OPTIMAL OPERATIONAL CONTROL OF AN ACTIVATED SLUDGE WASTEWATER TREATMENT PLANT IN A CHANGING ENVIRONMENT

By

DAVID ALLAN HORNER

Bachelor of Science in Civil Engineering

Oklahoma State University

Stillwater, Oklahoma

1983

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
MASTER OF SCIENCE
July, 1984

OPTIMAL OPERATIONAL CONTROL OF AN ACTIVATED
SLUDGE WASTEWATER TREATMENT PLANT
IN A CHANGING ENVIRONMENT

Thesis Approved:

Don F Kincannon
Thesis Adviser

John N. Veenstra

Enos L. Stover

Norman N. Durham
Dean of the Graduate College

ACKNOWLEDGMENTS

I would like to thank Dr. Don F. Kincannon for being my major thesis adviser and for allowing me the opportunity to have hands-on experience as both an undergraduate and graduate student. This has made my stay at Oklahoma State University an enjoyable and fascinating learning experience. I also would like to extend my gratitude to Dr. E. L. Stover and Dr. J. N. Veenstra for serving on my committee.

I would like to thank my wife Nancy, my parents Thomas and Yvonne, my brother Robert, and my sister Karen, for giving me emotional support during the course of my studies.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Since the energy crisis of 1972, the cost of energy has risen dramatically. This has led to a trend in the United States toward energy conservation. The increased cost of energy has directly affected the cost of treating wastewater. The Metropolitan Sanitary District of Greater Chicago's west-southwest sewage treatment works, which is believed to be the largest treatment plant in the world, estimated that between the years of 1977 and 1979, their cost for natural gas and electricity increased from $13.7 million to $19 million--almost 39 percent (10).

The added cost for treating wastewater has forced municipalities to search for ways to reduce the cost of operating a wastewater treatment plant. One method used for reducing operating costs is to upgrade the plant by adding more energy-efficient machinery. In past years this method was economically attractive due to federal government grants to aid in the upgrading of the plant. However, more recently the federal government has all but stopped grants to state and local governments. From 1981 to 1983, state and local grants fell from $269 million to $182 million, almost 32 percent (19).

Without the option of significantly upgrading the treatment plant, the local municipalities must reduce the cost of operating the plant through optimal operational controls. The Metropolitan Denver Sewage Disposal District No. 1 reduced their operation costs by adding a computer that provides real-time process control (11). The purpose of this study is to combine mathematical models of wastewater treatment unit processes with derived cost equations to determine the energy cost and effectiveness of various treatment strategies. Then with use of these data, trends will be determined for optimal operational control.

CHAPTER II

LITERATURE REVIEW

Since the early Sixties, engineers have been trying to obtain adequate and accurate data on the cost of treating wastewater. Tihansky (16) has summarized the historical development and use of cost functions for wastewater. One of the problems with cost estimating for wastewater treatment facilities is locating sources of cost data. Beatly (1) has defined some sources of cost data as plant records, published reports and articles, cost handbooks, and unpublished studies. Evans and Wilson (5) have provided cost information for advanced waste treatment from data they obtained at the South Lake Tahoe plant. The federal government (17) and private industry (18) have both published handbooks dealing with construction and operating costs of several unit processes at wastewater treatment plants. Hasit and Vesilind (7) have derived linear cost equations for different sludge handling unit processes.

Cost data have been used extensively by engineers to optimize the design of treatment facilities. An optimal design is defined as a design that will allow the plant to meet all effluent requirements and will result in the least cost of construction and operation during the life of the plant. Grady (6) reviewed one method--which could be done by a hand calculator--that used Bellman's principle of optimality to determine the size of several units in the treatment plant. However, this method is only good for systems with only one processing train; thus only the liquid treatment train could be optimized and the sludge treatment train could not be optimized. Parker and Daguge (12) studied optimal plant design and concluded that designing for the most efficient individual unit may not make the most efficient system. Kincannon and Koelling (8) derived the cost paid by the federal government and the cost paid by the local municipality over the life of the treatment plant. They concluded that the design that would produce the minimal cost for the federal government was not the same design that would give the minimal cost for the local municipality. Tarrer et al. (15) examined optimal design under certain uncertainties found in the field and found that changes in the mean cell residence time had little effect on the total plant cost while the total plant cost was very sensitive to the wastewater strength.

There have been some attempts to explain methods to reduce energy costs at existing treatment plants. Burris (2) discussed various ways to reduce energy costs by changing times of certain pumpings and using more efficient pumps. Burris noted that power companies are no longer charging for electricity on a flat rate of dollars per kilowatt hour but use a demand charge. With a demand charge, the monthly electricity bill is a function of the highest 15 or 20 minutes peak of kilowatt-hours (4). This means that it would be more energy-efficient to run the sludge pumps wasting in a semi-continuous mode rather than wasting sludge a couple of times a day. One of the problems with estimating the operating cost is determining the actual condition of the plant at any given time. Busby and Andrews (3) studied the use of dynamic modeling to predict the plant's performance under varying operating conditions. Stenstron and Andrews (14) investigated the cost interaction between oxygen transfer cost, anaerobically digested sludge cost, and methane digestion gas value. They provided a series of contour plots that showed the weekly operation cost under different operating conditions.

CHAPTER III

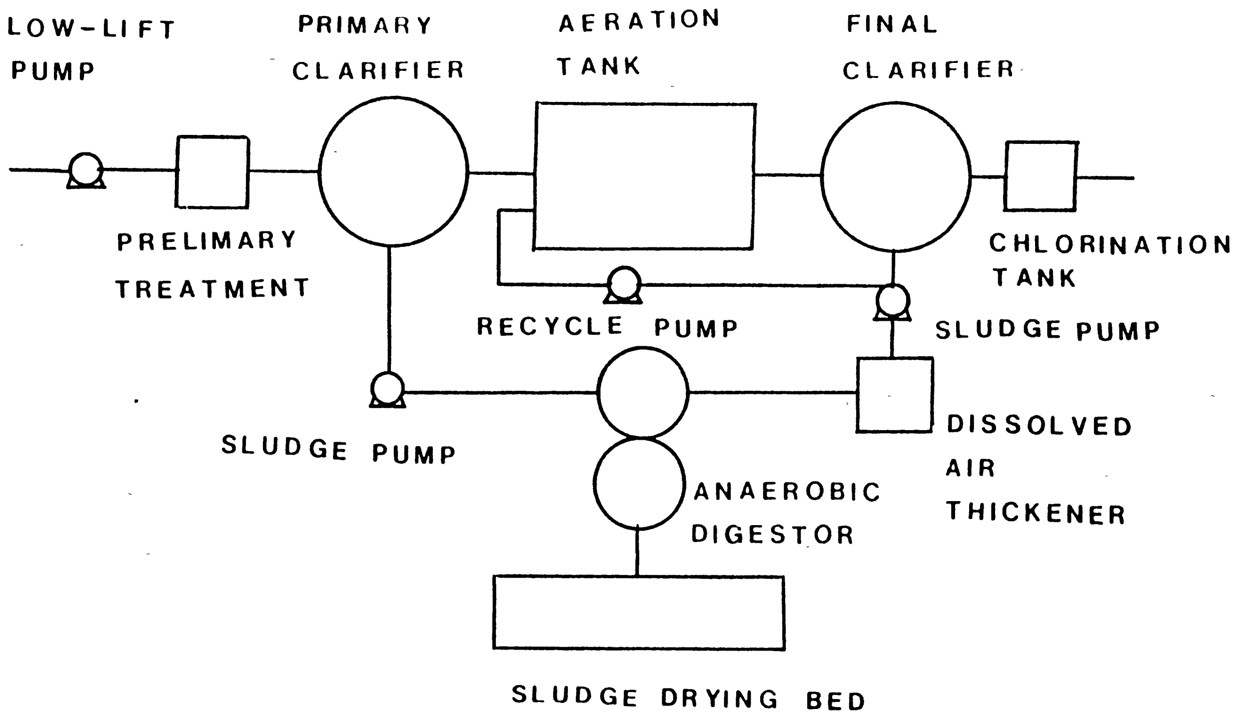
MATERIALS AND METHODS

For this study a computer program was written. The program was written in BASIC language for a Radio Shack TRS-80 computer. Appendix A contains a complete listing of the program. The objectives of this program are to describe the biological characteristics and estimate the annual operating cost of a wastewater treatment plant. The computer program combines mathematical models of single unit processes into an operational model for an entire treatment plant. The operator inputs influent wastewater strength, biokinetic characteristics of the waste, influent flow rate, physical characteristics of the treatment plant, and effluent requirements. The computer program then uses this information to determine wastewater strength and solids concentration at various locations in the treatment plant, the recycle rate from the final clarifier needed to maintain a required solids concentration in the aeration basin, the horsepower requirement needed to aerate the aeration basin, and sludge wasting volumes. Descriptions of the plant, mathematical models, and cost equations are given below.

Description of the Plant

Figure 1 shows the layout of the treatment plant. The physical and influent biological characteristics of the plant closely resemble those

Figure 1. Wastewater Treatment Plant Layout


LOW-LIFT PUMP
PRIMARY CLARIFIER
AERATION TANK
FINAL CLARIFIER
PRELIMARY TREATMENT
CHLORINATION TANK
RECYCLE PUMP
SLUDGE PUMP
SLUDGE PUMP
DISSOLVED AIR THICKENER
ANAEROBIC DIGESTOR
SLUDGE DRYING BED

at actual operating plants. The plant can be described as having two processing trains: the liquid treatment train and the sludge treatment train.

The first unit process in the treatment plant is a low-lift pump station. The pumps in the low-lift pump station have a total dynamic head of 30 feet. Also included in the pump station is a mechanical bar screen. Preliminary treatment follows the pump station. Preliminary treatment consists of a grit chamber with mechanical grit-handling equipment and parshall flume with flow-recording equipment. The primary clarifiers have a total surface area of 10,000 sq ft. The aeration basin, which is mechanically aerated, has a volume of 5 million gallons. The final clarifiers have a total surface area of 30,000 sq ft. Recycle sludge from the final clarifiers is pumped to the aeration basin by the recycle pump with a total dynamic head of 10 feet. The wastewater is finally treated with 10 mg/l of chlorine in a chlorination basin.

