disc pattern during a check for leaks in the air distribution system.

Design conditions for the aeration portion of the Ripon plant included the following: flow = 87.7 L/s (2.0 mgd), BOD₅ = 1,515 kg (3,340 lb)/d, NH₃-N = 76 kg (167 lb)/d, total oxygen requirements = 1 kg O₂/kg BOD₅ applied + 4.5 kg O₂/kg NH₃-N applied, and α = 0.55. This resulted in a design selection of 1,092 diffusers with an AD/AT of 0.08. The design airflow rate was 0.66 L/s (1.4 scfm)/diffuser.

III. SYSTEM PERFORMANCE

In the 17 months of operation reported, only one 112-kW (150-hp) centrifugal blower has been needed. Mixed liquor DO levels normally vary between 4 and 6

Figure 8-22. Checking for leaks and uniform air distribution - Ripon, WI.



mg/L, which are similar to the levels maintained prior to the retrofit. During the hottest period, mixed liquor DO dropped to below 2 mg/L and it was reported to be difficult to maintain aerobic conditions in the digester. Although treatment efficiency remained satisfactory, odors developed in the digester and steps were taken to supply auxiliary air to the digester to prevent odors in the future.

An analysis of plant performance for periods of 1 year prior to the retrofit and 1 year following the retrofit reveals an annual power savings of 853,800 kWh. This is equivalent to an annual savings of \$29,318. Although close to the projected annual savings of \$30,700, the cost of energy used in the estimate (\$0.04/kWh) was lower by about 10 percent. Ripon's energy bill has six components based on demand time and reserve arrangements. Energy costs averaged \$0.041/kWh for the period prior to the retrofit and \$0.044/kWh for the period following the retrofit. In the year prior to the retrofit, 2,630,400 kWh were used compared to 1,776,000 kWh in the year following the retrofit.

Gas cleaning will be employed for purely preventative reasons at a frequency of once per year or less. DWP measurements taken following the retrofit indicated no significant increases in the first 17 months.

IV. COST SAVINGS

Based on actual performance, allowing for one gas cleaning yearly (\$1,200), and using the actual equipment and installation costs (\$55,352), the simple payback period is approximately 2 years.

8.3.5 Saukville Wastewater Treatment Plant

LOCATION: Saukville, Wisconsin

OPERATING AGENCY: Village of Saukville

DESIGN FLOW: 21.9 L/s (0.5 mgd)

WASTEWATER: Municipal with Significant Butter Manufacturing Waste

ORIGINAL AERATION SYSTEM: Sanitaire Stainless Coarse Bubble Diffusers

FINE PORE AERATION SYSTEM: Sanitaire Ceramic Disc Diffusers

YEAR FINE PORE SYSTEM PLACED IN OPERATION: 1985

BASIS OF PERFORMANCE EVALUATION: Overall Process Performance and DWP Monitoring of Diffusers

CLEANING METHOD: In-Situ HCl Gas Cleaning

I. HISTORICAL BACKGROUND

The original Saukville treatment facility, constructed in 1982, consisted of comminution, grit removal, two 23.3-m (76.5-ft) diameter Sanitaire package plants with aeration, clarification, aerobic digestion, and disinfection. Alum is added to the aeration basins for phosphorus removal. The aeration compartment is 5.3 m (17.5 ft) wide with an SWD of 4.9 m (16 ft). Each package plant was designed for an organic loading of 380 kg (834 lb) BOD₅/d and can be operated in the contact stabilization or plug flow mode. Effluent standards are 30 mg/L for BOD₅ and TSS and 1 mg/L for P.

The original aeration system was composed of stainless steel coarse bubble diffusers. Each drop pipe was equipped with four wide-band diffusers causing a cross roll pattern around the circumference of the aeration tanks. Three 637-L/s (1,350-scfm), 56-kW (75-hp) centrifugal blowers were available, one for each plant with the third being a standby unit. One 19.7-m³ (5,200-gal) tank truck of butter waste averaging 40,000 mg/L BOD₅ was gradually pumped into the splitter box between the two plants each day, generally over a 12-hr period.

Beginning in 1984, the plant received an additional butter manufacturing waste load. While treating the butter waste, the plant was operated in a plug flow mode at an F/M loading of about 0.25 d⁻¹ and an MLSS concentration of 4,000 mg/L.

Projected energy savings were the principal reason for retrofitting one of the plants with fine bubble diffusers in 1985. Estimates of 50 percent reduction in energy due to the retrofit meant that 40 amps/plant could be saved. This was equivalent to 22,000 kWh/mo or about \$12,500/yr/plant. Energy costs were estimated

at \$0.049/kWh. Prior to the retrofit, each plant's blower cost about \$25,000/yr to operate.

II. FINE PORE AERATION SYSTEM DESIGN DESCRIPTION

In 1985, one of the two package plants was converted to fine pore aeration. The retrofitted plant contained 270 23-cm (9-in) diameter ceramic disc diffusers in a tapered grid pattern to provide a higher density of diffusers at the inlet end. Design flow to the retrofitted plant was 21.9 L/s (0.5 mgd), and design BOD₅ load was 380 kg (834 lb)/d, although the actual BOD₅ load proved to be about 535 kg (1,180 lb)/d. Design oxygen requirements were based on 1 kg O₂/kg BOD₅ and an α F of 0.5. AD/AT was 0.064, and the design airflow rate was 0.52 L/s (1.1 scfm)/diffuser, or 145 L/s (308 scfm).

A 340-L/s (720-scfm), 30-kW (40-hp) positive displacement blower was installed to provide air for the retrofitted aeration and aerobic digestion zones. Air piping was installed to either isolate the new smaller blower from the centrifugal air distribution system or interconnect the two systems so that one centrifugal and one positive displacement blower could supply air to both plants.

The retrofit was engineered, furnished, and installed in 5 months at a cost of \$43,990. In-situ HCl gas cleaning and DWP monitoring capability were provided. Cleaning costs were estimated at \$1,920/yr for three cleanings. The simple payback period was estimated at 4.2 years. Lease purchase financing was used at an interest rate of 10.49 percent for 5 years.

III. SYSTEM PERFORMANCE

By retrofitting only one plant, observations could be made about relative performance of the two systems.

Differences were noted in sludge volume index (SVI), mixed liquor DO, and diffuser fouling.

During the first 5 months operation, SVI increased slightly in the retrofitted plant. SVI then: 1) increased markedly, 2) decreased upon cleaning the fine pore diffusers with HCL gas, and 3) increased significantly within 2 months of cleaning. Subsequent gas cleanings reduced SVI only for relatively short periods following cleaning. The high SVIs were believed due, in part, to the lower DO levels in the new system.

In May 1986, 6 months following start-up of the retrofitted plant, DO could not be maintained at 1 mg/L during the 12 hours when the butter waste was being processed. To gain control, two centrifugal blowers were employed at that time. With the increased airflow and under maximum load conditions, the retrofitted plant maintained a DO of 1-2 mg/L, while the coarse bubble plant maintained a DO of 2-3 mg/L. Because the coarse bubble diffusers were placed 25-76 mm (1-3 in) higher than the fine pore diffusers, a separate bypass pipe was installed to dedicate the positive displacement blower to the fine pore system and allow the centrifugal blower to feed the coarse bubble aeration and aerobic digestion zones and the digester zone of the fine pore system. However, the redistribution of air did not completely remedy the DO problem.

Other changes made at the plant included: 1) increasing the feeding period of the butter waste from 12 to 24 hours, and 2) increasing airflow to the head end of the fine pore aeration tank by cracking open one of the coarse bubble droplegs. It was believed the increased turbulence at the head end of the fine pore system would improve α by breaking up fat-encapsulated bubbles thought to be the result of adding the butter waste. As a result of these and the changes mentioned previously, the fine pore aeration system SVI gradually stabilized.

DWP monitoring showed that the fine pore diffuser system was subject to rapid and heavy fouling. Cleaning, initially estimated as necessary 3-4 times a year, was required four times in the first 7 months of operation. Cleaning was considered necessary when: 1) DWP was high, 2) coarse bubbling was noticeable, and 3) DO could no longer be maintained at minimum levels. The fine pore diffusers in the contact and reaeration zones were cleaned five and six times, respectively, during 1986. Data on DWP were available before and after four of these cleanings and are presented in Table 8-34.

Table 8-34. DWP Monitoring Results - Saukville, WI

Basin	Date	Cleaning Time, minutes	DWP, in	
			Before	After
Contact Zone	1/30/86	38	35	5
	2/27/86	99	13	6
	7/29/86	60	40	15
	12/15/86	30	29	9
Reaeration Zone	1/30/86	26	46	4.5
	2/27/86	78	12	6.5
	7/29/86	105	40	7.5
	12/15/86	44	9.5	6.5

IV. COST SAVINGS

A comparison of power use for the 12 months prior to and following the retrofit shows a reduction of 14,225 kWh/mo and an annual savings of \$7,300. The fact that actual savings (\$7,300) were less than predicted savings (\$12,500) was attributed to: 1) increased electric rates following the retrofit, 2) initial poor air distribution that required the running of two 56-kW (75-hp) engines instead of one 30-kW (40-hp) and one 56-kW (75-hp) unit, a situation that was remedied during the first 12 months of retrofit operation, 3) increased BOD loadings (26.7 percent additional) from the butter waste, 4) a shift in the on-peak/off-peak utilization of energy by the plant, and 5) the implementation of a plant-wide energy savings program resulting from an energy audit by the local utility authority early in the 12-month period prior to the retrofit.

8.4 Sources of Information

The following reports and publications were used to develop the case histories presented in this chapter:

Aeration Technologies, Inc. Off-Gas Analysis Results and Fine Pore Retrofit Information for Glastonbury, CT Facility, Aeration Tank No. 2. Study conducted under Cooperative Agreement CR812167, Risk Reduction Engineering Laboratory, U.S. Environmental Protection Agency, Cincinnati, OH (to be published).

Aeration Technologies, Inc. Off-Gas Analysis Results and Fine Pore Retrofit Case History for Hartford, CT MDC Facility. Study conducted under Cooperative Agreement CR812167, Risk Reduction Engineering Laboratory, U.S. Environmental Protection Agency, Cincinnati, OH (to be published).

Boyle, W.C. *Oxygen Transfer Studies at the Madison Metropolitan Sewerage District Facilities*. Study conducted under Cooperative Agreement CR812167, Risk Reduction Engineering Laboratory, U.S. Environmental Protection Agency, Cincinnati, OH (to be published).

Donohue & Assoc., Inc. *Fine Pore Diffuser System Evaluation for the Green Bay Metropolitan Sewerage District*. Study conducted under Cooperative Agreement CR812167, Risk Reduction Engineering Laboratory, U.S. Environmental Protection Agency, Cincinnati, OH (to be published).

Ernest, L.A. *Case History Report on Milwaukee Ceramic Plate Aeration Facilities*. Study conducted under Cooperative Agreement CR812167, Risk Reduction Engineering Laboratory, U.S. Environmental Protection Agency, Cincinnati, OH (to be published).

Huibregtse, G.L., T.C. Rooney and D.C. Rasmussen. *Factors Effecting Fine Bubble Diffused Aeration*. JWPCF 55(8):1,057-1,064, 1983.

Leary, R.D., L.A. Ernest and W.J. Katz. *Effect of Oxygen-Transfer Capabilities on Wastewater Treatment Plant Performance*. JWPCF 40(7):1,298-1,310, 1968.

Leary, R.D., L.A. Ernest and W.J. Katz. *Full Scale Oxygen Transfer Studies of Seven Diffuser Systems*. JWPCF 41(3):459-473, 1969.

McNamee, Porter & Seeley Engineers/Architects. *Fine Pore Diffuser Case History for Frankenmuth, MI*. Study conducted under Cooperative Agreement CR812167, Risk Reduction Engineering Laboratory, U.S. Environmental Protection Agency, Cincinnati, OH (to be published).

Mueller, J.A. *Case History of Fine Pore Diffuser Retrofit at Ridgewood, NJ*. Study conducted under Cooperative Agreement CR812167, Risk Reduction Engineering Laboratory, U.S. Environmental Protection Agency, Cincinnati, OH (to be published).

Stenstrom, M.K. *Fine Pore Diffuser Fouling: The Los Angeles Studies*. Study conducted under Cooperative Agreement CR812167, Risk Reduction Engineering Laboratory, U.S. Environmental Protection Agency, Cincinnati, OH (to be published).

Vik, T.E. *Documented Energy Savings from Aeration System Retrofits*. Presented at the 60th Annual Meeting of the Central States Water Pollution Control Association, May 1987.

Warriner, R. *Oxygen Transfer Efficiency Surveys at the Jones Island East Plant, August 1985-June 1988*. Study conducted under Cooperative Agreement CR812167, Risk Reduction Engineering Laboratory, U.S. Environmental Protection Agency, Cincinnati, OH (to be published).

In addition, the following individuals provided information on specific facilities described in this chapter and their assistance is greatly appreciated:

Richard Finger, Seattle Metro Wastewater Treatment Facility, Renton, WA.

