PROCESS CONTROL OF THE OXIDATION DITCH

by

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APPROVAL

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TABLE OF CONTENTS

	Page
APPROVAL	ii
STATEMENT OF PERMISSION TO USE	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	vi
LIST OF FIGURES	vii
ABSTRACT	viii
INTRODUCTION	1
BIOLOGICAL PROCESSES IN ACTIVATED SLUDGE	2
Cell Growth in a Biological Reactor	2
Bacterial Growth Curve	2
Mass Balance	3
Cellular Metabolism	4
Characteristics of the Extended Aeration System	4
OPERATIONAL PARAMETERS FOR ACTIVATED SLUDGE	5
Mean Cell Retention Time	5
Definition of Mean Cell Retention Time	5
Total Systems Solids	6
Estimation of Clarifier Solids	6
Food to Microorganism Ratio	7
Definition of F:M	7
Typical Range for Food to Microorganism Ratio	7
BOD Sludge Age	7
Definition of BOD Sludge Age	7
Typical Range for BOD Sludge Age	8
Gould Sludge Age	8
Definition of Gould Sludge Age	8
Drawback of Gould Sludge Age	9
Sludge Volume Fraction	9

TABLE OF CONTENTS—Continued

Page

BULKING SLUDGE 10

Definition of Bulking Sludge 10
Characteristics of Bulking Sludge at Miles City 10
Sludge Volume Fraction 10
Microscopic Examination 10
Temporary Control of Bulking Sludge 10
Causes of Filamentous Bulking 11
Food to Microorganism Ratio 11
Anoxic Zones in Aerator 11
Remedies for Bulking Sludge 11
Increased Aeration and Chlorination of Return Lines 11
Contact Basin 12

STATEMENT OF OBJECTIVE 13

DESCRIPTION OF MILES CITY PLANT 14

Geographical Location 14
Plant Equipment and Capacity 14

RESULT OF DATA ANALYSIS 16

Mean Cell Retention Time 16
Food to Microorganism Ratio 16
BOD Sludge Age 16
Gould Sludge Age 20
Sludge Volume Fraction 20

SUMMARY 21

BIBLIOGRAPHY 22

APPENDIX 25

LIST OF TABLES

Tables Page

I. Table of Results 26

II. Table of Calculations. 30

LIST OF FIGURES

Figures		Page
I.	Typical bacterial growth curve	2
II.	Plant layout and plant piping	15
III.	BOD removal efficiency, mean cell retention time, and food to microorganism ratio for June 1981 to October 1981 at Miles City, Montana	17
IV.	BOD removal efficiency, mean cell retention time, and food to microorganism ratio for November 1981 to March 1982 at Miles City, Montana	18
V.	BOD removal efficiency, mean cell retention time, and food to microorganism ratio for April 1982 to August 1982 at Miles City, Montana	19

ABSTRACT

Parameters such as food to microorganism ratio (F:M), mean cell retention time (MCRT), and sludge age are evaluated in terms of their effectiveness in an extended aeration system. Through the analysis of data from fifteen months of operation of the Miles City, Montana, oxidation ditch, operating procedures are recommended. Optimum conditions as they relate to BOD removal efficiency have not been defined in terms of a specific value for MCRT, F:M, or BOD sludge age, but rather a range of values of 13-33 days for MCRT, 0.03-0.24 d^{-1} for F:M, and 4-33 days for BOD sludge age has been found to be most useful. No correlation between Gould sludge age and BOD removal of efficiency is found and so the use of Gould sludge age is not recommended for the Miles City facility. Sludge volume fraction should be used only as a description tool. Bulking sludge due to filamentous microorganisms remains a problem at Miles City. A remedial measure may be the use of a contact basin upstream from the aerator.

INTRODUCTION

Much has been written about the operational control of the conventional activated sludge process. Parameters such as mean cell retention time, food to microorganism ratio, and sludge age are traditionally used in solids control and in the evaluation of the performance of extended aeration systems such as the oxidation ditch, as well as conventional activated sludge. Because problems with solids control and sludge settleability were encountered in the operation of an oxidation ditch in Miles City, Montana, the author determined to analyze the above parameters in an effort to facilitate operational control at the Miles City facility. This paper uses the data from fifteen months of operation to illustrate properties of mean cell retention time, food to microorganism ratio, Gould sludge age, BOD sludge age, and sludge volume fraction in the oxidation ditch method of wastewater treatment.

BIOLOGICAL PROCESSES IN ACTIVATED SLUDGE

Biological processes will be described in terms of cell growth in general and in the specific case of the extended aeration system.

Cell Growth in a Biological Reactor

Cellular growth and metabolism may be described in terms of the bacterial growth curve and a mass balance expression.

Bacterial Growth Curve

Cell growth in a biological reactor may be illustrated by the bacterial growth curve in Figure I.

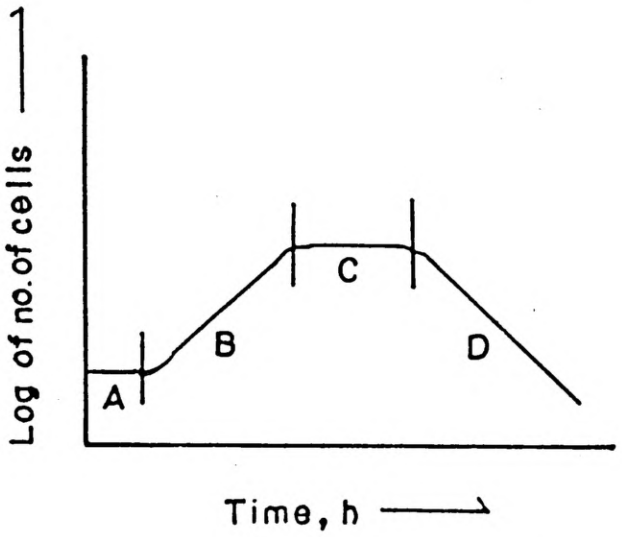


Figure I. Typical bacterial growth curve (Pelczar, 1977).

Segment A represents the lag phase in which the population remains temporarily unchanged when inoculum is added to new medium. B is the logarithmic growth phase where cells divide steadily. During this stage the growth rate is maximum. C is the stationary phase. Here the population remains constant because the reproduction rate equals the death rate. D is the log death phase in which endogenous respiration occurs. The term endogenous respiration indicates that because of the depletion of nutrients, the cells themselves become less massive. In this phase bacteria die faster than new cells are reproduced (Pelczar, 1977).

Cell growth in a biological reactor may be described mathematically by:

$$\frac{dx}{dt} = Y \frac{dF}{dt} - bx$$

where

dx/dt = growth rate of microorganisms

Y = cell yield coefficient (0.4-0.8 mg VSS/mg BOD)

dF/dt = rate of substrate utilization

b = endogenous respiration coefficient (0.04-0.075 d^{-1})

x = cell mass (EPA-600/2-75-058, 1975)

Mass Balance

As given by Metcalf and Eddy (1979), a general statement for the mass balance of microorganisms in an activated sludge system is

rate of accumulation of microbes within system boundary	=	rate of flow of microbes into system	-	rate of flow of microbes out of system	+	net growth of microbes within system

or:

accumulation	=	inflow	-	outflow	+	net growth

Cellular Metabolism

In a biological reactor such as the Miles City facility, microbial cell growth and metabolism may be characterized by an anabolic phase where nutrients are assimilated into microbial cells and by the catabolic phase in which compounds are oxidized to smaller and simpler products to provide energy to the cells (Brock, 1974). The net organism growth is that material which is produced by the system but is not oxidized by endogenous respiration (Stewart, 1964). These processes may be represented by the following chemical reactions:

i. Oxidation (catabolism)

$$\underset{\text{(organic matter)}}{COHNS} + O_2 + \text{bacteria} \rightarrow CO_2 + NH_3 + \text{energy} + \text{other end products}$$

ii. Synthesis (anabolism)

$$\underset{\text{(organic matter)}}{COHNS} + O_2 + \text{bacteria} + \text{energy} \rightarrow \underset{\text{(new bacterial cells)}}{C_5H_7NO_2}$$

iii. Endogenous Respiration

$$C_5H_7NO_2 + 5O_2 \rightarrow NH_3 + 2H_2O + \text{energy}$$

(Amirtharajah, 1979)

Characteristics of the Extended Aeration System

Typical volumetric loading for extended aeration systems is 20 lbs BOD/day/1000 cu. ft. of aerator volume (Stewart, 1964). The large aerator capacity enables the system to accommodate a large number of microorganisms. This characteristic, coupled with the low volumetric loading rate, give low loading factors that are typical of the extended aeration system (Stewart, 1964).