The wasted sludge from the clarifiers is pumped to the sludge-handling process by primary and secondary sludge pumps which have a total dynamic head of 10 feet. The wasted sludge from the secondary clarifiers is pumped to a dissolved air thickener, which has a total surface area of 500 sq ft. Then the total sludge volume is pumped to a two-stage anaerobic digestor. After the sludge is digested, it is placed on sludge drying beds that have a total surface area of 70,000 sq ft.

Mathematical Models

One of the best ways to quantitatively describe the biological process occurring at a wastewater treatment plant is to use mathematical models. There are a number of these models which are used to design various units in a treatment plant; however, by rearranging the variables, one may use these models for operational control. For this study, mathematical models were used to calculate wastewater strength, solids concentration, recycle rate from the final clarifier, oxygen requirement, and flows throughout the plant.

While some units, like the aeration basin of an activated sludge system, have been completely described through mathematical models, other units like the primary clarifiers have not been. Kincannon was able to take data from the literature to develop a mathematical model to describe the primary clarifiers (8):

$$X_i = X_o - X_o \left(0.711 - \frac{474\ F}{APC}\right) \qquad (3.1)$$

where

X_i = suspended solids concentration after the primary clarifier, mg/l;

X_o = influent suspended solids concentration, mg/l;

F = plant flow rate, million gallons per day (MGD); and

APC = surface area of primary clarifier, sq ft.

By doing a mass balance around the primary clarifier, the amount of sludge removed by the primary clarifier may be calculated:

$$PS = 8.34\ F\ X_o \left(0.711 - \frac{474\ F}{APC}\right) \qquad (3.2)$$

where PS is pounds of sludge per day.

Assuming that the solids in the wastewater contributes to BOD_5 concentration, then influent BOD_5 concentration may be written as:

$$S_i = S_o + (K_1)\ (X_i) \qquad (3.3)$$

where

S_i = influent BOD_5 concentration after the primary clarifier, mg/l;

S_o = soluble BOD_5 concentration entering the plant, mg/l; and

K_1 = soluble BOD_5 ratio of the suspended solids.

Likewise, the effluent BOD_5 concentration required to meet effluent standards is defined as

$$S_e = B_S - (K_1)\ (X_e) \qquad (3.4)$$

where

S_e = soluble effluent BOD_5 concentration, mg/l;

B_S = effluent BOD_5 standard, mg/l; and

X_e = effluent suspended solids standard, mg/l.

There are several different mathematical models that describe the biological processes occurring in the aeration basin of an activated sludge system. Kincannon and Stover's (9) model was chosen for this study because of its lack of variability in determining the model's biokinetic constants:

$$X = \frac{8.34\ F\ S_i/V}{\dfrac{U_m\ S_i}{S_i - S_e} - K_b} \qquad (3.5)$$

where

X = suspended solids concentration in the aeration basin, mg/l;

V = volume of the aeration basin, million gallons;

U_m = biokinetic constant; and

K_b = biokinetic constant.

The calculation of a recycle rate was determined by rearranging an equation that Dick (6) had developed for sizing the final clarifier.

Dick has developed a model to determine the proper overflow rate for the final clarifier:

$$\frac{F}{AFC} = \frac{0.01077\ A\ (N - 1)\ (\frac{N}{N - 1})^{N}\ (A_L)^{N-1}}{((1.0036 \times 10^{-6})\ X)^{N}\ (1 + A_L)^{N}} \tag{3.6}$$

where

AFC = surface area of final clarifier, sq ft;

A = settleability constant, ft/min;

N = settleability constant; and

A_L = recycle rate.

For operational control the equation may be rearranged to determine the recycle rate. The recycle rate must be solved for by trial and error.

$$\frac{A_L^{N-1}}{(1 + A_L)^{N}} = \frac{F\ ((1.0036 \times 10^{-6})\ X)^{N}}{0.01077\ (AFC)(A)(N - 1)(\frac{N}{N - 1})^{N}} \tag{3.7}$$

Once the proper recycle rate is determined, the underflow sludge solids concentration may be calculated:

$$X_R = \frac{\frac{K_d\ X\ V}{F} + (1 + A_L)\ X - \frac{Y_t\ U_m\ S_i}{K_b + \frac{F\ S_i}{X\ V}}}{A_L} \tag{3.8}$$

where

X_R = underflow suspended concentration, mg/l;

K_d = biokinetic constant; and

Y_t = biokinetic constant.

By taking a mass balance around the final clarifier, the amount of sludge wasted from the final clarifier may be described as:

$$SFC = 8.34 \cdot (X_R) \quad \frac{((1 + A_L)\ F\ X)}{X_R - X_E} - \frac{((A_L)(F)(X_R)) - F\ X_e)}{X_R - X_E} \qquad (3.9)$$

where SFC is pounds of sludge wasted from the final clarifier, lbs/day.

As stated before, the aeration basin was aerated by mechanical aerators. The daily oxygen requirement is defined as:

$$\frac{\text{lbs } O_2}{\text{hr}} = 8.34 \quad \frac{(S_i - S_e)\ F}{0.68\ (24)} - ((1 + A_L)FX - A_L(F)(X_R)\ \frac{1.42}{24})$$

(3.10)

The pounds of oxygen transferred by the aerators is defined as (13):

$$N_1 = N_0\ (\frac{B\ C_W - C_L}{9.17}\ (1.024)^{T-20}\ A_W) \qquad (3.11)$$

where

N_1 = lbs O_2/hp-hr transferred by the aerator at operating conditions;

N_0 = lbs O_2/hp-hr transferred in water at 20°C, and zero dissolved oxygen;

B = salinity-surface tension correction factor;

T = temperature of the wastewater, °C;

A_W = oxygen-transfer correction factor for the wastewater;

C_W = oxygen-saturation concentration for waste, mg/l; and

C_L = dissolved oxygen concentration, mg/l.

Cost Equations

The cost equations for this study were derived from cost curves found in the literature. A listing of these cost equations is located in Appendix B. The computer program is equipped to estimate the power, labor, and material cost for each unit in the treatment plant. However, for this study, only changes in energy cost were examined. Even though labor and material costs contribute significantly to the total operating cost of the plant, labor and material costs are more a function of the type and size of a treatment plant, rather than a function of the operating condition of the plant. For this reason, changes in labor and material costs were not studied.

All units except the sludge drying beds require power. The power requirement of each unit was computed under specific operating conditions and multiplied by the cost of electricity. For this study, the cost of electricity is assumed to be 0.03 dollars per kilowatt-hour.

CHAPTER IV

DISCUSSION OF RESULTS

A summary of the results of this study is presented in Table I. The energy cost data were collected over three different flow rates to illustrate the variation in flow rate seen by a treatment plant over the course of a day. The flow rates used were 6, 8, and 10 MGD. Figure 2 illustrates the energy cost at 8 MGD as a function of influent BOD_5 concentration (S_i) and effluent BOD_5 concentration (S_e). As S_i increases, the S_e required to produce the minimal energy cost increases. The overall energy cost also increases with increases in S_i.

After reviewing the results closer, it became apparent that the energy cost of some unit processes, such as the primary clarifier, did not fluctuate with changes in operating strategies, but rather by physical parameters that could not be controlled by the plant's operators. It was then determined that those unit processes whose energy cost did vary as operating strategies changed could be categorized into two groups: aeration basin energy cost and sludge handling energy cost. Aeration basin energy costs consist of the cost to aerate the activated sludge basin and the cost to pump the recycled solids. The sludge handling costs consist of the cost of sludge pumping, the cost of the dissolved air thickener, and the cost of the anaerobic digestors. Table II relates the cost-savings tradeoff between aeration basin energy cost and sludge handling energy cost with respect to S_e.Δ aeration basin energy cost is the

TABLE I

SUMMARY OF DATA

F MGD	S_o mg/l	S_i mg/l	S_e mg/l	X mg/l	X_R mg/l	Recycle Rate	Sludge Production lbs/day	Energy Cost $/yr	Loading lbs BOD/day
6	80	137	5	1951	9403	0.259	4270	85380	6855
6	80	137	6	1654	11368	0.168	4270	85193	6855
6	80	137	7	1432	13157	0.121	4270	85094	6855
6	80	137	8	1261	14848	0.091	4270	85033	6855
6	80	137	10	1013	17935	0.058	4624	85437	6855
6	80	137	15	666	20000	0.032	5614	86466	6855
6	80	137	20	486	20000	0.022	6118	86957	6855
6	100	157	8	1645	11433	0.166	4270	85188	7856
6	100	157	9	1470	12824	0.128	4270	85109	7856
6	100	157	10	1327	14140	0.102	4340	85167	7856
6	100	157	11	1209	15340	0.084	4684	85559	7856
8	60	127	5	2236	5117	0.769	4428	90333	8474
8	60	127	6	1892	7245	0.350	4428	89177	8474

TABLE I (Continued)

F MGD	S_o mg/l	S_i mg/l	S_e mg/l	X mg/l	X_R mg/l	Recycle Rate	Sludge Production lbs/day	Energy Cost $/yr	Loading lbs BOD/day
8	60	127	8	1437	10123	0.163	4428	88664	8474
8	60	127	10	1152	12510	0.099	5596	89253	8474
8	60	127	13	878	15692	0.057	5802	89973	8474
8	60	127	15	754	17660	0.042	6299	90290	8474
8	60	127	20	543	20000	0.025	6863	90810	8474
8	80	147	8	1917	7102	0.366	4428	89221	9808
8	80	147	10	1543	9348	0.195	4741	89170	9808
8	80	147	11	1404	10309	0.154	5143	89522	9808
8	80	147	12	1285	11216	0.126	5483	89812	9808
8	80	147	20	747	17479	0.041	7006	91111	9808
8	100	167	10	1987	6705	0.417	4428	93761	11142
8	100	167	13	1533	9352	0.191	5601	90119	11142
8	100	167	14	1422	10100	0.159	5919	90360	11142
8	100	167	15	1324	10814	0.135	6199	90576	11142

TABLE I (Continued)

