

MODELING, SIMULATION AND OPTIMIZATION OF THE
ACTIVATED SLUDGE WASTE WATER TREATMENT PROCESS

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by

349 5839

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B.S., National Taiwan University, 1970

A THESIS

submitted in partial fulfillment of the
requirements for the degree

MASTER OF SCIENCE

Department of Chemical Engineering

KANSAS STATE UNIVERSITY

Manhattan, Kansas

1973

Approved by:


Major Professor

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CHAPTER 1

INTRODUCTION

The activated sludge process is widely employed in the field of sewage treatment. Significant advances have been made in recent years, resulting in a better understanding of the complex variables affecting the performance of the various unit processes and unit operations in the activated sludge process system. Successful computer modeling, simulation and optimization based on such information are able to predict the performance of individual units and evaluate alternative designs for an activated sludge wastewater treatment plant. Various attempts, with varying degrees of success, have been carried out for modeling, simulation and optimization of the activated sludge process [1-8].

Conventionally a primary clarifier is included in the activated sludge process for the removal of suspended solids*. However, most of the primary clarifier designs have been based on past experiences rather than on the results of system analysis. The research work presented herein is an attempt to develop a new approach for the design of a primary clarifier in an activated sludge process system by use of computer modeling, simulation and optimization.

The results of a previous study by Mishra et al. [9] based on the conventional Monod kinetic model indicated that the inclusion of a primary

* In this work the term suspended solids refers to all suspended substances. Suspended solids contain viable biomass and nonviable suspended matter (suspended wastes). The suspended wastes are composed of organic biodegradable solids (suspended substrate) and non-biodegradable solids.

clarifier is not economically advantageous for the steady state operation of an activated sludge wastewater treatment system. These results may not be sufficiently realistic because their work was based on the assumptions that the removal rate of suspended substrate by microbes in the aeration tank is the same as that of soluble substrate and that suspended waste has no influence on the removal rate of soluble substrate.

It is well known that the removal rate of suspended waste by microbes is much less than that of soluble substrate [10, 11]. In addition, available information indicates that the suspended waste has an inhibition effect on the removal rate of the soluble substrate [11, 12]. Therefore, the first objective of this research was to construct a new biochemical oxidation kinetic model, which takes into account the low metabolic rate and inhibition effect of suspended waste, and to examine the effect of primary clarifier on the performance of the activated sludge system based on the newly constructed model.

Since the conventional model considers soluble substrate and suspended waste as a single complex waste, it is hard to investigate the influence of suspended solids on the performance of the secondary wastewater treatment system. The newly constructed model, however, distinguishes soluble substrate from suspended waste. The second objective of this work was to examine the influence of suspended solids on the optimal design of the secondary wastewater treatment system based on the newly constructed model.

The final objective of this research was to optimize the overall activated sludge process including the primary clarifier. The dynamic

programming computational procedure in conjunction with the optimal results of the secondary wastewater treatment system obtained in the second objective was employed to determine the optimal size of primary clarifier under various influent conditions.

This thesis has been prepared in such a fashion that each chapter is a self-contained unit. A new biochemical oxidation kinetic model is constructed based on the available experimental data in Chapter 2. The application of the new kinetic model to the design of a primary clarifier unit in an activated sludge system is also demonstrated. Chapter 3 considers the influence of suspended solids on the optimal design of the secondary treatment system including an aeration tank and a final settler. Chapter 4 employs the dynamic programming computation procedure to optimize the overall activated sludge process including the primary clarifier. Chapter 5 summarizes the results of the present research. Recommendations for future research are also given.

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CHAPTER 2

A PARALLEL BIOCHEMICAL OXIDATION KINETIC MODEL AND ITS APPLICATION TO THE DESIGN OF A PRIMARY CLARIFIER IN AN ACTIVATED SLUDGE SYSTEM

2.1 INTRODUCTION

The activated sludge process is widely employed in the field of sewage treatment. Conventionally a primary clarifier has been used in this process for the removal of suspended solids*. Most of the primary clarifier designs, however, have been based on past experience rather than on the results of system analysis.

The results of a previous study by Mishra et al. [1] based on the conventional Monod kinetic model, indicated that the inclusion of a primary clarifier is not economically advantageous for the steady state operation of an activated sludge wastewater treatment system. These results may not be sufficiently realistic because their work was based on the assumptions that the removal rate of suspended substrate by activated sludge in the aeration tank is the same as that of soluble substrate and that suspended wastes have no influence on the removal rate of soluble substrate. This study represents an attempt to remove such assumptions.

The purpose of this work is to build a new biochemical oxidation kinetic model, which takes into account the differences in oxidation rates

* In this work the term suspended solids refers to all suspended substances. Suspended solids contain viable biomass and nonviable suspended matter (suspended wastes). The suspended wastes are composed of organic biodegradable solids (suspended substrate) and non-biodegradable solids.

and the inhibition effect, or masking effect, of suspended wastes, and to develop a new approach for the design of a primary clarifier unit in an activated sludge system based on such a model. The scope includes mathematical modeling, parameter estimation, and an application of the new kinetic model to the design of the primary clarifier in an activated sludge system.

The derivation of the new model is accomplished by introducing both the concept of parallel reactions and the notion of a masking effect of suspended wastes. Estimation of the parameters in the model is carried out by fitting the model to the available experimental data. Application of the model to the design of a primary clarifier is demonstrated.

2.2 MODELING OF BIOCHEMICAL OXIDATION

2.2.1 Kinetics of Biochemical Oxidation

Many different models have been used to describe the kinetics of BOD or COD removal from complex wastes by activated sludge [2]. Those extensively applied during recent years are the modified Monod model and the first order reaction model [3, 4, 5]. However, all of these models consider soluble and suspended substrates as a single complex waste. Takahashi et al. [6] and McKinney [7] indicated that the removal rate of suspended substrate depends on the particle size and composition, and that generally the rate is much less than the removal rate for soluble substrate. Takahashi et al. [6] also reported that the adsorption activity of activated sludge is reduced by the adsorption of colloids and is recovered by metabolizing these colloids. This phenomenon is termed

masking effect. The difference in the removal rates of soluble and suspended substrates as well as the masking effect of suspended wastes should be taken into account in the reaction kinetic model.

The kinetic equations for soluble substrate removal, cell growth, and suspended substrate removal are, respectively,

$$\frac{dx_1}{dt} = - \frac{\mu_{m1} x_1 x_2}{Y_1 (K_s + x_1 + h_3 x_3)} \quad (1)$$

$$\frac{dx_2}{dt} = \frac{\mu_{m1} x_1 x_2}{K_s + x_1 + h_3 x_3} + \beta_3 x_2 x_3 - k_d x_2 \quad (2)$$

$$\frac{dx_3}{dt} = - \frac{\beta_3 x_2 x_3}{Y_3} \quad (3)$$

where

x_1 = concentration of soluble substrate (BOD ppm)

x_2 = concentration of activated sludge (weight ppm)

x_3 = concentration of suspended waste or suspended substrate (weight ppm)*

μ_{m1} = maximum specific growth rate with soluble substrate (hr⁻¹)

K_s = saturation constant for soluble substrate (ppm)

k_d = endogenous rate coefficient (hr⁻¹)

Y_1 = yield coefficient of soluble substrates (microbes ppm/BOD ppm)

* Since equation (3) predicts that x_3 approaches zero as t increases, x_3 should be suspended substrate; however, in equation (1) x_3 might be either suspended substrate or suspended waste. Adequate experimental information to distinguish between the masking effects of suspended substrate and non-biodegradable solids is not presently available.

β_3 = removal rate coefficient of suspended substrate
(1/hr·microbes ppm)

Y_3 = yield coefficient of suspended substrate (microbes ppm/
suspended substrate ppm)

h_3 = masking effect coefficient (—)

Equations (1), (2), and (3) represent, respectively, the removal rate of soluble substrate, the growth rate of micro-organisms, and the removal rate of suspended substrate in batch operation. The most significant aspects of this model are the concept of parallel reactions and the notion of a masking effect. Difference in removal rates between the soluble and suspended substrates are taken into account by means of a parallel reaction mechanism. The masking effect coefficient h_3 represents the specific degree of influence of suspended waste on the adsorption activity of activated sludge. The product $h_3 x_3$ implies the total masking effect. By putting $h_3 = 0$, eqs. (1) and (3) reduce to parallel reaction kinetic equations without any masking effect.

2.2.2 Nakanishi's Experiment

Nakanishi [8] conducted a series of batch experiments to observe the removal of soluble substrate for two cases: one case where only soluble substrate was present, the other case where both soluble substrate and suspended waste were used.

Nakanishi's results show that the removal rate of soluble substrate is reduced when suspended wastes are present. This is probably due to a decrease in adsorption activity of the bacteria flocs because of suspended wastes on the surface of the bacteria flocs. As mentioned

previously, this phenomenon is called masking effect. Typical data by Nakanishi [8] are given in Table I.

2.2.3 Parameter Estimation

The proposed model equations were fitted to Nakanishi's experimental data using a least square criterion. The parameters in the equations were varied to minimize the sum of squares of residuals.

$$\sigma = \sum (x_{1,\text{exp}} - x_{1,\text{pred}})^2$$

by using Bard's [9] nonlinear parameter estimation program on an IBM 360/50 series computer.

The parameters in eqs. (1) through (3) are μ_{ml} , K_s , k_d , Y_1 , β_3 , Y_3 , and h_3 . It would be very difficult to estimate all these parameters simultaneously from experimental data. To circumvent this difficulty, approximate values of Y_1 , k_d , β_3 , and Y_3 were obtained from information in the literature.^{2,6} The value of K_s was selected by conducting a preliminary study in which μ_{ml} and K_s were estimated using 20 points obtained from a curve drawn through Nakanishi's data for the case where only soluble substrate is present ($x_3 = 0$). The parameter μ_{ml} was then estimated from Nakanishi's six experimental data points for the case where only soluble substrate is present. Using these values of μ_{ml} , K_s , Y_1 , k_d , β_3 , and Y_3 , the parameter h_3 was estimated from the experimental data obtained where both soluble substrate and suspended wastes exist (the Case II data in Table I).

Table I Nakanishi's Experimental Data (Kyoto sewage + synthetic wastes)

Initial Condition	Case I: Only Soluble Substrate is Present $x_3(0) = 0$ ppm	Case II: Soluble Substrate and Suspended Waste Coexist $x_3(0) = 885$ ppm
$x_1(0) = 713.3$ BOD ppm		
$x_2(0) = 1,007$ ppm		
Time (hr)	Soluble substrates, x_1 , BOD ppm	Soluble substrates, x_1 , BOD ppm
0	713.0	713.0
0.5	379.9	400.0
1.1	299.9	339.9
2	113.3	146.6
3.5	46.6	80.0
4.9	13.3	46.6

The results of the estimation are listed in Table II. Calculated and experimental results are compared in Fig. 1. The solid line and circle points represent the calculated and experimental results, respectively, for the case where only soluble substrate is present. The dotted line and cross points indicate the calculated and experimental results, respectively, for the case where both soluble substrate and suspended waste exist. Fig. 1 indicates that the new model takes into account the masking effect reasonably well. The estimated value of the masking effect coefficient h_3 is 0.289 for the suspended solids in Kyoto sewage [8]. It should be noted that the value of the masking effect coefficient will be dependent on the nature of suspended solids.

2.3 SYSTEM DESCRIPTION

2.3.1 System Configuration

The activated sludge process system considered in this study is shown in Fig. 2.

The system consists of a primary clarifier, an aeration tank, and a secondary clarifier; a part of the activated sludge separated in the secondary clarifier is recycled to the aeration tank. The influent flow rate is constant and the effluent water quality is kept fixed at a set standard in terms of its BOD.

2.3.2 Primary Clarifier

The primary clarifier plays an important role in most wastewater treatment plants, and a substantial amount of the pollutant load is

Table II Estimated Values of Parameters

Parameters	Case I: Only Soluble Substrate Is Present	Case II: Soluble Substrate and Suspended Waste Coexist
Estimated Parameter	μ_{ml} 0.537	h_3 0.289
K_s	960.0	K_s 960.0
Y_1	0.5	Y_1 0.5
k_d	0.02	k_d 0.02
		μ_{ml} 0.537
		β_3 0.000001
		Y_3 0.5
σ	19.938	20.487

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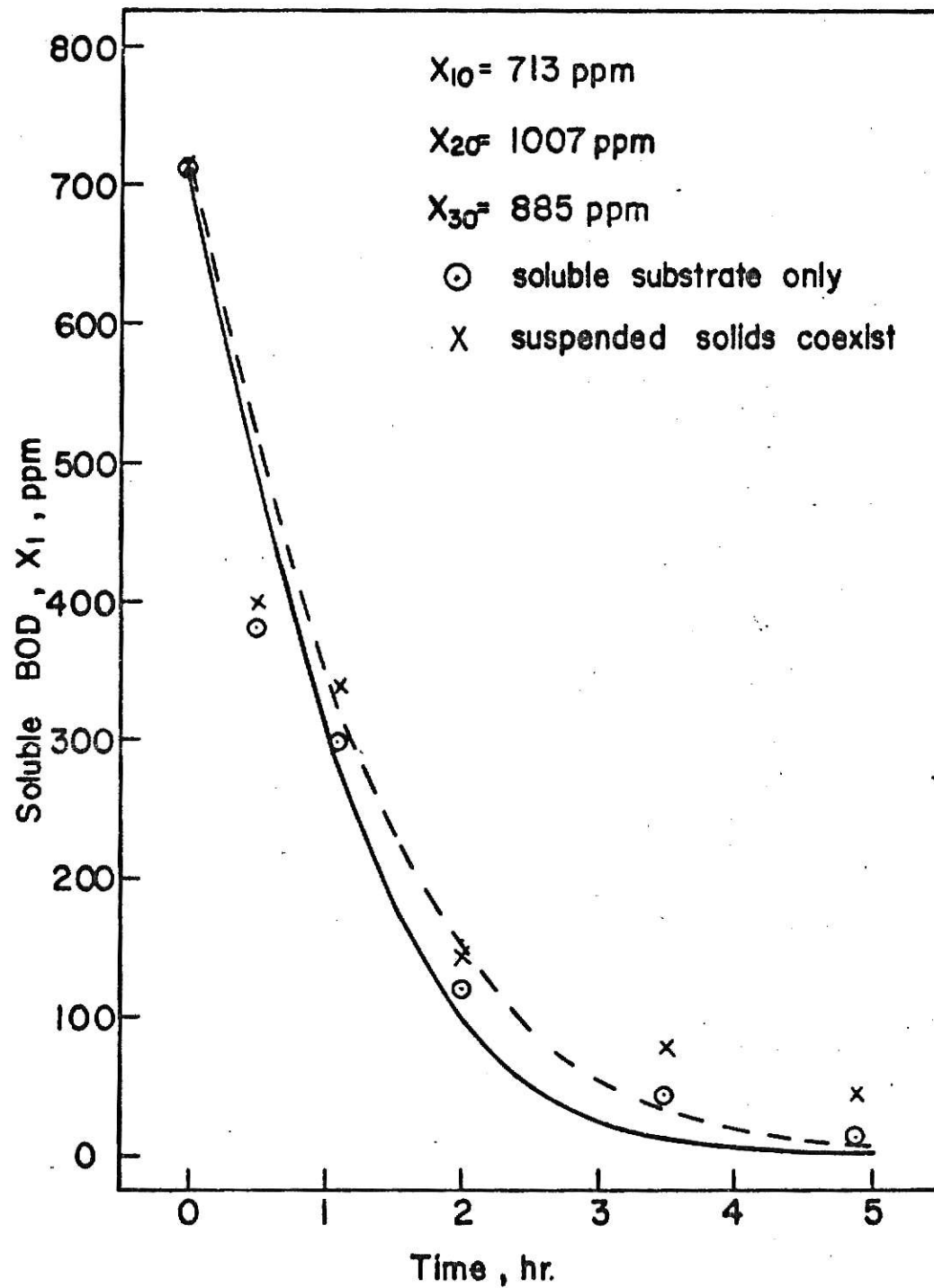


Fig. 1. Comparison of theoretical calculations with Nakanishi's experimental data .

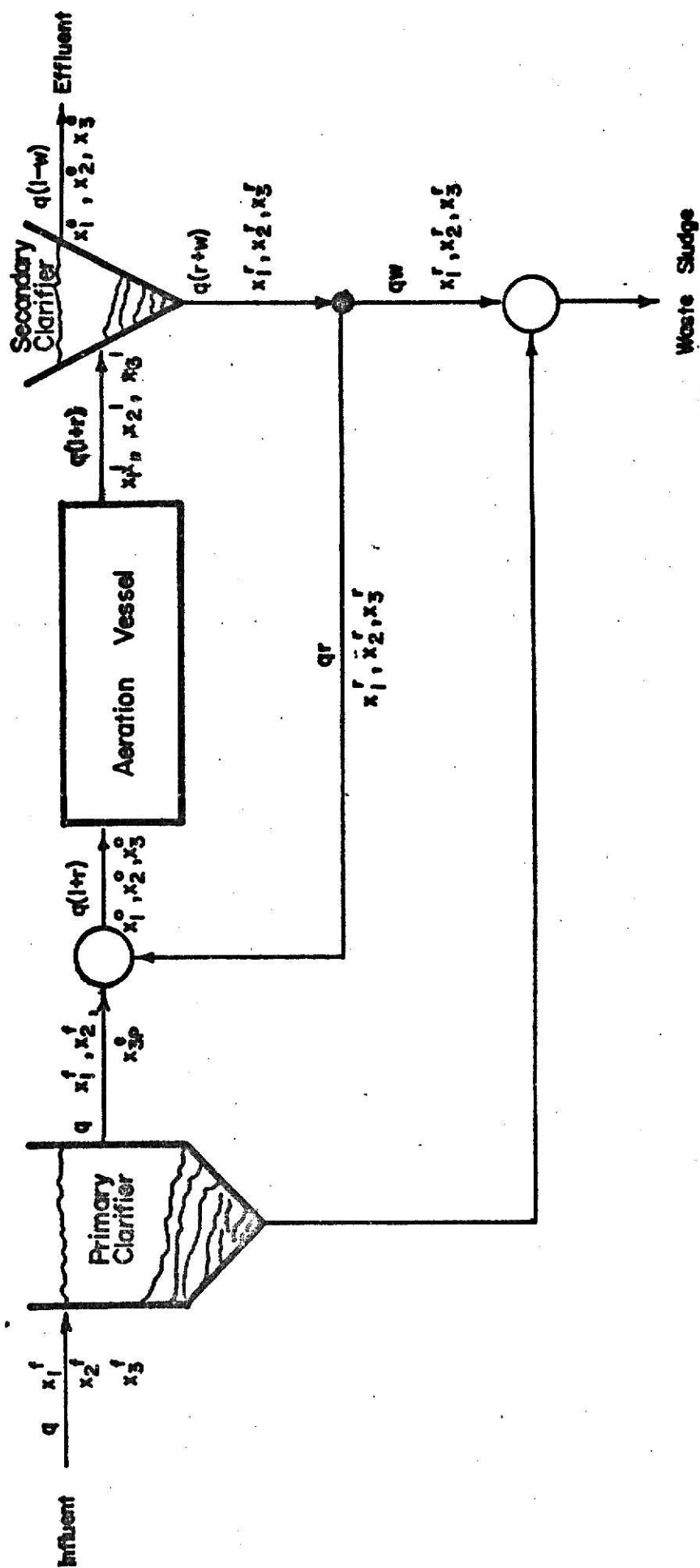


Fig. 2. Schematic Diagram of the Activated Sludge Process System.

removed here. The removal rate of suspended solids obtained in the primary clarifier operation is influenced by the plant design, the settleable solids characteristics, the degree of flocculation (natural or induced), solids loading, and the hydraulic loading. With the aid of polymeric coagulant at a controlled dosage to aid flocculation, the suspended solids removal efficiency of the primary clarifier can be enhanced considerably. Voshel and Sak [10] developed two empirical correlations for the removal of suspended solids in a primary clarifier, based on plant scale experiments. The first correlation is for the case when no flocculation agent is used and can be expressed as

$$(x_{2p}^e + x_{3p}^e) = (x_2^f + x_3^f) \left[1 - \frac{0.5675 (x_2^f + x_3^f)^{0.27}}{(q/A_p)^{0.22}} \right] \quad (4)$$

where the superscripts e and f refer to effluent and influent, respectively, and the subscript p refers to the primary clarifier. In eq. (4) all concentrations have the units of ppm and

q = volumetric flow rate of influent wastewater (MGD)

A_p = surface area of primary clarifier (ft²)

The second correlation is for the case when a polymeric coagulant is used at a dosage of 1 mg/l and can be expressed as

$$(x_{2p}^e + x_{3p}^e) = (x_2^f + x_3^f) \left[1 - \frac{0.7788 (x_2^f + x_3^f)^{0.17}}{(q/A_p)^{0.13}} \right] \quad (5)$$

Both expressions, eqs. (4) and (5), assume that the suspended solids removal in the primary clarifier is proportional to a power function of the

influent suspended solids concentration and is inversely proportional a power function of the surface overflow rate of the primary clarifier. It is assumed that the organisms and suspended waste have the same proportional compositions in the influent and effluent streams.

In this study the primary clarification operation is assumed to have no effect on the concentration of soluble substrate in the wastewater stream.

2.3.3 Mixing Point

The effluent from the primary clarifier and the thickened sludge recycled from the secondary clarifier are assumed to be mixed together and then fed as influent to the aeration tank. The material balances for the soluble substrate, the microbes, and the suspended waste can be written, respectively, as

$$x_1^0 = \frac{1}{1+r} x_1^f + \frac{r}{1+r} x_1^r \quad (6)$$

$$x_2^0 = \frac{1}{1+r} x_{2p}^e + \frac{r}{1+r} x_2^r \quad (7)$$

$$x_3^0 = \frac{1}{1+r} x_{3p}^e + \frac{r}{1+r} x_3^r \quad (8)$$

where r is the ratio of recycle flow rate to influent flow rate and the superscripts f , r , and 0 refer to influent (feed), recycle and flow from the mixing point, respectively.

2.3.4 Aeration Tank

The aeration tank is a key component of the activated sludge process system since it is here that the organic nutrients are biochemically

oxidized. As pointed out before, microbial oxidation rates are affected by the presence of suspended wastes due to the masking effect. The performance of the aeration tank is predicted by using a homogeneous flow model and the proposed new growth model which takes into account this masking effect.

The kinetics for soluble substrate consumption, microbial growth, and suspended waste removal in the aeration tank are given in eqs. (1) through (3), respectively. The completely mixed model (CSTR model) for the aeration tank as advocated by McKinney et al. [11, 12, 13] is often used in designs. For a CSTR, the steady state material balances for soluble substrate, microorganisms, and suspended waste can be written, respectively, as

$$x_1^0 - x_1^1 + T_A \left(\frac{-\mu_{m1} x_1^1 x_2^1}{Y_1 (K_s + x_1^1 + h_3 x_3^1)} \right) = 0 \quad (9)$$

$$x_2^0 - x_2^1 + T_A \left(\frac{\mu_{m1} x_1^1 x_2^1}{K_s + x_1^1 + h_3 x_3^1} + \beta_3 x_3^1 x_2^1 - k_d x_2^1 \right) = 0 \quad (10)$$

$$x_3^0 - x_3^1 + T_A \left(\frac{-\beta_3 x_3^1 x_2^1}{Y_3} \right) = 0 \quad (11)$$

$$T_A = \frac{V_A}{q(1+r)} \quad (12)$$

where superscript 1, refers to concentrations in the aeration tank and

T_A = detention time of the aeration tank (hr)

V_A = volume of the aeration tank (MG)

2.3.5 Secondary Clarifier

The performance of the secondary clarifier is estimated based on a model developed by Naito et al. [14] on the assumption that plug flow conditions prevail in it. According to this model, the rate of removal of suspended solids in the secondary clarifier can be represented by the semiempirical relationship

$$(x_2^e + x_3^e) = p (x_2^1 + x_3^1)^\alpha \exp [-\gamma T_s] \quad (13)$$

where p , α , and γ are parameters and superscript e refers to the clarifier effluent. In eq. (13)

$$T_s = \text{secondary clarifier detention time (hr)}$$

The values of parameters p , α , and γ depend on the characteristics of the sludge and equipment. It is assumed that the microbes and suspended wastes have the same proportional compositions both in the mixed liquor suspended solids entering the secondary clarifier and in the recycle stream. Therefore,

$$\frac{x_3^e}{x_2^e} = \frac{x_3^r}{x_2^r} = \frac{x_3^1}{x_2^1} \quad (14)$$

It is also assumed that the concentration of soluble substrate is not affected by the secondary clarifier operation. That is

$$x_1^1 = x_1^r = x_1^e \quad (15)$$

The material balances for the microbes and suspended waste around the secondary clarifier can be written, respectively, as

$$(1 + r) x_2^1 = (1 - w) x_2^e + (r + w) x_2^r \quad (16)$$

$$(1 + r) x_3^1 = (1 - w) x_3^e + (r + w) x_3^r \quad (17)$$

where

w = sludge wasting ratio (—)

2.3.6 Effluent Quality

The total BOD in the effluent depends on the concentrations of untreated soluble substrate, of microbes, and of suspended waste. The effluent BOD is given by

$$x_1^e + C_1 x_2^e + C_2 x_3^e = C_d \quad (18)$$

where

C_d = effluent BOD concentration (BOD ppm)

C_1 = conversion coefficient for microbes (BOD ppm/microbes ppm)

C_2 = conversion coefficient for suspended wastes (BOD ppm/
suspended waste ppm)

In the simulation studies, eq. (18) is used as an effluent quality constraint.

2.3.7 Cost Functions

Construction costs of the units involved in the activated sludge process system are estimated using correlations developed by Smith [15]. For the primary clarifier, the construction cost (in dollars) has been correlated to the surface area (in ft^2) and is given by the expression

$$C_p = 13.4 A_p + 2,600 A_p^{0.1} \quad (19)$$

The construction cost of the aeration vessel (in dollars) is correlated to its volume (in millions of gallons) and is expressed by

$$C_A = V_A (175,000 + 36,500 V_A^{-0.818}) \quad (20)$$

The capital cost of secondary clarifier (in dollars) can be estimated from its surface area (in thousands of ft^2) by using the correlation

$$C_s = 12,600 A_s + 5,350 A_s^{-0.126} \quad (21)$$

The total construction cost, C_T , of the system can be estimated by totaling the costs of the individual units and allowing 40% in excess for engineering fees, that is

$$C_T = 1.4 (C_p + C_A + C_s) \quad (\text{dollars}) \quad (22)$$

2.4 SIMULATION

The equations presented in the preceding section constitute a mathematical model for the activated sludge process system shown in Fig. 2. This model may be used in simulation studies to determine the effect of

primary clarifier size on system performance. By analyzing this system of equations, the computational degree of freedom for the system is determined to be one when the values of C_d , q , x_1^f , x_2^f , x_3^f , r , x_1^1 , and x_2^r (or $x_2^r + x_3^r$) are specified*. Hence, the performance of the system can be simulated by fixing one remaining variable A_p . In this study, the depth of the primary clarifier is fixed at 10 ft. The values of A_p range from 0 ft² to 6000 ft², i.e., the values of T_p range from 0.0 hr to 3.6 hr. For simplicity, only the case with flocculation in the primary clarifier is considered.

The numerical values used in simulation are as follows

$$\mu_{ml} = 0.1 \text{ hr}^{-1}$$

$$K_s = 100 \text{ ppm}$$

$$Y_1 = 0.5 \text{ microbes ppm/BOD ppm}$$

$$k_d = 0.002 \text{ hr}^{-1}$$

$$\beta_3 = 0.000001 \text{ hr}^{-1} \text{ ppm}^{-1}$$

$$Y_3 = 0.5 \text{ microbes ppm/suspended waste ppm}$$

$$h_3 = 0.0$$

$$0.25$$

$$0.5$$

$$p = 2.1$$

$$\alpha = 0.5$$

$$\gamma = 0.74$$

$$C_1 = 0.5 \text{ BOD ppm/microbes ppm}$$

* If r and x_1^1 are treated as decision variables, an optimization problem with 3 degrees of freedom is obtained. Only the simpler one dimensional optimization problem is considered here.

$$C_2 = 0.2 \text{ BOD ppm/suspended waste ppm}$$

$$C_d = 20 \text{ BOD ppm}$$

$$q = 3 \text{ MG/day}$$

$$x_1^f = 200 \text{ BOD ppm}$$

$$x_2^f = 0 \text{ microbes ppm}$$

$$x_3^f = 100$$

$$200 \text{ ppm}$$

$$300$$

$$r = 0.35$$

$$x_1^l = 11 \text{ ppm}$$

$$x_2^r \text{ (or } x_2^r + x_3^r) = 8,000$$

$$10,000 \text{ ppm}$$

$$12,000$$

2.5 RESULTS AND DISCUSSION

The results of simulation are presented in Figs. 3 through 17.

