HYDRAULIC DETENTION TIME, A FUNCTIONAL DESIGN AND OPERATIONAL CONTROL PARAMETER FOR ACTIVATED SLUDGE TREATMENT PROCESSES

By

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CHAPTER I

INTRODUCTION

With the tremendous increase in population and industrialization in this country the craving for water will multiply so extortionately that the increased reuse of water could be the most practical and economical means for furnishing future water requirements. Activated sludge process and its modifications are considered to be major and complete methods of organic wastewater treatment.

Activated sludge treatment is principally an aerobic fluidized bed system process in which the removal of soluble organics depends on the action of flocculated microorganisms in the presence of an injected air supply. This biological metabolism involves the conversion of the organic waste to new cell material, by the synthesis of biomass, which can be easily settled and separated out and metabolism end product, by the oxidation to carbon dioxide and water, and thus the organic waste is removed.

Parameters of importance that have been used for the design, control and operation of the activated sludge process include: organic level (in terms of COD or BOD values) of the influent wastewater, mixed liquor concentrations in the reactor, organic loading (such as: specific ultilization, U; food

to microorganism ratio, F/M; and volumetric loading, F/V etc.), air quantities, physical properties of the sludge (such as: SVI and SDI etc.), mean cell residence time (or specific growth rate of microorganism), sludge recycling, relative aeration tank dimensions, and hydraulic detention periods, either singly or in combinations with each other.

Among the above factors, organic loading (F/M or U), mean cell residence time (or specific growth rate of microorganism) and mixed liquor suspended solids concentrations in the reactor are three highly-appraised approaches for the design, control and operation of activated sludge systems. At the same time, the less complicated parameter of hydraulic detention time is either discarded or neglected or misused without perceiving the following importances of detention time control of the activated sludge process:

(a). elimination of regulation tanks and increasement of treatment loading

(b). reduction in plant size for the same volume of waste economically

(c). prediction of treatment efficiency and easy control of process to obtain ultimate treatment efficiency

(d). prevention of effects of quantitative and qualitative shock loadings

(e). prevention of sludge bulking in secondary clarifers

(f). maintenance of active organisms at a uniform physiological state over an indefinite period by combining with mean cell residence time as the control-

ling parameters, and

(g). understanding the relationships between hydraulic detention time and other controlling parameters.

Furthermore, laboratory and plant-scale investigations have only disclosed the qualitative relations which exist between a few of these parameters and the efficiency of organic waste removal, but a more functional loading parameter for the design, control and operation of aerobically complete mixed activated sludge treatment process still remains to be established. The following are the intents of this research:

(a). determine whether hydraulic detention time is a major parameter for the design and operational control of the activated sludge process,

(b). investigate the effect of hydraulic detention time on treatment efficiency, sludge production, mixed liquor suspended solids concentration in the reactor, cell yield coefficient, oxygen requirements, and other physiological growth parameters,

(c). understand whether sludge production is dependent upon hydraulic detention time of the system,

(d). establish the relationships between hydraulic detention time and other control parameters for the activated sludge process, and

(e). review the necessity of design requirements (1, 121) requiring a 6.0 to 7.5 hour hydraulic detention time.

In this study a completely mixed continous flow activa-

ted sludge treatment unit was run at various combinations of mean cell residence time and hydraulic detention time. An inflow substrate concentration of about 200 mg/l glucose with COD:N:P of 100:10:30 was used in this studies.

Steady state data for substrate concentration, biological solids concentration, pH value, oxygen uptake rate and temperature were determined at each combination. The air flow supply, the dissolved oxygen tension, the sludge recycle condition, and time for taking samples were controlled. Microscopic examination of the culture was made at each different combination of mean cell residence time and hydraulic detention time to help gain a complete understanding about the effect on population dynamics.

The author expresses his desire that this investigation will give additional insight to the understanding and controlling of hydraulic detention time to the completely mixed activated sludge processes.

CHAPTER II

LITERATURE REVIEW

Today's waste treatment plant is increasingly required to produce a highly treated secondary effluent in order to meet more demanding discharge requirements or to prepare wastewater for further processing. As a result, the need to make a reliable estimate of the performance of the biological wastewater treatment process under various operational conditions is of obvious importance. The determination of a functional parameter for the design and operational control of the treatment process and the establishment of a relationship between the performance and functional operating parameter would not only increase the reliability of the activated sludge process and the resulting treatment efficiency but also ease the pressures of the operator's heavy workload and overall operating costs.

The purpose of this chapter is to present literature which will be beneficial in the investigation of whether hydraulic detention time is a functional parameter for the operational control of the completely mixed activated sludge process. The literature reviewed will be delineated according to the following subjects: A. principle of aeraobic biological treatment, B. completely mixed activated sludge pro-

cess, C. performance of wastewater treatment process, D. factors affecting the performance of completely mixed activated sludge process, and E. hydraulic detention time.

A. Principal of Aerobic Biological Treatment

1. Mechanism of BOD Removal

The primary aim of aerobic biological treatment of wastewater is the removal of organic carbon. When organic matter is removed from solution by microorganisms, two basic phenomena occur: synthesis and respiration. These two processes are interrelated and can't be considered as separate distinct functions.

Synthesis results in the conversion of some of the soluble organic and inorganic matter in the wastewater into biological cell protoplasm which, although being a complex conglomeration of proteins, carbodydrates, and lipids, has a relatively uniform chemical formulation under identical environmental conditions. An empirical formulation of protoplasm found by Porges, et al. (2) was $C_5H_7NO_2$, while $C_5H_8O_2N$ was presented by Symons (3) to represent the protoplasm of young bacterial cells.

The conversion of the soluble organic compounds into protoplasm requires energy which is obtained by oxidation of a portion of the organic matter in the liquid wastes. In aerobic biological systems, the oxidation of organic matter, or

respiration, results in the formation of carbon dioxide and water which are the most stable chemical forms for carbon and hydrogen. The organisms also undergo progressive autoxidation of their cellular mass while their food supply is limited. This process is called endogenous respiration. Several other mechanisms are also happening during the removal of organic waste by biological stabilization. Large particles undergo subdivision by hydrolysis prior to biological oxidation while suspended and finely divided solids are removed by adsorption and coagulation. Therefore, the reactions involved in the removal of organic compounds from liquid waste during biological oxidation can be interpreted as:

(a). removal of BOD in direct proportion to biological microorganism growth.

(b). oxidation of biological cellular material through endogenous respiration.

These three phase reactions with a portion of the removed organic matter being oxidized and a portion being synthesized to new cellular material together with a subsequent oxidation of cellular material can be illustrated by the following general equations (4):

$$C_xH_yO_z + O_2 \xrightarrow{\text{microorganisms}} CO_2 + H_2O + \text{energy} \qquad (2.1)$$

$$C_xH_yO_z + NH_3 \xrightarrow{\text{microorganisms}} H_2O + CO_2 + \text{new cellular material} \qquad (2.2)$$

$$\text{Cellular material} + O_2 \longrightarrow CO_2 + H_2O + NH_3 + \text{energy} \qquad (2.3)$$

A diagram of the thermodynamic mechanism of the synthesis and oxidation of organic waste removal by microorganisms is further illustrated in Figure 1.

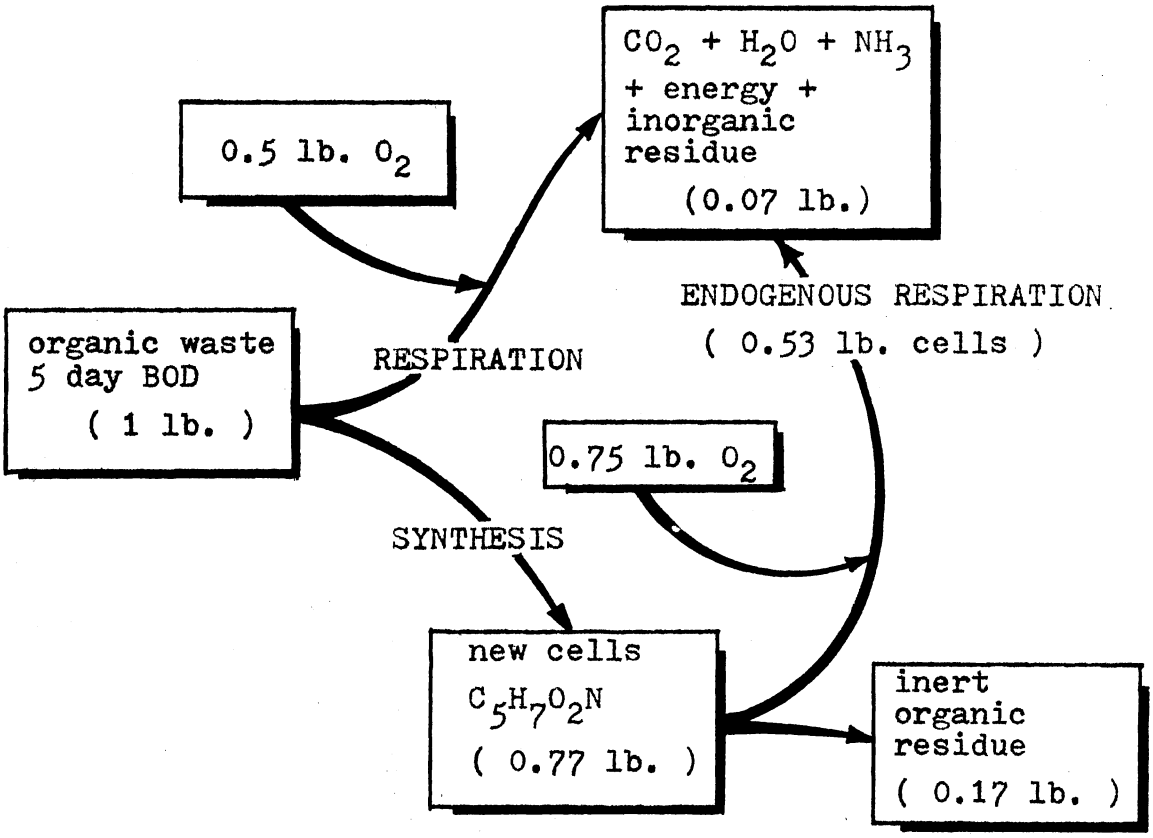

Figure 1. Biological Synthesis and Oxidation (5, 6).

2. Substrate Removal and Sludge Growth

There are two primary relationships between substrate removal and growth. The first relationship concerns the amount of biological solids accumulation which can be estima-

ted from the utilization of a given amount of substrate. The second one describes the relationship between the rate of biological growth and the concentration of substrate present.

When the supply of any required microbial nutrient is limited, it will become the critical functional factor determining the rate of biological growth and the amount of biological solids accumulation. For most biological wastewater treatment studies, however, it is assumed that only the organic carbon source is the limiting nutrient and the most important factor in determining the relationships between microbial growth and substrate removal during the purification phase.

Mathematically, the first stoichiometric relationship between organic substrate removed and microorganisms produced is usually expressed as a yield as shown below:

$$(dX/dt) = - Y(dS/dt) \qquad (2.4)$$

where

X = concentration of microorganisms

S = concentration of substrate

t = time of reaction

Y = yield coefficient

Some other contributions to the development of the relationship between net microbial growth and the amount of substrate utilized were made by Heukelekian, et al. (7), Weston, et al. (4), Hawkes (9), and McCarty, et al. (10). This relationship is shown and described below:

$$R_g = - Y_{max}R_{su} - k_dX \qquad (2.5)$$

where

R_g = net microbial growth

Y_{max} = cell yield coefficient

R_{su} = substrate utilization or organic removal rate

k_d = microorganism decay or maintenance energy coefficient

X = microorganism concentration.

The above equation has been explained as a two phase mathematical description of the batch microbial growth curve wherein the term $-Y_{max}R_{su}$ is attributed to oxidation of substrate for cellular energy requirements and the synthesis of the new cell tissue, and the term $-k_dX$ accounts for auto-oxidation of microbial mass in the endogenous phase to satisfy additional energy requirements.

A more conceptually valid equation that describes net microbial growth of continuous flow biological wastewater treatment systems has been used by Sherrard, et al. (11), as shown below:

$$R_g = - Y_{obs}R_{su} \qquad (2.6)$$

where Y_{obs} is a variable observed yield coefficient and the remaining terms are as defined previously. The observed yield coefficient can be calculated and plotted directly as a function of growth rate (reciprocal of mean cell residence time) for a continuous flow system.

The yield coefficient, Y in Equation 2.4 or Y_{max} in Equation 2.5, is a function of the predominant species of microorganism, type of substrate, and environmental conditions but

can be assumed constant, as a first approximation, for a given biological process (12).

The second quantitative relationship for the growth of microorganisms under exponential growth conditions is the common autocatalytic equation given below:

$$dX/dt = \mu X \tag{2.7}$$

where

μ = specific growth rate.

A more valuable expression of the above first order differential equation is in its integrated forms which produces a straight line plot on semilogarithmic paper:

$$\text{Ln } X_t - \text{Ln } X_o = \mu t \tag{2.8}$$

or $$\mu = \text{Ln } 2 / t_d = 0.693/t_d \tag{2.9}$$

where

t_d = time required for biological solids X to double in value by extrapolation

X_o = initial biological solids concentration at time, zero

X_t = biological solids concentration at time, t.

However, Monod (13) has shown that the specific growth rate is not a true constant, but is a function of a limiting nutrient concentration. He described this relationship with a hyperbolic function, as shown below:

$$\mu = \mu_{max} [S_o / (K_s + S_o)] \tag{2.10}$$

where

S_o = initial concentration of substrate in batch systems

K_s = a saturation coefficient used in the hyperbolic ex-

pression relating specific growth rate to substrate concentration. It is numerically equal to the substrate concentration at which the specific growth rate is equal to half of the maximum specific growth rate for the system, and

μ_{max} = the maximum specific growth rate for a system in exponential growth.

Although empirical, this relationship is not strictly fortuitous since adsorption, transport, and the enzymatic utilization of essential nutrients all fit into this general category of reactions. The Monod Equation is still the most commonly used relationship between specific growth rate and substrate concentration.

In most biological processes, however, the retained detention time of the microorganisms in the reactor is long enough for autooxidation, organism decay, endogenous metabolism, death with subsequent lysis, cryptic growth, or the destruction of microorganisms to be of importance, then, Eq. 2.7 should be modified to incorporate the effects of these factors as follows:

$$dX/dt = (\mu - k_d) X \qquad (2.11)$$

where

k_d = specific organism decay rate.

3. Oxygen Utilization

Oxygen plays an essential role in aerobic biological

treatment as shown in Equations 2.1, 2.2, and 2.3. During assimilation, microbial populations require oxygen to supply energy required for synthesis. In addition to the above oxidation, the new cell materials produced by the assimilation of organic matter is oxidized by its own mass endogenously. In the absence of available nutrients, cells oxidize their own tissue in order to meet the maintenance energy requirement. The resulting relationship was presented by Eckenfelder (5) as shown below:

$$dO_2/dt = a'(dS/dt) + b' \qquad (2.12)$$

where

a' = sludge yield coefficient from microbial synthesis

b' = sludge decay coefficient

During the log growth phase when the BOD concentration does not limit the rate of reaction, Equation 2.12 reduces to:

$$dO_2 = \text{Constant} \qquad (2.13)$$

During the declining growth phase the rate of sludge growth progressively decreases and the unit oxygen utilization rate decreases and approach the endogenous rate b' to yield the relationship

$$dO_2/dt = c'S + b' \qquad (2.14)$$

where

c' = constant

However, the specific oxygen uptake rate will also depend on the history and acclimatization of the sludge. For example, an actively growing sludge will exhibit a more rapid response to a BOD loading than will an advanced endogenous

sludge.

For optimum efficiency, oxygen must be supplied at a rate equal to or greater than its rate of utilization. Below certain critical oxygen tensions the rate of microbial activity may be limited. In a completely mixed activated sludge process this is usually accomplished by diffusion from air bubbles injected into the liquid-sludge mass under turbulent conditions.

However, Rickard and Gaudy (14) reported, in their study on the effects of dissolved oxygen tension on the growth of heterogeneous populations in a completely mixed continuous flow reactor, that under conditions approximating a steady state no change was observed in oxygen uptake rate, sludge yield, protein content, or RNA content of the sludge for a range of DO concentrations from 1.4 to 7.1 mg/l with constant agitation.

4. Nutritional Requirements

A minimal quantity of nitrogen, phosphorus, and several mineral elements such as potassium and calcium are essential for the efficient and successful biilogical metabolism of organic wastes by microorganisms. While domestic wastewater contains an excess of nitrogen and phosphorus, most industrial wastes are deficient in these nutrients essential to microbial growth.

Nutritional requirements have been defined by several parameters, namely, BOD:N:P ratio, COD:N:P ratio, lb N or P

per 100 lb BOD (or COD) removed, or Nitrogen or Phosphorus content of the mixed liquor biomass. From some early research works, the critical requirement of nutrients were revealed as belows:

4.3 lb N per 100 lb BOD removed (15)

12.3% Nitrogen contained in a cell with the empirical formula $C_5H_7O_2N$ (16)

a maximum utilization of 12% by weight of the cells synthesized and a minimum requirement of 1.0% by weight of that removed under conditions of total oxidation (17)

a BOD:N:P ratio of 100:5:1 in a waste will usually insure adequate nutrition (18), and

0.6 lb Phosphorus per 100 lb BOD removed (15).

When insufficient nitrogen is present, the amount of cellular material synthesized per unit of organic matter removed increases as an accumulation of polysaccharide. While nitrogen-limiting conditions restrict the rate of BOD removal , the nitrogen content will declined during the endogenous phase.

Not all organic nitrogen compounds are available for synthesis. Ammonia is the most readily available form for microbial metabolism. For an organic wastewater with a COD/ NH_3-N ratio greater than 20, nitrification will not occur in the activated sludge systems (18).

5. Effect of Temperature

The rate of the biological reaction will increase with temperature to an optimum value, approximately 30 ^{o}C for most aerobic wastewater systems. Further increases in temperature result in a decrease in rate for mesophilic organisms (19). Temperature correction factors have been commonly used in analyzing biological waste treatment processes to modify microorganism growth rates for temperature variations. These temperature corrections can be expressed in terms of the modified Arrhenius Equation (20, 21):

$$K_T = K_{20}\, \phi^{(T-20)} \qquad (2.15)$$

where

K_T = microorganism growth rate at some temperature, T

K_{20} = microorganism growth rate at 20 ^{o}C, and

ϕ = a constant called the temperature coefficient.

or

$$U = \frac{k_o\, e^{(C_2 T)}\, S}{K_{so}\, e^{(C_3 T)} + S} \qquad (2.17)$$

where

C_2 = a constant equal to the slope of log k vs. temperature line

C_3 = constant equal to the slope of log K_s vs. temperature line

k_o = k at a reference temperature, T

K_{so} = K_s at a reference temperature, T, and

U = specific utilization rate.

Normally, low-cell systems are more temperature-sensitive than processes where high organism levels are maintained , although a workable model for predicting temperature effect has not been developed yet.

6. Effect of the pH

The pH is another key factor in the growth of organisms and plays a vital role in the life and death of microorganisms as well as in other microscopic plants and animals. The effect of pH on the overall oxidation process is normally associated with specific enzymatic processes. Over some pH range for each particular enzyme the activity approaches a maximum and falls off above or below the optimum range. A relatively narrow effective pH range will exist for most bio-oxidation systems. Generally, the optimum pH for growth lies between 6.5 and 7.5. Most organisms cannot tolerate pH levels above 9.5 or below 4.0 .

It is well known that the pH level will affect the predominance of microorganisms. Slyter, et al. (28) found protozoa were present in low concentrations during periods of acid values, a finding in agreement with that of Gibson (29) and Rogers, et al. (38). He also found that at a pH level below 5.0 all strains of bacteria present were nonmotile and rod-shaped, and only 65% were gram negative. George in his pH shock load studies (30) observed that as the reactor pH drops from neutrality to the acid range, the predominating microbial species change from bacteria to filamentous types.

The chemical composition of cells has been observed to be dependent on the extracellular pH of the medium in which they are grown. Slyter, et al. (28), studying the morphological and biochemical changes occurring in a continuous culture of rumen microorganisms, found that the DNA concentrations in terms of weight per unit volume of reactor liquid decreased with decreasing pH. Another finding from George's investigations (30) revealed that in all cases the cell yield in the new steady state after a shock load of acid range pH was increased; protein content was decreased; and carbohydrate content was increased.

Other effects of pH level are listed as followings:

uptake of metallic ions by microbial cells (31, 32)

enzymatic reactions of all living cells (33)

periods of aeration for the oxidation of organic waste (34)

uptake of disolved oxygen (7, 35)

proteolytic activity of organisms (36)

sludge settling characteristis (37)

growth rate of organisms (39)

B. Completely Mixed Activated Sludge Process

The completely mixed activated sludge process, having received widespread attention and acceptance in recent years, has been defined by McKinney (59) as a process in which the incoming wastes are intimately, instantaneously and thorough-

ly mixed with the entire contents of the aeration tank in a minimum of time. The mixing is accomplished either by impellers or by gas diffusion. In order to obtain complete mixing in the aeration reactor it is necessary to introduce the incoming wastes into a relatively small tank volume with violent agitation so that the time for complete dispersion is a minimum. This implies that a uniform organic load exists throughout the aeration reactor, which results in a uniform oxygen demand and uniform biological growth. If the reactor is well operated under steady state conditions, the outflowing liquor will be identical in composition to the mixed liquor and the microbial growth will be in the exponential phase. The desired effluent quality determines the size of the completely mixed systems. It is possible to produce an effluent of any desired organic level from wastes of any organic strength.

Although there are several investigators in this field who feel that conventional plug flow activated sludge systems are mathematically more efficient than completely mixed activated sludge processes (61, 62, 63, 64, 65), McKinney (66) in his work of evaluating a completely mixed activated sludge plant at Grand Island, Neb. pointed out that together with an understanding of some basic microbiological relationships and with the proper controlling of flows and loads in the wastewater treatment operations CMAS (completely mixed activated sludge) processes did demonstrate superior performance in comparison with conventional activated sludge systems. Seve-

ral treatment plants were designed based on CMAS fundamental kinetics (67, 68). The operational results obtained from these plants definitely proved the value of the CMAS concept.

The completely mixed activated sludge system has many advantages over the other modifications of the activated sludge process. Some of these inherent important advantages are:

(a). producing an effluent of any desired BOD concentration in a single stage unit for a waste of any BOD concentration

(b). maximum equalization of the oxygen uptake rate

(c). maximum ability to absorb shock loads

(d). maximum neutralization of CO_2 produced during respiration

(e). reduction in the toxicity of a toxic material when the toxic material is biodegradable and is present in low concentrations

(f). not affected by hydraulic shock loads

(g). ability to produce little excess sludge or lots of sludge

(h). provision of relatively constant environmental conditions for the biological mass

(i). ability to give a standard design for domestic sewage or industrial wastes regardless of the chemical nature of the wastes; and lower the capital costs than conventional activated sludge.

Complete mixing occurs when the particles entering the

reactor are immediately dispersed throughout the tank. The particles leave the tank in proportion to their statistical population. Complete mixing can be accomplished if the contents of the tank are uniformly and continuously redistributed. The flow characteristics of a completely mixed reactor can be determined by injecting a nonreactive tracer into the inlet at concentration C_o when time is t_o. The effluent concentration, C, at the outlet as a function of time, t, can be determined from a material mass balance for the tracer around the reactor as shown below (49, 70):

$$C = C_o[\ 1 - e^{(-t/t_d)}\ ] \qquad (2.18)$$

where

C = effluent concentration of tracer at any time t

C_o = influent concentration of tracer

t_d = hydraulic detention time, V/Q

V = volume of reactor

Q = flowrate

The corresponding expression for the effluent concentration from a reactor that is being purged of tracer is derived similarly, and is given by

$$C = C_o\ e^{(-t/t_d)} \qquad (2.19)$$

By plotting Equation 2.18 and 2.19 in Figure 2, the flow characteristics of a particular completely mixed aeration reactor can be easily evaluated. From Figure 2 it can be seen that only when time t is equal to infinity will the effluent concentration of tracer be equal to C_o and zero, respectively.

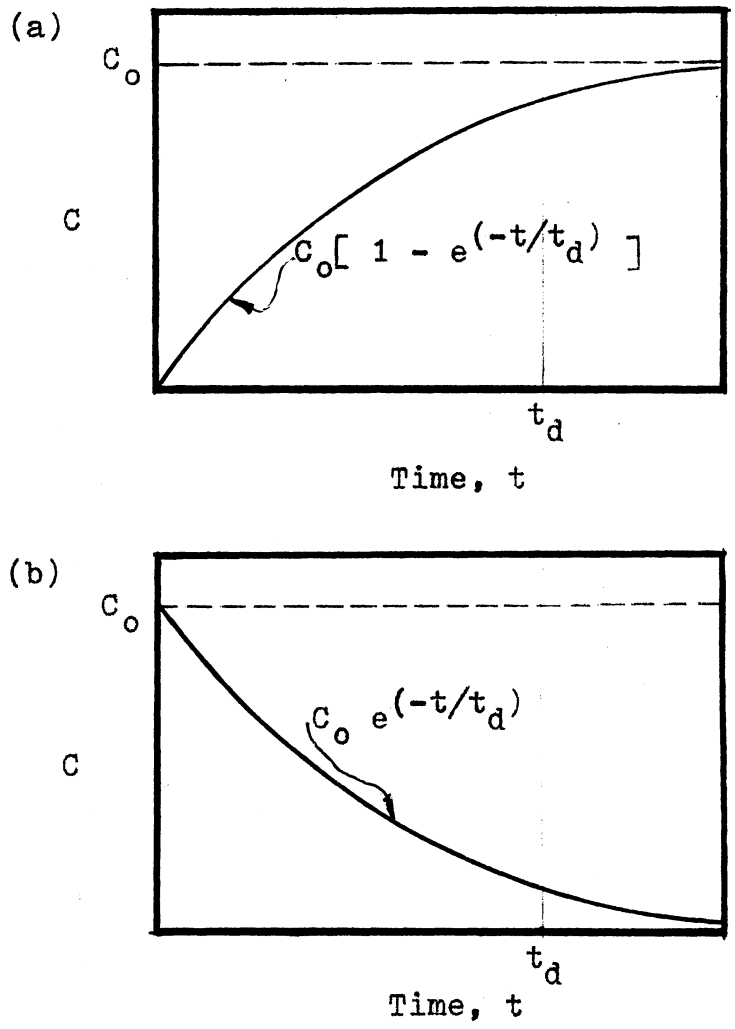

Figure 2. Out Put Tracer Response Curves for A Particular Completely Mixed Reactor, (a). Continuous Tracer Input, and (b). Slug Tracer Input (adapted from 69).

As mentioned before, the completely mixed activated sludge process has the ability to damp shock loads applied to the plant. The shock load is immediately mixed with the aeration tank contents and distributed throughout the aeration tank thus its effect is minimized. From a series of shock loading studies by Gaudy, et al. (30, 71, 73), a reasonable conclusion has been made that for CMAS reactors designed for operation with a mean hydraulic residence time of eight hours

the system can be expected to accommodate, without serious disruption of biochemical efficiency of substrate removal, hydraulic shocks consisting of step increases in flow rate up to 100% with no change in concentration of incoming substrate. Decreases in flow rate greater than 100% can be accommodated too. A more significant change in steady state yield of cells was found, when a hydraulic shock loading under constant organic loading was applied than that under constant concentration conditions. In both cases the yield decreased with decreased dilution rates, but increased at increased dilution rates. They concluded that in the interest of providing more steady and reliable performance with regard to substrate removal efficiency, CMAS systems should be protected against a change in flow rate greater than 100%.

Ramanathan (60) classified the control of the CMAS process into two kinds, namely as internally controlled and externally controlled systems. In the internally controlled system the rate of flow of nutrient to the reactor changes according to the variations in the bacterial density and is controlled by a sensing element such as a photo cell which detects internal changes in the system, such as bacterial density, pH, or chemical concentration. Thus the successful operation of an internally controlled system depends upon the sensitivity of the density detecting system. In any such system the organisms will grow at the maximum rate characterized by the environmental conditions in the reactor. The operator can select any desired bacterial density, but he can

produce a change in the growth rate only by a change in nutrients, temperature, or pH. In an externally controlled system the flow rate is kept constant at some fixed value below the maximum growth rate. The growth medium contains an excess of all nutrients except one. The nutrient which is not in excess is the growth limiting factor. Under these conditions the bacterial density will increase in the reactor ; however, as the bacterial density increases, the food to cell ratio will decrease and tend to become very small. Then the growth rate will begin to decrease. Soon an equilibrium at which the system parameters will not change with time is established. This system is thus said to be self-stabilizing , and free from oscillations.

McKinney (59) also pointed out that there are many different modifications of the basic process involing endogenous respiration with combination aeration-sedimentation units or separate aeration tanks and sedimentation tanks and varying rates of synthesis (high sludge synthesis). A completely mixed process can be run with or without feedback or cell recycling, since an equilibrium in the steady state is established between the microbial growth inside the reactor and the flow rate of the nutrient solution. Any change in the system parameters will result only in the shifting of the equilibrium position, but will never result in a permanent disturbance to equilibrium (60). Because there has been a tendency to utilize feedback modification of completely mixed process from an economical viewpoint, only that CMAS with

cell recycling system will be mentioned in this chapter.

1. Kinetics of Completely Activated Sludge

There has been at least five organic removal kinetic models developed based on mass balance for a completely mixed activated sludge process during the past two decades. Because the purpose of this research is to investigate whether hydraulic detention time is a primary functional parameter for the design and operational control of completely mixed activated sludge process and, if not, to try to inquisite an authentically functional parameter for it; and because these theoretical removal kinetics have been amply presented and discussed in the literature, only related formulations of importance will be reviewed in this chapter under the following subjects: (1). Eckenfelder's approach, (2). Herbert's approach, (3). McKinney's approach, (4). Gaudy's approach, and (5). mean cell residence time approach.

(1). Eckenfelder's Approach (4, 26, 42, & Figure 3):

$$S_e = S_o(1 + k X_v t)^{-1} \qquad (2.20)$$

$$E = k X_v t (1 + k X_v t)^{-1} \times 100\% \qquad (2.21)$$

$$X_v = (a S_r/t)(G^{-1} + b)^{-1} \qquad (2.22)$$

$$\Delta X = QX_o + a(S_r)Q - (bX_v V + QX_e) \qquad (2.23)$$

or $$\Delta X = a S_r/t - bX_v \qquad (2.23\text{-}1)$$

$$R_r V = a' S_r Q + b' X_v V \qquad (2.24)$$

or $$R_r = a' S_r / t + b' X_v \qquad (2.24\text{-}1)$$

Therefore

$$S_e = S_e(X_v t) \qquad (2.20\text{-}1)$$

$$X_v = X_v(S_r, t, G) \qquad (2.22\text{-}1)$$

$$\Delta X = \Delta X(S_r, X_v, t) \qquad (2.23\text{-}2)$$

$$R_r = R_r(S_r, X_v, t) \qquad (2.24\text{-}2)$$

$$E = E(X_v t) \qquad (2.21\text{-}1)$$

Where

S_o = raw waste substrate concentration

S_e = effluent substrate concentration

$S_r = S_o - S_e$

X_o = influent suspended solids concentration

X_v = MLSS concentration in reactor

X_e = effluent suspended solids concentration

t = hydraulic detention time

k = average waste removal rate coefficient, $k_{20\ ^oC}$ = 0.001 per hour for domestic waste at 20 ^oC, for other temperature, T: $k_T = k_{20\ ^oC}\ \phi^{(T-20)}$

ϕ = temperature coefficient

k_T = removal rate k at any temperature T

a = fraction of substrate converted to new cells

b = fraction per day of VSS oxidized

a' = fraction of substrate used for oxidation

b' = fraction per day of VSS oxidized

E = removal efficiency

V = aeration tank volume

Q = influent flow rate

ΔX = daily sludge production

R_r = oxygen utilization per day

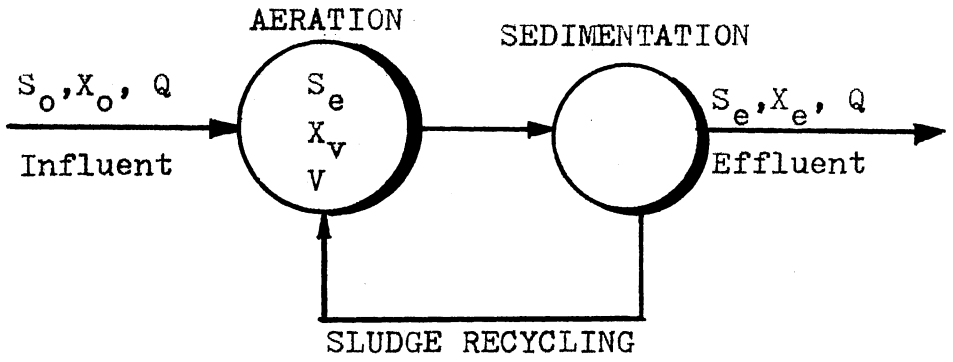

Figure 3. Schematic of A CMAS Process with Cellular Recycle for Eckenfelder's Approach.

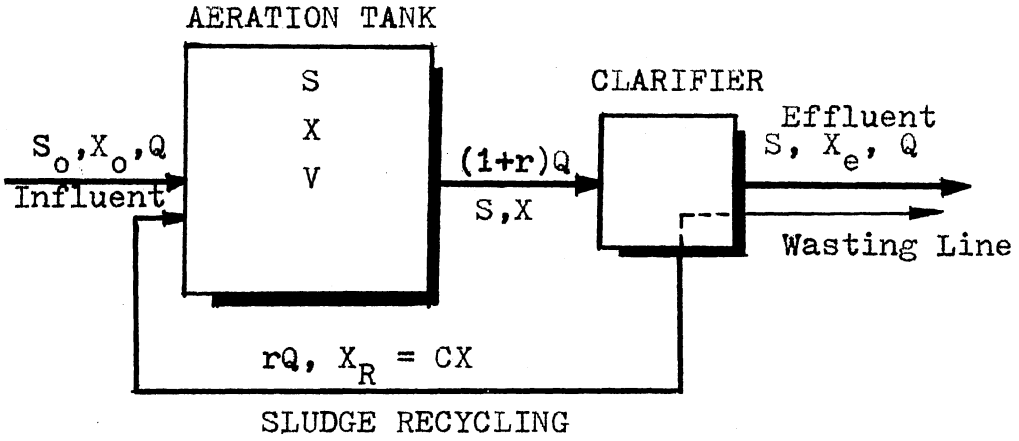

Figure 4. Schematic of A CMAS Process with Cellular Recycle for Herbert's Approach.

(2). Herbert's Approach (44, 45, & Figure 4):

$$\mu = D\ (\ 1 + r - rC\ ) \qquad (2.25)$$

or $$\mu = 1/\theta_c \qquad (2.25\text{-}1)$$

$$X = Y\ (S_o - S)(1 + r - rC)^{-1} \qquad (2.26)$$

or $$X = Y\ (S_o - S)(\mu)^{-1}D \qquad (2.26\text{-}1)$$

$$S = K_s D(\ 1 + r - rC\ )[\mu_{max} - D(\ 1+r-rC\ )]^{-1} \qquad (2.27)$$

or $$S = K_s\mu(\mu_{max} - \mu)^{-1} \qquad (2.27\text{-}1)$$

or $$S = K_s(\mu_{max}\theta_c - 1)^{-1} \qquad (2.27\text{-}2)$$

$$E = [S_o\mu_{max} - \mu(S_o - K_s)][S_o(\mu_{max} - \mu)]^{-1} \times 100\% \qquad (2.28)$$

or $$E = [S_o(\mu_{max}\theta_c - 1) - K_s][S_o(\mu_{max}\theta_c - 1)]^{-1} \times 100\% \qquad (2.28\text{-}1)$$

$$P_X = XV\mu \qquad (2.29)$$

Therefore

$$S = S(\ D,\ r,\ C\ ) \qquad (2.27\text{-}3)$$

$$X = X(\ D,\ r,\ C\ ) \qquad (2.26\text{-}2)$$

$$E = E(\ D,\ r,\ C\ ) \qquad (2.28\text{-}2)$$

$$P_X = P_X(\ D,\ r,\ C\ ) \qquad (2.29\text{-}1)$$

where

μ = specific growth rate

μ_{max} = the maximum specific growth rate for a system in exponential growth

D = dilution rate, Q/V or $1/\theta$

r = recycle flow ratio between the flow rate of recycle solids and flow rate of influent

C = X_R/X, sludge recycle concentration factor

X_R = biological solids concentration in the recycle so-

lids flow to a reactor in a CMAS process

X = steady state biological solids concentration in reactor

Y = true cell yield coefficient

S = effluent substrate concentration

K_s = saturation coefficient, or the substrate concentration when $dS/dt = 0.5\ k$

k = the maximum rate of substrate degradation

p_x = daily sludge production

θ = hydraulic detention time

θ_c = mean cell residence time

S_o, E, Q, V, as defined before.

