THE DEVELOPMENT OF A GRAPHICAL SOLUTION TO A MATHEMATICAL MODEL OF COMPLETE MIX ACTIVATED SLUDGE PROCESS

by

WENG-HSIANG HSIEH

B. S., National Taiwan University, 1971
Taipei, Taiwan

A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Civil Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1976

Approved by:

Lawrence A. Schmid
Major Professor

319

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

The purpose of this report is to develop a graphical solution to a mathematical model of the complete mix activated sludge process. The mathematical relationship between process parameters was used to develop the diagram. Trial and error solutions are normally required by the mathematical mothod. Graphical solutions would increase the numbers of alternatives that could be looked at.

Today the complete mix activated sludge(CMAS) treatment system has become the choice in a majority of industrial waste treatment applications and in a very significant number of municipal systems. This system has been shown to have definite advantages over the conventional activated sludge process for treating liquid waste.

This report will also point out the application and comparison of those two methods.

LIST OF TABLES

I. LITERATURE REVIEW

1. FUNDAMENTAL BIOCHEMISTRY

It is necessary to know the fundamental biochemistry of aerobic biological metabolism for understanding the complete mix sludge process.

Activated Sludge

a. Definition

Activated sludge is a flocculent assemlage of microorganisms, non-living organic matter and inorganic materials. The microorganisms which include bacteria, molds, protozoa, and metazoa, such as rotifer, insect larvae, and worms, are related to each other in a food chain. In this process, bacteria and molds decompose complex organic compounds to produce, through growth, cellular material on which protozoa feed. The protozoa, in turn, are consumed by metazoa. The latter may also feed directly upon the decomposers. The non-living organic matter is also called non-biodegradable volatile solids. The inorganic materials which include the products from the chemical reaction, such as sulfate, phosphate, nitrate, etc. Several terms are used to express the concentration of activated sludge in waste systems. (1) The active mass concentration, M_a, represents the fraction of suspended solids concentration consisting of microorganisms, (2) The inert solids, M_{ti}, refers to the inorganic fraction, (3) The nondegradable organic matter, M_{iv}, (4) Endogenous mass concentration, M_e, (5) Mixed liquor volatile suspended solids, MLVSS, which include the concentration of M_a, M_e, M_{iv}, (6) Mixed liquor suspended solids, MLSS, which include the concentration of M_a, M_e, M_{ti}, and M_{iv}, also called the total mass of sludge solids, the weight of sludge solids is illustrated in the Figure 1-1 by the total area enclosed in the sketch(1).

$$M_T = M_a + M_e + M_{iv} + M_{ti}$$

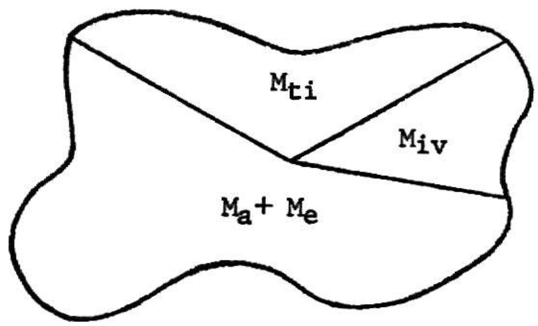

Fig. 1-1 The weight of sludge solids

b. Cell composition of activated sludge

Information about the composition of several activated sludge developed on various industrial wastes suggests an empirical formula of $C_5H_7NO_2$, yielding a molecular weight of 113 which is corrected to 124 when it is necessary to account for the inert inorganic or ash content of the microorganisms(2). Although the nutritional requirements can be estimated from an elemental analysis of the activated sludge, it has been found to be more convenient to relate these requirements to BOD_5 at 20°C of the waste on which the sludge feeds. The following ratios between phosphorus, nitrogen and BOD are recommended(3).

	BOD	N	P
High rate-high synthesis	100	5	1
Medium rate-medium synthesis	100	3	0.5
Low rate-low synthesis	100	2	0.3

Basic concepts of biological unit processes

a. Energy change in the activated sludge process

According to the conservation principle in thermodynamics, the flow of energy through each trophic level equals the sum of free energy, ΔF, available for growth and maintenance at that level and heat lost through respiration is $T\Delta S$. This process is expressed by Eq. (1-1).

$$\Delta H = \Delta F + T\Delta S \tag{1-1}$$

The energy flow through a decomposer food chain is represented in Fig. 1-2.

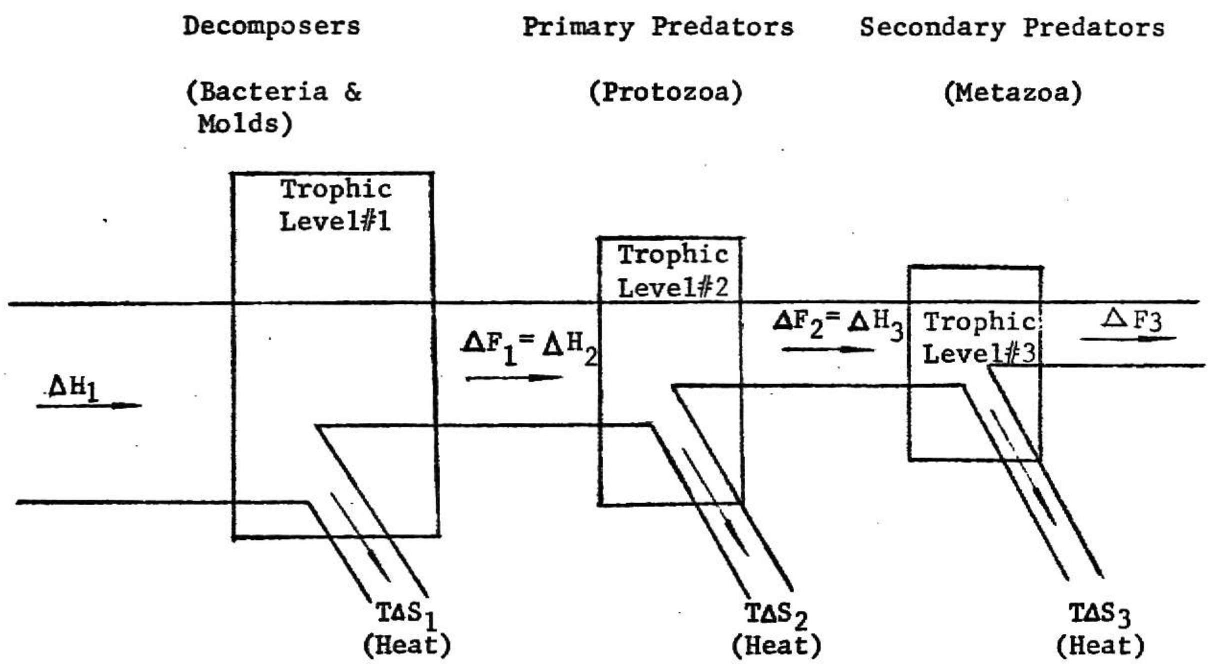

Fig. 1-2 Diagram of energy flow through a decomposer food chain

b. Conversion

From Fig. 1-3, bacteria use energy which they obtain by oxidizing a portion of organic molecules being metabolized for synthesis reaction. A small amount of energy is used to maintain normal functions such as motion and enzyme activation. The basal-energy requirement of the bacteria has been designated as endogenous respiration. The significance of this is simply that all the organic reaction, with the net protoplasm or sludge accumulation being the difference between the synthesis and endogenous reaction. This property is simplified by the following Eq. (1-2) , (1-3)(4). Also illustrated by Fig. 1-3.

Organic matter metabolized = Protoplasm synthesized + Energy for synthesis (1-2)

Net protoplasm accumulation = Protoplasm synthesized - Endogenous respiration (1-3)

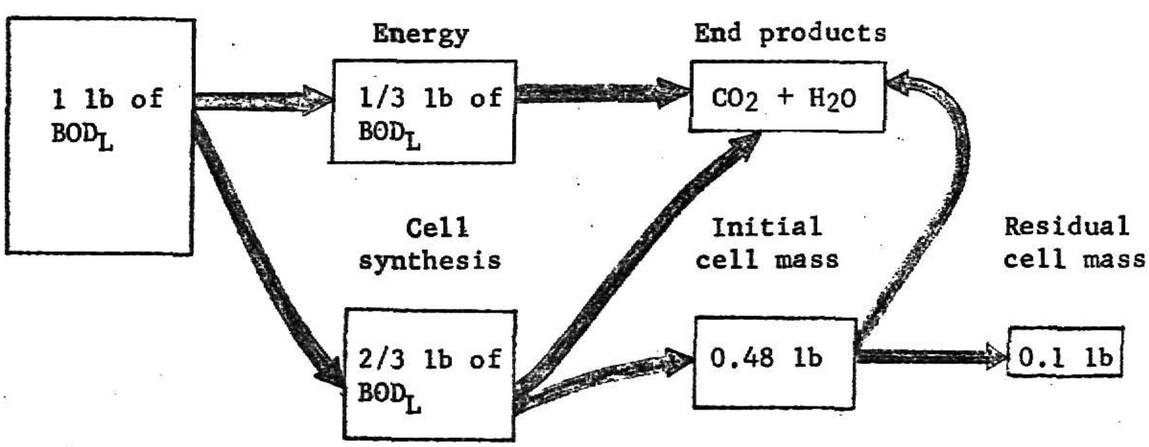

Fig. 1-3 Energy transfer in cell synthesis from domestic sewage

It can be seen from Fig. 1-3(5), that the stabilization of an organic substrate results in, 0.67 lbs BOD_L, being used for biological synthesis. Furthermore, the quantity of cell mass produced can be calculated from Eq. (1-4). Five moles of oxygen are required for cell oxidation.

$$C_5H_7O_2N + 5\ O_2 \longrightarrow 5\ CO_2 + 2\ H_2O + NH_3 \qquad (1\text{-}4)$$

GMW of $C_5H_7O_2N$ = 113 gm, GMW of O_2 = 32 gm

Then:

Five moles of O_2 = 5 x 32 gm/mole = 160 gm

This conversion factor between oxygen and cell mass is

$$160gm\ /\ 113gm = 1.42\ (O_2\ \text{equivalent}),$$

That is 1 lb of cell mass production requires 1.42 lbs of oxygen for their energy sources. Furthermore, the conversion factor will indicate that the cell mass produced for two-third lbs of BOD_L converted to synthesis(Fig. 1-3) is

0.67 lbs / 1.42 = 0.48 lbs cell mass produced (6)

Fig. 1-4 illustrates the quantity relationships between oxygen required and solids produced from the maximum cell synthesis to maximum endogenous respiration conditions.