The results indicate that, in general, the size of the primary clarifier can be based on the concentration and characteristics of the influent suspended solids. The optimal size of the primary clarifier, which leads to the minimum total volume or total construction cost, increases as the concentration and the masking characteristics of the influent suspended waste increase.

2.5.1 Primary Clarifier Performance

Figure 3 shows that the concentration of suspended waste in the primary clarifier effluent is a monotonically decreasing function of

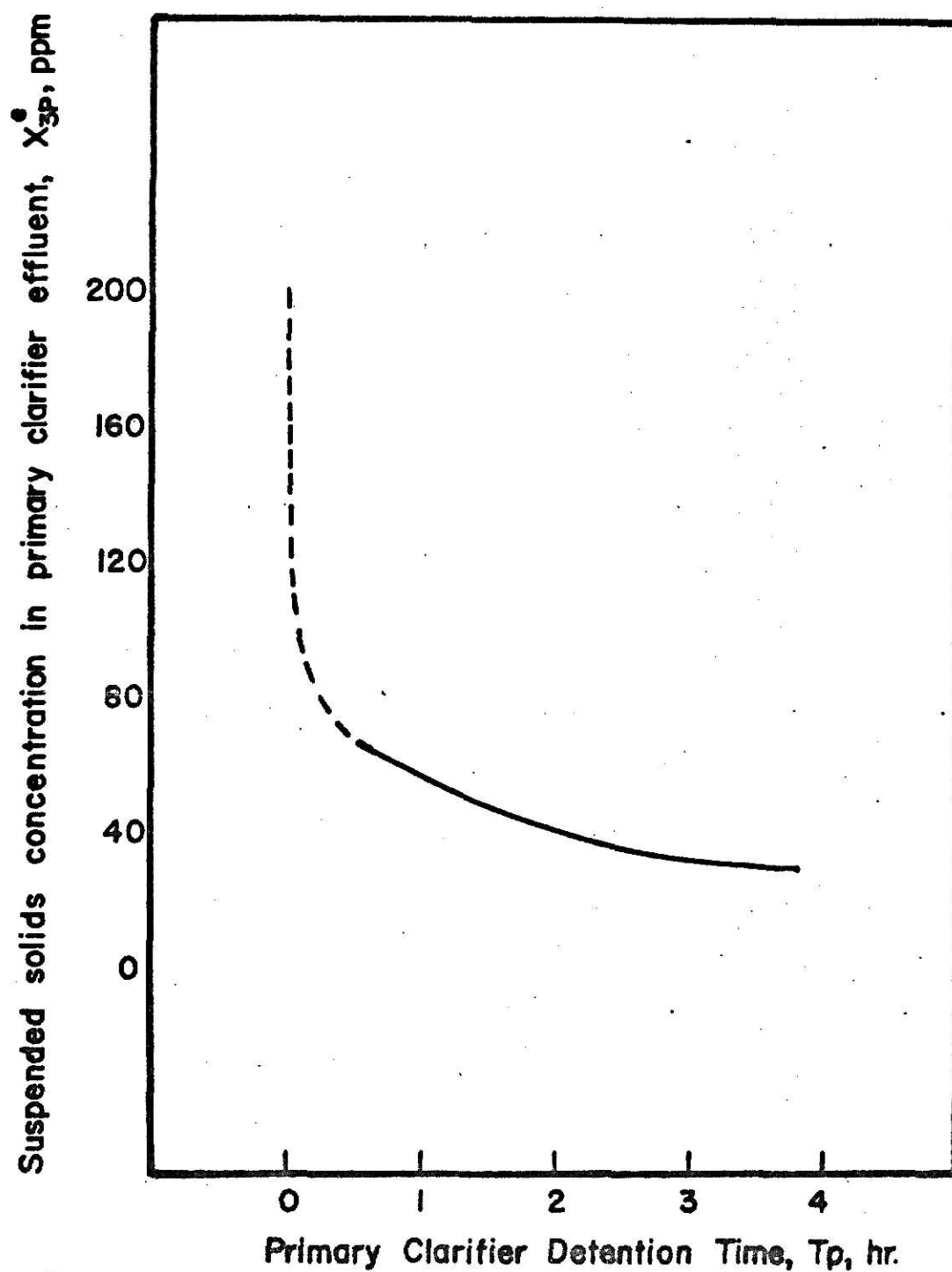


Fig. 3. Variation of X_{3P}^e with T_p for $q=3$ MGD and $X_3^f=200$ ppm

the primary clarifier detention time, as expected. However, increasing the detention time of the primary clarifier beyond a certain point results in only a very small increase in the suspended waste removal efficiency. It should be noted that Voshel's model is not able to predict the actual performance of the primary clarifier in the region where the detention time of the primary clarifier is less than 0.5 hr. This region is represented by the dotted line in Fig. 3 and also in Figs. 4 through 17.

2.5.2 Influence of the Masking Effect on the Optimal Size of the Primary Clarifier

Figure 4 shows the variation of the total system volume as a function of the primary clarifier detention time with the masking effect coefficient h_3 as parameter. It can be seen that the minimum total volume of the system occurs as the primary clarifier detention time approaches zero in the case where the masking effect does not exist, i.e., where $h_3 = 0$. However, the optimal size of the primary clarifier increases with an increase in the masking effect coefficient. For the case $h_3 = 0.5$, the optimal primary clarifier detention time is about 2.5 hr. Figure 5 shows the variation of the total system cost as a function of the primary clarifier detention time with the masking effect coefficient h_3 as parameter. The optimal primary clarifier detention time, for minimum total cost, increases with an increase in the masking effect coefficient.

The results given in Figs. 4 and 5 indicate that both the total volume and total cost increase with the increase in the masking effect

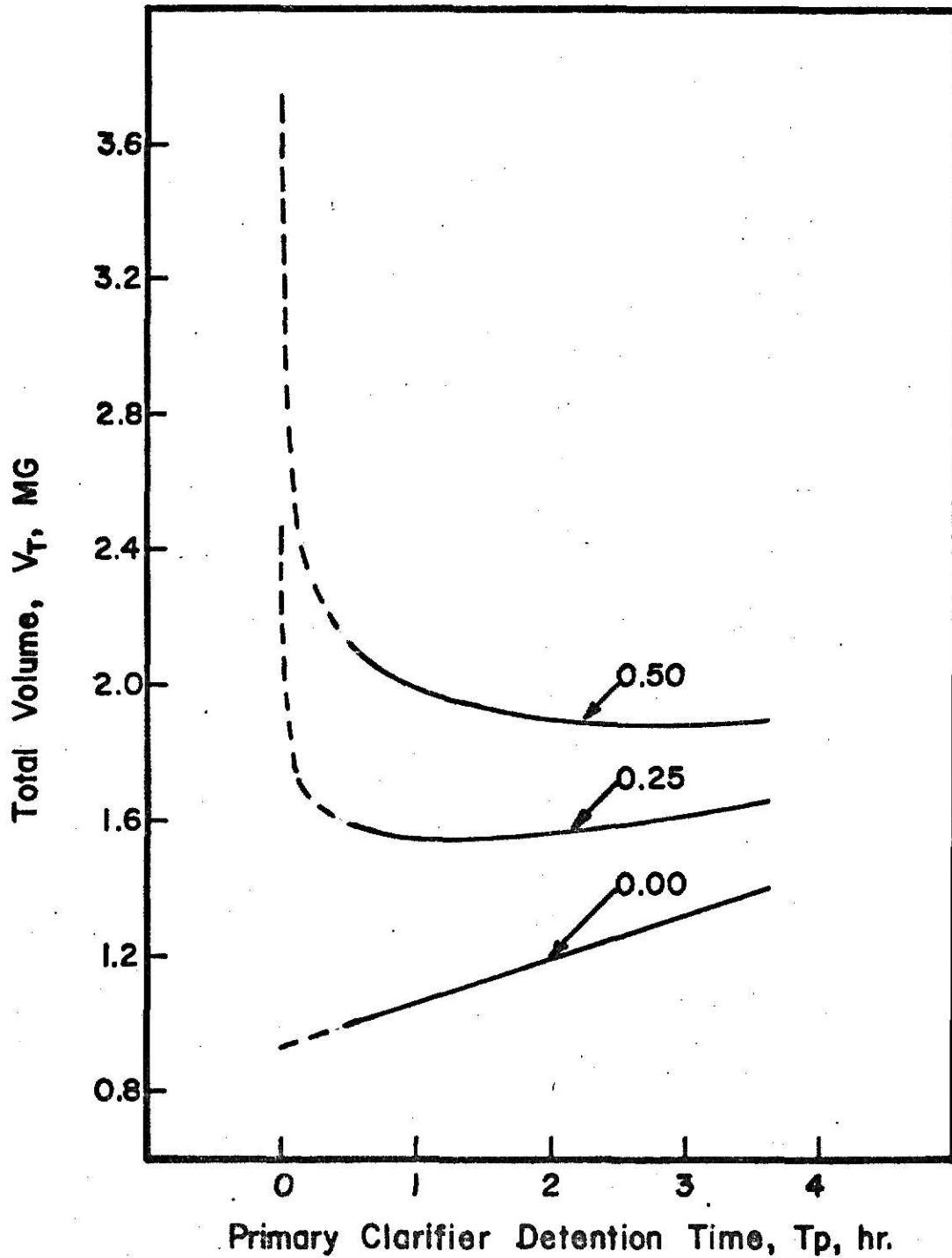


Fig. 4. Variations of V_T with T_p for $q=3\text{MGD}$, $X_1^f=200\text{ppm}$ and $X_2^r=8,000\text{ppm}$ with h_3 as parameter

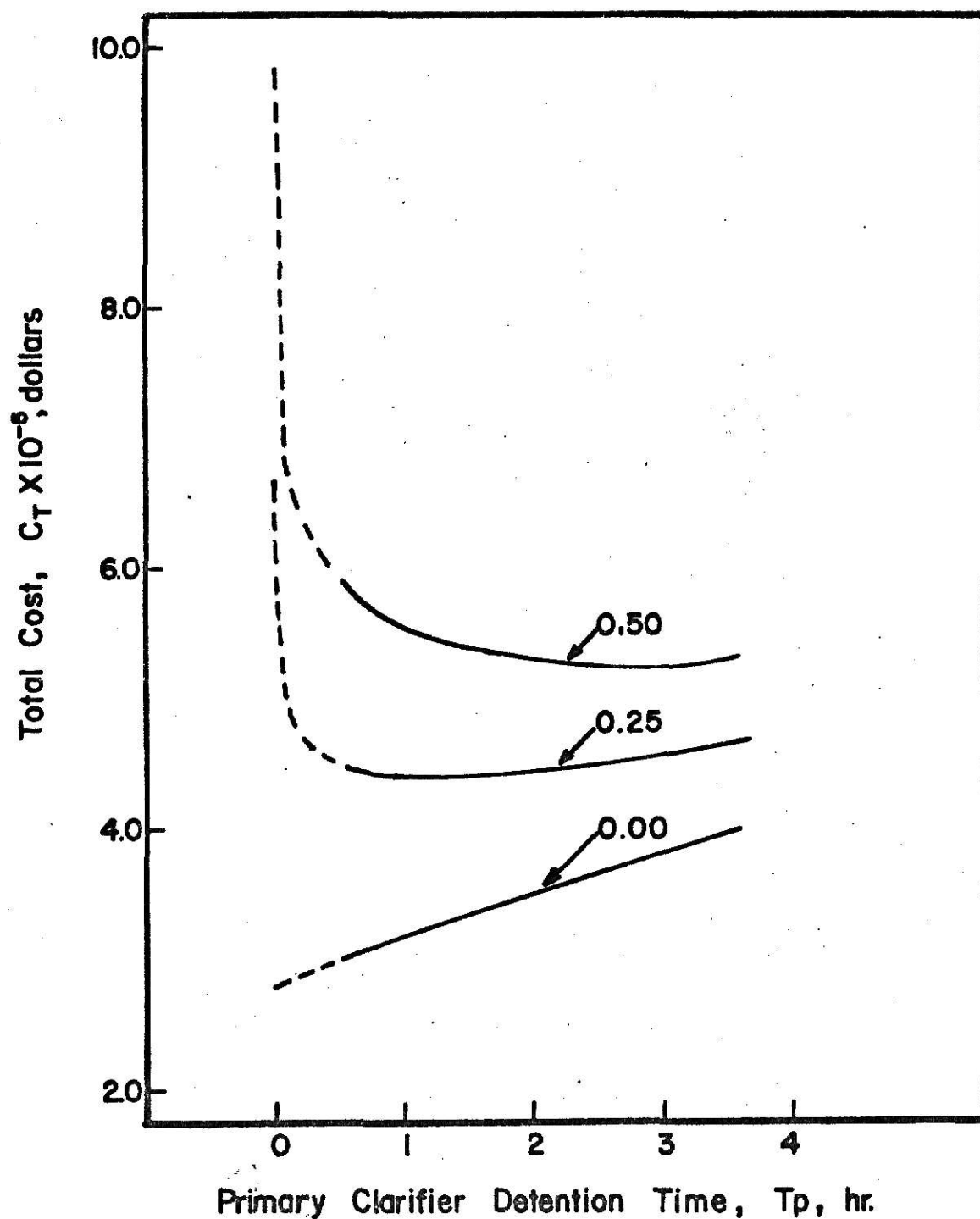


Fig. 5. Variation of C_T with T_p for $q=3\text{MGD}$, $X_1^f=200\text{ppm}$, $X_3^f=200\text{ppm}$ and $X_2^r=8,000\text{ppm}$ with h_3 as parameter

coefficient. This is attributed to the fact that the removal of soluble substrate by microbes is inhibited by the masking effect due to the suspended waste, and a greater detention time is required by the aeration tank when the masking effect is enhanced.

2.5.3 Influence of the Suspended Waste Concentration on the Optimal Size of the Primary Clarifier

Figure 6 exhibits the variation of the total system volume as a function of the primary clarifier detention time with the influent suspended waste concentration x_3^f as parameter. The optimal primary clarifier detention time for the minimum total volume increases with an increase in the influent suspended waste concentration. As x_3^f increases from 100 ppm to 200 ppm, the optimal value of the primary clarifier detention time increases approximately from 0.5 hr to 1 hr. Further increase of x_3^f to 300 ppm results in a value of the optimal primary clarifier detention time of about 3 hr. The variation of the total system cost is shown in Fig. 7 as a function of the primary clarifier detention time with the influent suspended waste concentration x_3^f as parameter. The optimal primary clarifier detention time, for the minimum total cost, increases as the influent suspended waste concentration increases.

Again, the results given in Figs. 6 and 7 indicate that the two economic models, both the total volume and the total cost, increase with the increase in the influent suspended waste concentration, as expected.

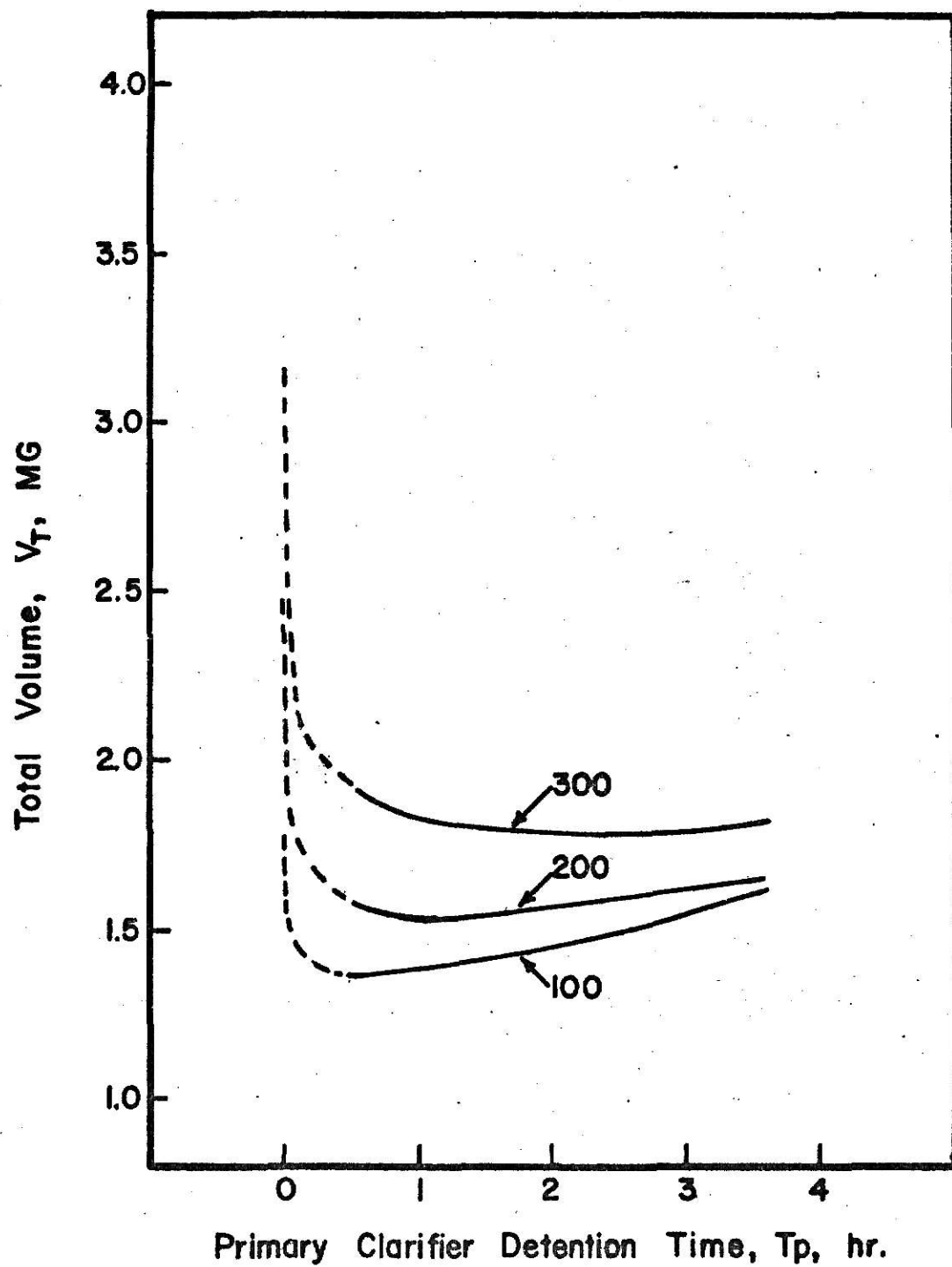


Fig. 6. Variations of V_T with T_p for $q=3\text{MGD}$, $X_1^f=200\text{ppm}$, $X_2^f=8,000\text{ppm}$ and $h_3=0.25$ with X_3^f as parameter

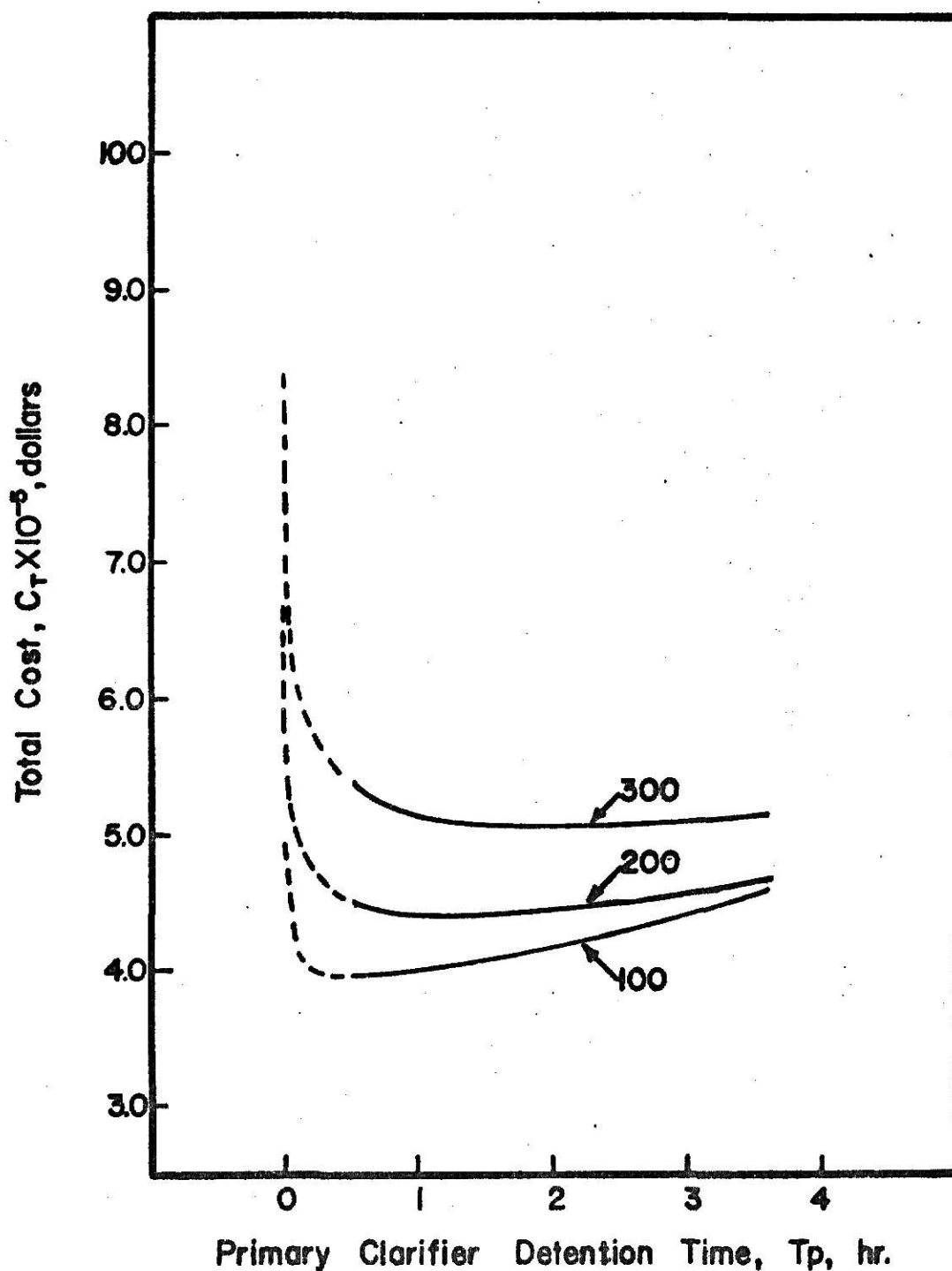


Fig. 7. Variations of C_T with T_p for $q=3\text{MGD}$, $X_1^f=200\text{ppm}$, $X_2^f=8,000\text{ppm}$ and $h_3=0.25$ with X_3^f as parameter

2.5.4 Size and Cost Relationships Among the Primary Clarifier, Aeration Tank and Secondary Clarifier

Figure 8 illustrates the size relationship among the primary clarifier, aeration tank, and secondary clarifier for certain influent conditions. It can be observed that increasing the size of the primary clarifier scarcely influences the volume of the secondary clarifier; however, it results in a reduction of the volume of the aeration tank. This is due to the fact that an increase in the primary clarifier detention time enhances suspended waste removal. This directly diminishes the masking effect and organic load in the aeration tank and, therefore, reduces the required volume of the aeration tank.

Figure 9 shows the costs of the primary clarifier, aeration tank, and secondary clarifier. The variations in the costs are similar to the variations in the volumes of the respective units.

2.5.5 Influence of the Primary Clarifier Size on the Composition of Mixed Liquor Suspended Solids in the Aeration Tank

Figure 10 exhibits the variations of concentrations of suspended wastes and microbes in the aeration tank with respect to the primary clarifier detention time for certain influent conditions. The underflow organism concentration x_2^r is fixed at 8,000 ppm. The results indicate that an increase in the primary clarifier detention time brings about a reduction in the concentration of suspended waste in the aeration tank. The ratio of suspended waste concentration to microbes concentration in the aeration tank decreases approximately from 0.5 to 0.1 as the primary clarifier detention time goes from 0.0 hr to 3.5 hr. This implies that

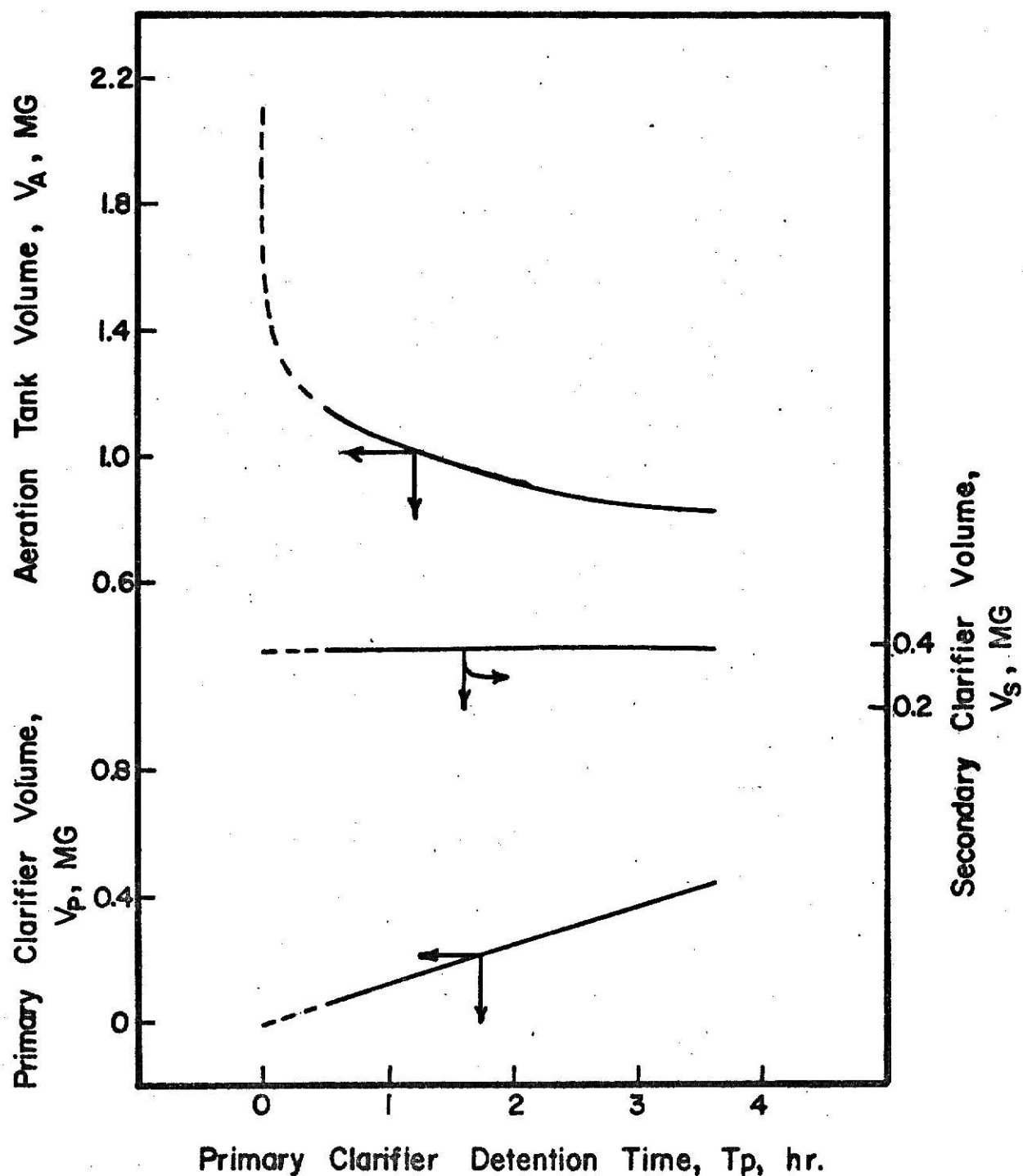


Fig. 8. Variations of V_p , V_a and V_s with T_p for $q=3\text{MGD}$, $X_1^f=200\text{ppm}$, $X_3^f=200\text{ppm}$, $h_3=0.25$ and $X_2^r=8,000\text{ppm}$