(3). <u>McKinney's Approach</u> (46, & Figure 5):

$$F = F_i(K_1 t + 1)^{-1} \tag{2.30}$$

$$M_a = K_2 F [(x-xw+sw)t^{-1} + K_3]^{-1} \tag{2.31}$$

$$M = M_a[1 + (K_4 t)(x+sw)^{-1}] + [(Mi)_i (x+sw)^{-1}] \tag{2.32}$$

$$R_o = (K_5 F + K_6 M_a) \tag{2.33}$$

$$P_x = swQM \tag{2.34}$$

$$E = (K_1 t)(K_1 t + 1)^{-1} \ (100\%) \tag{2.35}$$

Therefore

$$F = F(t) \tag{2.30-1}$$

$$M = M(s, w, x, t) \tag{2.32-1}$$

$$R_o = R_o(x, w, t) \tag{2.33-1}$$

$$P_x = P_x(s, w, x, t) \tag{2.34-1}$$

$$E = E(t) \tag{2.35-1}$$

where

F = effluent substrate concentration

F_i = influent substrate concentration

t = hydraulic detention time

M_a = active mass of biological solids

M = total mass of volatile suspended solids

$(Mi)_i$ = innert volatile solids in the raw waste

s = settling coefficiency = $(SDI)M_t \cdot 10{,}000$

SDI = sludge density index

M_t = total MLSS concentration

x = coefficient for nonsettling characteristics

w = fraction of flow Q wasted

R_o = oxygen uptake rate

P_x = daily sludge production

r = fraction of recycle solids flow

K_1 = overall BOD removal rate

K_2 = synthesis rate

K_3 = decay coefficient

K_4 = sbsorption constant

K_5 = oxygen utilization rate coefficient

K_6 = endogenous respiration rate

Q = influent flow rate

V = total volume of aeration tank

(4). Gaudy's Approach (47,48, & Figure 6):

$$X = [Y(S_o - S - rS) + rX_R][\,1 + r + k_d D^{-1}]^{-1} \qquad (2.36)$$

$$S = [-b \pm \sqrt{b^2 - 4ac}\,][2a]^{-1} \qquad (2.37)$$

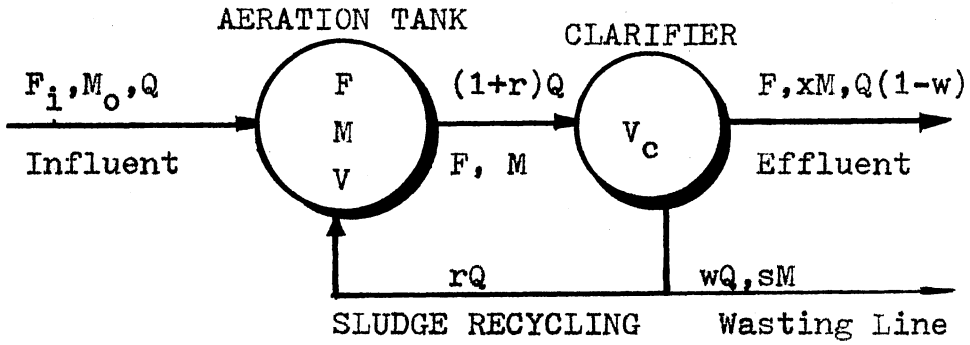

Figure 5. Schematic of A CMAS Process with Cellular Recycle for McKinney's Approach.

$$a = \mu_{max} - (1 + r)D + k_d \tag{2.38}$$

$$b = D[S_o-(1+r)K_s] - \mu_{max}(1+r)^{-1}[S_o + rX_R Y^{-1}] - k_d[S_o(1+r)^{-1} + K_s] \tag{2.39}$$

$$c = K_s D S_o + k_d K_s S_o(1+r)^{-1} \tag{2.40}$$

$$\mu = D(1+r-rX_R X^{-1}) = P_x(VX)^{-1} = 1/\theta_c \tag{2.41}$$

or $$\mu = YU - k_d \tag{2.41-1}$$

$$P_x = VXD(1+r-rX_R X^{-1}) = VX\mu \tag{2.42}$$

$$E = (S_o - S)/S_o \times 100\% \tag{2.43}$$

Therefore

$$X = X(D, r, X_R) \tag{2.36-1}$$

$$S = S(D, r, X_R) \tag{2.37-1}$$

$$E = E(D, r, X_R) \tag{2.43-1}$$

$$P_x = P_x(D, r, X_R) \tag{2.42-1}$$

where

P_x, X, S_o, X_R, r, Y, μ, μ_{max}, D, and k_d were already defined and X_R is maintained at constant value.

(5). Mean Cell Residence Time Approach (11, 49, 50, 51, 52, 53, 54, 56, 57, 58, & Figure 7):

$$S = K_s(1 + k_d\theta_c)[\theta_c(Yk - k_d) - 1]^{-1} \quad (2.44)$$

or $$S = UK_s(k - U)^{-1} \quad (2.45)$$

$$X = [\theta_c Y(S_o - S)][\theta(1 + k_d\theta_c)]^{-1} \quad (2.46)$$

$$U = (S_o - S)/\theta X = kS(K_s + S) = (dS/dt)/X \quad (2.47)$$

$$\mu = dX/dt/X \quad (2.48)$$

$$\mu = [1 + r - rX_R X^{-1}]\,\theta^{-1} \quad (2.49)$$

$$\mu = 1/\theta_c = YU - k_d \quad (2.50)$$

$$dX/dt/X = Y(dS/dt/X) - k_d \quad (2.51)$$

$$\theta_c = VX[Q_w X_R + (Q - Q_w)X_e]^{-1} \quad (2.52)$$

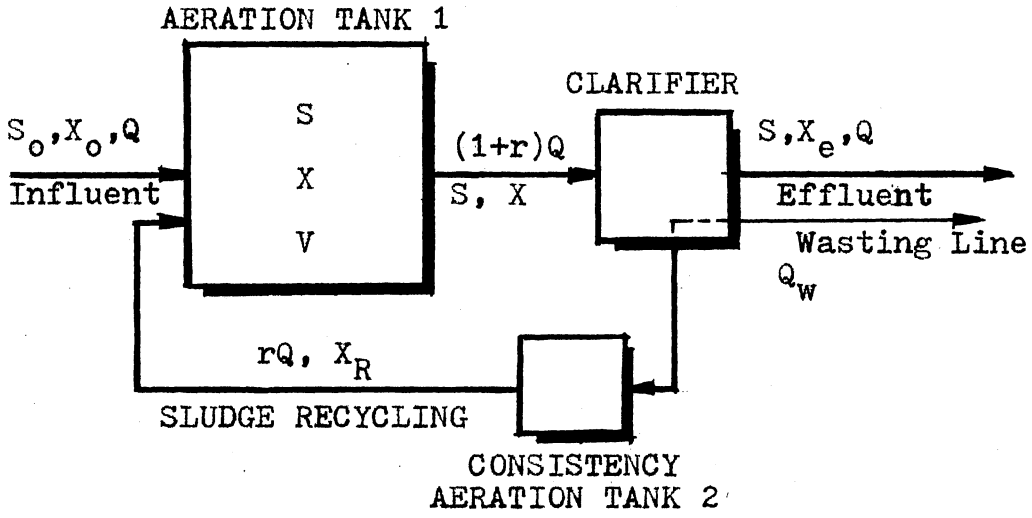

Figure 6. Schematic of A CMAS Process with Cellular Recycle for Gaudy's Approach.

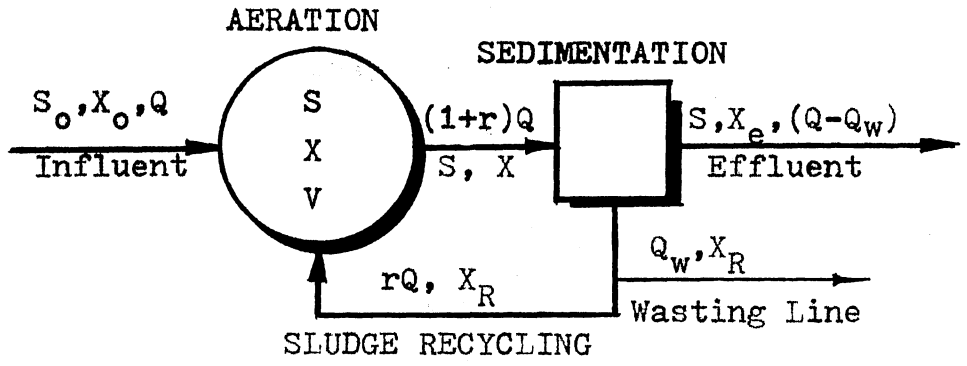

Figure 7. Schematic of A CMAS Process with Cellular Recycle for Mean Cell Residence Time Approach.

$$P_X = VX/\theta_c \tag{2.53}$$

$$E = (S_o - S)/S_o \times 100\% \tag{2.54}$$

$$dX/dt/X = Y_{obs}(dS/dt/X) \tag{2.55}$$

$$Y_{obs} = (U\theta_c)^{-1} \tag{2.56}$$

Therefore

$$S = S(\theta_c) = S(U) \tag{2.44-1}$$

$$X = X(\theta, \theta_c) \tag{2.46-1}$$

$$P_X = P_X(\theta, \theta_c) \tag{2.53-1}$$

$$E = E(\theta_c) = E(U) \tag{2.54-1}$$

where

Y_{obs} = observed cell yield coefficient

Q_w = flow rate of liquid containing fraction of cells wasted from reactor or sedimentation tank

All the remaining are previously defined.

2. Cell Yield Coefficient and Decay Coefficient

The concept of cell yield coefficient, Y, and cell decay coefficient, k_d, has been used to describe the relationship between net microbial growth and the amount of substrate utilized (4, 7, 9, 10). This relationship was shown and described in Equation 2.4, 2.5 . The cell yield, Y, in terms of the amount of sludge produced from a given amount of organic carbon source, is an important parameter in the design of biological wastewater treatment facilities, because this represents the portion (large amount or, in some cases, nearly all) of the sludge production which must be disposed of as a byproduct of the process. Also, the sludge yield, Y, is one of the growth constants (usually being assumed as an " constant " (56))employed in kinetic models and in mass and energy balance equations used to describe and predict the operational performances of the treatment process.

Acturally the yield, Y, is not a constant, although some works reported or assumed it as a " constant " (11, 56). There has been little agreement between yield values reported by different investigators for heterogeneous populations on a variety of wastes and pure compounds. One of the major problems encountered in the use of Y as a parameter for design and operation of biological treatment process is the great difficulty in the selection of a reasonable numerical value.

Sawyer (55) has, in his studies on bacterial nutri-

tion and synthesis, reported a yield coefficient of 50 to 60 % of the dry weight of organic food material consumed. For glucose he reported 44 to 64 % , which is in agreement with results (53 to 60 %) reported by Helmers, et al. (74) for cotton kiering, rag-rope kiering, and brewery wastes. Placak , et al. (75) reported sludge yields on carbohydrate wastes in the range of 65 to 85 % . Hoover, et al. (76) studied the assimilation of dairy waste using COD as a parameter for measuring substrate removal and found that approximately 67 % of the carbon source was channelled into synthesis during short-term experiments. McKinney (46) has concluded that about two -thirds of the ultimate BOD being metabolized is converted into cellular mass. Gellman, et al. (77) have summarized a yield of 50 % from their data of studying sludge growth during biological purification of jute cook liquor, yeast waste, gum waste liquor, and board mill white wastewater. Porges, et al . (16) reported a yield coefficient of 57 to 63 % in the treatment of skin milk waste by a continuous flow process. Gaudy, et al. (79), studying metabolism in growing and respiring systems by employing glucose as substrate, obtained a cell yield of 0.60. Rao, et al. (80) have, from their experiments of activated sludge studies, reported cell yields between 0.48 and 0.82 . By statistical investigating a collection of various cell yields over a period of eight year for heterogeneous populations of sewage origin acclimated to glucose in both batch and continuous culture, Gaudy, et al. (81) summarized that the cell yield for this sole source of

carbon ranged from 36 to 88% in batch culture, and 32 to 69% in continuous culture.

From the brief review above it is appraent that even for a relatively simple carbon source, such as glucose, considerable variety of cell yield values have been reported. The factors influencing the magnitude of the yield coefficient for a heterogeneous culture, as would be found in a wastewater treatment facility are summerized as follows:

(a). experimental condition of cultivation (82, 83)

(b). method employed for determining yield (80, 81, 85)

(c). ecological variations in predominance or selection of microbial species (56, 80, 81, 83)

(d). waste characteristics (83), such as:

oxidation-reduction state of the carbon source

oxidation-reduction state of nutrient elements

degree of polymerization of the substrate

(e). pathway of metabolism (83)

(f). net microorganism growth rate (83, 85)

(g). presence of growth factors such as amino acids and vitamins (83)

(h). degree of agitation in continous process (84)

(i). rate of death of cells (60)

It is to be noted that there are two very important engineering parameters, F/M ratio and hydraulic detention time, have been reported not to influence the cell yield coefficient (47, 80, 81). Gaudy, et al. (81), after their statistical analysis of a collection of cell yield values over a pe-

riod of eight years for heterogeneous populations of sewage origin, stated: " These variables, the ratio of initial substrate to initial solids for batch systems, and the detention time for continuous flow systems, were found not to exert a determining influence on yield." Hetling, et al. (86), after conducting continuous flow experiments with pure cultures, concluded that the true yield coefficient of an organism is proportional neither to the COD nor to the free energy of substrate.

However, some manifestations of the relationship between the cell yield and hydraulic detention time have been reported. Hetling, et al. (86), in their studys on the kinetics of steady state bacterial cultures, proposed a mathematical equation to describe this relationship as below:

$$1/Y_{obs} = 1/Y + \theta(k_{d1}/Y + k') \qquad (2.57)$$

or $$Y = Y_{obs}(1 + \theta k_{d1})(1 - k'\theta Y_{obs})^{-1} \qquad (2.58)$$

where

Y = true (maximum) uield coefficient, = $X/(S_o-S)$

Y_{obs} = observed (apparent) cell yield coefficient

θ = hydraulic detention time

k_{d1} = rate of death of cell per unit weight of active cells X

S_o = influent substrate concentration

S = substrate concentration in reactor at steady state

k' = specific rate of substrate consumption for basal metabolism.

The true yield coefficient (Y or Y_{max}) can vary for dif-

ferent organisms. Ramanathan (60), in a kinetic studies of CMAS processes, found that the relationship between growth and substrate consumption (yield) is variable with dilution rate (hydraulic detention time) and showed that these changes in yield coefficient with dilution rate can be described mathematically by Equation 2.57 which was proposed by Hetling, et al. (86).

An alternative approach to the analysis of net growth accounts for the variation of the yield by incorporating the decay coefficient, k_d, into an observed yield coefficient (Y_{Obs})which varies with the mean cell residence time depending upon conditions of process operation (11, 56) as shown in Equation 2.6 and Figure 8. As shown, the observed yield coefficient is greatest at low θ_c and decreases as θ_c increases . The decrease in the observed yield coefficient as net

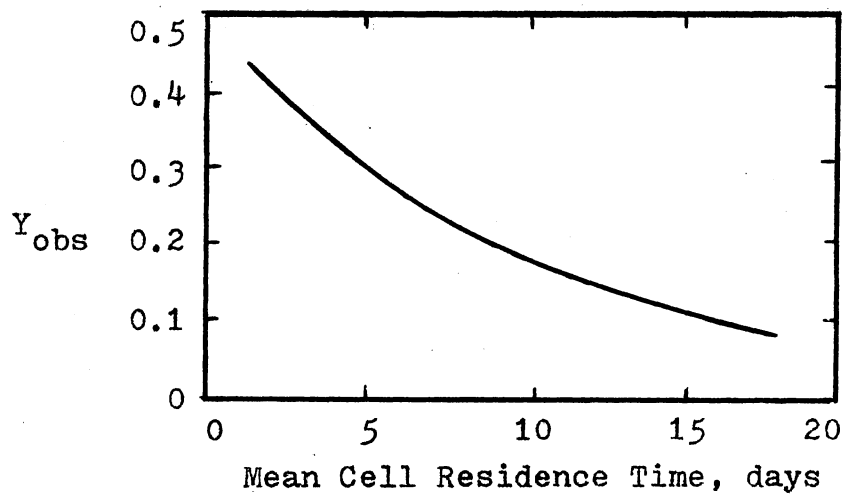

Figure 8. Observed Cell Yield (Y_{obs}) as A Function of Mean Cell Residence Time, θ_c.

growth rate decreases can be attributed to both maintenance energy requirements and the increased populations of predator organisms present (11, 87). The maintenance energy concept also serves to explain the higher yield obtained for a batch experiment, which would correspond to the value of observed yield when microorganisms would be washed out of a continuous flow process.

Another formula to express the relationship between Y and Y_{obs} proposed by Van Uden (88) for determining true cell yield coefficient, Y, and decay coefficient, k_d, is presented as follow:

$$Y/Y_{obs} = 1 + k_d\theta_c > 1 \qquad (2.59)$$

Decay coefficient, k_d, in Equation 2.59 accounts for factors such as death, predation, and the diversion of energy for cell maintenance reactions. Some of its values were reported between 0.04 and 0.093 (11, 49, 50).

C. Performance of Wastewater Treatment Processes

The performance of activated sludge plants may be considered to be the relation of the removal of pollutional matter to the plant resources used to produce the result. This might also be designated as the plant efficiency, waste purification, degree of treatment, degree of substrate removal, or any other synonyms.

The efficiency of waste stabilization can be defined as

$$E = 100\%\,(S_o-S)/S_o \qquad (2.60)$$

where

E = efficiency of waste stabilization expressed in percentage form

S_o = mass concentration of influent waste

S = mass concentration of influent waste not biologically degraded appearing in the effluent

The most widely employed measurement of performance for a biological wastewater treatment process is the amount of biochemical oxygen demanding material (BOD) which has been removed by the process. Satisfactory reduction in BOD includes, in general, a reasonable reduction in suspended solids. Accordingly, BOD removals may be used as an important single basic indicator of activated sludge treatment plant performance.

However, another parameter, ΔCOD, for more direct, rapid, simple, and reliable measuring of the amount of biologically available organic removal was proposed by Gaudy, et al. (47). ΔCOD, being defined as influent waste COD minus effluent COD, represents the amount of organic waste removed which is the same amount as BOD reduction. Although this fraction, ΔCOD/(COD of influent waste) or efficiency of COD removal, can be employed as a useful parameter for measuring the performance of biological treatment process, which is not equivalent to efficiency of waste purification or waste stabilization. It can be easily realized that COD of effluent may include some organic matter which is not biodegradable, depending upon the characteristics of wastewater concerned.

Thus efficiency of treatment, when considering the effect of effluent on the receiving stream, would be much higher than efficiency of COD removal for such a wastewater.

The performance of the treatment facility can be obtained based either on the overall process or on its separate units. It is not entirely correct to separate the performance of aeration and final (or secondary) sedimentation tanks; nevertheless doing so simplifies the investigational problem and works for design and operational control. Furthermore, performance of primary tanks and the aeration-final tanks undoubtedly is closely interrelated. In this study all the performances under consideration are based on the separately aeration-final reactors rather than on the over-all plant performance.

In one of Stanley's studies (91), operating results from 26 plants, averaged over periods from 1 to 6 years, show that the activated sludge sewage treatment process can be expected to give an over-all performance of from 92.5 to 95% of the BOD and suspended solids removal in properly designed and operated plants.

D. Factors Affecting The Performance of Completely Mixed Activated Sludge Processes

The employment of CMAS treatment systems has resulted in the attainment of a wide range in the efficiency of stabilization of organic substrates. Insufficient attention has

been given to the development of a rational functional parameter for such systems, although many loading parameters of an empirical nature have been employed in attempts to relate efficiency of stabilization of putrescible waste to controllable design features.

Influential factors affecting activated sludge plant performance in literatures are summarized below (30, 58, 60, 64, 66, 71, 73, 91, 92, 93, 94, 96, 98):

(a). variation in organic level and type, or shock loads

(b). mixed liquor suspended solids in aeration tank

(c). mean cell residence time, sludge age, or sludge growth rate

(d). organic loading:

specific utilization, U

food:microorganisms ratio, F/M

food:reactor volume ratio, F/V, or volumetric loading

(e). air quantity, DO level, or oxygen uptake rate

(f). physical property of sludge, such as

SVI

SDI

(g). characteristics of recycling sludge

(h). relative aeration dimension

(i). hydraulic detention time

(j). degree of nitrification

(k). temperature

(l). degree of mixing

(m). pH level

(n). nutritional requirement

(o). other combination factors, such as:

food:microorganisms:detention time ratio, F/M/θ

food:reactor area:detention time ratio, F/A/θ

product of MLSS concentration and hydraulic detention time, Xθ

Undoubtedly some of the foregoing factors are of major importance in reducing the pollutional load of an organic waste. Among which, mixed liquor suspended solids in aeration tank, F/M ratio, and mean cell residence time are three highly appraised influential parameters having an effect upon the efficiency of stabilization of such systems, while the hydraulic detention time, the less complicated engineering factor, is still questioned.

It would be audacious to attempt to cover herein all of the above factors affecting activated sludge plant performance. In the following presentation, only a few engineering factors closely related to this study of hydraulic detention time will be reviewed. A detailed review about the effect of the concerned hydraulic detention time on the performance of stabilization will be emphasized separately in the next section.

1. MLSS Concentration in Aeration Tank

The concentration of activated sludge solids in the ae-

ration tank definitely affects plant efficiency. A higher performance usually can be obtained in the treatment operation with a higher concentration of SS in the reactor than with a lower MLSS concentration. From a study of the efficiency of activated sludge plants by Stanley (91), however, it was found that the influence on BOD removals does not increase greatly for suspended solids concentrations above 1,500 mg/l. Doubling the suspended solids concentration appears to increase the percentage BOD removal from 91 to 95 percent. The suspended matter concentration appears to be more influential for concentration less than 1,500 mg/l. By making an analysis of a number of data on mixed liquor concentrations and BOD removals from some plants over time periods when known upsetting influences were at a minimum, Stanley found that a very definite logarithmic relationship between aeration tank solids concentration lower than 1,500 mg/l and plant efficiency.

To maintain a constant mixed liquor suspended solids level in aeration tanks is the first and most commonly used method of solids control for the operation of activated sludge processes. This approach is based on the concept which has been proposed by Ruchhoft, et al. (34) that a simple linear relationship between the rate of substrate removal and initial sludge concentration. Other similar relationships were also found by Eckenfelder, et al. (100) and Wuhrmann (101) between different substrates.

The following equation has been developed to express

this concept mathematically in terms of the amount of food consumed and the mass of activated sludge initially present in which the net daily increase in cell mass is equal to the amount of new cellular material produced each day less the amount of existing cellular material oxidized for endogenous respiration:

$$\Delta X/\Delta t = Y(\Delta S/\Delta t) - k_d X \qquad (2.61)$$

where

$\Delta X/\Delta t$ = net increase in activated sludge mass per day

$\Delta S/\Delta t$ = food removed per day by the activated sludge

All other terms were previously defined.

When operating an activated sludge treatment plant by maintaining a constant mixed liquor suspended solids level, the operator usually chooses an MLSS level that seems to give goood settling and effluent characteristics and then wastes just enough solids daily to maintain that solids level. From Equation 2.61, $\Delta X/\Delta t$ solids/day must be wasted because this is the net growth per day. The advantages of this fixed solids control method are that it can provide good operation if the plant BOD loading is fairly constant, and it requires only a minimum of laboratory control. However, it is well known that the relationship between solids and purification rate varies due to changes in predominance in the population no matter what constant operational conditions are maintained . That is to say that the relationship between initial solids concentration and rate of COD removal varies for a single substrate of different substrate in spite of the mainten-

ance of a constant mixed liquor suspended dolids concentrations. Finally, the control of activated sludge processes by fixed MLSS concentration would be end in failure, if a shock loading occurs, because this method of control ignores the important factor, F/M ratio, and places emphasis on something that does not directly relate to effluent or settling quality . Even if a shock load did not happen to cause serious problem, the quality of the effluent would undoubtedly be degraded by such erratic variations in the F/M ratio caused from fixed MLSS concentration control of activated sludge processes.

2. Organic Loading

The literature expresses organic loading as either: specific utilization, U; food:microorganisms ratio, F/M ratio; and food:reactor volume ratio, F/V ratio. Specific utilization is usually expressed as pounds COD removed per day per pound VSS in the reactor. Food-volume ratios have been proposed in terms of pounds BOD per day per 1,000 cu. ft. of aeration tank volume. The food-microorganism ratio can be explained in terms of pounds BOD or COD per day per pound VSS in the reactor. There is a relationship between F/M ratio and U, i.e., $U = E(F/M)$, here E is efficiency of stabilization. The substrate loading to aeration tank volume ratio can be used as a control parameter, but is not sensitive enough as large changes in this ratio usually do not result

in large changes in effluent quality.

A National Research Council report (96) containing excellent analysis of operating data from five activated sludge plants at military installations was the first to propose the measurement of performance based on volumetric loadings. Greeley (102) suggested 30 lb. per 1,000 cu. ft. as a basis of design. Loadings up to about 80 lb. per 1,000 cu. ft. of aeration tank volume have been used at Peoria and Decatur, Ill. (91) with no apparent reduction in BOD removal. Torpey (104) has reported that BOD loadings of 84 lb. per 1,000 cu. ft. at Bowery Bay Plant (New York City) have achieved an efficiency of 90% BOD removals. A analysis of monthly data collected from 15 activated sludge plants under good operation was made by Sumuel (105). They showed no trend toward a lesser percentage BOD removal with BOD volumetric loadings increasing from 15 to 50 lb. per day. From the above presentations, it can be seen that, in addition to volumetric loadings, other influential factors must be included.

In 1952, Garrett, et al. (106) studied the kinetics of the removal of soluble BOD in the activated sludge process. They are the first ones to propose the concepts of " biological loading ", which was defined as " the pounds BOD applied per day per pound aeration solids", for beneficial process operation. The relationship between the growth rate of microorganisms and this loading in direct proportion was found by them.

McKinney (59) revommended the use of a concept labeled

" food:microorganisms ratio " to express the relationship between the growth rate and the available food per unit of microorganisms. He also suggested that the rate of excess sludge production in the complete mixed system will be dependent on the F/M ratio. High F/M values were reported to produce large amounts of excess sludge than would lower F/M values. The flocculation ability of sludge was stated to be increased when F/M values were decreased.

In 1966, McCarty (107) presented a formula to express the rate of substrate utilization:

$$dF/dt = kXS(K_s+S)^{-1} = dS/dt \qquad (2.62)$$

or rearrange to yield

$$dF/dt/X = kS(K_s+S)^{-1} = dS/dt/X = U \qquad (2.63)$$

The term, dF/dt/X, is labeled as specific utilization. All other terms were previously defined.

The purpose of maintaining a fixed U for the operation of a CMAS process is to hold a constant environment for the activated sludge organism and avoid abrupt changes in order to obtain a peak efficiency. Unless plants are operated so that this ratio is between 0.2 to 0.5 lb. BOD (or 0.3 to 0.9 lb. COD) per lb. of VSS, problems with substrate removal and sludge settleability will occur. The procedure for maintaining a constant U is by varying the microorganism concentration which is accomplished by controlling the wasting rate of waste sludge.

From Equation 2.63, it can be seen, for a specific waste and a particular set of environmental conditions, that the

effluent waste concentration, thus efficiency of waste stabilization is a direct function of specific utilization. However, the use of this parameter is not entirely satisfactory, because of the variability of volatile matter in the waste that is not related to active cellular material.

3. Growth Rate, or Mean Cell Residence Time

In 1958, Garrett (53) proposed a method for the operational control of activated sludge plants. He has related specific growth rate to sludge age. Sludge age was defined as the total pounds of volatile suspended solids in the reactor divided by the pounds of volatile suspended solids wasted from the system each day. The reciprocal of growth rate was termed sludge age. Therefore, growth rate or sludge age could be hydraulically regulated by the wastage of solids from the reactor of sedimentation tank and thus could be used as a direct control in the operation of waste treatment plants. If the growth rate is controlled, the pounds of waste removed per day per pound of volatile solids in the aeration tanks, the sludge age, and the effluent substrate concentration will be controlled. Laboratory analytical determinations such as BOD, COD, and suspended solids could be eliminated too.

As mentioned before, an empirical equation developed by Ruchhoft, et al. (34) to express the mathematical relationship between the amount of net daily increase in cell mass

and the amount of substrate utilization that is commonly used for biological systems stabilizing organic wastes is (49, 52, 54, 56, 107, 110):

$$\Delta X/\Delta t = Y(\Delta S/\Delta t) - k_d X \qquad (2.61)$$

rearranging Equation 2.61 gives:

$$(X/\Delta X/\Delta t)^{-1} = (\Delta X/\Delta t)/X = Y(\Delta S/\Delta t/X) - k_d \qquad (2.64)$$

or $$(X/dX/dt)^{-1} = dX/dt/X = Y(dS/dt/X) - k_d \qquad (2.64\text{-}1)$$

The term $\Delta X/\Delta t/X$ on the left-hand side of Equation 2.64 is the net growth rate and its reciprocal, $X/\Delta X/\Delta t$, has often been referred to as the solids retention time, the mean cell residence time or the sludge age, and is often symbolized by θ_c.

Jenkins, et al. (50) state that mean cell residence time is a kinetically rational basis for the design, control, and operation of activated sludge plants. Control of the mean cell residence time will enable the regulation of the soluble COD quality of the system effluent. The authors also related the control of mean cell residence time to the nitrification of such processes.

By a study of biological treatment design and operation in 1970, for the purpose of developing unifying relationships which could be used in the description of various processes utilizing bacteria as the primary organism, Lawrence, et al. (51) presented mathematical formulations of parameters applicable to biological treatment process. They suggested that biological solids retention time, θ_c, be used as an independent parameter for design and operational control purposes,

because it is related to the performance of continuous biological processes employing suspensions of microorganisms in a fundamental way. Various parameters, such as: sludge production, solids concentration in reactor, flow rate and concentration of return sludge, and hydraulic detention time, were related to θ_c for use in the description of the three models. Additionally, the concept of minimum biological solids retention time, θ_c^m, was recognized as being important to the maintenance of a biological population in the systems. Physically, θ_c^m is the residence time at which the cells are washed out or wasted from the system faster than they can reproduce. To ensure adequate waste treatment, biological treatment systems are usually designed and operated with a θ_c value from 2 to 20 times θ_c^m.

Metcalf, et al. (49), applying the knowledges of biological kinetics to treatment systems, recommend that mean cell residence time or specific utilization be used separately as a principal performance parameter in the design and operational control of the activated sludge process. However, mean cell residence time is highly suggested because of its basic direct relation to microbial growth and specific utilization and ease of regulation and control.

By studying a mathematical model for a continuous flow completely mixed activated process employing cell recycle, Sherrard, et al. (112) found that mean cell residence time is a major parameter in the prediction of sludge production and system performance and works better than other parameters

such as: specific utilization (U), food-microorganism ratio (F/M), and observed yield coefficient (Y_{obs}).

On the basis of laboratory studies and actual operating data from a number of different treatment plants, Metcalf, et al. (49) found that mean cell residence times of about 6 to 15 days which are equivalent to values of specific utilization from 0.2 to 0.5 based on BOD determination or 0.3 to 0.9 for COD will result in the production of a stable, high-quality effluent and a sludge with excellent settling characteristics.

4. Combination Factors

Those 15 parameters, as having been presented in the begining of the section, are interrelated; in some cases the interrelation is quite complex. However, some investigations have been devoted to cap a corporeal engineering functional combiantion parameter (92, 114. 115. 117). Two of which having been used are Food:Microorganism:Detention Time Ratio, F/M/θ; and Food:Reactor Area:Detention Time Ratio, F/A/θ.

The N.R.C. Sub-Committee on Military Sewage Treatment (96) followed, in 1946, to utilize combination factors to describe the plant performance of activated sludge processes. By studying collected data from 12 municipal and 5 military activated sludge plants, they related the efficiency of BOD removal to a loading parameter expressed as pounds of 5-day BOD applied daily per 1,000 lb. of suspended solids in the aeration tank per hour of aeration. The report likewise es-

tablished a loading parameter for contact aeration plants. This parameter was given as pounds of 5-day BOD applied daily per 1,000 sq. ft. of contact surface per hour of aeration. Okun (113) applied a similar type of loading parameter to his results from bio-precipitation studies and found that a parameter of the form pounds of BOD applied daily per 1,000 lb. of volatile solids per hour of aeration corelated reasonably well with the efficiency of BOD removal.

In 1926, Harris, et al. (117) were the first to propose the combination of the three major factors into a loading parameter applicable to the activated sludge process. They evaluated the parameter in terms of the strength of applied sewage, the percentage of sludge, and the period of aeration.

However, the basis of such a combination loading parameter was not rationalized until Fair, et al. (114) presented their studies. A mathematical model of the activated sludge process with assumed conditions analogous to those existing in a conventional activated sludge process and under steady state was developed. Using the mass balance equations of continuity resulting from the conditions established for the mathematical model, they obtained a generalized relation of the following form:

$$E = 100\ (1 + mR^n)^{-1} \qquad (2.65)$$

in which R is the loading parameter expressed as pounds of 5-day BOD applied daily per 1,000 lb. of suspended solids per hour of aeration, E is the percent efficiency of BOD removal, and m and n are constants. Application of this loading parameter to the performance of activated sludge plants was shown

to be very excellent by Smith (92). Smith concluded that the relationship shown by Equation 2.65 is useful over high and intermediate ranges of activated sludge treatment. He also recommended that the above equation be used for an successful design and operational control of the performance of activated sludge processes.

E. Hydraulic Detention time

1. General Consideration

Although the activated sludge process has been used for many years and the literature on this process is voluminous, there is surprisingly little information available about the role played by hydraulic detention time in such a process.

No exact method has been devised to measure accurately the average time substrate is in contact with activated sludge in the aeration tanks. Thus an index number, detention time, must be designated to express the approximate contact time of substrate with microorganisms. Detention time may be based either on the raw waste flow (mean hydraulic detention time) disregarding recirculation of return sludge or on the flow of mixed liquor that includes recirculation (mixed-liquor detention time). Therefore, detention time can be defined as follows:

$$\theta = V/Q \tag{2.66}$$

$$\theta' = V/Q(1 + r) \tag{2.67}$$

where

θ = mean hydraulic detention time

θ = mixed-liquor detention time

V = the volume of the reactor; however, the total system volume (aeration tank plus settling tank) can be used for calculation, if the detention time for the total system (expressed as θ_s or θ_s', respectively) is needed.

Q = influent flow rate

r = recycling ratio of return sludge flow rate.

For most activated sludge models, kinetics having been developed are based on mean hydraulic detention time.

Hydraulic detention time in the aeration tanks is not controllable in most treatment plants. However, detention time could be changed by varying the number of aeration tanks in use (volume) or varying the influent pumping rate.

2. It's Not A Functional Factor for CMAS Process

In 1942, Pears (116) in a report on the operation and control of activated sludge sewage treatment works was one of the earliest investigators to relate BOD removals from several plants in different cities to detention periods. Data from 10 relatively large plants showing the relationship between 5-day BOD removal and aeration period are plotted in Figure 9. The plot shows a little trend towards a longer aeration period for accomplishing greater removal of BOD. However, the great degree of scatteringness among those points

reveals that there are some other concealed functional factors which could devil the predictions of plant performance. Other information from this report also shows that a higher quality of effluent could be obtained while operated at a lower aeration period than at a higher one. However, such short periods appear to lack flexibility, particularly where a high grade effluent is required.

Stanley, et al. (115), in 1947, presented a excellent paper comprising a comprehensive summary of an investigation of BOD laodings based on operating data from a selected number of activated sludge plants, relative to the interrelation of several major factors influential to effective plant operation. Among those chosen factors, aeration contact periods are graphically compared to BOD removals and to plant performances as shown in Figure 10 and Figure 11, respectively.

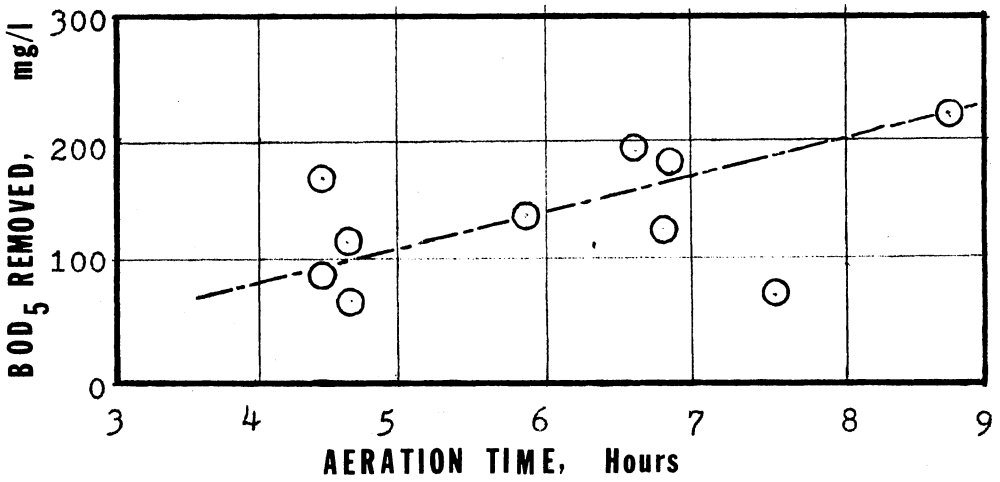

Figure 9. Relation Between BOD Removal and Aeration Period (116).