Bruce Neerhof, Village of Cleveland, WI.

S.R. Reusser, Madison Metropolitan Sewerage District, Madison, WI.

Thomas E. Vik, McMahon Associates, Inc., Menasha, WI.

Appendix A
Abstracts of Contractor Studies Completed Under
EPA/ASCE Fine Pore Aeration Project

Contractor

Study Description

Michigan Technological
University
(C. Robert Baillod)

Report: Author of Quality Assurance Program Plan (QUAPP); also involved in training project contractors and coordinating QA procedures for use during project (6-9 months).

Report/Interplant Fouling Study Director: Planning, development of protocol, liaison with contractors, review of data, and final report relative to interplant control study (four-lungers) (24-30 months).

Southern Methodist
University
(Edwin L. Barnhart)

Report/(1) North Texas MWD; (2) Trinity River Authority: (1) Off-gas testing in the field and evaluation of five ceramic dome diffuser cleaning methods in laboratory. Laboratory testing was performed using clean water with and without detergent addition (18-24 months); (2) Off-gas testing of coarse bubble diffusers and fine pore ceramic disc diffusers (12-18 months).

Liaison/consultation with EPA to provide economic information to develop life-cycle cost analysis.

Madison MSD
(William C. Boyle)

Report/Laboratory Study: Characterization of various types of diffusers from 20-30 plants (18-24 months).

Report/Madison: Full-scale evaluation of ceramic dome and disc diffuser performance under various process conditions (18-24 months).

University of Calgary
(J. William Costerton)

Report: Investigations of fine pore diffuser biofouling. Evaluation of relationship between biofilm growth characteristics and diffuser operating performance at seven contractor sites (12-15 months).

Lawrence A. Ernest

Report/Case Histories: Operating, diffuser cleaning, and performance experiences (over extended periods) of ceramic plate diffusers at Milwaukee Jones Island East and West Plants and South Shore Plant.

Milwaukee MSD
(Read Warriner)

Report/Jones Island East and West Plants and South Shore Plant. In-situ performance evaluation of old/new ceramic plate diffusers using off-gas testing (12-27 months).

AERTEC, Inc.
porous (R. Gary Gilbert)

Report/Glastonbury: In-situ performance evaluation of rigid plastic tube diffusers using off-gas testing (24-30 months).

	Report/Hartford: In-situ performance evaluation of ceramic dome diffusers using off-gas testing (24 months).
D. H. Houck and Assoc. (Daniel H. Houck)	Report/European Survey: Review/report of plant operating experiences (principally in Scandinavia) using rigid porous plastic tube and disc diffusers (12 months).
McNamee, Porter and Seeley (S. Joh Kang)	Report/Frankenmuth: Case history of plant retrofit from coarse bubble diffusers to fine pore ceramic disc diffusers. Limited in-situ off-gas testing to evaluate the effectiveness of gas cleaning on ceramic disc diffuser performance (12-15 months).
Green Bay MSD disc (James J. Marx)	Report/Green Bay: In-situ performance evaluation of ceramic and perforated membrane tube diffuser systems using off-gas testing; included evaluation of cleaning methods (15-18 months).
Manhattan College (James A. Mueller)	Report/Ridgewood: In-situ performance evaluation and case history of design, O&M, performance, and cleaning of ceramic dome diffusers used for retrofit (18-24 months).
University of Iowa (Wayne L. Paulson)	Report/Data Acquisition: Collection of data and coordination with authors relative to clean water performance of fine pore diffusers for interim summary report and design manual.
Ewing Engineering Co. (Lloyd Ewing and David T. Redmon)	Report/Monroe: In-situ testing of ceramic disc diffusers of various permeabilities using off-gas testing (24-30 months).
	Report: Summary of in-situ performance data on fine pore diffusers for inclusion in interim summary report and design manual.
	Report: Fine pore diffuser fouling/cleaning data compilation for interim summary report and final manual.
Univ. of California at Los Angeles (Michael K. Stenstrom)	Report/Whittier Narrows: In-situ comparative off-gas testing of ceramic dome and disc diffusers. Also, evaluation of impact of gas cleaning on system performance (30-36 months).
	Report/Valencia: In-situ performance evaluation of rigid porous plastic disc diffusers using off-gas testing (12-18 months).
	Report/Terminal Island: In-situ performance evaluation of perforated membrane tube diffusers, nonrigid porous plastic tube diffusers, and coarse bubble diffusers using off-gas testing (12 months).

Appendix B

Selected Diffuser Characterization and Cleaning Methods

B.1 Diffuser Characterization

B.1.1 Foulant Analysis

An important aspect of the characterization of fouled fine pore diffusers is the analysis of the nature of the diffuser foulant(s). Foulant analysis provides insights into the mechanism of fouling and can aid in the selection of diffuser cleaning techniques.

Foulant analysis consists of scraping the foulant off the surface of the diffuser medium and analyzing for the weight of dry solids per unit area, volatile and nonvolatile content, acid solubility, and elemental composition of the foulant by energy dispersive spectroscopy or inductively coupled plasma. The procedure for foulant analysis is:

1. Specify a certain area on the surface of a diffuser.
2. Scrape the materials off the surface, divide the materials, and put them into two vials.
3. Place each vial's contents in a tared evaporation dish.
4. Measure the wet weight.
5. Dry at 105°C (221°F) for >1 hr (to constant weight).
6. Cool, desiccate, and weigh for total solids.
7. Put the dishes into furnace, firing them at 550°C (1,022°F) for 20 minutes.
8. Cool, desiccate, and weigh the dishes for fixed solids.
9. Take one dish content for metallic ion analysis. Place in a vial.
10. Add approximately 10 mL of 14-percent HCl to the other dish and stir gently until the formation of gas bubbles ceases.
11. Centrifuge the solution at 20,000 rpm for 15 minutes. Decant the upper portion, add deionized water into the tube, centrifuge again, and decant. Repeat once more for a total of three decants.
12. Repeat the steps 5, 6, and 9 using the centrifuged solids. Compare the results with those of the non-acidified foulant.

B.1.2 Bubble Release Vacuum (BRV)

The BRV test provides a means of determining the effective pore diameter at any point on the surface of a ceramic diffuser element relative to other point(s) on its surface. This test procedure is useful in assessing

the uniformity of pores on the surface of clean as well as fouled diffusers.

BRV, as indicated by the name, is a measure of the vacuum in inches of water gauge required to emit bubbles from a localized point on the surface of a thoroughly wetted porous diffuser element. This is accomplished by applying a vacuum to a small area on the working surface of a wetted diffuser and measuring the differential pressure when bubbles are released from the diffuser at the specified flux rate at the point in question.

A large number of points are sampled to obtain a distribution of bubble release pressures. Typical test points for a ceramic dome diffuser are shown in Figure B-1.

The test apparatus consists of a probe, manometer, vacuum source, and rotameter as shown in Figure B-2. The manometer is filled with either water or mercury depending on foulant buildup. Water is acceptable for clean and lightly fouled diffusers. A switch to mercury is required when BRV pressures surpass the capacity of the water-filled manometer.

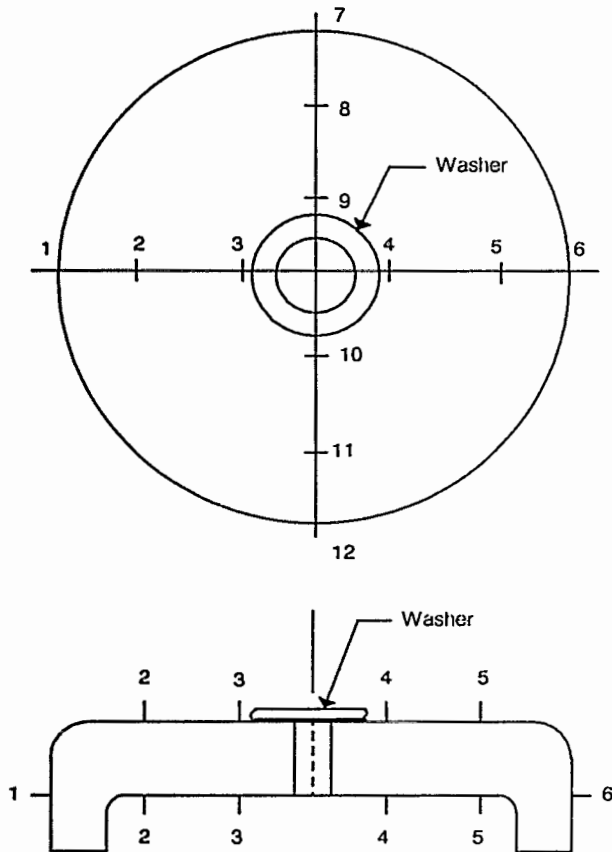
The probe used in this procedure has interchangeable tips for testing vertical and horizontal surfaces. Test points 1, 6, 7, and 12 require the vertical surface tip while other points require the horizontal surface tip.

The minimum airflow rate for ceramic dome and disc diffusers is normally 0.24 L/s (0.5 scfm)/diffuser. BRV flow rates are kept below this value so diffuser foulant will not be pulled off the stone. This translates to a flow rate of 0.9 mL/s (0.0019 scfm) for the 1.13-cm² (0.175-sq in) probe. A method for calibrating flow rate is illustrated in Figure B-3. With an in-line rotameter, flow calibration is done just once to check the rotameter calibration curve.

The recommended practice for BRV testing is listed below:

1. If the diffuser is new, immerse it in tap water until wetted. Remove the diffuser from water just prior to the test, and let it drain by gravity for not more than 30 minutes. Keep the diffuser in a horizontal plain while draining. Do not soak fouled diffusers.

Figure B-1. BRV test points for ceramic dome.



2. Set BRV flow rate.
3. Apply the probe to the BRV test location. The water surface will rise in the probe while bubbles are released at the diffuser surface. If the water level becomes too high, discard excess water by a quick lateral and upward movement of the probe. If the water level is too low, apply additional water onto the diffuser adjacent to the probe. This is especially useful when testing fouled diffusers.
4. Equilibrium has been reached when the rise of water in the probe equals the rate of rise in the manometer (inches w.g.). If the time to reach equilibrium is excessive, it may be reduced by operating the bypass valve momentarily. The flux rate increases dramatically when the bypass valve is open. The large suction force will pull foulant off a dirty diffuser. Because the loss of foulant may affect test results, the bypass valve should be used judiciously.
5. At equilibrium, record the manometer reading and height of water in the probe. BRV equals the

manometer reading (corrected to inches water gauge if using mercury) less the height of water in the probe.

6. Repeat steps 3 through 5 for all test locations.

B.1.3 Dynamic Wet Pressure (DWP)

DWP is the pressure differential across the diffusion element alone when operating in a submerged condition and is expressed in inches of water gauge.

In the DWP test, most of the pressure differential is due to the force or pressure required to form bubbles against the force of surface tension and only a small fraction of the total pressure gradient is required to overcome frictional resistance.

In-situ DWP is measured in the aeration basin as indicated in Figure B-4. These measurements are normally made two or three times per week. Comparison of the in-situ DWP to the clean water DWP, as measured in the laboratory, will indicate the degree of fouling. In making this comparison, correction should be made for possible differences in airflow.