Since the oxidation ditch operates in the endogenous respiration phase of the microbial growth curve, only a small amount of net growth of volatile sludge occurs (Stewart, 1964).

OPERATIONAL PARAMETERS FOR ACTIVATED SLUDGE

In this section mean cell retention time, food to microorganism ratio, BOD sludge age, Gould sludge age, and sludge volume fraction are defined and discussed.

Mean Cell Retention Time

Definition of Mean Cell Retention Time

The MCRT is an expression of the average time that a microorganism spends in the system (EPA-430-9-77-006, 1977). The total system MCRT as defined by Metcalf and Eddy (1979) is given by:

$$\theta_{ct} = \frac{V_t X_t}{Q_w X_r + Q_e X_e}$$

where:

V_t = total system volume (from clarifier and aerator)

X_t = total system solids (from clarifier and aerator)

Q_w = waste activated sludge flow rate (from clarifier)

X_r = suspended solids conc. in return sludge (from clarifier)

Q_e = plant flow rate

X_e = effluent suspended solids conc.

But because of the bulking problem at Miles City from January 1982 to April 1982 where solids were lost over the effluent weir (peak flow rate is 2.55 MGD, effluent SS concentration is about 100 mg/ℓ, and duration is 6 hours), the MCRT becomes:

$$\theta_{ct} = \frac{V_t X_t}{Q_w X_r + Q_B X_B + Q_e X_e}$$

where:

Q_B = flow rate during 6 hr. period of peak flow when solids were lost from clarifier

X_B = conc. of bulking sludge

Q_e = total effluent flow minus Q_B

X_e = effluent suspended solids concentration

The sum of Q_B and Q_e is the total effluent flow, Q.

Total System Solids

In determining the mean cell retention time (MCRT), there is some controversy as to whether the solids concentration in the entire system (includes aeration basin and secondary clarifier) should be used in the calculations, or only the aeration basin solids should be used (Karr, 1980). In support of the latter argument, it is assumed that the dissolved oxygen (D.O.) level in the secondary clarifier is too low for the growth of microorganisms. In addition, it is often difficult to obtain accurate measurements of clarifier solids. But in the Miles City facility, the clarifier operates in a solids overloaded condition during peak flow. This subsequently causes a decrease of solids in the aeration basin. If calculations of MCRT were based on aeration basin solids only, then values would vary depending on the time of day. For this reason the MCRT will be calculated using the total system solids.

Estimation of Clarifier Solids

The MLSS method of clarifier solids estimation as described by Karr (1980) involves the assumption that the average solids concentration in the clarifier is roughly equivalent to the MLSS concentration. So, by multiplying the clarifier volume by MLSS, one can obtain a value for clarifier solids.

Food to Microorganism Ratio

Definition of F:M

McKinney developed the concept of food to microorganism (F:M) ratio as a control parameter in the activated sludge process. By definition,

$$F{:}M = \frac{QC_o}{VX_a}$$

where:

Q = influent flow rate

C_o = influent BOD concentration

V = volume aerator

X_a = volatile suspended solids conc. aerator (MLVSS)

F:M control may be used to ensure that the activated sludge process is being loaded at a rate such that the microorganisms in the MLSS (as approximated by MLVSS) are able to use most of the substrate in the wastewater being treated. In general, the lower the F:M ratio, the higher the MLVSS.

Typical Range for Food to Microorganism Ratio

A typical range for F:M loading in an extended aeration system is 0.05-0.1 d^{-1} (EPA-430-9-77-006, 1977).

BOD Sludge Age

Definition of BOD Sludge Age

BOD sludge age (θ_{BOD}) is simply the reciprocal of the F:M as developed by McKinney (Stall et al., 1978).

$$\theta_{BOD} = \frac{VX_a}{QC_o}$$

where:

V = aerator volume

X_a = MLVSS

Q = influent flow rate

C_o = influent BOD conc.

Typical Range for BOD Sludge Age

A typical range for θ_{BOD} in an extended aeration system is 10 to 20 days.

In some cases the BOD sludge age may be easier to use than F:M because the units of days of the θ_{BOD} is more easily conceptualized than the units of $days^{-1}$ of the F:M ratio.

Gould Sludge Age

Definition of Gould Sludge Age

Gould sludge age (θ_g) as recognized by Stall (1978) is:

$$\theta_g = \frac{VX_a}{QX_o}$$

where:

V = aerator volume

X_a = mixed liquor volatile suspended solids conc. (MLVSS)

Q = influent flow rate

X_o = influent suspended solids conc.

This concept of sludge age is based on the ratio of the lbs/day of influent wastewater suspended matter to the solids inventory in the aeration tank (EPA-430-9-77-006, 1977). Thus, it must be assumed that the ratio between the influent BOD and influent SS is fairly constant.

Drawback of Gould Sludge Age

When the influent BOD:influent SS conc. ratio changes, θ_g is less effective as a control technique.

Sludge Volume Fraction

The sludge volume fraction (SVF) is an operational tool in which sludge settleability is described by the rate of sludge sedimentation in the settleometer test. The SVF, as given by Sanks, = volume sludge settled/total sample volume.

The real value in the SVF is in its use as a process stability indicator in which actual values of SVF are not as important as changes in the SVF as they occur over time.

BULKING SLUDGE

Definition of Bulking Sludge

A bulked sludge is one that has poor settling characteristics and poor compactibility. Two principal types of sludge bulking problems have been identified. One is caused by the growth of filamentous organisms and the other is caused by bound water in which the bacterial cells composing the floc swell to the extent that their density is reduced and they will not settle (Metcalf and Eddy, 1979).

Characteristics of Bulking Sludge at Miles City

Sludge Volume Fraction*

After the first three months of operation of the oxidation ditch at Miles City, sludge settleability deteriorated to the point where sludge volume fraction (SVF) remained in a range between 0.70 and 0.95.

Microscopic Examination

Upon microscopic examination, a predominance of filamentous microorganisms was noted. This microbial population was identified to be the cause of a bulking problem which began in January 1982 and has continued to the present.

Temporary Control of Bulking Sludge

Pipes (1978) observed that bulking sludge produces good effluent in terms of suspended solids removal if the operator can prevent the solids from overflowing the effluent

*Obtained from settleometer test: SVF = volume sludge settled/total sample volume (Sanks).

weir. At the Miles City plant this is accomplished by continuous return pumping and manipulation of return valves during periods of peak hydraulic flow.

Causes of Filamentous Bulking

Food to Microorganism Ratio

Pipes also noted that the most extreme cases of bulking were found in processes having F:M ratios less than 0.2 d^{-1}. Ninety-five percent of the time from June 1981 to August 1982 the Miles City oxidation ditch operated with F:M ratios under 0.2 d^{-1}.

Anoxic Zones in Aerator

In some areas anoxic zones (dissolved oxygen less than 0.7 mg/ℓ) exist in the ditch at depths from 8 feet to 10 feet. As Pitman (1980) observed, processes which incorporate zones for the purpose of denitrification will produce a sludge with poor settling properties. It would appear that the passage of sludge through non-aerated zones of the reactor, together with the lack of aeration in the aerobic zone, encourages the growth of filamentous organisms (Pitman, 1980).