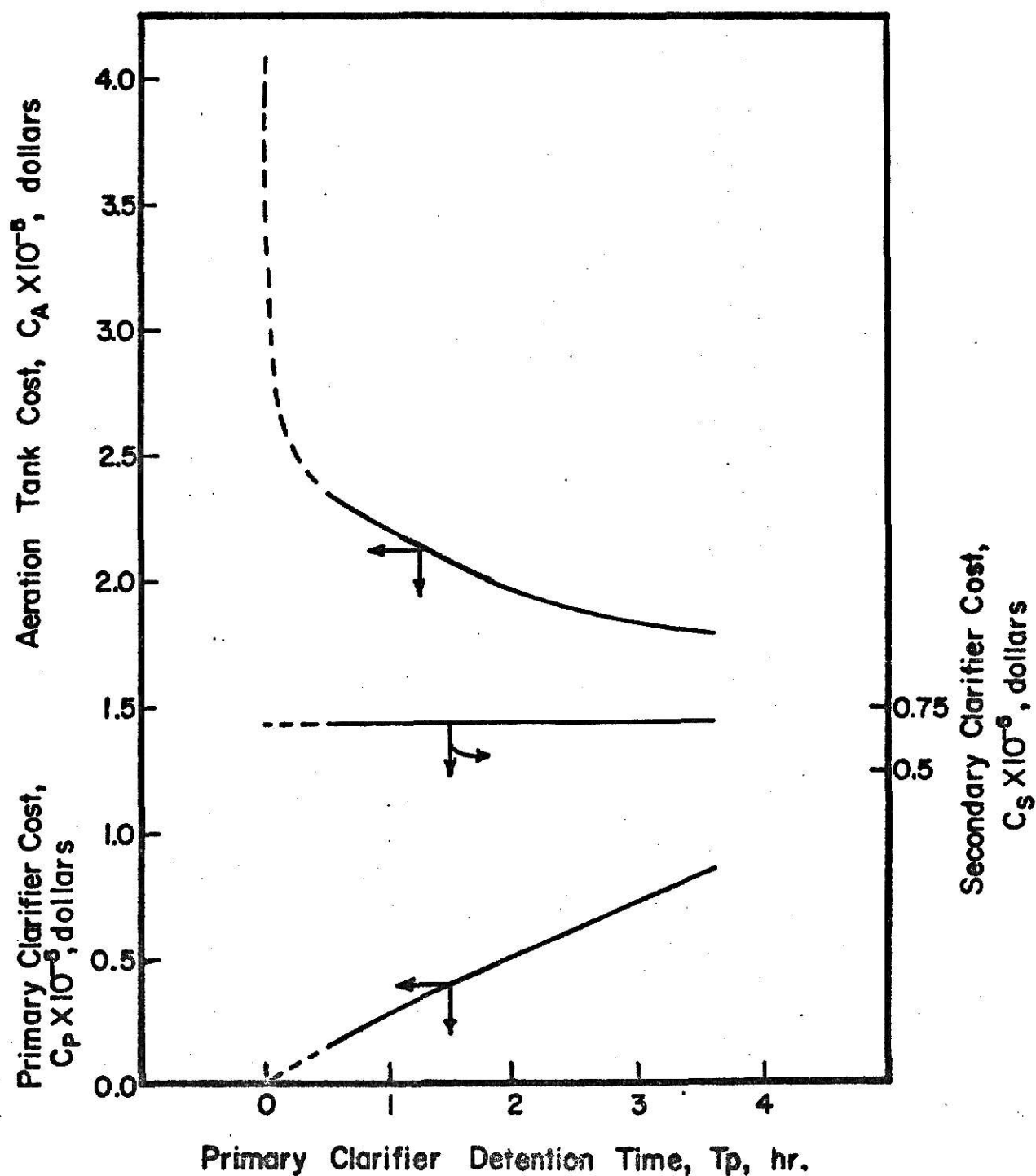


Fig. 9. Variations of C_p , C_A , and C_s with T_p for $q=3\text{MGD}$, $X_1^f=200\text{ppm}$, $X_3^f=200\text{ppm}$, $h_3=0.25$ and $X_2^f=8,000\text{ppm}$

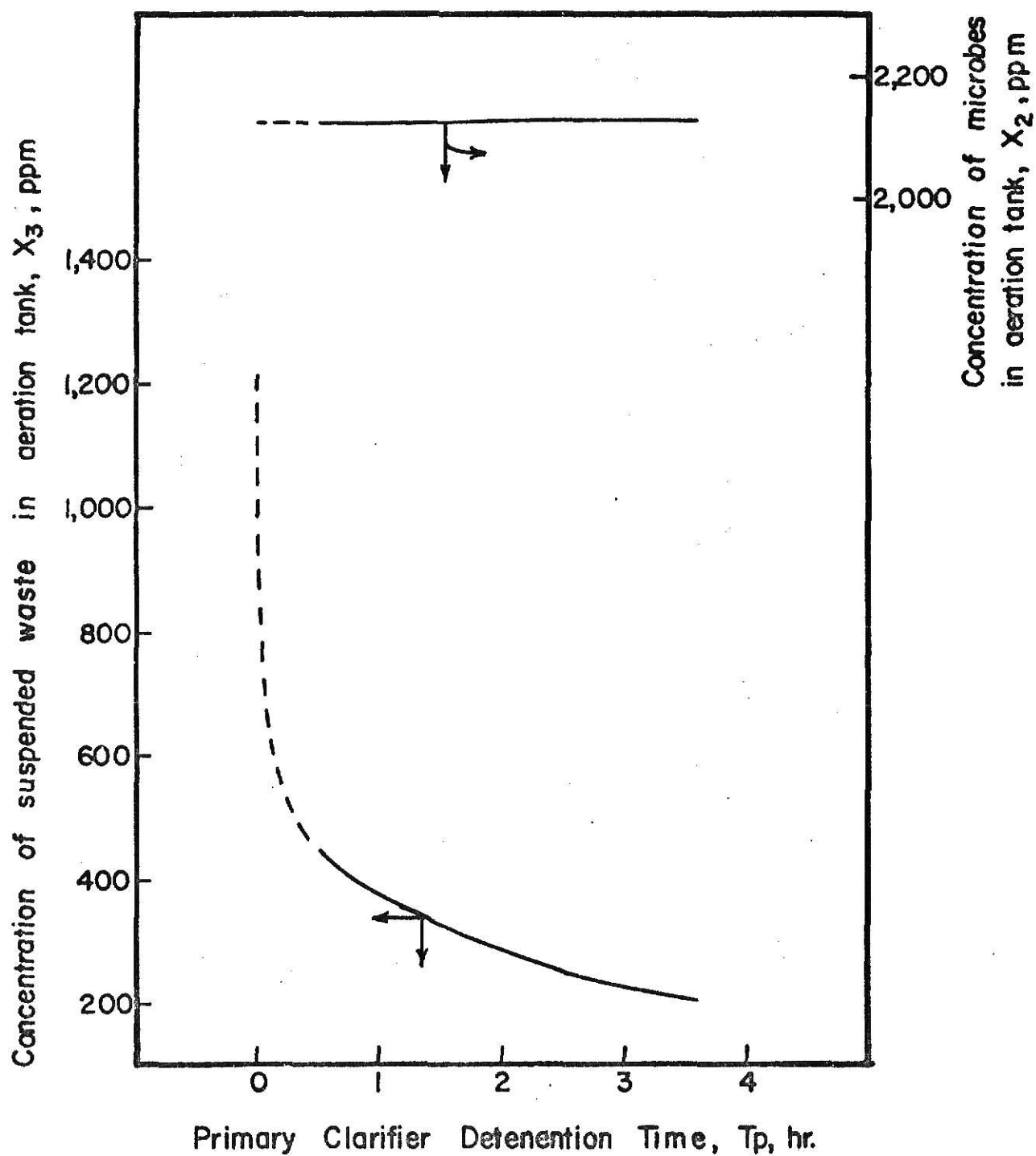


Fig.10. Variations of X_2 and X_3 with T_p for $q=3\text{MGD}$, $X_1^f=200\text{ppm}$, $X_3^f=200\text{ppm}$, $h_3=0.25$ and $X_2^r=8,000\text{ppm}$

the viability or activity of the mixed liquor suspended solids (organisms plus suspended waste) can be enhanced by increasing the primary clarifier size.

In Fig. 11, the mixed liquor suspended solids concentration in the recycle stream ($x_3^r + x_2^r$) is fixed at 10,000 ppm. The variations in concentration of suspended waste and of microbes in the aeration tank are given as functions of the primary clarifier detention time. The ratio of the suspended waste concentration to microbe concentration in the aeration tank decreases approximately from 0.93 to 0.17 as the primary clarifier detention time increases from 0.0 to 3.5 hr. Again, an increase in the primary clarifier detention time brings about an increase in the percentage of microbes in the mixed liquor suspended solids.

2.5.6 Parallel Biochemical Oxidation Model Without Masking Effect

Figure 12 shows the variation of the total system volume as a function of the primary clarifier detention time for the case without masking effect. The parameter is the influent suspended waste concentration x_3^f . Both $x_2^r = 8,000$ ppm and $x_2^r + x_3^r = 8,000$ ppm cases are compared. When $x_2^r = 8,000$ ppm, the total volume is a monotonically increasing function of the primary clarifier detention time. It can be observed that the inclusion of a primary clarifier is not economically advantageous in this case. This result is similar to that obtained by Mishra et al. [1], Sedzikowski [16] and Parkin [17]. It can also be seen that the effect of suspended waste concentration on the total volume is not appreciable for this case where x_2^r is fixed at 8,000 ppm.

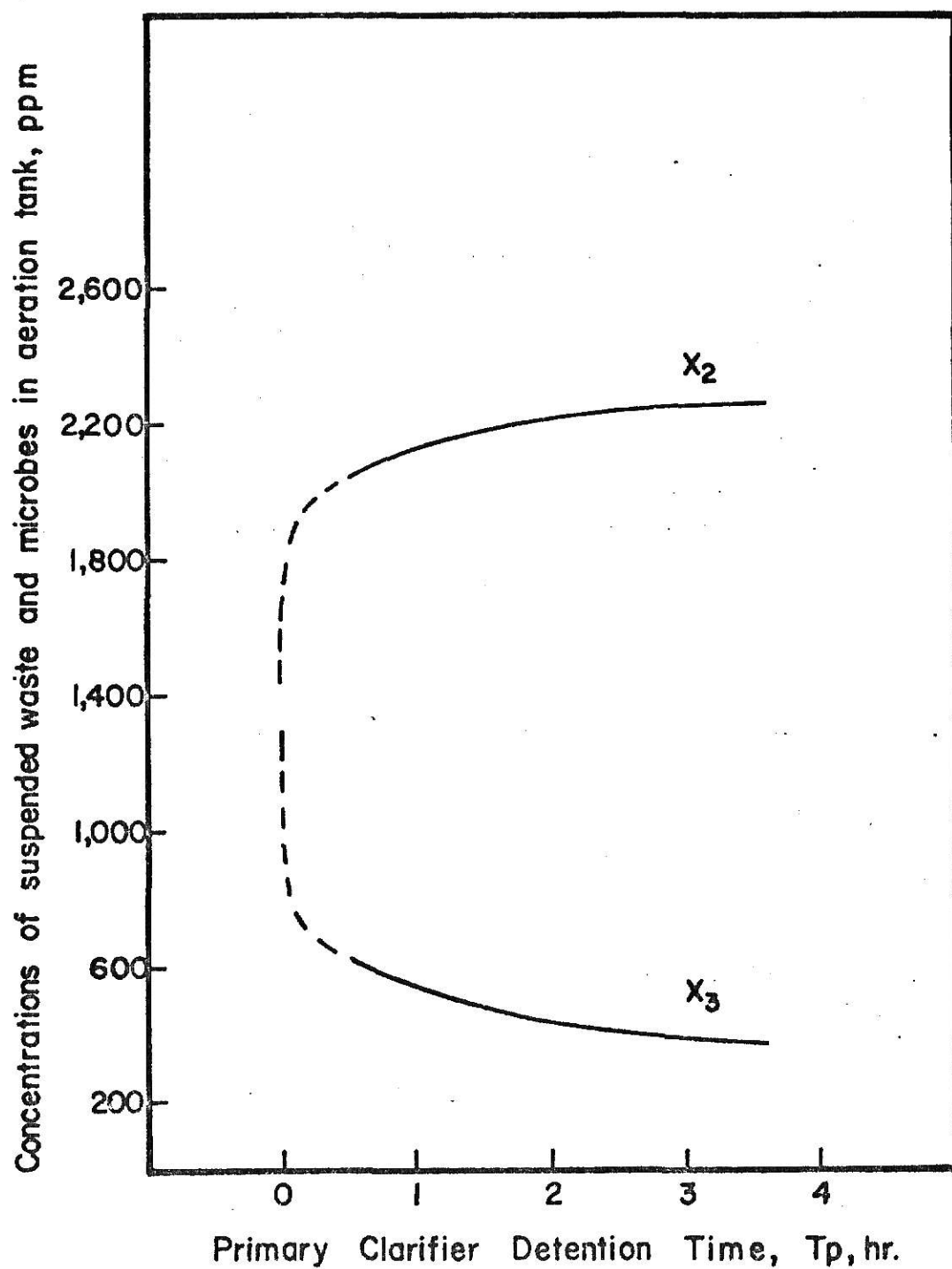


Fig.II. Variations of X_2 and X_3 with T_p for $q=3\text{MGD}$, $X_1^f=200\text{ppm}$, $X_3^f=200\text{ppm}$, $h_3=0.25$, and $X_2^r + X_3^r=10,000\text{ppm}$

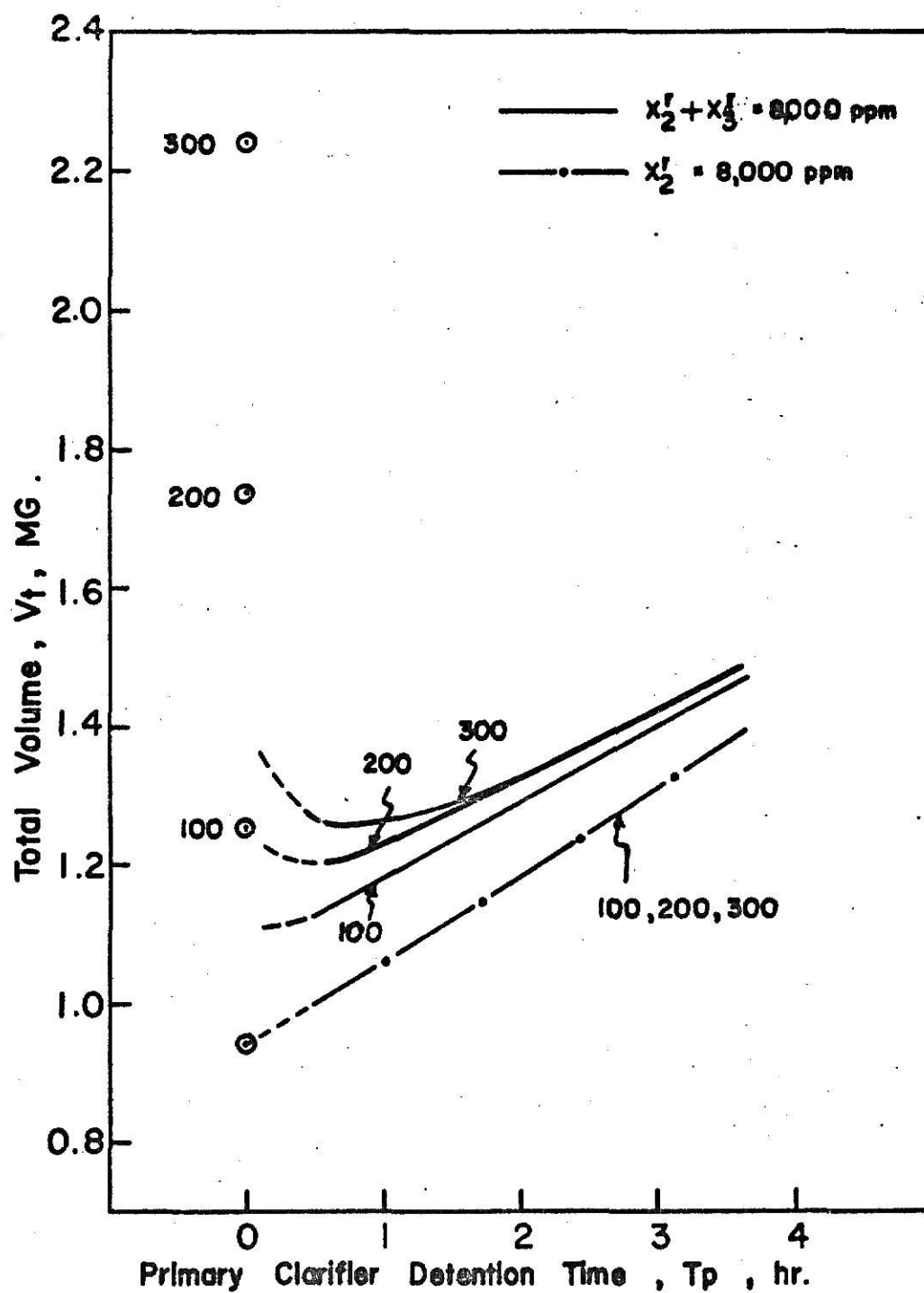


Fig. 12. Variations of V_t with T_p for $q = 3 \text{ MGD}$, $X_1^f = 200 \text{ ppm}$ and $h_3 = 0$ with $X_3^f = 100, 200, 300 \text{ ppm}$.

This result is supported by the plant scale study of Von der Emde [18]. He indicated that some activated sludge plants without primary sedimentation have the same degree of purification as some plants with primary tanks, for the same aeration tank detention time and same organic load. However, for the case $x_2^r + x_3^r = 8,000$ ppm, the optimal size of primary clarifier increases with an increase in the influent suspended waste concentration. The total volume generally increases with the increase in x_3^f in this case.

Figure 13 exhibits the variation of the total cost as a function of the primary clarifier detention time with the influent suspended waste concentration x_3^f as parameter. When $x_2^r = 8,000$ ppm, the total cost is lowest when the system does not contain the primary clarifier. Again, the effect of suspended waste concentration on the total cost of the system is negligible for this case. While for $x_2^r + x_3^r = 8,000$ ppm, the optimal primary clarifier detention time, for the minimum total cost, increases with the increase in x_3^f . The total cost also increases with the increase in x_3^f when $x_2^r + x_3^r = 8,000$ ppm.

2.5.7 Influence of the Underflow Sludge Concentration on the Optimal Primary Clarifier Size, Total Volume and Total Cost

Figures 14 and 15 present the variations of the total volume and cost of the system as functions of the primary clarifier detention time with x_2^r as parameter for certain influent conditions. The simulation results indicate that an increase in x_2^r reduces the optimal total volume and cost of the system. This can be attributed to the fact that an increase in x_2^r reduces the required volume of the aeration tank and only

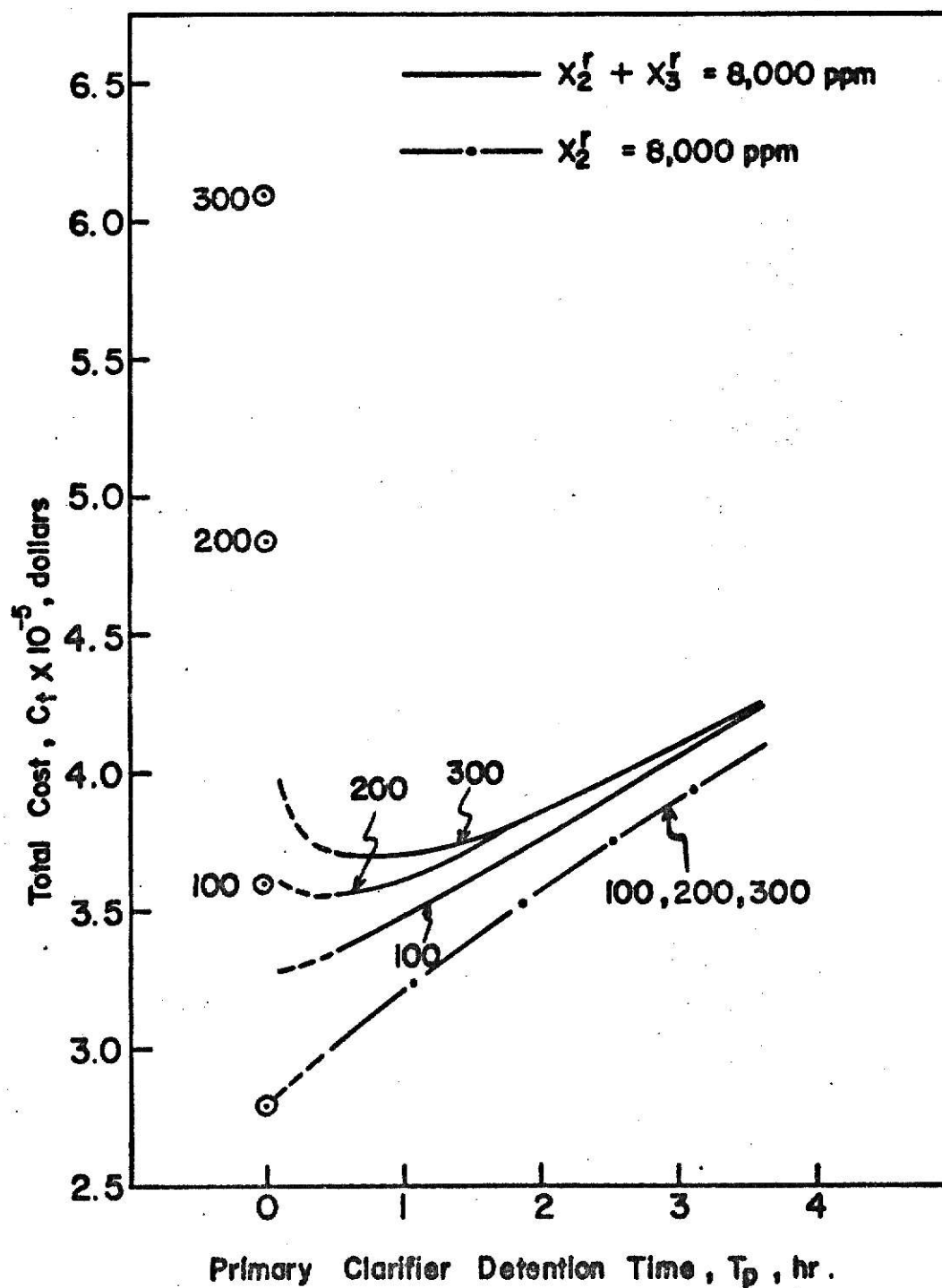


Fig. 13. Variation of C_t with T_p for $q = 3 \text{ MGD}$, $X_1^f = 200 \text{ ppm}$ and $h_3 = 0$ with $X_3^f = 100, 200, 300 \text{ ppm}$.

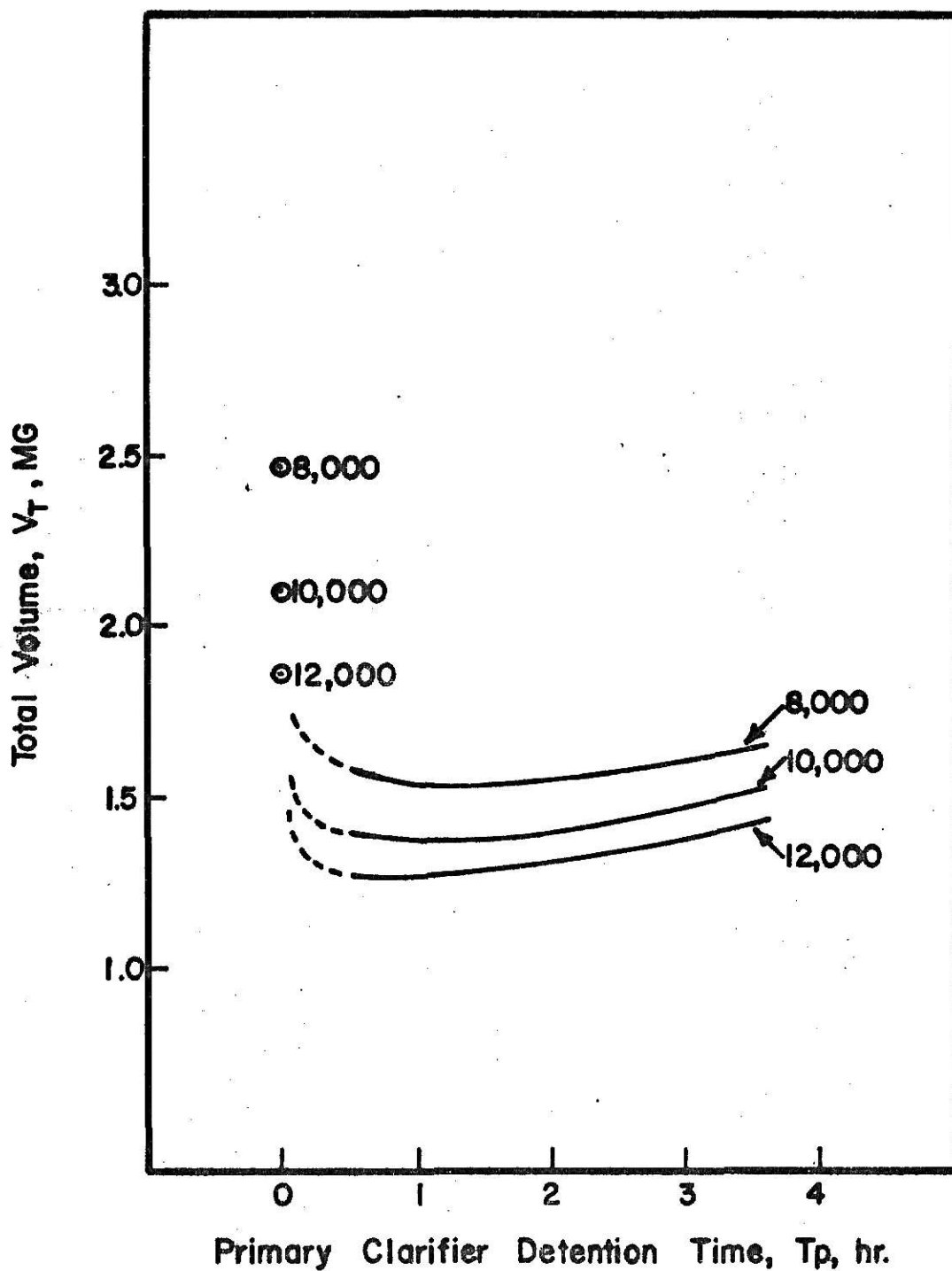


Fig. 14. Variations of V_T with T_p for $q=3$ MGD, $X_1^f=200$ ppm, $X_3^f=200$ ppm and $h_3=0.25$ with X_2^r as parameter

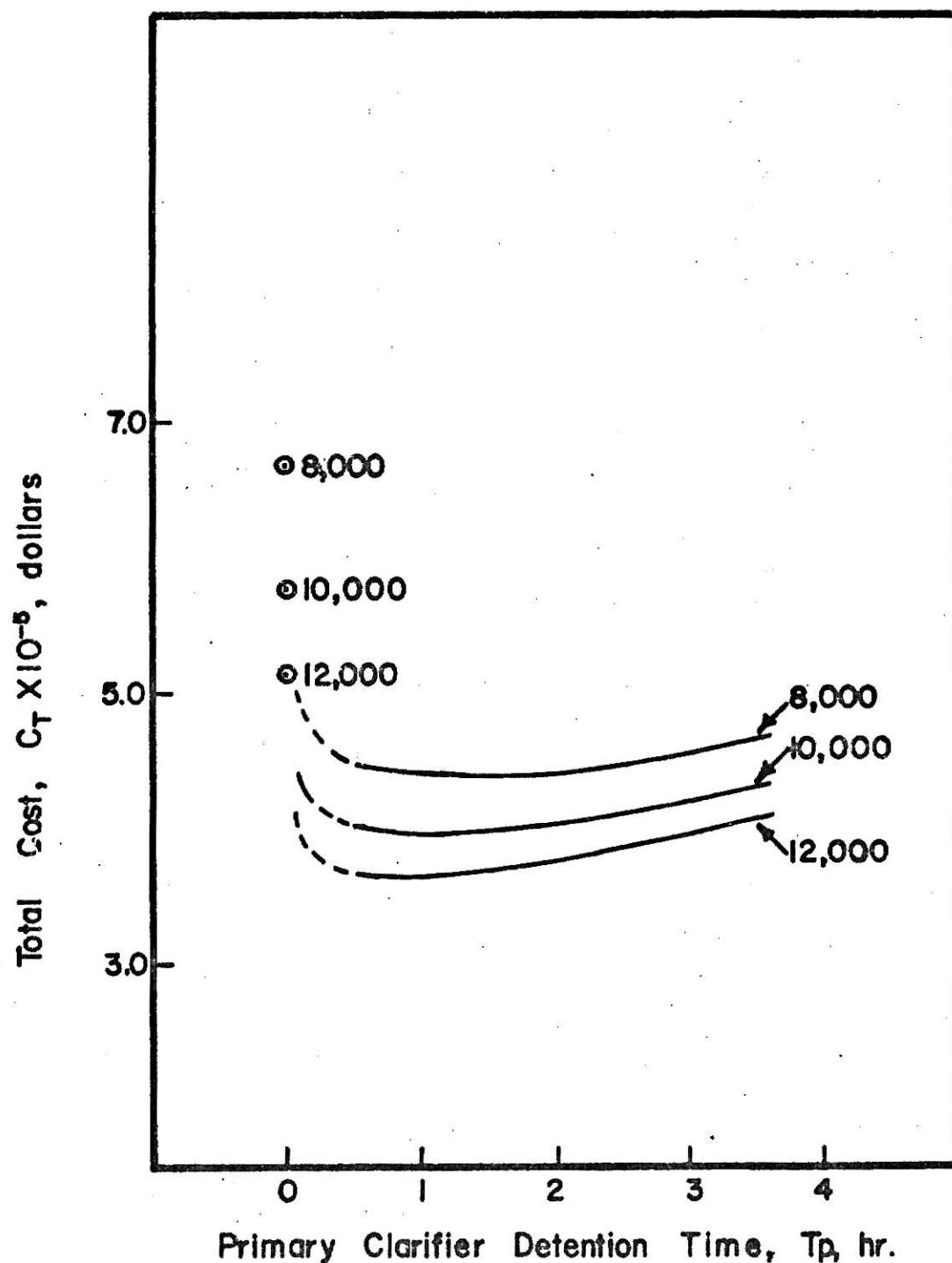


Fig. 15. Variation of C_T with T_p for $q=3\text{MGD}$, $X_1^r=200\text{ppm}$, $X_3^r=200\text{ppm}$ and $h_3=0.25$ with X_2^r as parameter

slightly increases the required volume of the final clarifier. It can also be seen that the optimal detention time of the primary clarifier decreases with an increase in x_2^r . For the minimum total volume, the optimal primary clarifier detention time decreases approximately from 1.25 hr to 0.8 hr as x_2^r increases from 8,000 ppm to 12,000 ppm as shown in Fig. 14; and for the minimum total cost, the optimal primary clarifier detention time decreases approximately from 1.5 hr to 0.75 hr as x_2^r increases from 8,000 ppm to 12,000 ppm as shown in Fig. 15.