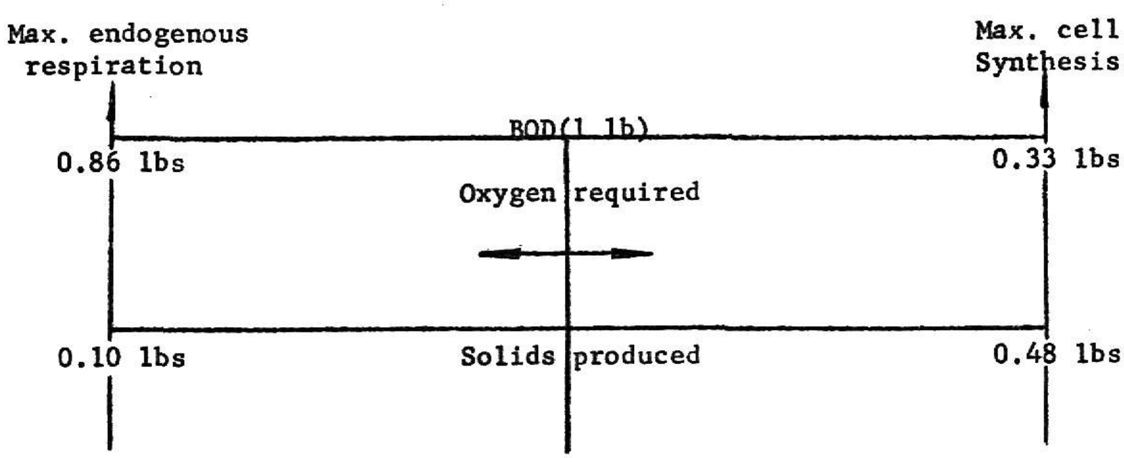

Fig. 1-4 Solids production and oxygen requirements for BOD conversion

c. Bacterial growth patterns

The growth pattern can be discussed in terms of the varition of the mass of microogranisms with time. This pattern consists of the following three phases (Fig. 1-5)

(i) The log growth phase. There is always an excess amount of food surrounding the microogranisms and the rate of metabolism and growth is only a function of the ability of microogranisms to process the substrate.

(ii) Declining growth phase. The rate of growth and hence the mass of bacteria decrease because of limitation in the food supply.

(iii) Endogenous phase. The microogranisms are forced to metabolize their own protoplasm without replacement, since the concentration of available food is at a minimum. During this phase, a phenomenon known as lysis can occur in which the nutrients remaining in the dead cell diffuse out to furnish the remaining cells with food.

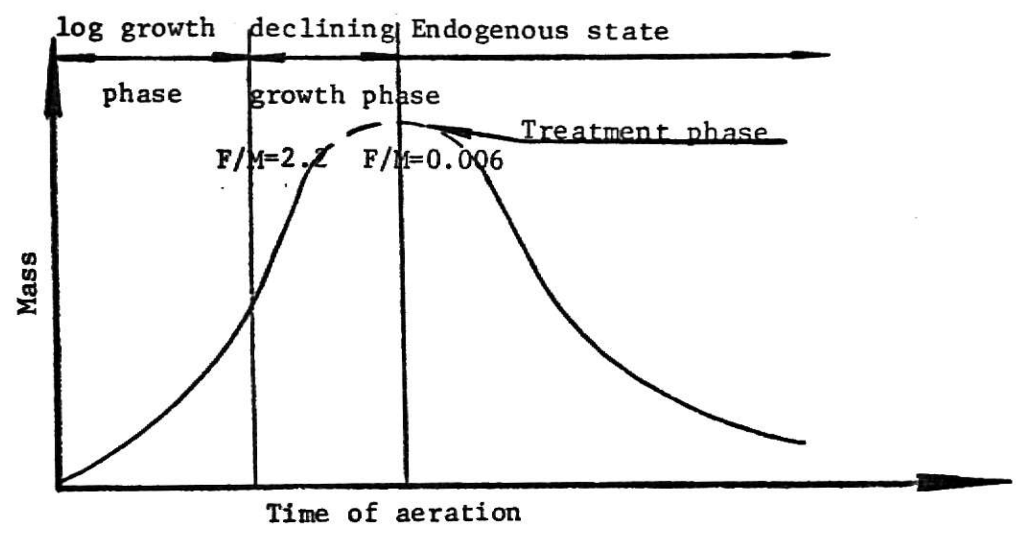

Fig. 1-5. Relationship of microogranism growth and food concentration.

d. Theory of operation

Normally, when the endogenous phase is reached, the tiny floc which has formed is seperated from the major fraction of liquid by sedimentation. In Fig. 1-5, the rate of organic removal is most rapid in growth phase (maximum synthesis), while floc formation is best in the endogenous phase (maximum endogenous respiration). Furthermore, F-M ratio and retention time are used to control the biological treatment system. The F-M ratio determines how far back along the growth curve the microorganisms start. The time of retention in a aeration tank will determine how far along the growth curve the reaction will progress. The long period of time in the endogenous phase permits the system to produce a well-clarified effluent of low organic content. The dash line on the growth curve in Fig. 1-5 is a treatment phase in which the activated sludge treatment system is often operated.

2. COMPLETE MIX ACTIVATED SLUDGE TREATMENT SYSTEM(CMAS)

Complete mix activated sludge systems are characterized by essentially constant level of solids, organic matter, and oxygen demand through-out the aeration basin. Importantly, this will help to solve the problems of shock loads and toxic wastes. Table 1-1 illustrates the soluble component of a waste before and after CMAS system treatment containing 300 mg/l non-degradable organics as COD(7).

Table 1-1 The soluble component of a waste in CMAS system

	Influent	Effluent	% of removal
COD(mg/l)	1000	319	68
BOD_L(mg/l)	645	17	97
BOD_5(mg/l)	530	10	98

Fig. 1-6 is the flow diagram of a CMAS with sludge return(8). In order to develop this system, two assumptions are made in design and operation (1) that all waste utilization by microorganisms take place in the aeration basin. (2) that the total biomass in the system is equal to the biomass in the aeration basin. The operating data from plants utilizing the CMAS system are presented in Table 1-2.

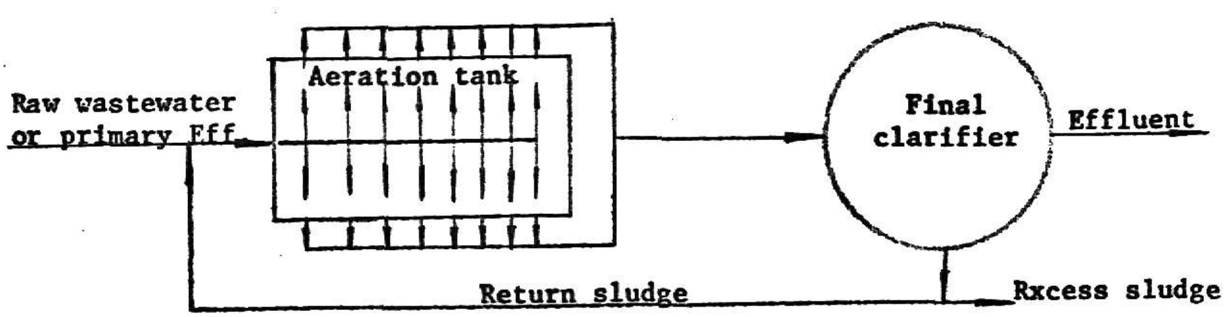

Fig. 1-6 Complete mix plant with sludge return

TABLE 1-2
OPERATING DATA FROM COMPLETE MIX ACTIVATED SLUDGE PLANTS

Plant Location	Influent Flow mgd	Sludge Recycle percent	BOD Secondary Influent mg/l	BOD Secondary Effluent mg/l	Aeration Tank MLSS mg/l	Organic Loading lb BOD/day / lb MLSS	Volumetric Loading lb BOD/day / 1,000 cu ft	Aeration Detention Time[1] hours	Air Supplied per lb of BOD Removed cu ft/lb	Secondary BOD Removal Efficiency percent	Reference
Illinois	1.6	21	102	8	6,500	0.17	74	2.2	1,670	92	18
	1.94	21	80	13	6,000	0.20	73	1.8	1,900	84	
	1.91	25	80	19	6,500	0.18	72	1.8	1,380	76	
	1.55	25	108	18	6,300	0.20	79	2.2	1,290	83	
Minnesota	9.8	158	177	15	3,750	0.31	73	3.6	– 2	92	19
Nebraska	4.1	87	260	26	4,400	0.27	80	4.5	540	90	20
	4.3	66	270	16	4,460	0.32	97	4.3	450	94	
	4.6	62	290	17	3,920	0.43	120	4.0	500	94	
	4.2	65	300	22	4,020	0.41	110	4.4	480	93	
	4.8	64	350	34	4,280	0.51	132	3.8	560	90	
	5.8	37	240	37	4,040	0.49	114	3.2	570	85	
	5.8	49	105	14	3,400	0.24	50	3.2	900	87	
Nebraska	3.4	50	250	15	4,500	0.27	80	5.0	500	94	21
	4.1	100	270	13.5	4,500	0.32	97	4.4	500	95	
	5.0	200	280	6	4,500	0.38	116	3.8	560	98	
Nebraska	0.38	26	225	25	4,230	0.48	126	2.6	–	89	22
	0.43	40	227	32	5,460	0.42	142	2.5	–	86	
Texas	0.29	82	115	9	3,820	0.21	50	3.7	–	92	23
	0.29	100	141	25	5,000	0.20	62	3.7	–	82	
	0.30	145	123	19	5,540	0.16	54	2.2	–	85	
	0.37	100	180	17	5,620	0.29	103	3.0	–	91	

1 Excluding sludge recycle.
2 Mechanical aerators.

3. MODELS FOR ACTIVATED SLUDGE PROCESSES IN THE CMAS SYSTEM

Introduction

The activated sludge waste treatment process was developed in England during the early 1900's. In 1954, Eckenfelder and O'connor(9) proposed a mathematical model for activated sludge wastewater treatment. This model was subsequently modified and expanded in publications by Eckenfelder(10-16) during the period from 1960 to 1971. These publications established a nomenclature and mathematical approach to the activated sludge process design that is widely used. In 1962, Mckinney(4) advanced a mathematical model for CMAS treatment systems. Among others, further publications by mckinney(17-19) followed in 1968, 1969, and 1970. These publications established a second nomenclature and mathematical approach to activated sludge process design that is also widely used. In 1974, a publication entitled "A Unified Model of the Activated Sludge Process", by Brain L. Goodman and Andrew J. Englande, Jr. has compared the two models that were advanced by Mckinney and Eckenfelder in detail, and found them to be identical. The unified model of CMAS system was constructed as follows. Explanation of terms is listed in Appendix.