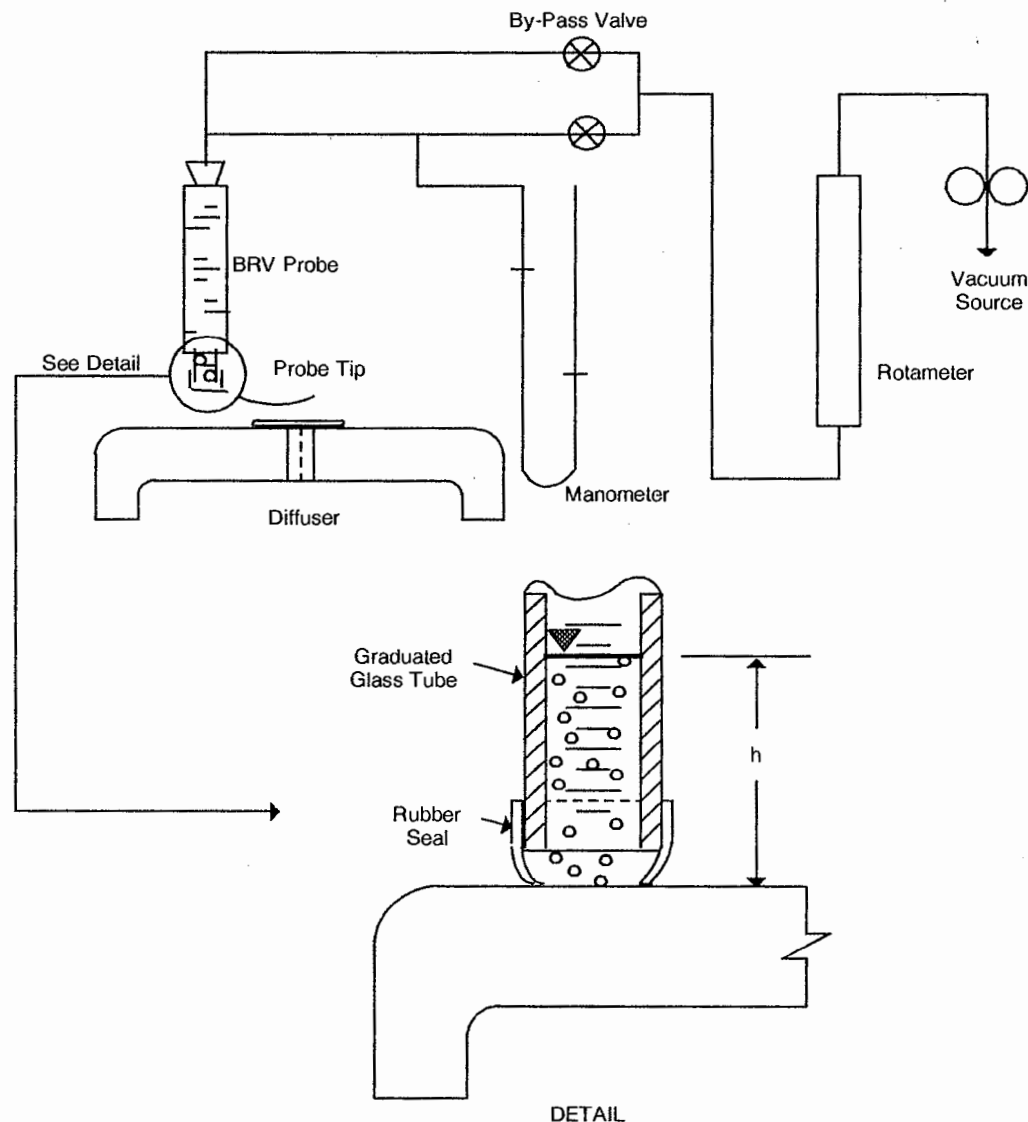
The DWP and BRV tests both measure bubble release pressure. DWP measures it for the whole diffuser, while BRV provides a distribution of pressure. For a new stone, average DWP:BRV is close to 1.0. As a stone fouls, the average BRV for the 12 points tested on the top surface becomes greater than DWP and average DWP:BRV becomes less than 1.0.

The equipment required for measuring DWP in the laboratory includes an air source, rotameter, in-line mercury manometer, thermometer, diffuser plenum with standard orifice, water-filled manometer, and aquarium. The test setup looks very much like Figure B-4 without manometer A and the bubbler. The water-filled manometer (manometer B in Figure B-4) is tapped into the plenum at one end and open to atmosphere at the other end. The water in the aquarium is high enough to cover the diffuser.

Laboratory Measurement of DWP

1. The aquarium should be filled with sufficient tap water to cover the diffuser by several inches. If this is done the day before testing, the water will warm to room temperature.
2. New diffusers should be wetted the same as for the BRV test. Do not soak fouled diffusers.
3. Place the diffuser securely in the plenum.
4. Hold the plenum over the aquarium and turn the air on. This allows water entrained in the diffuser to drain into the tank and not on the floor. If the diffuser is fouled, do not exceed the operating airflow rate.

Figure B-2. BRV apparatus.

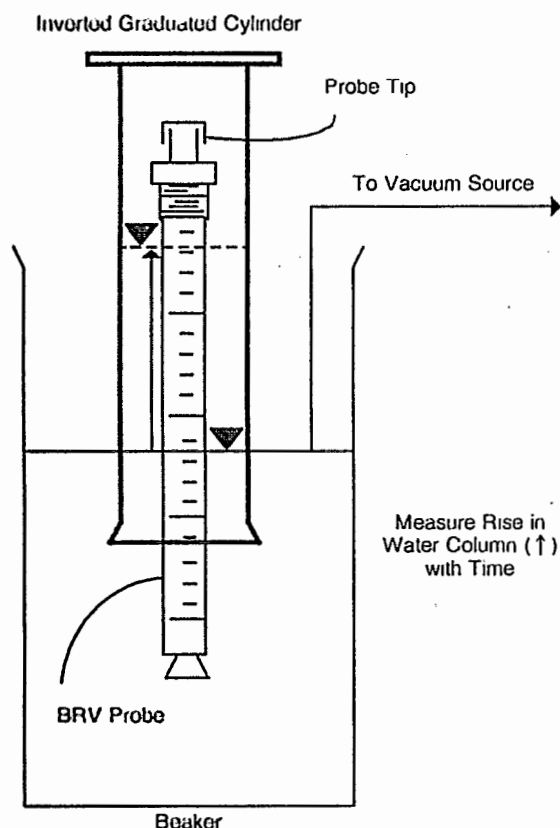


5. Place the plenum in the aquarium. Adjust airflow to the minimum suggested rate (0.24 L/s [0.5 scfm]/diffuser). Visually inspect the flow profile. If the diffuser is not mounted correctly, coarse bubbling will be evident. If this is the case, take the plenum out of the aquarium and reseal the diffuser.
6. Adjust airflow to the maximum allowable rate for the test being performed, and let the test system equilibrate for several minutes. This allows time for excess water to be driven out of stone. When testing fouled diffusers, do not exceed the operating airflow rate.
7. Perform a DWP profile. This is done by checking DWP at three or more air airflows. Typical airflows are 10, 20, 30, and 40 L/s/m² (2, 4, 6, and 8 scfm/sq ft). A bucket catch may be performed to check airflow rate. In line pressure and temperature readings are taken to translate airflow rates to standard conditions.
8. After the last DWP reading, turn airflow to almost zero. Measure the static head over the diffuser. The static head is subtracted from DWP manometer readings to give true DWP readings.
9. Correct airflow data to standard conditions. Regress DWP (y) on airflow (x). The correlation coefficient should be close to 1.0.

B.1.4 Airflow Profile Test

The airflow profile test uses quantitative techniques to evaluate the uniformity of air release across the surface of ceramic diffusers, while operating, rather

Figure B-3. BRV flow calibration.



than appraising uniformity by visual means. This is accomplished by testing the diffuser element at an airflow rate that is approximately equal to 10 L/s/m^2 (2 scfm/sq ft), or at the recommended design rate with 5-20 cm (2-8 in) of water over it.

The rate of air release from selected areas is measured by displacing water from an inverted container and recording the rate of displacement of water with a stopwatch. By combining the container area and the rate of air discharge, a flux rate, expressed as L/s/m^2 (scfm/sq ft) or other convenient units, can be calculated. By comparing the flux rates of the selected area readings with one another, a quantitative measure or graphical representation of the profile can be generated.

Flux rate is measured by displacement by the rising gas stream of water from a vessel inverted over the area of diffuser to be characterized. The vessel must first be filled with water, covered, and deftly inverted so that the mouth of the vessel is just submerged. Captured gas volume is measured over a time of a few seconds taking care to record the captured volume at atmospheric pressure, i.e., equal water surface levels inside and outside the inverted vessel.

The flow rate is determined by dividing the captured volume by the time interval. The flux rate is defined as flow rate divided by the area of the capture vessel. A flow profile for a typical diffuser requires flow measurements on each of three concentric circles as shown in Figure B-5. Flow rates for the annular areas are determined by difference.

These measurements are made by using three vessels, each with a different surface capture area. The large, 13.5-L (3.6-gal) vessel captures the entire flow. The 2-L (0.53-gal) vessel captures all but the periphery flow, whereas the 1,000-mL (0.26-gal) graduated cylinder captures the flow around the washer. By subtraction, flux rates are obtained for the outer, middle and inner areas of the diffuser. These flux rates are then compared to the average flux rate of the diffuser. Example flux calculations are shown in Table B-1.

The combination of DWP, BRV, and flow profile tests applied to new diffusers and at various stages in their operating history provides a useful diagnostic tool in evaluating the rate, nature, and effect of fouling, either organic or inorganic, on fine pore diffusion elements. It is also effective, if judiciously applied, in appraising the effectiveness of various cleaning procedures.

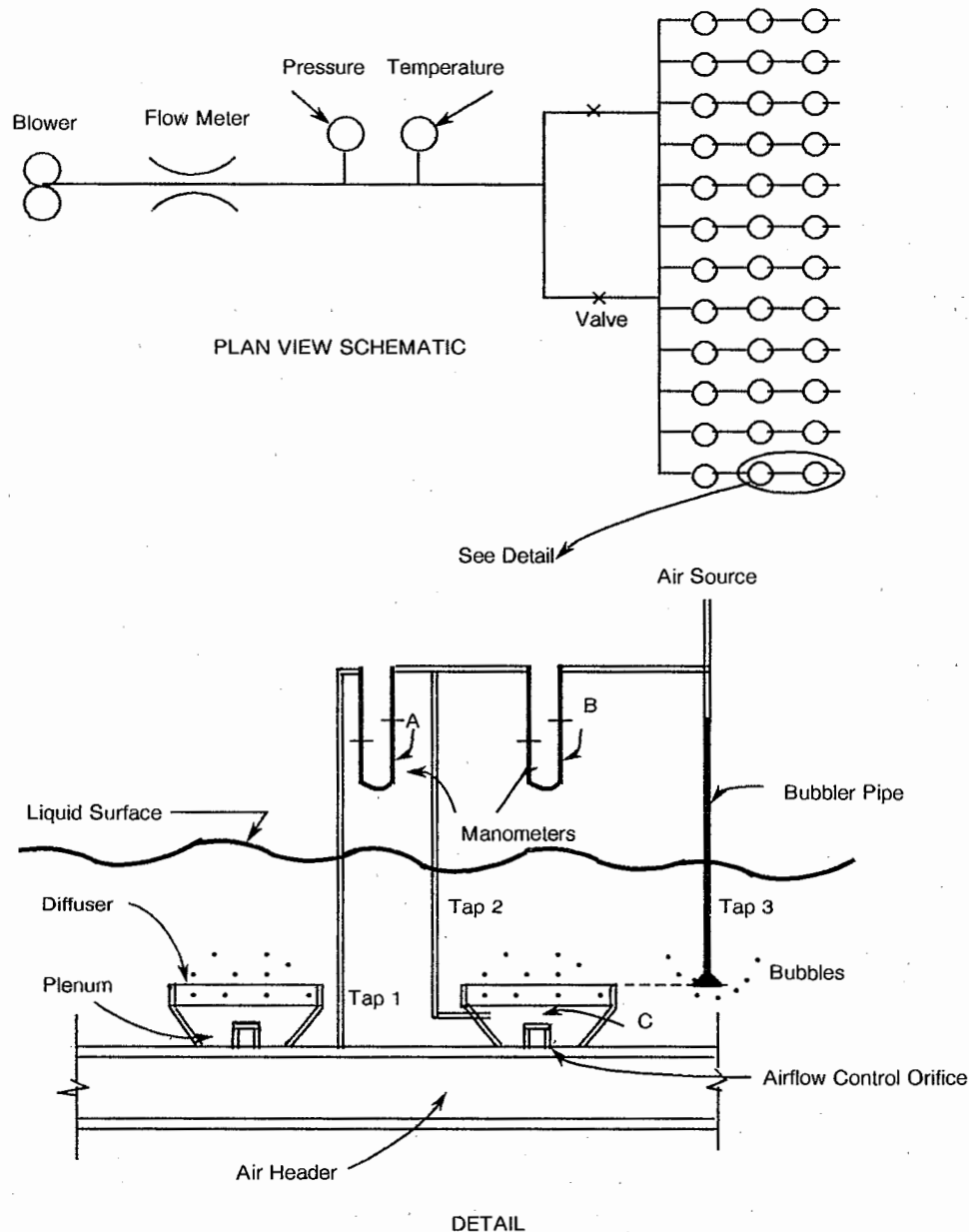
B.1.5 Specific Permeability

The manufacturers of ceramic diffusers have used and are familiar with the permeability test. It has served as a quality control procedure to assure that units sent to a job site are similar with respect to their average frictional resistance to flow, when dry, to within some specified limits. This was especially important in many older plants where several ceramic plates were installed in a single plenum without individual airflow balancing to achieve improved uniformity of airflow among the units when in operation.

The test generally consists of sealing the ceramic unit in a test fixture substantially as it is sealed in an actual aeration basin and then passing sufficient air through the dry element to produce a pressure differential of 5.1 cm (2.0 in) w.g. The permeability is reported as the airflow rate required to produce this differential. In English units, the airflow rate is in scfm (standard cubic feet per minute) where 1 standard cu ft of air is considered to occupy 1 cu ft of volume at 1 atm, 70°F, and 36 percent relative humidity. Historically, the test was carried out on ceramic plates 30.5 cm x 30.5 cm x 2.5 cm (12 in x 12 in x 1 in) thick.

As an example, if a permeability test is conducted on such a ceramic plate, it might take 11.8 L/s (25 scfm) to produce a 50.8-mm (2-in) w.g. differential pressure. In this case, the permeability rating would be 25. A plate of identical material, but half as thick, would be expected to have a permeability of 50 instead of 25, since the flow paths through the ceramic would be

Figure B-4. Measurement of air line and diffuser pressure..