F MGD	S_o mg/l	S_i mg/l	S_e mg/l	X mg/l	X_R mg/l	Recycle Rate	Sludge Production lbs/day	Energy Cost $/yr	Loading lbs BOD/day
8	100	167	20	976	14049	0.070	7183	91363	11142
10	80	157	13	1680	6684	0.328	5553	95693	13094
10	80	157	14	1557	7373	0.260	5906	94595	13094
10	80	157	15	1450	8008	0.214	6213	94738	13094
10	80	157	17	1270	9178	0.154	6721	95025	13094
10	80	157	20	1065	10783	0.103	7296	95396	13094
10	100	176	15	1852	5712	0.468	6098	105026	14678
10	100	176	17	1627	6938	0.296	6740	98384	14678
10	100	176	18	1532	7468	0.249	7009	95630	14678
10	100	176	19	1447	7967	0.213	7251	95734	14678
10	100	176	20	1369	8443	0.185	7469	95842	14678

Figure 2. Annual Energy Cost as a Function of S_i and S_e at F = 8 MGD

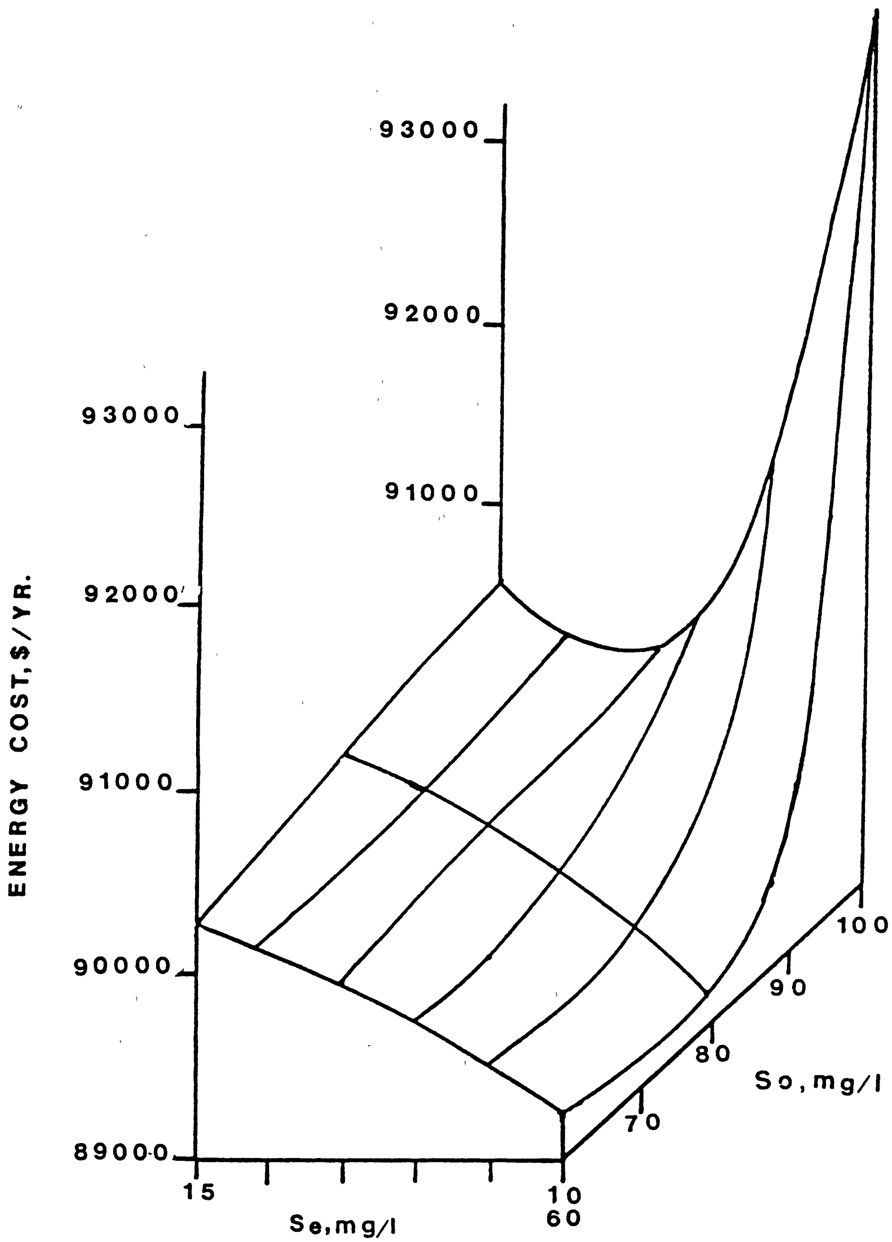

93000
92000
91000
93000
92000
91000
90000
89000
ENERGY COST, $/YR.
15
10
60
Se, mg/l
70
80
90
100
So, mg/l

TABLE II

ENERGY COST-SAVING AT HIGH LOADING

S_e mg/l	Aeration Cost, $/yr	Δ Aeration Cost, $/yr	Sludge Handling Cost, $/yr	Δ Sludge Handling Cost, $/yr	Added Cost, $/yr
20	73555	0	2926	0	0
17	73573	18	2630	-296	-278
15	73600	45	2360	-566	-526
13	73641	86	2003	-923	-837
10	73757	202	1165	-1761	-1559
8	77219	3664	399	-2527	1137

S_i = 127 mg/l; F = 8 MGD; Loading = 8475 lbs BOD/day.

difference between the aeration basin energy cost at a certain S_e value and the aeration basin energy cost when S_e = 20 mg/l. Likewise, the Δ sludge handling energy cost is the change in sludge handling energy cost of a certain S_e and the sludge handling energy cost when S_e = 20 mg/l. It is assumed for this plant that the maximum permissible S_e concentration is 20 mg/l. Thus, a Δ energy cost is the cost to the plant to operate the plant at a certain level below the maximum permissible S_e concentration.

Figure 3 graphically illustrates the information given in Table II. During higher S_e concentration, the Δ aeration basin energy cost curve does not increase very much. This is due to the fact that mixing controls the amount of air needed in the aeration basin rather than the metabolic oxygen requirements. A value of 75 times the volume of the aeration basin, in million gallons, was used to determine the minimum horsepower required for mixing. For Figure 3, at an S_e concentration around 11 mg/l, the metabolic oxygen requirements begin to control the aeration energy cost and the Δ aeration basin energy curve increases rapidly. A savings occurs in the Δ sludge handling energy cost curve as the S_e concentration decreases. This is due to the fact that as the S_e concentration decreases, there is a need for more solids in the aeration basin and fewer solids are being wasted, which creates a savings in the sludge handling energy cost. Under the specific flow and S_i concentration of this example, the S_e concentration which provides the least energy cost is 10 mg/l.

Another controlling factor for determining the optimal operating condition is when the amount of wasted sludge from the final clarifier goes to zero. An example of this is summarized in Table III. At low

Figure 3. Energy Cost-Savings Tradeoff Between the Aeration Basin Cost and Sludge Handling Cost, High Loading

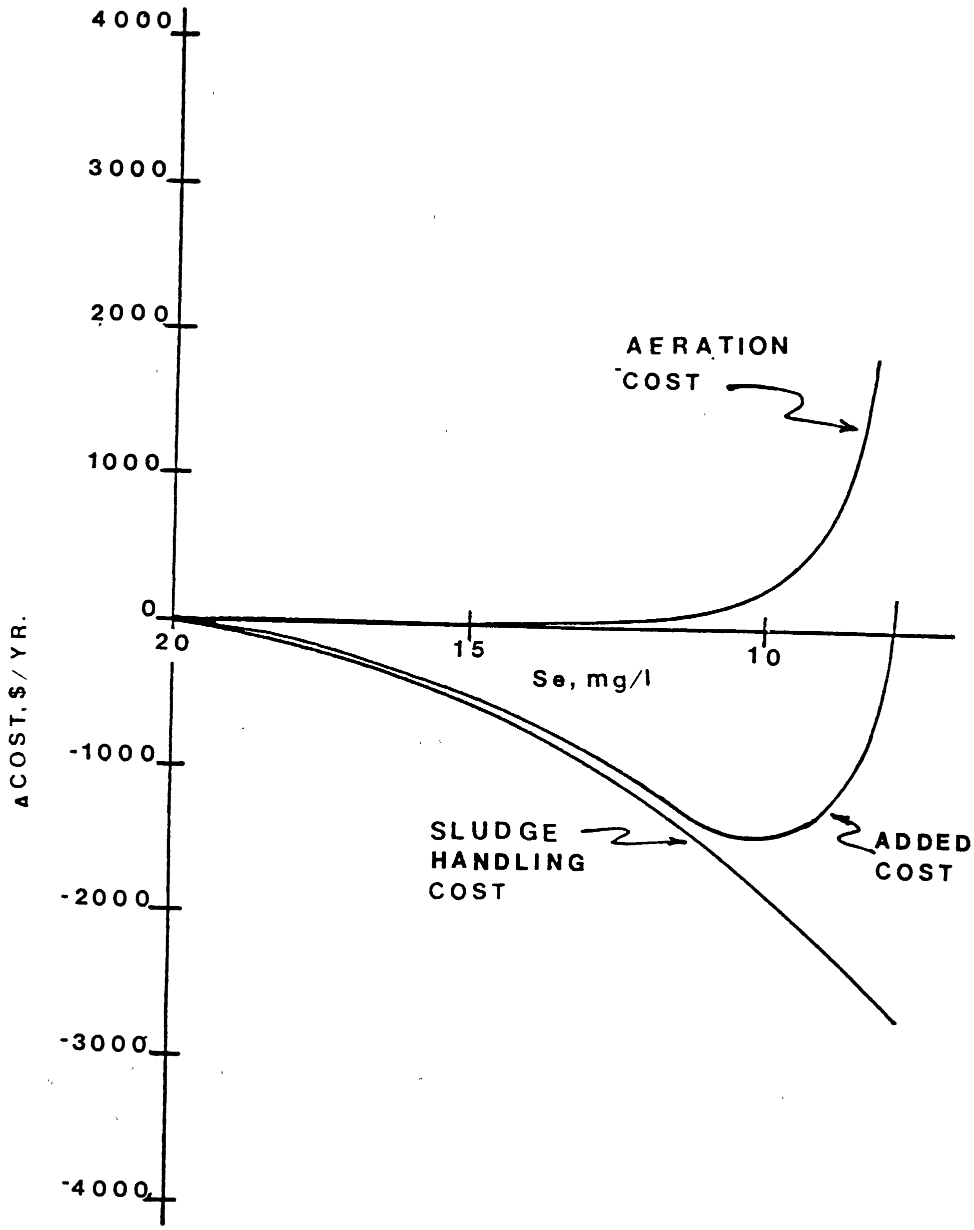

4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
ΔCOST, $/YR.
20
15
10
Se, mg/l
AERATION COST
SLUDGE HANDLING COST
ADDED COST