Figures 16 and 17 exhibit the variations of the total volume and cost of the system with respect to the primary clarifier detention time when $(x_2^r + x_3^r)$ is fixed at 8,000 ppm, 10,000 ppm and 12,000 ppm instead of x_2^r . Again, the results indicate that an increase in $(x_2^r + x_3^r)$ reduces the total volume and cost of the system. The optimal detention time of the primary clarifier decreases with an increase in $(x_2^r + x_3^r)$. For the minimum total volume, the optimal detention time decreases approximately from 2.0 hr to 1.0 hr as $(x_2^r + x_3^r)$ increases from 8,000 ppm to 12,000 ppm as shown in Fig. 16; and for minimum total cost, the optimal detention time decreases approximately from 2.25 hr to 1.25 hr as $(x_2^r + x_3^r)$ increases from 8,000 ppm to 12,000 ppm as shown in Fig. 17.

2.6 CONCLUSIONS

The concepts of parallel reaction and masking effect are mathematically modeled. The masking effect coefficient included in the model is estimated based on the available experimental data. Major features of the modified model appear to be consistent with the available experimental data.

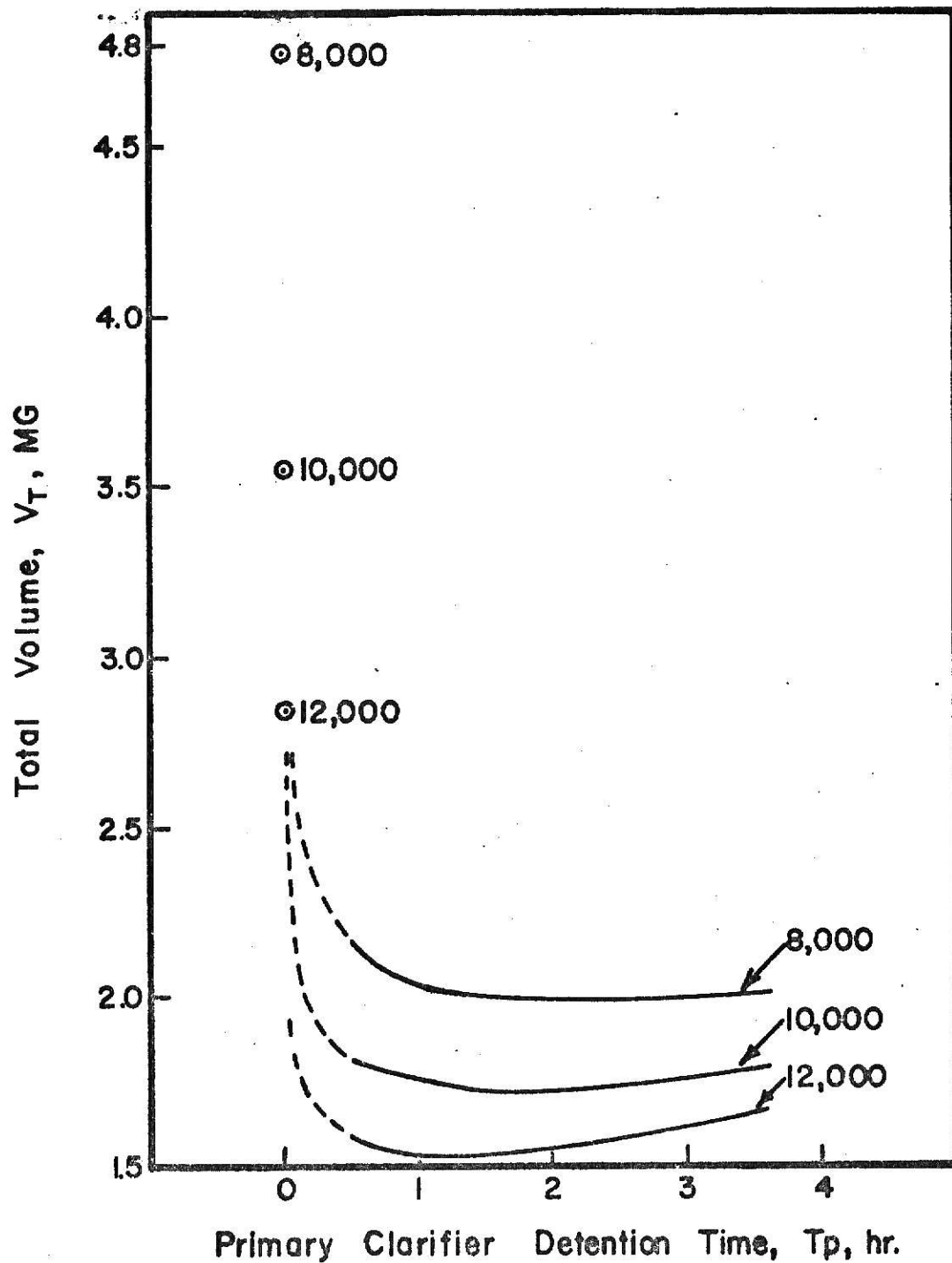


Fig. 16. Variations of V_T with T_p for $q=3\text{MGD}$, $X_1^f=200\text{ppm}$, $X_3^f=200\text{ppm}$ and $h_3=0.25$ with $X_2^f + X_3^f$ as parameter

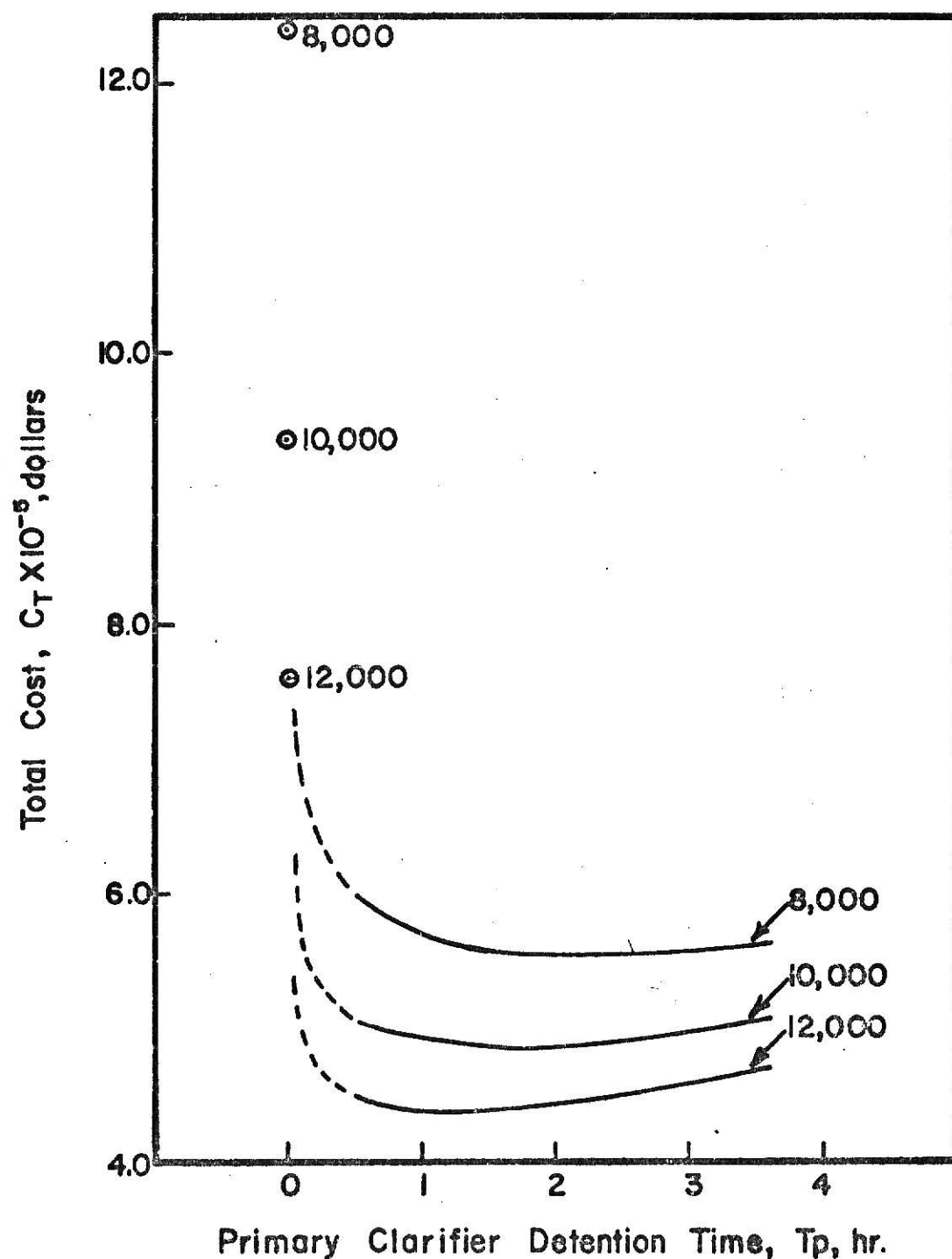


Fig.17. Variations of C_T with T_p for $q=3$ MGD, $X_1^f=200$ ppm, $X_3^f=200$ ppm and $h_3=0.25$ with $X_2^r + X_3^r$ as parameter

The proposed model can be effectively used for estimating the optimal size of the primary clarifier in the activated sludge process. The study points out that both the concentration and the masking effect of influent suspended waste are important factors for the determination of the optimal size of the primary treatment system.

The results of this investigation also indicate that an increase in the primary clarifier detention time gives rise to an increase in the content of microbes in the mixed liquor inside the aeration tank.

The optimal primary clarifier detention time obtained in this study is for the secondary waste treatment system with the recycle ratio and exit soluble substrate concentration fixed. Optimization of the overall activated sludge process including a primary clarifier is treated in Chapter 4 with both the recycle ratio and exit soluble substrate concentration relaxed as the design, or control variables.

2.7 NOMENCLATURE

A_p	Surface area of the primary clarifier, ft^2 .
A_s	Surface area of the secondary clarifier, 1000 ft^2 .
C_1	Conversion coefficient for microbes, BOD ppm/microbes ppm.
C_2	Conversion coefficient for suspended waste, BOD ppm/suspended waste
C_A	Construction cost of the aeration vessel, \$.
C_d	Effluent quality criterion, BOD ppm.
C_p	Construction cost of the primary clarifier, \$.
C_s	Construction cost of the secondary clarifier, \$.

C_T	Construction cost of the total treatment system, \$.
h_3	Masking effect coefficient, dimensionless.
k_d	Endogenous rate coefficient, hr^{-1} .
K_s	Saturation constant of soluble substrate, ppm.
p	Specific constant for secondary clarifier, dimensionless.
q	Volumetric flow rate of influent wastewater, MGD.
r	Sludge recycle ratio, dimensionless.
T_A	Aeration chamber detention time, hours.
T_P	Primary clarifier detention time, hours.
T_S	Secondary clarifier detention time, hours.
V_A	Aeration chamber volume, MG.
V_P	Primary clarifier volume, MG.
V_S	Secondary clarifier volume, MG.
V_T	Total system volume, MG.
w	Sludge wasting ratio, dimensionless.
x_1	Concentration of soluble substrate, ppm.
x_2	Concentration of microbes, ppm.
x_3	Concentration of suspended waste, ppm.
Y_1	Yield coefficient of soluble substrate, microbes ppm/BOD ppm.
Y_3	Yield coefficient of suspended waste, microbes ppm/suspended waste ppm.
α	Specific coefficient for secondary clarifier, dimensionless.
β_3	Removal rate coefficient of suspended waste, $1/\text{hr} \cdot \text{microbes ppm}$.

- γ Specific constant for secondary clarifier, hr^{-1} .
- μ_{ml} Maximum specific growth rate of microbes on
soluble substrate, hr^{-1} .

2.7.1 Superscripts

- 0 Influent to aeration tank from mixing point.
- 1 Effluent from aeration tank.
- e Effluent from clarifier overflow.
- f Feed or inflow to primary clarifier.
- r Secondary clarifier underflow and recycle flow.

2.7.2 Subscript

- p Effluent from primary clarifier overflow.

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CHAPTER 3

INFLUENCE OF SUSPENDED SOLIDS ON THE OPTIMAL DESIGN OF THE SECONDARY WASTE WATER TREATMENT SYSTEM

3.1 INTRODUCTION

In previous optimization studies of the activated sludge process [1-5], soluble and suspended substrates were considered as a single complex organic substrate to be removed by treatment systems composed of an aeration chamber and a secondary clarifier. Takahashi et al. [6] and McKinney [7] indicated that the removal rate of suspended waste* is generally much slower than that of soluble substrate. Takahashi et al. [6] also reported that the adsorption activity of activated sludge is reduced by the adsorption of colloids and is recovered by metabolizing these colloids. Nakanishi [8] conducted a series of batch experiments and showed that the removal rate of soluble substrate is decreased when suspended wastes coexist. Recently, Kuo et al. [9] proposed a parallel biochemical oxidation kinetic model to take into account the different removal rates of soluble and suspended substrate as well as the masking effect of suspended wastes. The effects of suspended wastes on the performance of secondary waste water treatment systems are not well understood. The rate of oxidation of both soluble and suspended substrate and the fraction of suspended solids that is

* In this work, the suspended wastes are nonviable suspended matter and are composed of organic biodegradable solids (suspended substrate) and non-biodegradable solids. The term suspended solids contain viable biomass and nonviable suspended matter (suspended wastes).

viable may be significantly affected by the concentration of suspended wastes.

The present study extends the earlier studies [2-5] by considering the masking effect and lower removal rate of suspended waste in the aeration chamber. The so-called parallel biochemical oxidation kinetic model [9] is employed to describe the removal kinetics of the soluble and suspended substrates in the aeration chamber. A pattern search technique [3, 10] is used to determine the optimal design of the secondary waste water treatment system depicted in Fig. 1. The exit concentration of soluble substrate from the aeration chamber and the sludge recycle ratio are optimally selected so that the total construction cost of the aeration tank, sedimentation vessel, and recycle pump is a minimum for a specified inlet sewage concentration and a fixed discharge criterion (total exit BOD concentration) which conforms to the water quality standard.

3.2 SYSTEM DESCRIPTION

Figure 1 is a schematic diagram of the secondary waste water treatment system considered in this study. The system consists of an aeration vessel, a secondary clarifier, and a recycle pump; the primary clarifier is not included in this study. Part of the sludge separated in the secondary clarifier is returned to the aeration vessel. The influent flow rate is considered constant. The effluent water quality is fixed at a set standard.

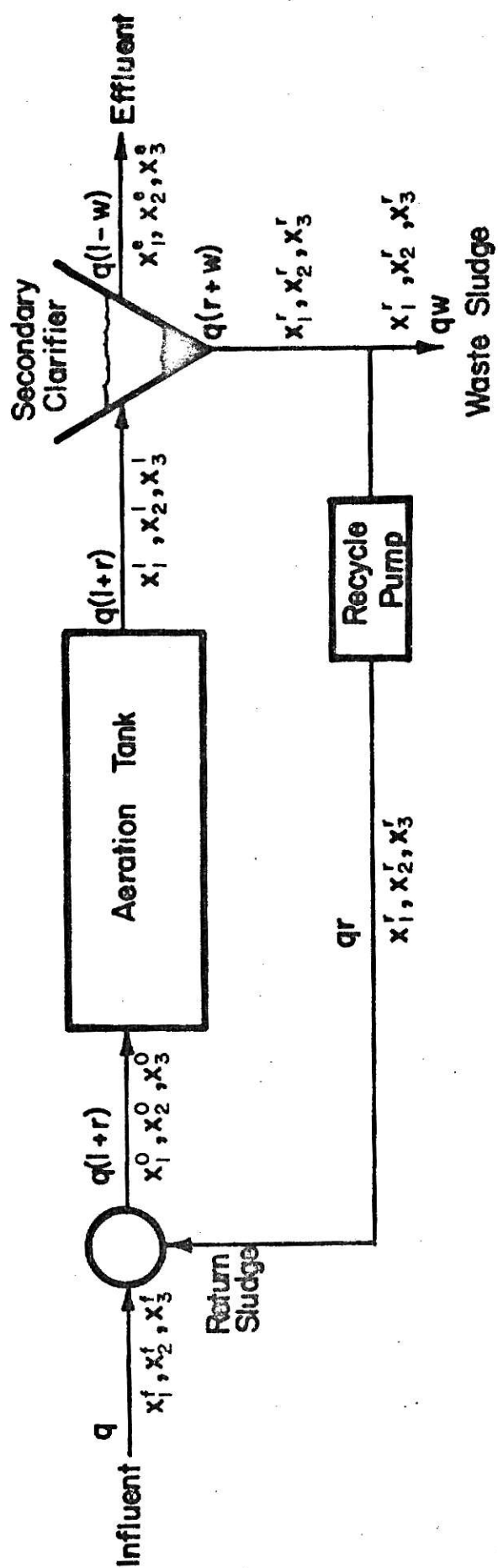


Figure 1. Schematic Diagram of the Activated-Sludge Process

3.2.1 Kinetic Model

As mentioned previously, a parallel biochemical oxidation kinetic model [9] is employed in this work. The different removal rates of soluble and suspended substrates as well as the masking effect of the suspended wastes are taken into account. The model equations are

$$\phi_1 = \frac{dx_1}{dt} = \frac{-\mu_{ml} x_1 x_2}{Y_1 (K_s + x_1 + h_3 x_3)} \quad (1)$$

$$\phi_2 = \frac{dx_2}{dt} = \frac{\mu_{ml} x_1 x_2}{K_s + x_1 + h_3 x_3} + \beta_3 x_3 x_2 - k_d x_2 \quad (2)$$

$$\phi_3 = \frac{dx_3}{dt} = -\beta_3 x_3 x_2 / Y_3 \quad (3)$$

Equations (1), (2), and (3) give, respectively, the removal rate of soluble substrates, the rate of increase of micro-organisms, and the removal rate of suspended wastes. The masking effect coefficient h_3 represents the specific degree of influence of suspended waste on the adsorption activity of activated sludge. The product $h_3 x_3$ implies the total masking effect.

3.2.2 Flow Model

In the aeration tank, a high degree of mixing is produced by the aeration device. For such a type of flow system, the so-called diffusion model has been successfully employed [3]. According to the diffusion model, the set of differential equations governing the steady state material balances for soluble substrate, microorganisms and suspended waste can be given by

$$\frac{1}{Pe} \frac{d^2 x_i}{d\eta^2} - \frac{dx_i}{d\eta} + \phi_i = 0 \quad i = 1, 2, 3 \quad (4)$$

For the simplicity of computation, the two extreme cases of the mixing in the aeration tank are considered in this study. One is the perfect mixing case in which $Pe \rightarrow 0$ and the other is the plug flow case in which $Pe \rightarrow \infty$.

3.2.3 Performance Equations

For the system shown in Fig. 1, the following system performance equations can be formulated.

3.2.3.1 Mixing point

A mixing point preceeding the aerator is used to represent the combination of the influent stream and the recycle stream from the secondary clarifier. Complete mixing is assumed at this point.

Material balances around the mixing point result in the equations

$$x_i^0 = \left(\frac{1}{1+r}\right) x_i^f + \left(\frac{r}{1+r}\right) x_i^r, \quad i = 1, 2, 3 \quad (5)$$

3.2.3.2 Aeration tank

In the case of plug flow, the steady state material balances for soluble substrate, microorganisms and suspended wastes can be given by

$$\frac{dx_i}{d\eta} = \phi_i, \quad i = 1, 2, 3 \quad (6)$$

subject to the boundary conditions at $\eta = 0$

$$x_i = x_i^0, \quad i = 1, 2, 3$$

For a CSTR, the steady state material balances for soluble substrate, microorganisms and suspended wastes can be written as

$$x_i^0 - x_i + T_A \phi_i = 0, \quad i = 1, 2, 3 \quad (7)$$

3.2.3.3 Secondary clarifier

Naito et al. [2] have proposed a model for the secondary clarifier by assuming that plug flow conditions prevail in it. According to this model, the rate of removal of micro-organisms and suspended waste in the secondary clarifier can be represented by the semi-empirical relationship.

$$(x_2^e + x_3^e) = p(x_2^1 + x_3^1)^\alpha \exp(-\gamma T_s) \quad (8)$$

In this expression, p , α , and γ are specific constants whose values depend on the characteristics of the sludge and equipment. It should be mentioned here that the mixed liquor suspended solids are assumed to be composed of microbes and suspended wastes when applying Naito's model. It is assumed that the microbes and suspended wastes have the same proportional compositions both in the mixed liquor suspended solids entering the secondary clarifier and in the recycle stream. Therefore,

$$\frac{x_2^1}{x_3^1} = \frac{x_2^e}{x_3^e} = \frac{x_2^r}{x_3^r} \quad (9)$$

It is also assumed that the concentration of soluble substrate is not affected by the secondary clarifier operation; that is,

$$x_1^l = x_1^r = x_1^e \quad (10)$$

The material balances for the microbes and suspended waste around the secondary clarifier can be written, respectively, as

$$(1 + r) x_2 = (1 - w) x_2^e + (r + w) x_2^r \quad (11)$$

$$(1 + r) x_3 = (1 - w) x_3^e + (r + w) x_3^r \quad (12)$$

3.2.3.4 Effluent quality

In this work, a constraint is imposed on the system performance in terms of the quality of the effluent. The total BOD in the effluent is composed of soluble substrate which remains untreated in the aeration tank, microbes and suspended wastes which result from incomplete clarification in the secondary clarifier. The total effluent BOD can be expressed as

$$x_1^e + C_1 x_2^e + C_2 x_3^e = C_d \quad (13)$$

In this equation, C_d represents the total BOD in the effluent, and C_1 and C_2 are conversion coefficients which allow the microbes and suspended wastes, respectively, to be expressed in terms of their BOD.

3.3 PERFORMANCE INDEX

In this study, the total construction cost of the aeration chamber, the secondary clarifier, and the recycle pump are used as the performance index. The cost function is the sum of the costs of the individual units plus 40% of such costs to account for engineering fees. Operating and maintenance costs are not included. The capital cost considered for each unit of the system is based on unit construction cost correlations as presented by Smith [11]. Mathematically, the performance index can be expressed as

$$C_T = 1.4 [C_A + C_S + C_{RP}] \quad (14)$$

where C_A , C_S , and C_{RP} account for the construction cost of the aeration tank, secondary clarifier, and recycle pump, respectively. According to Smith (1968), C_A , C_S and C_{RP} are given, respectively, by

$$C_A = V_A (175,000 + 36,500 V_A^{-0.818}) \quad (15)$$

$$C_S = 12,600 A_S + 5,350 A_S^{-0.126} \quad (16)$$

$$C_{RP} = 3,650 + 1,150 r \cdot q \quad (17)$$

where V_A , the volume of the aerator, is in "million gallons"; A_S , the surface area of the secondary clarifier, is in "1,000 ft²"; and q , the influent flow rate, is in "million gallons per day".

3.4 OPTIMIZATION PROBLEM

Equations (1) through (12) provide a mathematical model of the secondary wastewater treatment system shown in Fig. 1. Equations (14) through (17) represent the objective function that is to be minimized. The minimization, subject to the equality constraints given by eqs. (1) through (13), can be accomplished when the values of q , x_1^f , x_2^f , x_3^f and $(x_2^r + x_3^r)$ are fixed. The degrees of freedom for this optimization problem are two. Here, r and x_1^r can be chosen as the independent or decision variables. To accomplish the desired minimization, the simplex pattern search method [3, 10] can be used.

3.5 RESULTS AND DISCUSSION

The minimization calculations have been carried out for several values of the masking effect coefficient h_3 and influent concentration of suspended wastes x_3^f both of which characterize the masking effect within the aeration vessel. The value of masking effect coefficient h_3 was estimated to be 0.289 based on Nakanishi's [8] experimental data [9]. Four values of the masking effect coefficient, $h_3 = 0.0, 0.3, 0.5$ and 1.0 , and three values of the influent concentration of suspended wastes, $x_3^f = 10, 100$, and 300 ppm are employed. Optimal results are obtained for the influent soluble substrate concentrations x_1^f ranging from 100 ppm to 500 BOD ppm.

The numerical values used for other parameters are as follows

$$x_2^f = 0 \text{ ppm} \quad p = 2.1$$

$$\mu_{m1} = 0.1 \text{ hr}^{-1} \quad \alpha = 0.5$$

$$K_s = 100 \text{ ppm} \quad \gamma = 0.74$$

$$Y_1 = 0.5 \quad C_1 = 0.5$$

$$k_d = 0.002 \text{ hr}^{-1} \quad C_2 = 0.2$$

$$Y_3 = 0.5 \quad C_d = 20 \text{ ppm}$$

$$H = 10 \text{ ft} \quad q = 3 \text{ MG/day}$$

$$(x_2^r + x_3^r) = 8,000 \quad \beta_3 = 0.0001$$

$$10,000 \text{ ppm} \quad 0.00001 \text{ ppm}^{-1} \text{ hr}^{-1}$$

$$12,000 \quad 0.000005$$

3.5.1 Influence of Suspended Waste on Optimal Design Policies

Figures 2 and 3 show surface contours of the objective function, the total construction cost C_T , with respect to the two independent variables, the sludge recycle ratio r and the concentration of soluble substrate leaving the aeration chamber x_1^1 . Figure 2 is for the case $h_3 = 0.0$, while Fig. 3 is for $h_3 = 0.3$. Comparison of Figs. 2 and 3 indicates that the optimal sludge recycle ratio r increases when the masking effect increases, while the optimal concentration of soluble substrate leaving the aeration chamber x_1^1 is hardly affected. The optimal r increases from 0.45 to 0.58 as h_3 increases from 0.0 to 0.3. It can also be observed that the optimal construction cost of the total system C_T also increases when the masking effect is enhanced. The optimal C_T is 2.08×10^5 dollars at $h_3 = 0.0$ and is 2.70×10^5 dollars at $h_3 = 0.3$.