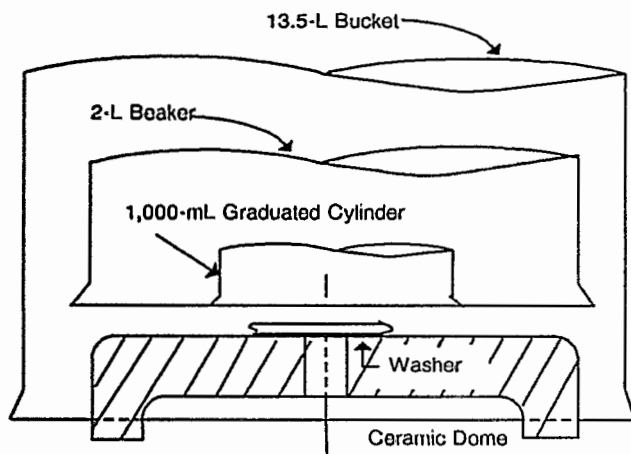
about half as long and offer correspondingly less frictional resistance. Had the element been 2.5 cm (1 in) thick with an area of 465 cm² (72 sq in) instead of 930 cm² (144 sq in), the permeability would be approximately 12.5, since there would have been only about half the area of the first case.

Even though these elements were made in identical ways with identical materials, the permeabilities of the three vary from 12.5 to 50. Thus, using permeability to compare ceramic elements of different shapes, thicknesses, and materials of construction is not

meaningful and has constituted a source of confusion in the engineering community.

In an effort to employ permeability test results as a measure of resistance characteristics of the material, the term specific permeability has been adopted. Specific permeability is the equivalent amount of air at standard conditions to produce 5.1 cm (2 in) differential pressure across the dry element if the element were 930 cm² (1 sq ft) in area (30.5 cm x 30.5 cm [12 in x 12 in]) and 2.5 cm (1 in) thick.

Figure B-5. Airflow profile apparatus.



An approximate expression to convert the permeability of any porous structure to specific permeability is as follows:

$$SP = P_0(A_0/t_0) \quad (B-1)$$

where,

- SP = specific permeability, scfm
- P_0 = permeability of the element itself, scfm
- A_0 = area of element when made to hypothetically conform to a flat surface, sq ft
- t_0 = mean weighted thickness of the element, in

B.2 Diffuser Performance

B.2.1 Steady-State Clean Water OTE Test

This test is usually conducted in a covered fiberglass column 60-90 cm (2-3 ft) in diameter with a sidewater depth approximately equal to that of the aeration basin of interest. The test is conducted in a manner similar to the nonsteady-state clean water test method, except that dissolved sodium sulfite is continuously pumped into the column through a distribution system to maintain a constant DO concentration. Once steady-state conditions are achieved, gas-phase oxygen transfer efficiency (OTE) is determined using the off-gas analysis method. The DO concentration is monitored at two depths corresponding to approximately 1/4 and 3/4 of the sidewater depth.

The method is normally used to compare clean water OTEs of two fine pore diffusers of interest (e.g., a new diffuser vs. a fouled one). Each has an independent air source. One of the diffusers is operated at a specified airflow rate, generally 0.5-1.4 L/s (1-3 scfm), and the other is idled at a very low airflow rate (<5 percent of the other), the object being to keep a slight positive pressure differential across the ceramic element. The airflow rates applied to the

diffusers are measured with variable-area rotameters. The test apparatus is illustrated in Figure B-6.

Once steady-state conditions are achieved, the OTE is measured by off-gas analysis. After appropriate data are obtained on one diffuser, air supply is rapidly switched, causing the other diffuser to operate at the specified airflow rate and the air to the first diffuser to be reduced to maintain only a slight positive pressure, as above.

Repeating the cycle several times in this manner, the relative oxygen transfer performance of the diffusers can be obtained. A comparison of clean water SOTEs can then be made for the two diffusers of interest.

This test procedure can also be used to:

- measure the effect of diffuser uniformity on OTE,
- determine the rate and consequence of fouling on fine pore diffusers, and
- evaluate fine pore diffuser cleaning methods.

B.3 Field Diffuser Cleaning Methods

B.3.1 Low-Pressure Hosing

This method is frequently used in conjunction with other methods and consists of hosing at a distance of 0.6-7.3 m (2-24 ft) using a low-pressure nozzle at 207-484 kPa (30-70 psi). The hosing period should continue until the readily removable foulant has been washed away. This time is generally on the order of 10 seconds but can vary from 5 seconds to 1 minute, depending on the resistance of the foulant, pressure, and distance. The air should be on during the hosing operation with each diffuser operating at roughly 0.5 L/s (1 scfm).

B.3.2 High-Pressure Hosing

This method consists of hosing at a distance of about 60 cm (2 ft) using a high-pressure nozzle at 552-689 kPa (80-100 psi). The hosing period should continue until the readily removable foulant has been washed away. This time is generally on the order of 15 seconds but can vary from about 5 seconds to 1 minute depending on the resistance of the foulant and pressure. Each diffuser should be operating at an airflow rate of approximately 0.5 L/s (1 scfm) during the hosing operation.

B.3.3 Milwaukee Method (Acid Application plus Hosing)

This method has been used at the Milwaukee, WI wastewater treatment plants for many years. A high-pressure water jet is applied to the diffuser surface followed by acid spraying and rehosing. The rationale is to first hose off the easily removable foulant so that the applied acid can solubilize the inorganic precipitate inside the pores of the diffuser. A second hosing is then performed to remove the solubilized foulant and residual acid. The materials needed for this method

Table B-1. Example Diffuser Flux Calculations

Apparent Flux: $AF = q/AD$
 Local Flux: $LF = q_i/A_i$
 Effective Flux: $NF = \{\sum[LF(q_i)]\}/\{\sum(q_i)\}$
 Effective Flux Ratio: $EFR = NF/\{\sum(LF)/i\}$

where,

q = airflow rate per diffuser, scfm
 AD = total projected media surface area of installed diffusers, sq ft
 q_i = local airflow rate, scfm
 A_i = local area sampled, sq ft
 i = no. of observations

Example:

Ceramic Disc Diffuser:

Diameter = 8.7 in

Effective Area (AD) = 0.413 sq ft/diffuser

Airflow Rate (q) = 0.65 scfm/diffuser

$AF = 0.65 \text{ scfm}/0.413 \text{ sq ft} = 1.57 \text{ scfm/sq ft}$

Local Flux:

Test 10 equal-area locations.

Use 100-mL graduate cylinder with $A_i = 0.0066 \text{ sq ft}$ for sampling.

Location	q_i , scfm	LF, scfm/sq ft	LF (q_i)
1	0.0129	1.96	0.0253
2	0.0154	2.33	0.0359
3	0.0147	2.22	0.0326
4	0.0081	1.22	0.0099
5	0.0025	0.38	0.0010
6	0.0138	2.09	0.0288
7	0.0115	1.74	0.0200
8	0.0060	0.91	0.0055
9	0.0098	1.49	0.0146
10	0.0105	1.59	0.0167
Sum	0.1052	15.93	0.1903
Average Flux: $MF = 15.93/10 = 1.59 \text{ scfm/sq ft}$			
Effective Flux: $NF = 0.190/0.105 = 1.81 \text{ scfm/sq ft}$			
Effective Flux Ratio: $EFR = 1.81/(15.93/10) = 1.14$			

are: high- or low-pressure water hosing equipment, acid spray applicator (Hudson Acid Sprayer or equivalent), and 50 percent by volume of 18 Baume inhibited muriatic acid. This is equivalent to a 14-percent HCl solution.

The procedure to be followed is:

1. Clean the diffuser by high- or low-pressure hosing with the air on at approximately 0.5 L/s (1 cfm)/diffuser.
2. Apply approximately 50 mL (1.7 oz) of 14-percent HCl to the surface of the diffuser using the spray applicator. No air should be applied to the diffuser during the acid application period.

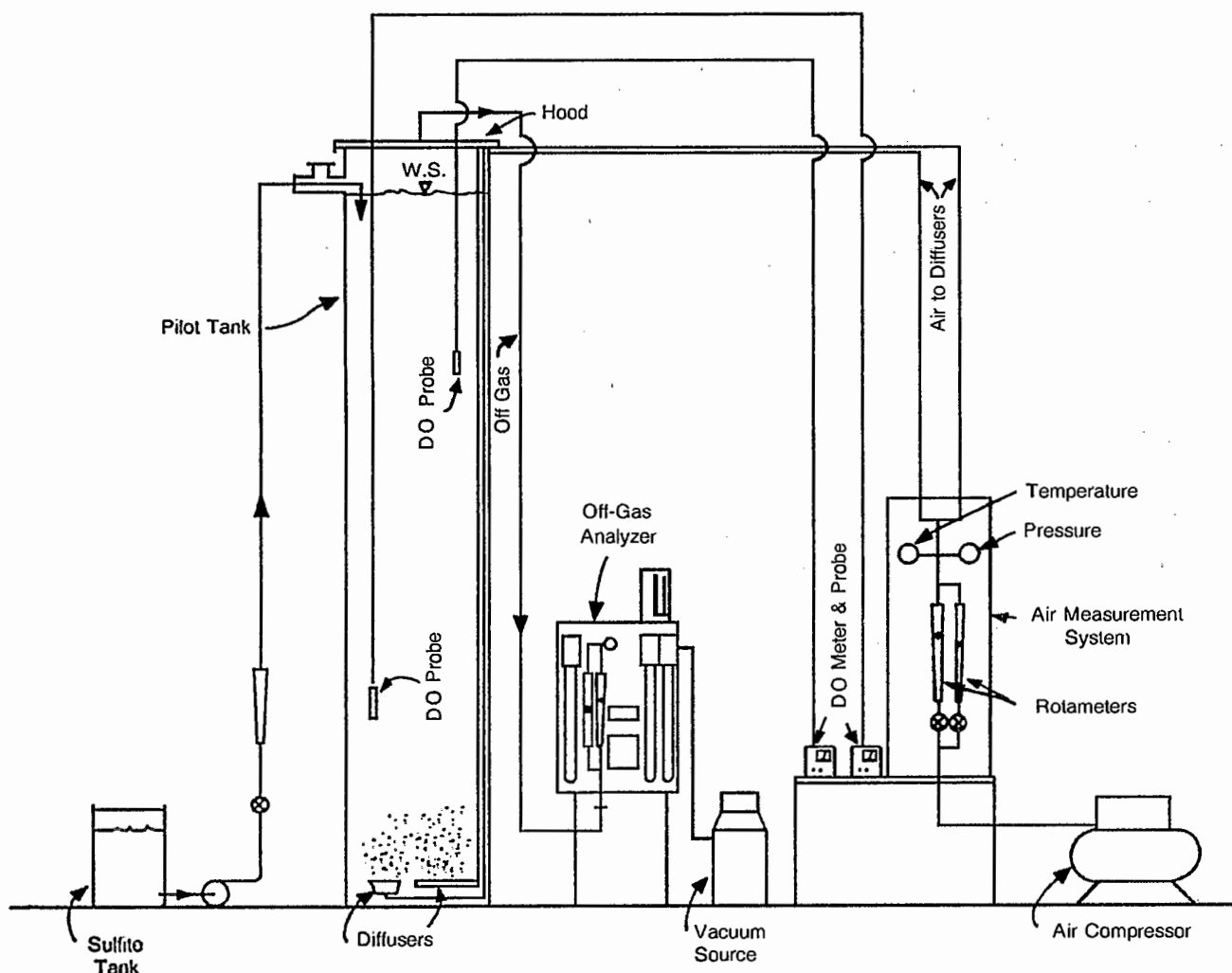
3. Let the acid remain on the diffuser for 30 minutes. Turn the air on for 5 minutes.

4. Hose the diffuser again to remove all the residual acid.

B.3.4 Steam Cleaning

This method has been used at the Madison, WI treatment plant for several years. The principle of the method is to use the scrubbing and heating power of a steam jet to remove the material attached to the diffuser's surface. The high temperature of the steam may lessen the ability of the foulant to attach to the diffuser surface. Equipment required for this test includes a steam generator and nozzle. The procedure to be followed is:

Figure B-6. Steady-state clean water OTE test apparatus



1. Turn on the steam generator, and let it run for several minutes to reach constant temperature (200C [392F]).
2. Apply the steam jet to the diffuser surface from a distance of approximately 60 cm (2 ft) at a minimum pressure of 1,135 kPa (150 psi) until all the foulant has been visibly removed. The diffuser air should be on during this operation.
3. Let the diffuser cool to ambient temperature.

B.3.5 Firing (Kilning)

This method is widely used in England. The diffuser stones are removed, placed in a kiln, fired to remove foulant material, and gradually cooled. A typical British furnace is capable of firing 650 domes per 24-hr cycle. The procedure to be followed is:

1. Load the diffuser stones into the furnace, and heat the furnace to 950°C (1,742°F) over a period of 10 hours.
2. Hold the temperature at 950-1,000°C (1,742-1,832°F) for 4 hours.
3. Cool down over a period of 10 hours.