The unified model

(1) Substrate removal

$$S_e = S_o \ / \ (K_m t + 1) \qquad (1\text{-}5)$$

The substrate removal rate coefficient, K_m, can be determined by the plotting of substrate removal rate versus substrate remaining(the slope of this line is K_m).

It has been variously reported as 15 hr^{-1} (22), and 7.2 hr^{-1} (18) at 20°C. Considering the difficulty of obtaining accurate substrate concentration measurements, especially at low concentration levels, an average K_m value of 15 hr^{-1} at 20°C seems reasonable for municipal wastewater. Eq. (1-5) is used in both aeration only and aeration with sludge return system.

(2) Active mass accumulation(M_a)

aeration only: $M_a = a\ K_m\ S_e\ /\ (1/t + k_b)$ (1-6a)

aeration with sludge return: $M_a = a\ K_m\ S_e\ /\ (1/t_s + k_b)$ (1-6b)

Various values of a and a_5 (Table 1-3) have been advanced. Generally, a is computed as 0.44 and a_5 is computed as 0.53.

(3) Endogenous mass accumulation(M_e)

aeration only: $M_e = (1-f_d)\ k_b\ M_a\ t$ (1-7a)

aeration with sludge return: $M_e = (1-f_d)\ k_b\ M_a\ t_s$ (1-7b)

Table 1-3. Sludge yield per unit of substrate metabolized

	a	a_5
Mckinney (4)	0.47	0.7
Mckinney and Ooten (18)	0.47	0.7
Reynolds and Yang (23)	0.39	0.6
Servizi and Bogan (24)		
Carbohydrates	0.38	0.6
Aromatics & Aliphatic acids	0.34	0.5
Heukelekian et al (25)	0.34	0.5
Gellman and Heukelekian (26)	0.34	0.5
Sawyer (27)	0.34	0.5
Burkhead and Mckinney (17)		
Carbohydrates	0.53	0.8
Noncarbohydrates	0.38	0.5
Hoover and Porges (2)	0.34	0.5
Eckenfelder and O'connor (9)	0.4-0.5	0.6-0.7

Eq (1-6a) and Eq (1-7a) are used for aeration only. In aeration with sludge return, all parameters are computed in a manner similar to that employed in connection with aeration only system except that the sludge age, t_s, is utilized in the calculation rather than the aeration period, t. In aeration only systems, sludge age is set by the displacement rate V/Q, hence $t_s = t$, but in aeration and sludge return, the sludge age, t_s, is a cell residence time, that is set by the selection of the total weight of solids to be maintained in the aeration tank, weight of solids to wasted daily as well as the weight of solids in the effluent daily and the weight of solids change in the tank daily. The sludge age is expressed by Eq. (1-8).

$$t_s = M_T \; / \; (M_{Tw} + M_{Te} + \Delta M_T) \qquad (1\text{-}8)$$

(4) Inert mass accumulation(M_{ti})

Inert mass accumulation is the total mass concentration of inert inorganic mass in the influent and the inorganic mass accumulated in the cell produced by metabolism of organic matter. This is indicated by the following Eq. (1-9).

$$M_{ti} = M_{ii} \; (t_s/t) + f_{ndi} \; (M_a + M_e) \qquad (1\text{-}9)$$

Inorganic inert fraction of microbial mass, f_{ndi}, is 0.1 lb inorganic inert microbial mass per lb microbial mass (4),(18).

(5) Total mass accumulation(M_T)

$$M_T = M_a + M_e + M_{ti} + M_{iv} \qquad (1\text{-}10)$$

(6) Oxygen uptake rate(R_r)

$$R_r = \frac{(S_o - S_e) - 1.4(M_a + M_e)(t/t_s)}{t} \qquad (1\text{-}11)$$

In order to maintain the treatment system in an aerobic condition, sufficient oxygen must be provided to meet the microbial synthesis and oxidation.

(7) BOD_L effluent

$$BOD_L = S_e + 1.1 \; (M_a)_{eff.} \qquad (1\text{-}12)$$

(8) Sludge return ratio(r)

$$r = M_T \;/\; (SDI\ (10{,}000) - M_T) \qquad (1\text{-}13)$$

Sludge density index, SDI, is mg/l suspended solids(MLSS) per ml of settled sludge multiplied by 10, (28).

Correction of K_m and k_b

Both K_m and k_b are temperature dependent. The value of K_T at T^oC can be corrected by the following Eq. (1-14), over the range of 5-35^{o}C.

$$K_T = K_{20}\ (1.075^{\ T\ -\ 20}) \qquad (1\text{-}14)$$

In addition k_b, is also sludge age dependent. Analysis of the data of Schmidt (29) indicates that k_b is related to sludge age according to the Eq. (1-15).

$$K_{bts} = k_{b20}\ (0.75^{\ \ln t_s\ /\ \ln 2}) \qquad (1\text{-}15)$$

This relationship is illustrated in Fig. 1-7 where 20^{o}C values are plotted.

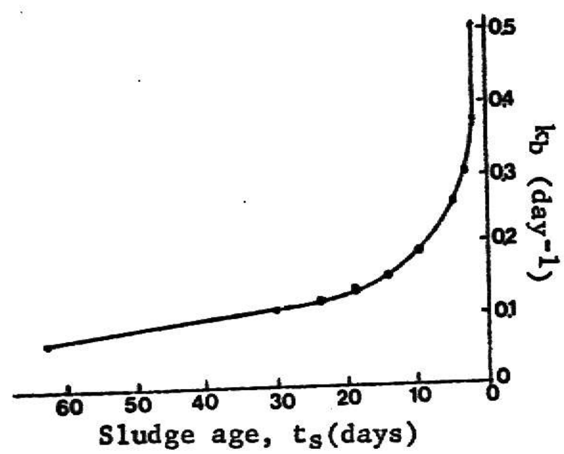

Fig. 1-7 Effect of sludge age on the rate of endogenous oxidation, k_b

II. DEVELOPMENT OF A GRAPHICAL SOLUTION FOR THE UNIFIED MODEL OF THE ACTIVATED SLUDGE PROCESS IN CMAS SYSTEM

Mathematical relation between the process parameters

a. Substrate removal

Eq. (1-5) can be modified to Eq. (2-1),

$$S_o = (K_m t + 1)\ S_e \qquad (2\text{-}1)$$

that is a straight line equation of slope, $K_m t + 1$, is temperature dependent. If K_m and t are varied for a given influent substrate, S_o, different values of effluent substrates, S_e, will be obtained. The slope, $K_m t + 1$, is calculated in Table 2-1 for different values of K_m, and t.

Table 2-1 The slope of straight line, $K_m t + 1$

t(hrs)	2	4	6	8	10	12	24
$K_m(hr^{-1})$							
10.5@15°C	22	43	64	85	106	127	253
15.0@20°C	31	61	91	121	151	181	361
21.5@25°C	44	87	130	173	216	259	517

From Table 2-1, the ratio of the slope between T=15°C and T=20°C is approximately 0.704, the ratio of slope between 25°C and 20°C is approximately 1.428. Hence, three scales of S_e at three different temperatures(ie. different K_m) will be set on the abscissa in Fig. 2-1.

b. Active mass and endogenous mass accumulation

Substituting Eq. (1-6b) into Eq. (1-7b) and simplifing, M_e will be found in Eq. (2-2), $M_a + M_e$, will be expressed as Eq. (2-3).