TABLE III

ENERGY COST-SAVING AT LOW LOADING

S_e mg/l	Aeration Cost, \$/yr	Δ Aeration Cost, \$/yr	Sludge Handling Cost, \$/yr	Δ Sludge Handling Cost, \$/yr	Added Cost, \$/hr
20	73531	0	2454	0	0
15	73551	20	1942	-512	-492
10	73605	74	857	-1597	-1523
8	73673	142	387	-2067	-1925
7	73734	203	387	-2067	-1864
6	73832	301	387	-2067	-1766
5	74020	489	387	-2067	-1578

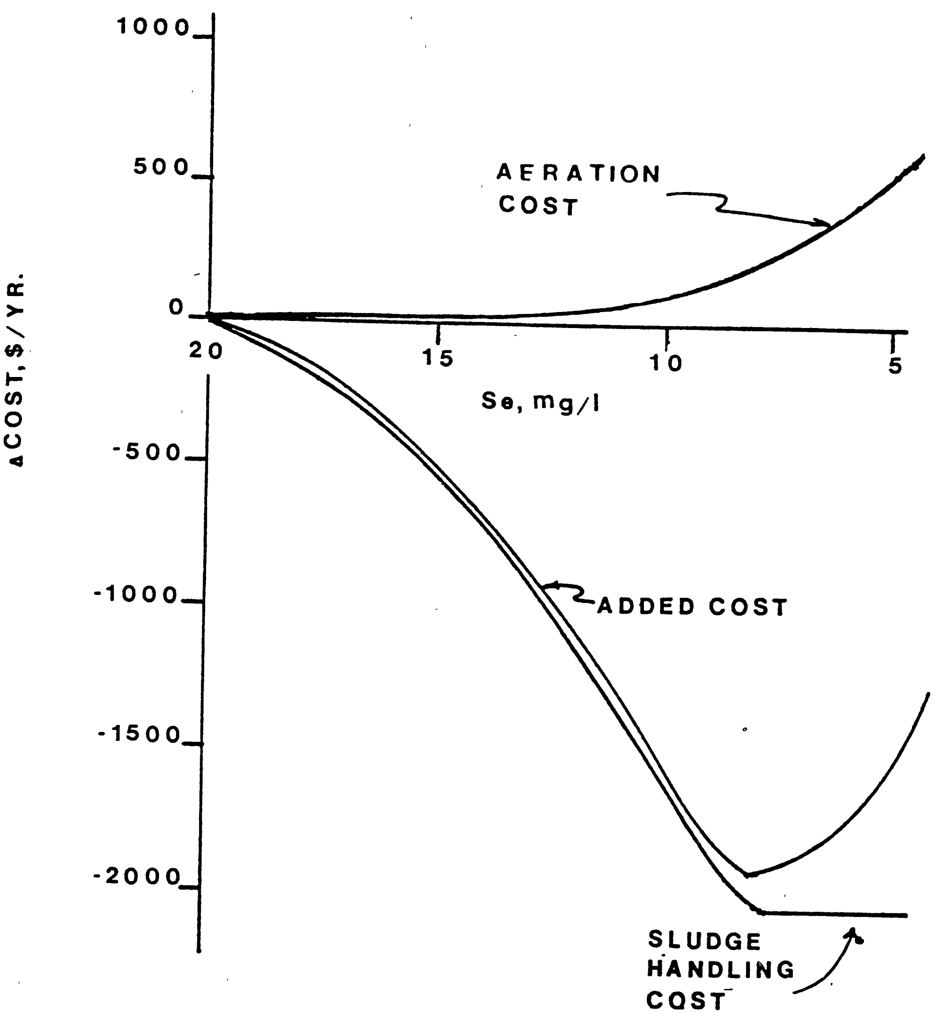
S_i = 137 mg/l; F = 6 mgd; Loading = 6855 lbs BOD/day.

loading rates, the aeration basin energy cost is controlled by mixing and the small increase in the Δ aeration basin energy cost is due to an increase in the rate of recycled solids pumped. These solids were needed to increase the solids concentration in the aeration basin to provide a lower S_e concentration. The sludge handling energy cost produces a savings at lower S_e values; however, this savings levels off to a constant value at S_e = 8 mg/l, as seen in Figure 4. At this point, there is no more sludge being wasted from the final clarifier.

Figures 5, 6, and 7 show the total energy cost as a function of solids concentration in the aeration basin at 6, 8, and 10 MGD, respectively. For the most part, the solids concentration which provides the minimal operating cost is between 1450 and 1550 mg/l. The lowest optimal solids concentration was 1261 mg/l, which occurred at the lowest loading rate studied. At this condition, the final clarifier sludge wasting amount went to zero. From the summary of data, it appears that optimal solids concentration remains for all practical purposes constant when aeration costs control the optimal operating condition. When the solid wasting amount controls the optimal operating condition, it appears that the optimal solids concentration in the aeration basin becomes smaller with smaller loadings applied to the aeration basin.

Figure 8 is a plot of solids concentration in the aeration basin at different flow rates as a function of the recycle sludge rate. This graph illustrates the fact that as the flow increases, the recycle rate must increase to achieve the same solids concentration. At higher flow rates, the solids in the final clarifier have less time to settle. A graph of this nature could also be a valuable tool for plant operators.

Figure 4. Energy Cost-Savings Tradeoff Between the Aeration Basin Cost and Sludge Handling Cost, Low Loading



1000
500
0
-500
-1000
-1500
-2000
ΔCOST, $/YR.
20
15
10
5
Se, mg/l
AERATION
COST
ADDED COST
SLUDGE
HANDLING
COST

Figure 5. Annual Energy Cost Versus Solids Concentration at F = 6 MGD

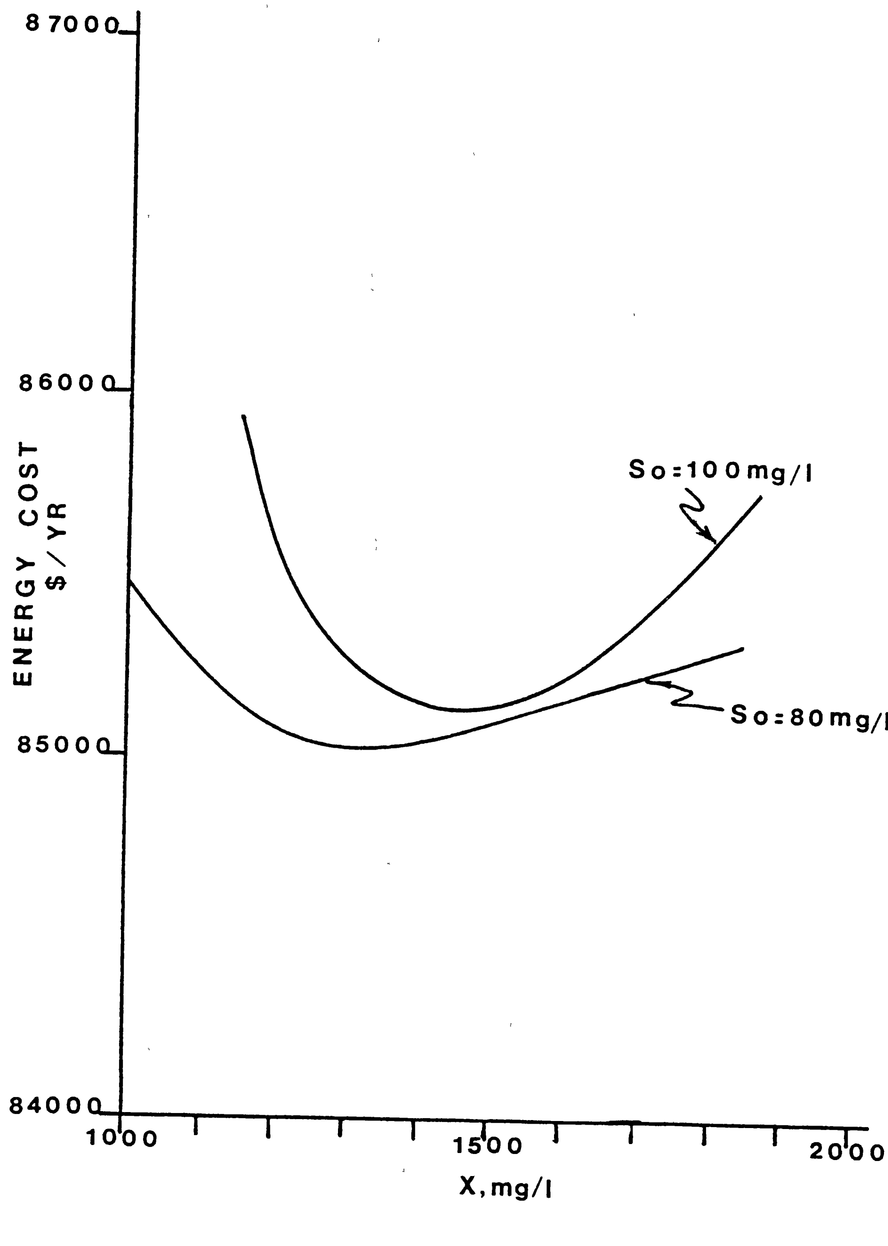

87000
86000
85000
84000
ENERGY COST
$ / YR
So=100 mg/l
So=80 mg/l
1000
1500
2000
X, mg/l