B.3.6 Gas Cleaning

Gas cleaning refers to a method whereby a fine pore diffusion system is cleaned by injecting a small percentage of HCl gas into the air supply line leading to the diffusers. The HCl gas solubilizes some foulant deposits and aids in cleaning the diffusers. The gas cleaning system evaluated in the EPA/ASCE Fine Pore Aeration Project is a proprietary system marketed by Sanitaire - Water Pollution Control Corp. under U.S. Patent No. 4,382,867. The test

installations were operated under license from Sanitaire, and the gas cleaning operations were carried out following the recommendations of Sanitaire personnel.

Gas cleaning test results to date have indicated that a minimum gas concentration is required for effective periodic cleaning. Above the minimum concentration, the amount of gas required to clean deposits is substantially constant. However, the time required to clean is less at higher concentrations. Mole ratios of HCl gas in air between 0.0000818 and 0.0309 have been used successfully in gas cleaning. Based on experience, it appears that about 113 g (0.25 lb) HCl gas is required per diffuser.

In operation, the need to apply gas cleaning treatment is judged by monitoring the DWP drop across each of four diffusers installed on a removable header. The onset of fouling is indicated by an increase in the DWP loss across the diffuser at a constant airflow rate. The allowable pressure increase before initiating cleaning should be specified on a case-by-case basis. If the DWP is allowed to rise to a level where the desired combined system pressure during cleaning exceeds the blower capability, one available option is partial dewatering of the basin being cleaned.

During the cleaning cycle, it is important to achieve uniform gas distribution both between diffusers and throughout the area of the individual diffuser elements. Higher airflow rates promote more uniform gas distribution throughout the media pores. Because of this, it is recommended that cleaning be done at a higher airflow rate than used during normal operation, e.g. about 30-40 L/s/m² (6-8 scfm/sq ft) diffuser surface, or 1.2-1.4 L/s (2.5-3 scfm)/diffuser. The increased airflow rate also increases the pressure differential across the diffuser element, thus distributing cleaning gas to partially clogged pores.

The increased airflow rate needs to be applied only to the grid being cleaned. This can be accomplished by operating an extra blower for a short period of time, throttling air to the rest of the basins, or dropping the water level in the basin being cleaned. If the water level is reduced a few feet, the normal system pressure would be adequate to provide the increased airflow rate to the basin being cleaned. This may be the most economical alternative as no additional power is required.

Appendix C

Selected Physical and Chemical Tables and Graphs

Table C-1. DO Saturation Values

Solubility of Oxygen (mg/L) in Water Exposed to Water-Saturated Air at Atmospheric Pressure = 101.3 kPa, (14.7 psia)

Temp., °C	Chlorinity ^a			Temp., °C	Chlorinity ^a		
	0	5.0	10.0		0	5.0	10.0
0.0	14.62	13.73	12.89	21.0	8.91	8.46	8.02
1.0	14.22	13.36	12.55	22.0	8.74	8.30	7.87
2.0	13.83	13.00	12.22	23.0	8.58	8.14	7.73
3.0	13.46	12.66	11.91	24.0	8.42	7.99	7.59
4.0	13.11	12.34	11.61	25.0	8.26	7.85	7.46
5.0	12.77	12.02	11.32	26.0	8.11	7.71	7.33
6.0	12.45	11.73	11.05	27.0	7.97	7.58	7.20
7.0	12.14	11.44	10.78	28.0	7.83	7.44	7.08
8.0	11.84	11.17	10.53	29.0	7.69	7.32	6.96
9.0	11.56	10.91	10.29	30.0	7.56	7.19	6.85
10.0	11.29	10.66	10.06	31.0	7.43	7.07	6.73
11.0	11.03	10.42	9.84	32.0	7.31	6.96	6.62
12.0	10.78	10.18	9.62	33.0	7.18	6.84	6.52
13.0	10.54	9.96	9.41	34.0	7.07	6.73	6.42
14.0	10.31	9.75	9.22	35.0	6.95	6.62	6.31
15.0	10.08	9.54	9.03	36.0	6.84	6.52	6.22
16.0	9.87	9.34	8.84	37.0	6.73	6.42	6.12
17.0	9.67	9.15	8.67	38.0	6.62	6.32	6.03
18.0	9.47	8.97	8.50	39.0	6.52	6.22	5.93
19.0	9.28	8.79	8.33	40.0	6.41	6.12	5.84
20.0	9.09	8.62	8.17				

^a Chlorinity = Salinity/1.80655 (See p. 415: *Standard Methods for the Examination of Water and Wastewater*, 16th Edition, for definition of salinity.)

Adapted from pp. 413-415: *Standard Methods for the Examination of Water and Wastewater*, 16th Edition. American Public Health Association, Washington, DC, 1985.

Table C-2. Hydraulic Headlosses for Appurtenances

Appurtenance - Alphabetically	Headloss as Multiple of ($v^2/2g$)	Appurtenance - Alphabetically	Headloss as Multiple of ($v^2/2g$)
1. Butterfly Valves		9. Gate Valves	
Fully open	0.3	Open	0.19
Angle closed, $\theta = 10^\circ$	0.46	1/4 closed	1.15
$\theta = 20^\circ$	1.38	1/2 closed	5.6
$\theta = 30^\circ$	3.6	3/4 closed	24.0
$\theta = 40^\circ$	10	also see Sluice Gates	
$\theta = 50^\circ$	31	10. Increasers	
$\theta = 60^\circ$	94	$0.25 (v_1^2/2g - v_2^2/2g)$	
2. Check (Reflux) Valves		where v_1 = velocity at small end	
Ball Type (fully open)	2.5-3.5	11. Miter Bends	
Horizontal Lift Type	8-12	Deflection angle, θ	
Swing Check	0.6-2.3	5°	0.016-0.024
Swing Check (fully open)	2.5	10°	0.034-0.044
3. Contraction - Sudden		15°	0.042-0.062
4:1 (in terms of velocities of small end)	0.42	22.5°	0.066-0.154
2:1	0.33	30°	0.130-0.165
4:3	0.19	45°	0.236-0.320
also see Reducers		60°	0.471-0.684
4. Diaphragm Valve	2.3	90°	1.129-1.265
Fully open	2.6	12. Obstructions in Pipes (in terms of pipe velocities) Pipe to Obstruction Area Ratio	
3/4 open	4.3	1.1	0.21
1/2 open	21.0	1.4	1.15
1/4 open		1.6	2.40
5. Elbow - 90°	0.21-0.30	2.0	5.55
Flanged - Regular	0.18-0.20	3.0	15.0
Flanged - Long Radius		4.0	27.3
Intersection of two cylinders (welded pipe - not rounded)	1.25-1.8	5.0	42.0
Screwed - Short Radius	0.9	6.0	57.0
Screwed - Medium Radius	0.75	7.0	72.5
Screwed - Long Radius	0.60	10.0	121.0
6. Elbow - 45°		13. Orifice Meters (in terms of velocities of pipe) Orifice to Pipe Diameter Ratio	
Flanged - Regular	0.20-0.30	0.25 (1:4)	4.8
Flanged - Long Radius	0.18-0.20	0.33 (1:3)	2.5
Screwed - Regular	0.30-0.42	0.50 (1:2)	1.0
7. Enlargement - Sudden		0.67 (2:3)	0.4
1:4 (in terms of velocities of small end)	0.92	0.75 (3:4)	0.24
1:2	0.56	14. Outlet Losses	
3:4	0.19	Bell mouthed outlet	$0.1(v_1^2/2g - v_2^2/2g)$
also see Increasers		Sharp cornered outlet	$(v_1^2/2g - v_2^2/2g)$
8. Entrance Losses		Pipe into still water or air (free discharge)	1.0
Bell mouthed	0.04		
Pipe flush with tank	0.5		
Pipe projecting into tank (Borda Entrance)	0.83-1.0		
Slightly rounded	0.23		
Strainer and foot valve	2.50		

Table C-2. (continued)

Appurtenance - Alphabetically	Headloss as Multiple of $(v^2/2g)$	Appurtenance - Alphabetically	Headloss as Multiple of $(v^2/2g)$
15. <i>Plug Globe or Stop Valve</i>		19. <i>Tees</i>	
Fully open	4.0	Standard - bifurcating	1.5-1.8
3/4 open	4.6	Standard - 90° turn	1.80
1/2 open	6.4	Standard - run of tee	0.60
1/4 open	780.0	Reducing - run of tee	
		2:1 (based on velocities of smaller end)	0.90
16. <i>Reducers</i>		4:1 (based on velocities of smaller end)	0.75
Ordinary (in terms of velocities of small end)	0.25	20. <i>Venturi Meters</i>	
Bell mouthed	0.10	The headloss occurs mostly in and downstream of throat, but losses shown are given in terms of velocities at inlet ends to assist in design.	
Standard	0.04	Long Tube Type - Throat-to-inlet diameter ratio	
Bushing or coupling	0.05-2.0	0.33 (1:3)	1.0-1.2
17. <i>Return Bend (2 nos. 90°)</i>		0.50 (1:2)	0.44-0.52
Flanged - Regular	0.38	0.67 (2:3)	0.25-0.30
Flanged - Long Radius	0.25	0.75 (3:4)	0.20-0.23
Screwed	2.2	Short Tube Type - Throat-to-inlet diameter ratio	
18. <i>Sluice Gates</i>		0.33 (1:3)	2.43
Contraction in conduit	0.5	0.50 (1:2)	0.72
Same as conduit width without top submergence	0.2	0.67 (2:3)	0.32
Submerged port in 12-in wall	0.8	0.75 (3:4)	0.24

Source, pp. 702-704: Amirtharajah, A. Design of Granular-Media Filter Units. In: Water Treatment Plant Design for the Practicing Engineer, Edited by R.L. Sanks, Ann Arbor Science, Ann Arbor, MI, 1978.,

Table C-3. Typical Air Velocities in Air Delivery Systems

Pipe Diameter (in)	Velocity (fpm)
1-3	1,200-1,800
4-10	1,800-3,000
12-24	2,700-4,000
30-60	3,800-6,500

Source, p. 287: Stephenson, R. L. and H. E. Nixon. Centrifugal Compressor Engineering. Hoffman Air and Filtration Division, New York, NY, 1973.

Table C-4. Properties of Standard Atmosphere

Altitude, ft	Temp., °F	Pressure, psia	Density, slugs/cu ft	Kinematic Viscosity x 10 ⁴ , sq ft/sec	Velocity of Sound, fps
0	59	2,116.2	0.00238	1.56	1,117
1,000	55.44	2,040.9	0.00231	1.60	1,113
2,000	51.87	1,967.7	0.00224	1.64	1,109
3,000	48.31	1,896.7	0.00218	1.68	1,105
4,000	44.74	1,827.7	0.00211	1.72	1,104
5,000	41.18	1,760.8	0.00205	1.77	1,098
10,000	23.36	1,455.4	0.00176	2.00	1,078
15,000	5.54	1,194.3	0.00150	2.28	1,058

Source, p. 36: Daily, J.W. and D.R.F. Harleman. *Fluid Dynamics*. Addison-Wesley, Reading, MA, 1966.