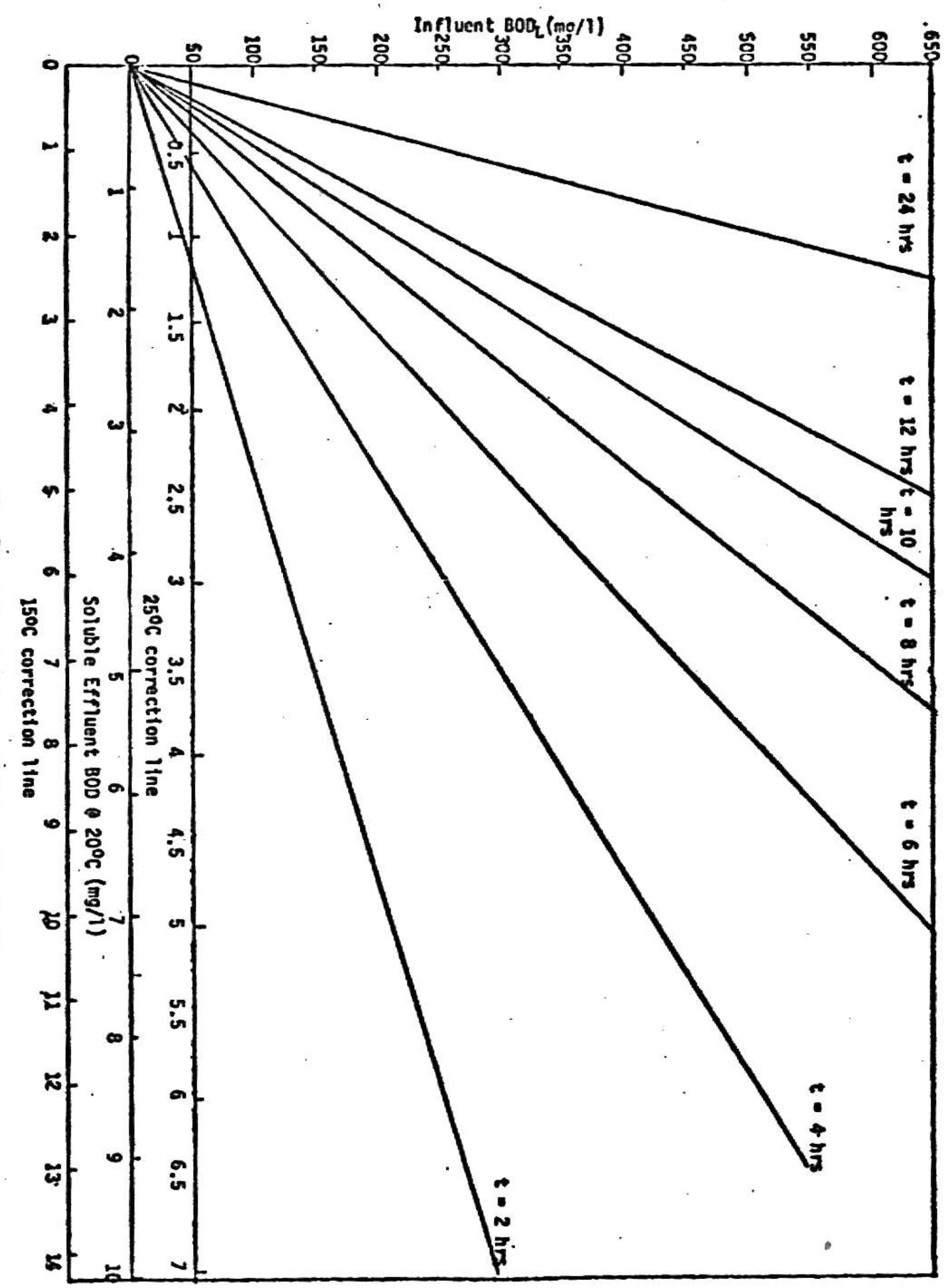

Fig. 2-1 Influent BOD vs. Soluble Effluent BOD

$$M_e = 0.23\ k_b\ t_s\ (0.44\ K_m\ S_e\ /\ (1/t_s + k_b)) \qquad (2\text{-}2)$$

$$M_a + M_e = (0.23\ k_b\ t_s + 1)\ (0.44\ Km\ Se\ /\ (1/t_s + kb)) \qquad (2\text{-}3)$$

Set $y = (0.23\ k_b\ t_s + 1)\ (0.44\ K_m\ /\ (1/t_s + k_b))$, then $M_a + M_e$ can be simplified by Eq. (2-4).

$$M_a + M_e = y\ S_e \qquad (2\text{-}4)$$

Eq. (2-4) is also a straight line equation. The slope of straight line, y, is a function of k_b, t_s, K_m. K_m and k_b are temperature dependent, Eq. (2-4) is also expressed by the following equation.

$$M_a + M_e = f(t_s,\ T)\ S_e \qquad (2\text{-}5)$$

From Eq. (2-5), it can be seen that the slope, $f(t_s, T)$, can be used for determining, $M_a + M_e$, under the given S_e which was determined from Fig. 2-1. The slope, $f(t_s, T)$, is represented in Table 2-2.

Table 2-2 $f(t_s, T)$ values

t_s(days)	1	2	3	5	7	9	11
T(^{o}C)							
15	89	165	235	360	468	580	678
20	119	215	304	459	601	733	856
25	156	277	389	584	766	929	1085

From the Table 2-2, the ratio of $f(t_s, T)$ between 15^{o}C and 20^{o}C is approximately 0.766, the ratio between 25^{o}C and 20^{o}C is approximately 1.280. Therefore, the same procedure as was used in Fig. 2-1 will be employed. Three scales of, $M_a + M_e$, at three different temperatures will be set on the ordinate and S_e set on abscissa in Fig. 2-2.

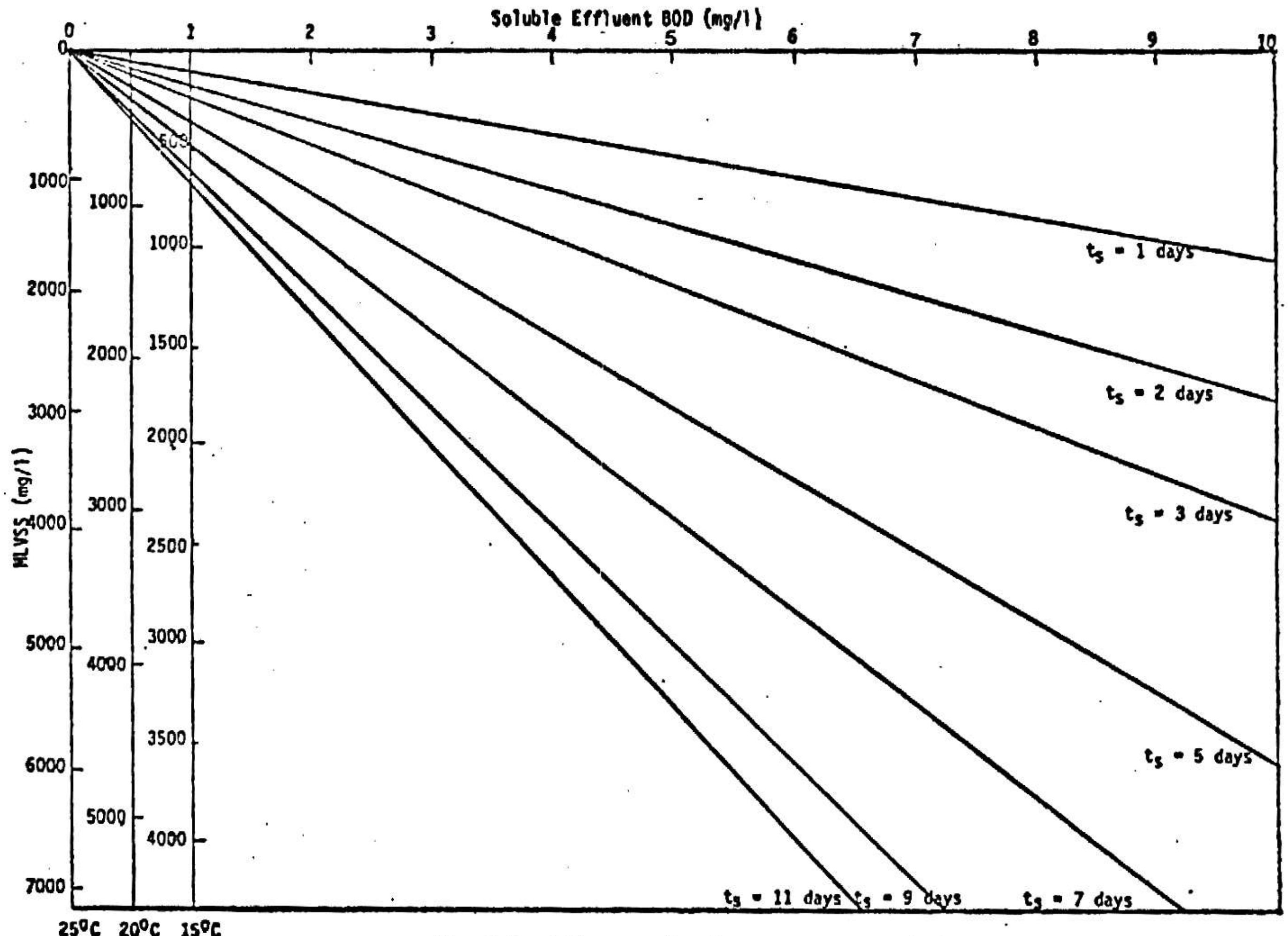

Fig. 2-2. Active mass & endogenous mass accumulation

c. MLVSS and oxygen uptake rate

The oxygen uptake rate can be found from Eq. (1-11), and the oxygen uptake per pass through the system, $R_r t$, will be expressed by the following Eq. (2-6).

$$R_r t = (S_o - S_e) - 1.4\ (M_a + M_e)\ t/t_s \qquad (2\text{-}6)$$

In Eq. (2-6), S_o is large compared to S_e. If S_e can be considered negligible, Eq. (2-6) can be simplified to Eq. (2-7).

$$R_r t = S_o - 1.4\ (M_a + M_e)\ t/t_s \qquad (2\text{-}7)$$

The ratio of oxygen required per day, $R_r t$ (8.34) Q, and BOD in the tank per day, S_o (8.34) Q, is set as Y, in Eq. (2-8).

$$Y = R_r t\ (8.34)\ Q\ /\ S_o\ (8.34)\ Q = R_r t\ /\ S_o \qquad (2\text{-}8)$$

Substituting Eq. (2-7) into Eq. (2-8) and simplifying

$$(1-Y)\ S_o = 1.4\ (M_a + M_e)\ t/t_s \qquad (2\text{-}9)$$

In Eq. (2-9), Y indicates the relation between oxygen requirement and MLVSS. Furthermore, we will set S_o on the ordinate, and 1.4 $(M_a + M_e)\ t/t_s$ on the abscissa. The slope, 1-Y, of the straight line will be as shown in Fig. 2-3.

d. Food-microorganism ratio

Food-microorganism ratio is rate of organic loading or a ratio of food that is the influent substrate to microorganisms in the aeration tank. It is generally expressed as lbs of BOD per day per lb of MLVSS. This is a means of indicating the amount of BOD given to the " bugs " or how much biodegradable material is being supplied to the microorganisms. The ratio of food and microorganisms is illustrated by Eq. (2-10).