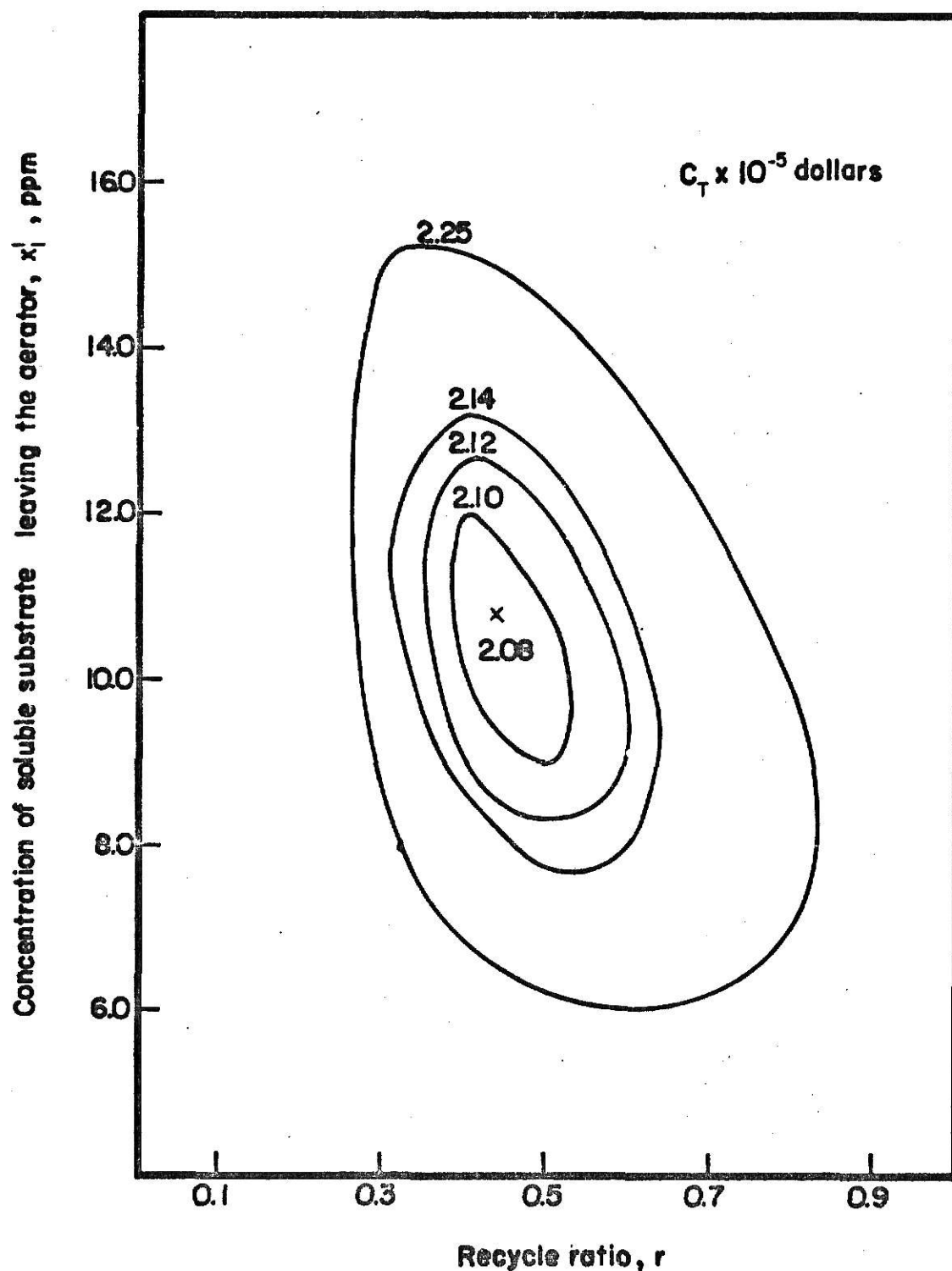


Fig.2. Surface contours of construction cost, C_T , with respect to r and x_1' with $x_2' + x_3' = 10,000$ ppm, $x_1' = 100$ ppm, $x_3' = 100$ ppm, $\beta_3 = 0.000001$ ppm⁻¹hr⁻¹ and $h_3 = 0.0$ (CSTR).

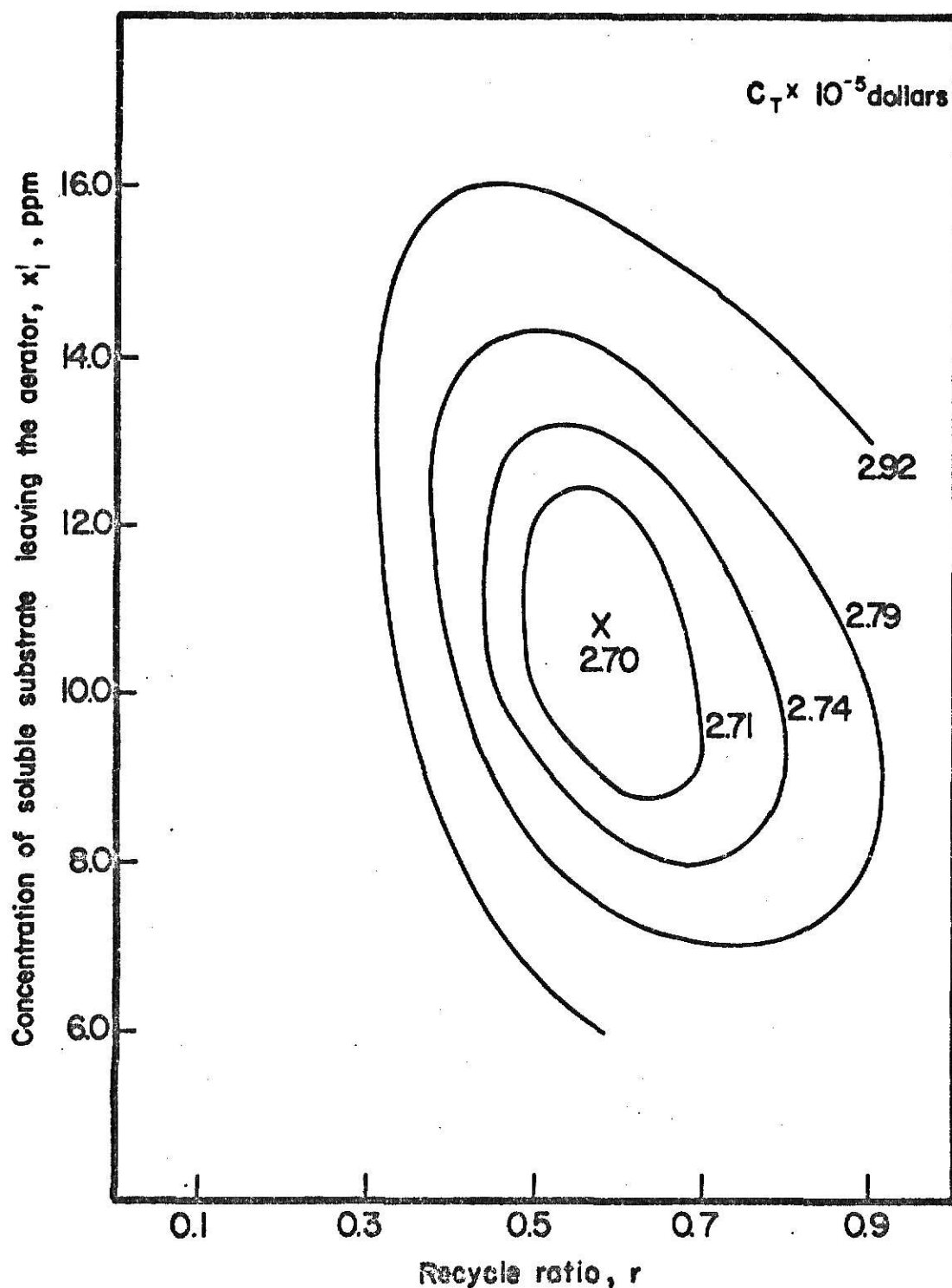


Fig. 3. Surface contours of construction cost, C_T , with respect to r and x'_1 with $x'_2 + x'_3 = 10,000$ ppm, $x'_1 = 100$ ppm, $x'_3 = 100$ ppm, $\beta_3 = 0.00001$ ppm⁻¹ hr⁻¹ and $h_3 = 0.3$ (CSTR).

Figures 4 through 9 show the variation of optimal design policies with influent soluble substrate concentration x_1^f . Figures 4 and 5 exhibit the variations of the optimal sludge recycle ratio r , the optimal aeration chamber detention time T_A , and the optimal detention time ratio of the aeration chamber to the secondary clarifier T_A/T_s . The parameters for Figs. 4 and 5 are h_3 and x_3^f , respectively. The results indicate that the magnitudes of r , T_A and T_A/T_s increase with an increase in x_1^f . This is consistent with the previous results obtained by Fan et al. [3]. Moreover, the optimal values of r , T_A and T_A/T_s increase with an increase in the masking effect. The changes are substantial when h_3 increases from 0.0 to 1.0 or x_3^f increases from 10 ppm to 300 ppm. For example, the optimal recycle ratio increases about 70% when h_3 goes from 0.0 to 1.0 and increases over 100% when x_3^f goes from 10 ppm to 300 ppm. Similarly, the optimal value of T_A increases approximately 80% with the increase in h_3 and increases about 50% with the increase in x_3^f . Similar increases are also observed in the values of the ratio T_A/T_s .

Figures 6 and 7 show the variations of the optimal concentrations leaving the aeration tank with respect to inlet soluble substrate concentration x_1^f ; x_1^1 is soluble substrate, x_2^1 is organism concentration, and x_3^1 is suspended wastes. The parameters are the masking effect coefficient h_3 in Fig. 6 and the influent suspended waste concentration x_3^f in Fig. 7. It can be seen that the optimal values of both x_1^1 and x_2^1 increase with an increase in x_1^f , while the optimal value of x_3^1 decreases with an increase in x_1^f . The optimal value of x_2^1 increases as h_3 increases. The optimal value of x_3^1 decreases and x_1^1 is unaffected by increases in h_3 .

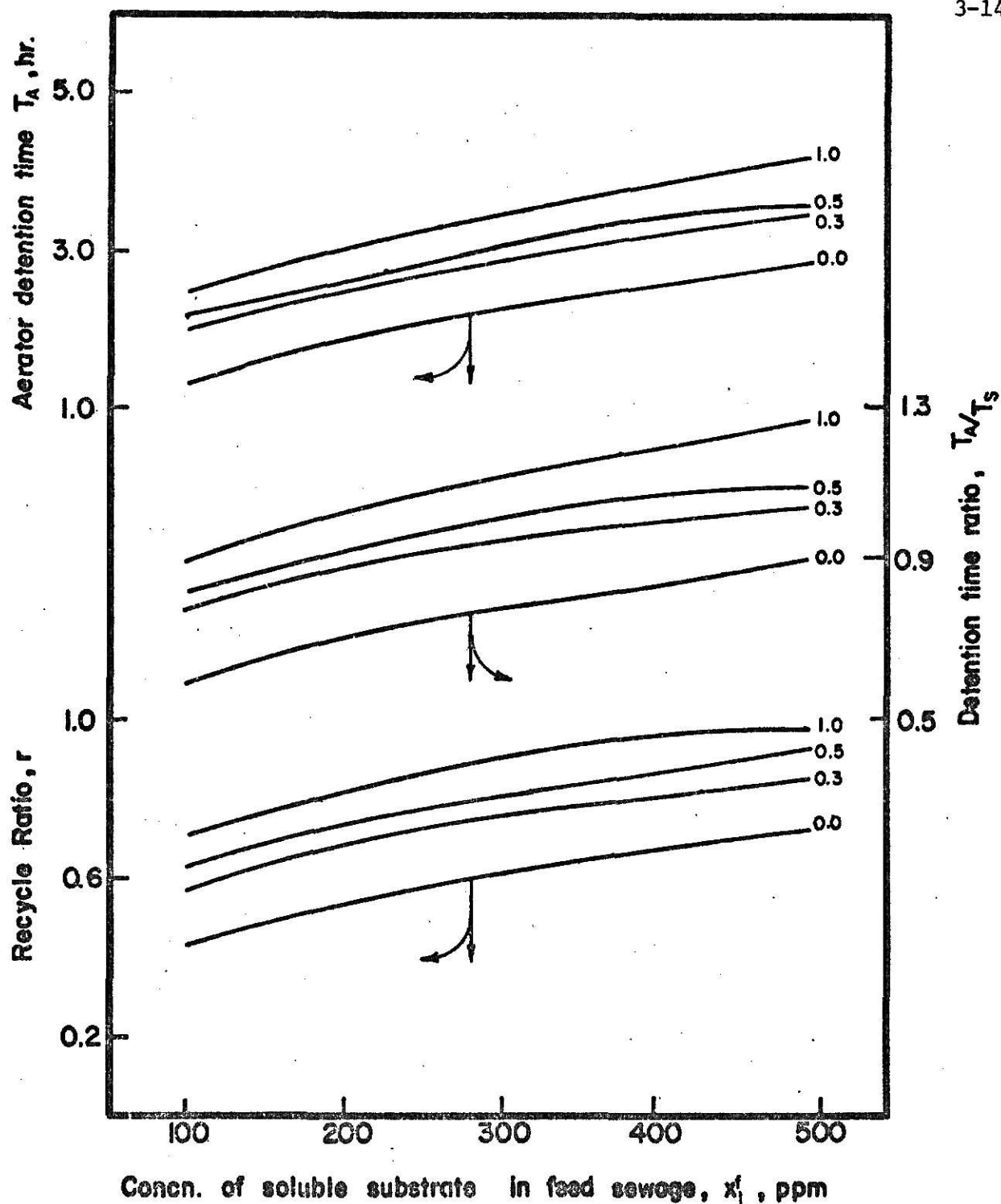


Fig. 4. Variation of optimal r , T_A and T_A/T_s with x'_1 for $\beta_3 = 0.00001 \text{ ppm}^{-1} \text{ hr}^{-1}$, $x'_3 = 100 \text{ ppm}$ and $x'_2 + x'_3 = 10,000 \text{ ppm}$ with h_3 as parameter (CSTR).

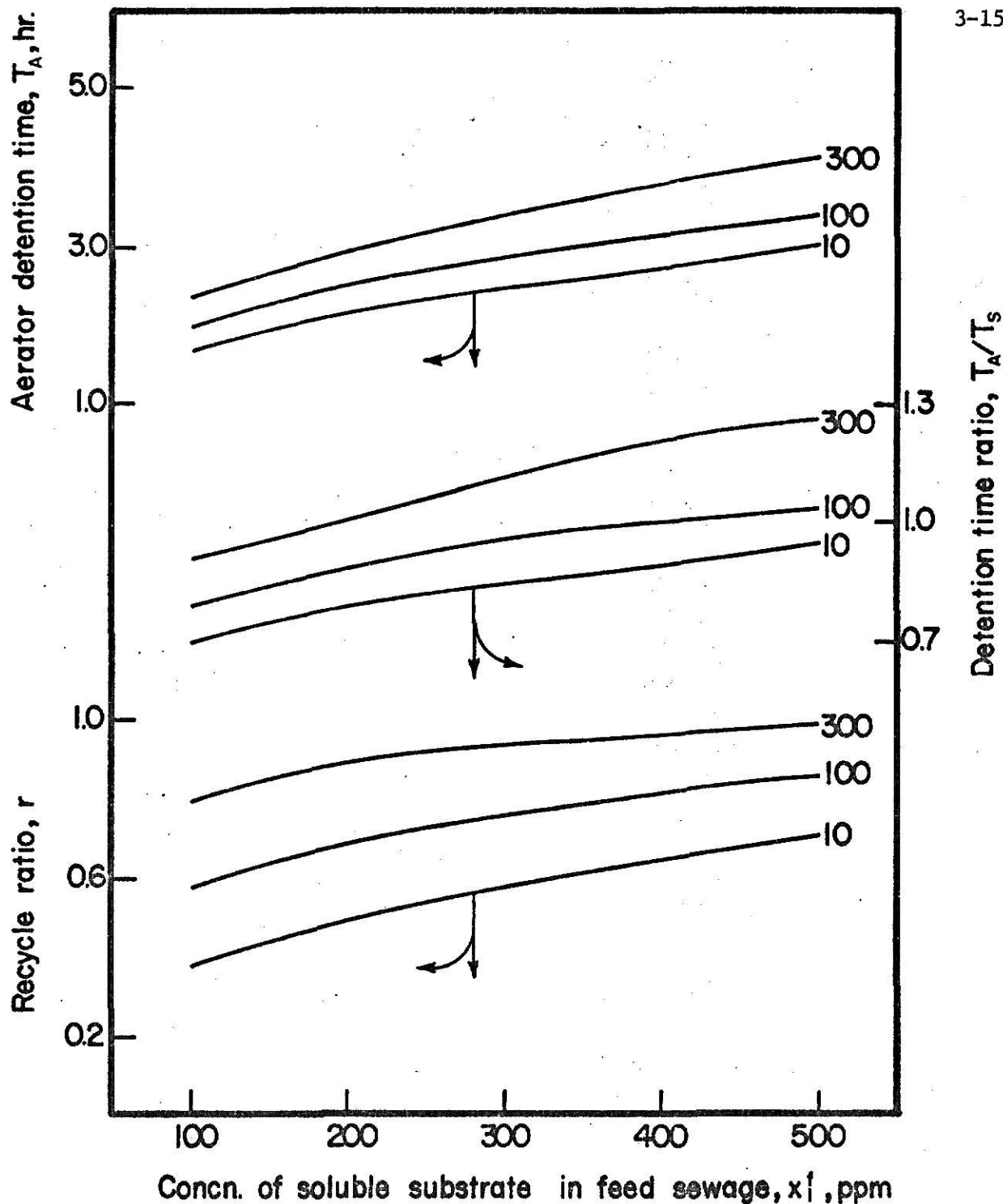


Fig. 5. Variation of optimal r , T_A and T_A/T_s with x_1^f for $\beta_3 = 0.000001 \text{ ppm}^{-1} \text{ hr}^{-1}$, $h_3 = 0.3$ and $x_2^f + x_3^f = 10,000 \text{ ppm}$ with x_1^f as parameter (CSTR).

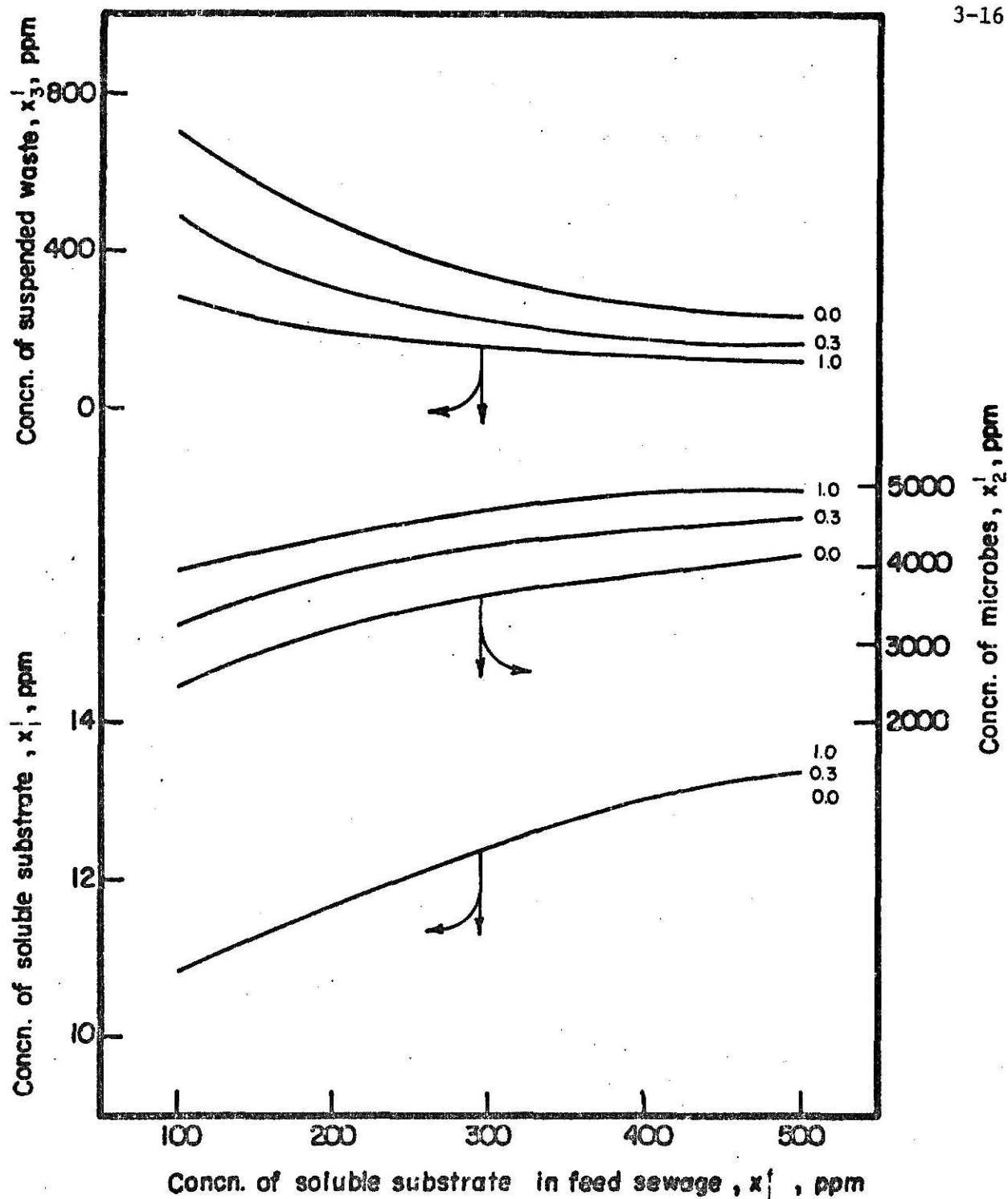


Fig.6. Variation of optimal x_1^f , x_2^f and x_3^f with x_1^f for $\beta_3 = 0.000001 \text{ ppm}^{-1} \text{ hr}^{-1}$, $x_3^f = 100 \text{ ppm}$ and $x_2^f + x_3^f = 10,000 \text{ ppm}$ with h_3 as parameter (CSTR).

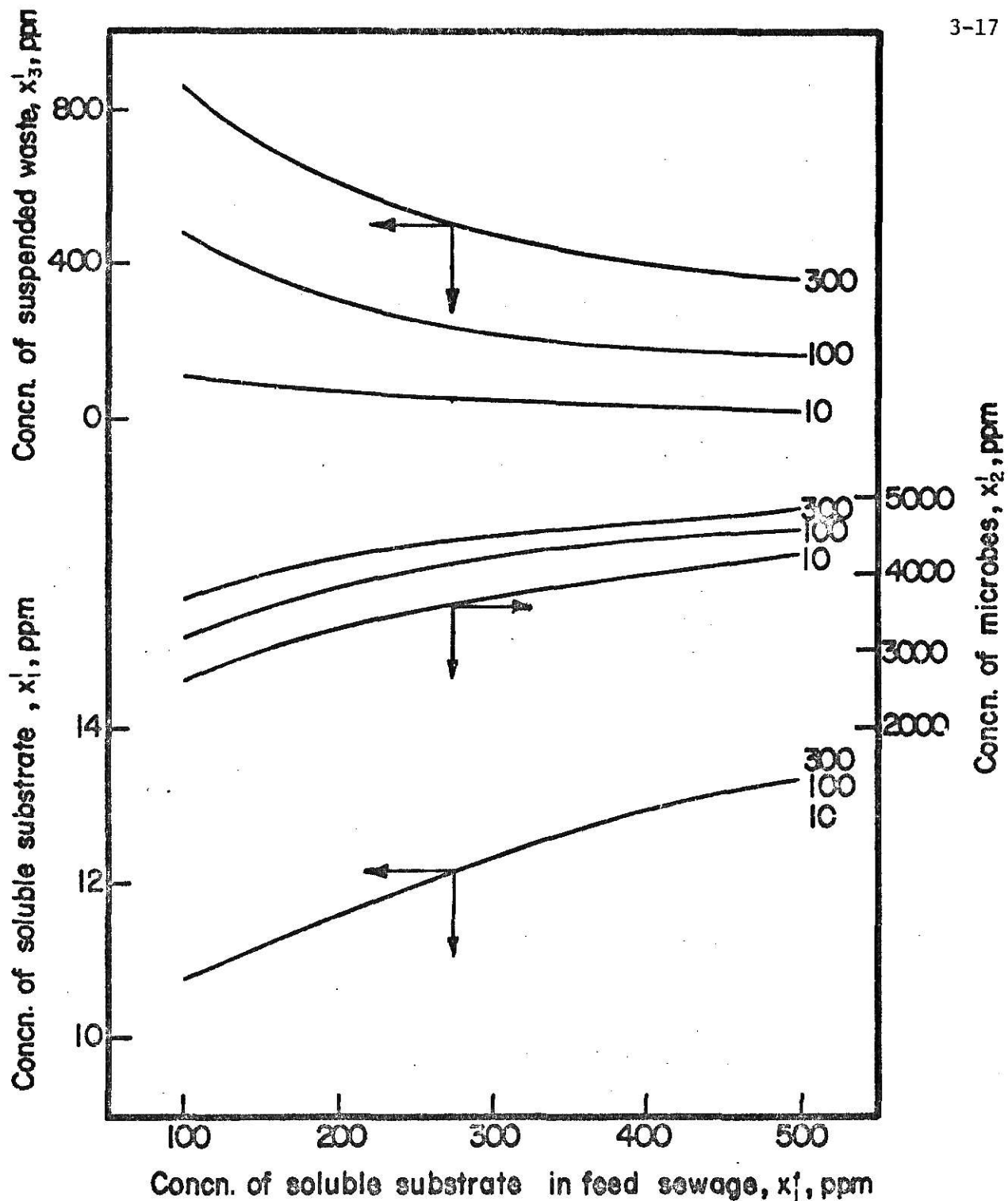


Fig. 7. Variation of optimal x_1' , x_2' , and x_3' with x_1' for $\beta_3 = 0.00001 \text{ ppm}^{-1} \text{ hr}^{-1}$, $h_3 = 0.3$ and $x_2' + x_3' = 10,000 \text{ ppm}$ with x_3' as parameter (CSTR).

The increase in x_2^1 is needed to consume the soluble substrate as the masking effect coefficient is enhanced. The reduction in x_3^1 results from increased consumption of suspended waste because of the increase in x_2^1 and the increase in T_A . In Fig. 7, the optimal value of x_1^1 is unaffected by a change in x_3^f ; however, both the optimal values of x_2^1 and x_3^1 increase as x_3^f increases. The increase in x_2^1 can be attributed to the need for microbes to consume the soluble substrate as the masking effect is enhanced, while the increase in x_3^1 results from the increase in x_3^f .

Figure 8 shows the variation of the optimal total construction cost C_T with respect to inlet soluble substrate concentration x_1^f . The parameter is the masking effect coefficient h_3 . The results indicate that the optimal value of C_T increases with an increase in h_3 . For example, C_T increases from 2.10×10^5 dollars to 3.25×10^5 dollars (about 55%) when h_3 goes from 0.0 to 1.0 at $x_1^f = 100$ ppm. Figure 9 shows the variation of the optimal value of C_T with respect to x_1^f with the influent suspended waste concentration x_3^f as parameter. The value of C_T increases with x_3^f ; for instance, C_T increases from 2.20×10^5 dollars to 3.25×10^5 dollars (about 45%) when x_3^f varies from 10 ppm to 300 ppm at $x_1^f = 100$ ppm. Since the aeration tank costs make up a greater portion of the total cost as x_1^f increases, the masking effect has a greater effect on cost when the inlet soluble substrate concentration is higher. For example, Fig. 8 indicates that the increase in C_T , due to a change in h_3 from 0.0 to 1.0, is 1.45×10^5 dollars at $x_1^f = 500$ ppm and is 1.00×10^5 dollars at $x_1^f = 100$ ppm. Similar results are also observed in Fig. 9.