Figure 6. Annual Energy Cost Versus Solids Concentration at F = 8 MGD

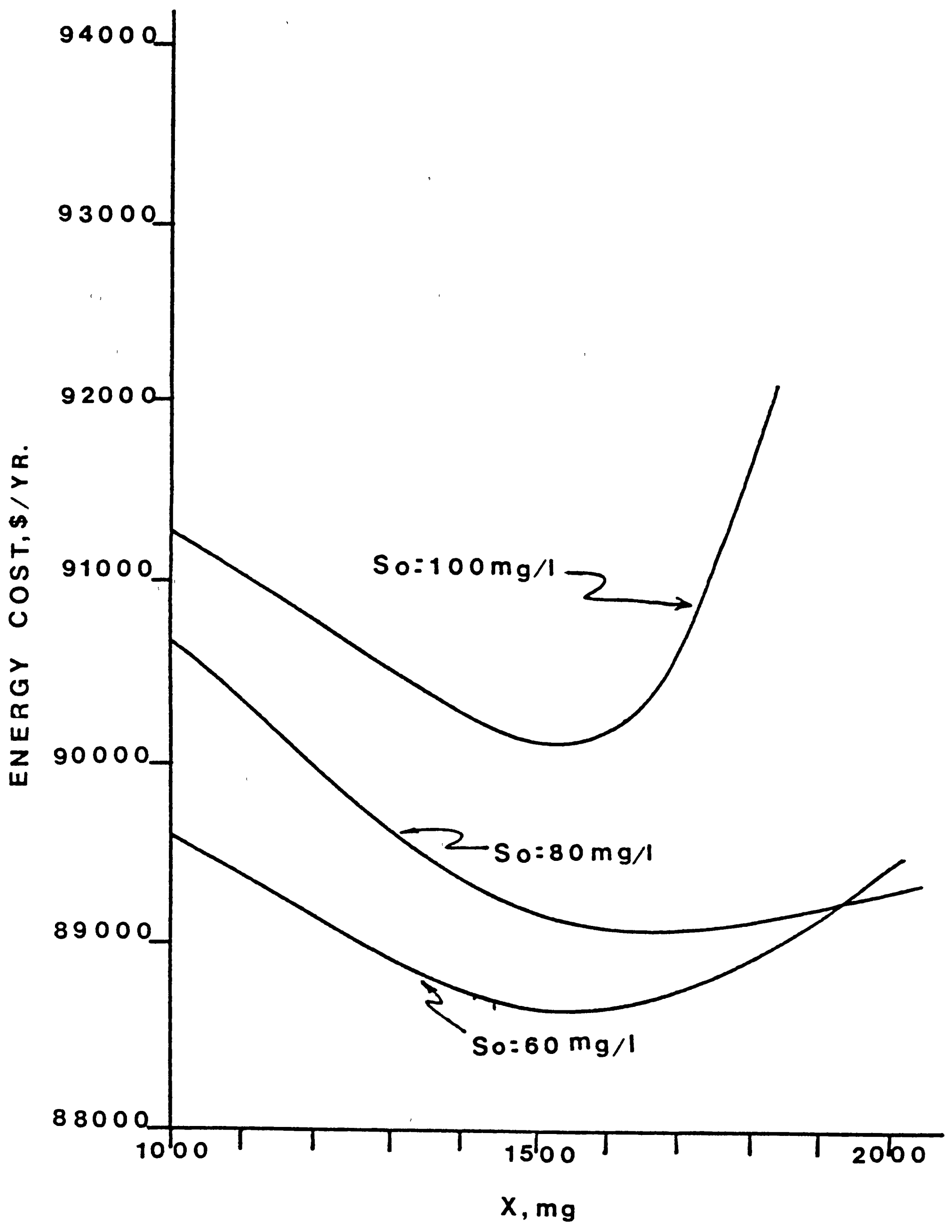
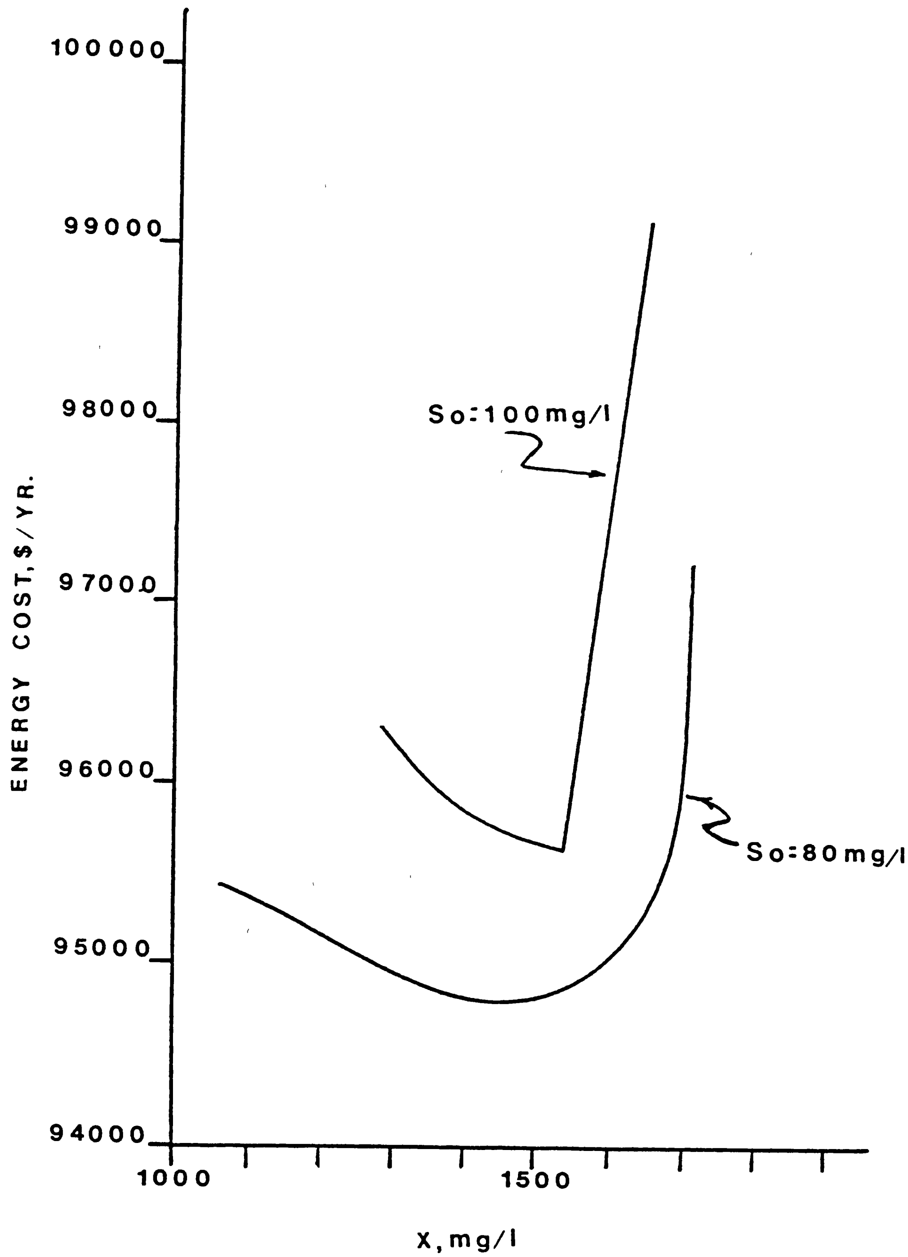
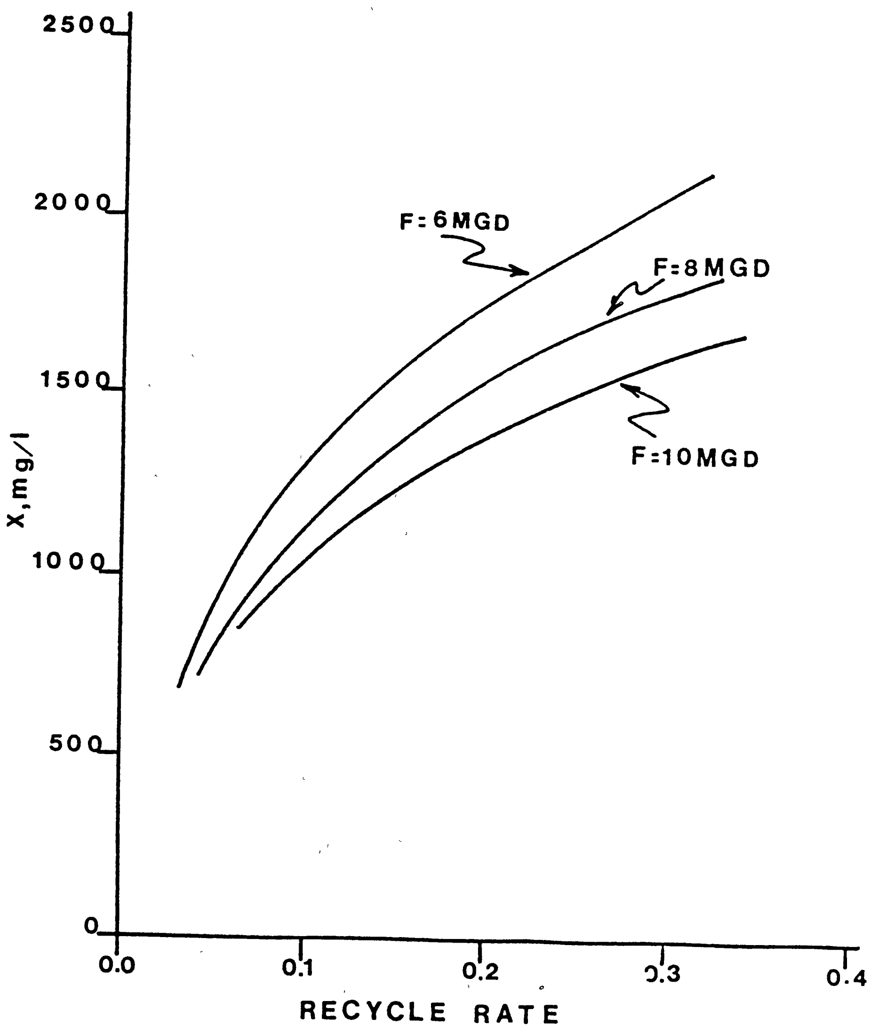

94000
93000
92000
91000
90000
89000
88000
ENERGY COST, $/YR.
So:100mg/l
So:80mg/l
So:60 mg/l
1000
1500
2000
X, mg

Figure 7. Annual Energy Cost Versus Solids Concentration at F = 10 MGD



100000
99000
98000
97000
96000
95000
94000
ENERGY COST, $/YR.
So:100mg/l
So:80mg/l
1000
1500
X, mg/l

Figure 8. Effect of Recycle Rate on Solids Concentration at Various Flows


2500
2000
1500
1000
500
0
X, mg/l
F: 6MGD
F=8MGD
F=10MGD
0.0
0.1
0.2
0.3
0.4
RECYCLE RATE

It would allow the operators to know what recycle rate to set to achieve a required solids concentration in the aeration basin.