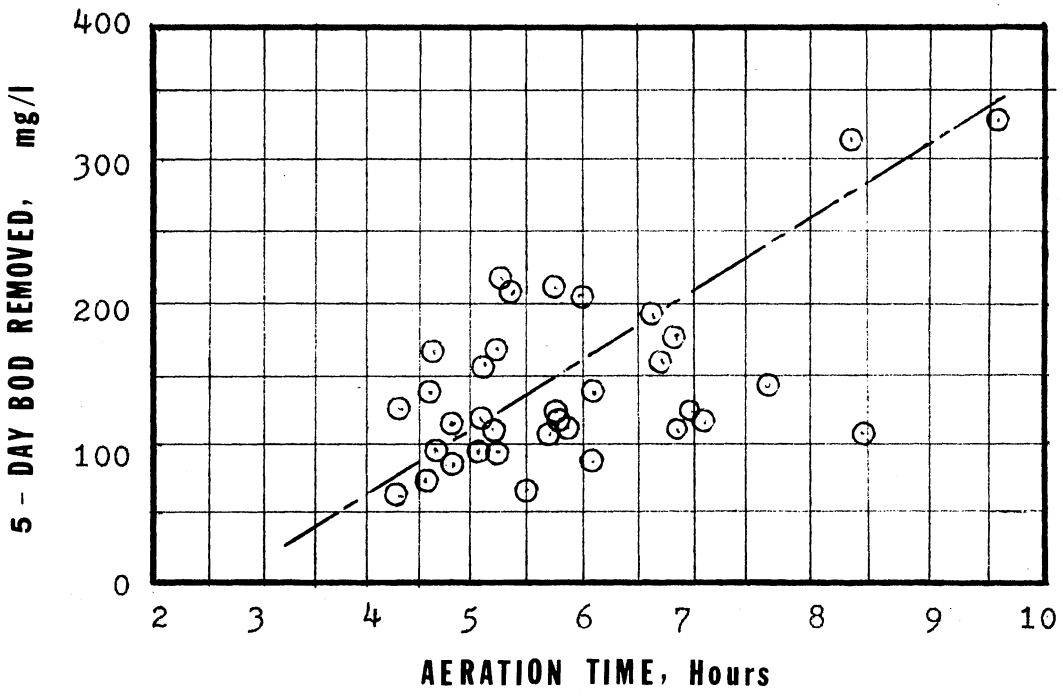

Figure 10. Relation of BOD Removal and Aeration Contact Periods (115).

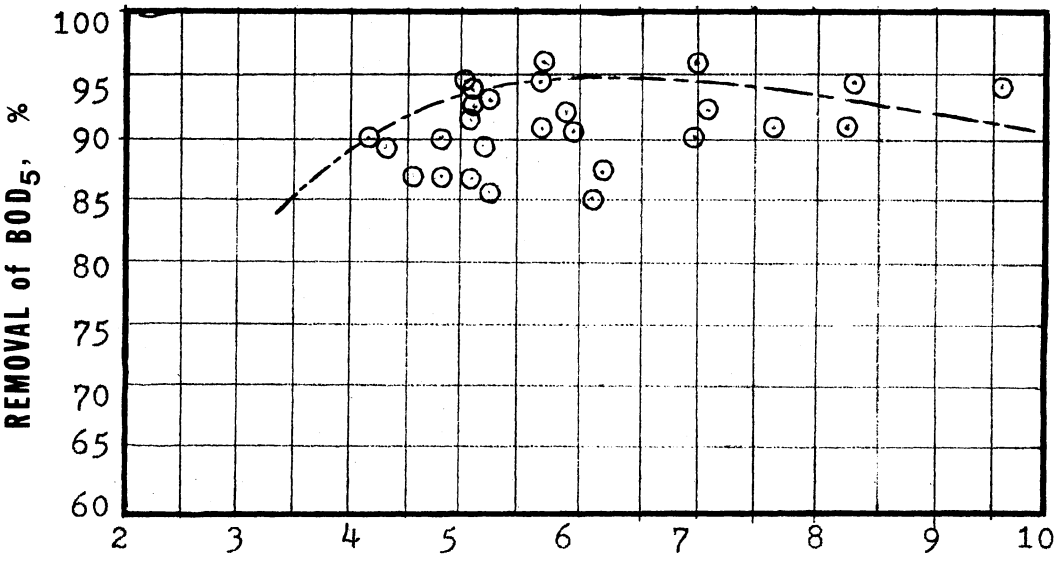

Figure 11. Relation of Percent BOD Removal and Aeration Contact Period (115).

The plotted points are so widely scattered it seems evident that other controlling factors are involved to influence the efficiency of activated sludge treatment. So it was concluded by the investigators that it is not feasible to determine the relationship of BOD removals or percentage of stabilizations and the aeration period by a simple plotting of these two factors. The effect of these factors along with the aeration period can be detected from Figure 11. There appears to be a reduction in the percentage of removal for aeration contact periods less than 4.0 hours and longer than 7 or 8 hours. Later Stanley concluded that, with mixed liquor suspended matter concentrations greater than 1,500 mg/l there appears little improvement in BOD removals for aeration periods greater than 5 hours (91).

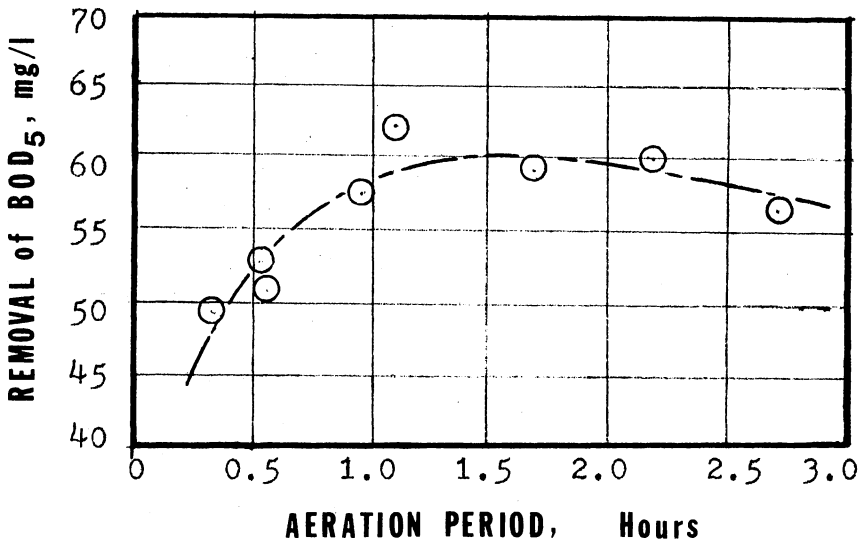

Figure 12. Owls Head Treatment Results vs. Aeration Period at Constant Sludge Age(118).

Another excellent study of the effects of aeration period on the performance of the activated sludge process was reported by Torpey, et al. in 1958 (118). Data represented five years of continuous use of the modified aeration process , treating 85 MGD of raw sewage at the Owls Head Plant, New York City, were used to help establish the graphical relationship between the removal efficiency and aeration period as shown in Figure 12. The same pattern of efficiency curve vs. aeration period as that of Stanley's studies (115) was shown. The curve for BOD removal indicates that the efficiency was not affected by lowering the detention time from 2.7 hours to one hour, averaging 60 percent over this interval, but thereafter decreased to 50 percent at 0.33 hours.

The effect of hydraulic detention time on the conventional activated sludge system at the Baltimore wastewater treatment plant was evaluated by studying the operating results when the flow was varied from 4.7 to 19.3 MGD, equivalent to a detention time from 10.0 to 2.3 hours (119). The results show that the removal performances for 5-day BOD, total carbon, and total phosphorus are higher at a detention time of 2.3 hours than at a detention time of 10.0 hours. The reversly effect of detention time on Kjeldahl Nitrogen removal was reported. It was concluded that the detention time was not long enough for nitrification.

In 1970, when evaluating a CMAS plant at Grand Island, Neb., McKinney, et al. (66) found that the efficiency in BOD removal increased with a decrease in aeration basin detention

time. They concluded that aeration time alone is not a good criterion for the design or operation of a biological waste treatment system. The aeration time must be considered along with organic loading to yield a meaningful design parameter.

In 1972, Metcalf, et al. (49) reported that θ is not a controlling factor for a CMAS recycle system. Utilizing a completely mixed activated sludge mathematical model, they reported that the efficiency of stabilization (or the effluent waste concentration is directly related to θ_c or U. Because θ_c and U are theoretically independent of the hydraulic retention time of the reactor θ and of the total system θ_s. Thus it is possible to achieve a good treatment efficiency at a reasonable high θ_c, without raising θ or θ_s.

3. It's A Functional Factor for CMAS Process

In the operation of an activated sludge plant, Palmer (120) was one of the earlier to suggest that activated sludge aeration period is a variable which influences the control of the plant.

In 1944, Setter (108, 109) started a program of experimentation for the studies of modified sewage aeration. Three types of treatment were considered: 1, sewage aeration without the return of activated sludge or liquor, 2, sewage aeration with the continuous return of the fourth or last pass aeration tank liquor, and 3, sewage aeration with the return of final settling tank activated sludge to maintain an aeration tank suspended solids concentration less than 500 mg/l.

A correlation of BOD removal with mean aeration detention time for the three type of sewage aeration studies are shown in Figure 13.

The curves more clearly show the effect of the detention time and type of aeration on the efficiency of waste removal. The shorter the aeration time the greater the removal efficiency is shown. These results are identical to Stanley's(91). However, a greater fluctuation of effluent quality during a 24-hour cycle for the shorter aeration time was also found. A logarithmic relation between removal rate and the time of contact was found in Setter's study as shown in Figure 14. A conclusion was also made that the high degree of treatment achieved by activated sludge requires a longer aeration period, somewhat higher aerator solids and a greater air supply .

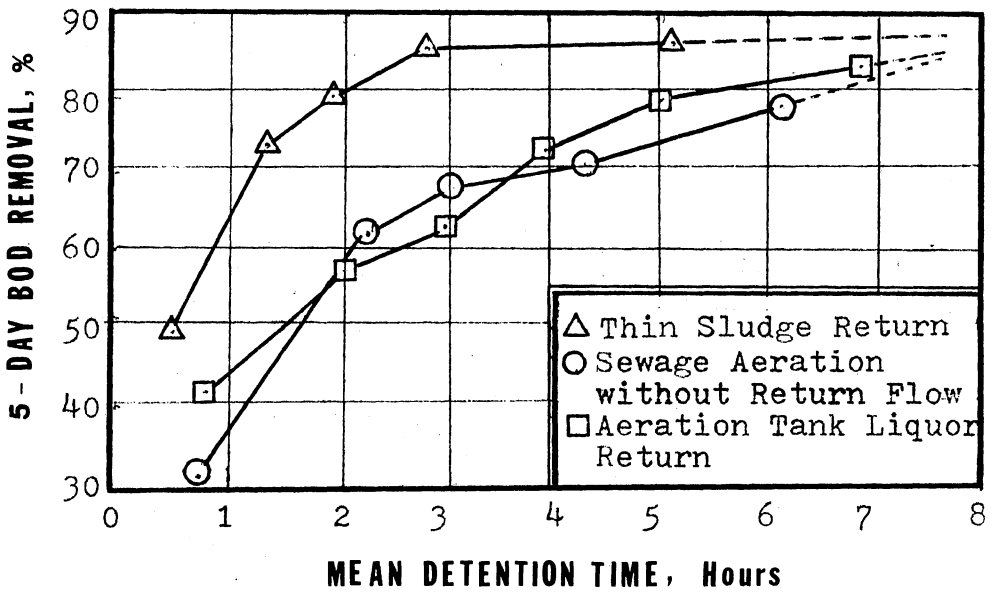

Figure 13. The 5-Day BOD Removal of Three Types of Modified Sewage Aeration for Different θ.

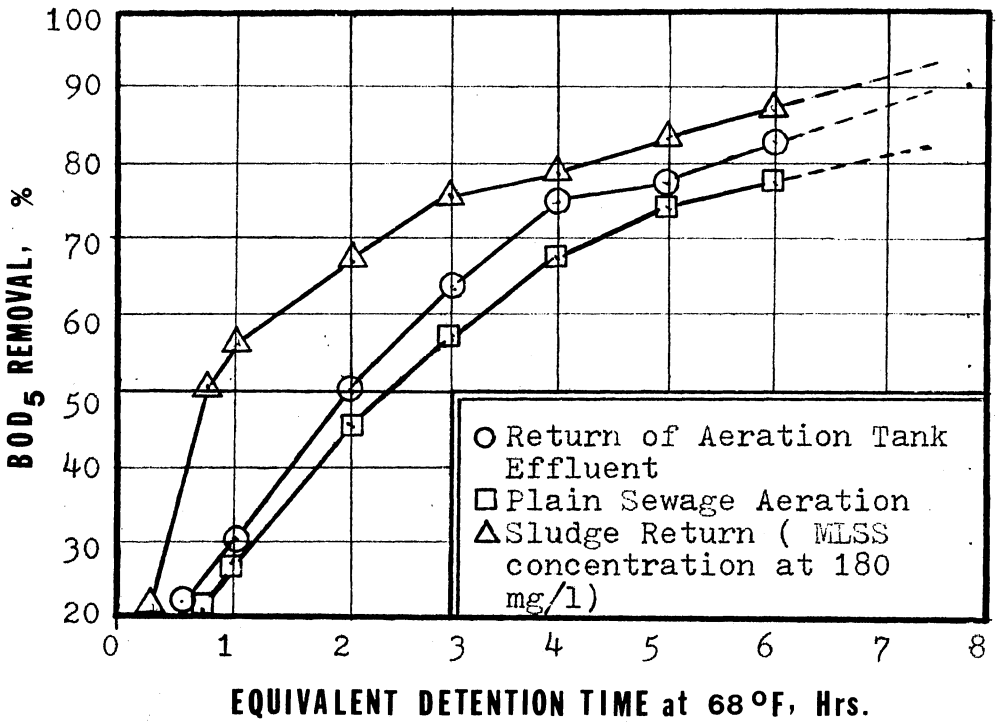

Figure 14. A Correlation of Secondary Treatment Efficiencies by Modified Sewage Aeration at Equivalent Aeration Periods Which Had Been Corrected with Temperature Factor (Replotted from 109).

Some investigators used organic removal kinetic models based on a mass balance for a CMAS process to show the direct relationship between θ and E. Eckenfelder (4, 26, 42) assumed a first order utilization rate model to develop an equation showing organic removal as a function of MLVSS and θ. McKinney (46) assumed a first order substrate utilization rate model to develop a relationship in which the removal was a function of θ. Herbert (44, 45) assumed a first order substrate utilization rate model with a constant return sludge ratio to develop a relationship in which organic reduction was a function of r, C, and θ. Gaudy (47, 48) using the as-

sumption of a first order utilization rate model with a modification of constant return sludge concentration to develop a similar relationship that organic removal is a function of θ, r, and X_R.

Other experiences strongly support the more direct relationship between efficiency of removal and detention time than other factors were published by Emde (111), Chasick (103), and Meron (99).

4. Required Hydraulic Detention Time for Design and Operation

The hydraulic aeration time for a given degree of treatment is greatly dependent on the initial removal characteristics of mixed liquor present in the aeration tank. Therefore, to establish a rational range of optimum contact time is necessary for successful design and operation of a activated sludge treatment process.

A regulation of The Standards for Water Pollution Control Facilities, published by the Oklahoma Department of Health (1) in 1963, requires that the hydraulic detention time of activated sludge aeration tanks be within the following ranges:

> " For design flows (exclusive of return sludge) from 0.2 to 0.8 MGD the tank volume shall provide a detention time of 7.5 hours; in excess of 1.0 MGD the tank volume shall provide a detention time of 6 hours; and between 0.8 and 1.0 MGD the volume shall provide a dete-

ntion time varying from 7.5 hours at 0.8 MGD to 6.0 hr. at 1 MGD, the detention time decreasing in proportion to the increase in design flow within these limits."

The Ten States Standards also limit a sewage detention period (hydraulic detention time) of 6.0 hours for flows greater than 1.0 mgd and 7.5 hours for flows in the range of 0.2 to 0.8 mgd (121).

Torpey, et al. (30) gave a suggestion for the criteria of activated sludge operation. For essentially domestic sewage from communities with normal per capita water consumption rates, the required detention time should be about as follows: preliminary sedimentation for about one hour; final sedimentation at an overflow rate of 1,000 gal. per sq. ft. per day; and aeration for six hours, based on sewage flow plus 25% return sludge.

However, other experiences have suggested a shorter detention time for the design and operation of such processes. For diffused air plants, a national survey of State Health Department (95) requirements specified an aeration period of 4 to 8 hours based on sewage flow plus return sludge, which was usually specified to be 25% of the sewage flow, and an air supply of 0.5 to 2.0 cubic feet per gallon of sewage.

Metcalf, et al. (49) suggested that a range of from 3 to 5 hours of hydraulic detention time is reasonable as a completely mixed activated sludge system design parameter.

McKinney, et al. (66), in their evaluation work for the Grand Island, Neb., treatment plant, have revealed that with

a 3.8 hours detention time, a 5-day BOD loading rate of 116 lb. per 1,000 cubic feet per day, about 4,000 to 5,000 mg/l MLSS, and 560 cubic feet of air per pound of BOD_5 load, the plant can achieve a 5-day BOD removal between 98 and 99%.

5. Relationship between Hydraulic Detention Time and Other Parameters

The understanding of relationships between hydraulic detention time and other parameters should be useful to the operational control of activated sludge processes.

Haseltine (90) in his study of a rational approach to the design of activated sludge plants in 1955 pointed out that the average sewage aeration period is independent of the amount of the return sludge (r and X_R). That is easy to understand. For example, with 100% return sludge the mixed liquor aeration period will be just half of what the sewage aeration period (hydraulic detention time, θ) would have been with no return at all. However, on the average, all of the sewage would pass through the aeration tank twice, instead of once, so the effective sewage aeration period (θ) is unchanged.

Contary to Metcalf, et al.'s conclusion (49), hydraulic detention time is independent of mean cell residnece time (θ_c) and specific utilization (U), Sterling (89) has developed a formula to demostrating that (a). flow is not a factor in the determination of design aeration detention time, and (b). de-

tention time varies directly as BOD concentration and inversely as the product of loading and MLSS factors. This equation is introduced as

$$\theta = 21.6\ S_o / UX \qquad (2.68)$$

All terms were previously defined.

CHAPTER III

MATERIALS AND METHODS

To study the influence of hydraulic detention time on the removal efficiency in the activated sludge system, a bench scale unit was operated under closely controlled conditions.

The parameters used in this study include suspended solids concentration, chemical oxygen demand, dissolved oxygen uptake rate, and pH level. The detention times investigated cover a wide range, from 8 hours which is one of the required minimum value for the operation and design of activated sludge treatment plants specified by the regulation authorities in U.S.A. (1, 121) to 4 hours and 2 hours at which the feasibility of operation and design of such treatment plants was studied. The corresponding dilution rates were 1/8, 1/4 and 1/2 $hour^{-1}$, respectively.

With a variation of three different mean cell residence times (12, 6, and 3 days) this unit was run at each detention time studied for a time sufficiently long so that a reliable statistical estimation of the steady state parameters could be determined. The experimental unit was operated under closely controlled conditions in which a continuous, smooth, and gentle shift of various combination of conditions was arran-

ged so the operation condition was not changed violently that an optimum result might be obtained.

COD samples were collected from the effluent line daily, and another set of samples were also collected from the mixed liquor in the reactor when steady state had been reached so that any deviations from complete mixing conditions or error in operations could be detected and corrected. These data determined from collected samples were then used in the analysis and comparison of various parameters.

A. Laboratory Appratus

A schematic diagram of the laboratory bench scale activated sludge unit employed in this experimental investigation is shown in Figure 15. This experimental system consisted of (a). a storage tank for mixing and preserving the synthetic waste; (b). a pump for applying the synthetic waste at a desired uniform rate; (c). a reactor, in which the biochemical system was maintained; (d). an air supply; and (e). an effluent storage tank.

A 5.81-liter plexiglass reactor with internal recycle of microorganisms served as the aeration chamber and secondary clarifier. The liquor volume in the aeration chamber and clarifier was separated by an adjustable baffle. The volumes were 4.1 liters and 1.40 liters, respectively.

The feed medium was delivered to the reactor through a pump calibrated to deliver various rates of inflow, at a rate depending upon the desired detention time.

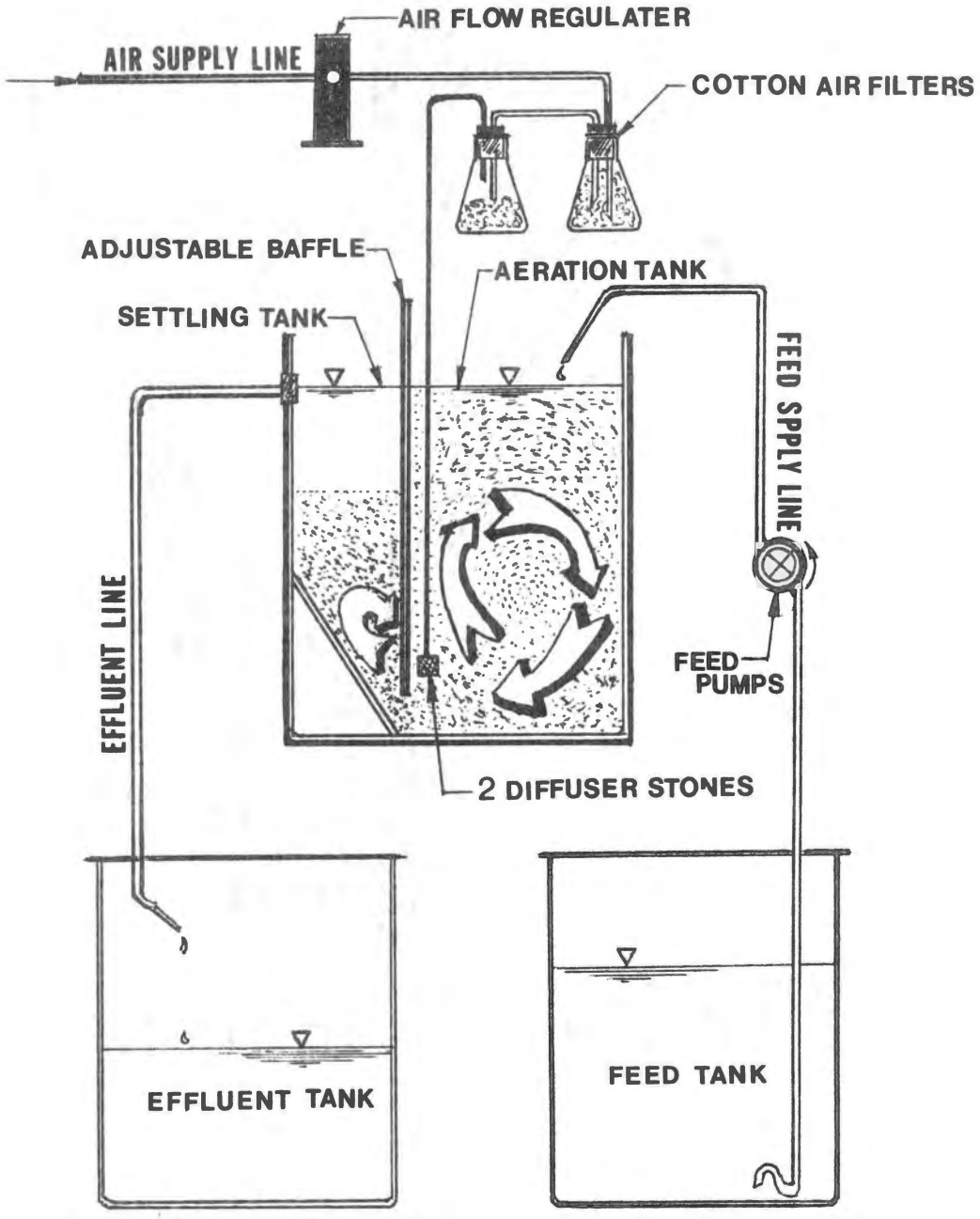

Figure 15. Experimental Bench-Scale Activated Sludge Unit with Internal Recycle.

A variable speed Masterflex tubing pump employed for delivering the synthetic feed solution was a production with catalog No. 7545-17 from Cole-Parmer Instrument Company, Ill. Suction and delivery line were equipted with Tygon tubing manufactured by the above-named company and glass junctions linkaged together to provide a continuous flow of waste water to the treatment unit. Used feed lines and junctions were discarded and then changed with already-disinfected new ones for every four days while pumping rates were checked three times everyday by means of a graduated cylinder and timer and together by drawing out the dilapidated section of feed line which was already worn down by the compaction of pump rotor assembly. Thus, a constant desired feed flowrate was maintained.

Compressed air with an air flow rate of between 3.8 and 4.2 liters per minute, which was adequate to provide good agitation and mixing and also sufficient oxygen for the microorganisms, was supplied to the reactor through two porous diffuser stones at two different levels of mixed liquor for good recirculation of settled sludge.

This unit was run at room temperature at a range of 25 $^{o}C \pm 1\ ^{o}C$, although no particular controlling equipment was used in this study.

B. Feed Solution

A concentration of approximate 200 mg/l synthetic waste employing glucose as the carbon source and the growth-limit-

ing nutrient was used in all experiments.

The chemical composition of feed solution is given in Table I. The ratio of COD:N:P of the synthetic waste is 100: 10.6 : 30. This ratio is much higher than the values (100: 5 : 1) reported in literature to insure that the carbon source is the only limiting nutritional substrate.

A phosphate buffer solution was used as a means of controlling the pH level in the aeration tank to maintain the pH between 6.8 and 7.3 together with the normal influence of bu-

TABLE I

COMPOSITION OF SYNTHETIC FEED SOLUTION FOR 200 mg/l GLUCOSE AS GROWTH-LIMITING SUBSTRATE

Constituents	Stock Concentration Per Two Liters (Grams)	Quantity Used For Preparing 50-l Feed Solution (ml)	Final Concentration in 50-l Feed Solution (mg/l)
Glucose	500	40	200
$(NH_4)_2\ SO_4$	250	20	100
$MgSO_4 \cdot 7H_2O$	50		20
$FeCl_3 \cdot 6H_2O$	0.25		0.1
$CaCl_2$	0.365	20	1.5
$MnSO_4 \cdot H_2O$	5		2.0
Phosphate Buffer Solution 1.0 M, pH = 7.6 (K_2HPO_4+KH_2PO_4)		100	2 ml/l
Tap Water	to volume of 50 liters		

ffering effect of the tap water.

Concentrated stock solutions which were kept frozen until their use were made for easily preparing daily 50-liter feed solution each day. For this reason, the COD values of the feed solution were almost always the same for each daily run, and the variance that did occur can be attributed to the inaccuranies in running the COD test.

C. Development of Microbial Population

This experiment was initiated by seeding the synthetic waste (5,81 liters) with 100 ml of the effluent of the primary clarifier of the Stillwater, Oklahoma numicipal sewage treatment plant. The unit was operated on a 24-hour batch feeding basis by using a more concentrated synthetic waste containing 500 mg/l of glucose (with the COD:N:P ratio of 100 :10.6:30) as the sole carbon source until the solids concentration had built up to approximately 3,000 mg/l. Then, the unit was switched to continuous flow operation concitions with the 200 mg/l glucose feed solution at a flow rate of 52.92 l/day (equivalent to 2 hours detention time) together with the wasting of mixed liquor at the amount of 0.368 l/day (equivalent to a mean cell residence time of 12 days).

Under such conditions, the reactor was run for approximately three weeks in order for the bacteria to become acclimated to the continuous flow process. When the first steady state conditions were reached, at a MLSS concentration around 4,300 mg/l and with an effluent COD concentration of 18 mg/l,

the monitoring of the parameters listed as follow was initiated:

Daily monitorings:

I. Feed Solution:
   - COD
   - pH Level

II. Effluent:
   - COD (Feltered)
   - pH Level
   - SS Concentration

III. Biological Reactor:
   - MLSS Concentration in Aeration Tank
   - pH Level
   - Temperature

At steady state conditions:
- Oxygen Uptake rate in Reactor

D. Experimental Protocal

After a 3-week acclimation period under continuous operation at θ = 2 hours and θ_c = 12 days, the first chemostatic steady state was reached. Then a minimum of four days was allowed thereafter for acclimation at each particular detention time and mixed liquor wasting rate. To insure that the unit had reached equilibrium, samples were taken until the results of efflulent COD and MLSS concentration in the reactor were comparable at least for three consecitive days.

1. Feed Solutions

A 50-liter synthetic feed solution was prepared daily according to the proportions shown in Table I. From this a 20-ml sample was taken to be filtered for a COD analysis. The pH level of the feed solution was checked daily and maintained within the range of 6.8 and 7.3 .

2. Flow Rate of Feed Solution

The desired flow rates were checked three times daily (8 a.m., 4 p.m., and midnight) by means of a graduate cylinder to assure that a constant detention time was maintained.

3. Effluent

About a 50 ml sample of effluent was collected directly from the effluent line with a cylinder and then was filtrated through a 0.45 μ, type HA, millipore filter pad. From the filtrate, a 20-ml sample was used for the COD analysis. The COD determination was made from the discharged effluent rather than from the effluent collection tank, since the biological solids which may be present in the effluent tank could cause further metabolism of organic matter in the tank and the results would be lower than the results actually obtained by measuring at the effluent discharge. However this was not imperative when the steady state condition was reached, because the solid concentrations in the effluent tank were determined to be zero.

After the sample was collected from the effluent line, the effluent tank was well mixed, and a 25-ml sample was collected and filtered through a 0.45 μ, type HA millipore filter pad for the determination of the effluent solid concentration while another 50 ml of effluent was collected and checked for pH level.

4. Mixed Liquor in Reactor

A 25-ml sample was collected directly from the aeration basin before the wasting of the mixed liquor and then filtrated for the determination of the MLSS concentrations. Before the volume of mixed liquor wasted was replaced, another 25-ml of the aeration basin mixed liquor was collected again (usually done accompanying the adjusting work for flow rate) and was then filtered for the determination of MLSS concentration after wasting. This solid value after wasting was averaged with the last solid value before wasting as the averaged MLSS concentration in the reactor for each day. This procedure for obtaining the MLSS concentration is very important especially when the unit was run under a very short value of mean cell residence time.

E. Analytical Techniques

To provide the necessary data for this investigation, the chemical oxygen demand, biological solids concentration in the reactor and in the effluent, pH, temperature, and oxygen uptake rate were monitored. The following is a brief description of the method and equipment used to measure these parameters.

1. Chemical Oxygen Demand

The COD procedure employed was made in accordance with Standard Methods (78). Mercuric sulfate and silver sulfate were used in all determinations.

2. Biological Solids

The suspended solids concentrations were determined by fiters (0.45 u, type HA, Millipore Filter Corp., Bedford, Mass.) as described in Standard Methods (78). The filters were weighted on a Mettler Instrument Corporation Balance (No. 1-910).

3. pH Level

The pH level was determined using a Beckman Expandomatic 55-2 pH meter immediately after collection from feed solution , mixed liquor and effluent tank. The pH meter had been previously adjusted by the use of a buffer solution of a pH of 7.6 .

4. Oxygen Uptake Rate

The dissolved oxygen was measured on a Precision Galvanic Cell Oxygen Analyser (Cat. No.65850, Precision Scientific Co., Chicago, Ill.) at each minuite for ten minuites immediately after the air supply was stopped. By plotting DO vs. time, the oxygen uptake rates could be calculated from the slopes divided by the MLSS in the reactor. The detailed techniques and calculations are described in the manual published by the manufacters.

5. Temperature

The temperature was measured with a Sargent-Welch thermometer equipped along the wall of reactor.

F. Methods of Data Analysis

Although considerable mathematical models have been developed in the studying of biological CMAS systems as reviewed in Chapter II, only the mathematical relationships which are based upon first order rate of organic removal and upon the concept of mean cell residence time together as given by Sherrard, et al. (112) will be employed for data analysis. By using this method, all possible parameters can be obtained for comparisons.

1. Removal Efficiency, E

The efficiency of stabilization or purification (or equal to COD removal efficiency in this study) was calculated according to the expression

$$E = (S_o - S)S_o^{-1} \cdot 100\% \qquad (3.1)$$

where

E = COD removal efficiency, %

S_o = influent substrate concentration, COD mg/l

S = effluent substrate concentration, COD mg/l

2. Mean Cell Residence Time, θ_c

The mean cell residence time which is equal to the reciprocal of the net growth rate was determined by the following expression:

$$\theta_c = VX(Q_w X + Q_{eff} X_{eff})^{-1} \qquad (3.2)$$

where

θ_c = mean cell residence time, days

V = volume of aeration chamber, liters

Q_w = waste liquid flow rate, liters/day

Q_{eff} = effluent liquid flow rate, liters/day

X = MLSS concentration in reactor, mg/l

X_{eff} = SS concentration in effluent, mg/l

3. Hydraulic Detention Time, θ

The hydraulic detention time is defined as below:

$$\theta = V/Q \qquad (3.3)$$

where

Q = influent flow rate (does not include return sludge flow), liters/day

The remaining terms are as previously defined.

4. Specific Utilization, U

The specific utilization is defined as the amount of substrate used per day divided by the amount of microorganisms in the reactor and can be calculated from the following formula:

$$U = (S_o - S)/(\theta X) \qquad (3.4)$$

where

U = Specific utilization, day^{-1}

All remaining terms are as previously defined.

5. Observed Yield Coefficient, Y_{obs}

For constant environmental conditions and a specific wastewater, the magnitude of the variable is depend upon θ_c (

112). It can be determed according to the following two expressions:

$$Y_{obs} = (QwX + Q_{eff}X_{eff})/(S_o - S)Q \quad (3.5)$$

or $$Y_{obs} = 1/U\,\theta_c \quad (3.5\text{-}1)$$

where

Y_{obs} = observed cell yield coefficient

All other terms have been previously defined.

6. Food-Microorganism Ratio, F/M

The food-Microorganisms-Ratio is defined as the amount of substrate applied divided by the amount of microorganisms in the reactor per day. From a materials balance analysis, a relationship for the food-to-microorganism ratio can also be developed. It can be represented as shown belows:

$$F/M = 100\ U/E \quad (3.6)$$

or $$F/M = S_oQ/(VX) \quad (3.7)$$

All the termed used have been defined previously.

7. True (Maximum) Cell Yield Coefficient, Y_{max}, and Cell Decay Coefficient, k_d

Y_{max} and k_d can be obtained from the linearination of the observed yield data with two methods accomplished by employing the techniques of the least squares statistical analysis.

The first method used a plot of the reciprocal of the observed yield versus the mean cell residence time (88). The resulting equation took the form of

$$1/Y_{obs} = 1/Y_{max} + (k_d/Y_{max})\theta_c \quad (3.8)$$

where

Y_{max} = true cell yield coefficient; or the reciprocal of the line at the vertical axis

k_d = Cell decay coefficient, day^{-1}; or calculated from the slope of the line derived by Y_{max}.

All other terms have defined before.

The second method used is the most common one often found in literature (49, 52, 54, 56, 107, 110). The true yield coefficient and the cell decay coefficient may be determined from the plot of specific growth rate ($1/\theta_c$) versus specific utilization (U). This equation took the form of

$$1/\theta_c = Y_{max}U - k_d \quad (3.9)$$

All the remaining terms have been previously defined.

8. Sludge Production, P_x

Sludge production is defined as the amount of excess sludge wasted per day, and can be expressed as below:

$$P_x = Q_w X + Q_{eff} X_{eff} \quad (3.10)$$

or $$P_x = VX/\theta_c \quad (3.11)$$

where

P_x = sludge production daily, mg/day

All other terms have defined previously.

9. Oxygen Uptake Rate, R_o

Oxygen uptake rate can be obtained either by a graphic method or by a simple mathematical calculation. For graphi-

cal methods, the slope of the plot of Dissolved oxygen vs. time devided by the concentration of MLSS is equal to oxygen uptake rate. For mathematical calculation, the oxygen uptake rate can be derived by the following expression:

$$R_o = 1440(D.O._{t_2} - D.O._{t_1})/(t_2-t_1)X \qquad (3.12)$$

where

R_o = oxygen uptake rate, O_2 mg/l/day/mg/l MLSS

$D.O._{t_1}$, and $D.O._{t_2}$ = D.O. level in mixed liquor at time t_1 and t_2, respectively, while aeration was stopped , mg/l

X = MLSS concentration in reactor, mg/l

t_1, t_2 = time, minuite

10. Oxygen Requirements, D_o

Oxygen requirement is the amount of oxygen supply required for the total aeration system per day. It is defined by the following equation:

$$D_o = R_oXV \times 10^{-3} \qquad (3.13)$$

where

D_o = the amount of O_2 required per day, Gram O_2/day

R_o = oxygen uptake rate, mg/l O_2/day/mg/l MLSS

X = MLSS concentration in reactor, mg/l

V = reactor volume

CHAPTER IV

RESULTS

The laboratory activated sludge unit was operated under closely controlled conditions for a period of approximately ten weeks. The influent COD, pH and temperature in the reactor was maintained essentially constant at 200 mg/l, 7.0, and 25 ± ^{o}C, respectively. For a internal recycling laboratory activated sludge system utilized in this investigation, a very important hypothesis is made that when the settled sludge level is held or approaches a constant height in the sedimentation tank, the sludge recirculation characteristics are constant, i.e., the recycled sludge concentration and the ratio of return sludge flow rate are controlled at constant values.