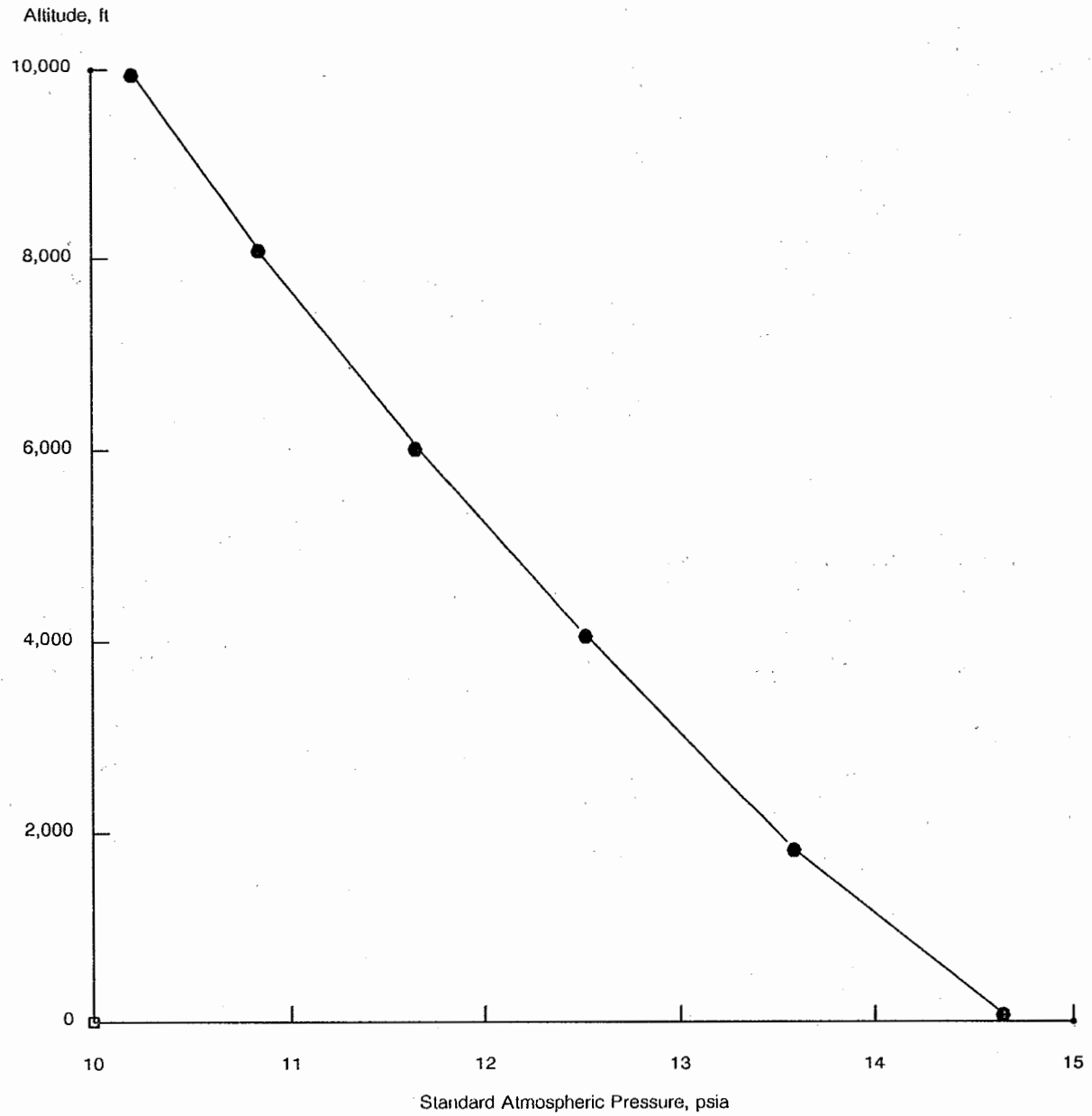
Table C-5. Physical Properties of Water

Temp., °F	Specific weight (γ_w), lb/cu ft	Density (ρ), slug/cu ft*	Modulus of elasticity ($E/10^3$), lb/sq in	Dynamic viscosity ($\mu \times 10^5$), lb-s/sq ft	Kinematic viscosity ($\nu \times 10^5$), sq ft/s	Surface tension (σ), lb/ft	Vapor pressure (P_v), lb/sq in
32	62.42	1.940	287	3.746	1.931	0.00518	0.09
40	62.43	1.940	296	3.229	1.664	0.00614	0.12
50	62.41	1.940	305	2.735	1.410	0.00509	0.18
60	62.37	1.938	313	2.359	1.217	0.00504	0.26
70	62.30	1.936	319	2.050	1.059	0.00498	0.36
80	62.22	1.934	324	1.799	0.930	0.00492	0.51
90	62.11	1.931	328	1.595	0.826	0.00486	0.70
100	62.00	1.927	331	1.424	0.739	0.00480	0.95
110	61.86	1.923	332	1.284	0.667	0.00473	1.27
120	61.71	1.918	332	1.168	0.609	0.00467	1.69
130	61.55	1.913	331	1.069	0.558	0.00460	2.22
140	61.38	1.908	330	0.981	0.514	0.00454	2.89
150	61.20	1.902	328	0.905	0.476	0.00447	3.72
160	61.00	1.896	326	0.838	0.442	0.00441	4.74
170	60.80	1.890	322	0.780	0.413	0.00434	5.99
180	60.58	1.883	318	0.726	0.385	0.00427	7.51
190	60.36	1.876	313	0.678	0.362	0.00420	9.34
200	60.12	1.868	308	0.637	0.341	0.00413	11.52
212	59.83	1.860	300	0.593	0.319	0.00404	14.70

Source, p. 876: Mottcalf & Eddy, Inc., *Wastewater Engineering: Treatment/Disposal/Reuse*, 2nd Edition. McGraw-Hill Book Co., New York, NY, 1979.

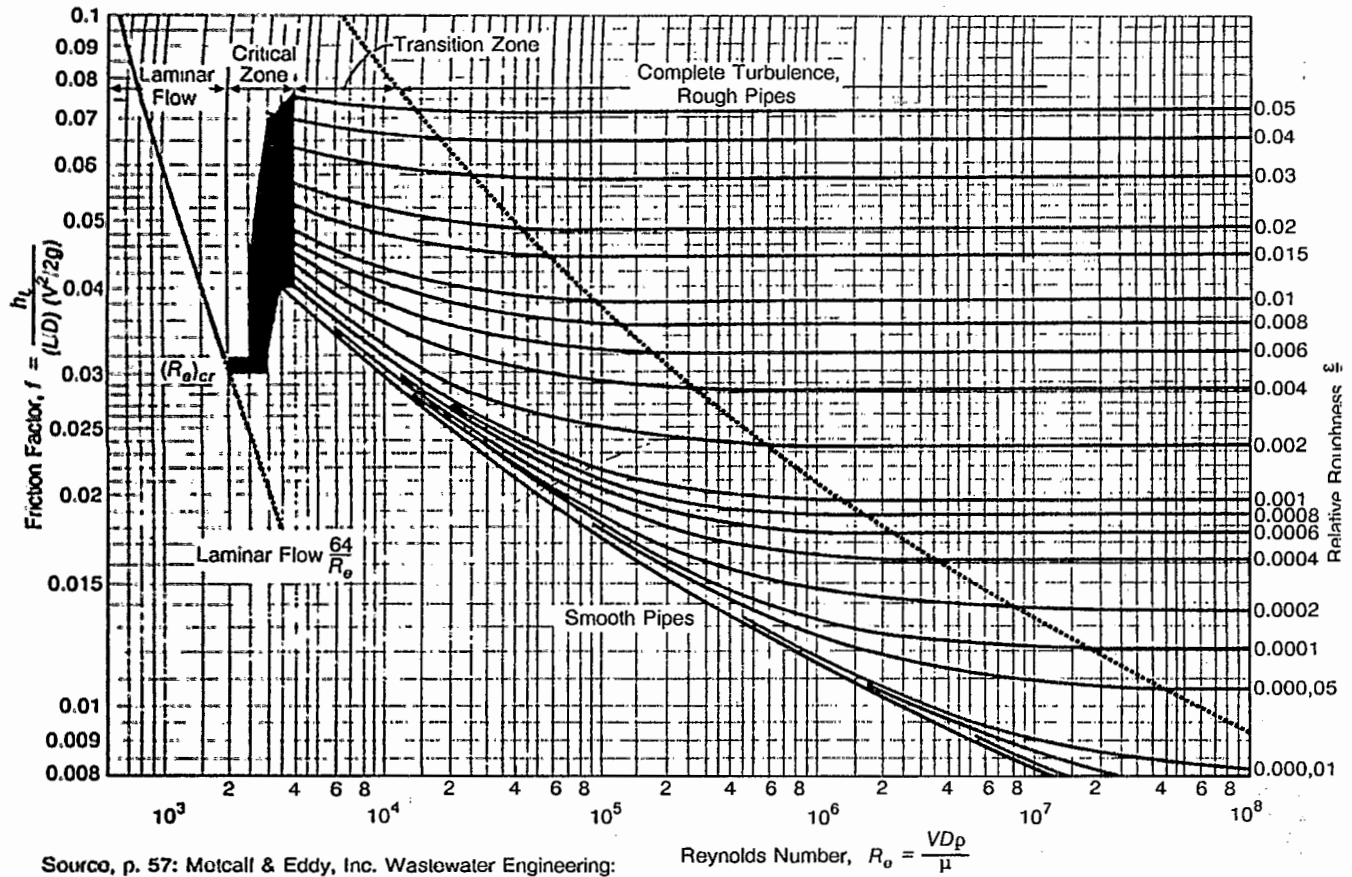
*1 slug mass = 32.17 lb weight

Figure C-1. Standard atmospheric pressure for altitudes of sea level to 10,000 ft



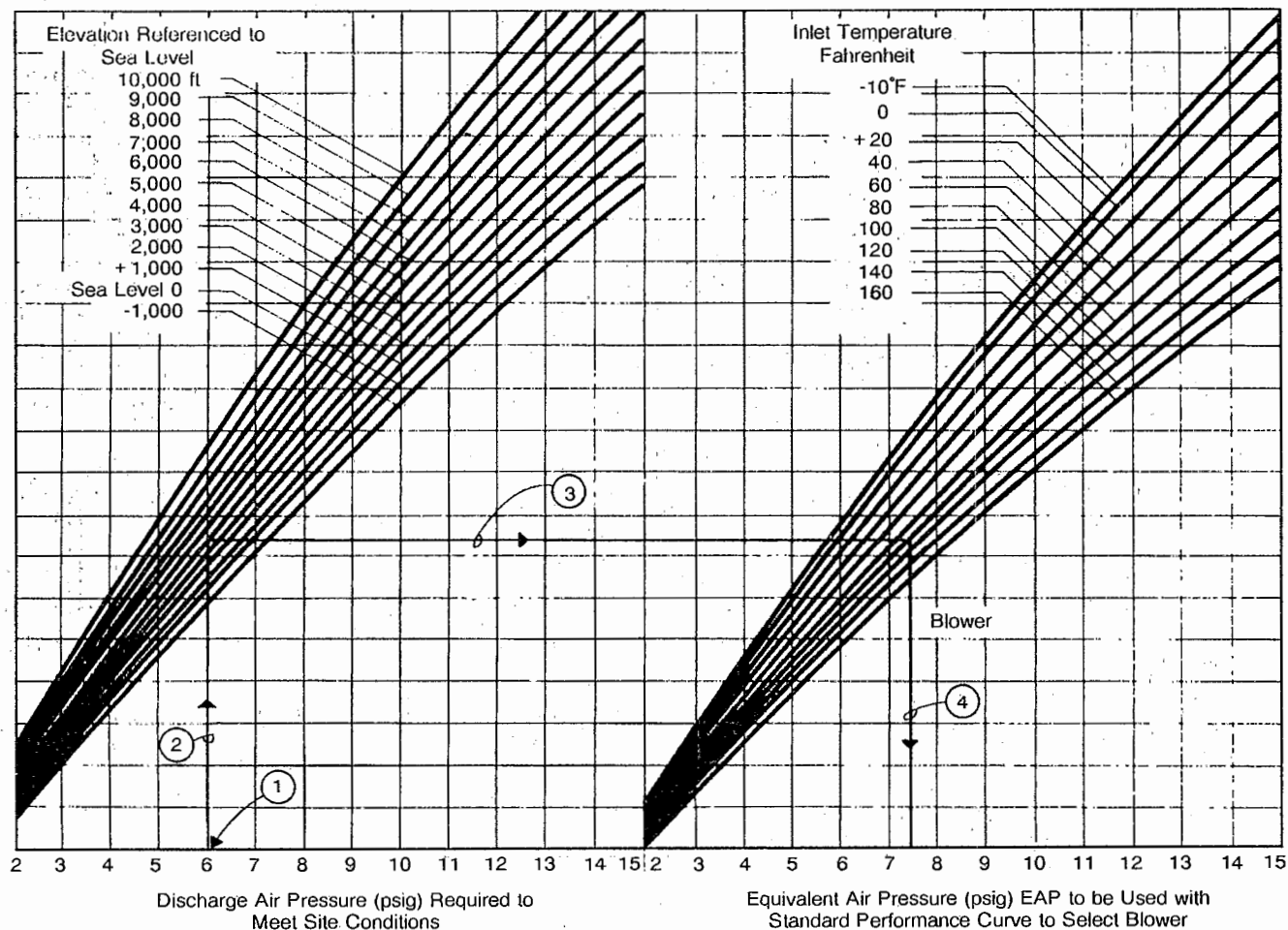
Source, p. 36: Daily, J.W. and D.R.F. Harleman. Fluid Dynamics. Addison-Wesley, Reading, MA, 1966.

Figure C-2. Moody diagram for friction factor in pipes.



Source, p. 57: Motcalf & Eddy, Inc. Wastewater Engineering: Collection/Treatment/Disposal, 1st Edition. McGraw-Hill Book Co., New York, NY, 1972.

Figure C-3. Equivalent air pressure (EAP) curves for use in blower selection.



- 1) Enter left-hand side of chart X-Axis with required discharge pressure at site conditions.
- 2) Move up to line corresponding to elevation at site.
- 3) Move right to line corresponding to inlet air temperature (note that both minimum and maximum air temperature conditions should be considered).
- 4) Move down to the equivalent air pressure (EAP) to be used in selecting the blower.

Source, p. 18: Stephenson, R.L. and H.E. Nixon, Centrifugal Compressor Engineering. Hoffman Air and Filtration Division, New York, NY, 1973.