Remedies for Bulking Sludge

Increased Aeration and Chlorination of Return Lines

Measures taken in an attempt to suppress the numbers of filamentous organisms included increased wasting, increased aeration, and chlorination of sludge return lines. All of the above measures failed to bring about a long term solution to the bulking problem. Chlorine was dosed to the return sludge lines in January, February, and March at levels reaching 4.5 lbs Cl_2/1000 lbs MLVSS. This chlorination failed to inhibit filamentous growth, but may have been responsible for the break-up of filaments and the subsequent decrease in SVF and BOD removal efficiency as these broken filaments were being carried over into the effluent.

Contact Basin

A method of filamentous organism control suggested by Tchobanoglous involves the addition of an aerobic contact basin (detention time = approximately one hour) upstream of the reactor. As the return sludge is exposed to influent wastewater all organisms incorporate substrate as a carbon source but only the non-filamentous organisms are able to store carbon. In this way the growth of filamentous organisms is restricted in the reactor and non-filamentous organisms predominate and enhance settling characteristics. Although this method was not attempted at the Miles City oxidation ditch, its use as a possible remedy for filamentous bulking is worthy of note.

STATEMENT OF OBJECTIVE

The purpose of this paper is to evaluate parameters that are commonly used in the control of activated sludge systems in terms of their effectiveness in BOD and suspended solids removal. Possible solutions to operational problems, as they relate to solids control and bulking sludge at the Miles City oxidation ditch, will be suggested.

DESCRIPTION OF MILES CITY PLANT

Geographical Location

Miles City, Montana, population about 10,000, is situated in a rural area of southeastern Montana where the winters are long and severe (temperatures dropping to -30°F) and summertime temperatures peak at 100°F. Influent wastewater temperatures range from 9°C to 23°C. Freezing on the oxidation ditch surface is a problem inasmuch as the ice bends rotor blades as it passes through. Freezing in the scum tank of the clarifiers makes scum removal difficult.

Plant Equipment and Capacity

Domestic wastewater treatment is accomplished by two oxidation ditches that are ten feet deep. With both ditches operational, design flow is 1.98 MGD. There are two peripheral feed clarifiers (248,000 gal. capacity), a chlorine contact basin, aerobic digester (177,000 gal. capacity), sludge drying beds, and an aerobic sludge storage basin (745,000 gal. capacity). At present, one ditch and both clarifiers are in operation. A schematic of the plant layout, piping, and flow is shown in Figure II.

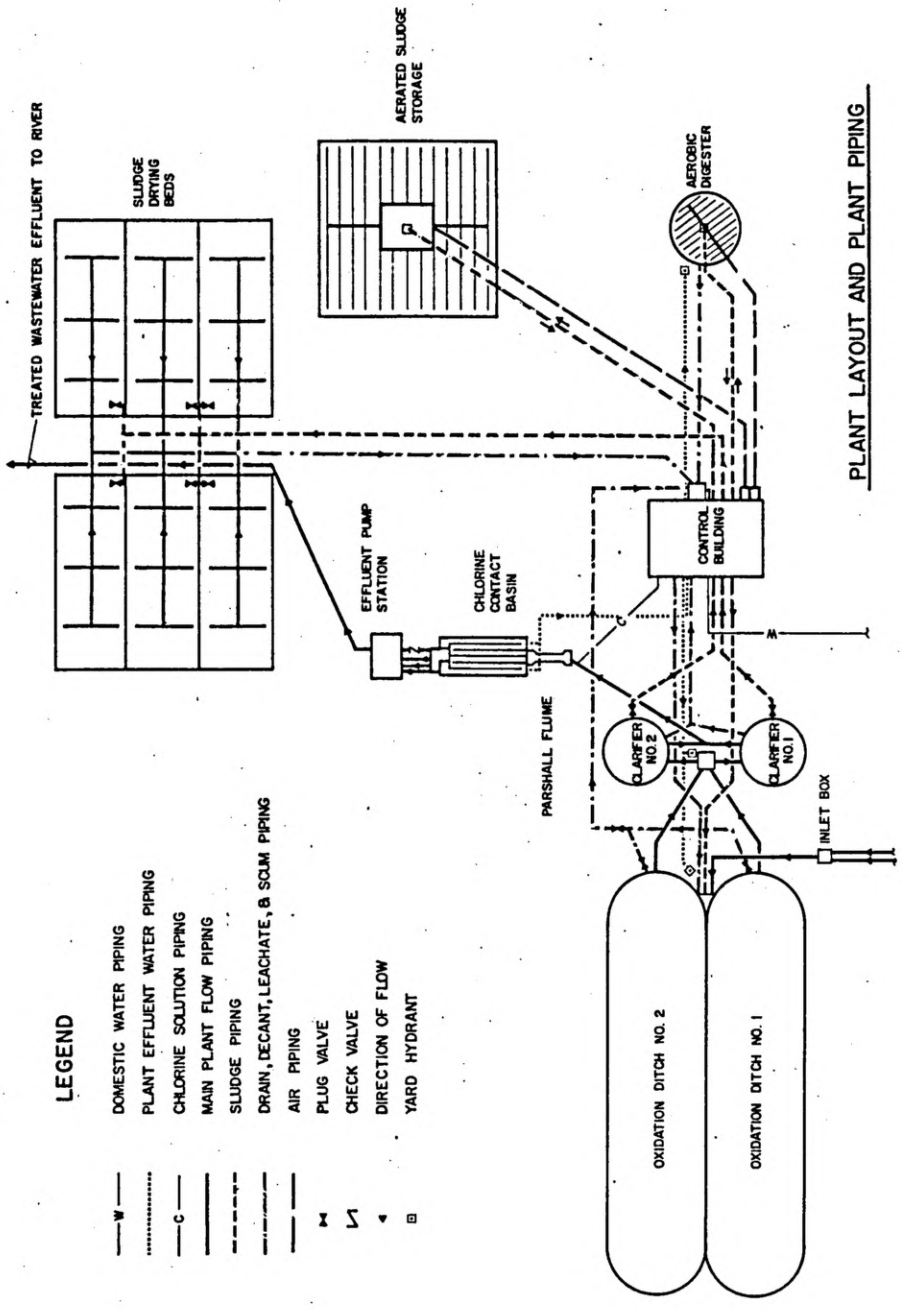


Figure II. Plant layout and plant piping (Morrison-Maierle, Inc.).

RESULTS OF DATA ANALYSIS

Mean Cell Retention Time

The average MCRT at Miles City was in the range between 13 and 30 days. In comparing MCRT with BOD and SS removal efficiency, little correlation was found. The correlation coefficient for MCRT versus BOD removal efficiency is 0.21 (see Figures III, IV, and V). Results indicate a lack of sensitivity in MCRT as an operational tool at the Miles City facility.

Although a specific MCRT was periodically used to calculate waste sludge flow rates, results suggest that a range of values between 13 and 30 days provides adequate BOD removal and is more practical than the selection of one MCRT value.

Food to Microorganism Ratio

In terms of operational control at Miles City, acceptable BOD removal may be effected by maintaining F:M ratio greater than 0.03 d^{-1} but less than 0.24 d^{-1} (see Figures III, IV, and V).

BOD Sludge Age

The range for θ_{BOD} at Miles City is 3.85 to 33.0 days with a mean value of 12.2 days. Acceptable BOD removal efficiencies are obtained by the maintenance of θ_{BOD} between 4.0 and 33.0 days.