The mean cell residence time and hydraulic detention time were varied from 3 to 12 days and from 2 to 8 hours, respectively. Steady-state condition were assumed when constant values for the aeration reactor microorganism concentration, effluent COD and constant sludge level in settling tank were obtained. Tabular raw data for each of the nine experimental runs are found in Table II.

The remainder of this chapter shall be devoted to a detailed presentation of the results of this investigation in

the following major sections: (A). efficiency of stabilization; (B). MLSS concentration in reactor and sludge production; (C). yield coefficient and decay coefficient; and (D). oxygen uptake rate and oxygen requirement.

In general, the results of each item examined were plotted against the following parameters: θ_c, θ, U (or F/M), and some other needed parameters. Following the presentation of results, the significant of these findings will be discussed in the next chapter.

A. Evaluation of COD Removal

The performance characteristics of the system are presented in Table II. Values are given for hydraulic detention time, mean cell residence time, COD, pH, MLSS concentration X , U, $F/M/\theta$, F/M, and performance characteristics.

Figure 16 shows the COD removal efficiency versus mean cell residence time for various hydraulic detention times. The percent COD removal can be related to mean cell residence time as shown in this plot. In general, the efficiency increased as the mean cell residence time is increased. However, it is apprant that the hydraulic detention time also affects the COD removal . When this system was run at a particular θ_c, the optimum efficiency was obtained at a hydraulic detention time of 4 hours. This result shows that COD removal efficiency is a function of both θ_c and θ.

Figure 17 represents an evaluation of COD removal efficiency vs. hydraulic detention time for the three different

TABLE II

SUMMARY OF STEADY STATE PERFORMANCE DATA

θ_c	θ	S_o	S	E	X	P_x	Y_{obs}	R_o	D_o	U	F/M	F/M/θ	Xθ	pH
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
12	2	216	17.5	91.9	4300	1580	0.150	0.15	2.87	0.55	0.60	0.30	8600	7.2
12	4	202	4.8	97.6	3880	1426	0.273	0.18	3.03	0.31	0.31	0.08	15520	7.3
12	8	215	20.1	90.6	3098	1139	0.442	0.12	1.68	0.19	0.21	0.03	24784	7.1
6	8	203	25.1	87.6	1654	1216	0.519	0.26	1.91	0.32	0.37	0.05	13232	6.8
6	4	228	21.0	90.8	2362	1736	0.319	0.34	3.50	0.53	0.58	0.15	9448	7.3
6	2	195	19.0	90.3	2730	2006	0.216	0.25	2.99	0.77	0.86	0.44	5460	7.3
3	2	205	27.9	86.4	2415	3550	0.378	0.22	2.29	0.88	1.02	0.51	4830	7.3
3	4	201	23.4	88.4	2058	3026	0.644	0.31	2.79	0.52	0.59	0.15	8232	7.1
3	8	201	29.9	85.1	1248	1835	0.810	0.24	1.33	0.41	0.48	0.06	9984	7.2

UNITS: 1 = days, 2 = hours, 3 = mg/l, 4 = mg/l, 5 = %, 6 = mg/l, 7 = mg/l, 8 = mg/l/mg/l, 9 = mg/l O_2 / day /mg/l MLSS, 10 = gram O_2 /day, 11 = 1/day, 12 = 1/day, 13 = 1/(day·hour), 14 = mg·hour/l, 15 = Unit.

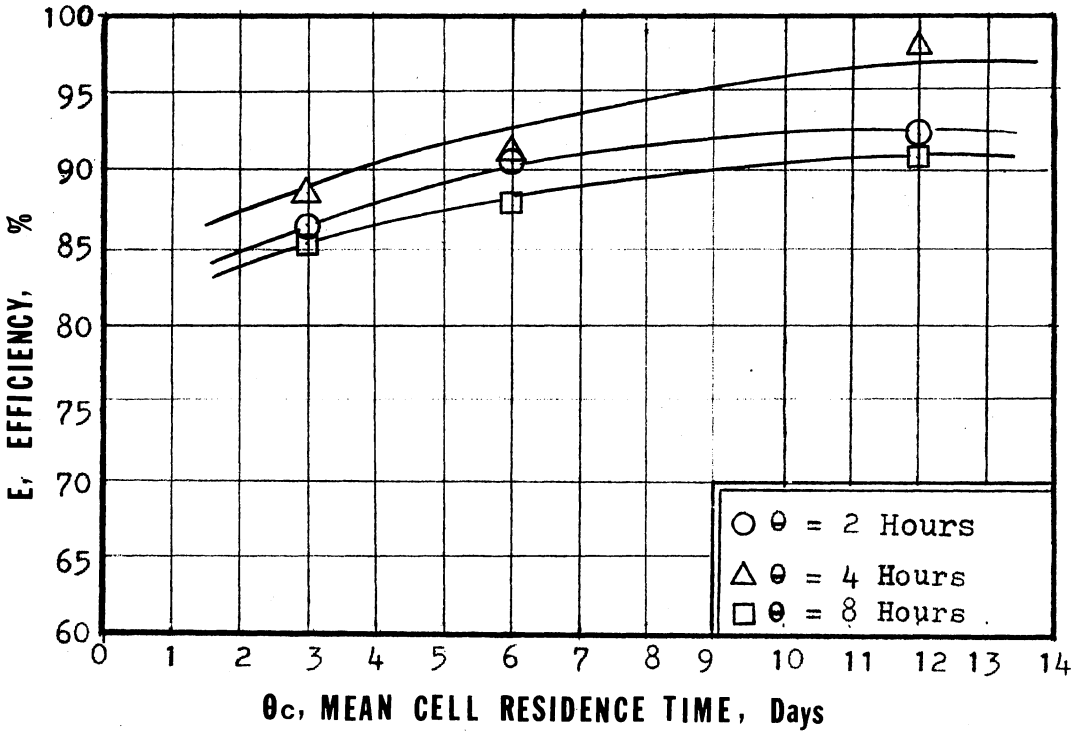

Figure 16. Relationship between Treatment Efficiency, E , and Mean Cell Residence Time, θ_c, Plotted on Regular Paper.

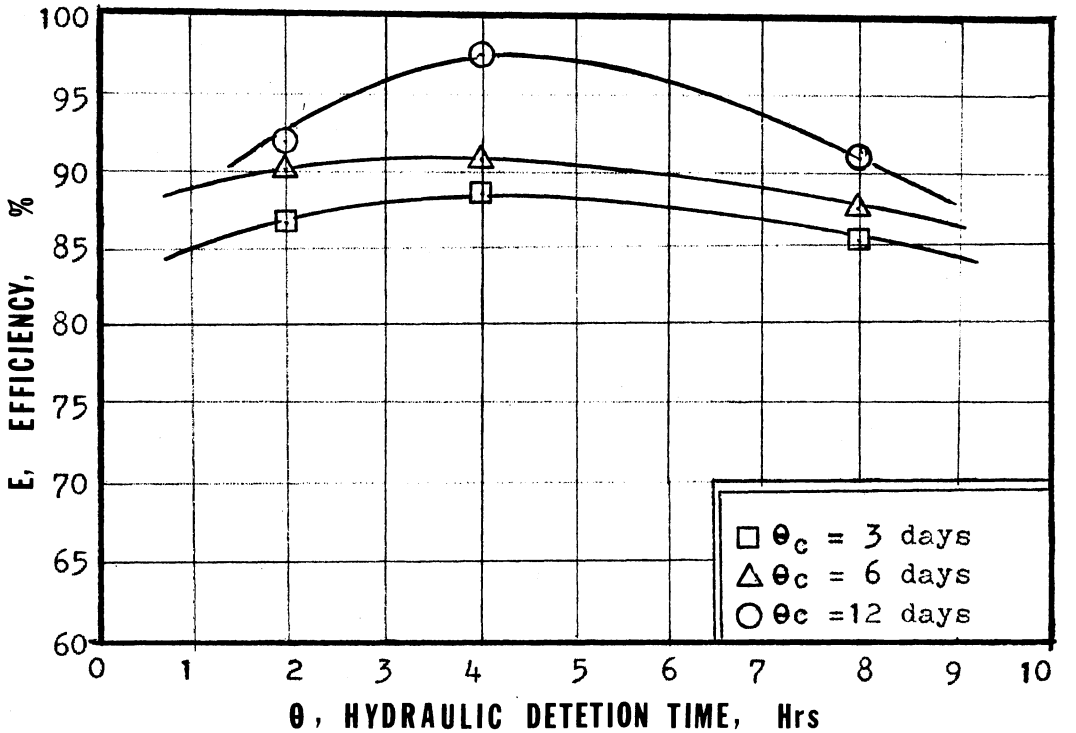

Figure 17. Relationship between Treatment Efficiency E and Mean Cell Residence Time θ_c Plotted on Semilogarithmic Paper.

mean cell residence times studied. It can be seen that the efficiency is a function of both θ_c and θ. However, the optimum COD removal efficiency occurred when this system was operated at a hydraulic detention time of 4 hours and a mean cell residence time of 12 days. In fact the highest efficiency achieved for any particular mean cell residence time was at a hydraulic detention time of 4 hours. This plot shows that both θ and θ_c should be important parameters for the removal efficiency of the CMAS process.

Figure 18, 19, 20, and 21 shows the COD removal efficiency when compared with the parameters, U and F/M. It shows that there is poor correlation between COD removal efficiency and the loading parameters, U or F/M. In general, the COD removal efficiency decreased with an increase loading value of U or F/M. However, it appears that both θ and θ_c show their influences on the relationships between COD removal and the loading factors U or F/M individually. For a particular value of U or F/M, the highest COD removal is obtained at a hydraulic detention time and a high mean cell residence time. From both Figure 19 and Figure 21, it can be seen that for a given hydraulic detention time, the COD removal efficiency decreases with an increase in U or F/M or with a decrease in the mean cell residence time. For a particular mean cell residence time the optimum COD removal efficiency occurred at a specific hydraulic detention time and at a specific F/M or U value. Beyond these values, the efficiency decreased no matter how U or the F/M ratio or θ was varied. The high degree

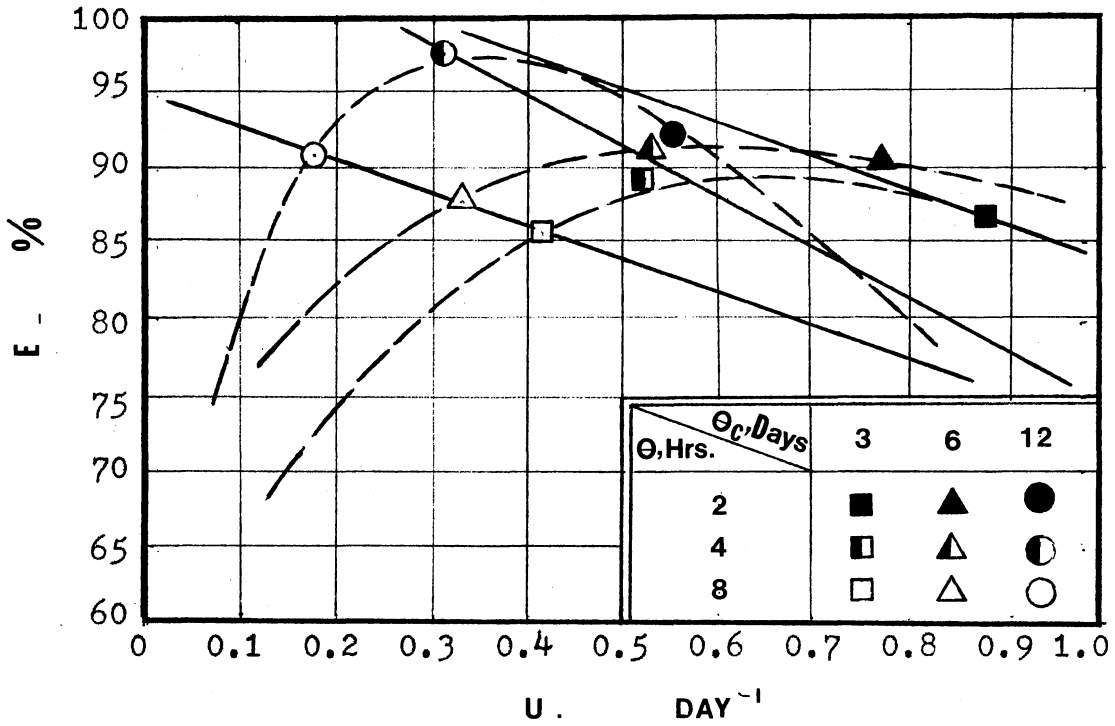

Figure 18. Relationship between Treatment Efficiency E and Specific Utilization U Plotted on Regular Paper.

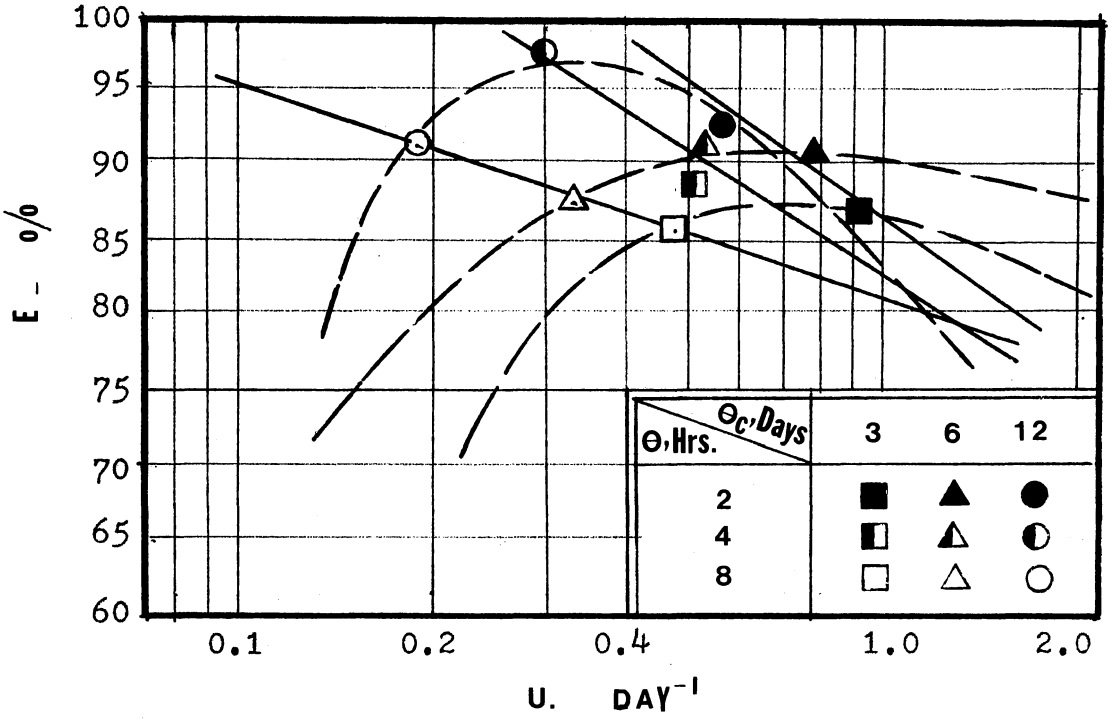

Figure 19. Relationship between Treatment Efficiency E & Specific Utilization U Plotted on Semilogarithmic Paper.

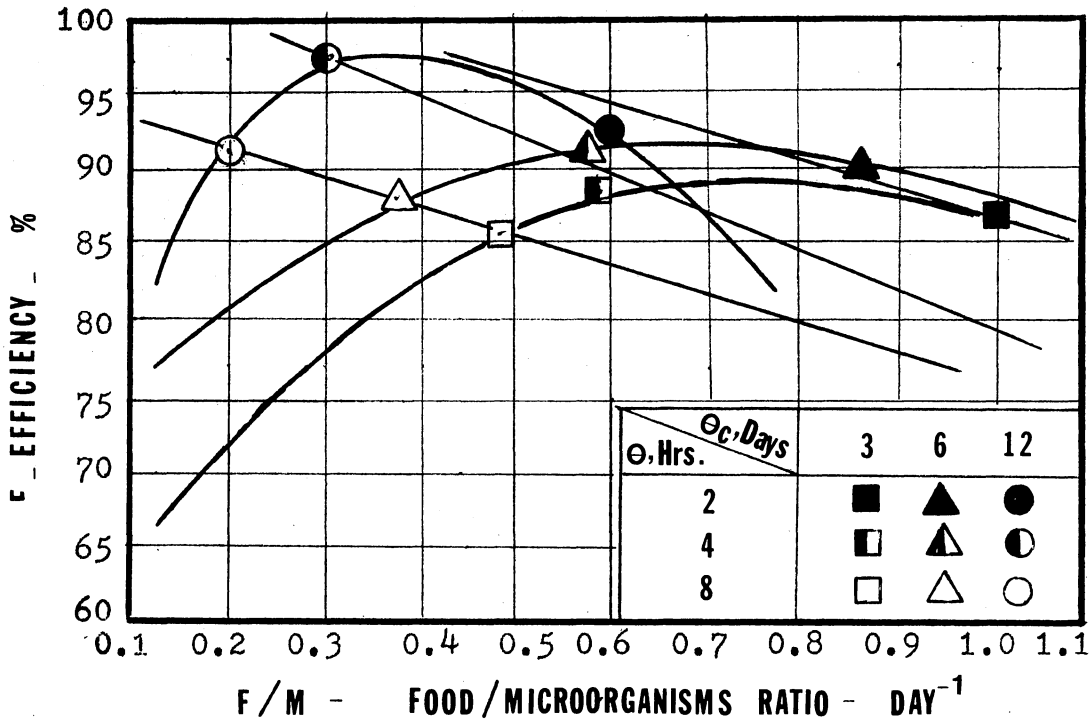

Figure 20. Relationship between Treatment Efficiency E & Food/Microorganisms Ratio F/M Plotted on Regular Paper.

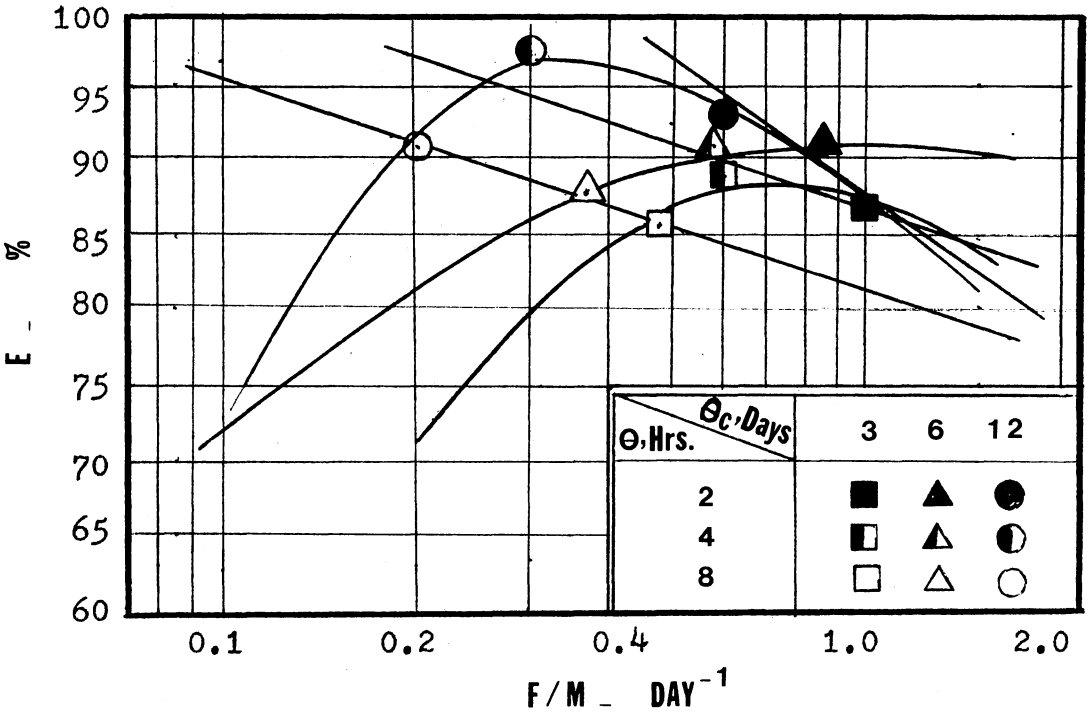

Figure 21. Relationship between Treatment Efficiency E and Food/Microorganisms Ratio F/M Plotted on Semilogarithmic Paper.

of scatterness caused by different θ_c and θ values is evidence that both θ_c and θ have a greater influence on COD removal than U or F/M.

Another parameter which has been reported as usuable for the operation and design of the CMAS processes is the F/M/θ ratio. Its relationship to COD removal efficiency is shown in Figures 22 and 23. A poor relationship was found between COD removal efficiency and F/M/θ ratio.

The product of MLSS concentration and hydraulic detention time, θX, has been reviewed in Chapter II as a functional combination parameter in Eckenfelder's CMAS kinetic model (4, 26, 42, & Figure 3) previously. A plot of COD removal efficiency vs. θX, however, shows that no direct relationship between efficiency of stabilization and θX occurred in this study. This is shown in Figures 24 and 25.

Shown in Figure 26 and Figure 27 are plots of COD removal efficiency vs. MLSS concentration. These data show a fairly good correlation with COD removal efficiency and MLSS concentration which is in agreement with other investigation results (34, 100, 101). For MLSS concentrations below 2,300 mf/l, a very excellent relationship existes between COD removal efficiency and MLSS concentration in reactor. However, the relationship seems to be controlled by other parameters when the MLSS concentrations are greater than 2,300 mg/l.

Figure 28 shows relationship between efficiency of stabilization and the pH level. It is easy to see that pH has no influence on the COD removal efficiency under normal pH

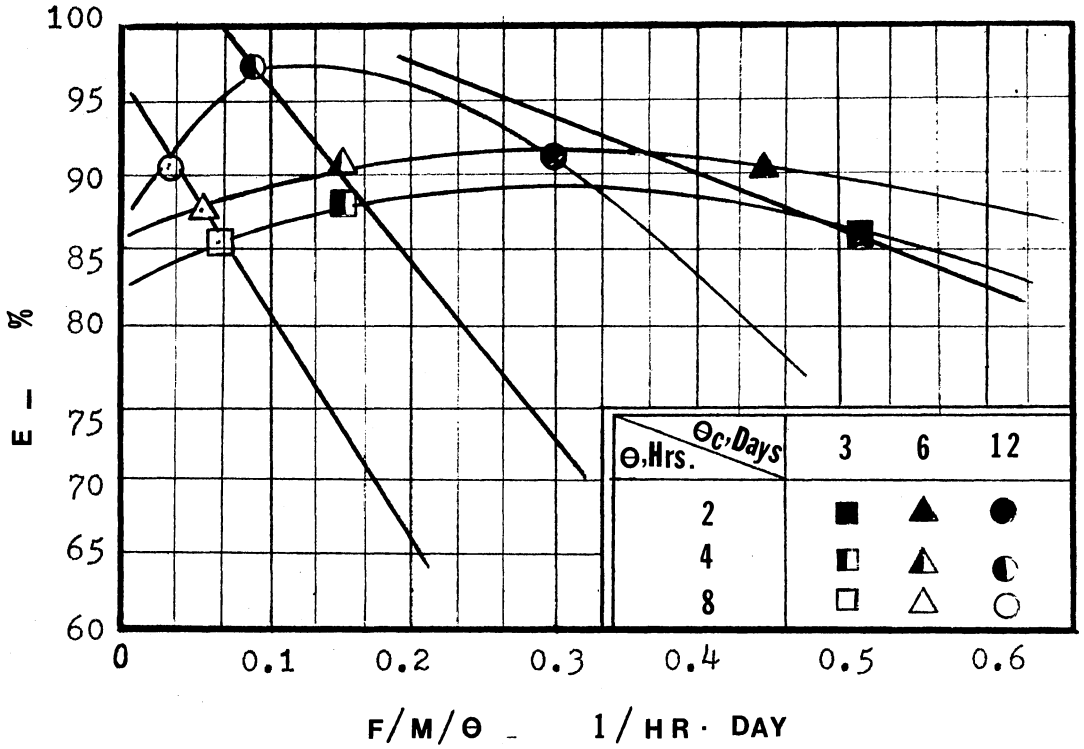

Figure 22. Relationship between Treatment Efficiency, E , and Combination Factor F/M/Θ Plotted on Regular Paper.

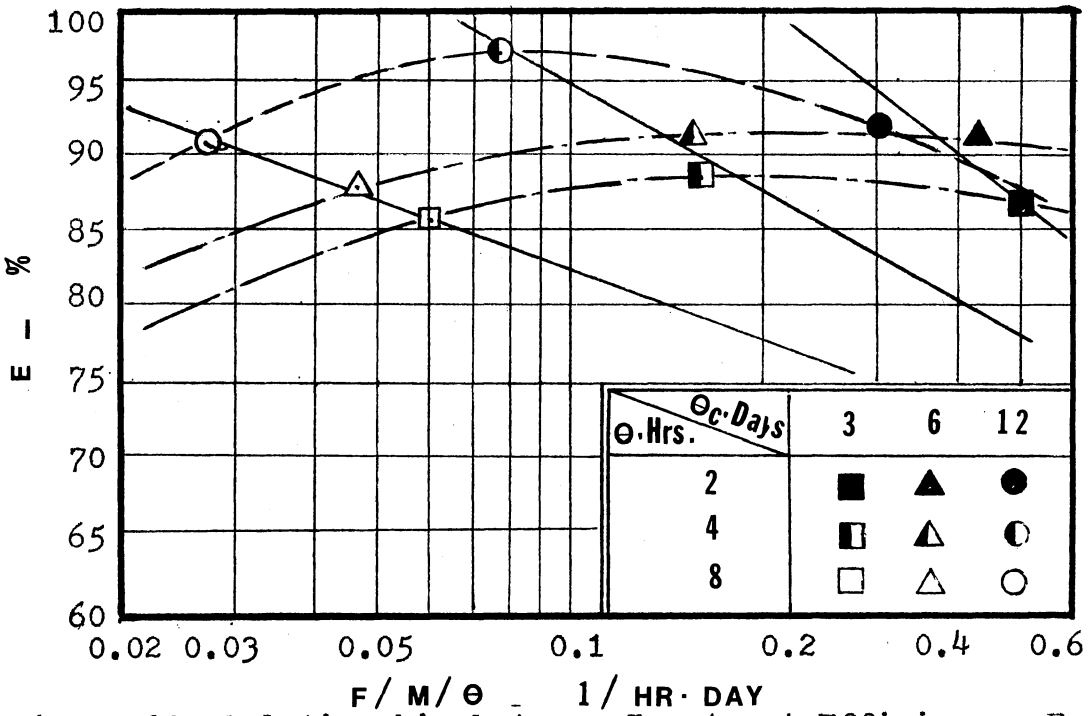

Figure 23. Relationship between Treatment Efficiency, E, and Combination Factor F/M/Θ Plotted on Semilog Paper.

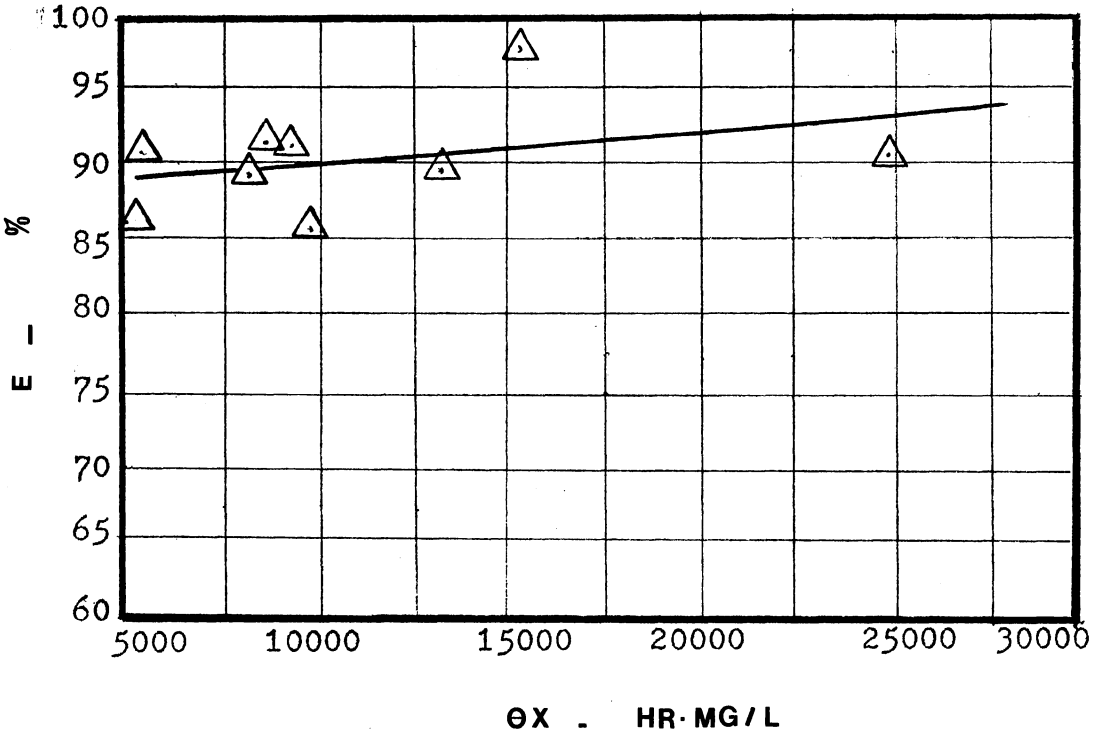

Figure 24. Relationship between Treatment Efficiency E & Combination Factor θX Plotted on Regular Paper.

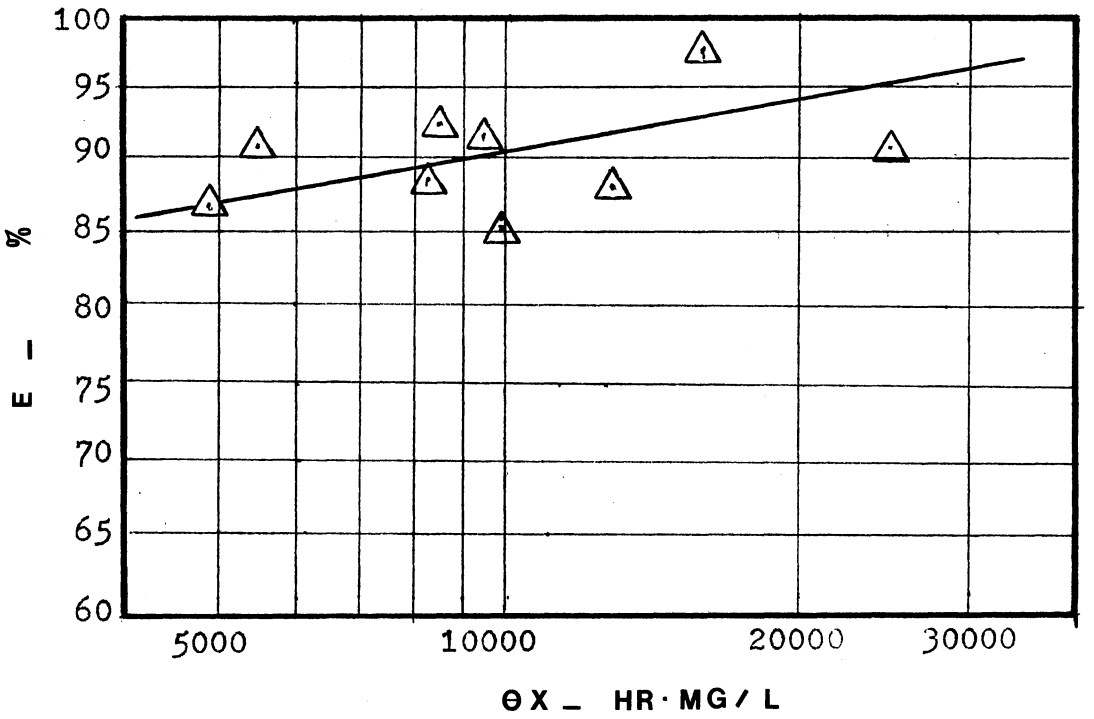

Figure 25. Relationship between Treatment Efficiency E & Combination Factor θX Plotted on Semilogarithmic Paper.

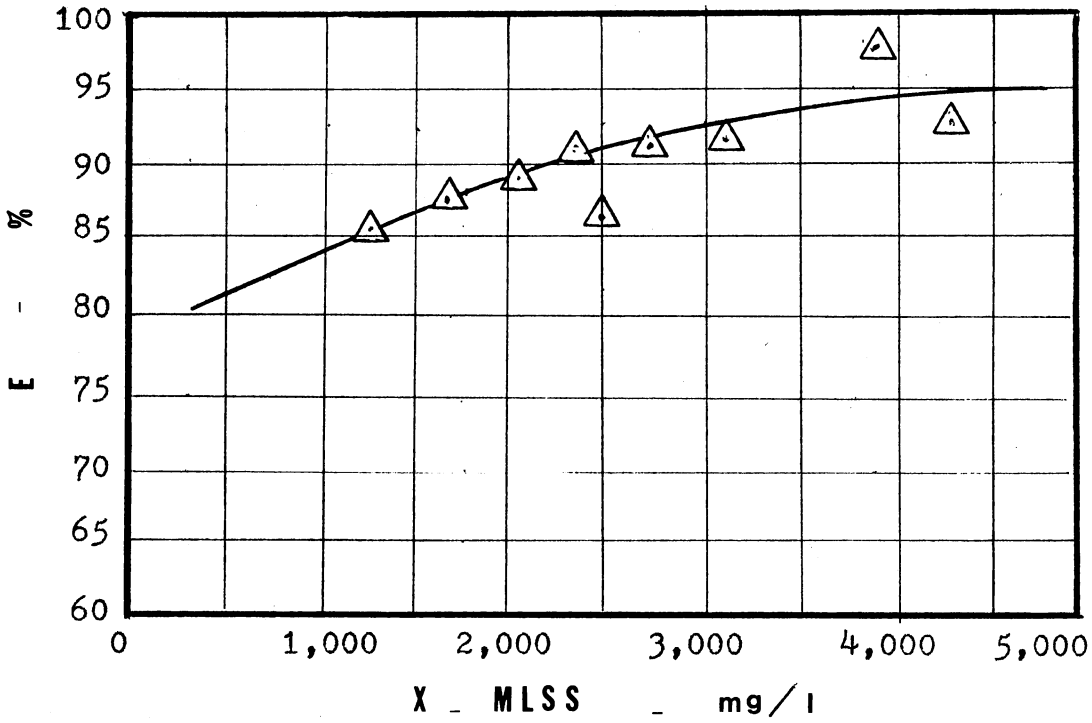

Figure 26. Relationship between Treatment Efficiency E and Mixed Liquor Suspended Solids Concentration X in Reactor Plotted on Regular Paper.

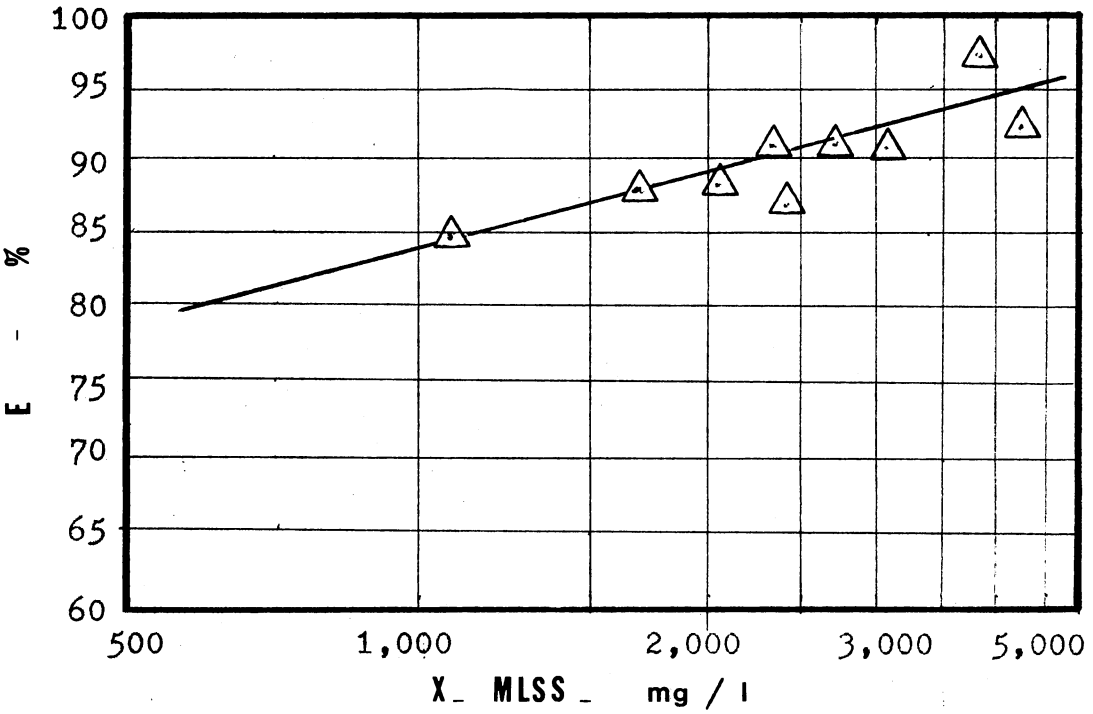

Figure 27. Relationship between Treatment Efficiency E & Mixed Liquor Suspended Solids Concentration X in Reactor Plotted on Semilogarithmic Paper.

ranges.