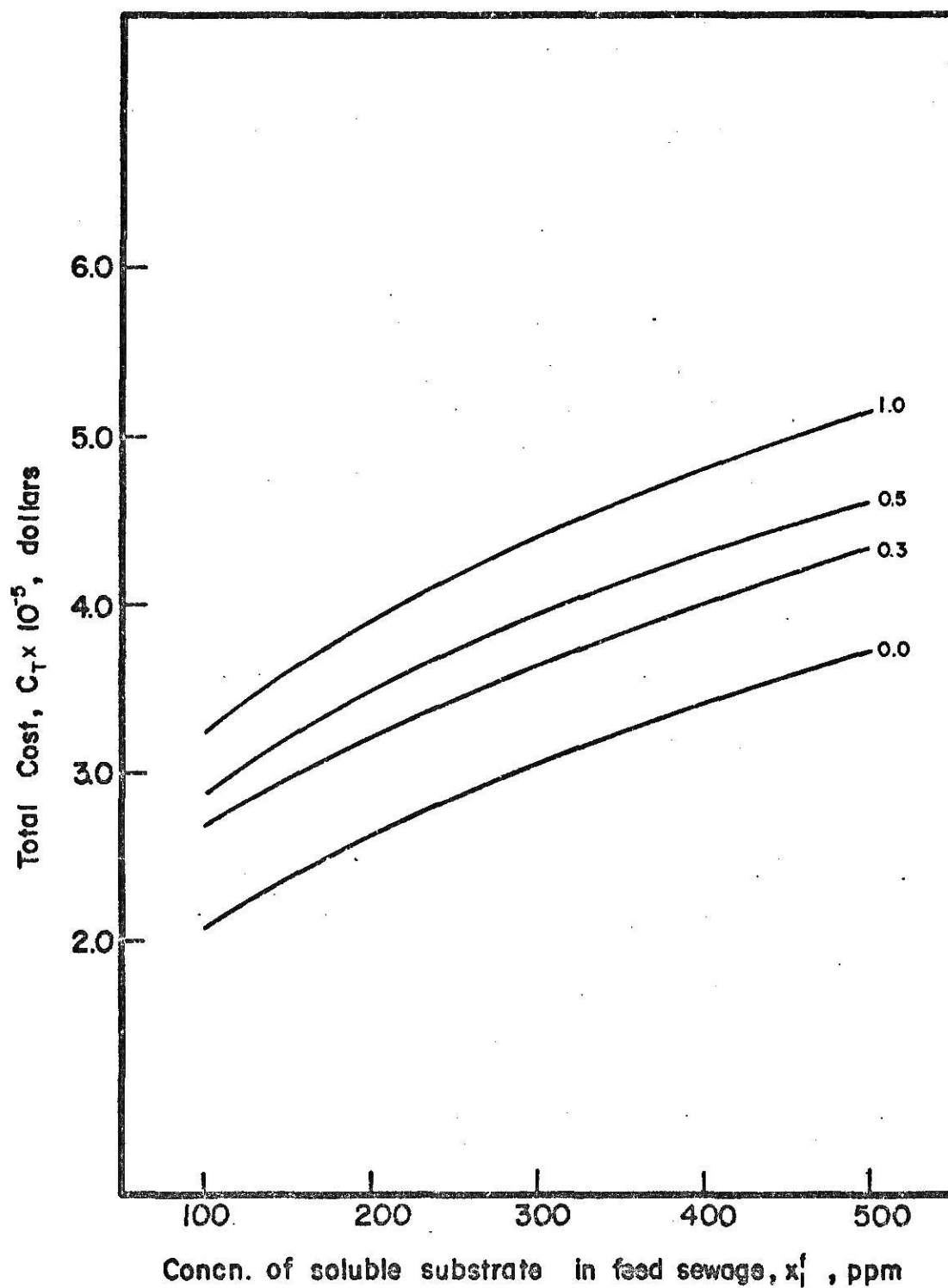


Fig. 8. Variation of optimal C_T with x_1^f for $\beta_3 = 0.00001 \text{ ppm}^{-1} \text{ hr}^{-1}$, $x_3^f = 100 \text{ ppm}$ and $x_2^f + x_3^f = 10,000 \text{ ppm}$ with h_3 as parameter (CSTR).

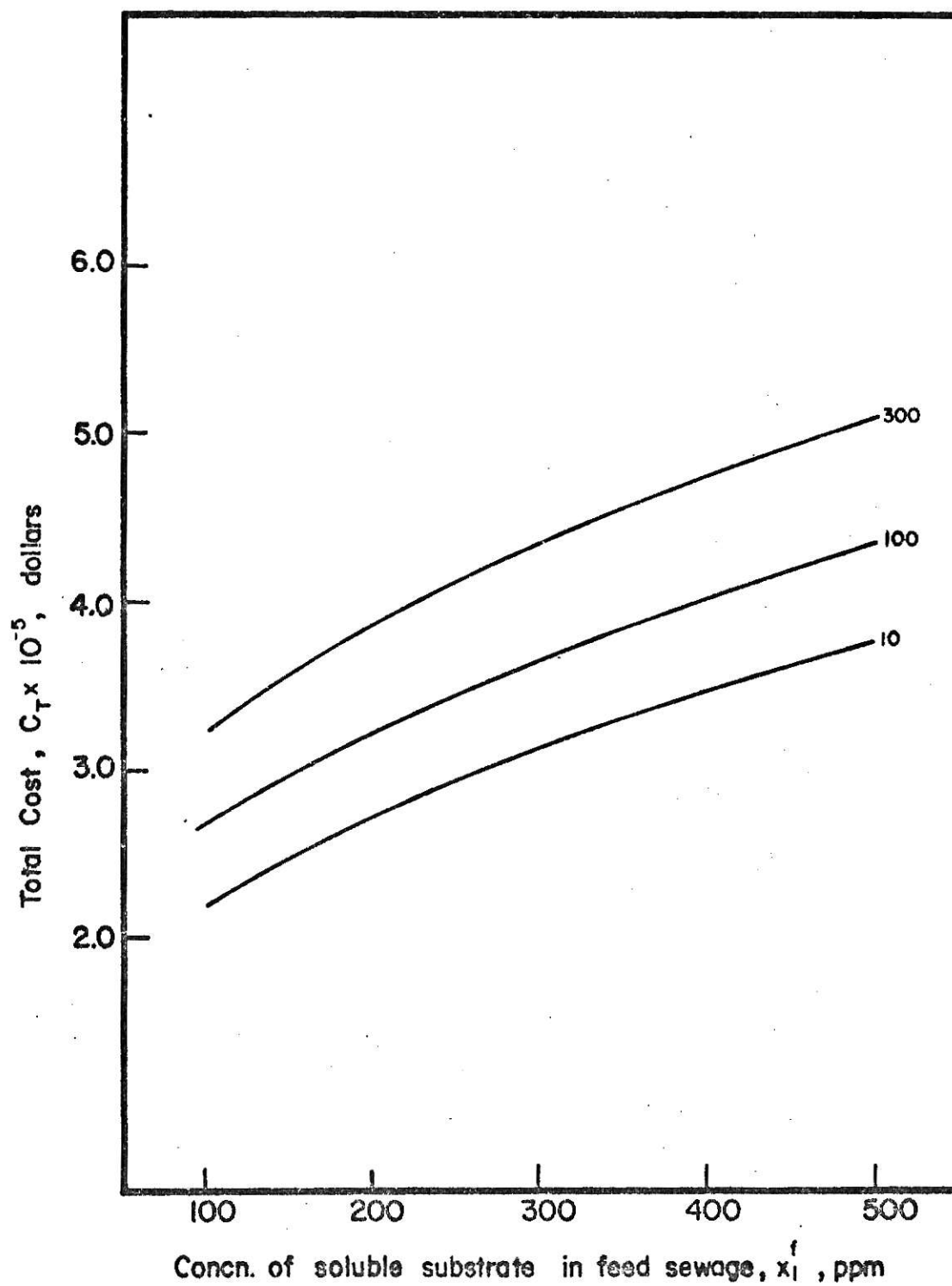


Fig. 9. Variation of optimal C_T with x_1^f for $\beta_3 = 0.00001 \text{ ppm}^{-1} \text{ hr}^{-1}$, $h_3 = 0.3$ and $x_2^f + x_3^f = 10,000 \text{ ppm}$ with x_3^f as parameter (CSTR).

Figures 10 through 12 present the effect of parameter β_3 , the metabolic rate constant for suspended waste, on the optimal design policies. Figure 10 indicates that the optimal values of r , T_A and T_A/T_S increase as β_3 decreases because the smaller suspended waste removal rate results in a greater masking effect. Figure 11 indicates that the optimal values of both x_2^1 and x_3^1 increase as β_3 decreases, but the optimal value of x_1^1 is not affected by the change in β_3 . The increase in x_2^1 is the result of an increase in the recycle ratio, but the increase in r can be attributed to the masking effect. The increase in x_3^1 is due to the reduction in the specific removal rate of suspended waste and the increase in recycle ratio. Figure 12 shows that the optimal value of C_T increases as β_3 decreases, as expected.

3.5.2 Effect of Secondary Clarifier Performance on the Optimal Design Policies

Figures 13 and 14 show the variation of the optimal design conditions with inlet soluble substrate concentration x_1^f at various underflow sludge concentrations $(x_2^r + x_3^r)$. The results indicate how the performance of the secondary clarifier affects the optimal design policies for the overall system. Figure 13 shows that the optimal values of r , T_A and T_A/T_S decrease as $(x_2^r + x_3^r)$ increases. Figure 14 indicates that the optimal value of x_1^1 decreases as $(x_2^r + x_3^r)$ increases, while x_2^1 increases with an increase in underflow concentration. The optimal value of x_3^1 is unaffected by the change in $(x_2^r + x_3^r)$. The increase in the organism concentration leaving the aeration tank x_2^1 is directly due to the increase in the underflow sludge concentration $(x_2^r + x_3^r)$. The

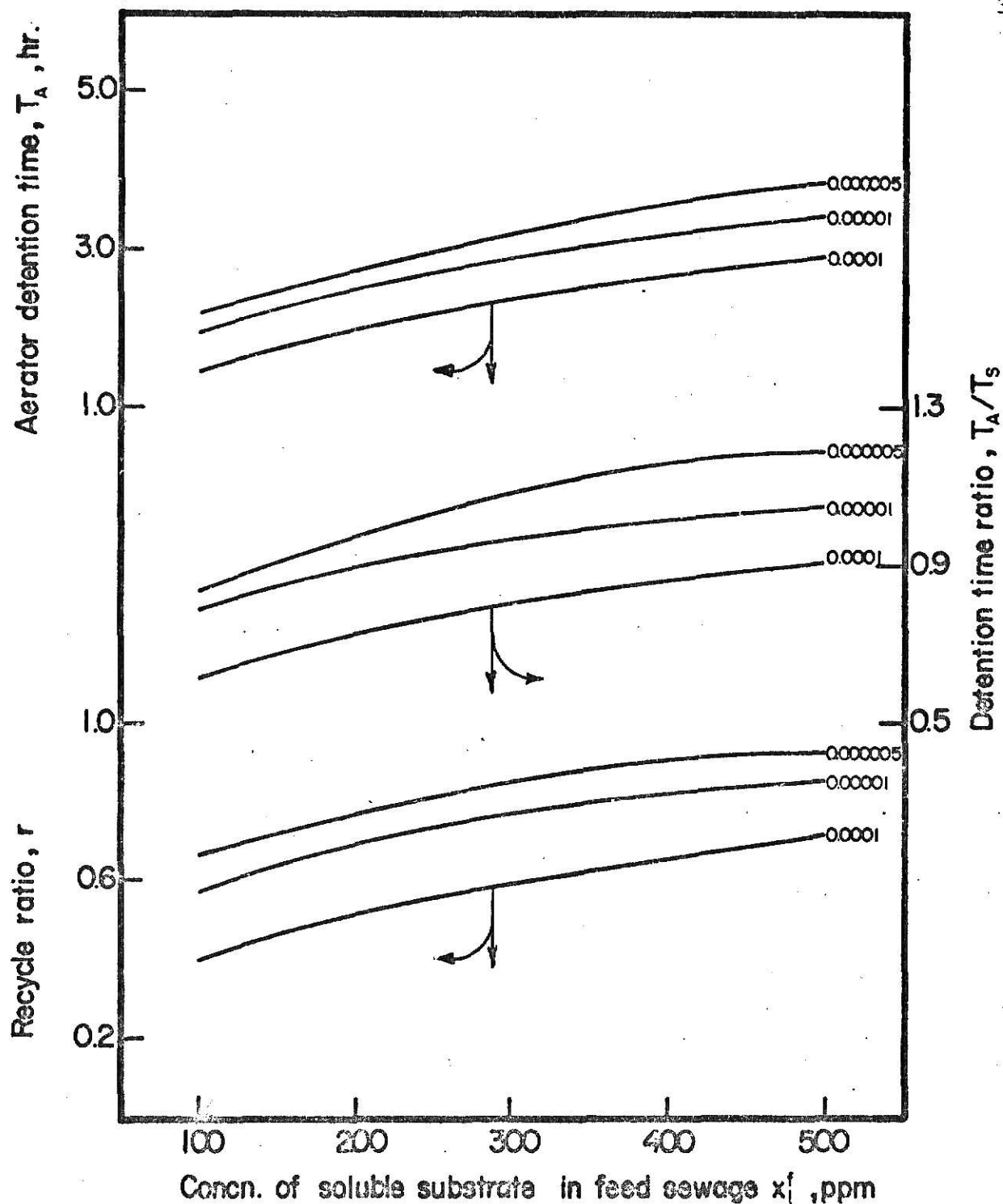


Fig.10. Variation of optimal r , T_A and T_A/T_s with x'_1 for $h_3=0.3$, $x'_3=100$ ppm and $x'_2+x'_3=10,000$ ppm with β_3 as parameter (CSTR).

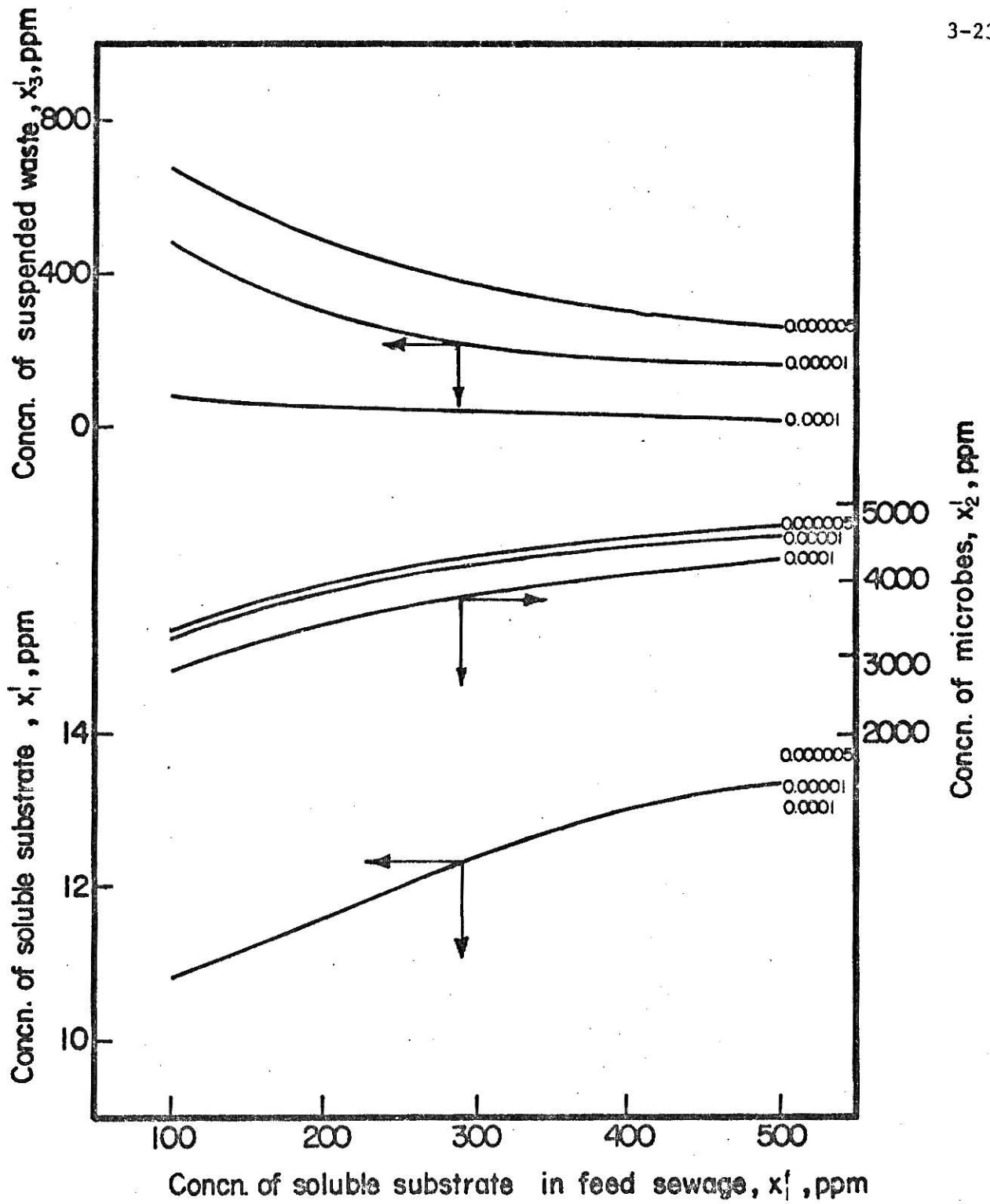


Fig.11. Variation of optimal x_1' , x_2' and x_3' with x_1^f for $h_3=0.3$, $x_1^f=100$ ppm and $x_2^f+x_3^f=10,000$ ppm with β_3 as parameter (CSTR).

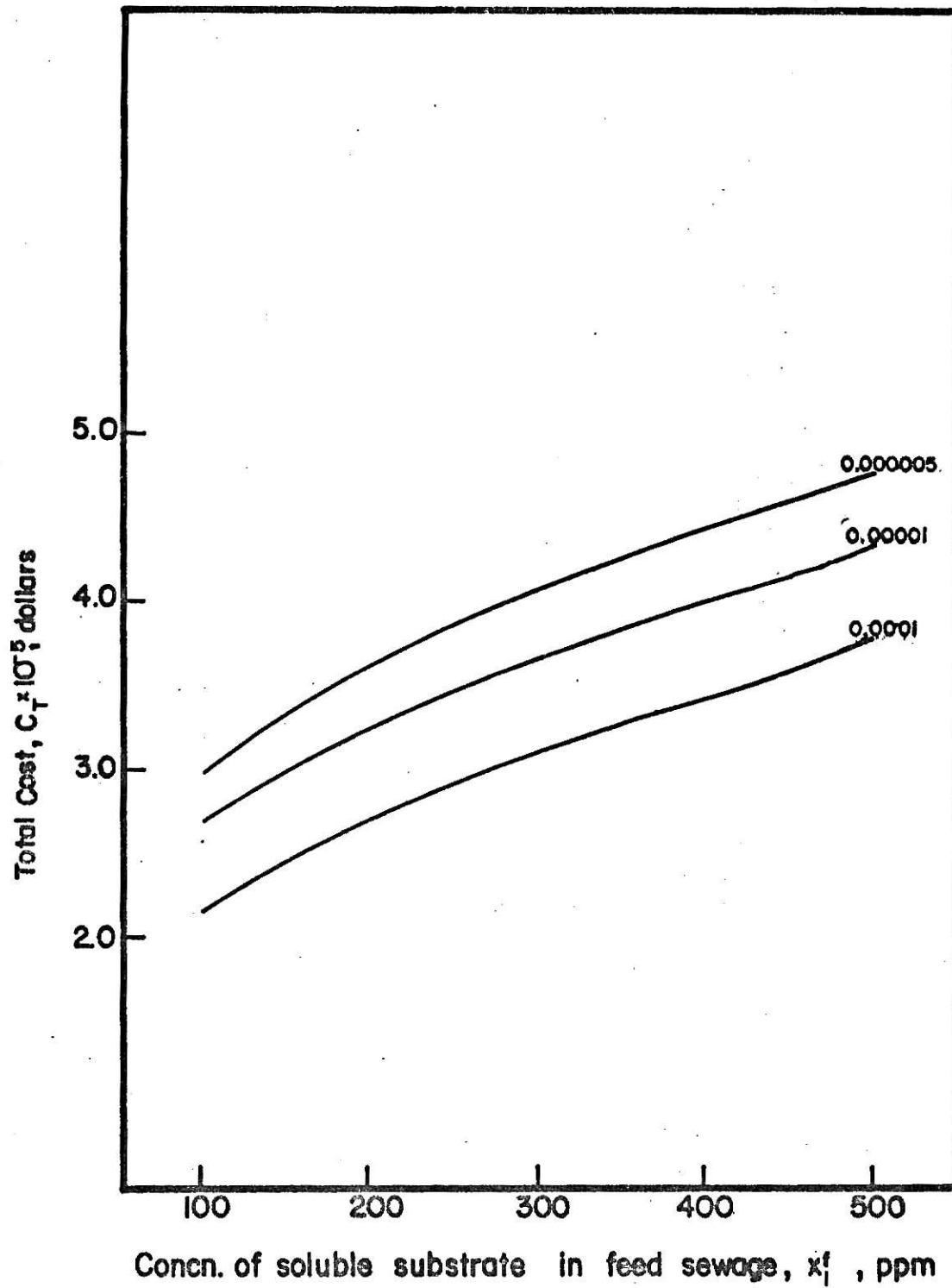


Fig. 12. Variation of optimal C_T with x_1^f for $h_3 = 0.3$, $x_3^f = 100$ ppm and $x_2^f + x_3^f = 10,000$ ppm with β_3 as parameter (CSTR).

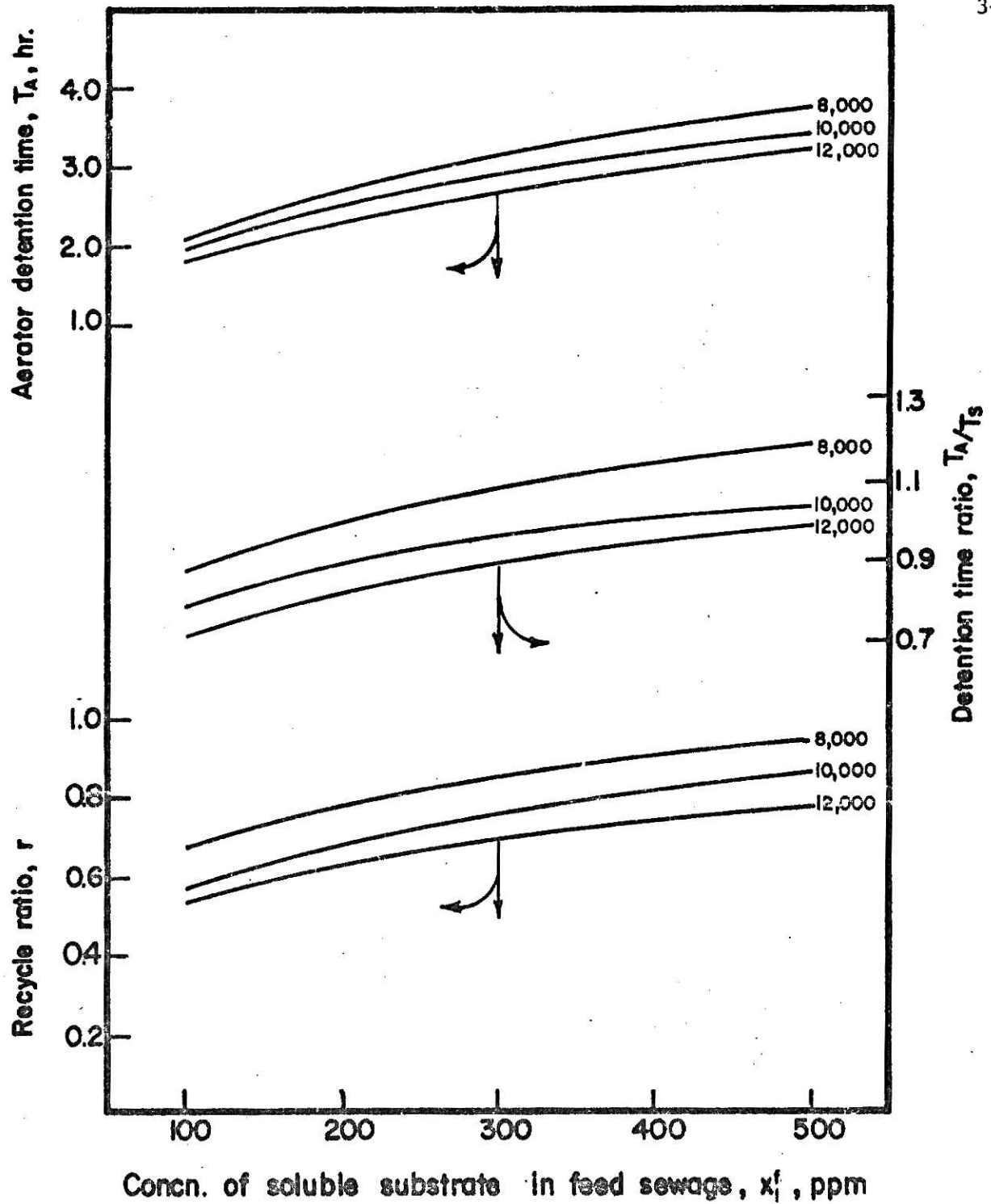


Fig. 13. Variation of optimal r , T_A and T_A/T_s with x_1^f for $\beta_3 = 0.00001 \text{ ppm}^{-1}, \text{ hr}^{-1}$, $h_3 = 0.3$ and $x_3^f = 100 \text{ ppm}$ with $x_2^f + x_3^f$ as parameter (CSTR).