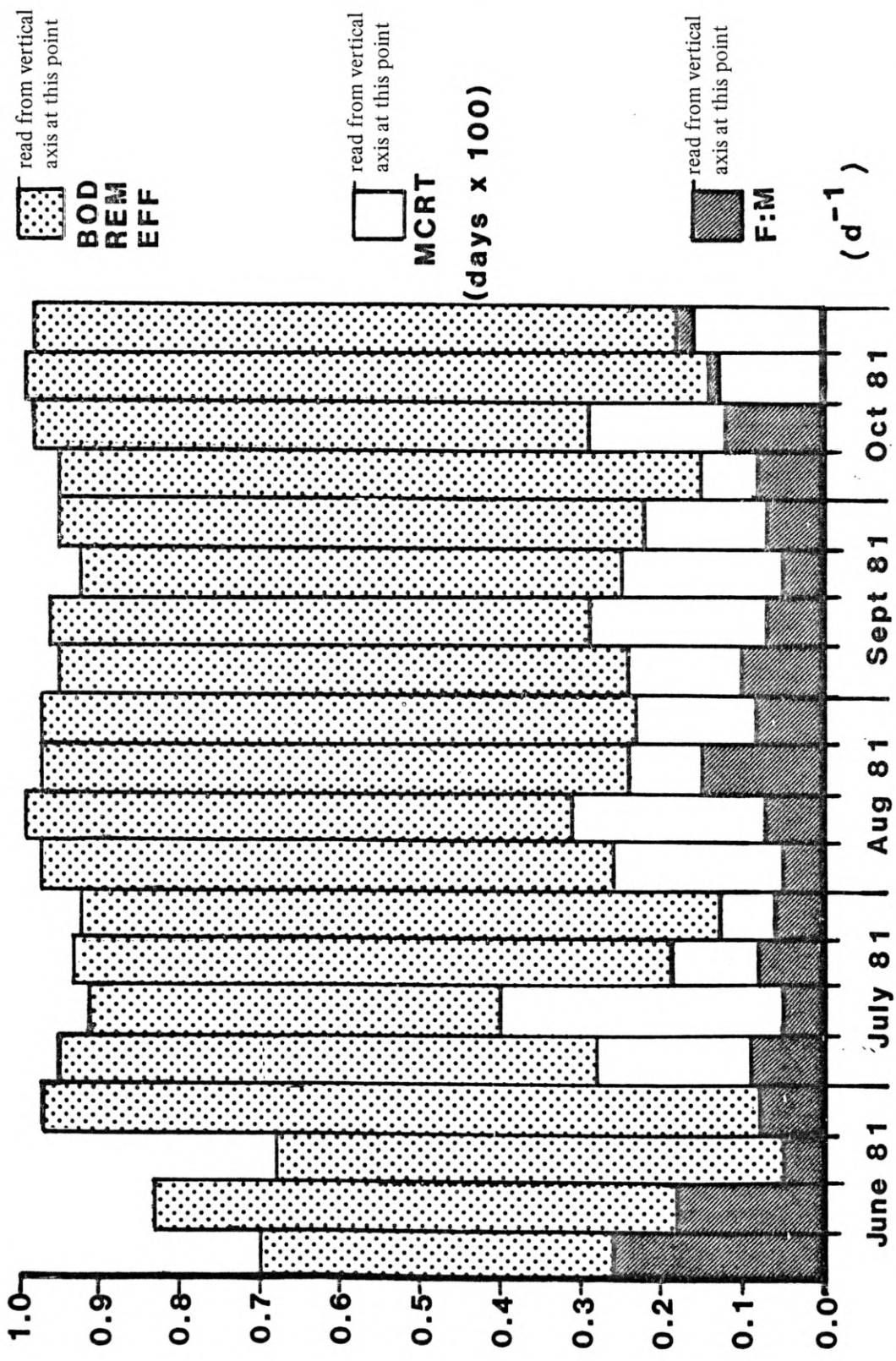


Figure III. BOD removal efficiency, mean cell retention time, and food to microorganism ratio for June 1981 to October 1981 at Miles City, Montana.

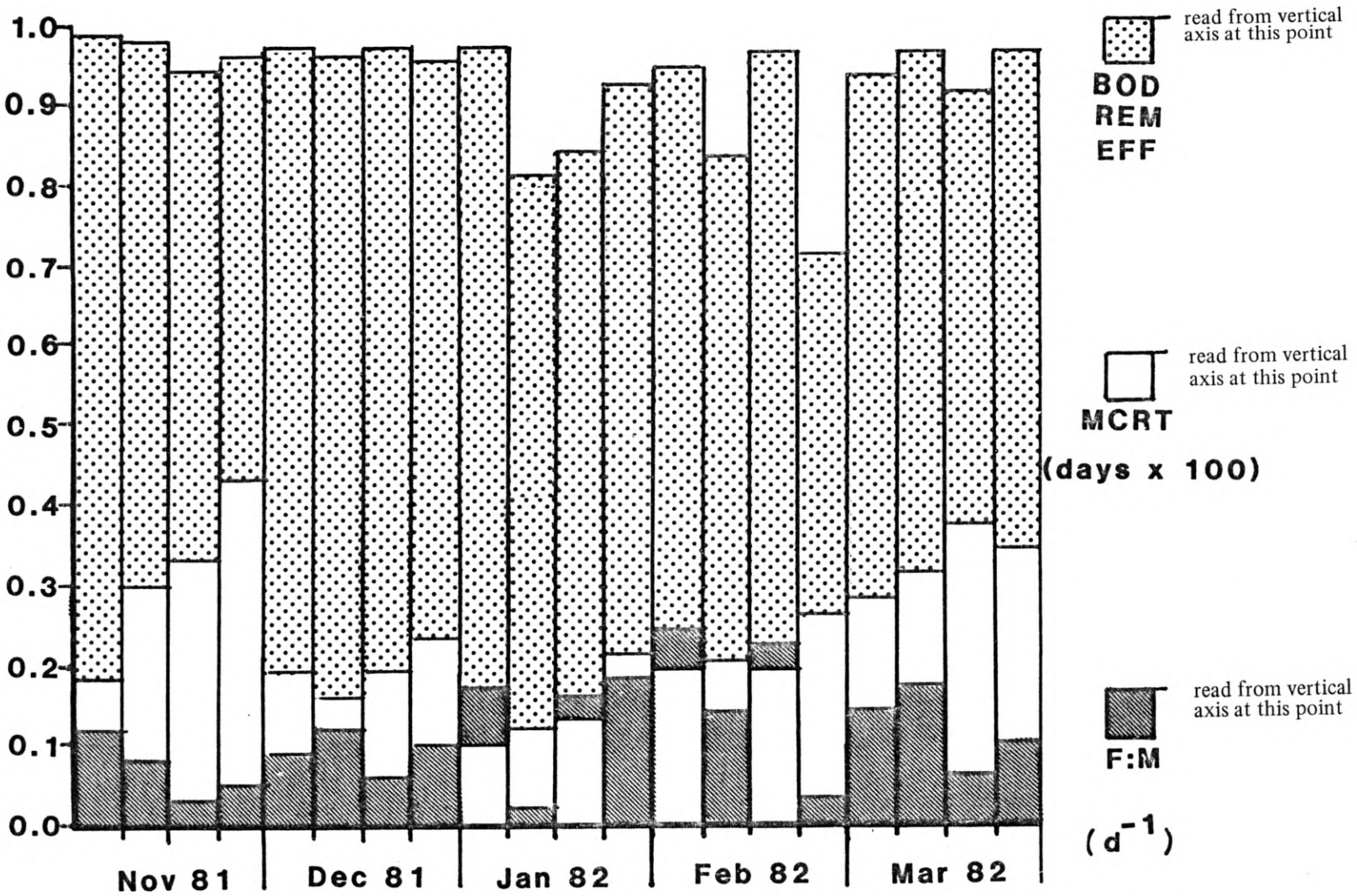


Figure IV. BOD removal efficiency, mean cell retention time, and food to microorganism ratio for November 1981 to March 1982 at Miles City, Montana.