An overall analysis of data presented thus far shows that none of the above parameters investigated can be considered as a sole junctional parameter in the control of CMAS processes. Although both mean cell residence time and MLSS concentrations showed a greater influence on the COD removal efficiency individually, their relationships with COD removal were also governed by the hydraulic detention time which is related to the contact time for organic substrate and microorganisms and is also related to available food supply for a specific charactered waste.

B. MLSS Concentration in Reactor and Solids Production

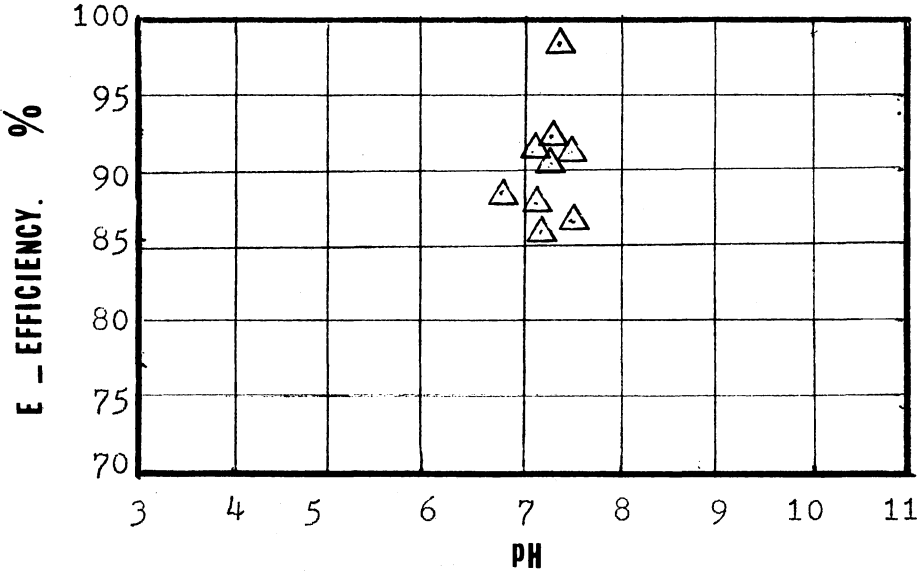

Figure 28. Relationship between Treatment Efficiency E & pH Values in Mixed Liquor in the Reactor.

A summary of the reactor MLSS concentrations and daily production of biological solids are presented in Table II. Figure 29 shows the relationship between mean cell residence time and the corresponding MLSS concentration for each hydraulic detention time. It can be seen that as the mean cell residence time is increased MLSS concentration is increased. It can also be seen that for a particular mean cell residence time, the MLSS concentration increased as the hydraulic detention time was decreased. Both θ_c and θ showed influences on the amount of MLSS concentration for a specific waste influent.

The MLSS concentration can also be evaluated by the method shown in Figure 30. A more definite linear relationship exists between MLSS concentration and hydraulic detention time at a particular growth rate condition.

Figure 31 and Figure 32 show the relationship between the MLSS concentration and loading factors, U or F/M. For the mean cell residence times & hydraulic detention times studied, it appears that there is a definite relationship between biological solids concentrations and U or F/M values. For a particular hydraulic detention time, the MLSS concentration in the reactor decreased with increasing loading factors, U or F/M (or with decreasing mean cell residence time). On the other hand, the MLSS concentration associated with a particular growth rate decreased with decreasing loading factors, U or F/M (or with decreasing influent flow rates). From this data it can be seen that these engineering factors, θ,

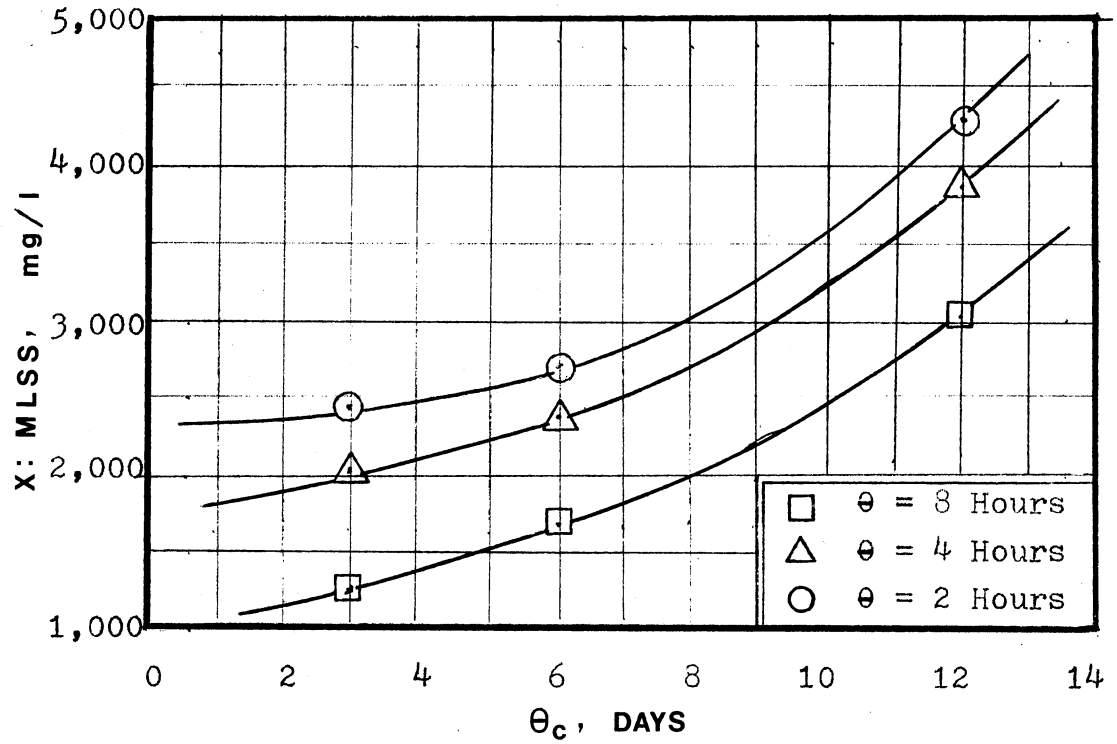

Figure 29. Relationship between MLSS X and Mean Cell Residence Time θ_c Plotted on Regular Paper.

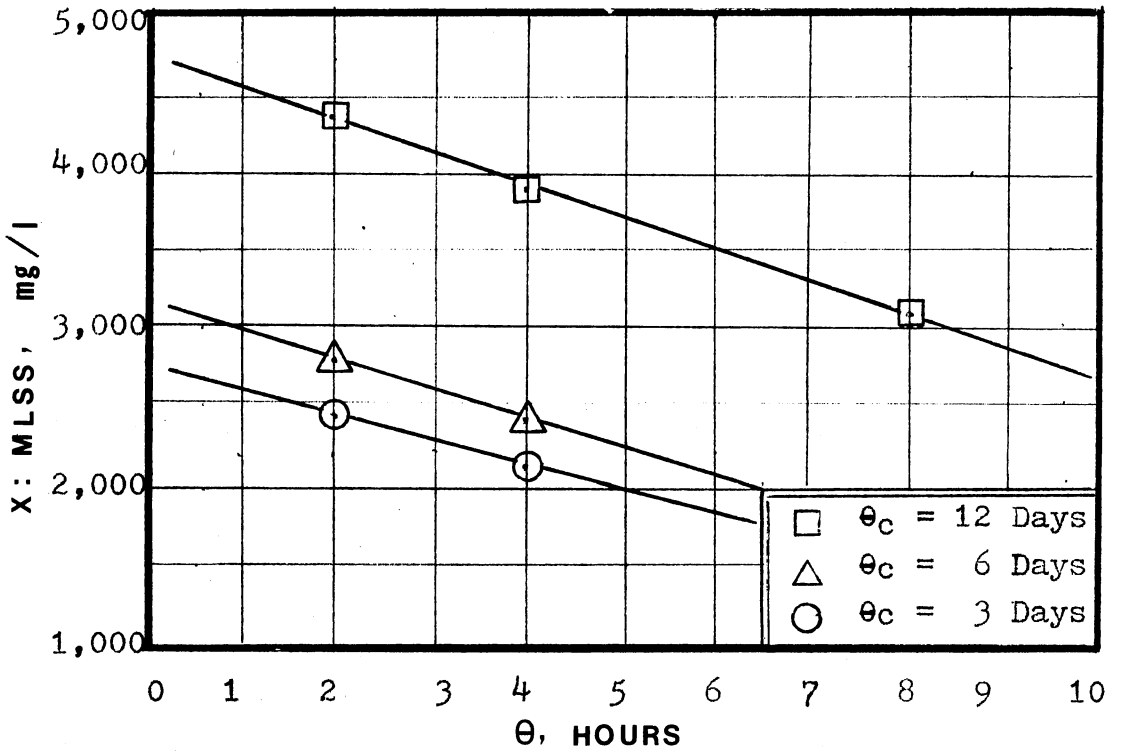

Figure 30. Relationship between MLSS X and Hydraulic Detention Time θ Plotted on Regular Paper.

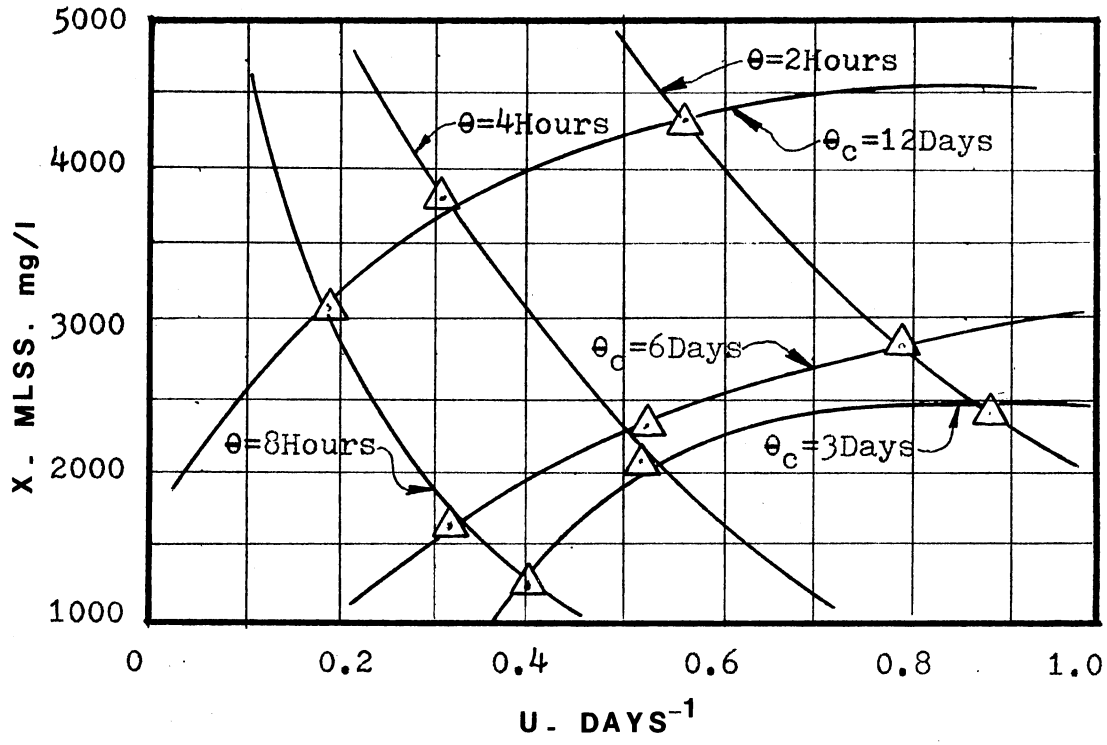

Figure 31. Relationship between MLSS X and Specific Utilization U Plotted on Regular Paper.

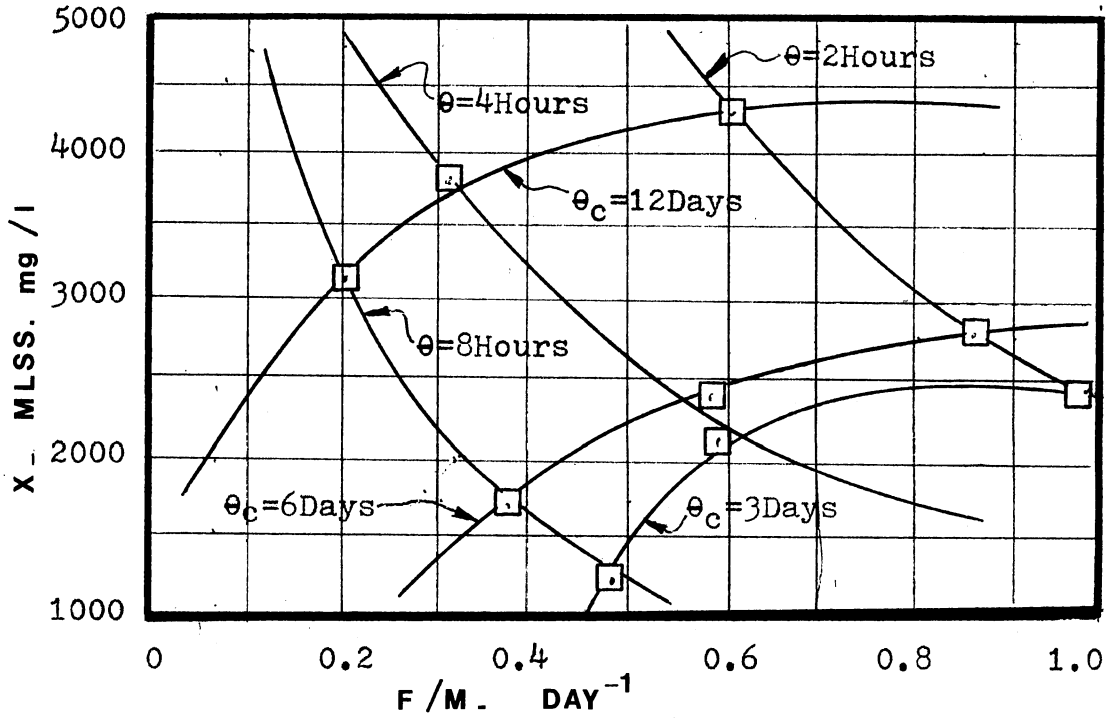

Figure 32. Relationship between MLSS X and Food/Microorganisms Ratio F/M Plotted on Regular Paper.

θ_c, and U or F/M, do exercise nutual influences on the MLSS concentration in a system.

Sludge production can be expressed in terms of either weight of biological solids accumulated per day or weight of biological solids accumulated per unit weitht of COD removed. In this part, only the sludge production expressed as mg of MLSS accumulated per day is evaluated. The sludge production expressed as mg of MLSS accumulated per mg of COD removed is actually termed as the observed sludge yield coefficient and will be presented later.

Figure 33 and Figure 34 show the sludge produced for various mean cell residence times and hydraulic detention times. Similary to the results of treatment efficiency and MLSS concentrations, this data shows that both the mean cell residence time and the hydraulic detention time influence the daily sludge production. A larger quantity of daily sludge production can be expected when the system is run at a low hydraulic detention time and low mean cell residence time.

In Figures 35 and 36, the sludge production is plotted against specific utilization, U. A good correlation was found, i.e., for a small loading factor value, the daily sludge production will be minimum.

C. Yield Coefficient and Decay Coefficient

The observed cell yield coefficient, Y_{obs}, is also called: "Unit-Weight-Basis Sludge-Production" in term of weight of sludge accumulated per unit weight of COD removed. A sum-

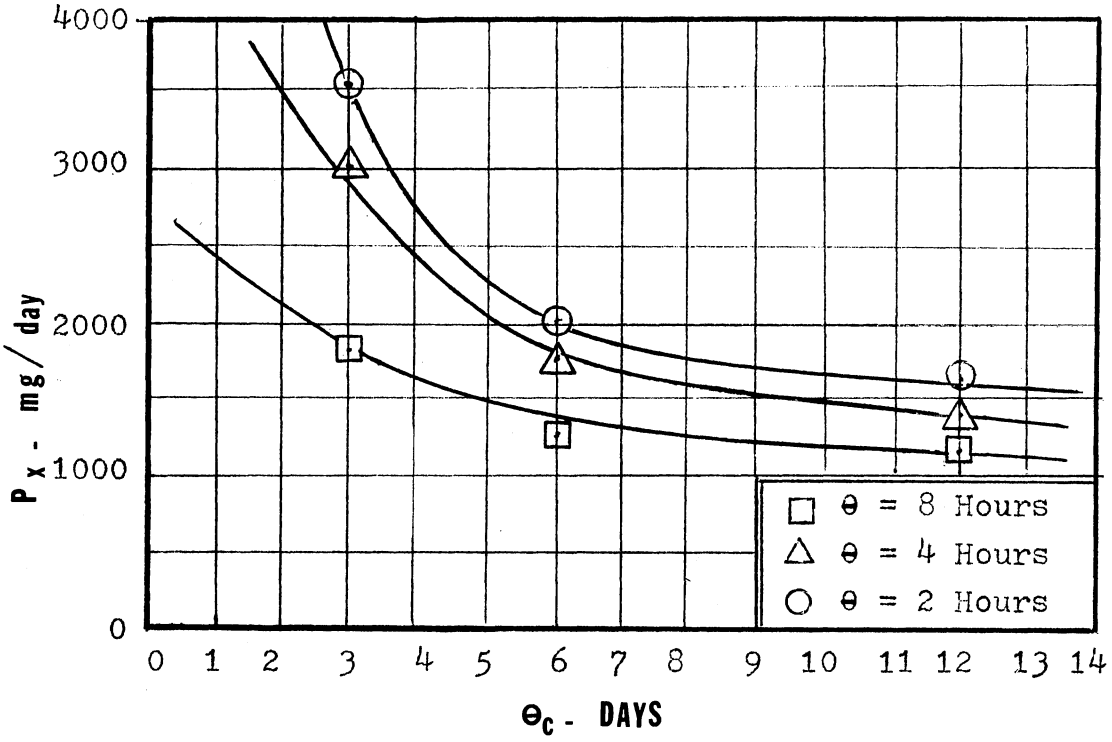

Figure 33. Relationship between Daily Sludge Production P_x and Mean Cell Residence Time θ_c Plotted on Regular Paper.

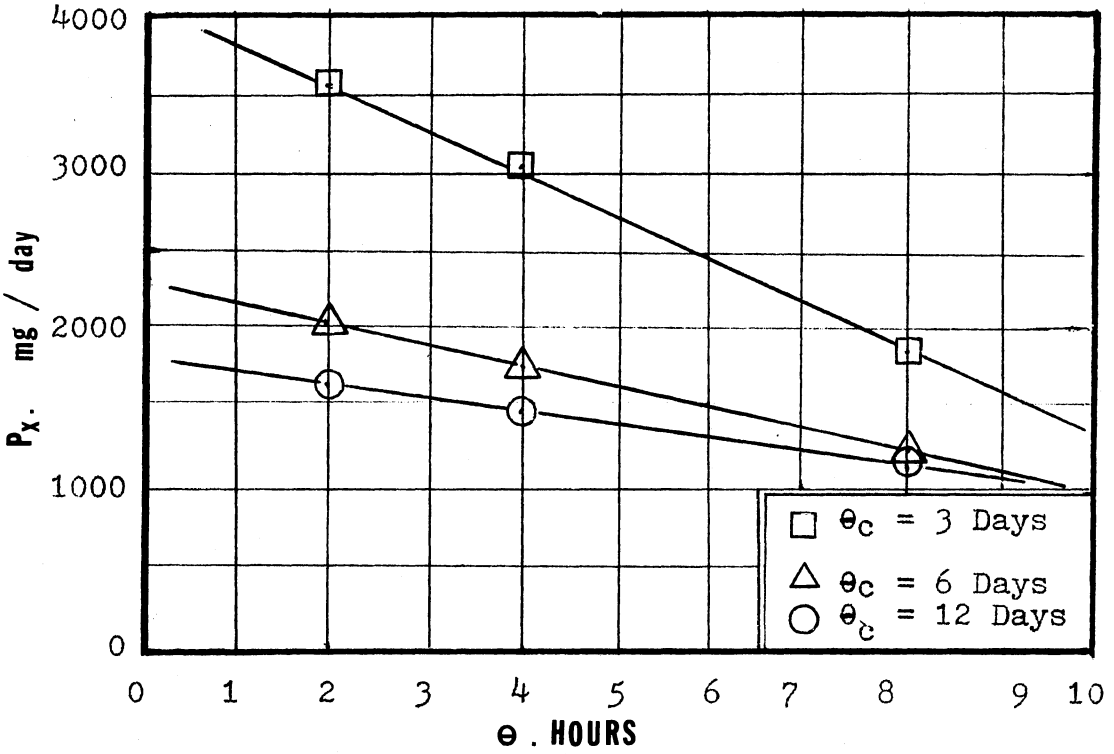

Figure 34. Relationship between Daily Sludge Production P_x and Hydraulic Detention Time θ Plotted on Regular Paper.

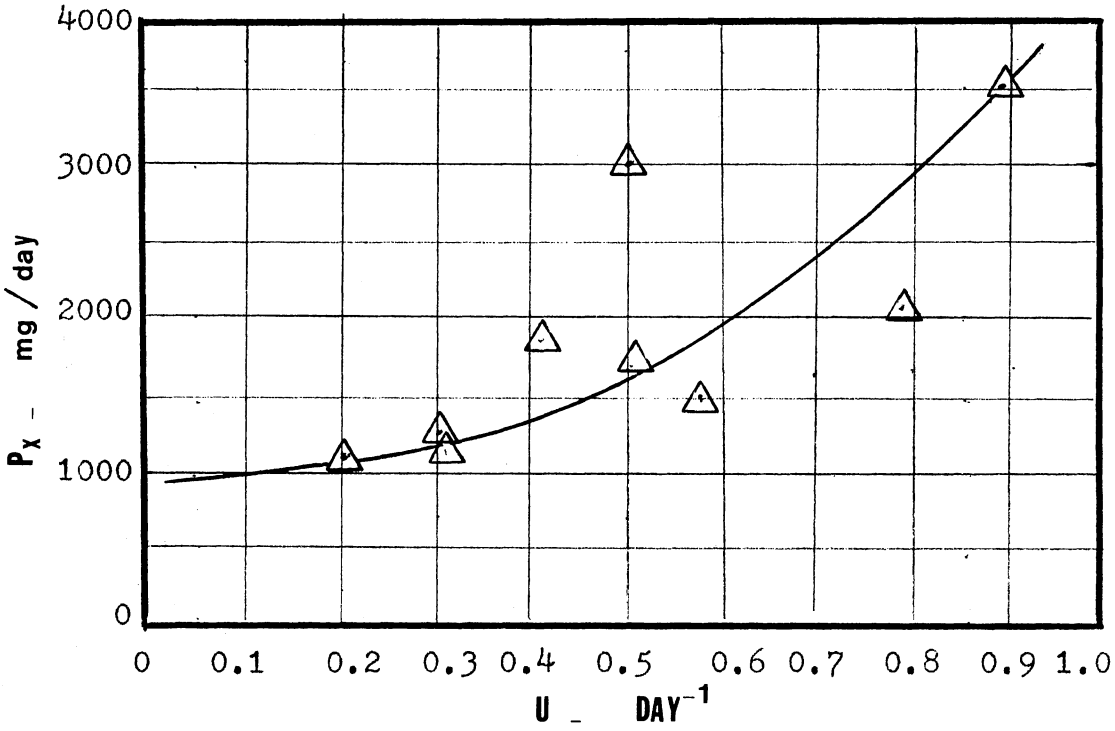

Figure 35. Relationship between Daily Sludge Production P_x and Specific Utilization U Plotted on Regular Paper.

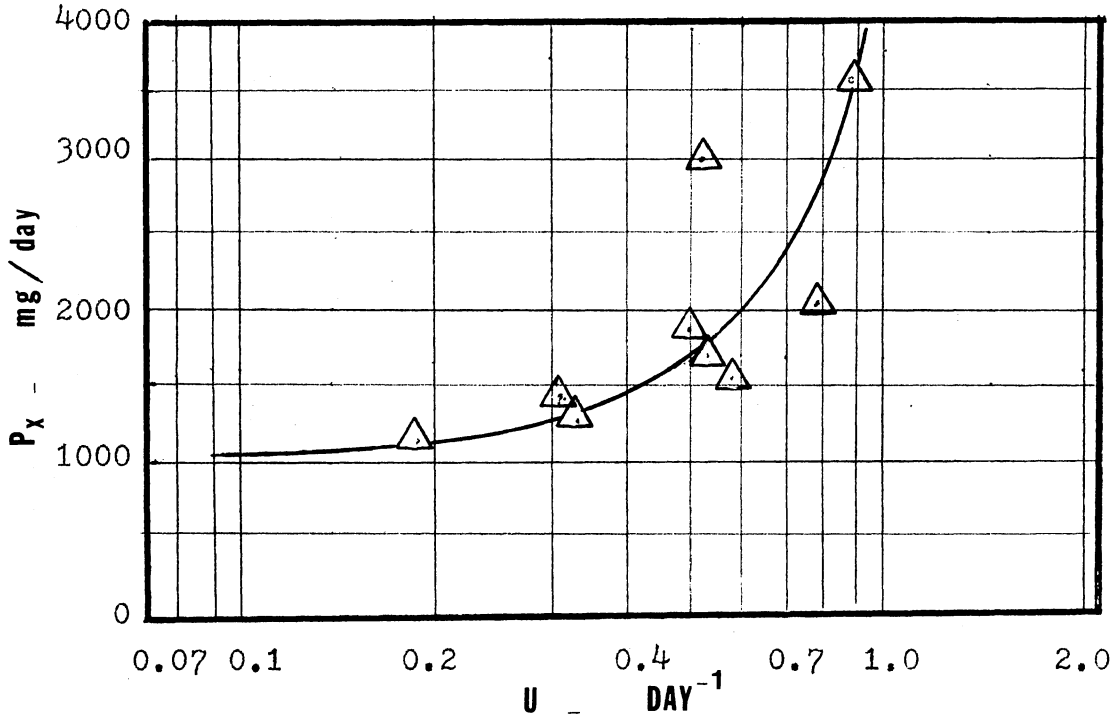

Figure 36. Relationship between Daily Sludge Production Px and Specific Utilization U Plotted on Semilogarithmic Paper.

mary of the observed cell yield coefficient at different operational conditions is listed in Table II. The variation of Y_{obs} as a function of θ_c, θ, and U are shown in Figures 37, 38, and 39, respectively. The Y_{obs} can be seen to be a function of the hydraulic detention time and mean cell residence time. However, a mutual influence of θ and θ_c on the observed yield coefficient can be found again. This interesting results of such binary influences by θ and θ_c is also shown in the plot of observed cell yield against specific utilization (Figure 39).

From the overall inspection of the variation between Y_{obs} and U, no trend can be concluded. Nevertheless, for a particular mean cell residence time, the observed cell yield (or unit-weight-basis sludge production) did decrease with the increase in specific utilization and increase in flow rate of the waste (or decrease in hydraulic detention time), while the observed cell yield increased with a increase in specific utilization and a decrease in mean cell residence time (or increase in sludge production) for a particular hydraulic detention time.

The mean cell residence time can also be related to the true cell yield coefficient by a plot of specific growth rate ($1/\theta_c$) vs. specific utilization as shown in Figure 40. It was found that both the true cell yield coefficient (Y_{max}) and cell decay coefficient (k_d) are not so-called "constant". Apparently, they vary as a funtion of hydraulic detention time. This interesting and useful result can be certified

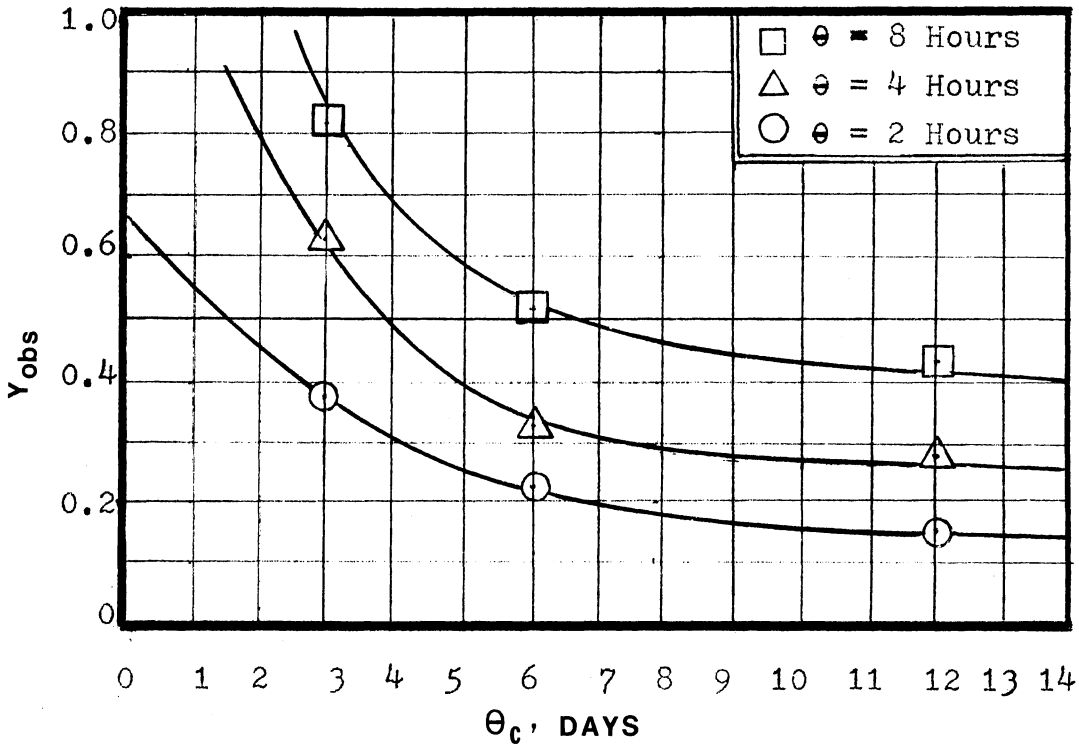

Figure 37. Relationship between Observed Cell Yield Coefficient Y_{obs} and Mean Cell Residence Time θ_c Plotted on Regular Paper.

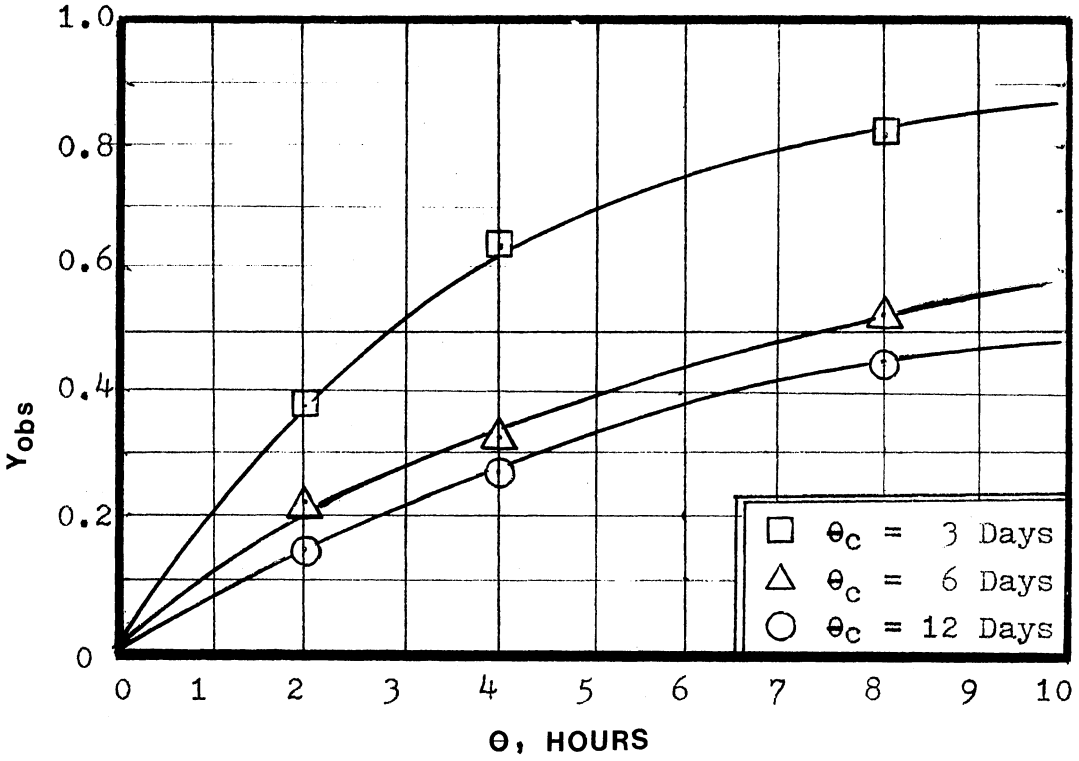

Figure 38. Relationship between Observed Cell Yield Coefficient Y_{obs} and Hydraulic Detention Time θ Plotted on Regular Paper.

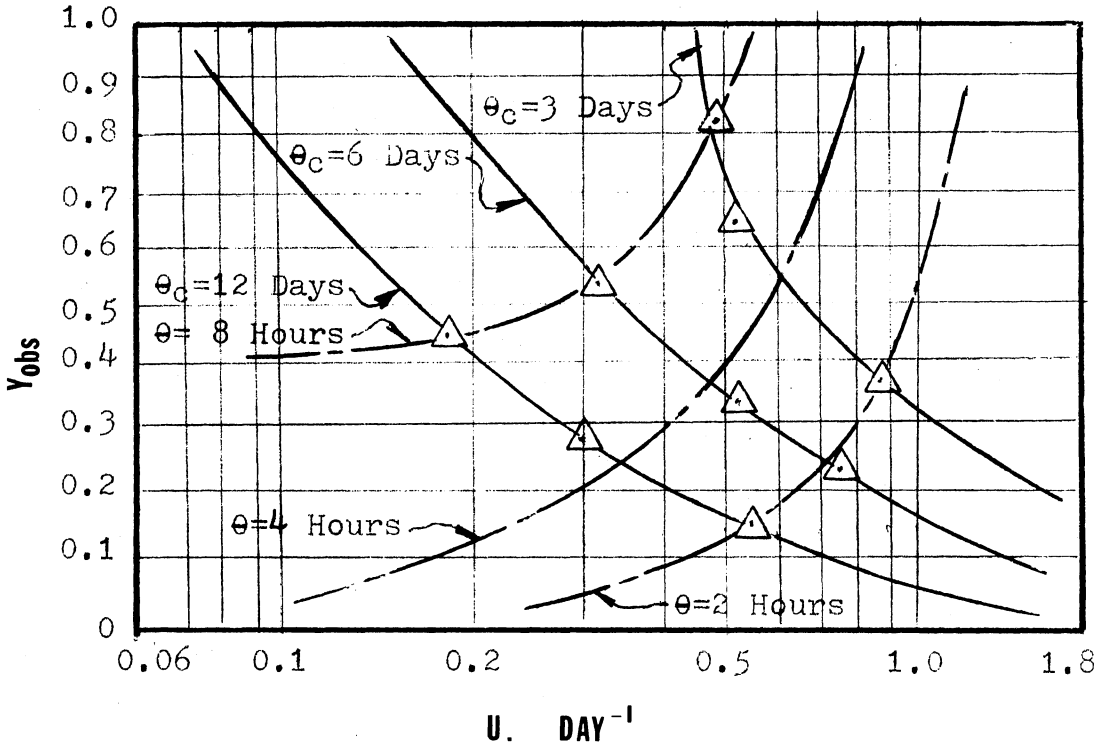

Figure 39. Relationship between Observed Cell Yield Coefficient Y_{obs} and Specific Utilization U at Various Hydraulic Detention Time θ and Mean Cell Residence Time θ_c Plotted on Semilogarithmic Paper.

with a different evaluation by plotting the reprocical of observed cell yield coefficient against mean cell residence time. The variation of Y_{max} and k_d as a function of hydraulic detention time are shown in Figures 40, 41, and 42. For the range of hydraulic detention time studied in this investigation, Y_{max} increases as θ increases, while k_d decreases as θ increases. The Y_{max} and k_d varied from 0.588 to 0.870 and from 0.083 to 0.252, respectively.