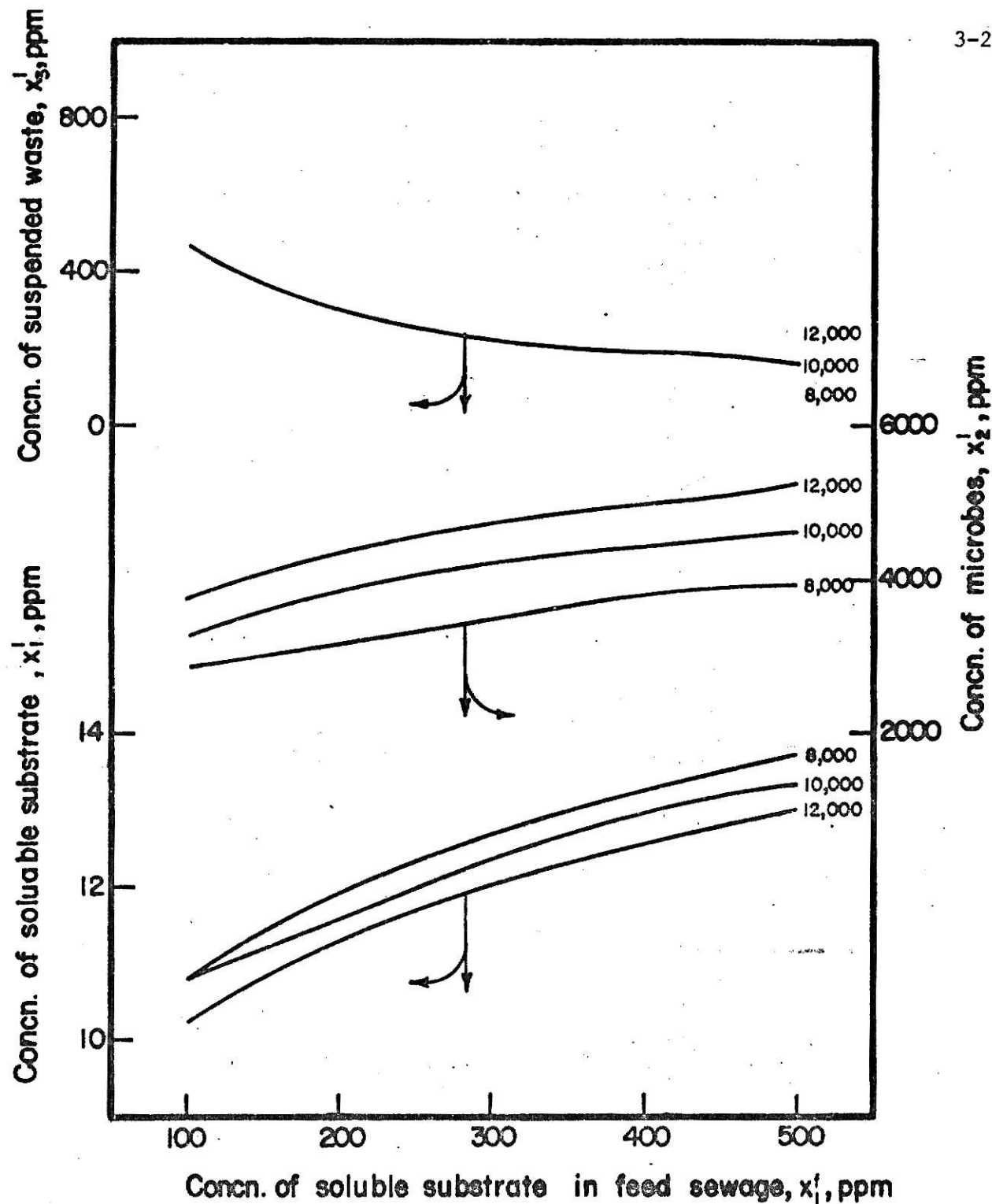


Fig.14. Variation of optimal x_1' , x_2' , and x_3' with x_1' for $\beta_3 = 0.00001 \text{ ppm}^{-1} \text{ hr}^{-1}$, $h_3 = 0.3$ and $x_3' = 100 \text{ ppm}$ with $x_2' + x_3'$ as parameter (CSTR).

increase in x_2^1 leads to reductions in the aeration tank detention time T_A and the exit soluble substrate concentration from the aeration tank x_1^1 . Meanwhile, the detention time of the secondary clarifier T_s needs to be increased to clarify the larger concentration of microbes to meet the water quality in the effluent.

Figure 15 exhibits the variation of the optimal total construction cost with respect to the inlet soluble substrate concentration x_1^f at various underflow sludge concentrations $(x_2^r + x_3^r)$. It can be observed that C_T decreases with an increase in $(x_2^r + x_3^r)$. The effect of $(x_2^r + x_3^r)$ on C_T is more apparent when x_1^f is higher. For example, the optimal value of C_T is 4.72×10^5 dollars for $(x_2^r + x_3^r) = 8,000$ ppm and is 4.07×10^5 dollars for $(x_2^r + x_3^r) = 12,000$ ppm when $x_1^f = 500$ ppm, $x_3^f = 100$ ppm, $h_3 = 0.3$ and $\beta_3 = 0.00001 \text{ ppm}^{-1} \text{ hr}^{-1}$. The results imply that the thickening function of the settling vessel does influence the economics of the whole treatment system. Although both the thickening and clarification functions of final settling tanks influence the quality of effluent produced by the activated sludge process, the thickening function is commonly ignored in design [12]. Therefore, successful optimal design of the treatment system depends upon the ability of the final clarifier to withdraw thickened sludge at the desired concentration for recycle.

3.5.3 Comparison of Two Flow Regimes - Completely Mixed Flow and Plug Flow

Figures 16 through 18 present the variation of the optimal design conditions with inlet soluble substrate concentration x_1^f for two extreme

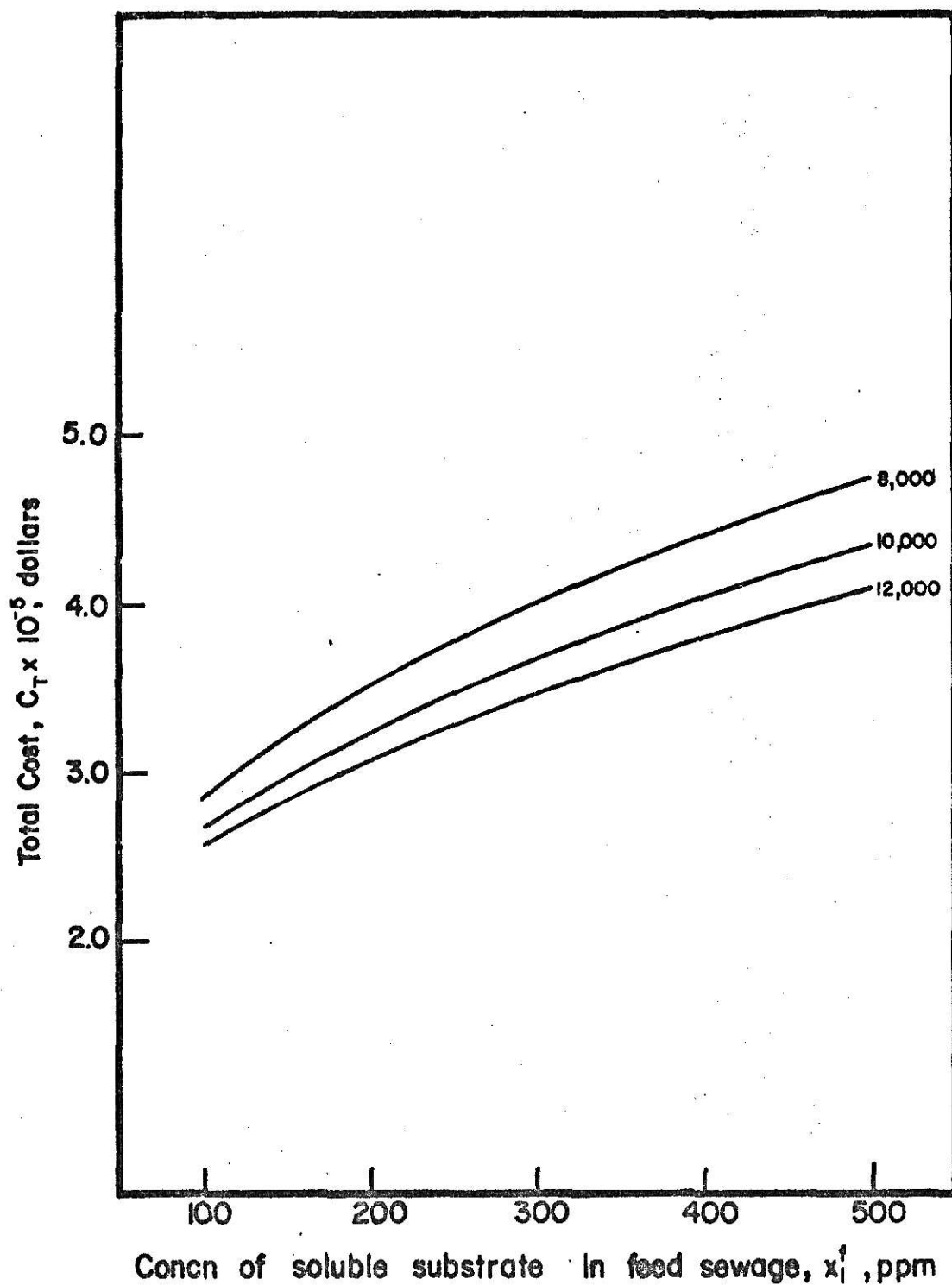


Fig. 15. Variation of optimal C_T with x_1' for $\beta_3 = 0.00001$ ppm⁻¹ hr⁻¹, $h_3 = 0.3$ and $x_3' = 100$ ppm with $x_2' + x_3'$ as parameter (CSTR) .

flow regimes - completely mixed flow and plug flow. Figure 16 shows that the optimal values of r , T_A and T_A/T_S all increase as x_1^f increases for the case of completely mixed flow. For the case of plug flow, however, only r is a monotonically increasing function of x_1^f , while both T_A and T_A/T_S exhibit maxima. The existence of these maxima may be due to the increase in the viable fraction of suspended solids. It can also be observed that the optimal values of r , T_A and T_A/T_S for the case of completely mixed flow are greater than those for the case of plug flow.

Figure 17 shows the variations of the optimal values of x_1^1 , x_2^1 , and x_3^1 as functions of x_1^f for the two flow regimes. The plug flow aeration tank has a better efficiency for removing soluble substrate than the completely mixed aeration tank. However, for a fixed concentration of underflow sludge, $(x_2^r + x_3^r) = \text{constant}$, the ratio of microbes to suspended waste in the completely mixed aeration tank is greater than that in the plug flow aeration tank. For example, the ratio x_2^1/x_3^1 is 6.66 in the completely mixed aeration tank and 1.73 in the plug flow aeration tank at $x_1^f = 100$ ppm.

Figure 18 exhibits the variation of the optimal value of C_T with respect to x_1^f for both cases. It can be seen that for the case of plug flow C_T is substantially less than that for the case of completely mixed flow. For the case of completely mixed flow, the increase in the optimal value of C_T , which accompanies the increase in x_1^1 from 100 to 500 ppm, is about 80%. For the case of plug flow, however, the corresponding increase is only about 40%. This means that the plug flow aeration tank is less sensitive than the completely mixed aeration tank to the variation in x_1^f . Moreover, the difference in the optimal value

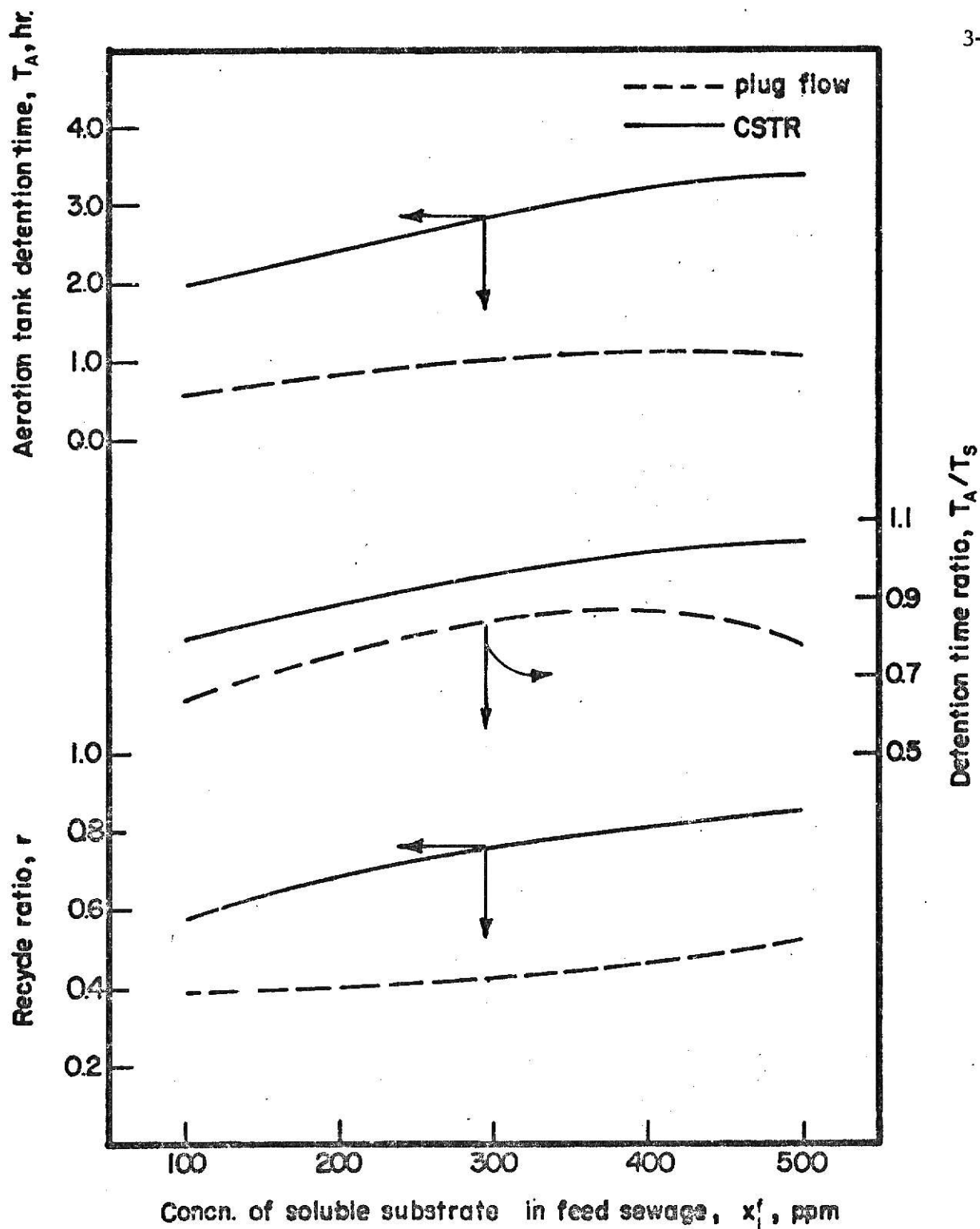


Fig.16. Variation of optimal r , T_A and T_A/T_s with x_1^f for $\beta_3=0.00001 \text{ ppm}^{-1} \text{ hr}^{-1}$, $h_3=0.3$, $x_3^f=100 \text{ ppm}$ and $x_2^f+x_3^f=10,000 \text{ ppm}$ with CSTR and plug flow.

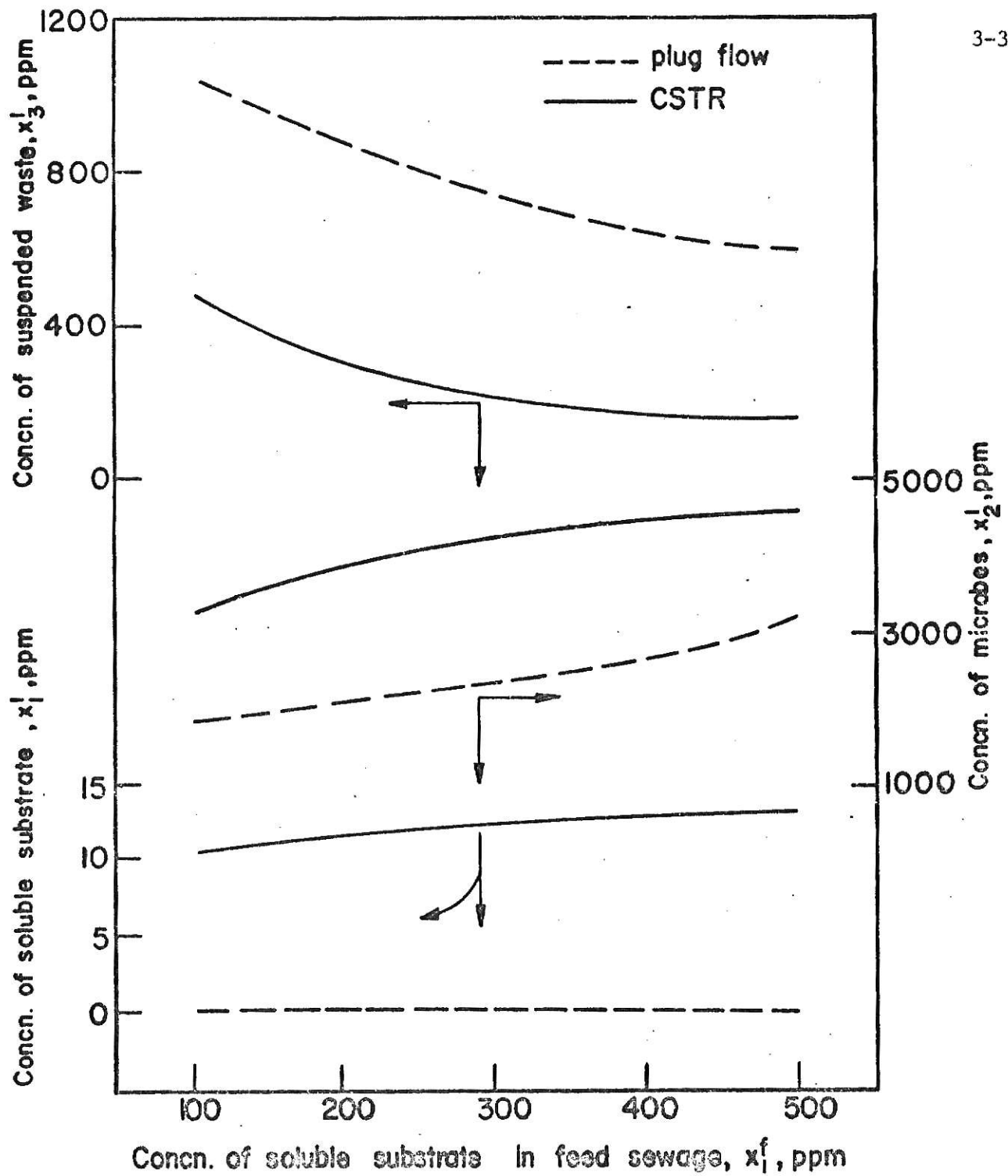


Fig.17. Variation of optimal x_1^l , x_2^l and x_3^l with x_1^f for $\beta_3 = 0.00001 \text{ ppm}^{-1} \text{ hr}^{-1}$, $h_3 = 0.3$, $x_3^f = 100 \text{ ppm}$ and $x_2^f + x_3^f = 10,000 \text{ ppm}$ with CSTR and plug flow .

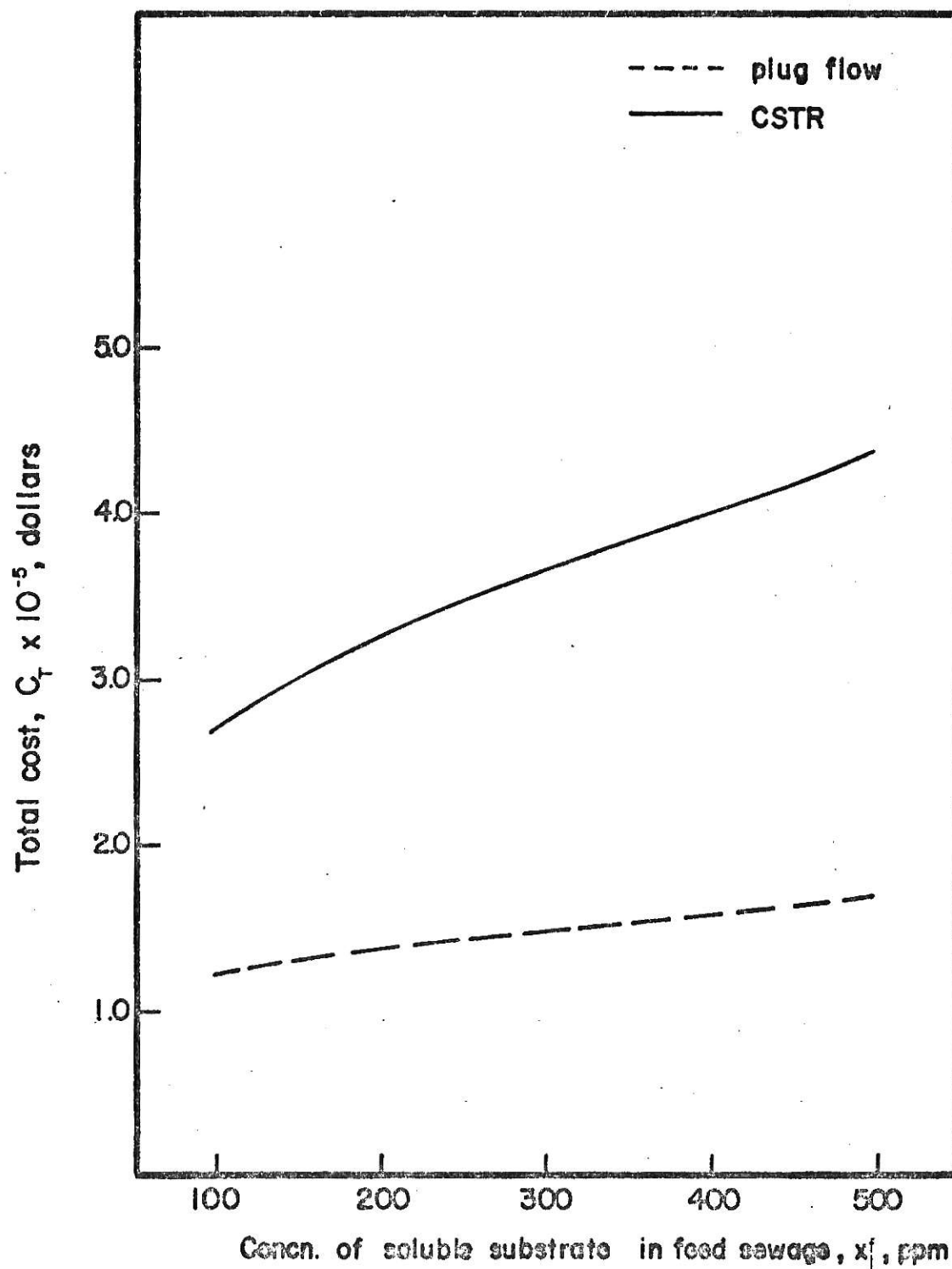


Fig. 18. Variation of optimal C_T with x'_1 for $\beta_3 = 0.00001 \text{ ppm}^{-1} \text{ hr}^{-1}$, $h_3 = 0.3$, $x'_3 = 100 \text{ ppm}$ and $x'_2 + x'_3 = 10,000 \text{ ppm}$ with CSTR and plug flow.

of C_T between the two cases is more appreciable when x_1^f is higher. These results are consistent with those of previous work [2, 3].

3.6 CONCLUSIONS

The results of this investigation show that the masking effect of suspended wastes, which is quantitatively expressed by $h_3 x_3$, and the feed concentration of soluble substrate and suspended waste to the aeration chamber significantly affect the optimal design policies of the secondary waste water treatment system.

The results indicate that the masking effect due to suspended waste in the aeration chamber is undesirable and that efforts should be made to minimize it. Primary clarification and settling of suspended waste may be an economic way to reduce the masking effect. Optimization of the overall activated sludge process including a primary clarifier is considered in the next chapter.

3.7 NOMENCLATURE

A_s	Surface area of the secondary clarifier, 1000 ft ² .
C_1	Conversion coefficient for microbes, BOD ppm/microbes ppm.
C_2	Conversion coefficient for suspended waste, BOD ppm/suspended waste ppm
C_A	Construction cost of the aeration vessel, \$.
C_d	Effluent quality criterion, BOD ppm.
C_{Rp}	Construction cost of the recycle pump, \$.
C_s	Construction cost of the secondary clarifier, \$.

C_T	Construction cost of the total treatment system, \$.
h_3	Masking effect coefficient, dimensionless.
H	Height of secondary clarifier, ft.
k_d	Endogenous rate coefficient, hr^{-1} .
K_s	Saturation constant of soluble substrates, ppm.
p	Specific constant for secondary clarifier, dimensionless.
q	Volumetric flow rate of influent waste water, MGD.
r	Sludge recycle ratio, dimensionless.
T_A	Aeration chamber detention time, hours.
T_s	Secondary clarifier detention time, hours.
V_A	Aeration chamber volume, MG.
V_s	Secondary clarifier volume, MG.
w	Sludge wasting ratio, dimensionless.
x_1	Concentration of soluble substrate, ppm.
x_2	Concentration of microbes, ppm.
x_3	Concentration of suspended waste, ppm.
Y_1	Yield coefficient of soluble substrate, microbes ppm/BOD ppm.
Y_3	Yield coefficient of suspended waste, microbes ppm/ suspended waste ppm.
α	Specific coefficient for secondary clarifier, dimensionless.
β_3	Removal rate coefficient of suspended waste, 1/hr. microbes ppm.
γ	Specific constant for secondary clarifier, hr^{-1} .
μ_{ml}	Maximum specific growth rate of microbes on soluble substrate, hr^{-1} .

ϕ_1	Soluble substrate consumption rate.
ϕ_2	Microbes growth rate.
ϕ_3	Suspended waste consumption rate.
η	Dimensionless aeration vessel length.

3.7.1 Superscripts

0	Influent to aeration tank from mixing point.
1	Effluent from aeration tank.
e	Effluent from clarifier overflow.
f	Feed or inflow to mixing point.
r	Clarifier underflow and recycle flow.

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CHAPTER 4

APPLICATION OF DYNAMIC PROGRAMMING TO THE OPTIMAL DESIGN OF PRIMARY CLARIFIER IN THE ACTIVATED SLUDGE PROCESS

4.1 INTRODUCTION

In earlier papers [1, 2, 3, 4, 5] the optimization of the activated sludge process was studied. The system investigated was a subsystem of the complete sewage treatment system and was composed of an aeration chamber and a secondary clarifier. The studies were carried out with the hope that they would contribute to a better understanding and an eventual optimal design of the total sewage treatment system. In these earlier works, the primary clarifier was not included.

A parallel biochemical oxidation model [6] which takes into account the low oxidation rate and masking effect of suspended wastes, has been employed to investigate the influence of suspended wastes on the optimal design of the activated sludge process [5]. The results indicate that the masking effect of the suspended wastes in the aeration tank is undesirable and that removal of at least a portion of the suspended wastes before they enter the aeration tank may be desirable. Primary settling appears to be an economical way to remove the suspended wastes. Primary clarifier design, however, has usually been based on past experience and subsystem performance rather than on the results of systems analysis.

The results of previous systems analysis studies [7, 8] indicated that the inclusion of a primary clarifier is not economically advantageous for the steady state operation of an activated sludge waste treatment

system. These results may not always be realistic because their work was based on the assumption that the removal rate of suspended waste by activated sludge in the aeration tank is the same as that of soluble substrate and that suspended wastes have no influence on the removal rate of soluble substrate.

By means of the parallel biochemical oxidation model, Kuo et al. [6] showed that the inclusion of the primary clarifier might be economically advantageous when the masking effect is appreciable. The present study is to extend this work. The dynamic programming computational procedure in conjunction with the optimal results of the secondary system obtained in the previous work [5] is used to optimize the overall activated sludge process including the primary clarifier.

4.2 DYNAMIC PROGRAMMING

4.2.1 General Problem Formulation

The following is an outline of general problem formulation to which the conventional dynamic programming computational procedure applies.

A multistage decision process containing K stages in sequence is schematically shown in Fig. 1. The essential elements of the problem are the system equations, the performance criterion, and the constraints. The system equations are a set of relations between three types of variables: the stage variable, the state variables, and the control or decision variables.

The stage variable is that variable which determines the order in which events occur in the system. If it is discrete, it is defined as the sequence $k = 0, 1, 2, \dots, K$.

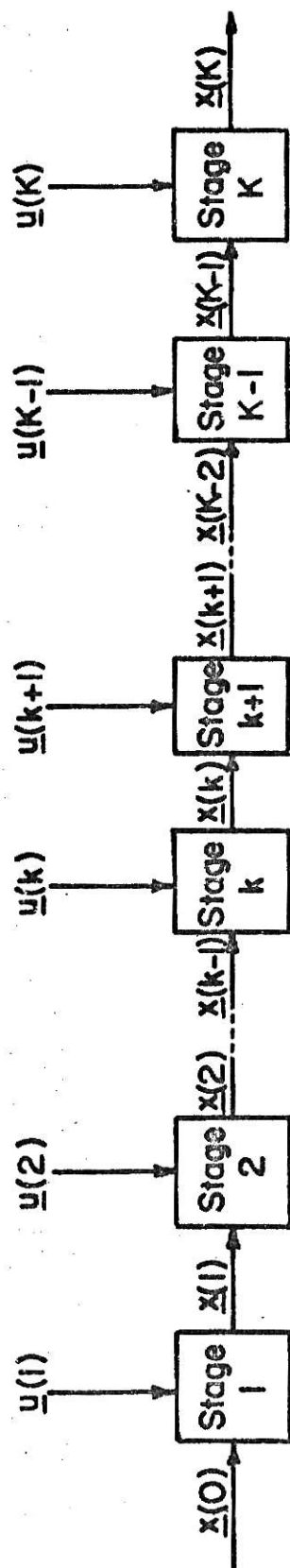


Fig. 1. A Typical Multi-Stage Process.