$$F\ /\ M = 8.34\ S_o\ Q\ /\ (M_a + M_e)\ 8.34\ Q\ t \qquad (2\text{-}10)$$

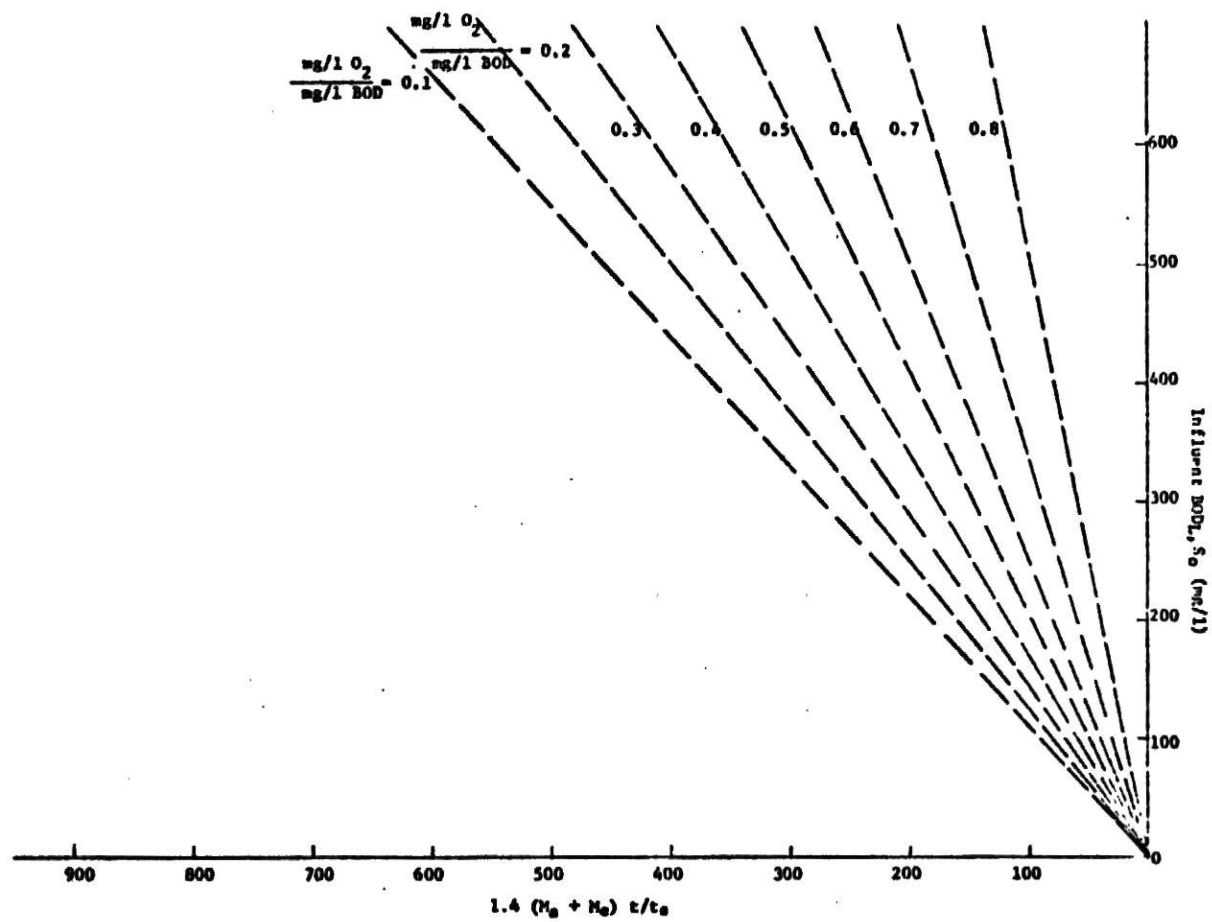

Fig. 2-3 Relationship between Influent BOD and O_2 Equivalent in Biomass

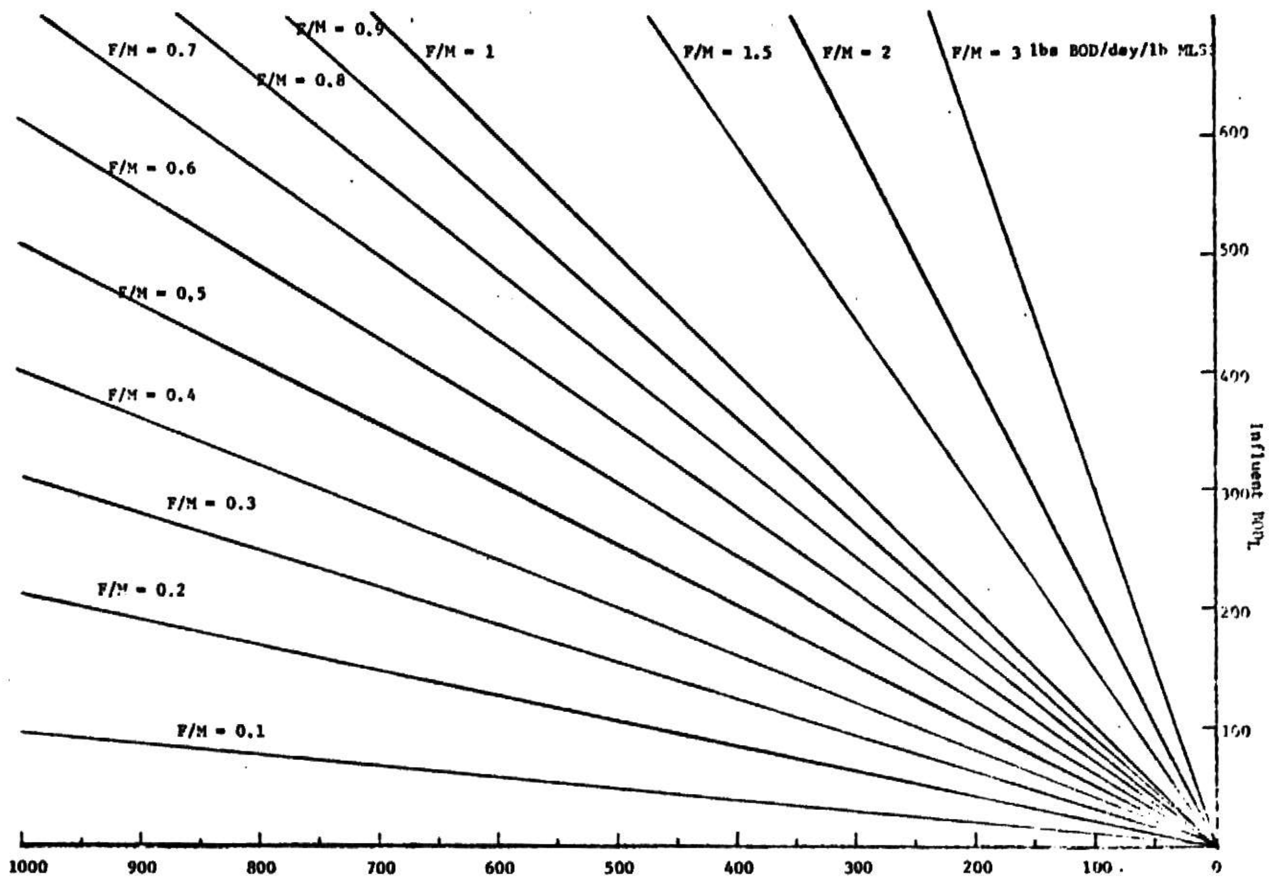

Fig. 2-4 Relationship between influent BOD_L and MLVSS in the tank

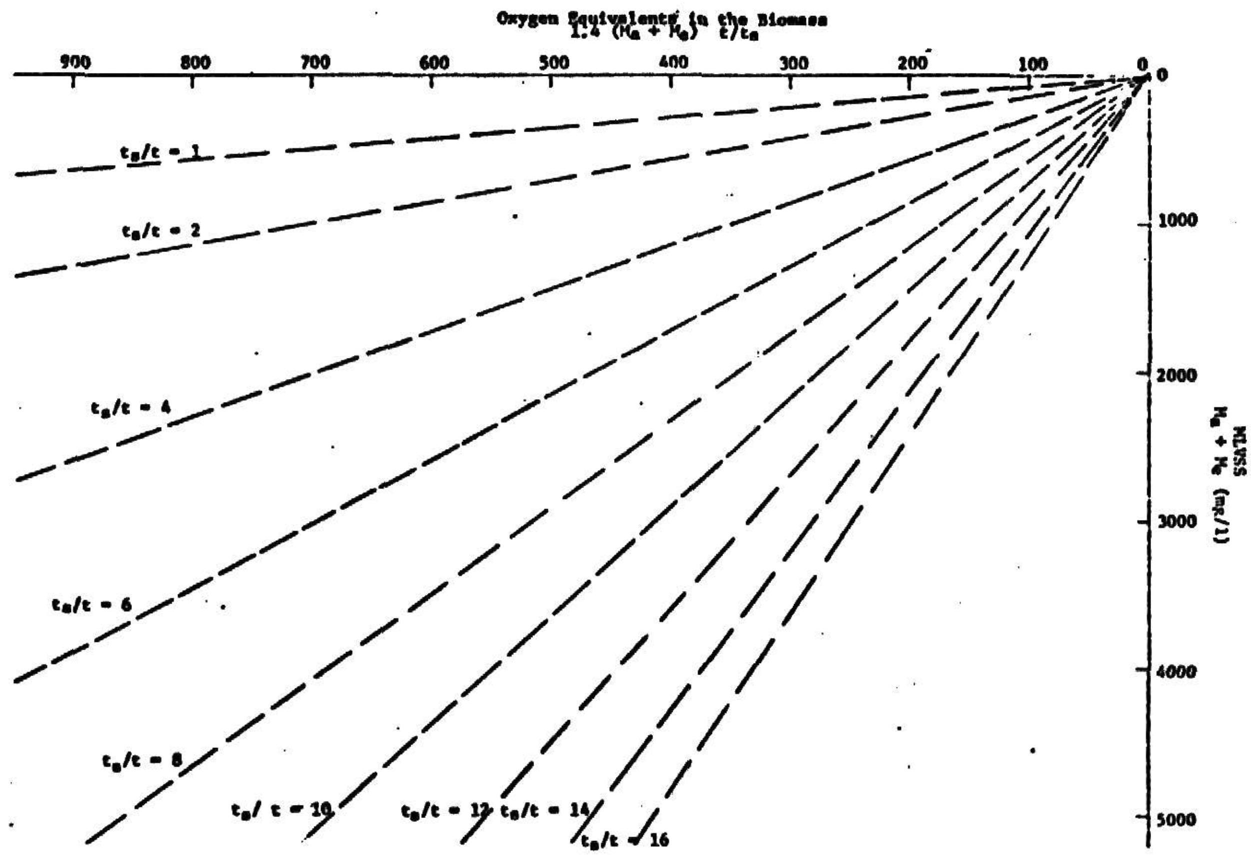

Fig. 2-5. Parameters transposed diagram (I)