D. Oxygen Uptake Rate and Oxygen Requirement

The evaluation of the oxygen uptake rate and oxygen re-

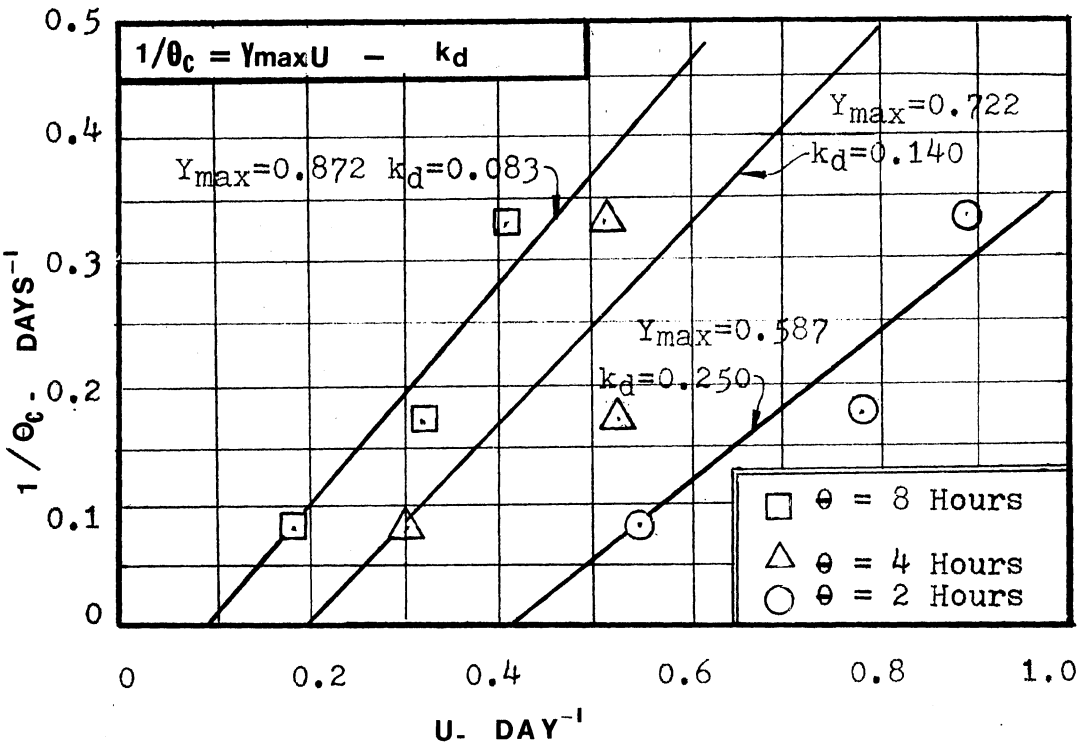

Figure 40. Relationship between Specific Growth Rate $1/\theta_c$ and Specific Utilization at Various Hydraulic Detention Times θ.

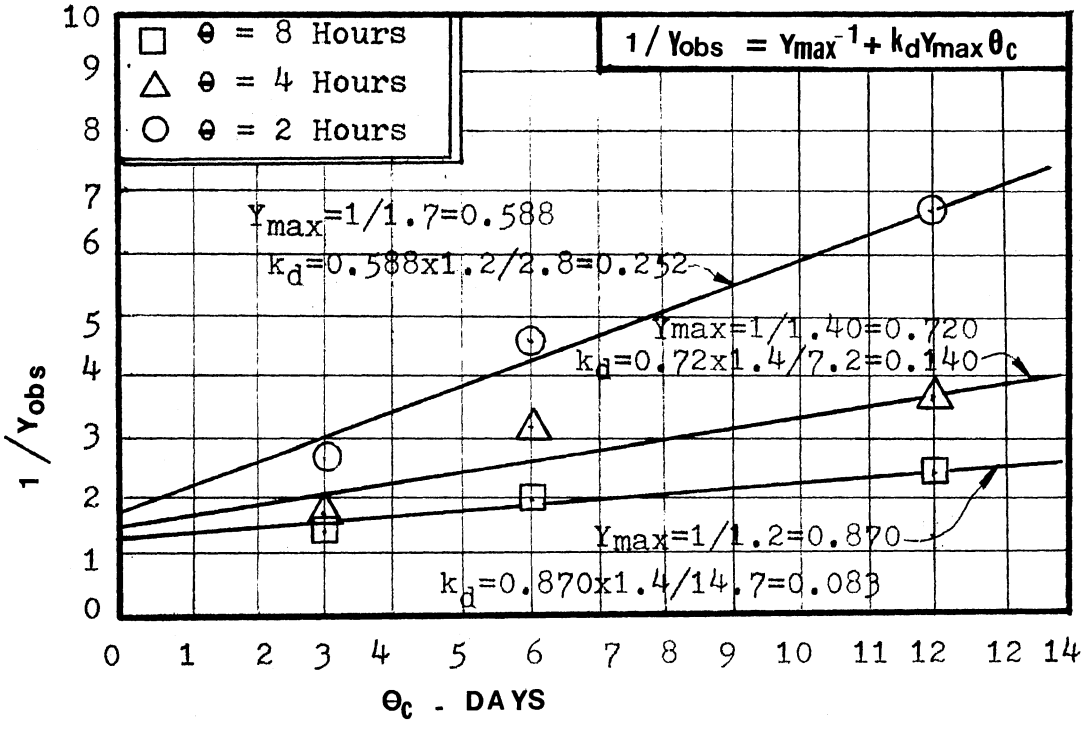

Figure 41. Relationship between the Reciprocal of Y_{obs} and Mean Cell Residence Time θ_c at Various Hydraulic Detention Time.

quirements for various mean cell residence times and hydraulic detention times is presented in Table II and Figures 43, 44, 45, and 46, respectively. Again, the dual effects of θ_c and θ on the oxygen uptake rate (R_o) and oxygen requirements (D_o) are found in these plots. In this investigation, both the maximum R_o (0.34 mg/l of O_2 per day per mg/l of MLSS in reactor) and D_o (3.5 grams of O_2 per day for total system) are found to be at a θ_c and θ of about from 6 to 8 days and from 4 to 5 hours, respectively.

Another evaluation of R_o and D_o with respect to specific utilization U is shown in Figure 47. The range of R_o and D_o values for this investigation were 0.15 to 0.34 mg/l of O_2 /

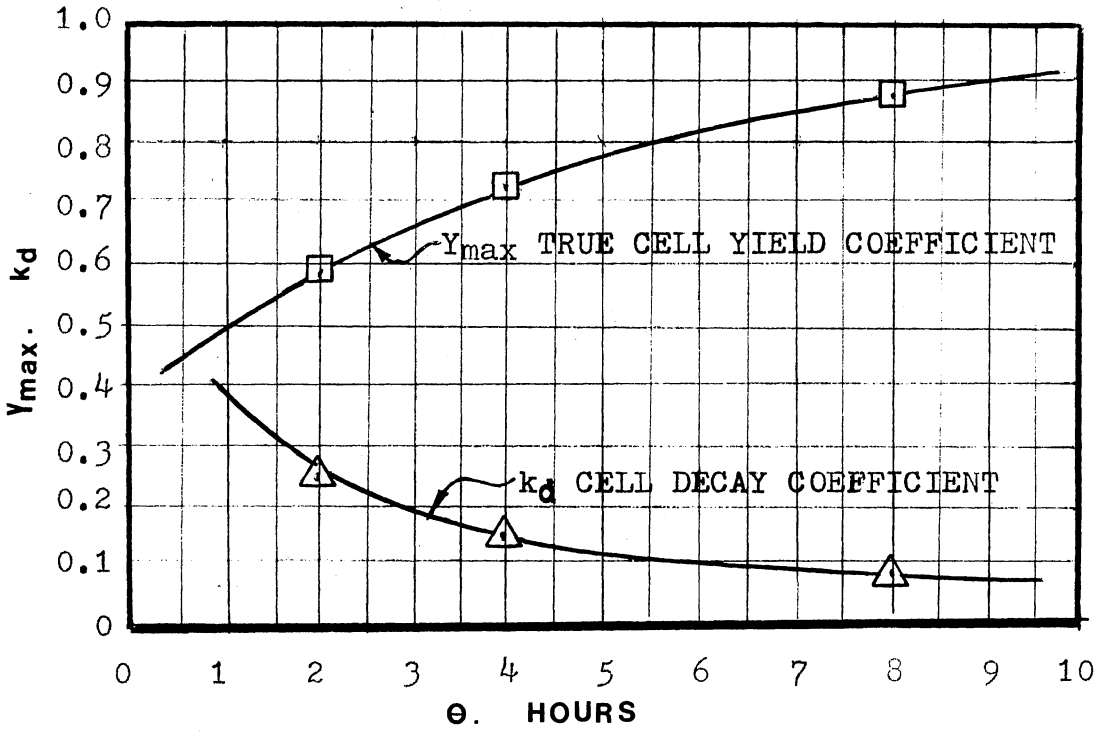

Figure 42. Relationship between Hydraulic Detention Time and Y_{max} with k_d.

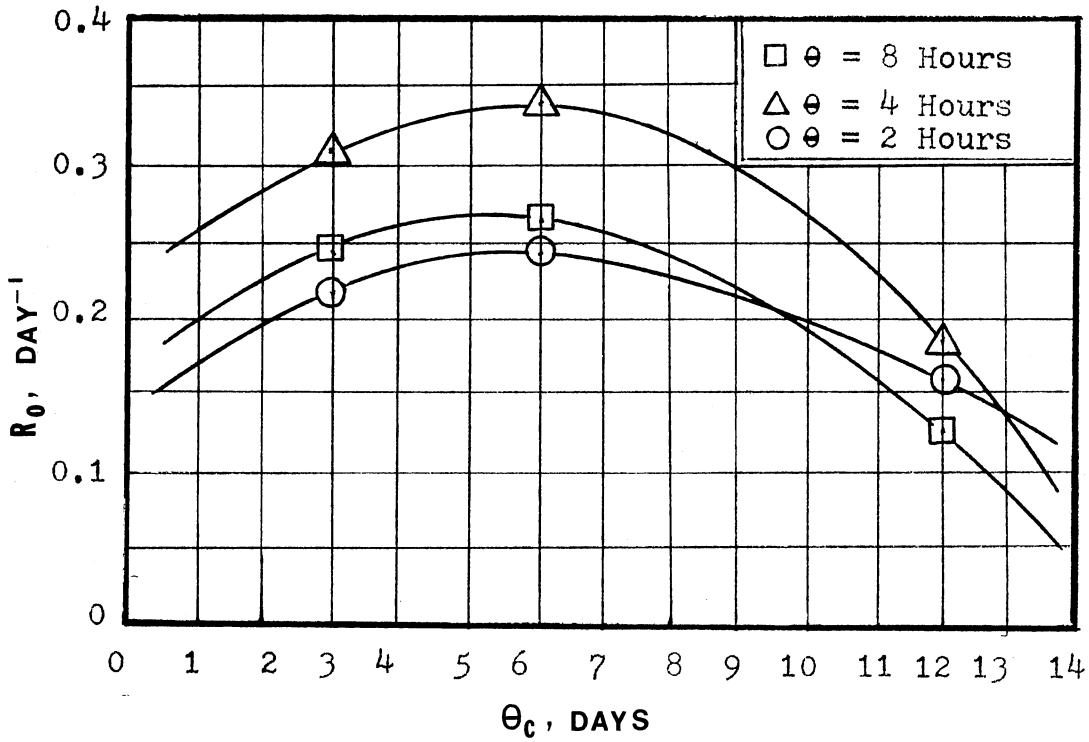

Figure 43. Relationship between Oxygen Uptake Rate R_o & Mean Cell Residence Time θ_c at Various Hydraulic Detention Time θ.

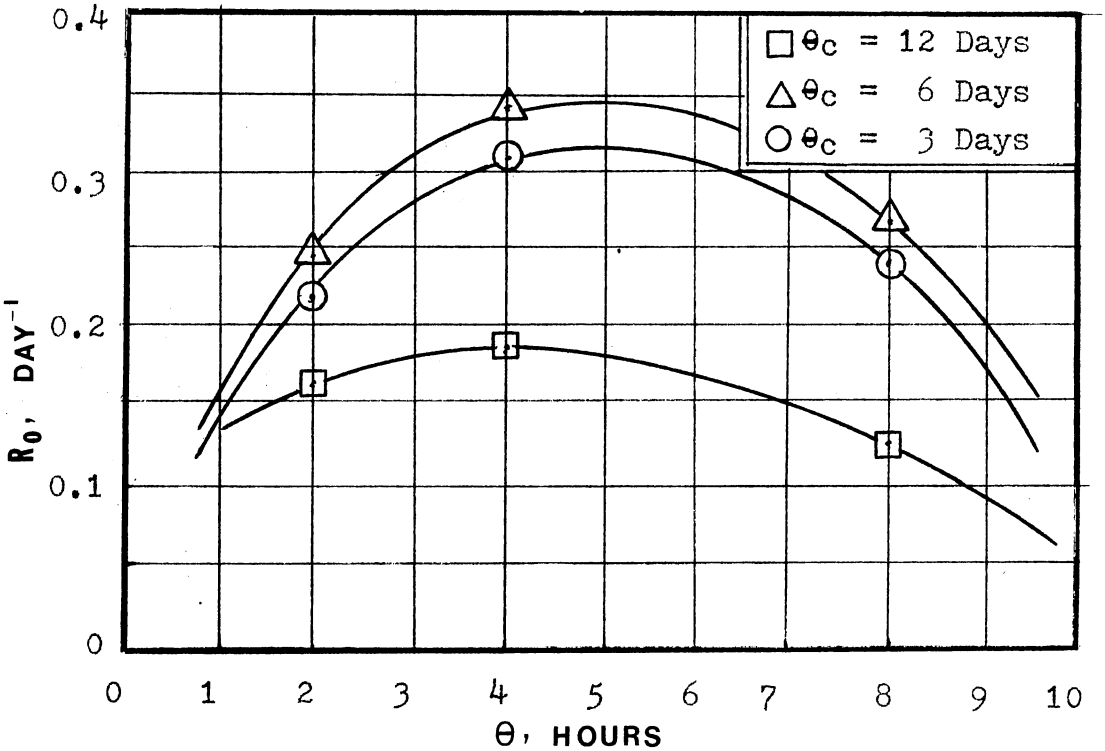

Figure 44. Relationship between Oxygen Uptake Rate R_o & Hydraulic Detention Time θ at Various Mean Cell Residence Time θ_c .

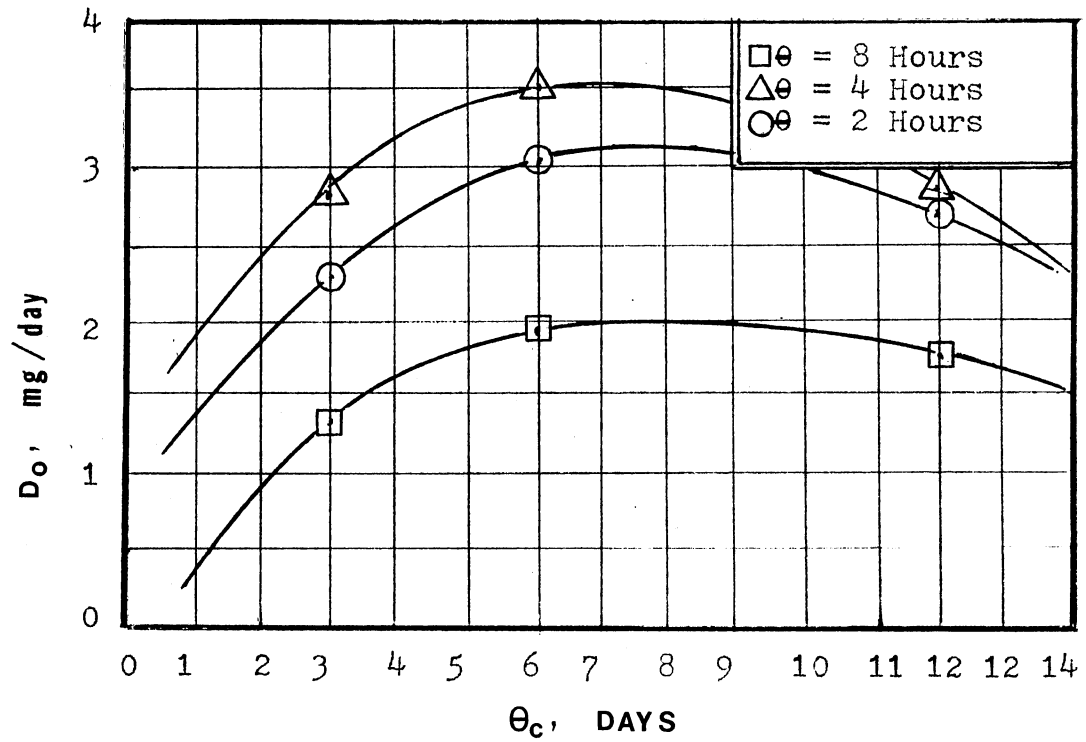

Figure 45. Relationship between Oxygen Demand D_o and Mean Cell Residence Time θ_c at Various Hydraulic Detentime Time θ.

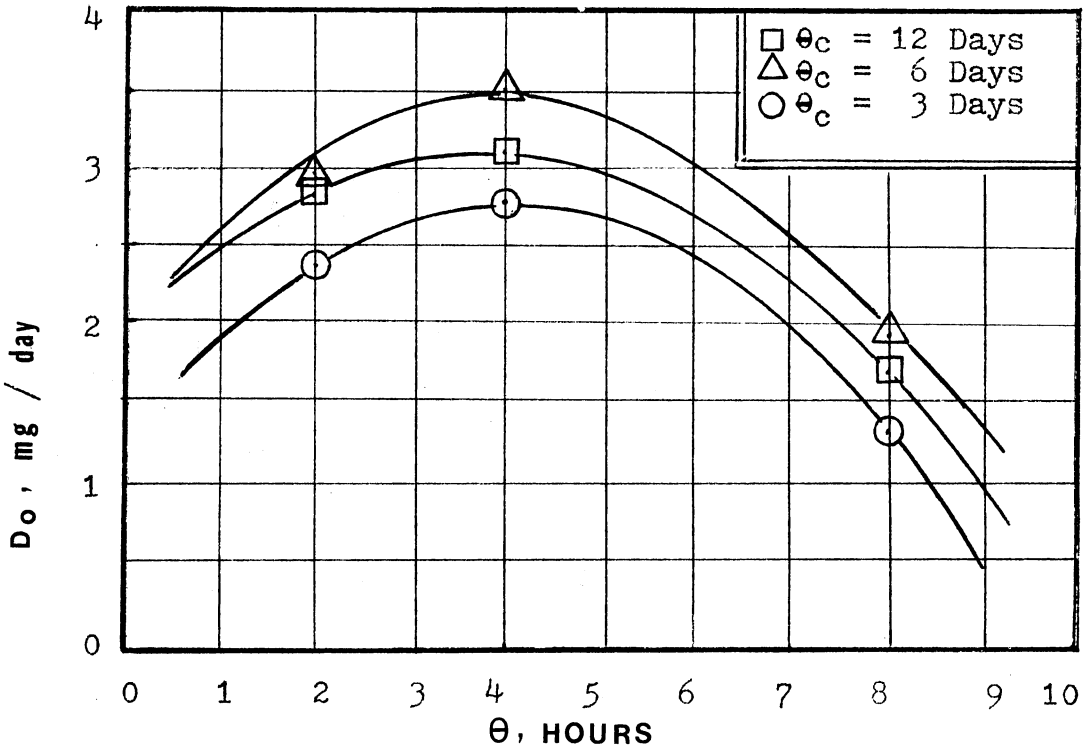

Figure 46. Relationship between Oxygen Demand D_o and Hydraulic Detention Time θ at Various Mean Cell Residence Time θ_c .

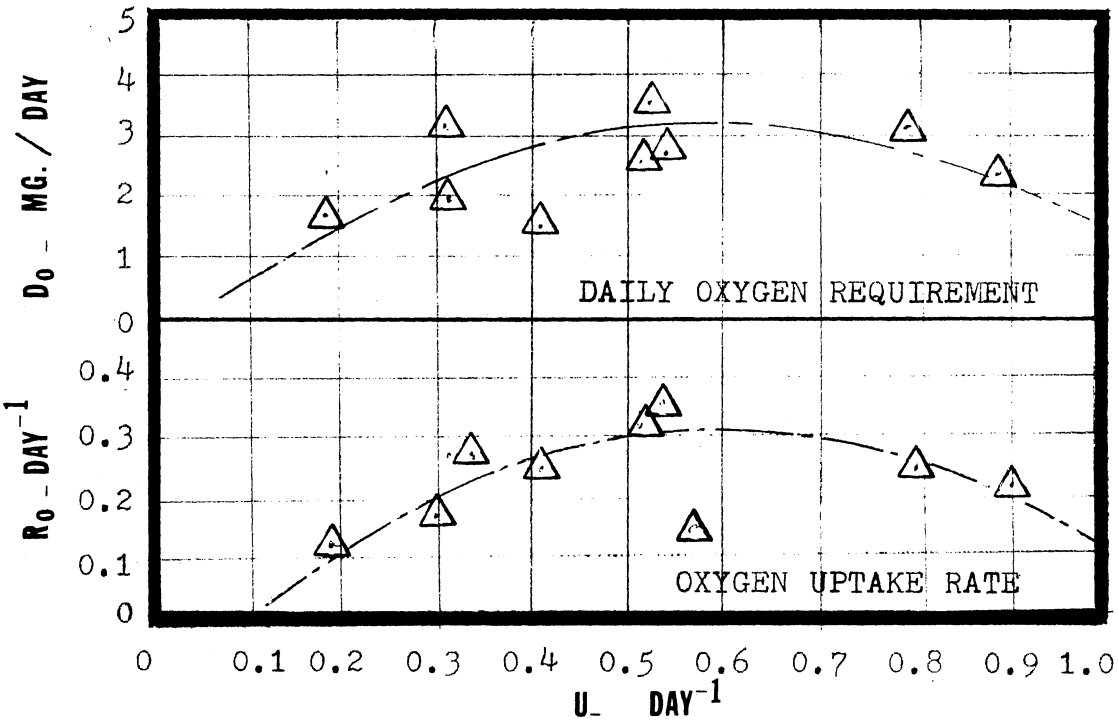

Figure 47. Relationship between Specific Utilization U & Oxygen Uptake Rate R_o with Oxygen Requirements D_o.

day/mg/l MLSS and 1.33 to 3.50 grams of O2/day, respectively. The optimum oxygen uptake rate and oxygen demand were found to be at U = 0.54 day^{-1},

E. Relationships between U and θ or θ_c

Figure 48 shows the relationship between U and θ_c, while Figure 49 relates the relationship between U and θ. As shown , both θ and θ_c excercised mutual influences on U. Figure 48 is in agreement with those presented by Sherrard, et al. (112 , 8).

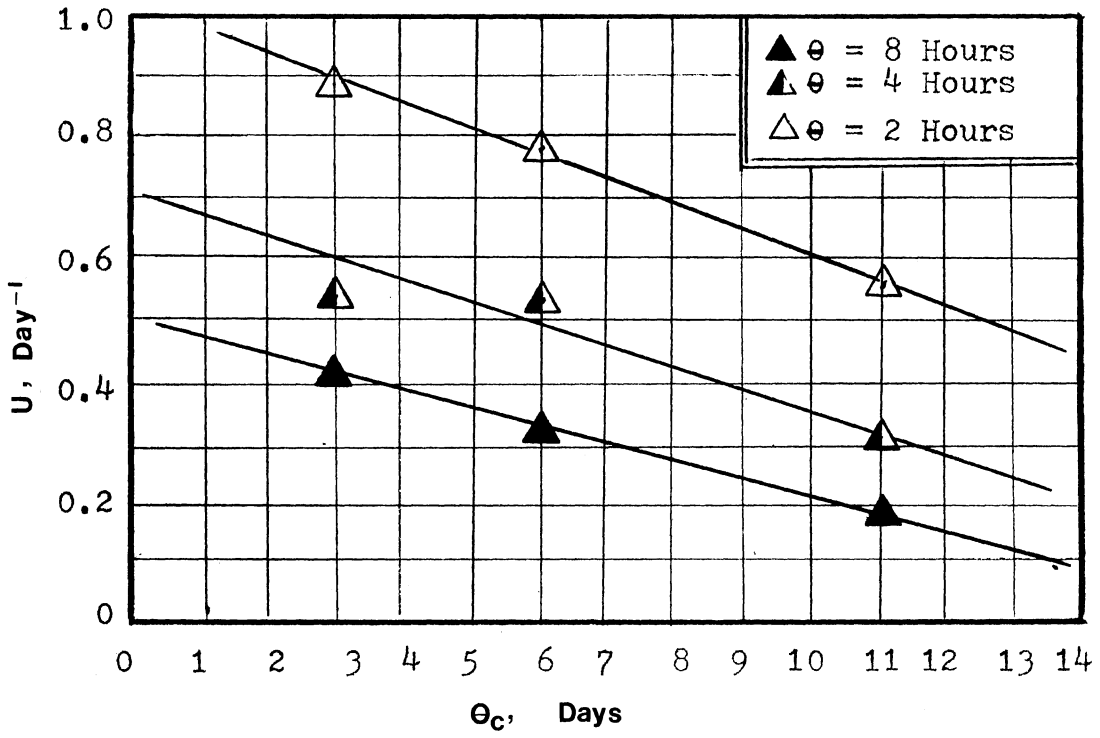

Figure 48. Relationship between Specific Utilization U & Mean Cell Residence Time θ_c at Various Hydraulic Detention Time θ.

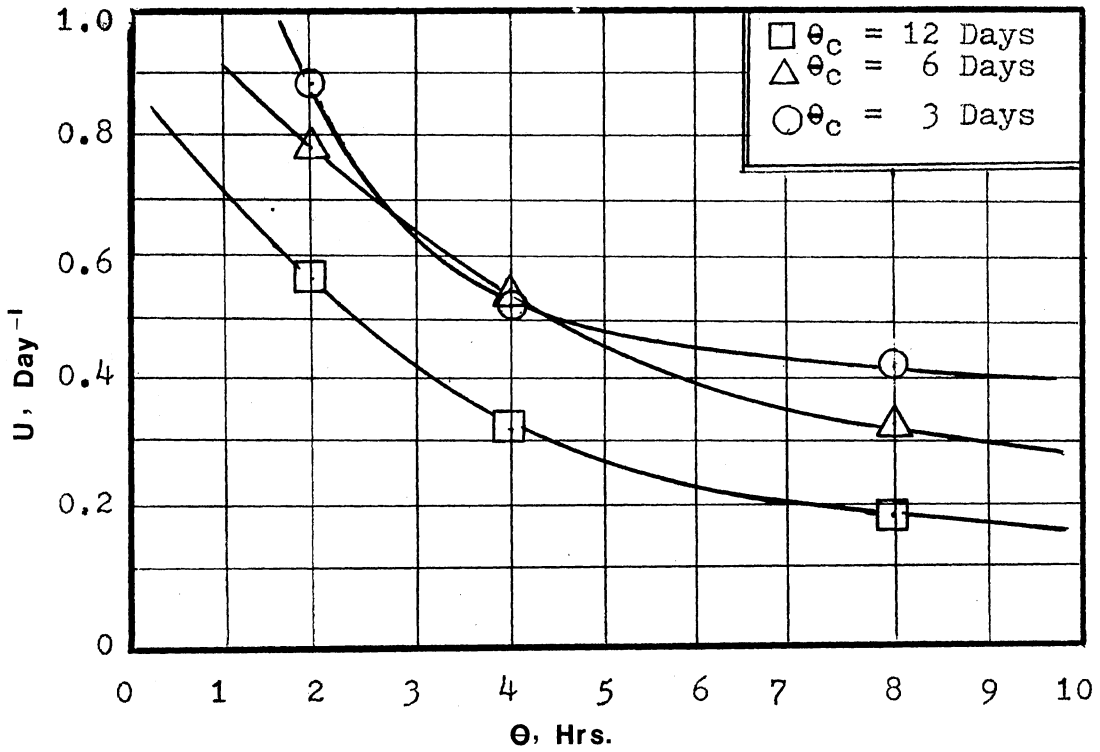

Figure 49. Relationship between Specific Utilization U & Hydraulic Detention Time θ at Various Mean Cell Residence Time θ_c.

CHAPTER V

DISCUSSION

The primary purpose of this investigation was to determine whether the hydraulic detention time is a primary functional factor for the design and operation of completely mixed activated sludge processes and, if not, to propose a actual functional parameter which would include the function of the θ.

From the results of this study, it is apparent that the hydraulic detention time did exercise a potential influence on the operational performance and other characteristics of CMAS processes just as other parameters used at present (such as θ_c, U, or F/M) do.

A. Evaluation of Effects of Parameters Used at Present on The Performance of Completely Mixed Activated Sludge Unit

Hydraulic detention time is refered to the contact time between the substrate and biological solids. A rapid reduction in biochemical oxygen demand (BOD) occurs during the first 30 minuites of the activated sludge treatment of wastewater. Soluble COD was reduced to a relatively stable level

after one hour of aeration. This phenomenon has long been noted (40, 41, 43, 58, 90). In this investigation, the efficiency of treatment was greater than 85 % for all hydraulic detention times in the range of 2 to 8 hours. An interesting result was found in this study in which the maximum efficiency did not occur at the highest hydraulic detention time (more than 6 hours) nor at the lowest hydraulic detention time (less than 3 hours). The maximum performance of purification for a completely mixed activated sludge system occurred at a medium hydraulic detention time. This phenomenon is quite in agreement with other studies (91, 115, 118, 119).

In this investigation, the optimum hydraulic detention time for maximum plant efficiency seem to be at a value between 3.5 to 5 hours, which agrees with that proposed by Metcalf, et al. (49) for design of CMAS processes. However, the maximum plant efficiency varied as a function of θ_c. In general, the maximum plant efficiency occurred when the system was operated at the above optimum θ along with a higher mean cell residence time. Figure 50 shows the suggested ranges of θ and θ_c required for the CMAS systems to perform with a COD removal efficiency of greater than 90 % and with a MLSS concentration smaller than 3,000 mg/l. The present regulations (1, 121) require that the hydraulic detention time for activated sludge plants be 6.0 hours for flows greater than 1.0 mgd and 7.5 hours for flows in the ranges of 0.2 to 0.8 mgd. It is not economical to require such a long detention time for the design of aeration systems. The above-reported

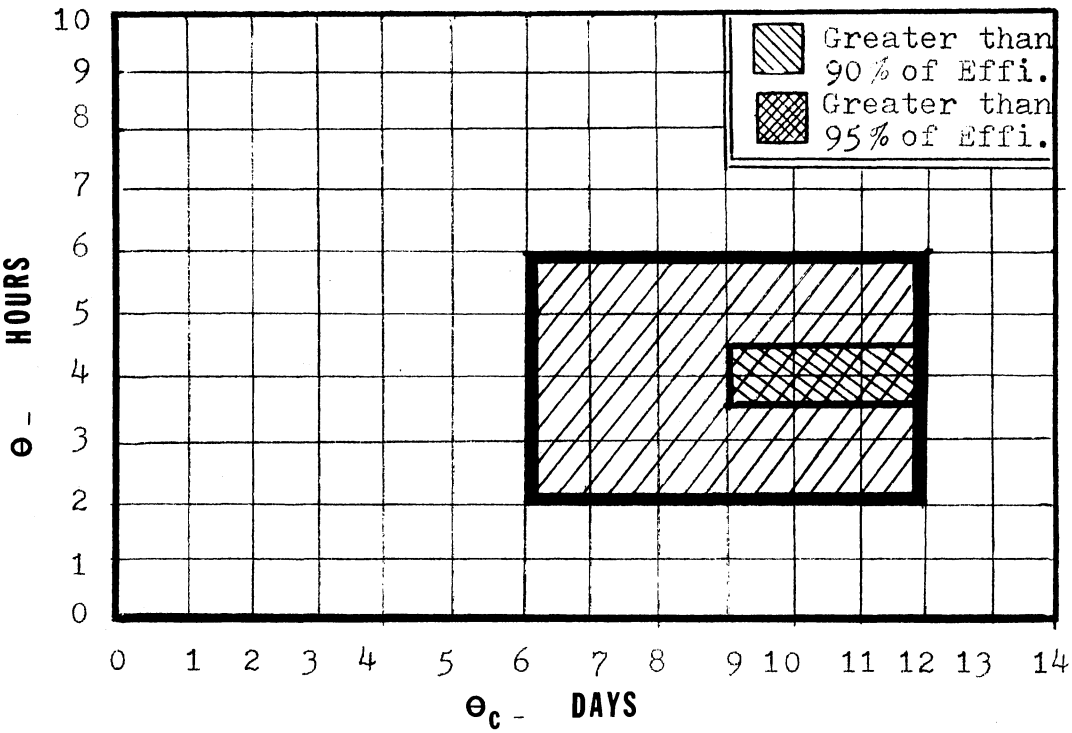

Figure 50. Suggested Ranges of Hydraulic Detention Time θ and Mean Cell Residence Time θ_c Required for A System to Perform with a COD Removal Efficiency of Greater than 90% and with A MLSS Concentration of Smaller than 3,000 mg/l for Minimum Sludge Production.

ranges, a high degree of treatment efficiency (97 % for a θ_c of 12 days, 91 % for a θ_c of 6 days, and 88 % for a θ_c of 3 days) would be generally achieved.

The relationship between percent COD removal and hydraulic detention time (Figure 17) was found to be dependent upon the mean cell residence time of microorganisms. For each particular mean cell residence time, there exists an optimum θ, beyond which no increase in efficiency can be expected. A small hydraulic detention time is equivalent to a system which is treating a large flow rate of wastewater or a large waste loading. When the food supply is greater than the

amount required for microbial energy maintenance and synthesis, the excess supply of food will be discharged in the effluent. The smaller the hydraulic detention time is held, the smaller the contact time between microorganisms and substrate will be. The greater the flow rate, a greater amount of excess food is discharged into the receiving water. However, for a longer period of hydraulic detention time, the supply food is reduced due to a smaller flow rate of wastewater. Thus a gigh degree of treatment can be expected due to high necessity of food and high ability of utilization. But when the hydraulic detention time is too long, the available food becomes critical because of substrate shortage. At this condition of shortage of food, a contest for food consumption would occur among different species of microorganisms. Thus a selection of predominances would happen. For those unable to successfully complete for the food, an endogeneous respiration stage will be continuously processed. Further shortage in food supply would cause some cells to die and release organic biomass into system due to biolysis of dead microorganisms. This is the reason why a further increase in θ from its optimum value did not increase the degree of treatment. At the optimum hydraulic detention time, the food supply rate is in equlibrium to absolute food utilization rate and the contact period is equal to the time required for metabolism of microorganisms. A maximum degree of treatment will thus result for a particular growth condition. The absolute food utilization rate is governed by growth rate of microorganisms

or by mean cell residence time. In general, the absolute food utilization rate decreases with the increase in rate of growth.

Figures 18, 19, 20, and 21 are presentations of the relationship of efficiency of stabilization, E, to specific utilization, U, and food-to-microorganisms ratio, F/M. These results agree with other studies (8). However, both θ and θ_c exercised their dual influences on the relationships between E and U or F/M. It is obvious that U or F/M can not be considered as a primary functional factor for the operational control of activated sludge processes.

Figure 30 shows the relationship between MLSS concentration and hydraulic detention time. In general, for a particular mean cell residence time, a linear relationship exists between MLSS concentration and θ. However, the MLSS concentration increases with the increase of θ_c for a particular θ. The results can be explanied in that a high rate of food supply produced a large concentration of MLSS in the reactor while a shortage of food supply caused a reduction in the MLSS concentration.

From Figure 30, it can be seen that the MLSS concentration at θ_c = 12 days is double that at θ_c = 3 days. Also the ratio of the increase in MLSS concentration to the decrease of θ (or the amount of food supply rate increase) is constant for each θ_c.

Figure 29 shows the effect of θ on the relationship between MLSS concentration and θ_c. The longer the MLSS are re-

tained in the system and greater the food supplu rate, the greater will be the MLSS concentration. This result is in agreement with the results presented by Sherrard, et al. (112). Both curves in Figures 29 and 30 can be used for the design and operation of a CMAS process to control or to determine the MLSS concentration level in such system. However , both θ and θ_c should be considered together if a accurate result is to be obtained.

Again, θ and θ_c exercised their influence on the relationship between MLSS concentration and U or F/M. It can be concluded that the control of MLSS by varying only the value of U or F/M is impossible without the accompanying varying of θ and θ_c (Figures 29 and 30).

An important result of this investigation found that Y_{max} and k_d varied as a function of θ. This finding is in well agreement with that reported by Ramanathan (60) and Hetling, et al. (86). These variations can be attributed to a species selection imposed on the system by the influence of the food supply rate (or equvalent to θ) (Figures 40, 41 and 42).

The hydraulic control of the CMAS process by means of θ_c has been widely recommended (49, 50, 52, 54). This method controls the MLSS level in the activated sludge process by maintaining a constant θ_c in the system. This concept is based upon the fact that for any given wastewater there is a direct relationship between θ_c and U (or F/M ratio) which can be mathematically expressed in the following equation:

$$1/\theta_c = UY_{max} - k_d \qquad (2.50)$$

However, this investigation has shown that Y_{max} and k_d are not constants. Y_{max} and k_d varied as a function of the hydraulic detention time (Figure 42). Thus, to maintain a constant mean cell residence time does not necessarily mean a constant loading factor, U or F/M value will be maintained for a particular situation. For example, in this investigation,

$Y_{max} = 0.870$, and $k_d = 0.083$, for θ = 8 hours

$Y_{max} = 0.588$, and $k_d = 0.252$, for θ = 2 hours

therefore,

$1/\theta_c = 0.870\ U - 0.083$ for θ = 8 hours

and $1/\theta_c = 0.588\ U - 0.252$ for θ = 2 hours

or

$$U = \frac{1/\theta_c + 0.083}{0.870} \quad \text{for } \theta = 8 \text{ hours}$$

$$U = \frac{1/\theta_c + 0.252}{0.588} \quad \text{for } \theta = 2 \text{ hours}$$

If the system is run at a constant θ_c of 12 days, the corresponding U will be 0.191 and 0.570 per day, respectively (the variance of these values is very large comparing to the acceptable range of COD loading factors from 0.30 to 0.90 day^{-1}).

From the above discussions, it can be concluded that, for the successful design and operational control of the CMAS process, it is not feasible to consider only θ_c or U (or F/M) as a functional parameter without taking into account the θ

of the system.