CHAPTER V

CONCLUSIONS

The following conclusions may be drawn from the observations made in this study:

1. The optimal operational condition is determined by a cost-savings tradeoff between aeration basin energy cost and the sludge handling energy cost.

2. Total energy cost increases when the flow rate increases.

3. Total energy cost increases when S_i increases.

4. When aeration costs control the optimal operating condition, the solids concentration in the aeration basin remains fairly constant over a wide range of loading conditions.

5. When sludge handling costs control the optimal operating conditions, the solids concentration in the aeration basin decreases as the loading to the plant decreases.

A SELECTED BIBLIOGRAPHY

(1) Beatty, Fred K., "Available Sources and Reliability of Cost Data for Estimating Cost Effectiveness." (Paper presented at the 2nd Mid-America Environmental Engineering Design Conference, Western Hills Resort, Wagoner, Oklahoma, May 26-27, 1977.)

(2) Burris, Bruce E., "Energy Conservation for Existing Wastewater Treatment Plants." J. Water Pollution Control Federation, 53, 536-545 (1981).

(3) Busby, J.B., and Andrews, J. F., "Dynamic Modeling and Control Strategies for Activated Sludge Process." J. Water Pollution Control Federation, 46, 1055-1080 (1981).

(4) Clingenpeel, W. H., "Optimizing Pump Operating Cost." J. American Water Works Association, 75, 502-509 (1983).

(5) Evans, David R., and Wilson, Jerry C., "Capital and Operating Cost --AWT." J. Water Pollution Control Federation, 44, 1-13 (1972).

(6) Grady, C. P. L., "Simplified Optimization of Activated Sludge Process." J. Sanitary Engineering Division, Proceedings, ASCE, 103, 413-429 (1981).

(7) Hasit, Y., and Vesilind, P. A., "Economics of Sludge Management." J. Water Pollution Control Federation, 53, 560-564 (1981).

(8) Kincannon, D. F., and Koelling, C. P., "Cost Minimization of the Wastewater Treatment Process." (Paper presented at ORSA/TIMS Joint National Meeting, San Diego, Calif., October 27, 1982.)

(9) Kincannon, D. F., Stover, E. L., McCarty, D. E., and Dehkordi, F., "Reliable Design of Activated Sludge System to Remove Organic Priority Pollutants." (Paper presented at Process Design Session, 55th Annual Conference, Water Pollution Control Federation, St. Louis, Mo., October 3-8, 1982.)

(10) McMillan, H. H., Rimkus, R. R., and Neil, F. C., "Metro Chicago's Study of Energy Alternatives for Wastewater Treatment." J. Water Pollution Control Federation, 2, 155-161 (1981).

(11) Nelson, J. K., and Mishra, B. B., "Digital On-Line Closed Loop Control for Wastewater Treatment Operation." J. Water Pollution Control Federation, 52, 406-415 (1980).

(12) Parker, G. F., and Dague, R. R., "Optimal Design of Wastewater Treatment System by Enumeration." J. Sanitary Engineering Division, Proceedings, ASCE, 98, 833-851 (1972).

(13) Reynolds, T. D., Unit Operation and Process in Environmental Engineering. 1st Ed. Monterey, Calif.: Brooks/Cole Engineering Division, 1982.

(14) Stenstrom, M. K., and Andrews, J. F., "Cost Interaction in Activated Sludge Systems." J. Sanitary Engineering Division, Proceedings, ASCE, 106, 787-795 (1980).

(15) Tarrer, A. R., Grady, C. P. L., Lim, H. C., and Koppel, K. B., "Optimal Activated Sludge Design Under Uncertainty." J. Sanitary Engineering Division, Proceedings, ASCE, 102, 657-673 (1976).

(16) Tihansky, D. P., "Historical Development of Water Pollution Control Cost Function." J. Water Pollution Control Federation, 46, 813-829 (1974).

(17) Estimating Cost and Manpower Requirements for Conventional Wastewater Treatment Facilities. U.S. Environmental Protection Agency, Water Pollution Control Research Service, 17090 DAN 10/71, Washington, D.C. (October, 1971).

(18) Wastewater Treatment Processes and Systems, Cost and Performance. West Chester, Penn.: Weston Environmental Consulting Engineers (October, 1977).

(19) "Washington Notebook." J. Water Pollution Control Federation, 54, 167a-172a (1982).