Appendix D

Economic Analysis Spreadsheet

Instructions for constructing the spreadsheet are:

1. Begin with a new 1-2-3 worksheet and enter the formulas listed in Table D-1.
2. Execute the command scripts listed in Table D-2.
3. Save the worksheet under a name of your choice and exit 1-2-3.

Whenever the worksheet is loaded into 1-2-3, a Main Menu with four choices is presented to the user. The menu choices are:

Data	enters/edits aeration system data
Calculate	calculates aeration system costs
Graph	graphs results of cost calculation
Quit	returns to 1-2-3's READY mode

The Data option presents a second menu from which a category of aeration system data is chosen for data entry/editing. The options on this menu are:

Name	names the plant or data set being analyzed
Oxygen	input table of monthly oxygen demands and ratios of OTR _s to SOTRs for up to three aeration zones
Diffusers	input form for diffuser characteristics in each aeration zone
Blowers	input form for blower data
Costs	input form for unit cost factors, interest rate, analysis period, and diffuser cleaning frequency

Data is entered or changed in each table or form using the normal 1-2-3 procedures. After a form or table is completed, the user can return to the Main Menu by pressing the ALT-M key combination or to the Data Menu by pressing ALT-D.

The Calculate option of the Main Menu computes the total present worth costs of the aeration system based on the current set of design data. On completion, a table of capital, energy, maintenance, cleaning, and total present worth costs is displayed and the Main Menu reappears.

The Graph option is used to display plots of the results of the cost computation. Three different types of graphs can be drawn (providing that the computer is able to display graphics):

Airflows	monthly total airflow and flow to each aeration zone
Operating Costs	monthly energy and total (energy + cleaning) costs
Total Costs	bar chart of present worth cost by category

The last option on the Main Menu, Quit, returns the user to the native 1-2-3 environment. At this point, the worksheet can be saved under a new name for future use by using the 1-2-3 File Save command. To restart the economic analysis worksheet again, one only has to press ALT-M.

Table D-1 Cell Entries For Economic Analysis Spreadsheet

B2: ' ECONOMIC ANALYSIS OF DIFFUSED AERATION

A5: \=

B5: \=

C5: \=

D5: \=

E5: \=

F5: \=

G5: \=

B7: 'Operating Period, Months

B8: 'PRESENT WORTH COSTS, \$1,000:

B9: ' Capital

D9: \

E9: \

B10: ' Energy

D10: \

E10: \

B11: ' Cleaning

D11: \

E11: \

B12: ' Maintenance

D12: \

E12: \

B13: ' Total

D13: \

E13: \

D30: 'OXYGEN REQUIREMENTS

A31: \-

B31: \-

C31: \-

D31: \-

E31: \-

F31: \-

G31: \-

H31: \-

B32: ' Oxygen Demand, lb/d

F32: ' OTR(field)/SOTR

A33: "Month

B33: "ZONE 1

C33: "ZONE 2

D33: "ZONE 3

F33: "ZONE 1

G33: "ZONE 2

H33: "ZONE 3

A34: \-

B34: \-

C34: \-

D34: \- E34: \-

F34: \-

G34: \-

H34: \-

A35: "JAN

A36: "FEB

A37: "MAR

A38: "APR

A39: "MAY

A40: "JUN

A41: "JUL

A42: "AUG

A43: "SEP

A44: "OCT
 A45: "NOV
 A46: "DEC
 A47: \-
 B47: \-
 C47: \-
 D47: \-
 E47: \-
 F47: \-
 G47: \-
 H47: \-
 C48: 'Press <Alt-M> to return to Main Menu
 C49: 'Press <Alt-D> to return to Data Menu
 C50: ' DIFFUSER CHARACTERISTICS
 A51: \-
 B51: \-
 C51: \-
 D51: \-
 E51: \-
 F51: \-
 G51: \-
 D52: '
 E52: "ZONE 1
 F52: "ZONE 2
 G52: "ZONE 3
 E53: "-----
 F53: "-----
 G53: "-----
 A54: 'Minimum Airflow, cfm/diffuser
 A55: 'Maximum Airflow, cfm/diffuser
 A56: 'SOTE at Minimum Airflow, percent
 A57: 'SOTE at Maximum Airflow, percent
 A58: 'OTE loss rate, percent/mo
 A59: 'Maximum percent OTE Loss
 A60: 'Minimum (Clean) DWP, in
 A61: 'Maximum (Fouled) DWP, in
 A62: 'Orifice P-drop at 1 scfm, in
 A63: 'Mixing Requirement, scfm
 A64: 'Number of Diffusers
 A65: \- B65: \-
 C65: \-
 D65: \-
 E65: \-
 F65: \-
 G65: \-
 C66: 'Press <Alt-M> to return to Main Menu
 C67: 'Press <Alt-D> to return to Data Menu
 C70: 'ECONOMIC FACTORS
 A71: \-
 B71: \-
 C71: \-
 D71: \-
 E71: \-
 A72: "Factor
 E72: "Value
 A73: \-
 B73: \-
 C73: \-
 D73: \-
 E73: \-
 A74: 'Discount Rate, percent

A75: 'Diffuser Installation Cost, \$/unit
 A76: 'Other Capital Costs, \$
 A77: 'Electricity Rate, \$/kWh
 A78: 'Diffuser Cleaning Cost, \$/unit
 A79: 'Cleaning Interval, months
 A80: 'Routine Maintenance, \$/yr
 A81: 'Analysis Period, months
 A82: 'Start-up Month (Jan = 1, etc.)
 A83: \-
 B83: \-
 C83: \-
 D83: \-
 E83: \-
 A84: ' Press <Alt-M> to return to Main Menu
 A85: ' Press <Alt-D> to return to Data Menu
 C90: 'BLOWER DATA
 A91: \-
 B91: \-
 C91: \-
 D91: \-
 E91: \-
 A92: ' Item
 E92: "Value
 A93: \-
 B93: \-
 C93: \-
 D93: \-
 E93: \-
 A94: 'Barometric Pressure, psia
 A95: 'Pressure Head w/o Diffusers, psig
 A96: 'Overall Blower Efficiency, percent A97: \-
 B97: \-
 C97: \-
 D97: \-
 E97: \-
 A98: ' Press <Alt-M> to return to Main Menu
 A99: ' Press <Alt-D> to return to Data Menu
 P1: 'CALCULATIONS
 S1: "ZONE 1
 T1: "ZONE 2
 U1: "ZONE 3
 P2: \=
 Q2: \=
 R2: \=
 S2: \=
 T2: \=
 U2: \=
 P3: 'Operating period
 P4: 'Month of year
 S4: @IF(@MOD(S3 + E82-1,12) > 0,@MOD(S3 + E82-1,12),12)
 P5: 'Months Uncleaned
 S5: @IF(E79 < = 0,S3,@IF(@MOD(S3,E79) > 0,@MOD(S3,E79),E79))
 P6: 'Oxygen Demand
 S6: @INDEX(B35..D46,0,S4-1)/24.87/@IF(E64 > 0,E64,1)
 T6: @INDEX(B35..D46,1,S4-1)/24.87/@IF(F64 > 0,F64,1)
 U6: @INDEX(B35..D46,2,S4-1)/24.87/@IF(G64 > 0,G64,1)SOTE
 P7: 'OTEf/SOTE
 S7: @INDEX(F35..H46,0,S4-1)
 T7: @INDEX(F35..H46,1,S4-1)
 U7: @INDEX(F35..H46,2,S4-1)
 P8: 'Fouling Factor

S8: $1 - \text{@MIN}((S5 - 0.5) * E58, E59) / 100$
 T8: $1 - \text{@MIN}((S5 - 0.5) * F58, F59) / 100$
 U8: $1 - \text{@MIN}((S5 - 0.5) * G58, G59) / 100$
 P9: 'Kote
 S9: $\text{@IF}(E55 > E54, (E57 - E56) / 100 / (E55 - E54), 0)$
 T9: $\text{@IF}(F55 > F54, (F57 - F56) / 100 / (F55 - F54), 0)$
 U9: $\text{@IF}(G55 > G54, (G57 - G56) / 100 / (G55 - G54), 0)$
 P10: 'OTE0
 S10: $+ E56 / 100 - S9 * E54$
 T10: $+ F56 / 100 - T9 * F54$
 U10: $+ G56 / 100 - U9 * G54$
 P11: 'CFM1
 S11: $+ S10 * S10 + 4 * S9 * S6 / S7 / S8$
 T11: $+ T10 * T10 + 4 * T9 * T6 / T7 / T8$
 U11: $+ U10 * U10 + 4 * U9 * U6 / U7 / U8$
 P12: 'CFM2
 S12: $\text{@IF}(S11 > 0, (-S10 + \text{@SQRT}(S11)) / (2 * S9), \text{@ERR})$
 T12: $\text{@IF}(T11 > 0, (-T10 + \text{@SQRT}(T11)) / (2 * T9), \text{@ERR})$
 U12: $\text{@IF}(U11 > 0, (-U10 + \text{@SQRT}(U11)) / (2 * U9), \text{@ERR})$
 P13: 'CFM3
 S13: $\text{@IF}(S12 > 0, \text{@MAX}(E63 / E64, E54, S12), S12)$
 T13: $\text{@IF}(T12 > 0, \text{@MAX}(F63 / F64, F54, T12), T12)$
 U13: $\text{@IF}(U12 > 0, \text{@MAX}(G63 / G64, G54, U12), U12)$
 P14: 'CFM4
 S14: $\text{@IF}(S13 > E55, \text{@ERR}, S13)$
 T14: $\text{@IF}(T13 > F55, \text{@ERR}, T13)$
 U14: $\text{@IF}(U13 > G55, \text{@ERR}, U13)$
 P15: 'CFM5
 S15: $\text{@IF}(S6 > 0, + S14 * E64, 0)$
 T15: $\text{@IF}(T6 > 0, + T14 * F64, 0)$
 U15: $\text{@IF}(U6 > 0, + U14 * G64, 0)$
 P16: 'CFMtot
 S16: $\text{@SUM}(S15..U15)$
 P17: 'DWP, in
 S17: $+ E60 + (E61 - E60) * \text{@IF}(E59 > 0, (1 - S8) / E59 * 100, 0)$
 T17: $+ F60 + (F61 - F60) * \text{@IF}(F59 > 0, (1 - T8) / F59 * 100, 0)$
 U17: $+ G60 + (G61 - G60) * \text{@IF}(G59 > 0, (1 - U8) / G59 * 100, 0)$
 P18: 'TDP, in
 S18: $\text{@IF}(S6 > 0, + S17 + E62 * S14 * S14, 0)$
 T18: $\text{@IF}(T6 > 0, + T17 + F62 * T14 * T14, 0)$
 U18: $\text{@IF}(U6 > 0, + U17 + G62 * U14 * U14, 0)$
 P19: 'PDtot, psig
 S19: $\text{@MAX}(S18, T18, U18) * 0.036 + E95$
 P20: 'Energy Used
 S20: $8.39 * E94 * S16 * (((E94 + S19) / E94) \sim 0.283 - 1) * 100 / E96$
 P21: 'Energy Cost
 S21: $+ E77 * S20$
 P22: 'Cleaning Cost
 S22: $\text{@IF}(E79 > 0, \text{@IF}(\text{@MOD}(S3, E79) = 0, E78 * \text{@SUM}(E64..G64), 0), 0)$
 P23: 'Maintenance Cost
 S23: $+ E80 / 12$
 P24: 'Total Cost
 S24: $+ S21 + S22 + S23$
 AA1: '\0
 AB1: '{BRANCH \M}
 AA4: '\M
 AB4: '{HOME}
 AB5: '{MENU\BRANCH Menu1}
 AA8: 'Menu1
 AB8: 'Data
 AC8: 'Calculate