Results of this research suggest several concepts which are important to the control and design applications. Parameters which are used at present show that none of them (θ_c, θ, F/M, U, F/M/θ, and θX) can be used as a valid single functional parameter in the description of system performance without considering the mutual influences of each other.

Although X seems to be a good simple parameter for the evaluation of E as shown in Figures 26 and 27, it is not an engineering independent parameter, and there are many disadvantages for using X as a controlling parameter, such as: not valid to shock loadings, over emphasis on something that does not directly relate to effluent quality, and also does not consider the food-to-microorganisms ratio. Basically, the MLSS in reactor is influenced by θ and θ_c mutually.

Generally, in this investigation, θ, θ_c, and U seem to be three most correlated parameters for the design and control of the performance and other characteristics of CMAS systems. Therefore, a further investigation was needed to try to set up a functional combination factors for the successful description of the performance and other characteristics of such systems.

B. Development for a New Functional Combination Parameter

The CMAS systems are characterized by a feed-back process in which concentrated cell suspension from the final

settling tank is continuously returned to the aeration tank in order to maintain a high mixed liquor suspended solids concentration. A Schematical diagram is shown in Figure 51.

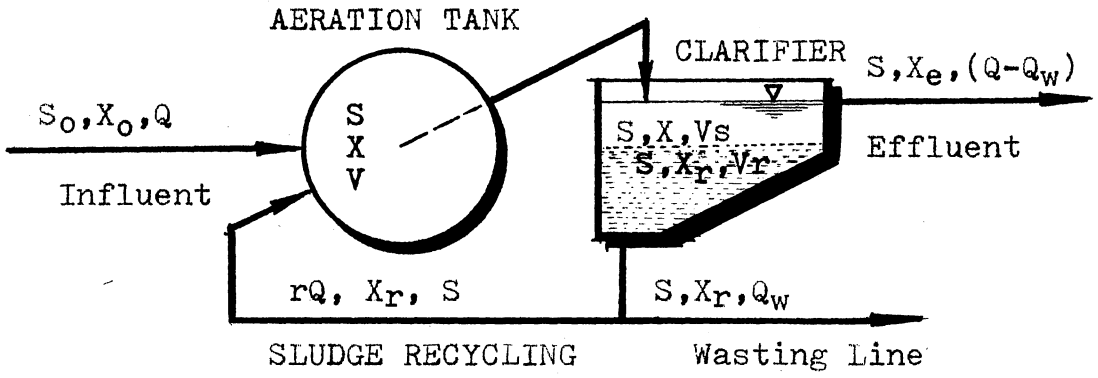

Figure 51. Schematic of A Completely Activated Sludge System with Cellular Recycle.

For developing equations in such a system, seven assumptions are made:

(a). the wastewater is biodegradable and non-toxic

(b). organic carbon sources act as the nutritional limiting substrate

(c). sufficient oxygen is supplied to the MLSS to maintain aerobic conditions in the aeration basin

(d). the volume used in calculation of the θ_c and θ for the system include only the volume of the aeration basin

(e). waste stabilization and microorganism growth occur

only in the aeration basin

(f). a ready settleable sludge is maintained in the process and the secondary clarifier is adequately designed, and

(g). the process is operating under steady state conditions.

The following notations will be used in the kinetic equations development:

R_g = net microbial growth rate

R_{su} = substrate utilization rate

Y_{obs} = variable observed yield coefficient

Y_{max} = true cell yield coefficient

Q = influent flow rate

Q_w = wasting sludge flow rate

S_o = influent substrate concentration

S = effluent substrate concentration

r = recycle flow ratio between the flow rate of recycle solids and flow rate of influent

V = volume of aeration rank

θ_c = mean cell residence time

X = steady state biological solids concentration in reactor

X_r = biological solids concentration in the recycle solids flow to the aeration tank in a CMAS process

X_e = biological solids concentration in effluent

θ = hydraulic detention time

k_d = cell decay coefficient

U = specific utilization

P_X = daily sludge production

E = efficiency of stabilization

X_o = biological solids concentration

Because both substrate utilization and microbial growth occur in the process, two stoichiometric relationships between net microbial growth and the amount of substrate are usually expressed as below:

$$R_g = - Y_{max} R_{su} - k_d X \qquad (2.5)$$

or $$R_g = - Y_{obs} R_{su} \qquad (2.6)$$

For this system the mean cell residence time is determined from:

$$\theta_c = VX[\ Q_w X_r + (Q - Q_w)\ X_e\ ]^{-1} \qquad (2.52)$$

and the sludge production

$$P_X = Q_w X_r + (Q - Q_w) X_e \qquad (5.1)$$

Combining Equations 2.52 and 5.1,

$$P_X = VX/\theta_c \qquad (2.53)$$

also

$$P_X = VR_g \qquad (5.2)$$

Combine Equation 2.5 and Equation 2.6 and use the definition of specific utilization

$$U = R_{su}/X \qquad (5.3)$$

to obtain the following equation for observed cell yield coefficient

$$Y_{obs} = Y_{max} - k_d / U \qquad (5.4)$$

A mass balance for the substrate utilization around the aeration basin can be expressed as:

$$QS_o + rQS + VR_{su} = (1+r)QS + V(dS/dt) \quad (5.5)$$

Under steady state conditions, Equation 5.5 reduces to

$$QS_o + rQS + VR_{su} = (1 + r)QS \quad (5.6)$$

Equation 5.6 can then be rearranged to give

$$VR_{su} = - Q(S_o - S) \quad (5.7)$$

Substitution of Equation 2.6, 2.53, and 5.2 into Equation 5.7 results in an expression that can be used to calculate needed effluent substrate concentration and waste sludge production.

$$VR_g = P_X = Y_{obs}Q(S_o - S) \quad (5.8)$$

or $$VX/\theta_c = Y_{obs}Q(S_o - S) \quad (5.9)$$

Rearrange Equation 5.9 to give a formulation for effluent substrate concentration:

$$S = S_o - (X/Y_{obs})(\theta/\theta_c) \quad (5.10)$$

A mass balance for the microbial growth in the aeration tank gives:

$$QX_o + rQX_r + VR_g = (1 + r)QX + V(dX/dt) \quad (5.11)$$

If it is assumed that microbial solids concentration in the influent is negligible, i.e., X_o is nearly equal to zero, and with the steady state conditions, Equation 5.11 can be simplified to give

$$VR_g = (1 + r)QX - rQX_r \quad (5.12)$$

or $$VR_g = (1 + r - rX_r/X)QX \quad (5.13)$$

By utilizing Equation 2.53, Equation 5.13 can be manipulated to yield

$$VR_g = P_X = VX/\theta_c = (1 + r - rX_r/X)QX \quad (5.14)$$

or simply

$$\theta/\theta_c = (1 + r - rX_r/X) \quad (5.15)$$

Solving Equation 5.15, the MLSS concentration can be determined from the following expression:

$$X = \frac{rX_r}{1 + r - (\theta/\theta_c)} \qquad (5.16)$$

The above equation describes that the MLSS concentration can be controlled by four engineering controlable factors, θ, θ_c, r, and X_r.

Substitution of Equation 5.16 into Equation 5.10 results in a expression that can be used to calculate effluent substrate concentration:

$$S = S_o - (\theta/\theta_c)(1/Y_{obs})[\ rX_r/(\ 1 + r - \theta/\theta_c\ )\ ] \qquad (5.17)$$

A further development of Equation 5.17, by utilizing Equation 5.4, gives a useful equation for the prediction of effluent substrate concentration:

$$S = S_o - (\theta/\theta_c)[\ Y_{max} - (k_d/U)]^{-1}[\ (rX_r)/(1 + r - \theta/\theta_c)\ ] \qquad (5.18)$$

For a particular wastewater, the influent substrate concentration is a funtion of θ, θ_c, r, and X_r.

Because the efficiency of treatment is defined as

$$E = (\ S_o - S\ )/S_o \times 100\% \qquad (3.1)$$

then

$$E = S_o^{-1}(\theta/\theta_c)[\ Y_{max} - (k_d/U)]^{-1}[\ (rX_r)/(\ 1 + r - \theta/\theta_c)] \qquad (5.19)$$

For a particular wastewater, the efficiency of treatment can be controlled by five engineering controllable functional factors: θ, θ_c, U, r, and X_r.

Daily sludge production is also expressed as

$$P_X = Q(\theta/\theta_c)[\ (rX_r)/(\ 1 + r - \theta/\theta_c\ )] \qquad (5.20)$$

or $$P_X = (V/\theta_c)[\ (rX_r)/(\ 1 + r - \theta/\theta_c\ )\ ] \qquad (5.21)$$

This shows that P_X is a function of θ. θ_c, r, and X_r.

A summary of the above-developed equations for the S, X, E, and P_X of a completely mixed activated sludge process with cellular recycle for a particular waste water are listed as follows:

$$S = S_o - (\theta/\theta_c)[\ Y_{max} - (k_d/U)]^{-1}[\ (rX_r)/(1 + r - \theta/\theta_c)] \qquad (5.18)$$

$$X = (rX_r)/(\ 1 + r - \theta/\theta_c) \qquad (5.16)$$

$$E = (S_o)^{-1}(\theta/\theta_c)[\ Y_{max} - (k_d/U)]^{-1}[\ (rX_r)/(1 + r - \theta/\theta_c)] \qquad (5.19)$$

$$P_X = (V/\theta_c)[\ (rX_r)/(\ 1 + r - \theta/\theta_c)\ ] \qquad (5.21)$$

or expressed in their function forms:

$$S = S(\ \theta/\theta_c,\ U,\ r,\ X_r\ ) \qquad (5.18\text{-}1)$$

$$X = X(\ \theta/\theta c,\ r,\ X_r\ ) \qquad (5.16\text{-}1)$$

$$E = E(\ \theta/\theta_c,\ U,\ r,\ X_r\ ) \qquad (5.19\text{-}1)$$

$$P_X = P_X\ (\ \theta,\ \theta_c,\ r,\ X_r\ ) \qquad (5.21\text{-}1)$$

If a CMAS system is operated at a constant ratio of return sludge flow rate and with a constant return sludge concentration, i.e., both r and X_r are maintained constant, the relationships will be simplified as:

$$S = S(\ \theta/\theta_c,\ U\ ) \qquad (5.18\text{-}2)$$

$$X = X(\ \theta/\theta_c\ ) \qquad (5.16\text{-}2)$$

$$E = E(\ \theta/\theta_c,\ U\ ) \qquad (5.19\text{-}2)$$

$$P_X = P_X(\ \theta,\ \theta_c\ ) \qquad (5.21\text{-}2)$$

From the above development, it can be concluded that for

such a system,

(a). both θ and θ_c exercise an important influence on the performance of treatment, effluent substrate concentration, MLSS concentration in aeration tank, and sludge production,

(b). the ratio of hydraulic detention time and mean cell residence time could be utilized as a functional parameter along with the specific utilization, and

(c). another combination parameter, i.e., $U(\theta/\theta_c)$, could be developed as a "sole" functional parameter for the design and operational control of the activated sludge process.

The term $U(\theta/\theta_c)$ is defined as "Food-Microorganisms-Contact-Coefficient", while the other term (θ/θ_c) is called "Food-Microorganisms-Contact-Time-Ratio".

C. Evaluation of New Combination Parameters, (θ/θ_c) and $U(\theta/\theta_c)$

In this research, as mentioned before, for a internal cell recycling laboratory activated sludge system, an important hypothesis has been made that when the settled sludge level is held or approaches automatically to a constant height in the settling tank, the sludge recirculation characteristics is identical. Thus, a constant recycle sludge concentration and constant ratio of recycling sludge flowrate were obtained, because in this research a constant sludge level in settling tank was under close control at steady state.

This hypothesis simplified the following evaluation.

A summary of the effect of (θ/θ_c) and $U(\theta/\theta_c)$ on the S, E, X, P_x, Y_{obs}, R_o, and D_o is listed in Table III.

TABLE III

SUMMARY OF STEADY STATE PERFORMANCE DATA

θ_c	θ	E	X	P_x	Y_{obs}	R_o	D_o	(θ/θ_c)	$U(\theta/\theta_c)$
1	2	3	4	5	6	7	8	9	10
12	2	91.9	4300	1580	0.150	0.15	2.87	0.167	0.0925
12	4	97.6	3880	1426	0.273	0.18	3.03	0.334	0.1019
12	8	90.6	3098	1139	0.442	0.12	1.68	0.667	0.1261
6	8	87.6	1654	1216	0.519	0.26	1.91	1.334	0.4295
6	4	90.8	2362	1736	0.319	0.34	3.50	0.667	0.3488
6	2	90.3	2730	2006	0.216	0.25	2.99	0.334	0.2585
3	2	86.4	2415	3550	0.378	0.22	2.29	0.667	0.5883
3	4	88.4	2058	3026	0.644	0.31	2.79	1.334	0.6910
3	8	85.1	1248	1835	0.810	0.24	1.33	2.667	1.0960

UNITS: 1 = days, 2 = hours, 3 = %, 4 = mg/l, 5 = mg/day,
6 = mg/l/mg/l, 7 = mg/l O_2 /day/ mg/l MLSS,
8 = grams O_2 /day, 9 = hours/day, 10 = hours/day/day.

An evaluation of the relationship between E and $U(\theta/\theta_c)$ is presented in Figures 52 and 53. Results seem to be excellent. These plots show that the removal efficiency is a direct function of $U(\theta/\theta_c)$. When the food-microorganisms-Contact-coefficient decreases, the removal efficiency increa-

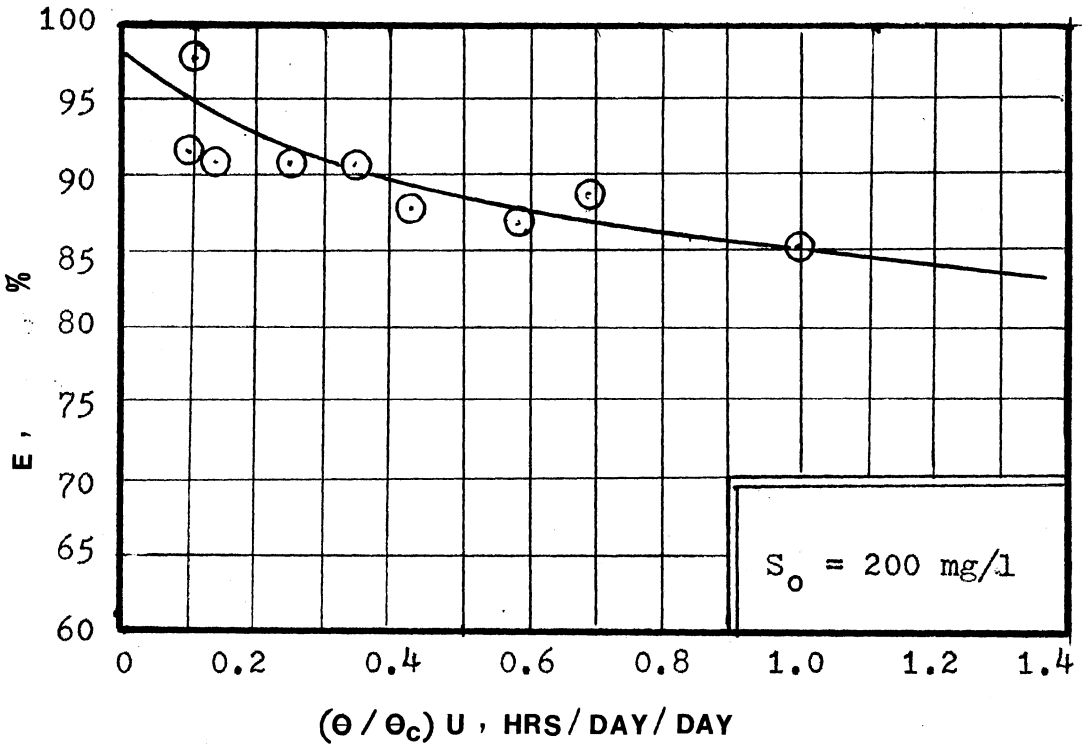

Figure 52. Relationship between Treatment Efficiency E and the Food-Microorganisms-Contact-Coefficient $(\theta/\theta_c)U$ Plotted on Regular Paper.

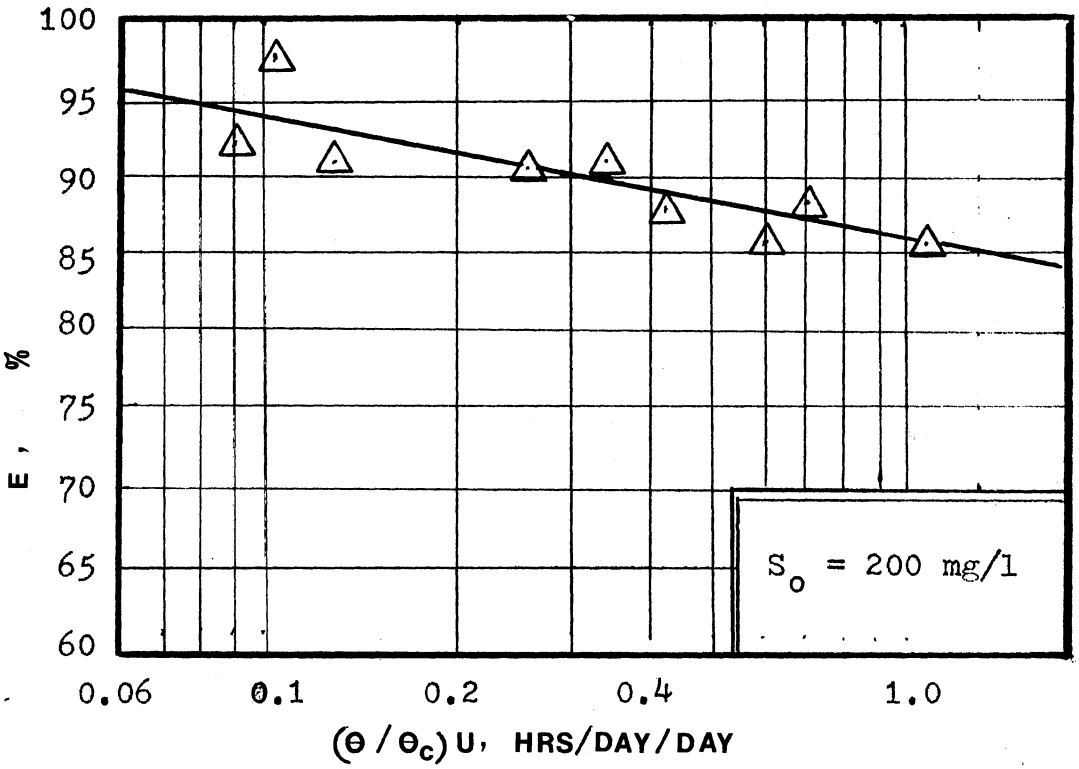

Figure 53. Relationship between Treatment Efficiency E and the Food-Microorganisms-Contact-Coefficient $(\theta/\theta_c)U$ Plotted on Semilogarithmic Paper.

ses correspondingly. In this research, the food-microorganisms-contact-coefficient falls within the range of 0.09 to 1.10 hours/day/day which is equivalent to a condition of θ_c = 12 days with θ = 2 hours and θ_c = 3 days with θ = 8 hours, respectively. For a process achieves a 90% treatment efficiency a $U(\theta/\theta_c)$ coefficient value not greater than 0.30 hours/day/day should be maintained.

Figures 54 and 55 show the relationship between the efficiency of treatment and the food-microorganisms-contact-time ratio, (θ/θ_c). A good correlation was found in Figure 55, although the relationship is not as good as that for $U(\theta/\theta_c)$. For the normal ranges of θ and θ_c which are 2 - 8 hours, and 6 - 15 days, respectively, the effluent can be predicted from such plot as 85 - 97% for different combinations of θ and θ_c. It seems to be fairly simple to use the (θ/θ_c) ratio as a easy method for treatment plant operation. For a process which requires a minimum of 90% treatment efficiency, a critical value of (θ/θ_c) ratio equal to 0.77 hours/day is required.

Shown in Figures 56 and 57 are evaluations of the relationship between MLSS concentration and the $U(\theta/\theta_c)$ coefficient. A first order relationship is obtained as shown in Fig. 57. The MLSS concentration is shown to be a direct function of the $U(\theta/\theta_c)$ coefficient. High $U(\theta/\theta_c)$ values are equivalent to high MLSS concentration. As the value of $U(\theta/\theta_c)$ decreases, MLSS concentration decreases. For a system to be maintained at a MLSS concentration lower than 3,000 mg/l, the

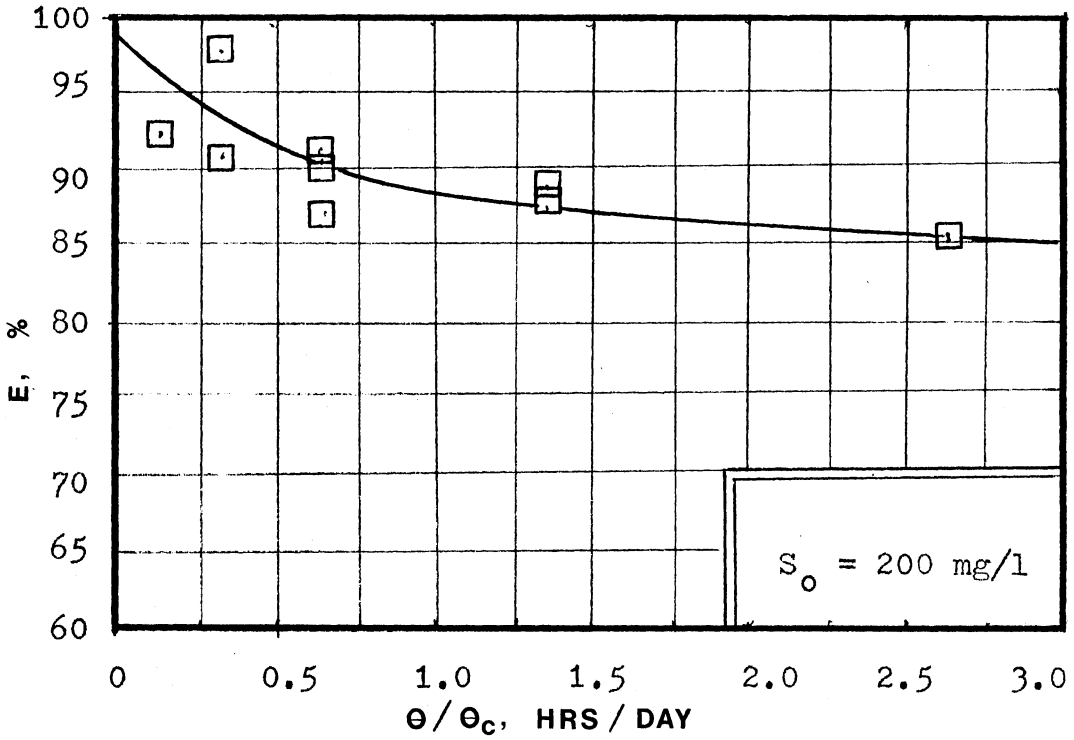

Figure 54. Relationship between Treatment Efficiency E and Food-Microorganisms-Contact-Time-Ratio (θ/θ_c) Plotted on Regular Paper.

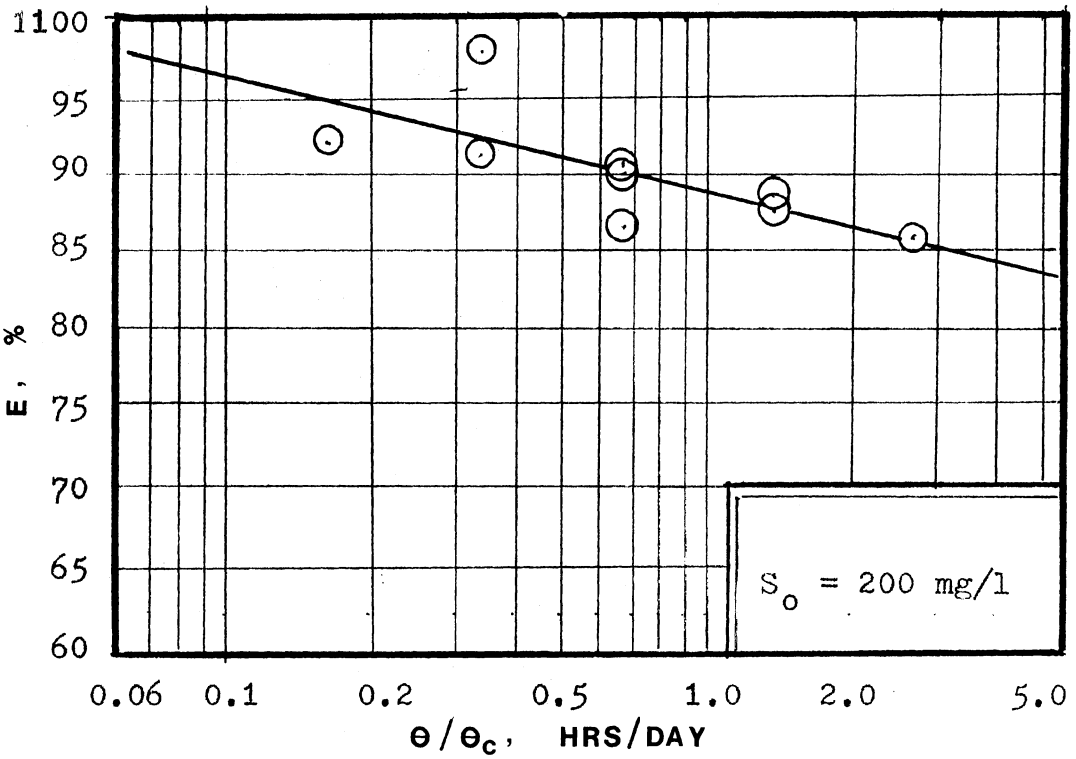

Figure 55. Relationship between Treatment Efficiency E and Food-Microorganisms-Contact-Time-Ratio (θ/θ_c) Plotted on Semilogarithmic Paper.

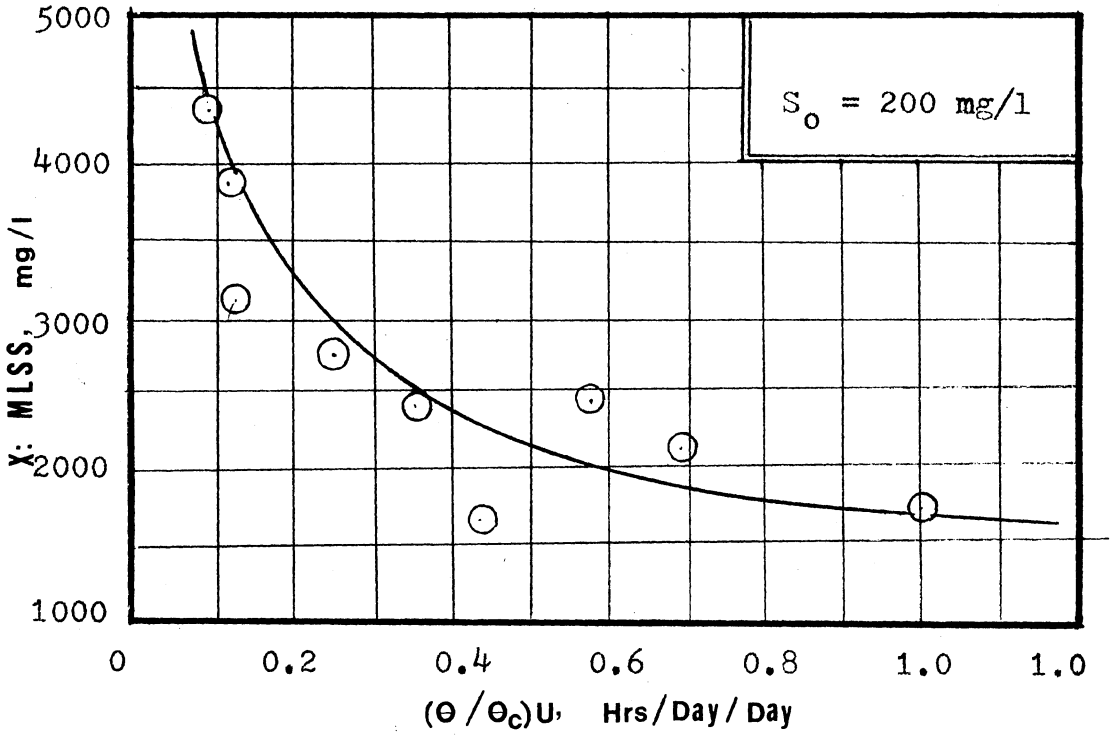

Figure 56. Relationship between MLSS X and Food-Microorganisms-Contact Coefficient $(\theta/\theta_c)U$ Plotted on Regular Paper.

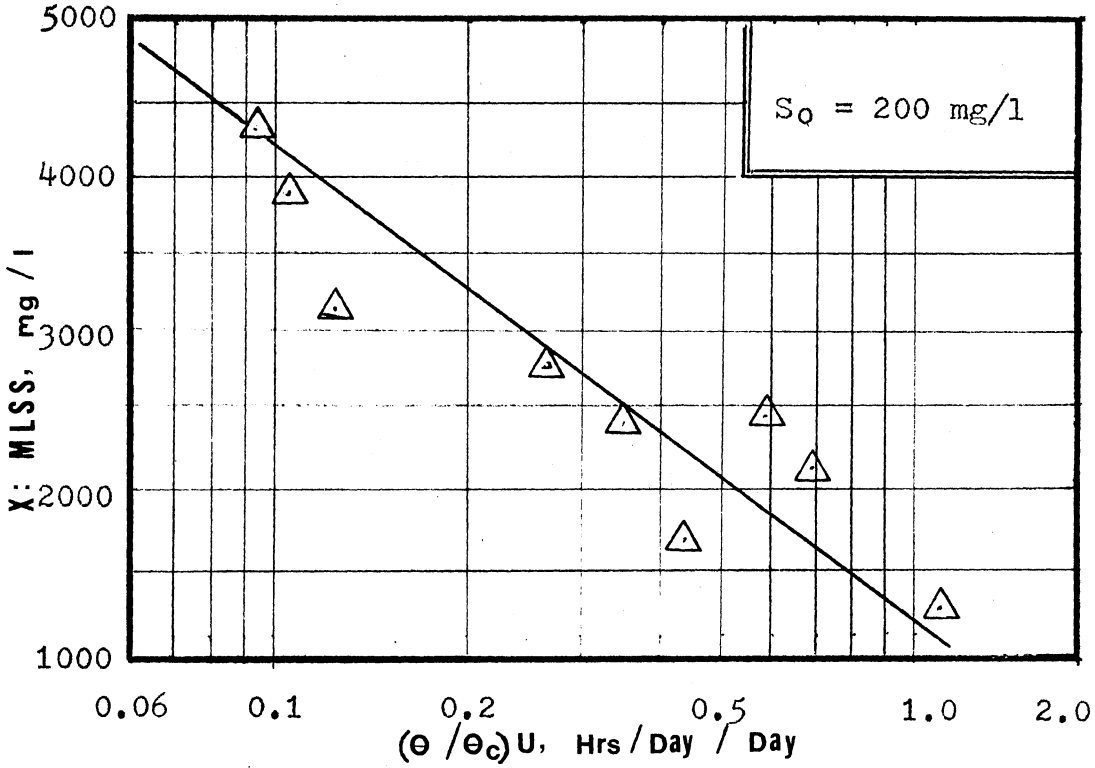

Figure 57. Relationship between MLSS X and Food-Microorganisms-Contact Coefficient $(\theta/\theta_c)U$ Plotted on Semilogarithmic Paper.

equivalent critical value of $U(\theta/\theta_c)$ will be greater than 0.24 hours/day/day.

A very good relationship between MLSS concentration and (θ/θ_c) ratio is shown in Figures 58, and 59. It reveals that the (θ/θ_c) ratio can be used as a fast-easily-controlled functional parameter for the operation of completely mixed activated sludge processes.

Equations 5.21, 5.21-1 and 5.21-2 indicate that (θ/θ_c) and $U(\theta/\theta_c)$ are not direct controlling parameters for predicting daily sludge production. This conclusion is also shown in Figures 60 and 61. Those two similar plots with obvious indications show that θ and θ_c should be considered separately for the predicting of daily sludge production.

Another method to predict sludge production is determination of unit-weight-basis sludge production or the observed cell yield coefficient. The relationship between Y'_{obs} and parameters (θ/θ_c) amd $U(\theta/\theta_c)$ were evaluated in Figures 62, 63, 64, and 65. The (θ/θ_c) ratio seems to be an excellent parameter for the prediction of Y_{obs} or unit-weight-basis sludge production.

Figure 66, 67, 68, and 69 represent the variation of R_o and D_o as a function of (θ/θ_c) and $U(\theta/\theta_c)$, respectively. In general, R_o increases when (θ/θ_c) or $U(\theta/\theta_c)$ increase, and D_o decreases with the increase of (θ/θ_c) or $U(\theta/\theta_c)$.

Generally, from the above evaluations, both (θ/θ_c) and $U(\theta/\theta_c)$ seem to have possibilities as a functional design and operation parameters for the CMAS processes. Although $U(\theta/\theta_c)$ shows better a relationship than (θ/θ_c), both of them show

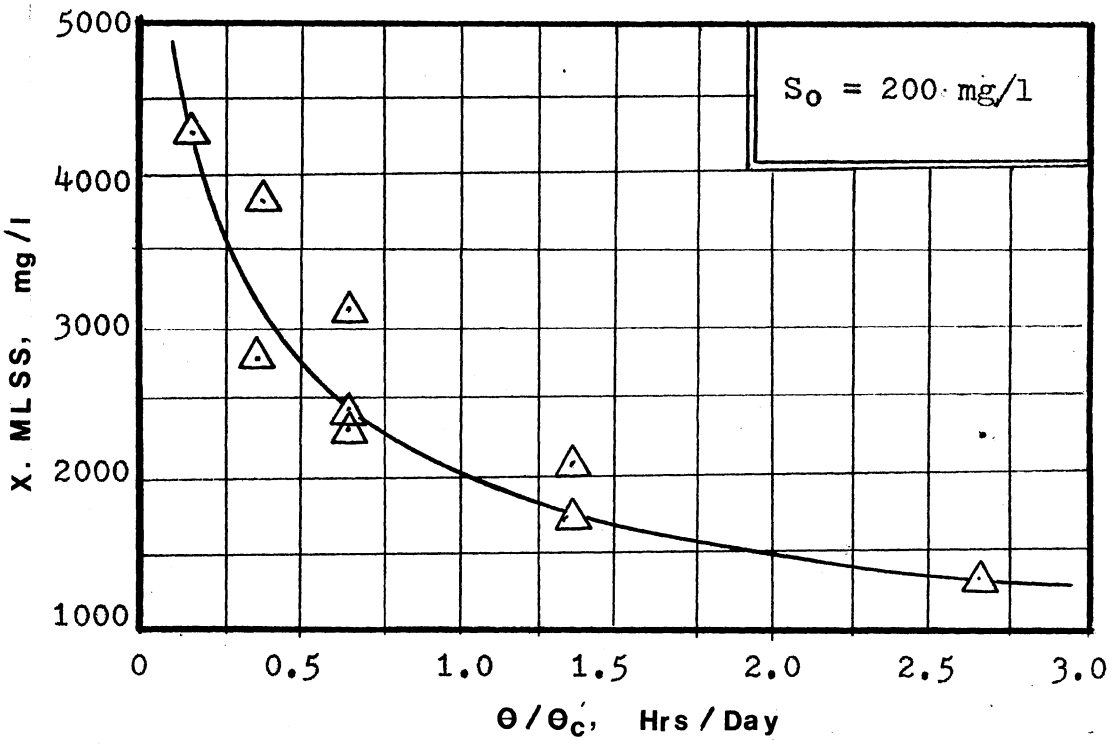

Figure 58. Relationship between MLSS X and Food-Microorganisms-Contact-Time-Ratio (θ/θ_c) Plotted on Regular Paper.