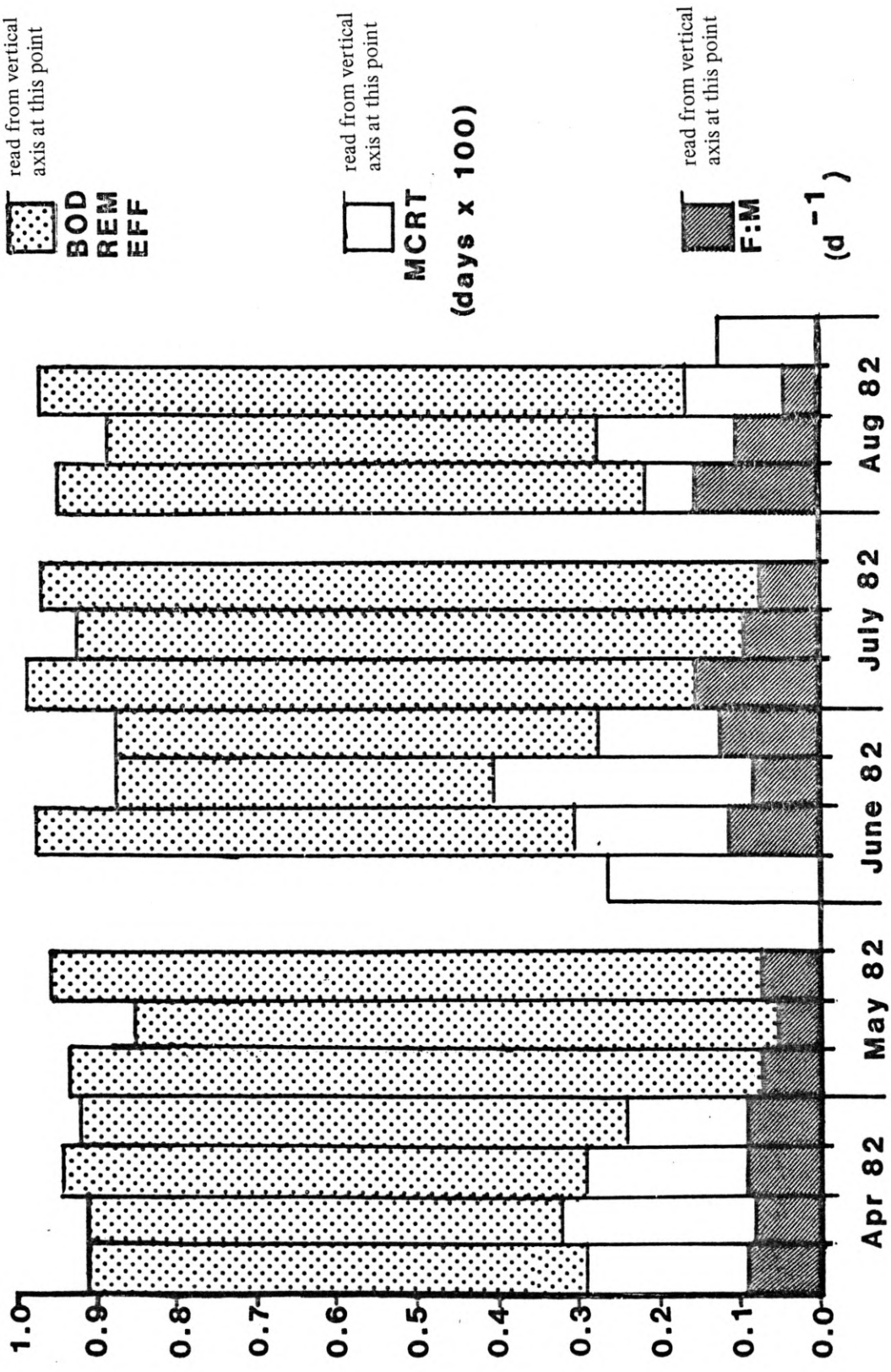


Figure V. BOD removal efficiency, mean cell retention time, and food to microorganism ratio for April 1982 to August 1982 at Miles City, Montana.

Gould Sludge Age

During fifteen months of operation the influent BOD:influent SS ratio range from 0.22 to 2.97, the mean value was 2.44, and standard deviation was 11.36. Thus the influent BOD:influent SS ratio does change significantly and this is probably why no correlation was found between θ_g and BOD removal efficiency. It may be concluded that for Miles City, the θ_g is an insensitive control technique in the optimization of BOD removal.

Sludge Volume Fraction

Typically, the sludge volume fraction at the Miles City plant was high because of the presence of excess numbers of filamentous microorganisms and their hindrance of sludge settleability. Even when wide variations of SVF were experienced, the BOD removal remained high as long as bulking solids did not overflow the effluent weir. No correlation was found between BOD removal efficiency and SVF. Derivation of an optimal range of SVF values was not possible for the Miles City facility. Also, no correlation was found between F:M ratio and SVF.

SUMMARY

Based on the results of this study, it may be concluded that for the Miles City oxidation ditch, a range of values for the MCRT between 13 and 30 days is more desirable as an operational parameter than the use of any one specific value.

As with MCRT, a range of values for the food to microorganism ratio is more useful than the derivation of a specific value. Adequate BOD removal efficiencies were accomplished when F:M values were between 0.03 d^{-1} and 0.24 d^{-1}.

BOD sludge age is simply the reciprocal of the F:M ratio, so technically, the results of calculations involving BOD sludge age are identical to those using F:M. But the units of days as given by BOD sludge age facilitate operator understanding. This fact may favor the use of BOD sludge over the use of F:M ratio.

Since results show Gould sludge age to be an insensitive parameter in terms of process efficiency, its use is not recommended for the Miles City oxidation ditch.

Sludge volume fraction is useful only in the description of sludge settleability. The only variation in SVF occurring after initial start-up was due to temporarily enhanced settleability. This was a result of the disintegration of filamentous microorganisms after the chlorination of return activated sludge.

As remedies for the control of bulking sludge due to filamentous organisms, increased wastage, increased aeration, and return sludge chlorination were unsuccessful at Miles City.

It is not intended that the results of this study be extrapolated for use in all activated sludge or extended aeration systems. The results are unique to the oxidation ditch at Miles City, Montana. It is hoped that these conclusions will expedite operation at Miles City and provide useful background to others in the start-up and operation of an extended aeration system.

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APPENDIX

Table I. Table of Results

Parameter	Week 1	2	3	4
June 1981				
Inf. BOD:Inf. SS ratio	1.1	1.12	2.97	0.62
Sludge volume fraction, SVF	–	–	0.20	0.53
BOD sludge age, θ_{BOD} (days)	3.85	5.56	20.0	12.5
Gould sludge age, θ_g (days)	5.86	5.70	16.3	6.81
Mean cell retention time, θ_{ct} (days)	77.8	60.8	71.3	114
Food to microorganism ratio, F:M ($days^{-1}$)	0.26	0.18	0.05	0.08
BOD removal efficiency (%)	70	83	68	97
SS removal efficiency (%)	90	83	96	88
July 1981				
Inf. BOD:Inf. SS ratio	4.0	0.64	1.35	0.22
Sludge volume fraction, SVF	0.87	0.92	0.44	0.26
BOD sludge age, θ_{BOD} (days)	11.1	20.0	12.5	16.7
Gould sludge age, θ_g (days)	42.6	24.0	17.1	19.2
Mean cell retention time, θ_{ct} (days)	28.0	40.0	19.0	13.0
Food to microorganism ratio, F:M ($days^{-1}$)	0.09	0.05	0.08	0.06
BOD removal efficiency (%)	95	91	93	92
SS removal efficiency (%)	78	91	91	75
August 1981				
Inf. BOD:Inf. SS ratio	0.24	0.60	0.31	0.83
Sludge volume fraction, SVF	0.63	0.25	0.61	0.23
BOD sludge age, θ_{BOD} (days)	20.0	14.3	6.7	12.5
Gould sludge age, θ_g (days)	5.6	8.1	2.1	7.3
Mean cell retention time, θ_{ct} (days)	26.4	31.0	24.0	23.0
Food to microorganism ratio, F:M ($days^{-1}$)	0.05	0.07	0.15	0.08
BOD removal efficiency (%)	97	99	97	97
SS removal efficiency (%)	95	93	95	95
September 1981				
Inf. BOD:Inf. SS ratio	0.64	1.22	0.44	0.58
Sludge volume fraction, SVF	0.27	0.37	0.49	0.52
BOD sludge age, θ_{BOD} (days)	10.0	14.3	20.0	14.3
Gould sludge age, θ_g (days)	6.5	18.2	9.2	14.7
Mean cell retention time, θ_{ct} (days)	23.7	28.9	25.3	21.7
Food to microorganism ratio, F:M ($days^{-1}$)	0.10	0.07	0.05	0.07
BOD removal efficiency (%)	95	96	92	95
SS removal efficiency (%)	97	98	98	87
October 1981				
Inf. BOD:Inf. SS ratio	0.78	1.56	1.00	1.16
Sludge volume fraction, SVF	0.66	0.55	0.62	0.70
BOD sludge age, θ_{BOD} (days)	12.5	8.3	7.1	5.6
Gould sludge age, θ_g (days)	9.6	12.7	6.8	6.6
Mean cell retention time, θ_{ct} (days)	15.4	28.9	12.8	15.6