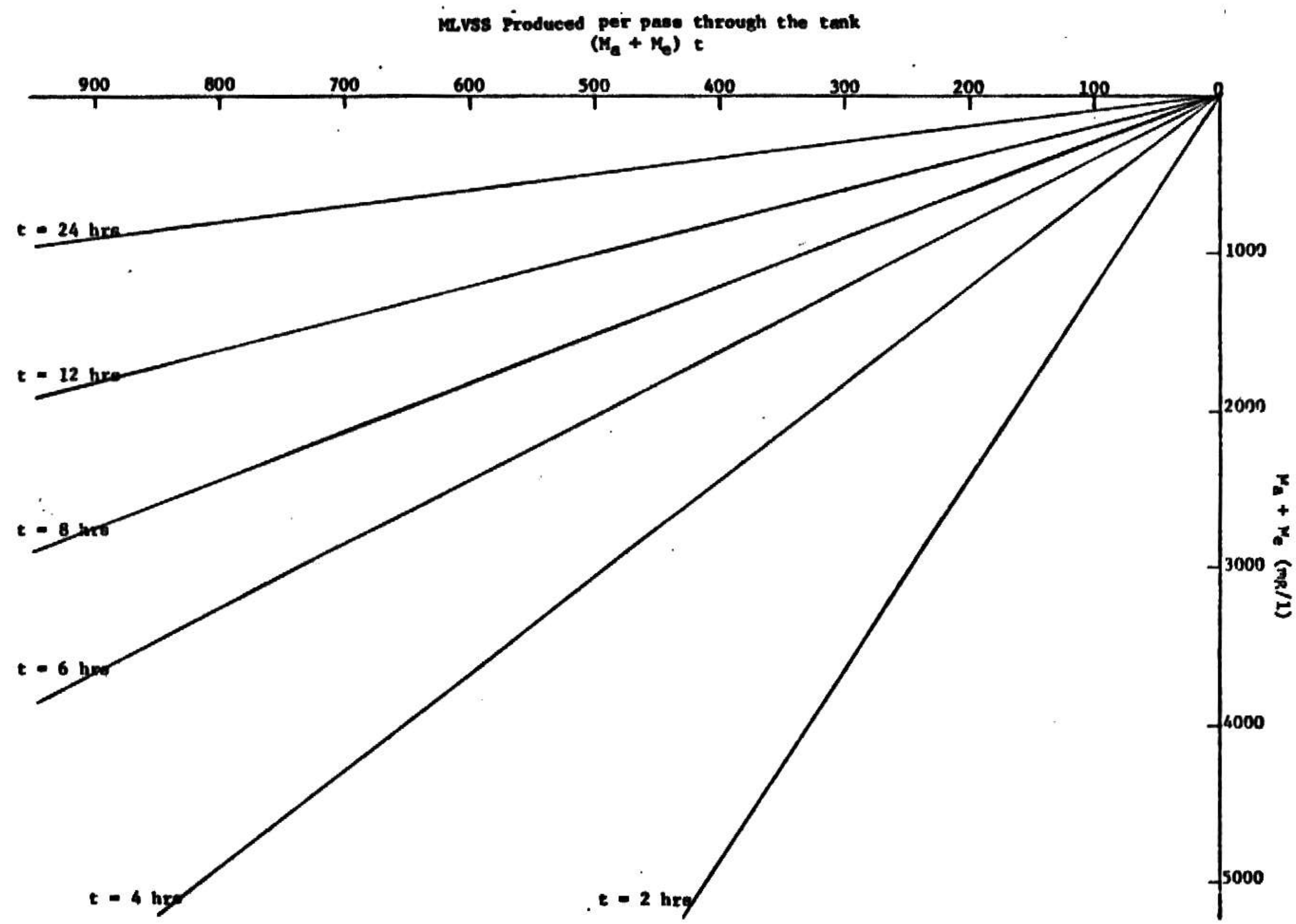

Fig. 2-6. Parameters transposed diagram (II)

e. The graphical solution

Fig. 2-7 is the diagram which combines the diagram, Fig. 2-1, 2-2, 2-3, 2-4, and the added plottings, Fig. 2-5, 2-6 which are transposed by the parameter, $M_a + M_e$. Those diagrams are the means of determining all parameters in the activated sludge process design. The application of the graphical solution in the activated sludge process design problems will be illustrated by the following chapter.

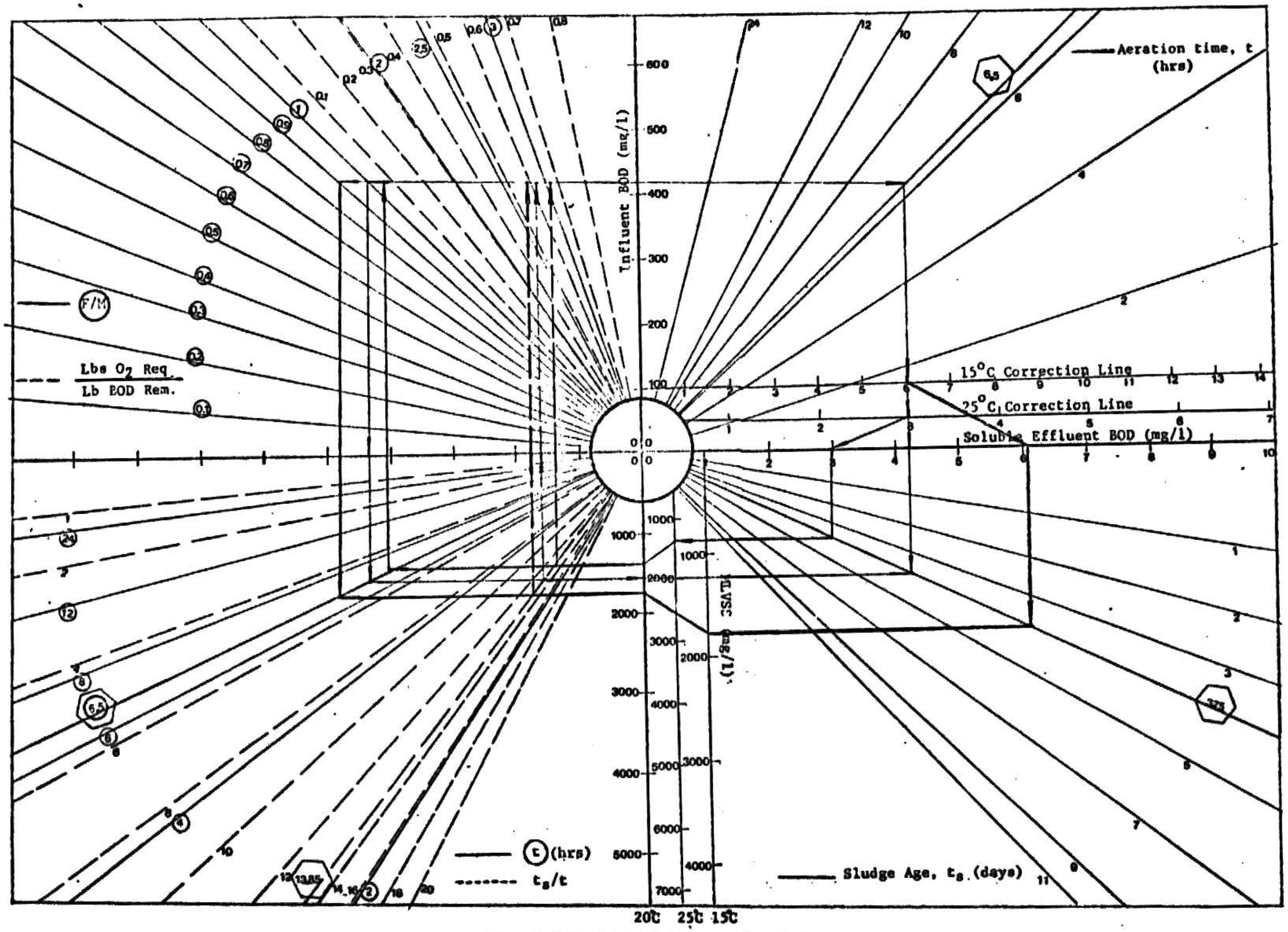

Fig. 2-7 Graphical Solution In CMAS Plants

III. COMPARISON OF CALCULATED RESULTS WITH GRAPHICAL RESULTS FOR A HYPOTHETICAL DESIGN PROBLEM

1. APPLICATION OF THE CALCULATED SOLUTION IN A HYPOTHETICAL DESIGN PROBLEM

The hypothetical design data is presented in Table 3-1.

Table 3-1 Hypothetical design data from a CMAS plant

Influent flow(MGD)	6.2
Influent BOD_L(mg/l)	418
Organic loading(lb BOD_L/day/lb MLVSS)	1.0
Influent S. S.(mg/l)	195
% of VSS to TSS	60
t(hrs)	6.5
K_m(hr^{-1})	15
Temperature(^oC)	20

Calculate soluble BOD_L remaining

S_e = 418 /((15) (6.5) + 1) = 4.25 mg/l

BOD_L remaining, S_e, 4.25 mg/l

Calculate M_a for F/M = 1

Assume sludge age, t_s, is five days

then, M_a = 0.44(360)(4.25) / ((1/5) + 0.24) = 1530 mg/l

Since F/M = 1, the maximum design MLVSS, $(M_a + M_e)_{max}$ is

(418) (8.34) (6.2) = 21639.8 lbs

For the assumed sludge age, 5 days, we have the lbs of M_a in the tank as follow:

(1530) (8.34) (6.2) (6.5) / 24 = 21600 lbs

Therefore, MLVSS in the tank will be greater than $(M_a + M_e)_{max}$. By trial and error solution we can find the sludge age in this design problem at 3.75 days. Once we get sludge age, MLVSS can be determined.