APPENDIX A

COMPUTER PROGRAM LISTING

```
10 CLEAR 1000:DEFINT I:DEFSTR W,Z
12 DIM PC(12),LC(12),MC(12)
15 ZA=CHR$(128):ZB=CHR$(140):ZC=CHR$(160):ZD=CHR$(176):ZE=CHR$(144):ZF=CHR$(184
20 ZG=CHR$(133):ZH=CHR$(138):ZI=CHR$(180):ZJ=CHR$(173):Zk=CHR$(158):ZL=CHR$(137)
25 ZM=CHR$(134):ZN=CHR$(149):ZO=CHR$(170):ZP=CHR$(131):ZQ=CHR$(179):ZU=CHR$(141
:ZZ="SLUDGE"
30 WA=ZC+ZD+ZB+ZB+ZB+ZB+ZD+ZE WW=STRING$(22,140):WB=STRING$(6,128):WD=ZF+ZG:WE=Z
H+ZI
35 WH=ZA+ZA+ZA+ZA+ZA:WC=STRING$(11,176):WG="ACTIVATED":WI=STRING$(5,131):WJ=STRI
NG$(6,128)
37 W8=" P.C. ":W9=" F.C. "
40 WZ=STRING$(11,131):WM=STRING$(4,128):WL=ZL+ZB+ZD+ZD+ZD+ZD+ZB+ZM:ZZ="SLUDGE" W
K=ZA+ZA
99 GOSUB 4000
100 REM **PRIMARY CLARIFIER**
110 CLS:INPUT"BOD EFFLUENT STANDARD =",BS
120 INPUT"S.S. EFFLUENT STANDARD =";XE
130 INPUT"INFLUENT SUSPENDED SOLIDS (MG/L) =";XO
140 INPUT"BOD RATIO OF S.S. <K1> =",K1
150 INPUT"SOLUBLE INFLUENT BOD (MG/L) =",SO
160 INPUT"FLOW (MGD) =",F
170 INPUT"AREA OF PRIMARY CLARIFIER (SQ.FT.) =";APC
180 PRINT:INPUT"IS ALL THE DATA CORRECT (Y)ES OR (N)O ";T1$
190 IFLEFT$(T1$,1)="N"THEN110
200 SE=BS-(K1*XE):XI=XO-(XO*(.711-((4.74*F*100)/APC)))
210 SI=SO+(K1*XI):PS=F*XO*(.711-((4.74*F*100)/APC))*8.34
220 REM**ACTIVATED SLUDGE**
230 CLS:INPUT"VOLUME OF REACTOR (MG) =";V
240 PRINTTAB(20)"BIOKINECTIC CONSTANTS"
250 INPUT"U MAX =";UM
260 INPUT"KB =";KB
270 REM**FINAL CLARIFIER**
280 INPUT"DECAY COEFFICIENT (1/DAY) =",KD
290 INPUT"SLUDGE YIELD (YT) =";YT
300 PRINTTAB(29)"SETTLEABILITY CONSTANTS"
310 INPUT"A =";A
320 INPUT"N =";N
330 INPUT"AREA OF FINAL CLARIFIER (SQ.FT.) =",AFC
335 INPUT"MAXIMUM POSSIBLE XR (MG/L) =";MXR
340 PRINT:INPUT"IS ALL THE DATA CORRECT (Y)ES OR (N)O ",T2$
350 IFLEFT$(T2$,1)="N"THEN230
360 CLS:X=(8.34*F*SI/V)/((UM*SI/(SI-SE))-KB)
390 KA=F*((1.0036*10[-6*X)[N)
400 KA=KA/(AFC*1.077*.01*A):KA=KA/(N-1):KA=KA/((N/(N-1))[N)
410 FORC=1TO6
420  FORC1=0TO10
430   AA=(C1*10[-C)+AC
440   CA=(AA[(N-1))/(1+AA)[N)
450 IFCA>=KATHEN480
460 NEXTC1
470 IF AL>=1 THEN CLS:PRINT"AREA FINAL CLARIFIER IS TOO SMALL":END
480 AL=AC+((C1-1)*10[-C):AC=AL
```

```
490 NEXTC
510 XR=((KD*X*V/F)+((1+AL)*X)-(YT*UM*SI/(KB+(F*SI/(X*V)))))/AL
512 IFXR<MXRTHEN 520
513 XR=MXR:E1=-1
514 AL=((((KD*X*V/F)-(YT*UM*SI/(KB+(F*SI/(X*V)))))/XR)+(X/XR))/(1-(X/XR))
520 FW=(((1+AL)*X*F)-(AL*XR*F)-(F*XE))/(XR-XE)
522 IFFW>0THEN 530
524 FW=0:XR=X-((XE-X)/AL):E1=-1
525 IFXR<MXR THEN 530
527 XR=MXR:AL=(XE-X)/(X-XR)
530 SFC=FW*XR*8.34
540 CLS:PRINT"ENTER TYPE OF AERATION DEVICE : (1) MECHANICAL
550 INPUT"                                  (2) DIFFUSED";T4
560 ONT4GOTO570,710,540
570 POH=((SI-SE)*F/16.32)-((((1+AL)*F*X)-(AL*F*XR))*1.42/24)
580 CLS:PRINTTAB(15)"MECHANICAL AERATION"
590 INPUT"OXGYEN RATING OF AERATOR <NO>";NO
600 PRINT:PRINT"SALINITY-SURFACE TENSION CORRECTION"
610 INPUT"FACTOR , USUALLY 1";B
620 PRINT:PRINT"OXYGEN-SATURATION CONCENTRATION FOR WASTE AT GIVEN"
630 INPUT"TEMPERATURE AND ALTITUDE <CW>";CW
640 PRINT:INPUT"D.O. CONCENTRATION",CL
650 PRINT:INPUT"TEMPERATURE (CENTIGRADE)";TW
660 PRINT:INPUT"OXYGEN-TRANSFER CORRECTION FACTOR FOR WASTE";AW
670 PRINT:INPUT"IS ALL THE DATA CORRECT (Y)ES OR (N)O";T5$
680 IFLEFT$(T5$,1)="N"THEN580
690 N1=NO*AW*((B*CW)-CL)*(1.024[(TW-20))/9.17
700 HP=8.34*POH/N1:GOTO830
710 CLS:PRINTTAB(15)"DIFFUSED AERATION"
720 POD=((SI-SE)*F/.68)-((((1+AP)*X)-(AP*XR))*F*1.42)
730 INPUT"TRANSFER EFFICIENCY OF AERATOR";AE
740 INPUT"ABSOLUTE INLET PRESSURE (PSIA)";PI
750 INPUT"ABSOLUTE OUTLET PRESSURE (PSIA)";PO
760 INPUT"TEMPERATURE (CENTIGRADE)";TP
770 INPUT"COMPRESSOR EFFICIENCY";E
775 INPUT"LOCAL AIR DENSITY (#/CU. FT.)";LAD
780 PRINT:INPUT"IS ALL THE DATA CORRECT (Y)ES OR (N)O";T6$
790 IFLEFT$(T6$,1)="N"THEN710
795 CFM=(POD/1440)/LAD
800 PAS=POD/(20044.8*AE)
805 DE=(.6659*(TP+273))/PI
806 CFM=DE*PAS*60
810 TP=(1.8*TP)+32
820 HP=8.34*53.5*PAS*(460+TP)*(((PO/PI)[.283)-1)/(550*.283*E)
830 MHP=V*75
840 IFMHP>HPTHENHP=MHP
850 CLS:INPUT"LIFT STATION PUMP HEAD (FT)";H:INPUT"PRIMARY SLUDGE PUMP HEAD (FT)
";H1
860 INPUT"FINAL SLUDGE PUMP HEAD (FT)";H2
870 INPUT"RECYCLE PUMP HEAD (FT)";H3
880 INPUT"ELECTRIC POWER COST ($/KWH)";EC
890 INPUT"LABOR COST ($/HR)";LC
895 INPUT"INDUSTRIAL PRICE INDEX ";IPI
```

```
897 INPUT"CHORINE DOSAGE (MG/L)";CD
900 INPUT"SOLIDS LOADING TO AIR FLOTATION (LBS/DAY SQ.FT.)";LO
910 INPUT"AREA OF THICKENER (SQ.FT.)";AT
920 INPUT"AREA OF DRYING BEDS (SQ.FT.)";ADB
925 OT=(7*SFC)/(LO*AT)
930 INPUT"PRIMARY SLUDGE UNDERFLOW CONCENTRATION (MG/L)";FS
940 PRINT:INPUT"IS ALL THE DATA CORRECT (Y)ES OR (N)O";T7$
950 IFLEFT$(T7$,1)="N"THEN850
954 IFOT>168THENTOT=168
960 F1=PS/(8.34*FS):F2=(SFC/(8.34*XR/(10E6)))/(10E6):F3=AL*F
1000 CLS:INPUT"DO YOU WANT A HARD PRINT (Y) OR (N) ";Q1$
1010 IFLEFT$(Q1$,1)="N" THEN 1400
1020 CLS:PRINT"SET PRINTER , PRESS ENTEP."
1030 IF INKEY$=""THEN1030
1040 LPRINT:LPRINT:LPRINTTAB(30)"SUMMARY OF VARIABLES"
1050 LPRINT:LPRINTTAB(5)"1) INPUT VARIABLES :"
1060 LPRINT:LPRINTTAB(7)"A. GENERAL"
1070 LPRINT:LPRINTTAB(8)"BS=";BS;"Mg/l";TAB(24)"Xe=";XE;"Mg/l";TAB(43)"K1=";K1;T
AB(62)"So=";SO;"Mg/l"
1080 LPRINTTAB(8)"F=";F;"MGD";TAB(24)"APC=";APC;"SQ.FT.";TAB(43)"Xo=";XO;"Mg/l";
TAB(62)"V=";V;"MG"
1090 LPRINTTAB(8)"Um=";UM;"#/DA/#";TAB(24)"Kb=";KB;"#/DA/#";TAB(43)"Kd=";KD;"1/D
A";TAB(62)"YT=";YT;"LB/LB"
1100 LPRINTTAB(8)"a=";A;"FT/MIN";TAB(43)"n=";N
1105 LPRINTTAB(8)"AFC=":AFC
1110 ON T4GOTO 1120,1165
1120 LPRINT:LPRINTTAB(7)"B. MECHANICAL AERATION"
1130 LPRINT:LPRINTTAB(8)"No=";NO;"#/HP/HR";TAB(26)"B=";BTAB(43);"Cw=";CW;"Mg/l";
TAB(62)"Cl=";CL;"Mg/l"
1140 LPRINTTAB(8)"TEMP=";TW;"DEG. C":TAB(43)"AW=";AW
1150 LPRINT:LPRINTTAB(7)"C. DIFFUSED AERATION"
1160 LPRINT:LPRINTTAB(8)"NONE":GOTO 1200
1165 LPRINT:LPRINTTAB(7)"B. MECHANICAL AERATION":LPRINT:LPRINTTAB(8)"NONE"
1170 LPRINT:LPRINTTAB(7)"C. DIFFUSED AERATION"
1180 LPRINT:LPRINTTAB(8)"AE=";AE;TAB(24)"Pi=";PI;"PSIA";TAB(43)"Po=";PO;"PSIA";T
AB(62)"TEMP=";TP;"DEG. F"
1190 LPRINTTAB(8)"e=";E
1200 LPRINT:LPRINTTAB(7)"D. MISCELLANEOUS"
1208 LPRINTTAB(8)"H=";H;"FT";TAB(24)"AT=";AT;"SQ.FT.";TAB(60)"ADB=";ADB;"SQ.FT"
1210 LPRINT:LPRINTTAB(8)"H1=";H1;"FT";TAB(24)"H2=";H2;"FT";TAB(43)"H3=";H3;"FT";
TAB(62)"EC=";EC;"$/KWH"
1220 LPRINTTAB(8)"LC=";LC;"$/HR";TAB(24)"LO=";LO;"#/DA/SQ.FT.";TAB(45)"CD=";CD;"
Mg/l";TAB(62)"FS=";FS
1240 LPRINT:LPRINT:LPRINTTAB(5)"2) OUTPUT VARIABLES"
1250 LPRINT:LPRINTTAB(7)"A. GENERAL"
1260 LPRINT:LPRINTTAB(8)"Se=";SE;"Mg/L";TAB(24)"Si=";SI;"Mg/l";TAB(43)"Xi=";XI;"
Mg/l";TAB(62)"PS=";PS;"LB/DA"
1270 LPRINTTAB(8)"X=";X"Mg/l";TAB(24)"ALPHA=";AL;TAB(43)"Xr=";XR;"Mg/l";TAB(62)"
Fw=";FW;"MGD"
1275 IFE1<>-1THEN1280
1276 LPRINTTAB(8)"WARNING: MAXIMUM Xr WAS USED !!"
1280 LPRINTTAB(8)"SFC=";SFC;"LB/DA"
1290 ON T4GOTO 1300,1340
```

```
1300 LPRINT:LPRINTTAB(7)"B. MECHANICAL AERATION"
1310 LPRINT:LPRINTTAB(8)"POH=";POH;"LB(O2)/HR";TAB(43)"N1=";N1;"Mg/l";TAB(62)"HP
=";HP;"Hp"
1320 LPRINT:LPRINTTAB(7)"C. DIFFUSED AERATION"
1330 LPRINT:LPRINTTAB(8)"NONE":GOTO 1380
1340 LPRINT:LPRINTTAB(7)"B. MECHANICAL AERATION"
1350 LPRINT:LPRINTTAB(8)"NONE"
1360 LPRINT:LPRINTTAB(7)"C. DIFFUSED AERATION"
1370 LPRINT:LPRINTTAB(8)"POD=";POD;"LB(O2)/DA";TAB(30)"PAS=";PAS;"LB/SEC";TAB(62
);"Hp=";HP;"Hp":LPRINTTAB(8)"MHp=";MHP;"Hp"
1380 LPRINT:LPRINTTAB(7)"D. MISCELLANEOUS"
1390 LPRINT:LPRINTTAB(8)"F1=";F1;"MGD";TAB(26)"F2=";F2;"MGD";TAB(50)"F3=";F3;"MG
D"
1400 INPUT"DO YOU WANT COST";Q2$
1410 IFLEFT$(Q2$,1)="N" THEN END
1420 CLS:PRINT"SET PRINTER, PRESS ENTER"
1430 IFINKEY$=""THEN1430
1440 GOSUB 5000
1450 END
4000 CLS
4010 PRINT@64," F,SO,XO                SI,XI     ";STRING$(2,92);"O2";STRING$(2,92);"
   SE                F,SE,XE"
4020 PRINT@139,WA+WB+WC+WB+WA
4030 PRINT@202,WD+WB+WE+WH+ZN+WG+ZO+WH+WD+WB+WE
4040 PRINT@261,WI+ZJ+ZE+W8+ZC+ZK+ZP+ZP+ZP+ZO+ZQ+ZN+WK+ZZ+ZA+ZO+WI+ZJ+ZE+W9+ZC+ZK
+WI
4050 PRINT@331,WL+WM+ZN+ZA+WZ+WJ+WL
4060 PRINT@398,ZO+ZA+ZA+ZA+ZA+ZA+ZA+ZA+ZU+WW+ZN
4070 PRINT@448,"               ";STRING$(2,92);"SLUDGE";STRING$(2,92);"      RECYCLE F
LOW     ";STRING$(2,92);"SLUDGE";STRING$(2,92)
4080 PRINT:PRINT:PRINT"PRESS SPACE BAR TO CONTINUE"
4090 IFINKEY$=""THEN4090
4100 RETURN
5000 REM COST CURVES
5020 PC(1)=1800*EC*F*H:LC(1)=893*LC*F[.253:MC(1)=7.2*IPI*F[.737
5030 PC(2)=14000*EC*F[.404:LC(2)=1133*LC*F[.414:MC(2)=11.7*IPI*F[.402
5037 PC(3)=APC*EC/40.4
5040 LC(3)=560*LC*((APC/1000)[.454):MC(3)=2.6*IPI*(APC/1000)[.768
5050 ONT4GOTO5060,5070
5060 PC(4)=6532*HP*EC:LC(4)=2090*LC*(HP/1000)[.519:MC(4)=17.3*IPI*F[.485:GOTO508
0
5070 PC(4)=6532*HP*EC:LC(4)=1480*LC*(CFM/1000)[.483:MC(4)=17.3*1PI*F[.485
5080 LC(5)=560*LC*(AFC/1000)[.454:MC(5)=2.6*IPI*(AFC/1000)[.768
5083 PC(5)=AFC*EC/40.4
5090 PC(6)=10000*EC*F[.097:LC(6)=467*LC*F[.58
5100 MC(6)=11.1*IPI*F[.439+4200*(F*CD/10)[.957
5110 PC(7)=1148*H1*F1*EC:LC(7)=1400*LC*(6.94*F1)[.434
5120 MC(7)=15.1*IPI*(6.94*F1)[.615
5130 PC(8)=1148*F2*H2*EC:LC(8)=1400*LC*(6.94*F2)[.434
5140 MC(8)=15.1*IPI*(6.94*F2)[.615
5150 PC(9)=1148*F3*H3*EC:LC(9)=1400*LC*(6.94*F3)[.434
5160 MC(9)=15.1*IPI*(6.94*F3)[.615
```

```
5169 IFOT=0THEN5190
5170 PC(10)=31500*EC*(AT/(2870/OT))[.891:LC(10)=440*LC*(AT/(2870/OT))[.385
5180 MC(10)=2.1*IPI*(AT/(2870/OT))[.101
5190 PC(11)=6250*EC*((PS+SFC)/1900)[.778:LC(11)=1053*LC*((PS+SFC)/1900)[.306
5200 MC(11)=12.8*IPI*((PS+SFC)/1900)[.272
5210 LC(12)=933*LC*(ADB/16425)[.854:MC(12)=2.4*IPI*ADB/6844
5300 DIMNU$(12)
5310 FORI=1TO12:READNU$(I):NEXTI
5320 FORI=1TO3:READCN$(I):NEXTI
5330 CLS:PRINT"SET PRINTER ,PRESS ENTER"
5340 IFINKEY$=""THEN5340
5350 LPRINT:LPRINT:LPRINTTAB(20)"ANNUAL COST":LPRINT:LPRINT
5360 FORI=1TO12
5370 LPPINT:LPRINTTAB(5)NU$(I)
5380 IFI=4ANDT4=1THENLPRINTTAB(6)"(MECHANICAL AERATION)"
5390 IFI=4ANDT4=2THENLPRINTTAB(6)"(DIFFUSED AERATION)"
5400 LPRINTTAB(6)CN$(1);TAB(25)CN$(2);TAB(45)CN$(3)
5410 LPRINTTAB(8)PC(I);TAB(27)LC(I);TAB(47)MC(I)
5420 PPC=PC(I)+PPC:LLC=LLC+LC(I):MMC=MMC+MC(I)
5430 NEXTI
5440 LPRINT:LPRINTTAB(20)"TOTAL COST"
5450 LPRINT:LPRINTTAB(6)CN$(1);TAB(25)CN$(2);TAB(45)CN$(3)
5460 LPRINTTAB(8)PPC;TAB(27)LLC;TAB(47)MMC
5470 END:END
5480 DATA LOW-LIFT PUMP STATION,PRELIMINARY TREATMENT,PRIMARY CLARIFIER
5490 DATA ACTIVATED SLUDGE BASIN,FINAL CLARIFIER,CHLORATION
5500 DATA PRIMARY SLUDGE PUMP,SECONDARY SLUDGE PUMP,RECYCLE SLUDGE PUMP,DISSOLVE
D AIR FLOATION THICKENER
5510 DATA TWO-STAGE ANAEROBIC DIGESTER,SLUDGE DRYING BEDS
5520 DATA ELEC. POWER,LABOR,MATERIALS
```