Table I. (continued)

Parameter	Week 1	2	3	4
October 1981 (continued)				
Food to microorganism ratio, F:M ($days^{-1}$)	0.08	0.12	0.14	0.18
BOD removal efficiency (%)	95	98	99	98
SS removal efficiency (%)	94	94	97	99
November 1981				
Inf. BOD:Inf. SS ratio	1.34	0.65	0.84	0.48
Sludge volume fraction, SVF	0.88	0.89	0.87	0.89
BOD sludge age, θ_{BOD} (days)	8.3	12.5	33.3	20.0
Gould sludge age, θ_g (days)	10.5	8.5	29.7	8.7
Mean cell retention time, θ_{ct} (days)	17.6	29.7	33.3	43.1
Food to microorganism ratio, F:M ($days^{-1}$)	0.12	0.08	0.03	0.05
BOD removal efficiency (%)	99	98	94	96
SS removal efficiency (%)	96	97	89	99
December 1981				
Inf. BOD:Inf. SS ratio	1.34	0.57	0.75	1.02
Sludge volume fraction, SVF	0.89	0.90	0.93	0.95
BOD sludge age, θ_{BOD} (days)	11.1	8.3	16.7	10.0
Gould sludge age, θ_g (days)	14.3	–	9.7	8.7
Mean cell retention time, θ_{ct} (days)	18.5	16.2	19.3	23.1
Food to microorganism ratio, F:M ($days^{-1}$)	0.09	0.12	0.06	0.10
BOD removal efficiency (%)	97	96	97	95
SS removal efficiency (%)	93	–	85	91
January 1982				
Inf. BOD:Inf. SS ratio	0.97	0.81	0.64	0.64
Sludge volume fraction, SVF	0.95	0.94	0.94	0.86
BOD sludge age, θ_{BOD} (days)	5.9	–	6.3	5.6
Gould sludge age, θ_g (days)	5.8	24.0	4.6	3.6
Mean cell retention time, θ_{ct} (days)	10.4	11.9	13.1	20.8
Food to microorganism ratio, F:M ($days^{-1}$)	0.17	0.02	0.16	0.18
BOD removal efficiency (%)	97	81	84	92
SS removal efficiency (%)	97	77	96	92
February 1982				
Inf. BOD:Inf. SS ratio	1.15	0.54	0.79	0.37
Sludge volume fraction, SVF	0.94	0.85	0.82	0.78
BOD sludge age, θ_{BOD} (days)	4.2	7.1	4.6	33.3
Gould sludge age, θ_g (days)	4.4	3.9	3.5	11.6
Mean cell retention time, θ_{ct} (days)	19.4	20.4	19.2	26.4
Food to microorganism ratio, F:M ($days^{-1}$)	0.24	0.14	0.22	0.03
BOD removal efficiency (%)	94	83	96	71
SS removal efficiency (%)	89	98	98	98

Table I. (continued)

Parameter	Week 1	2	3	4
March 1982				
Inf. BOD:Inf. SS ratio	0.81	1.00	0.43	0.88
Sludge volume fraction, SVF	0.87	0.73	0.77	0.81
BOD sludge age, θ_{BOD} (days)	7.1	5.9	16.7	10.0
Gould sludge age, θ_g (days)	5.6	6.3	6.6	8.8
Mean cell retention time, θ_{ct} (days)	28.3	31.3	36.6	33.9
Food to microorganism ratio, F:M ($days^{-1}$)	0.14	0.17	0.06	0.10
BOD removal efficiency (%)	93	96	91	96
SS removal efficiency (%)	96	95	96	88
April 1982				
Inf. BOD:Inf. SS ratio	0.63	0.69	0.85	0.51
Sludge volume fraction, SVF	0.84	0.79	0.75	0.78
BOD sludge age, θ_{BOD} (days)	11.1	12.5	11.1	11.1
Gould sludge age, θ_g (days)	7.2	8.5	9.5	5.6
Mean cell retention time, θ_{ct} (days)	29.4	31.9	28.7	23.6
Food to microorganism ratio, F:M ($days^{-1}$)	0.09	0.08	0.09	0.09
BOD removal efficiency (%)	91	91	94	92
SS removal efficiency (%)	91	95	86	92
May 1982				
Inf. BOD:Inf. SS ratio	0.44	0.44	–	–
Sludge volume fraction, SVF	0.71	0.71	0.74	0.78
BOD sludge age, θ_{BOD} (days)	14.3	20.0	14.3	–
Gould sludge age, θ_g (days)	7.6	9.0	–	7.6
Mean cell retention time, θ_{ct} (days)	–	–	–	–
Food to microorganism ratio, F:M ($days^{-1}$)	0.07	0.05	0.07	–
BOD removal efficiency (%)	93	85	95	–
SS removal efficiency (%)	91	92	–	88
June 1982				
Inf. BOD:Inf. SS ratio	–	0.81	0.80	–
Sludge volume fraction, SVF	0.77	0.76	0.80	0.89
BOD sludge age, θ_{BOD} (days)	–	9.1	12.5	8.3
Gould sludge age, θ_g (days)	7.7	7.2	9.7	9.5
Mean cell retention time, θ_{ct} (days)	26.2	29.7	39.9	27.3
Food to microorganism ratio, F:M ($days^{-1}$)	–	0.11	0.08	0.12
BOD removal efficiency (%)	–	97	87	87
SS removal efficiency (%)	95	–	91	94
July 1982				
Inf. BOD:Inf. SS ratio	1.0	0.96	0.34	–
Sludge volume fraction, SVF	0.78	0.82	0.85	0.87
BOD sludge age, θ_{BOD} (days)	6.7	11.1	14.3	–
Gould sludge age, θ_g (days)	7.0	7.7	5.1	–
Mean cell retention time, θ_{ct} (days)	–	–	–	–

Table I. (continued)

Parameter	Week 1	2	3	4
July 1982 (continued)				
Food to microorganism ratio, F:M ($days^{-1}$)	0.15	0.09	0.07	–
BOD removal efficiency (%)	98	92	96	–
SS removal efficiency (%)	96	92	98	–
August 1982				
Inf. BOD:Inf. SS ratio	0.89	0.90	1.0	–
Sludge volume fraction, SVF	0.87	0.87	0.88	0.87
BOD sludge age, θ_{BOD} (days)	6.7	10.0	25.0	–
Gould sludge age, θ_g (days)	6.1	9.4	9.4	7.2
Mean cell retention time, θ_{ct} (days)	21.4	26.5	15.8	11.7
Food to microorganism ratio, F:M ($days^{-1}$)	0.15	0.10	0.04	–
BOD removal efficiency (%)	94	88	96	–
SS removal efficiency (%)	95	92	77	72