M_a = 0.44 (360) (4.25) / ((1/3.75) + 0.28) = 1232 mg/l

Calculate endogenous mass M_e

M_e = 0.23 (0.28) (1232) (3.75) = 298 mg/l

Calculate inert mass M_{ti}

$M_{ti} = M_{ii} (t_s/t) + 0.1 (M_a + M_e)$

= (0.4) (195) (3.75 / 6.5) (24) + 0.1 (1530)

= 1233 mg/l

Calculate VSS that are non-biodegradable M_{iv}

Influent VSS = 195 (0.6) = 117 mg/l

Assume 40 % are non-biodegradable, then M_{iv} is calculated as

M_{iv} = 0.4 (117) (3.75) (24) /(6.5) = 648 mg/l

Calculate MLSS M_T

$M_T = M_a + M_e + M_{iv} + M_{ti}$ = 1232 + 298 + 648 + 1233

= 3411 mg/l

Calculate % of MLVSS

% of MLVSS = $((M_T - M_{ti}) / M_T)$ 100 = 64 %

Calculate BOD of effluent

Assume effluent SS @ 20 mg/1, then effluent active mass is calculated as follows,

$(M_a)_{eff.}$ = Eff. S.S. (M_a/M_T)in tank = 20 (1232/3411)

= 7.2 mg/1

Eff. $BOD_L = S_e + 1.1\ (M_a)_{eff.} = 4.25 + 7.2\ (1.1)$

= 12.2 mg/1

Eff. BOD_5 = 12.2 / 1.5 = 8.13 mg/1

Calculate oxygen uptake rate R_r

$R_r = ((S_o - S_e) - 1.4\ (M_a + M_e)\ t/t_s)\ /\ t$

$= ((418 - 4.25) - 1.4\ (1530)\ (6.5/(24)(3.75)))\ /\ 6.5$

= 40 mg / 1 / hr

Calculate lbs oxygen required

Oxygen required per pass through tank = 40 (6.5) = 260 mg/1

260 / (418 - 4.25) = 0.63 lbs O_2 req. / lb BOD_L rem.

Calculate sludge recycle @ SDI = 1

MLSS = SDI (10,000) / (1/r + 1)

r = MLSS / (10,000 - MLSS) @ SDI = 1

= 3411 / (10,000 - 3411) = 0.52

Calculate solid wasted per day per MG flow

Solids wasted / day / MG flow = ((MLSS / (t_s/t)) - Eff. S.S.) 8.34

Solids wasted / day / MG flow = ((3411/13.85) - 20) 8.34

= 1887 lbs / day / MG flow

If the temperature changes in this problem, then k_b and K_m should be changed by Eq. (1-14). The value of k_b and K_m at 25°C and 15°C is calculated as follow.

T = 25°C :

$$k_{b25} = k_{b20}\ (1.075^{25-20}) = 0.48\ (1.075^{5}) = 0.69\ \text{day}^{-1}$$

$$K_{m25} = K_{m20}\ (1.075^{25-20}) = 15\ (1.075^{5}) = 21.53\ \text{hr}^{-1}$$

T = 15°C

$$k_{b15} = k_{b20}\ (1.075^{15-20}) = 0.48\ (1.075^{-5}) = 0.33\ \text{day}^{-1}$$

$$K_{m15} = K_{m15}\ (1.075^{15-20}) = 15\ (1.075^{-5}) = 10.45\ \text{hr}^{-1}$$

Once K_{mT} and k_{bT} have found, the same procedure as before can be used to solve the design problem. The results of these changes are presented in Table 3-2.

2. APPLICATION OF THE GRAPHICAL SOLUTION TO THE DESIGN PROBLEM

Soluble BOD_L remaining, S_e

From the upper right hand side of Fig. 2-7, the soluble effluent BOD_L, S_e = 4.2 mg/l, is determined from the given influent BOD_L, S_o = 418 mg/l, and the aeration period, t = 6.5 hrs.

Active and endogenous mass, $M_a + M_e$

From the upper left hand side of Fig. 2-7, the active and endogenous mass per pass through the tank, $(M_a + M_e)$ t = 418, is determined from the given food-microorganism ratio, F/M = 1, and influent BOD_L, S_o = 418 mg/l. Furthermore, the value of $(M_a + M_e)$ which is determined from the lower left hand side of Fig. 2-7 under the given t and $(M_a + M_e)$ t is 1545 mg/l.

Sludge age, t_s

From the lower right hand side of Fig. 2-7, the sludge age, t_s = 3.75 days, is determined from the value of $M_a + M_e$ and S_o which are mentioned above.

Oxygen uptake rate, R_r

From the lower and upper left hand side of Fig. 2-7, the lbs of oxygen required per lb of BOD_L removal = 0.61 is determined from the values, t_s / t = 13.85, $M_a + M_e$ = 1545 mg/l, and S_o = 418 mg/l. Furthermore, the oxygen uptake rate is easy to calculate by the following.

R_r = (lbs O_2 req. / lb BOD_L rem.) (BOD_L rem.) / t

R_r = (0.61) (418) / 6.5 = 39 mg/1

MLSS, M_T

M_T = 1.1 (M_a + M_e) + (Inf. nonvolatile SS) t_s/t + M_{iv}

= 1.1 (1545) + (0.4) (195) (13.85) + (0.24) (195) (13.85)

= 3428 mg/1

% of MLVSS

(M_a + M_e) / M_T = 1545 / 3428 = 0.64 ⟶ 64 %

Sludge return ratio, r

r = M_T / (10,000 (SDI) - M_T) = 3428 / (10,000 - 3428)

= 0.52

BOD Of effluent

Eff. BOD_L = S_e + 1.1 $(M_a)_{eff.}$

= 4.2 + 1.1 (1217 / 3428) (20) = 12.01 mg/1

Eff. BOD_5 = Eff. BOD_L / 1.5 = 12.01 / 1.5 = 8.01 mg/1

Solids wasted per day per MG flow

Solids wasted / day / MG flow = (MLSS / (t_s/t) - Eff. SS) 8.34

= ((3428/13.85) - 20) 8.34

= 1897 lbs / day / MG flow

The results of the graphical solution were represented the above procedures. If temperature changes, the correction line at different temperatures was employed. The changes in other parameters like aeration time, sludge age, and food-microorganism ratio will be expressed in the Table 3-3, 3-4. The procedures of the graphical solution were presented in Fig. 2-7.

3. COMPARISON OF THE RESULTS BETWEEN THE TWO METHODS

There are three major parameters (1) temperature, (2) sludge age, and (3) aeration periods, which may change in the system. These cases are represented by the following Table 3-2, 3-3, and 3-4.

Table 3-2 Temperature change in CMAS plant

t = 6.5 hrs	Calculated results			Graphical results		
t_s = 3.75 days	25°C	20°C	15°C	25°C	20°C	15°C
S_e(mg/l)	2.97	4.25	6.07	3.03	4.20	6.14
M_a(mg/l)	1010	1232	1451	1030	1217	1468
M_e(mg/l)	352	298	269	370	328	232
$M_a + M_e$(mg/l)	1362	1530	1720	1400	1545	1700
M_{ti}(mg/l)	1216	1233	1252	1220	1235	1250
M_{iv}(mg/l)	648	648	648	648	648	648
M_T(MLSS)(mg/l)	3226	3411	3620	3268	3428	3598
% of Volatile	62	64	65	63	64	65
r recycle(%)	48	52	57	49	52	56
BOD_5 Eff.(mg/l)	6.57	8.13	9.93	6.64	8.01	10.08
BOD_L Eff.(mg/l)	9.86	12.20	14.89	9.96	12.01	15.12
lbs O_2 req. per lb BOD_L rem.	0.67	0.63	0.58	0.65	0.61	0.59
O_2 uptake rate (mg/l/hr)	43	40	37	42	39	38
F / M (lb BOD/ day/lb MLVSS)	1.14	1.00	0.90	1.10	1.00	0.90
lbs waste sludge /day/MG flow	1776	1887	2013	1807	1897	2000

Table 3-3 Sludge age change in CMAS plant

t = 6.5 hrs T = 20°C S_o = 418 mg/l S.S. = 195 mg/l	t_s = 5 days		t_s = 2 days	
	Calculation	Graphical	Calculation	Graphical
S_e (mg/l)	4.25	4.20	4.25	4.20
M_a (mg/l)	1509	1492	783	774
M_e (mg/l)	427	408	130	126
M_a + M_e(mg/l)	1936	1900	913	900
M_{ti} (mg/l)	1591	1630	654	666
M_{iv} (mg/l)	864	864	864	864
M_T(MLSS)(mg/l)	4391	4394	1913	1912
% of volatile	64	63	66	65
r recycle(%)	78	78	24	24
BOD_5 Eff.(mg/l)	7.87	7.78	8.84	8.74
BOD_L Eff.(mg/l)	11.81	11.67	13.25	13.11
lbs O_2 req. per lb BOD_L rem.	0.65	0.65	0.58	0.58
O_2 uptake rate (mg/l/hr)	41	41	37	37
F / M (lb BOD/ day/lb MLVSS)	0.80	0.82	1.69	1.73
lbs waste sludge /day/MG flow	2477	2479	985	985

Table 3-4 Aeration period change in CMAS plant

t = 3.75 days S_o = 418 mg/l S.S. = 195 mg/l T = 20°C	t increase to 13 hrs		t decrease to 3.25 hrs	
	Calculation	Graphical	Calculation	Graphical
S_e (mg/l)	2.14	2.15	8.41	8.40
M_a (mg/l)	620	623	2437	2434
M_e (mg/l)	150	137	589	606
$M_a + M_e$ (mg/l)	770	760	3026	3040
M_{ti} (mg/l)	602	602	2404	2403
M_{iv} (mg/l)	324	324	1296	1296
M_T (MLSS)(mg/l)	1696	1686	6726	6739
% of Volatile	65	64	64	64
r recycle(%)	20	20	205	205
BOD_5 Eff. (mg/l)	6.80	6.85	10.92	10.90
BOD_L Eff. (mg/l)	10.18	10.28	16.38	16.35
lbs O_2 req. per lb BOD_L rem.	0.62	0.62	0.63	0.63
O_2 uptake rate (mg/l/hr)	20	20	79	80
F / M (lb BOD/day/lb MLVSS)	1.00	1.02	1.02	1.02
lbs waste sludge /day/MG flow	855	849	3883	3891

IV. CONCLUSIONS

1. From Table 3-1, 3-2, 3-3, and 3-4, the results of the two methods have been compared and found to be close.
2. The graphical solution provides a rapid procedure for evaluating many alternatives in activated sludge process design.
3. For a given MLVSS level the graphical solution provides a direct determination of the sludge age without resorting to trial and error solution.