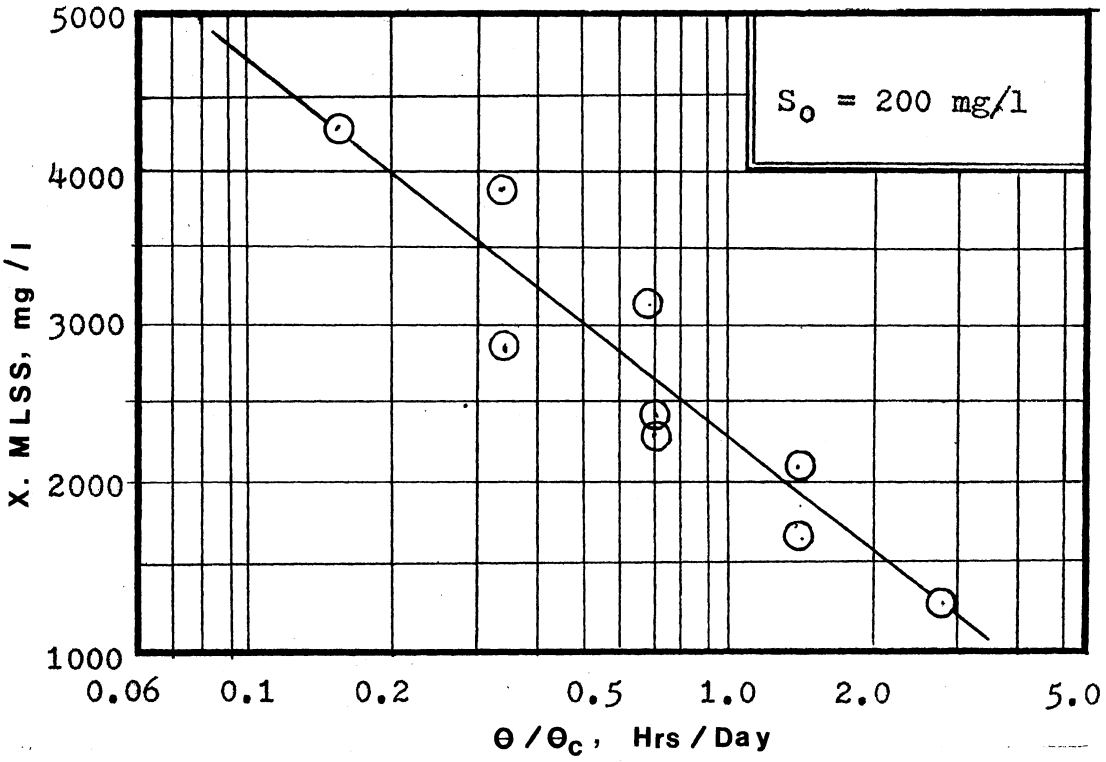

Figure 59. Relationship between MLSS X and Food-Microorganisms-Contact-Time-Ratio (θ/θ_c) Plotted on Semilogarithmic Paper.

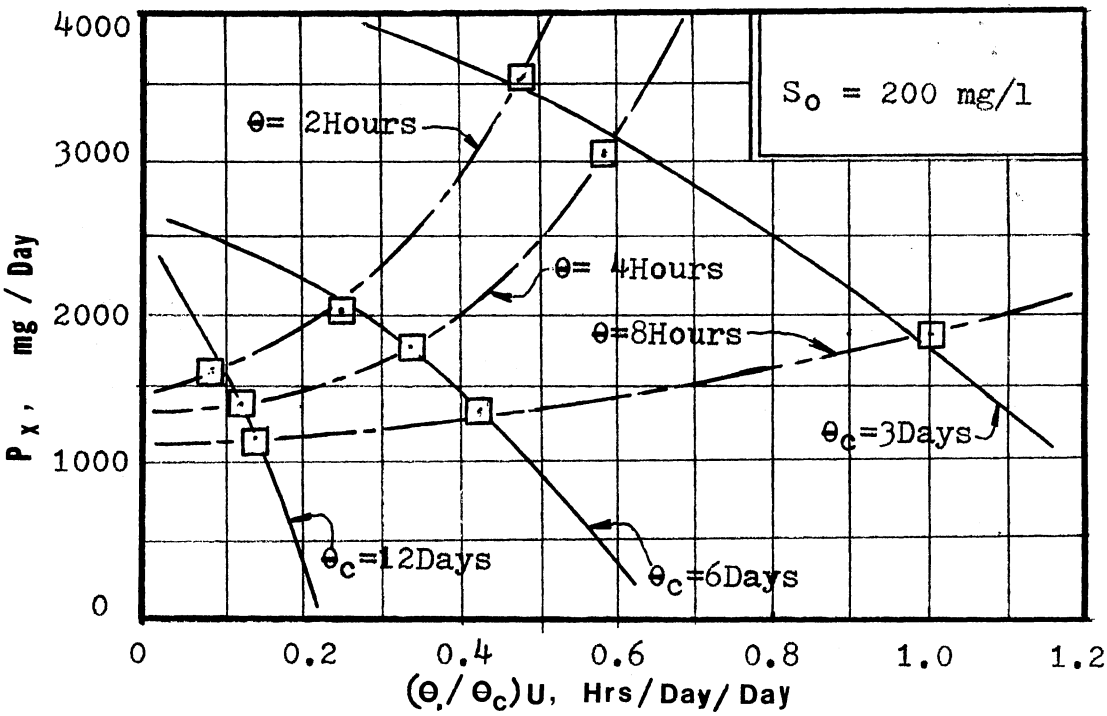

Figure 60. Relationship between Daily Sludge Production P_x and Food-Microorganisms-Contact-Coefficient $(\theta/\theta_c)U$.

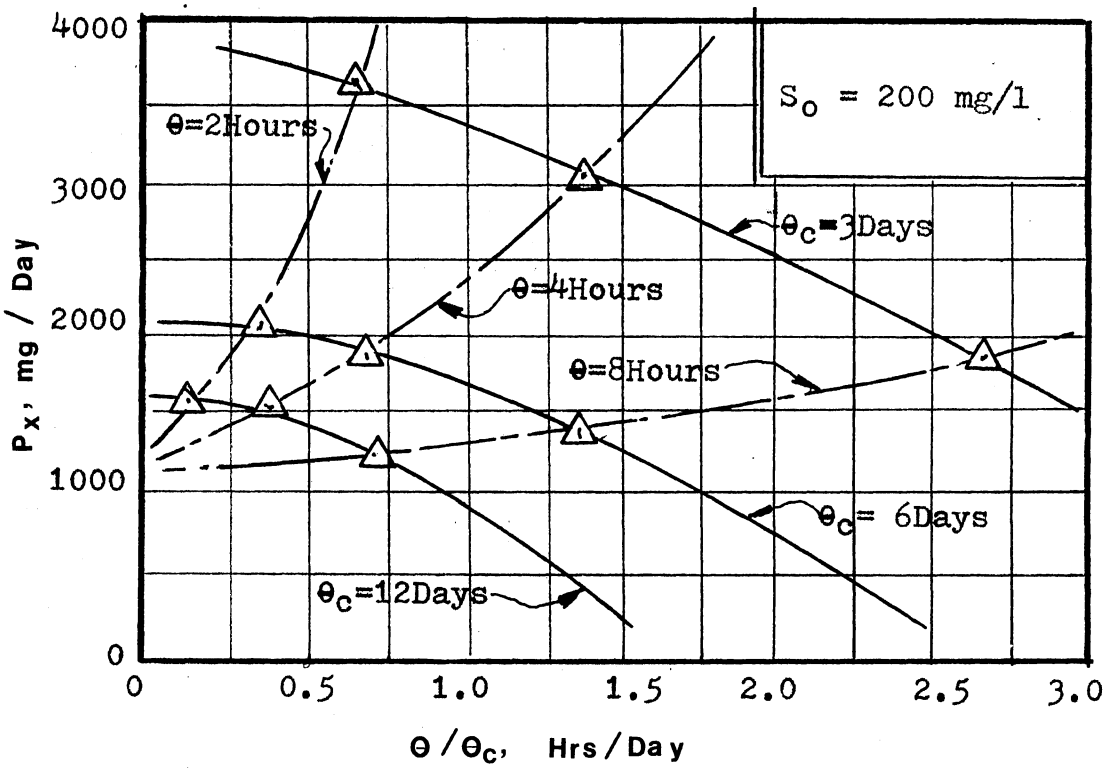

Figure 61. Relationship between Daily Sludge Production P_x and Food-Microorganisms-Contact-Time-Ratio (θ/θ_c).

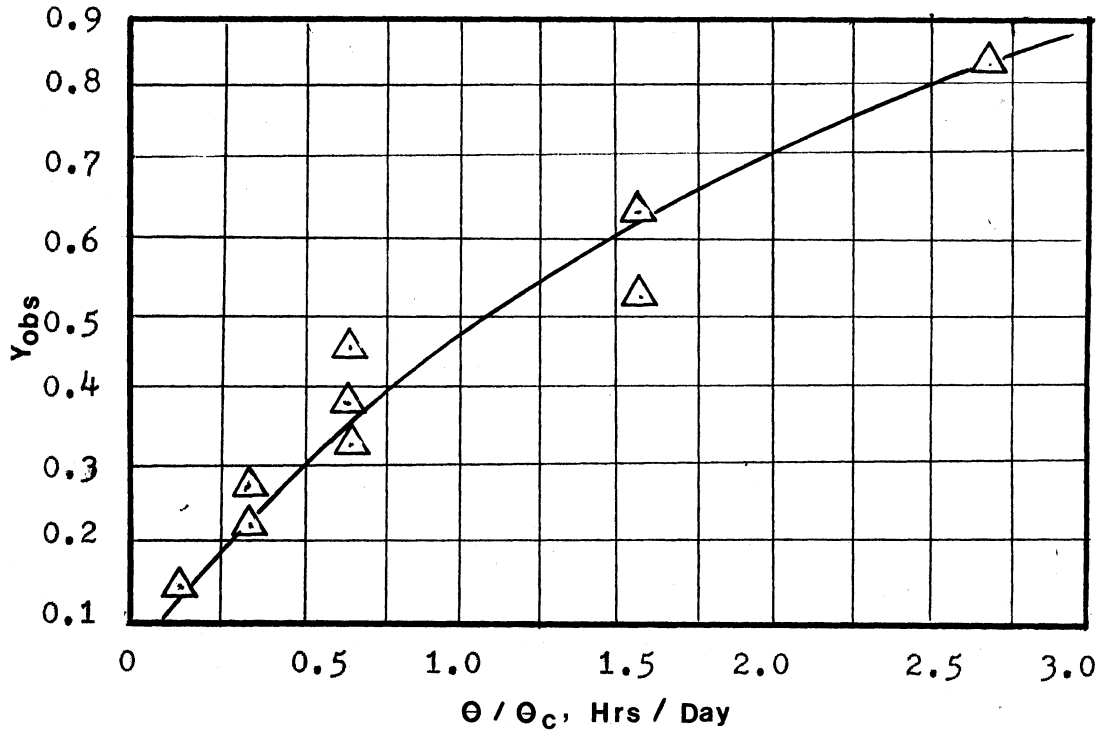

Figure 62. Relationship between Observed Cell Yield Y_{obs} and Food-Microorganisms-Contact-Time-Ratio (θ/θ_c) Plotted on Regular Paper.

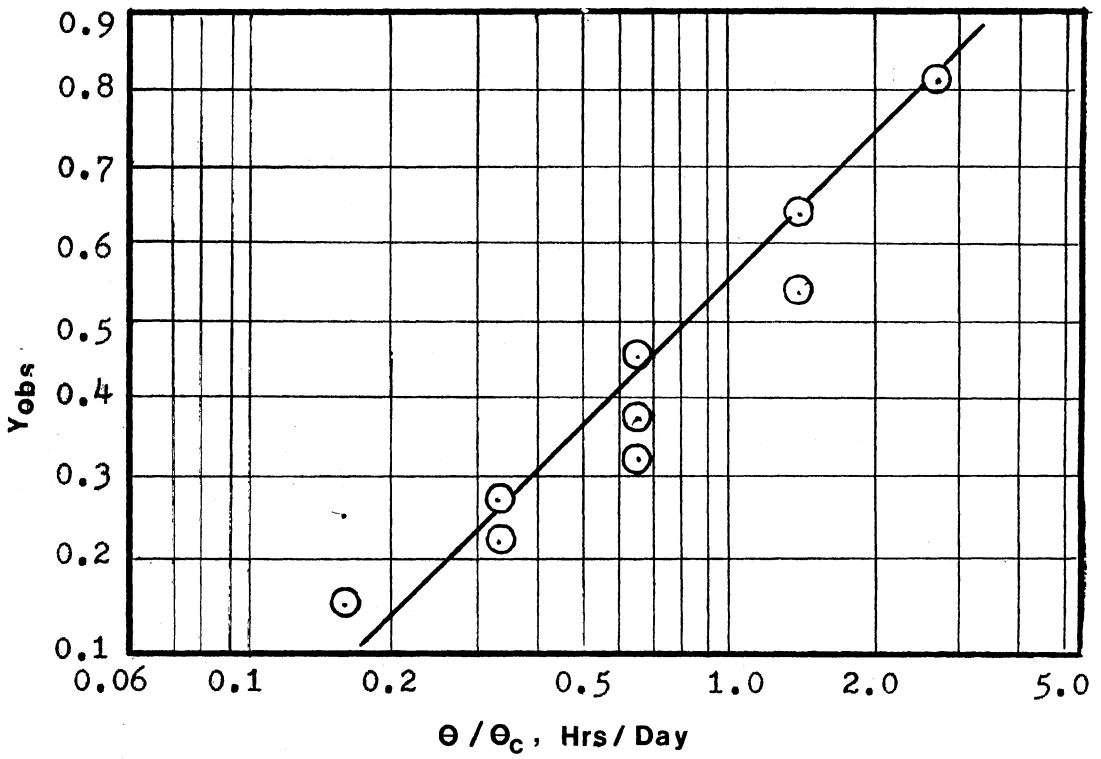

Figure 63. Relationship between Observed Cell Yield Y_{obs} and Food-Microorganisms-Contact-Time-Ratio (θ/θ_c) Plotted on Semilogarithmic Paper.

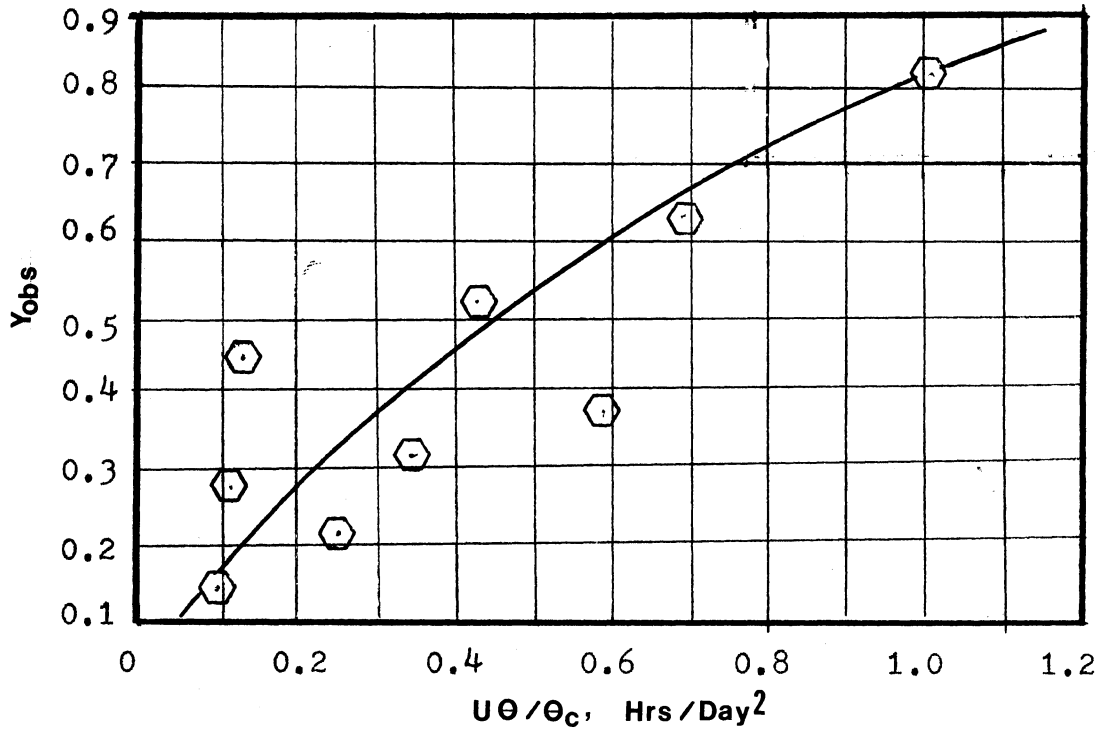

Figure 64. Relationship between Observed Cell Yield Y_{obs} and Food-Microorganisms-Contact-Coefficient $U\theta/\theta_c$ Plotted on Regular Paper.

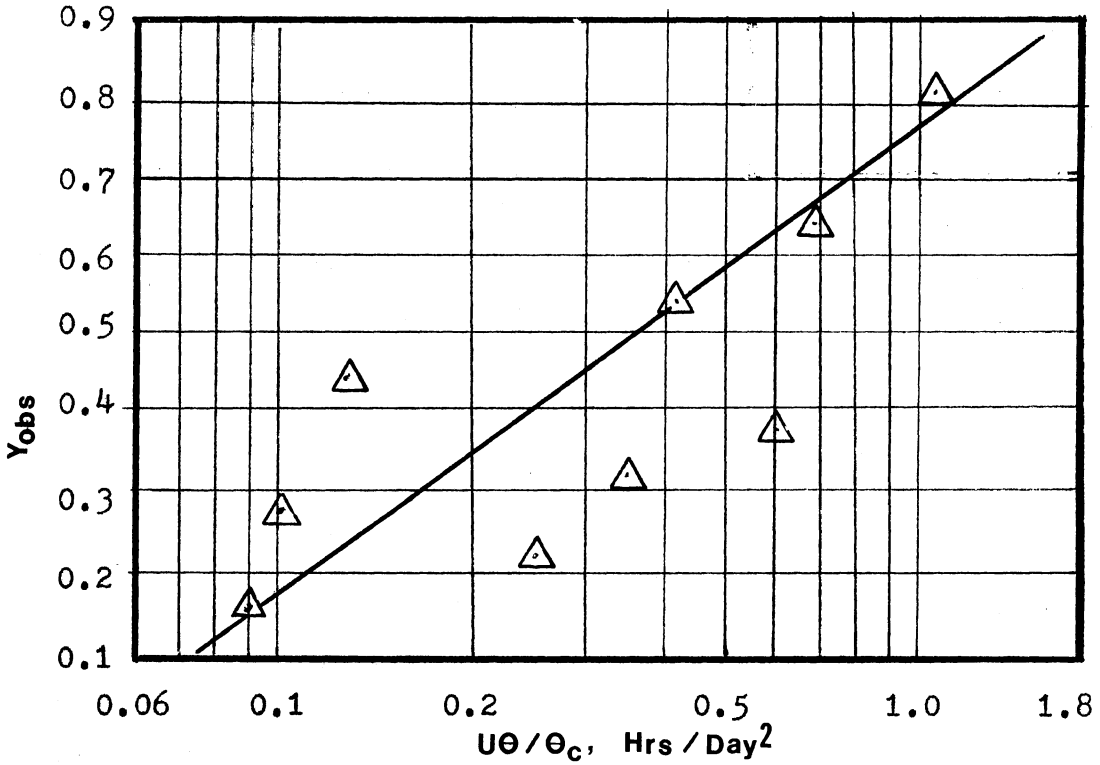

Figure 65. Relationship between Observed Cell Yield Y_{obs} and Food-Microorganisms-Contact-Coefficient $(\theta/\theta_c)U$ Plotted on Semilogarithmic Paper.

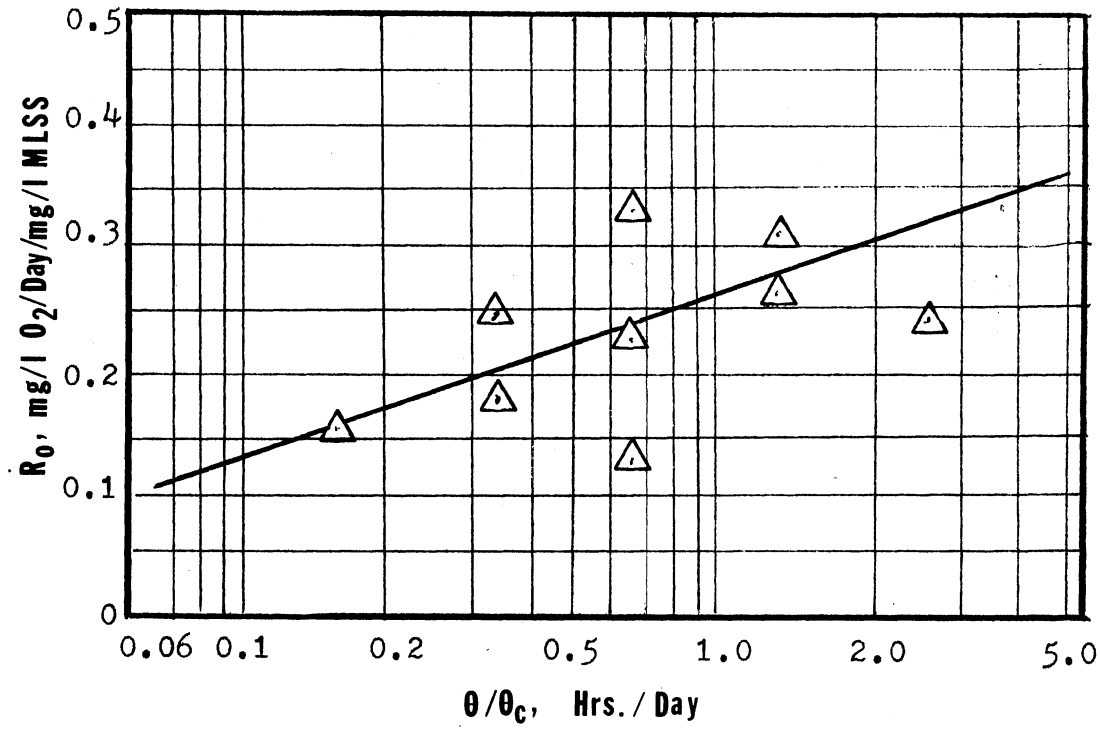

Figure 66. Relationship between Oxygen Uptake Rate R_o & Food-Microorganisms-Contact-Time-Ratio (θ/θ_c) Plotted on Semilogarithmic Paper.

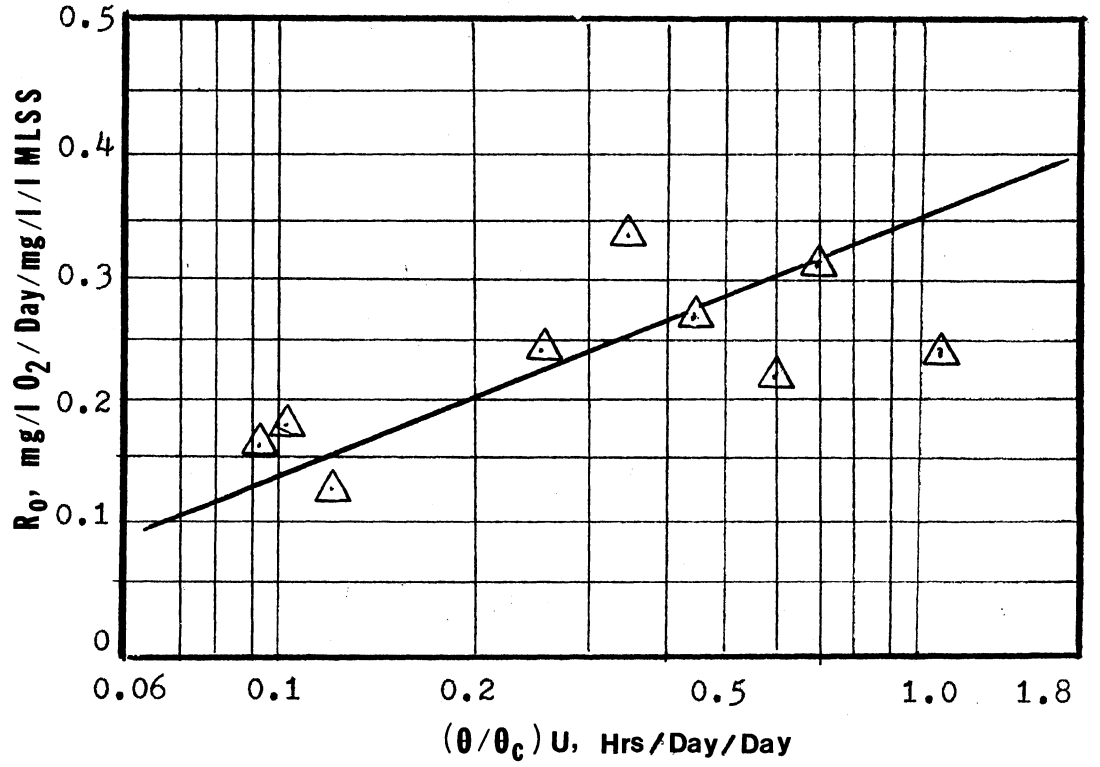

Figure 67. Relationship between Oxygen Uptake Rate R_o & Food-Microorganisms-Contact-Coefficient $(\theta/\theta_c)U$ Plotted on Semilogarithmic Paper.

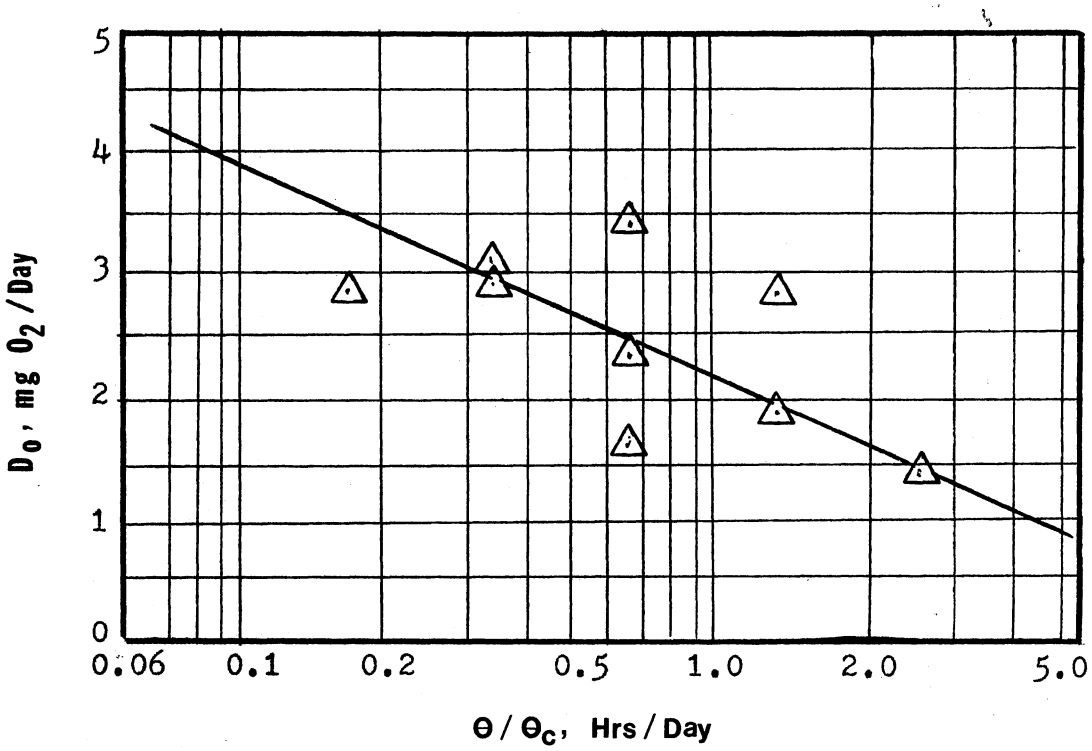

Figure 68. Relationship between Oxygen Demands D_o and Food-Microorganisms-Contact-Time-Ratio (θ/θ_c) Plotted on Semilogarithmic Paper.

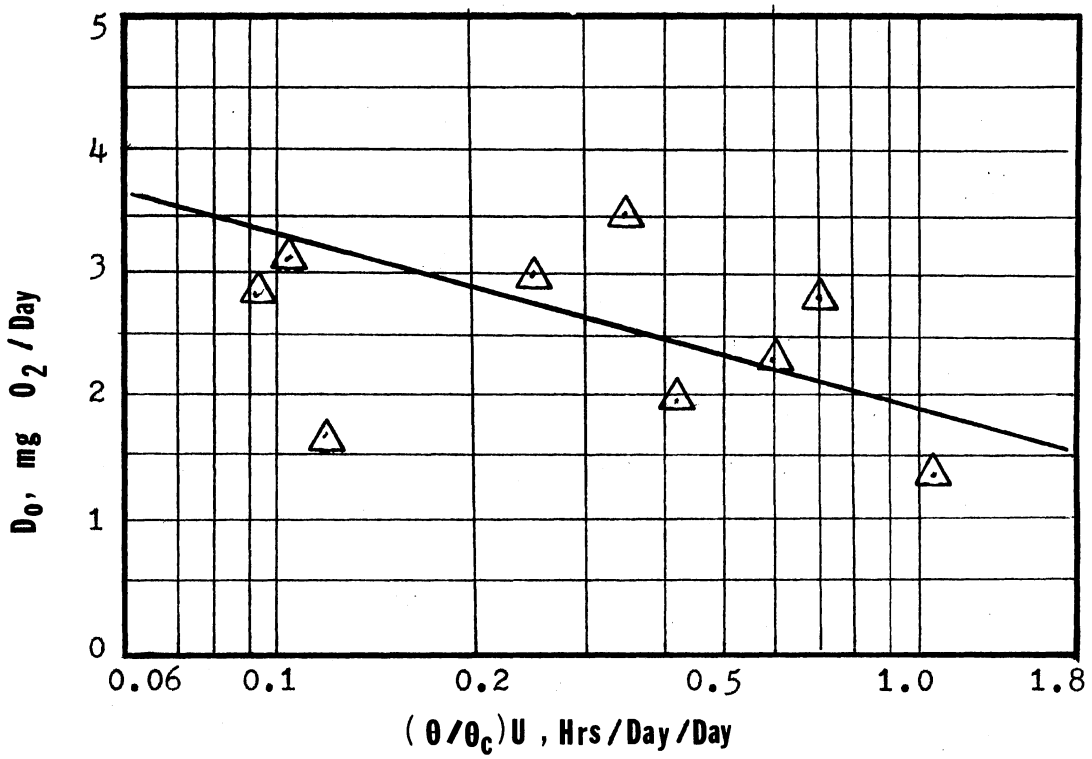

Figure 69. Relationship between Oxygen Demands D_o and Food-Microorganisms-Contact-Coefficient $(\theta/\theta_c)U$ Plotted on Semilogarithmic Paper.

advantages for process design and operation over those being used at present: such as mean cell residence time, constant MLSS concentration, constant F/M ratio or other approaches.

D. Applications of (θ/θ_c) and $U(\theta/\theta_c)$

Because $U(\theta/\theta_c)$ showed better correlation than (θ/θ_c) in the operational control of CMAS processes, the former is recommended as the best method, while the latter still seems to be able to act as a rapid and easy but less accurate method for the design and operational approaches for such processes.

1. Operation and Control Applications

(1). The (θ/θ_c) Method. In general, the present plants are those of hydraulic-detention-time-unadjustable types. Hydraulic detention time, θ, is thus a variable parameter depending upon the flow rate of wastewater. With the (θ/θ_c) method, the operator will need to operate his plant experimently at a particular r and X_r and at different combinations of θ and θ_c to determine the critical value of (θ/θ_c) which is required to achieve the treatment requirement. As soon as the relationship between treatment efficiency and the (θ/θ_c) ratio has been established, the operator can operate his plant at any desired treatment efficiency by increasing or decreasing the θ_c of the system in order to match an increase or decrease in the wastewater flow rate entering the plant.

With this method, is no need to adjust the recycling sludge flow rate or recycling sludge concentration, although

the control of the recycling flow and recycling sludge concentration can control the efficiency of treatment. By employing Equation 5.16, MLSS concentration can be predicted as soon as the corresponding θ_c is determined. For predicting P_x, either Equation 5.20 or 5.21 can be used.

(2). The $U(\theta/\theta_c)$ Method. With this method, the operator can use the same procedures as proposed before to operated his unit to set up a critical $U(\theta/\theta_c)$ value for a particular treatment performance. However, the operator also needs to pripare a plot of the relationship between Y_{max} with k_d and hydraulic detention time as shown in Figure 42. As soon as the desired efficiency of treatment is determined the operator can decide on the needed θ_c and U values for operation by determining the corresponding Y_{max} and k_d values equivalent to the θ of entering wastewater flow and by using Equation 2.50.

For example:

If k' is the critical $U(\theta/\theta_c)$ value to be maintained for the desired treatment efficiency which is found in a plot similar to Figure 53, and if Y_{max} and k_d are obtained from the already-prepared plot similar to Figure 42, then

$$U(\theta/\theta_c) = k' \qquad (5.22)$$

or $$U/\theta_c = k'/\theta = k'' \qquad (5.23)$$

and $$1/\theta_c = Y_{max}\, U - k_d \qquad (5.24)$$

Solving the above two equations, the needed value of θ_c or U can be obtained. By maintaining this system either at this obtained θ_c or this needed U value, the desired treatment

efficiency could be achieved accurately. The U value can be maintained by means of controlling this system at the corresponding F/M value, because the relationship, F/M = 100 U/E , exists.

The MLSS concentration and daily sludge production can be determined by Equation 5.16, and 5.20 or 5.21, respectively, following the determination of the needed θ_c or U value.

If it is desired to use r and X_r as a combined means of process control, sets of plots similar to Figures 53 and 42 must be prepared for each condition of r and X_r. By the same procedures, the desired treatment efficiency can be achieved by operating the system at different combinations of r, X_r pt θ_c or U values.

2. Design Applications

(1). The (θ/θ_c) Method. To use this method for designing the CMAS process, a plot similar to Fligure 55 should first be prepared. For a particular treatment efficiency, a design value of (θ/θ_c) can be chosen. By choosing a θ_c value from the range of 5 to 15 days, a needed minimum θ can be decided, thus the volume of the reactor is also decided. The MLSS concentration is depended upon the decided (θ/θ_c) value and chosen the r and X_r value. No special limitation is required, if both r and X_r are chosen from an acceptable range. The daily sludge production can be obtained by using Equation 5.20 or 5.21.

(2). The $U(\theta/\theta_c)$ Method. With this method, the designer must operate a laboratory unit for preparation of a plot si-

milar to Figure 53. When this plot is available, the required $U(\theta/\theta_c)$ value can be obtained for the required treatment efficiency. Any desired θ value with the corresponding combination of θ_c and U can be obtained according to the desired U value. The determination of θ_c and U should be checked by Equation 5.24, after θ is decided. MLSS concentration is dependent upon the chosen value of r, X_r, θ, and θ_c values. P_X can be predicted according to Equation 5.20 or 5.21 .

CHAPTER VI

CONCLUSIONS

The operation of a completely mixed activated sludge laboratory unit with internal cellular recycle at various combinations of mean cell residence time and hydraulic detention time has led to the following conclusions:

1. Hydraulic detention time did exercise a potential influence on the operational performance and other characteristics of the CMAS processes (such as MLSS concentration in aeration basin, daily sludge production, oxygen uptake rate, oxygen requirements, and observed cell yield coefficient).

2. In this investigation, the performance of stabilization was greater than 85% for all hydraulic detention times studied.

3. The maximum performance of purification for a completely mixed activated sludge system occurred at a hydraulic detention time of 4 hours. A decrease or increase in the hydraulic detention time from this optimum value decreased the plant efficiency.

4. The maximum plant efficiency also varied as a function of θ_c. In general, the maximum plant efficiency was greatest when the system was operated at θ = 4 hours along with a higher mean cell residence time.

5. This study has shown the Y_{max} and k_d are not constant. Y_{max} and k_d varied as a direct function of hydraulic detention time. Thus, control of system at a constant mean cell residence time value does not mean to maintain a constant loading factor, U or F/M value for a particular operational situation as reported by many investigators (49, 50, 52, 54). Therefore, for a successful design and operational control of the CMAS processes, it is not feasible only considering θ_c or U (F/M) as a functional parameter without taking care of θ of such systems.

6. From the development of a mathematical kinetic model for the CMAS process with cellular recirculation, the following results were found:

(a). Both θ and θ_c exercise a mutual important influence on the performance of treatment, effluent substrate concentration, MLSS concentration in reactor, daily sludge production, oxygen uptake rate, and oxygen demands.

(b). A useful mathematical equation was developed for each process characteristic (E, S, X, and P_X).

(c). Ratio of hydraulic detention time and mean cell residence time, (θ/θ_c), could be utilized as a functional parameter along with the specific utilization or could be used singly as a rapid and easy method for design and operational applications.

(d). The parameter, $U(\theta/\theta_c)$ was also developed which

could be utilized as an over-all functional parameter for the design and operational control of the CMAS processes.

(e). The recommended values for the design and operation of the completely activated sludge plants by means of these two developed parameters to achieve a performance of 90% are 0.77 hours/day for (θ/θ_c) and 0.30 hours/day/day for $U(\theta/\theta_c)$.

CHAPTER VII

SUGGESTIONS FOR FUTURE STUDY

Based on the findings of this investigation, the following suggestions are presented for further studies of the design and operational control parameters in the completely mixed activated sludge process:

1. Study the effects of hydraulic detention time on nitrification and denitrification in the CMAS processes.

2. Study the effects of the two developed parameters, (θ/θ_c) and $U(\theta/\theta_c)$., on the nitrogen and phosphorus removal efficiency, and on the nitrification and denitrification in such systems.

3. Study the effects of hydraulic detention time on sludge characteristics such as: SVI, and SDI.

4. Study the effects of (θ/θ_c) and $U(\theta/\theta_c)$ on sludge characteristics.

5. Develop a mathematical relationship between growth coefficients (Y_{max} and k_d) and hydraulic detention time.

6. Study the effects of (θ/θ_c) and $U(\theta/\theta_c)$ on the economical viewpoints of activated sludge plant design and operation.

7. Develop standard curves for the applications of (θ/θ_c) and $U(\theta/\theta_c)$ for the operation and design of activated

sludge systems.

8. Study the feasibility of the application of these two parameters, (θ/θ_c) and $U(\theta/\theta_c)$, on the performance of trickling filters or other modifications of activated sludge treatment processes.

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