Table II. Table of Calculations

Wk.	MLVSS (mg/ℓ)	Clar. Solids (mg)	Aerator Solids (mg)	x_t Tot. Sys. Solids (mg)	Q_w (ℓ/d)	x_r (mg/ℓ)	Q_e (ℓ/B)	x_e (mg/ℓ)	θ_{ct} MCRT (d)	$\theta(\frac{V}{Q})$ (d)	S_o (mg/ℓ)	F:M (d^{-1})	Inf. SS (x_o)(mg/ℓ)	θ_g (d)	θ_{BOD} (d)	BOD Rem. Effic. (%)	SS Rem. Effic. (%)	SVF	Inf. BOD: Inf. SS
June 1981																			
1	941	8.86×10^8	3.99×10^9	4.88×10^9	0	–	4.92×10^6	12.75	77.8	0.86	211	0.26	138	5.86	3.85	70	90		1.1
2	1,385	1.30×10^9	5.88×10^9	7.18×10^9	0	–	4.92×10^6	23.75	60.8	0.86	209	0.18	209	5.70	5.56	83	83		1.12
3	2,019	1.89×10^9	8.58×10^9	1.05×10^{10}	0	–	5.08×10^6	29.25	11.3	0.84	80	0.05	104	16.3	20.0	68	96	0.195	2.97
4	2,807	2.64×10^9	1.19×10^{10}	1.46×10^{10}	0	–	5.12×10^6	25.31	114	0.83	179	0.08	342	6.81	12.5	97	88	0.528	0.62
	(assume MLVSS = .75 (MLSS) for this month)																		
July 1981																			
1	2,948	2.77×10^9	1.25×10^{10}	1.53×10^{10}	4.00×10^4	12,500	5.21×10^6	8.25	28	0.81	225	0.09	56	42.6	11.11	95	78	0.865	4.0
2	3,933	3.70×10^9	1.67×10^{10}	2.04×10^{10}	6.98×10^4	7,107	5.29×10^6	3.75	40	0.79	150	0.05	125	24.9	20.0	91	91	0.920	0.64
3	2,484	2.34×10^9	1.06×10^{10}	1.29×10^{10}	6.45×10^4	9,845	5.35×10^6	6.0	19	0.79	155	0.08	115	17.1	12.5	93	91	0.444	1.35
4	1,703	1.60×10^9	7.23×10^9	8.83×10^9	8.18×10^4	7,567	5.29×10^6	9.75	13	0.79	83	0.06	70	19.2	16.67	92	75	0.258	0.22
	(assume MLVSS = .75 (MLSS) for this month) where have no MLVSS data																		
August 1981																			
1	2,124	1.99×10^9	9.02×10^9	1.10×10^{10}	1.03×10^5	3,457	5.69×10^6	10.75	26.7	0.73	75	0.05	277	5.60	20.0	97	95	0.632	0.24
2	2,048	1.93×10^9	8.69×10^9	1.06×10^{10}	9.37×10^4	3,135	5.45×10^6	10.88	30.98	0.77	116	0.07	19.4	8.13	14.29	99	93	0.246	0.60
3	964	9.07×10^8	4.09×10^9	4.99×10^9	6.76×10^4	2,102	5.57×10^6	12.0	23.89	0.75	109	0.15	351	2.06	6.67	97	95	0.160	0.31
4	1,571	1.48×10^9	6.67×10^9	8.15×10^9	1.14×10^5	2,892	5.49×10^6	5.78	22.55	0.76	95	0.08	163	7.32	12.5	97	95	0.229	0.83
September 1981																			
1	1,639	1.54×10^9	6.96×10^9	8.5×10^9	1.06×10^5	3,118	5.24×10^6	5.25	23.7	0.79	127	0.10	200	6.47	10.0	95	97	0.272	0.64
2	2,387	2.25×10^9	1.01×10^{10}	1.23×10^{10}	1.05×10^5	3,971	5.39×10^6	1.7	28.9	0.77	123	0.07	101	18.20	14.29	96	98	0.374	1.22
3	2,358	2.22×10^9	1.00×10^{10}	1.22×10^{10}	1.15×10^5	4,100	5.16×10^6	1.9	25.3	0.80	91	0.05	206	9.16	20.0	92	98	0.488	0.44
4	1,986	1.87×10^9	8.43×10^9	1.03×10^{10}	1.11×10^5	3,730	5.06×10^6	12.0	21.7	0.82	111	0.07	161	14.67	14.29	95	87	0.517	0.58
October 1981																			
1	1,699	1.59×10^9	7.22×10^9	8.81×10^9	9.94×10^4	5,431	4.59×10^6	6.75	15.4	0.91	125	0.08	161	9.60	12.5	95	94	0.658	0.78
2	1,197	1.13×10^9	5.08×10^9	6.21×10^9	6.25×10^4	3,152	4.93×10^6	3.68	28.9	0.85	124	0.12	80	12.72	8.33	98	94	0.439	1.56
3	1,464	1.38×10^9	6.22×10^9	7.60×10^9	1.40×10^5	4,077	4.49×10^6	5.4	12.8	0.92	200	0.14	199	6.77	7.14	99	97	0.619	1.00
4	1,557	1.47×10^9	6.61×10^9	8.08×10^9	1.52×10^5	3,389	4.68×10^6	.76	15.6	0.88	240	0.18	207	6.62	5.56	98	99	0.698	1.16
November 1981																			
1	1,919	1.81×10^9	8.15×10^9	9.96×10^9	1.34×10^5	4.057	4.56×10^6	5.03	17.6	0.90	220	0.12	164	10.53	8.33	99	96	0.876	1.34
2	2,259	2.14×10^9	9.64×10^9	1.18×10^{10}	8.67×10^4	4,305	4.54×10^6	5.18	29.7	0.92	160	0.08	246	8.49	12.5	98	97	0.892	0.65
3	3,986	3.75×10^9	1.69×10^{10}	2.07×10^{10}	1.55×10^5	3,722	4.57×10^6	9.9	33.3	0.90	102	0.03	121	29.65	33.3	99	89	0.872	0.84
4	2,144	2.02×10^9	9.11×10^9	1.11×10^{10}	6.12×10^4	4,013	4.55×10^6	2.63	43.1	0.92	109	0.05	228	8.65	20.0	96	99	0.887	0.48

Table II. (continued)

Wk.	MLVSS (mg/ℓ)	Clar. Solids (mg)	Aerator Solids (mg)	x_t Tot. Sys. Solids (mg)	Q_w (ℓ/d)	x_r (mg/ℓ)	Q_e (ℓ/B)	x_e (mg/ℓ)	θ_{ct} MCRT (d)	$\theta(\frac{V}{Q})$ (d)	S_o (mg/ℓ)	F:M (d^{-1})	Inf. SS (x_o)(mg/ℓ)	θ_g (d)	θ_{BOD} (d)	BOD Rem. Effic. (%)	SS Rem. Effic. (%)	SVF	Inf. BOD: Inf. SS
December 1981																			
1	2,033	1.91×10^9	8.63×10^9	1.05×10^{10}	1.68×10^5	3,261	4.39×10^6	4.6	18.5	0.93	177	0.09	132	14.32	11.11	97	93	0.893	1.34
2	2,111	1.99×10^9	8.97×10^9	1.09×10^{10}	1.07×10^5	3,937	4.33×10^6	58.1	16.2	0.96	238	0.12			8.33	96		0.901	0.57
3	2,486	2.34×10^9	1.06×10^{10}	1.29×10^{10}	1.29×10^5	4,201	4.53×10^6	27.8	19.3	0.91	140	0.06	245	9.74	16.67	97	85	0.927	0.75
4	1,684	1.58×10^9	7.15×10^9	8.73×10^9	1.03×10^5	3,226	4.24×10^6	10.9	23.1	0.98	165	0.10	189	8.73	10.0	95	91	0.946	1.02

Note: January–April 1982–started losing solids into river during peak flows from approximately 10:00 a.m. to 4:00 p.m. During this time, using an average peak flow value from April 1982 of 2.55 MGD. Solids concentration is 100 mg/ℓ. So $Q_{TOTAL} = Q_e + Q_B$. So 2.55 MGD for 6 hours = 6.4×10^5 gal/d = 2.41×10^6 ℓ/d.