AD8: 'Graph
 AE8: 'Quit
 AB9: 'Enter/edit aeration system data
 AC9: 'Calculate aeration costs
 AD9: 'Graph results of cost calculation
 AE9: 'Return to 123's READY mode
 AB10: '{BRANCH D}
 AC10: '{BRANCH C} Figure 7-8. Continued
 AD10: '{BRANCH G}
 AE10: '{HOME}
 AE11: '{QUIT}
 AA13: 'D
 AB13: '{MENUBRANCH Menu2}
 AA15: 'Menu2 AB15: 'Name
 AC15: 'Oxygen
 AD15: 'Diffusers
 AE15: 'Blowers
 AF15: 'Costs
 AG15: 'Return
 AB16: 'Name the plant being analyzed
 AC16: 'Specify oxygen demands & transfer efficiencies
 AD16: 'Describe diffuser characteristics
 AE16: 'Describe blower characteristics
 AF16: 'Provide cost factors & cleaning frequency
 AG16: 'Return to Main Menu
 AB17: '{GETLABEL "Name of plant being analyzed? ",C4}~
 AC17: '{GOTO}A30~
 AD17: '{GOTO}A50~
 AE17: '{GOTO}A90~
 AF17: '{GOTO}A70~
 AG17: '{BRANCH M}
 AB18: '{BRANCH D}
 AC18: '{DOWN 5}
 AD18: '{DOWN 4}
 AE18: '{DOWN 4}
 AF18: '{DOWN 4}
 AC19: '{RIGHT 1}
 AD19: '{RIGHT 4}
 AE19: '{RIGHT 4}
 AF19: '{RIGHT 4}
 AA22: 'C
 AB22: '{HOME}
 AB23: '{LET S3,0}~
 AB24: '{BLANK F7..F13}
 AB25: '{BLANK B15}
 AB26: '{BLANK P31..Y271}~
 AB27: '{GOTO}F7~
 AB28: '{WINDOWSOFF}
 AB29: '{FOR T3,1,@MIN(+ E81,240),1,MCOST}
 AB30: '{WINDOWSON}
 AB31: '{LET F9,(E75*@SUM(E64..G64) + E76)/1000}
 AB32: '{LET F10,@NPV(+ E74/1200,V31..V271)/1000}
 AB33: '{LET F11,@NPV(+ E74/1200,W31..W271)/1000}
 AB34: '{LET F12,@NPV(+ E74/1200,X31..X271)/1000}
 AB35: '{LET F13,@SUM(F9..F12)}~
 AB36: '{IF @ISERR(S24)}{LET B15,*** Insufficient Aeration Capacity ***}~
 AB37: '{BRANCH M}
 AA40: 'MCOST
 AB40: '{LET S3, + S3 + 1}
 AB41: '{LET F7, + S3}~
 AB42: '{RECALC S4..U24}

```

AB43: '{IF @ISERR(S24)}{FORBREAK}
AB44: '{PUT P31..Y271,0, + S3-1, + S3}
AB45: '{PUT P31..Y271,1, + S3-1, + S15}
AB46: '{PUT P31..Y271,2, + S3-1, + T15}
AB47: '{PUT P31..Y271,3, + S3-1, + U15}
AB48: '{PUT P31..Y271,4, + S3-1, + S16}
AB49: '{PUT P31..Y271,5, + S3-1, + S20}
AB50: '{PUT P31..Y271,6, + S3-1, + S21}
AB51: '{PUT P31..Y271,7, + S3-1, + S22}
AB52: '{PUT P31..Y271,8, + S3-1, + S23}
AB53: '{PUT P31..Y271,9, + S3-1, + S24}
AA55: '\G
AB55: '{MENUBRANCH Menu3}
AB56: '{BRANCH \M}
AA59: 'Menu3
AB59: 'Airflows
AC59: 'Operating-Costs
AD59: 'Total-Costs
AE59: 'Return
AB60: 'Graph monthly airflows
AC60: 'Graph monthly operating costs
AD60: 'Graph total present worth costs
AE60: 'Return to Main Menu
AB61: '/gnuAIRFLOW~q
AC61: '/gnuCOSTS~q
AD61: '/gnuPWCOSTS~q
AE61: '{BRANCH \M}
AB62: '{BRANCH \G}
AC62: '{BRANCH \G}
AD62: '{BRANCH \G}

```

Table D-2 Command Script For Economic Analysis Spreadsheet

```

/rnr
/rnc\0~AB1~
/rnc\M~AB4~
/rncMENU1~AB8~
/rnc\D~AB13~
/rncMENU2~AB15~
/rnc\C~AB22~
/rncMCOST~AB40~
/rnc\G~AB55~
/rncMENU3~AB59~

/gnrrgtxxP31..P271~aV31..V271~bY31..Y151~
olaPower~lbTotal~fgbqtfMONTHLY OPERATING COSTS~
txMonth~tyDollars~qncCOSTS~
rgtxxP31..P271~aQ31..Q271~bR31..R271~cS31..S271~dT31..T271~
olaZone 1~lbZone 2~lcZone 3~ldTotal~fgbqtfAIRFLOW REQUIREMENTS~
txMonth~tyCFM~qncAIRFLOW~rgtbxB9..B13~aF9..F13~
otfPRESENT WORTH COSTS~ty$1,000~daF9..F13~aqqncPWCOSTS~q

/rff1~F9..F13~
/wgrm

```

NOTE: The symbol ~ represents a carriage return

1. Introduction. The purpose of this paper is to study the properties of the function $f(x)$ defined by

$$f(x) = \sum_{n=1}^{\infty} \frac{1}{n^x}.$$

It is well known that $f(x)$ is the Riemann zeta function, denoted by $\zeta(x)$.

2. Preliminary results. In this section, we shall prove some preliminary results which will be used in the main part of the paper.

3. Main results. In this section, we shall prove the main results of the paper. The first result is the following theorem:

4. Conclusions. In this section, we shall conclude the paper by summarizing the main results and discussing some open problems.

5. Acknowledgments. The authors would like to thank the referee for his/her valuable comments and suggestions.

6. References. The following references are included in the paper:

7. Appendix. The following appendix is included in the paper:

Appendix E

Symbols, Terms, and Acronyms Used in this Manual

ABS	acrylonitrile butadiene styrene
AD	total projected media surface area of installed diffusers
α	(process water $K_L a$ of a new diffuser)/(clean water $K_L a$ of a new diffuser)
αF	term representing combined effect of wastewater characteristics and diffuser fouling/aging on oxygen transfer performance
$\alpha F(\text{SOTE})$	oxygen transfer efficiency under field conditions corrected to 20°C, 1 atm, and a driving force of $C^*_{\infty 20}$
$\alpha F(\text{SOTR})$	oxygen transfer rate under field conditions corrected to 20°C, 1 atm, and a driving force of $C^*_{\infty 20}$
AOR	actual oxygen requirement
AP	adiabatic power consumption
AT	aeration basin floor area
b	decay coefficient
β	(process water C^*_{∞})/(clean water C^*_{∞})
BOD	biochemical oxygen demand
BOD ₅	5-day BOD
BOD _R	BOD ₅ removed
BOD _{ult}	ultimate BOD
BRV	bubble release vacuum
BRV ₀	bubble release vacuum of a new diffuser
C	DO concentration of clean or process water
C^*_s	tabular value of DO surface saturation concentration at water temperature T, standard atmospheric pressure P_s , and 100 percent relative humidity
C^*_{∞}	steady-state DO saturation concentration attained at infinite time at water temperature T and field atmospheric pressure P_b
$C^*_{\infty 20}$	steady-state DO saturation concentration attained at infinite time at 20°C and 1 atm
CBOD ₅	carbonaceous BOD ₅
COD	chemical oxygen demand
CRF	capital recovery factor
CVPC	chlorinated polyvinyl chloride
d_e	effective saturation depth at infinite time
D	inside diameter of pipe
DO	dissolved oxygen
DO _{dif}	DO _{set-point} - DO _{measured}
dP	pressure drop
dP _{d1}	pressure drop across a clean diffuser
dP _{d2}	pressure drop across a fouled diffuser
dP _i	diffuser pressure drop in Zone i
dP _{line}	pressure drop in air piping
dP ₀₁	orifice drop at airflow of 1 scfm/diffuser
dP _{sub}	head of water above diffusers
DWP	dynamic wet pressure
e	combined blower/motor efficiency
EAC _c	equivalent annual diffuser cleaning cost
EAP	equivalent air pressure
EAP _p	equivalent annual power cost
E _p	unit power cost

EF	efficiency factor (see Equation 4-6)
EFR	effective flux ratio
EPDM	ethylenepropylene dimer
f	friction factor, from the Moody diagram
f_F	fouling rate (see Equation 3-6)
F	fouling factor = (process water K_La of a diffuser after a given time in service)/(K_La of a new diffuser in the same process water)
F_a	average fouling factor
F_{min}	minimum value for F
F/M	food-to-microorganism loading
F_w	future expenditure
FRP	fiberglass reinforced plastic
γ_w	specific weight of water at temperature T
γ_a	specific weight of air in pipe
g	acceleration due to gravity
h_f	headloss
$h_f/100$	headloss per 100 ft of pipe
H	water depth
H_d	relative humidity of blower discharge air
H_s	relative humidity at standard conditions
H_v	velocity head in pipe
HDPE	high density polyethylene
HDT	hydraulic detention time
HRT	hydraulic retention time
i	periodic discount rate
i_m	monthly interest rate
IOD	immediate oxygen demand
k	ratio of specific heats for air
k_s	absolute roughness factor
K	coefficient for adiabatic equation = $(k - 1)/k$
K_D	derivative time
K_h	headloss coefficient
K_I	integral time constant
K_{La}	apparent volumetric mass transfer coefficient in clean water at temperature T
K_{La20}	apparent volumetric mass transfer coefficient in clean water at 20°C
K_P	proportional gain
l	length of pipe
L	aeration basin length
m	constant that reflects the effect of airflow rate on SOTE (see Equation 2-2)
M	number of cleanings over the life of the system
MLSS	mixed liquor suspended solids
MLVSS	mixed liquor volatile suspended solids
μ	viscosity
n	total number of time periods
n_m	number of months between cleanings
N	equivalent number of basins-in-series
N_d	number of diffusers in the zone
N_i	number of diffusers in Zone i
NH_3-N	ammonia nitrogen
NH_4-N	ammonium nitrogen
NO_3-N	nitrate nitrogen
NOD	nitrogenous oxygen demand
NPDES	National Pollution Discharge Elimination System
NPT	National pipe thread
Ω	pressure correction for C^*_∞
OTE	oxygen transfer efficiency
OTE_f	oxygen transfer efficiency under process conditions
OTR_f	oxygen transfer rate under process conditions
P_b	field atmospheric pressure
P_d	blower discharge pressure
P_s	atmospheric pressure at standard conditions

PD	positive displacement
PSPWF	periodic series present worth factor
PVC	polyvinyl chloride
P_{vd}	vapor pressure of water in blower discharge air
P_{vs}	vapor pressure of water at standard conditions
P_{vT}	saturated vapor pressure of water at temperature T
P_w	present worth cost
P_x	biomass produced
PWF	present worth factor
q	airflow rate per diffuser
q_a	actual airflow rate
q_d	design airflow rate per diffuser
q_{di}	design airflow rate per diffuser in Zone i
q_{min}	manufacturer's recommended minimum airflow rate per diffuser
q_{mix}	minimum airflow rate required for solids suspension per diffuser
q_{max}	manufacturer's recommended maximum airflow rate per diffuser
q_s	field standardized volumetric airflow rate
Q	wastewater flow rate
Q_w	waste solids flow rate
r	volumetric respiration rate
r_r	return activated sludge recycle ratio
R	ideal gas constant
Re	Reynolds No.
s	sample standard deviation
SAE	standard aeration efficiency
SAN	styrene-acrylonitrile
SBOD	soluble 5-day BOD
SEM	scanning electron microscopy
SOTE	standard oxygen transfer efficiency
SOTR	standard oxygen transfer rate
SPWF	uniform series present worth factor
SRT	solids retention time
S.S.	stainless steel
SVI	sludge volume index
SWD	sidewater depth
τ	temperature correction for C^*_{ω}
θ	temperature correction for $K_L a$
t	time
T	clean or process water temperature
ΔT	temperature rise through blower
T_a	blower inlet air temperature
T_p	air temperature in pipe
T_s	air temperature at standard conditions
TBOD	total 5-day BOD
TKN	total Kjeldahl nitrogen
TN	total nitrogen = TKN plus oxidized nitrogen
TOC	total organic carbon
TOD	total oxygen demand
TP	total phosphorus
TSS	total suspended solids
v	airflow velocity in pipe
V	water volume
V_s	specific volume
VS	volatile solids
VSS	volatile suspended solids
w	mass rate of air
W	aeration basin width
W_{CARB}	mass rate of carbonaceous oxygen demand removed
W_{NITR}	mass rate of nitrogenous oxygen demand removed
W_{ODR}	mass rate of oxygen demand removed
W_{O_2}	mass rate of oxygen supplied

WE_M	monthly average wire energy consumption
w.g.	water gauge
WP	wire power consumption (approximately equal to brake horsepower)
WP'	average wire power consumption
WP_0	wire power consumption for an aeration system when operating with clean diffusers
WP_1	wire power consumption for an aeration system when operating with fouled diffusers just before cleaning
WP_1/WP_0	power ratio, fouled/clean diffuser operation
$\bar{x}$	average of individual sample points
$\bar{X}$	MLVSS
X_w	waste VSS
Y_g	yield coefficient
Z_c	period diffuser cleaning cost
Z_e	present worth power cost
Z_p	period power cost

Appendix F

Conversion Factors

Multiply	by	To Get
cm	0.393	in
cm ²	0.155	sq in
ha	2.47	ac
kg	0.454	lb
kg/m ²	0.205	lb/sq ft
kg/m ³ /d	62.4	lb/d/1,000 cu ft
kW	1.341	hp
kPa	0.145	psi
L/s	0.023	mgd
L/s	2.12	scfm
L/s/m ²	0.197	scfm/sq ft
L/s/m ³	8.024	scfm/1,000 gal
m	3.28	ft
m ²	10.76	sq ft
m ³	35.3	cu ft
m ³	264.2	gal
m ³ /d	264.2	gpd
m ³ /m ² /d	24.55	gpd/sq ft