List of Computer Variables

BS	BOD_5 effluent standard, mg/l
XE	suspended solids effluent standard, mg/l
K1	BOD_5 ratio of suspended solids
SO	soluble influent BOD_5, mg/l
F	flow, MGD
APC	area of primary clarifier, ft^2
SE	soluble effluent BOD_5, mg/l
SI	soluble influent after primary clarifier, mg/l
XO	influent suspended solids, mg/l
XI	influent suspended solids after primary clarifier, mg/l
PS	sludge produced from primary clarifier, lbs/day
UM	biokinetic constant
KB	biokinetic constant
KD	biokinetic constant
YT	biokinetic constant
V	volume of aeration basin, MGD
A	settleability constant
N	settleability constant
X	suspended solids concentration in aeration basin, mg/l
AL	sludge recycle rate
XR	suspended solids concentration in underflow, mg/l
FW	wasted sludge flow, MGD
SFC	sludge production from final clarifier, lbs/day
H	low-lift pump station head, ft
H1	primary clarifier sludge pump head, ft
H2	final clarifier sludge pump head, ft

H3	recycle pump head, ft
EC	electric power cost, $/KW-hr
LC	labor cost, $/hr
IPI	industrial price index
LO	solids loading to air flotation unit, lbs/day/ft^2
ED	efficiency of anaerobic digestor
LD	solids loading to digestors, lbs/day
SF	solids concentration of primary sludge, mg/l

Mechanical Aeration

NO	oxygen rating of aerator, lbs O_2/hp hr
B	salinity-surface tension correction factor
CW	oxygen-saturation concentration for wastewater, mg/l
CL	dissolve oxygen concentration, mg/l
TW	temperature of wastewater, °C
AW	oxygen-transfer correction factor
POH	pounds O_2/hr
N1	oxygen rating for plant conditions, lbs O_2/hp hr
HP	horse-power requirement of aerator

Diffused Aeration

AE	transfer efficiency of aeration
PI	absolute inlet pressure, PSIA
PO	absolute outlet pressure, PSIA
TP	temperature of wastewater, °C
E	compressor efficiency
POD	pounds O_2/day

PAS	pounds air/day
MHP	horse-power for mixing
LAD	local air density, lbs/ft^3

APPENDIX B

COST EQUATIONS

1. Low-Lift Pump Station

Power

$\$/YR = 1800\ (EC)\ (F)\ (H)$

Labor

$\$/YR = 893\ (LC)\ (F)^{0.253}$

Materials

$\$/YR = 7.7\ (IPI)\ (F)^{0.737}$

2. Preliminary Treatment (Bar Screens, Grit Chamber)

Power

$\$/YR = 14{,}000\ (EC)\ (F)^{0.404}$

Labor

$\$/YR = 1133\ (LC)\ (F)^{0.414}$

Materials

$\$/YR = 11.7\ (IPI)\ (F)^{0.402}$

3. Primary Clarifier

Power

$\$/YR = APC\ (EC)/40.4$

Labor

$\$/YR = 560\ (LC\ (APC/1000)^{0.454}$

Materials

$\$/YR = 2.6\ (IPI)\ (APC/1000)^{0.768}$

4. Activated Sludge (Diffused Aeration)

Power

$\$/YR = 6532\ (HP)\ (EC)$

Labor

$\$/YR = 2090\ (LC)\ (HP/1000)^{0.519}$

Materials

$\$/YR = 17.3\ (IPI)\ (F)^{0.485}$

5. Final Clarifier

Power

$$\$/YR = AFC\ (EC)/40.4$$

Labor

$$\$/YR = 560\ (LC)\ (AFC/1000)^{0.454}$$

Materials

$$\$/YR = 2.6\ (IPI)\ (AFC/1000)^{0.768}$$

6. Chloration

Power

$$\$/YR = 10{,}000\ (EC)\ (F)^{0.097}$$

Labor

$$\$/YR = 467\ (LC)\ (F)^{0.580}$$

Materials

$$\$/YR = 11.1\ (IPI)\ (F)^{0.439} + 4200\ (F\ (CD)/10)^{0.957}$$

7. Primary Sludge Pump

Power

$$\$/YR = 1148\ (H1)\ (EC)\ (F1)$$

Labor

$$\$/YR = 1400\ (LC)\ (6.94\ (F1))^{0.434}$$

Materials

$$\$/YR = 15.1\ (IPI)\ (6.94\ (F1))^{0.615}$$

8. Secondary Sludge Pump

Power

$$\$/YR = 1148\ (H2)\ (EC)\ (F2)$$

Labor

$$\$/YR = 1400\ (LC)\ (6.94\ (F2))^{0.434}$$

Materials

$$\$/YR = 15.1\ (IPI)\ (6.94\ (F2))^{0.615}$$

9. Recycle Sludge Pump

Power

$\$/YR = 1148\ (H3)\ (EC)\ (F3)$

Labor

$\$/YR = 1400\ (LC)\ (6.94)\ (F3))^{0.434}$

Materials

$\$/YR = 15.1\ (IPI)\ (6.94\ (F3))^{0.615}$

10. Dissolved Air Flotation Thickener

Power

$\$/YR = 31{,}500\ (EC)\ (AT/(2870\ (TOT)))^{0.891}$

Labor

$\$/YR = 440\ (LC)\ (AT/(2870\ (TOT)))^{0.385}$

Materials

$\$/YR = 2.1\ (IPI)\ (AT/(2870\ (TOT)))^{0.101}$

11. Two Stage Anaerobic Digestor

Power

$\$/YR = 6250\ (EC)\ ((PS + SFC)/1900)^{0.778}$

Labor

$\$/YR = 1053\ (LC)\ ((PS + SFC)/1900)^{0.306}$

Materials

$\$/YR = 12.8\ (IPI)\ ((PS + SFC)/1900)^{0.272}$

12. Sludge Drying Beds

Labor

$\$/YR = 933\ (LC)\ (ADB/16{,}425)^{0.854}$

Materials

$\$/YR = (IPI)\ (ADB)/6844$

VITA

David Allan Horner

Candidate for the Degree of

Master of Science

Thesis: OPTIMAL OPERATIONAL CONTROL OF AN ACTIVATED SLUDGE WASTEWATER TREATMENT PLANT IN A CHANGING ENVIRONMENT

Major Field: Bioenvironmental Engineering

Biographical:

Personal Data: Born October 4, 1961, in Ft. Worth, Texas, the son of Thomas and Yvonne Horner. Married to Nancy L. Gieseker on August 7, 1982.

Education: Graduated from Hale High School, Tulsa, Oklahoma, in May, 1979; received the Bachelor of Science in Civil Engineering Degree from Oklahoma State University in May, 1983; completed requirements for the Master of Science Degree at Oklahoma State University in July, 1984.