REFERENCES

1. Rich, L. G., "Unit Process of Sanitary Engineering", John Wiley & Sons, Inc., 1974.

2. Hoover, S. R., and Porges, N., "Assimilation of Dairy Wastes by Activated Sludge, II. The Equation of Synthesis and Rate of Oxygen Utilization", Sew. & Ind. Wastes, 24, 306, 1952.

3. EPA Technology Transfer Seminar Publication, "Wastewater Treatment System - Upgrading Textile Operation to Reduce Pollution", vol. 2, Oct. 1974.

4. Mckinney, R. E., "Mathematics of Complete - Mixing Activated Sludge", Trans. Amer. Soc. Civil Eng. 128, Part III, Paper No. 3516, 1962.

5. Eckenfelder, W. W., Jr., "Manual of Tratment Process", vol. 1, Environmental Science Services Co., 1970.

6. Brian, L. Goodman and Andrew J. Englande, Jr., "An Unified Model of The Activated Sludge Process", Jour. Water Poll. Control Fed., 46, No. 2, Feb. 1974.

7. Metcalf & Eddy, Inc. "Wastewater Engineering", The Maple Press Co., 1972.

8. EPA Technology Transfer, "Process Design Manual for Upgrading Existing Wastewater Treatment Plants", Oct. 1974.

9. Eckenfelder, W. W., Jr., and O'connor, D. J., "The Aerobic Treatment of Organic Wastes", Proc. 9th Ind. Waste Conf., Purdue Univ., W. Lafayette, Ind., Ext. Ser. 89, 39, 2, 512, March 1955.

10. Eckenfelder, W. W., Jr., and O'connor, D. J., "Biological Waste Treatment" Pergamon Press, Oxford, Eng., 1961.

11. Eckenfelder, W. W., Jr., "Theory and Practice of Activated Sludge Process Modifications", Water Sew. Works, 108, 4, 145, 1961.

12. Eckenfelder, W. W., Jr., "Industrial Water Pollution Control", Mcgraw - Hill Book Co., New York, N. Y., 1966.

13. Eckenfelder, W. W., Jr., "Theory of Biological Treatment of Trade Waste", Jour. Water Pollution Control Fed., 39, 240, 1967.

14. Eckenfelder, W. W., Jr., and Ford, D. L., "Water Pollution Control", Pemberton Press, Austin, Tex., 1970.

15. Eckenfelder, W. W., Jr., "Water Quality Engineering for Practicing Engineers", Barnes and Noble, New York, N. Y., 1970.

16. Bernard, J. L., et al., "Design Optimization for Activated Sludge and Extended Aeration Plants", 6th Intl. Water Poll. Res. Conf., Jersusalem, Israel, 1972.

17. Burkhead, C. E., and Mckinney, R. E., "Application of Complete - Mixing Activated Sludge Design Equation to Industrial Wastes", Jour. Water Poll. Fed., 40, 557, 1968.

18. Mckinney, R. E., and Ooten, R. J., "Concepts of Complete - Mixing Activated Sludge", Trans. 19th Annual Conf. San. Eng., Bull, Eng. A-chitecture No. 60, Univ. of Kansas, Lawerence, 1969.

19. Mckinney, R. E., "Design and Operation of Complete - Mixing Activated Sludge Systems", EPCS-Reports, 1, 3, 1, 1970.

20. Mohanrao, G. J., "Hi - Lo Activated Sludge Process for Subdivision Sewage Treatment", MS thesis, M. I. T., Cambridge, 1957.

21. Von der Emde, W., "Aspects of the High Rate Activated Sludge Process", In Advances in Biological Waste Traetment", Mavmillan, New York, N. Y., 1963.

22. Goodman, B. L., "Activated Sludge Treatment of Small Waste Volumes", 6th Intl. Water Poll. Res. Conf., Jerusalem, Israel, 1962.

23. Reynolds, T. D., and Yang, J. T., "Model of the Completely-mixed Activated Sludge Process", Proc. 21st Ind. Waste Conf., Purdue Univ. W. Lafayette Ind., Ext. Ser. 121, 50, 3, 696, May 1966.

24. Servizi, J. A., and Bogan, R. H., "Free Energy as a Parameter in Biological Treatment", Jourq San. Eng. Div., Proc. Amer. Soc. Civil Engr., 89, Paper No. 3539, 1963.

25. Heukelekian, H., et al., "Factors Affecting the Quality of Sludge Production in the Activated Sludge Process", Sew. & Ind. Wastes, 23, 945, 1951.

26. Gellman, I., and Heukelekian, H., "Studies of Biochemical Oxidation by Direct Methods. III. Oxidation and Purification of Industrial Wastes by Activated Sludge", Sew. and Ind. Wastes, 25, 1196, 1953.

27. Sawyer, C. N., "Bacterial Nutrition and Synthesis", Biological Treatment of Sewage and Industrial Waste", I, Reinhold, New York, N. Y., 1956.

28. APHA, AWWA, WPCF, "Standard Methods for Examination of Water and Wastewater", P. 561, 3rd Edition, 1971.

29. Schmidt, R. K., "Parameter Reponses to Influent Suspended Solids in the Activated Sludge Treatment Process", Ph. D. dissertation, Univ. of texas, Austin, 1970.

APPENDIX

LISTS OF SYMBOLS

ALGEBRAIC #		UNIT
a	Mass yield rate, BOD_L or COD basis, lb VSS produced per lb substrate metabolized	
a_5	Mass yield rate, BOD_5 or COD basis, lb VSS produced per lb substrate metabolized	
BOD_L	Ultimate biochemical oxygen demand, 20 days	mg/l
BOD_5	Five-day BOD	mg/l
f_d	Biodegradable fraction of microbial organic mass	
f_{ndi}	Inorganic inert fraction of microbial mass	
ΔF	Free energy change	Kcal/mole
ΔH	Enthalpy change	Kcal/mole
K_m	Overall BOD removal rate, BOD_L or BOD_5 basis, mg/l BOD removed per mg/l BOD remaining per day	hr^{-1} or day^{-1}
K_T	Value of specified reaction rate at specified temperature	
K_{20}	Value of specified reaction rate at 20^oC	
k_b	Endogenous oxidation rate, mg/l degradable mass oxidized per mg/l degradable mass remaining per day	hr^{-1} or day^{-1}
M_a	Active mass concentration, VSS basis	mg/l
$(M_a)_{eff.}$	Effluent active mass concentration	mg/l
M_e	Endogenous mass concentration, VSS basis	mg/l
M_{iv}	Inert organic mass concentration	mg/l
M_T	Total mass concentration	mg/l
ΔM_T	The weight of solids change in the tank daily	mg/l
M_{Te}	The weight of solids in the effluent daily	mg/l

M_{ti}	Inert inorganic mass concentration	mg/1
M_{Tw}	The weight of solids to wasted per day	mg/1
Q	Influent flow rate	mgd
r	Sludge return ratio	%
ΔS	Entropy change	Kcal/mole
SDI	Sludge density index, mg/1 suspended solids(MLSS) per ml of settled sludge multiplied by 10	
S_e	Effluent soluble substrate concentration, BOD_L or BOD_5 basis	mg/1
S_o	Influent substrate concentration, BOD_L or BOD_5 basis	mg/1
T	Temperature	^oC
t	aeration period	hrs or days
t_s	Sludge age	days
Y	Relation between oxygen requirement and influent substrate, R_rt/S_o, lbs oxygen requirement per lb substrate removal	

AKNOWLEDGEMENT

The author wishes to express his most sincere appreciation and deep gratitude to Dr. Schmid, L. A., his adviser, for his patient guidance, everlasting encouragement, and constructive criticism, during his graduate study at K-State.

Thanks are also greatly indebted to Dr. Zovne, J. J. and Dr. Annis, J. C., for their serving in advisory committes. Finally, he would like also to thank Dr. Peter B. Cooper for his serving chairperson in the final oral examination.

THE DEVELOPMENT OF A GRAPHICAL SOLUTION TO A MATHEMATICAL MODEL OF COMPLETE MIX ACTIVATED SLUDGE PROCESS

by

WENG-HSIANG HSIEH

B.S., National Taiwan University, 1971
Taipei, Taiwan

AN ABSTRACT OF A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Civil Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1976

ABSTRACT

The purpose of this report was to develop a graphical solution to a mathematical model of the complete mix activated sludge process. The mathematical relationship between process parameters were used to develop the diagram. This solution provides a direct determination of the major parameter without resorting to trial and error solution. Also it provides a rapid procedure for evaluating many alternatives in activated sludge process design.

This report also pointed out the application of calculated and graphical solution in a hypothetical design problem. Furthermore, the comparison of these two results are found to close.

This report comprises the following four chapters: literature review; development of a graphical solution for the unified model of the activated sludge process in complete mix activated sludge system; comparison of calculated results with graphical results for a hypothetical design problem; conclusions.