Wk.	Tot. Sys. Solids (mg)	Q_w (ℓ/d)	x_r (mg/ℓ)	Q_B (ℓ/d)	x_B (mg/ℓ)	Q_e (ℓ/d)	x_e (mg/ℓ)	θ_{ct} (d)	$\theta(\frac{V}{Q})$ (d)	S_o (mg/ℓ)	F:M (d^{-1})	Inf. SS (x_o)(mg/ℓ)	θ_g (mg/ℓ)	θ_{BOD} (d)	BOD Rem. Effic. (%)	SS Rem. Effic. (%)	SVF	Inf. BOD: Inf. SS
January 1982																		
1	6.78×10^9	1.19×10^5	2,799	2.41×10^6	100	2.06×10^6	39.0	10.36	0.92	202	0.17	208	5.78	5.89	97	97	0.945	0.97
2	6.99×10^9	1.07×10^5	3,139	2.41×10^6	100	2.14×10^6	3.98	11.94	0.91	27	0.02	51	24.03	50	81	77	0.935	0.81
3	5.47×10^9	5.45×10^4	2,571	2.41×10^6	100	2.12×10^6	18.23	13.1	0.93	156	0.16	213	4.61	6.25	84	96	0.937	0.64
4	5.28×10^9	0	2,817	2.41×10^6	100	2.13×10^6	5.78	20.81	0.94	170	0.18	267	3.58	5.56	92	92	0.860	0.64
February 1982																		
1	5.84×10^9	5.73×10^3	2,094	2.41×10^6	100	2.08×10^6	23	19.4	0.77	205	0.24	194	4.35	4.17	94	89	0.936	1.15
2	5.84×10^9	0	2,275	2.41×10^6	100	2.12×10^6	4.0	20.4	0.94	128	0.14	237	3.89	7.14	83	98	0.849	0.54
3	6.15×10^9	2.6×10^4	2,470	2.41×10^6	100	3.01×10^6	5.0	19.2	0.77	205	0.22	259	3.52	4.55	96	98	0.816	0.79
4	6.56×10^9	0	3,446	2.41×10^6	100	3.21×10^6	2.2	26.4	0.85	34	0.03	93	11.55	33.3	71	98	0.778	0.37
March 1982																		
1	7.78×10^9	0	5,600	2.41×10^6	100		14	28.3	0.88	187	0.14	235	5.62	7.14	93	96	0.868	0.80
2	8.38×10^9	0	5,800	2.41×10^6	100		10.5	31.1	0.84	228	0.17	217	6.26	5.89	96	95	0.730	0.43
3	1.1×10^{10}	0	8,250	2.41×10^6	100		20.5	36.6	0.81	111	0.06	258	6.64	16.67	91	96	0.773	0.43
4	1.09×10^{10}	1.8×10^4	4,726	2.41×10^6	100		22.7	33.9	0.80	205	0.10	234	8.76	10.0	96	88	0.812	0.88

Table II. (continued)

Wk.	MLVSS (mg/ℓ)	Clar. Solids (mg)	Aerator Solids (mg)	Q_w (ℓ/d)	x_r (mg/ℓ)	Q_B (ℓ/d)	x_B (mg/ℓ)	Q_e (ℓ/d)	x_e (mg/ℓ)	θ_{ct} (d)	$\theta(\frac{V}{Q})$ (d)	S_o (mg/ℓ)	F:M (d^{-1})	Inf. SS (x_o)(mg/ℓ)	θ_g (mg/ℓ)	θ_{BOD} (d)	BOD Rem. Effic. (%)	SS Rem. Effic. (%)	SVF	Inf. BOD: Inf. SS
April 1982																				
1	2,076	1.95×10^9	8.8×10^9	1.5×10^4	4,644	2.41×10^6	100	2.4×10^6	23	29.4	0.88	168	0.09	253	7.22	11.11	91	91	0.841	0.63
2	2,400	2.26×10^9	1.02×10^{10}	2.6×10^4	4,786	2.41×10^6	100	2.3×10^6	11	31.9	0.90	166	0.08	240	8.54	12.5	91	95	0.788	0.69
3	1,865	1.76×10^9	7.92×10^9	1.02×10^4	3,670	2.41×10^6	100	2.57×10^7	24	28.7	0.87	144	0.09	170	9.54	11.11	94	86	0.746	0.85
4	1,734	1.63×10^9	7.36×10^9	6.35×10^3	3,321	2.41×10^6	100	2.9×10^6	17	23.6	0.80	130	0.09	247	5.62	11.11	92	92	0.775	0.51

Wk.	MLVSS (mg/ℓ)	Clar. Solids (mg)	Aerator Solids (mg)	Tot. Sol. (mg)	Q_w (ℓ/d)	x_r (mg/ℓ)	Q_e (ℓ/d)	x_e (mg/ℓ)	θ_{ct} (d)	$\theta(\frac{V}{Q})$ (d)	S_o (mg/ℓ)	F:M (d^{-1})	Inf. SS (x_o)(mg/ℓ)	θ_g (mg/ℓ)	θ_{BOD} (d)	BOD Rem. Effic. (%)	SS Rem. Effic. (%)	SVF	Inf. BOD: Inf. SS
May 1982																			
1	2,175	2.05×10^9	9.24×10^9	1.13×10^{10}	0	4,600	4.62×10^6	25		1.04	1.55	0.07	299	7.57	14.29	93	91	0.708	0.44
2	2,461	2.32×10^9	1.05×10^{10}	1.28×10^{10}	0	4,590	4.36×10^6	16		0.87	105	0.05	238	9.00	20.0	85	92	0.710	0.44
3	2,170	2.04×10^9	9.22×10^9	1.13×10^{10}	0	5,395	5.6×10^6			0.83	124	0.07			14.29	95		0.744	
4	2,313	2.18×10^9	9.82×10^9	1.2×10^{10}	0	4,602	5.1×10^6	30		0.84			255	7.62			88	0.780	
	(assume MLVSS = .70 x MLSS for this month) (no bulking this month)																		
June 1982																			
1	2,312	2.18×10^9	9.82×10^9	1.2×10^{10}	8.7×10^9	4,895	5.69×10^6	11	26.2	0.74			223	7.67			95	0.771	
2	2,505	2.36×10^9	1.06×10^{10}	1.3×10^{10}	5.19×10^4	8,086	5.48×10^6	4.2	29.7	0.77	218	0.11	269	7.17	9.09	97		0.755	0.81
3	2,690	2.53×10^9	1.19×10^{10}	1.39×10^{10}	5.37×10^4	6,000	5.22×10^6	4.8	39.9	0.81	179	0.08	225	9.68	12.5	87	91	0.799	0.80
4	2,342	2.2×10^9	9.95×10^9	1.22×10^{10}	7.87×10^4	5,377	5.8×10^6	4.4	27.3	0.72	209	0.12	178	9.47	8.33	87	94	0.886	
	(assume MLVSS = .60 x MLSS for this month) (no bulking this month)																		
July 1982																			
1	2,403	2.26×10^9	1.02×10^{10}	3.28×10^{10}	0		6.11×10^6	9.5		0.70	247	0.15	242	6.95	6.67	98	96	0.780	1.0
2	2,101	1.98×10^9	8.92×10^9	1.02×10^{10}	0		5.77×10^6	18		0.74	180	0.09	207	7.71	11.11	92	92	0.815	0.96
3	2,093	1.97×10^9	8.89×10^9	1.09×10^{10}	0		5.61×10^6	6		0.76	106	0.07	315	5.05	14.29	96	98	0.853	0.34
4							5.73×10^6			0.74								0.865	
	(no bulking this month)																		
August 1982																			
1	2,094	1.97×10^9	8.9×10^9	1.09×10^{10}	9.02×10^4	4,975	5.6×10^6	11	21.4	0.75	230	0.15	259	6.06	6.67	94	95	0.869	0.89
2	2,280	2.15×10^9	9.7×10^9	1.19×10^{10}	7.79×10^4	4,850	4.8×10^6	15	26.5	0.87	190	0.10	211	9.40	10.0	88	92	0.868	0.90
3	2,148	2.02×10^9	9.12×10^9	1.11×10^{10}	9.8×10^4	4,960	5.8×10^6	37	15.8	0.72	167	0.04	164	9.43	25.0	96	77	0.878	1.0
4	1,976	1.86×10^9	8.4×10^9	1.03×10^{10}	1.39×10^5	4,755	5.56×10^6	39	11.7	0.75			205	7.23			72	0.866	
	(no bulking this month)																		