The state variables are a set of variables that completely describe the state of a system. In general, the state variables of the system form a n dimensional state vector, $\underline{x}$.

$$\underline{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}$$

The control or decision variables are those independent variables in the system that can be specified directly. In general, the control variables of the system constitute a q dimensional control vector, $\underline{u}$.

$$\underline{u} = \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_q \end{bmatrix}$$

The system equations describe the manner through which the state variables at stage k are related to the state variables at stage $k - 1$ and the control variables at stage k . The system equations are generally expressed as

$$x_1(k) = g_1[x_1(k-1), x_2(k-1), \dots, x_n(k-1), u_1(k), u_2(k), \dots, u_q(k)]$$

$$x_2(k) = g_2[x_1(k-1), x_2(k-1), \dots, x_n(k-1), u_1(k), u_2(k), \dots, u_q(k)]$$

$$\vdots$$

$$\vdots$$

$$x_n(k) = g_n[x_1(k-1), x_2(k-1), \dots, x_n(k-1), u_1(k), u_2(k), \dots, u_q(k)]$$

or more compactly as

$$\underline{x}(k) = \underline{g}[\underline{x}(k-1), \underline{u}(k), k]$$

where $\underline{g}$ is a vector representing the n functional relationships.

The performance of a system resulting from a given control sequence, $\underline{u}(1), \underline{u}(2), \dots, \underline{u}(K)$, is measured against the so-called performance criterion or objective function, S . This criterion is either a reward function to be maximized, or a cost function to be minimized. The performance criterion depends on the control vectors and the initial state vectors, i.e.

$$S = S[\underline{x}(0), \underline{u}(k)]$$

If the objective function is the summation of the stage costs, it can be written as

$$S = \sum_{j=1}^K l_j(\underline{x}(j-1), \underline{u}(j), j)$$

where $\ell_j(\underline{x}(j-1), \underline{u}(j), j)$, the stage cost function, is a function of the state, control and stage variables.

The constraints place restrictions on the values that the state and control variables can assume. In general, the state vector at stage k is constrained to be in the set $X(k)$. This constraint is expressed mathematically as

$$\underline{x}(k) \in X(k)$$

Generally, the control vector applied at state $\underline{x}$, stage k is constrained to be in the set $U(\underline{x}, k)$. This constraint is written as

$$\underline{u}(k) \in U(\underline{x}, k)$$

The optimization problem can then be stated as follows:

Given:

(i) A system described by

$$\underline{x}(k) = \underline{g}[\underline{x}(k-1), \underline{u}(k), k]$$

(ii) Constraints that $\underline{x}(k) \in X(k)$, $\underline{u}(k) \in U(\underline{x}, k)$

(iii) An initial state $\underline{x}(0)$

(iv) A performance criterion S

Find:

The control sequence, $\underline{u}(0), \underline{u}(1), \dots, \underline{u}(K)$, that minimizes S while satisfying the constraints.

4.2.2 Principle of Optimality and Functional Equation

The foundation of dynamic programming is the principle of optimality [9]. It states "An optimal policy has the property that whatever the initial state and initial decisions are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision."

When the principle of optimality is applied to a given system, the mathematical transliteration yields the so-called functional equation (see Appendix 4-1). The functional equation is related to the principle of optimality in that the minimum cost in going from stage k [state $\underline{x}(k-1)$] to the end of the process is found by choosing the optimal decision at stage k , $\underline{u}(k)$, so that the sum of the stage cost of stage k and the minimum cost in going from stage $k + 1$ to the end of the process is minimized.

Mathematically, the functional equation can be written as

$$I(\underline{x}(k-1), k) = \min_{\underline{u}(k) \in U} \{ \ell[\underline{x}(k-1), \underline{u}(k), k] + I[\underline{g}(\underline{x}(k-1), \underline{u}(k), k), k+1] \} \quad (1)$$

where $\ell[\underline{x}(k-1), \underline{u}(k)]$, which is the stage cost function at stage k , is a function of the state variable $\underline{x}(k-1)$, control variable $\underline{u}(k)$ and stage variable k . The minimum cost function, $I(\underline{x}(k-1), k)$, expresses the minimum cost obtainable for the $[K - (k-1)]$ stage process starting from state $\underline{x}(k-1)$ at stage k and terminating at the last stage.

4.3 PROBLEM FORMULATION

4.3.1 System Configuration

The activated sludge process system, consisting of primary and secondary treatment, as considered in this study is shown in Fig. 2. The primary treatment is accomplished by a primary clarifier. The secondary treatment subsystem consists of an aeration tank, a secondary clarifier, and a recycle pump; a part of the activated sludge separated in the secondary clarifier is recycled to the aeration tank. The influent flow rate is constant and the effluent water quality is kept fixed at a set standard in terms of its BOD.

4.3.2 Primary Clarifier

The primary clarifier plays an important role in most wastewater treatment plants and a substantial amount of the pollutant load is removed here. The removal rate of suspended solids obtained in the primary clarifier operation is influenced by the plant design, the settleable solids characteristics, the degree of flocculation (natural or induced), the solids loading, and the hydraulic loading. With the aid of a polymeric coagulant at a controlled dosage to aid flocculation, the suspended solids removal efficiency of the primary clarifier can be enhanced considerably. Voshel and Sak [10] developed two empirical correlations for the removal of suspended solids in a primary clarifier, based on plant scale experiments. The first correlation is for the case when no flocculating agent is used and can be expressed as

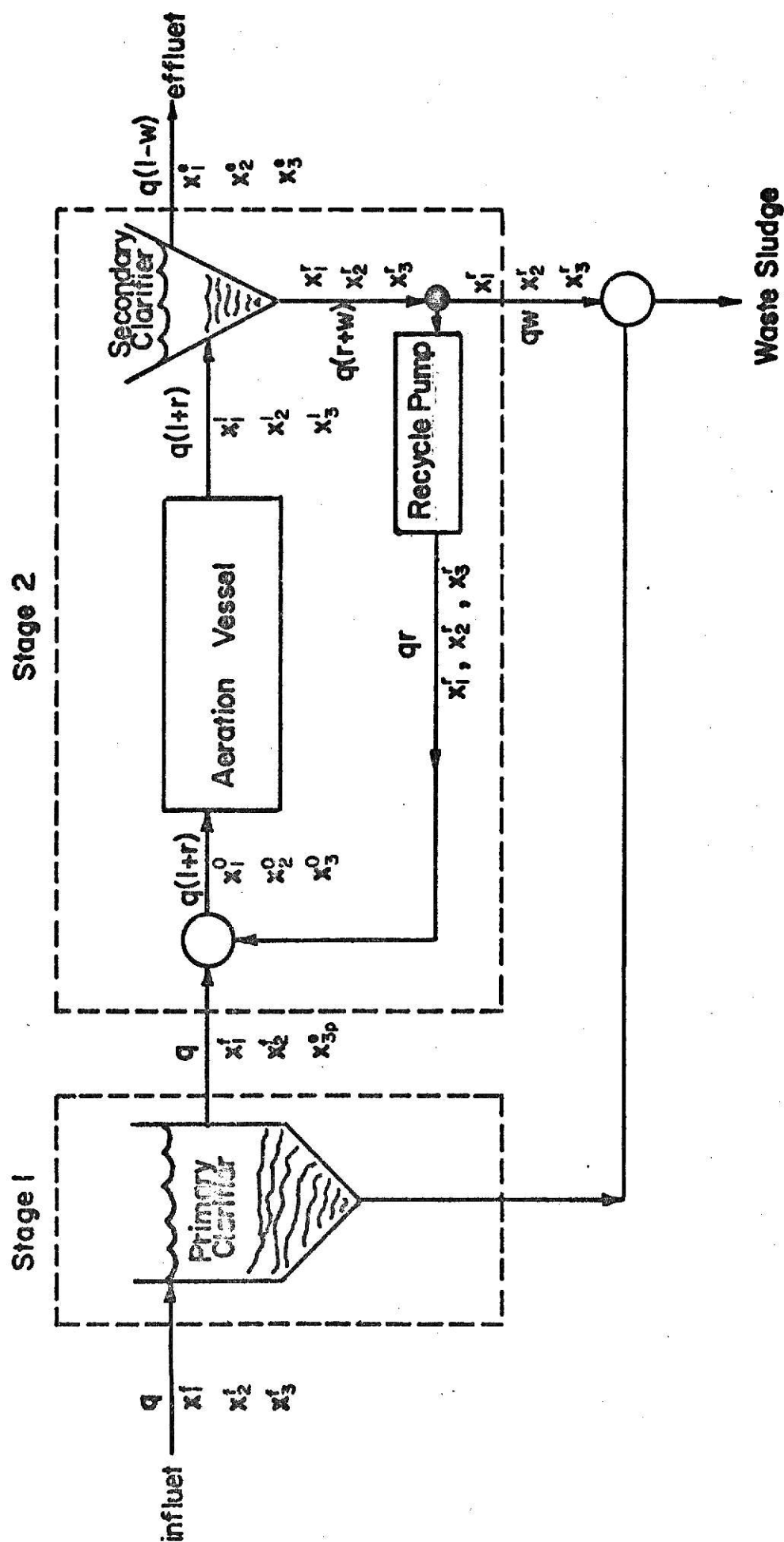


Fig. 2. Schematic Diagram of the Activated Sludge Process System.

$$(x_{2p}^e + x_{3p}^e) = (x_2^f + x_3^f) \left[1 - \frac{0.5675 (x_2^f + x_3^f)^{0.27}}{(q/A_p)^{0.22}} \right] \quad (2)^*$$

where

$x_2^f + x_3^f$ = concentration of suspended solids (organisms plus suspended waste, respectively) in influent wastewater (ppm)

$x_{2p}^e + x_{3p}^e$ = concentration of suspended solids in primary clarifier effluent (ppm)

q = volumetric flow rate of influent wastewater (MGD)

A_p = surface area of primary clarifier (ft^2)

The second correlation is for the case when a polymeric coagulant is used at a dosage of 1 mg/l and can be expressed as

$$(x_{2p}^e + x_{3p}^e) = (x_2^f + x_3^f) \left[1 - \frac{0.7788 (x_2^f + x_3^f)^{0.17}}{(q/A_p)^{0.13}} \right] \quad (3)$$

Both expressions, eqs. (2) and (3), assume that the suspended solids removal in the primary clarifier is proportional to a power function of the influent suspended solids concentration and inversely proportional to a power function of the surface overflow rate of the primary clarifier.

* In equations (2) and (3) the relative removal efficiencies of cells and suspended waste may differ; in this work the assumption is made that

$$\frac{x_2^f}{x_3^f} = \frac{x_{2p}^e}{x_{3p}^e}$$

4.3.3 Mixing Point

The effluent from the primary clarifier and thickened sludge recycled from the secondary clarifier are assumed to be mixed together and then fed as influent to the aeration tank. The volumetric flow rate of the effluent from the primary clarifier is assumed the same as that of the influent to the primary clarifier. The material balances for the soluble substrate, the microbes, and the suspended waste can be written, respectively, as

$$x_1^0 = \frac{1}{1+r} x_1^f + \frac{r}{1+r} x_1^r \quad (4)$$

$$x_2^0 = \frac{1}{1+r} x_{2p}^e + \frac{r}{1+r} x_2^r \quad (5)$$

$$x_3^0 = \frac{1}{1+r} x_{3p}^e + \frac{r}{1+r} x_3^r \quad (6)$$

where

x_1 = concentration of soluble substrate (BOD ppm)

x_2 = concentration of microbes (ppm)

x_3 = concentration of suspended waste (ppm)

r = sludge recycle ratio (ratio of return flow to influent flow) (-----)

and the superscripts f , r , and 0 refer to influent, recycle, and flow from the mixing point, respectively.

4.3.4 Aeration Tank

The aeration tank is a key component of the activated sludge process system since it is here that the organic nutrients are biochemically

oxidized. Nakanishi [11] conducted a series of experiments and pointed out that the removal of soluble substrates by microorganism is affected by the presence of suspended wastes. Recently, Kuo et al. [5, 6] proposed a parallel biochemical oxidation model to take into account the masking effect and low oxidation rate of suspended wastes. In this study, this model will be used to predict the performance of the aeration tank.

According to Kuo et al. [5, 6], the kinetics for soluble substrate consumption, microbial growth and suspended waste removal in the aeration tank are given in eqs. (7) through (9), respectively.

$$\frac{dx_1}{dt} = \frac{-\mu_{m1} x_1 x_2}{Y_1 (K_s + x_1 + h_3 x_3)} \quad (7)$$

$$\frac{dx_2}{dt} = \frac{\mu_{m1} x_1 x_2}{K_s + x_1 + h_3 x_3} + \beta_3 x_3 x_2 - k_d x_2 \quad (8)$$

$$\frac{dx_3}{dt} = \frac{-\beta_3 x_2 x_3}{Y_3} \quad (9)$$

where

μ_{m1} = maximum specific growth rate of soluble substrate (hr^{-1})

K_s = saturation constant of soluble substrate (ppm)

k_d = endogenous rate coefficient (hr^{-1})

Y_1 = yield coefficient of soluble substrate (microbes ppm/
BOD ppm)

β_3 = removal rate coefficient of suspended waste
($1/\text{hr} \cdot \text{microbes ppm}$)

Y_3 = yield coefficient of suspended waste (microbes ppm/
suspended waste ppm)

h_3 = masking effect coefficient (-----)

Environmental design engineers often use the completely mixed model for the aeration tank as advocated by McKinney et al. [12, 13, 14, 15]. For a CSTR, the steady state material balances for soluble substrate, microorganisms, and suspended waste can be written, respectively, as

$$x_1^0 - x_1^1 + T_A \left(\frac{-\mu_m^1 x_1^1 x_2^1}{Y_1 (K_s + x_1^1 + h_3 x_3^1)} \right) = 0 \quad (10)$$

$$x_2^0 - x_2^1 + T_A \left(\frac{\mu_m^1 x_1^1 x_2^1}{K_s + x_1^1 + h_3 x_3^1} + \beta_3 x_3^1 x_2^1 - k_d x_2^1 \right) = 0 \quad (11)$$

$$x_3^0 - x_3^1 + T_A \left(\frac{-\beta_3 x_3^1 x_2^1}{Y_3} \right) = 0 \quad (12)$$

where

$$T_A = \frac{V_A}{q(1+r)} = \text{detention time of the aeration tank (hr)}$$

$$V_A = \text{volume of the aeration tank (MG)}$$

and the superscript 1 refers to flow from the aeration tank.

4.3.5 Secondary Clarifier

The performance of the secondary clarifier is estimated based on a model developed by Naito et al. [1] on the assumption that plug flow conditions prevail in it. According to this model, the rate of removal of activated sludge and suspended waste in the secondary clarifier can be presented by the semi-empirical relationship

$$(x_2^e + x_3^e) = p(x_2^1 + x_3^1)^\alpha \exp [-\gamma T_s] \quad (13)$$

where

p = parameter

α = parameter

γ = parameter (hr^{-1})

T_s = detention time (hr)

and the superscript e refers to the overflow stream from the clarifier. The values of parameters p , α , and γ depend on the characteristics of the sludge and equipment. It should be mentioned here that the mixed liquor suspended solids are assumed to be composed of microbes and suspended waste when applying Naito's model. It is assumed that the microbes and suspended wastes have the same proportional compositions both in the mixed liquor suspended solids entering the secondary clarifier and in the recycle and effluent streams. Therefore,

$$\frac{x_2^r}{x_3^r} = \frac{x_2^e}{x_3^e} = \frac{x_2^1}{x_3^1} \quad (14)$$

It is also assumed that the concentration of soluble substrate is not affected by the secondary clarifier operation. That is

$$x_1^1 = x_1^r = x_1^e \quad (15)$$

The material balances for the microbes and suspended waste around the secondary clarifier can be written, respectively, as

$$(1 + r) x_2^1 = (1 - w) x_2^e + (r + w) x_2^r \quad (16)$$

$$(1 + r) x_3^1 = (1 - w) x_3^e + (r + w) x_3^r \quad (17)$$

where w is the ratio of the sludge wasting rate q_w to the influent flow rate q .

4.3.6 Effluent Quality

A constraint is imposed on the system performance in terms of the quality of the effluent. The total BOD in the effluent is composed of soluble substrate which remains untreated in the aeration tank, microbes and suspended wastes which result from incomplete clarification. The constraint can be expressed as

$$x_1^e + C_1 x_2^e + C_2 x_3^e = C_d \quad (18)$$

where

C_d = effluent quality criterion (BOD ppm)

C_1 = conversion coefficient for microbes (BOD ppm/microbes ppm)

C_2 = conversion coefficient for suspended waste
(BOD ppm/suspended waste ppm)

4.3.7 Performance Index

In this study, the total construction cost of the aeration tank, the secondary clarifier, and the recycle pump are used as the performance index. Specifically, the cost function is computed as the sum of the costs of the individual units and 40% of such costs to account for

engineering fees. Operating and maintenance costs are not included.

The capital cost considered for each unit of the system is based on unit construction cost correlations as presented by Smith [16]. Mathematically, the performance index can be expressed as

$$C_T = 1.4 [C_P + C_A + C_S + C_{RP}] \quad (19)$$

where C_P , C_A , C_S , and C_{RP} account for the construction cost of the primary clarifier, aeration tank, secondary clarifier, and recycle pump, respectively. According to Smith (1968), C_P , C_A , C_S and C_{RP} are given, respectively, by

$$C_P = 13.4A_P + 2,600A_P^{0.1} \quad (20)$$

$$C_A = V_A (175,000 + 36,500 V_A^{-0.818}) \quad (21)$$

$$C_S = 12,600 A_S + 5,350 A_S^{-0.126} \quad (22)$$

$$C_{RP} = 3,650 + 1,150 r. q \quad (23)$$

where A_P , the surface area of the primary clarifier, is in "sq. ft."; V_A , the volume of the aeration tank, is in "million gallons", A_S , the surface area of the secondary clarifier, is in "1,000 ft²"; and q , the influent flow rate, is in "million gallons per day".

4.3.8 Dynamic Programming Optimization Problem

In this study, the influent concentration of microbes is assumed to be zero. The concentration of suspended waste is defined as the state variable. If the primary clarifier is designated as stage 1, the

secondary subsystem as stage 2, then the state variable at different stages can be written as

$$x(0) = x_3^f$$

$$x(1) = x_{3p}^e$$

$$x(2) = x_3^e$$

The primary clarifier detention time, T_p , is selected as the control variable in stage 1; the sludge recycle ratio, r , and the exit soluble substrate concentration from the aeration tank, x_1^1 , are the control variables in stage 2, i.e.,

$$u(1) = T_p$$

$$\underline{u}(2) = \begin{bmatrix} r \\ x_1^1 \end{bmatrix}$$

The Voshel and Sak model for primary clarifier performance, eqs. (2) or (3) with $x_2^f = 0$ and $x_{2p}^e = 0$, represents the system equation of stage 1, $g(x(0), u(1), 1)$.

The system equations of stage 2, $\underline{g}(x(1), \underline{u}(2), 2)$, consists of a set of equations, eqs. (4) through (18).

The objective function, S , is defined as the sum of the costs from stages one and two; that is,

$$S = \ell(x(0), u(1), 1) + \ell(x(1), \underline{u}(2), 2)$$

where

$$l(x(0), u(1), 1) = 1.4 C_p$$

$$l(x(1), u(2), 2) = 1.4 (C_A + C_S + C_{RP})$$

Hence the optimization problem for the activated sludge process system including a primary clarifier is now in the form of a dynamic programming optimization problem.

4.4 COMPUTATIONAL ASPECTS

In dynamic programming, the computation is initiated from the last stage, proceeding backwards to the initial stage. The optimal value of the objective function of stage 2 (i.e. the secondary treatment subsystem) corresponding to various initial states $I(x_{3p}^e, 2)$, at different dissolved substrate concentrations x_1^f and different masking effect coefficients h_3 have been obtained by Kuo et al. [5] using a simplex pattern search technique [2, 17]. Figures 3 and 4 show two typical results of $I(x_{3p}^e, 2)$ vs. x_{3p}^e with x_1^f as parameter for the cases $h_3 = 0.0$ and $h_3 = 2.0$, respectively. Specifically, the values of $I(10, 2)$, $I(25, 2)$, $I(50, 2)$, $I(100, 2)$, $I(150, 2)$, $I(200, 2)$, $I(250, 2)$, and $I(300, 2)$ are read into the computer. A linear interpolation subroutine is written for interpolating any $I(x_{3p}^e, 2)$ in the range $0 \leq x_{3p}^e \leq 300$ ppm.

By means of the functional equation, eq. (1), and the optimal objective function of stage 2, $I(x_{3p}^e, 2)$, a one dimensional Golden Section search method [18] is used to determine the optimal primary

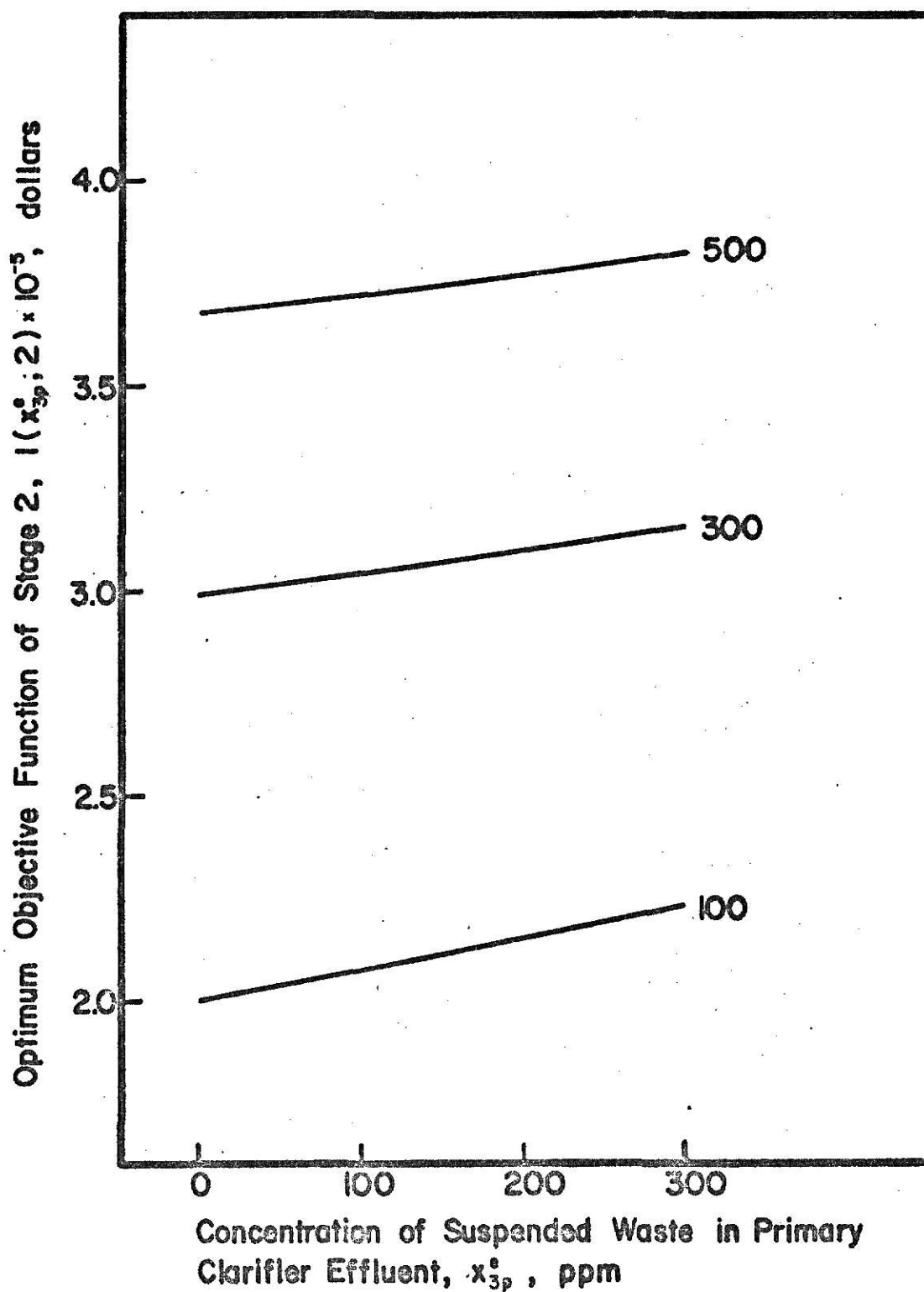


Fig. 3. Variation of $I(x_{3p}^*, 2)$ with x_{3p}^* for $h_3 = 0.0$ with x_1' as parameter.

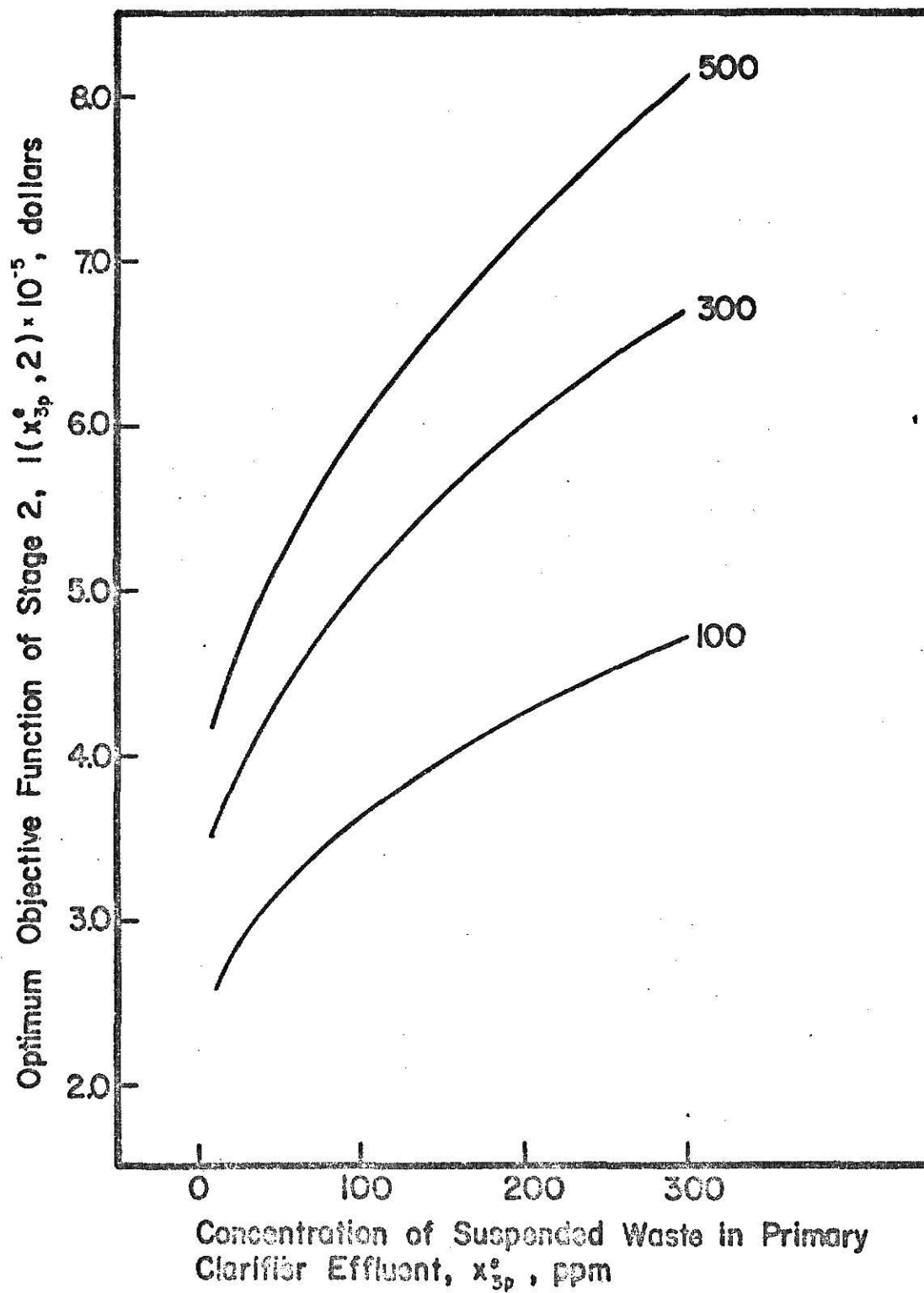


Fig. 4. Variation of $I(x_{3p}^*, 2)$ with x_{3p}^* for $h_3 = 2.0$ with x_1' as parameter.

clarifier detention time, T_p , at stage 1 (i.e. the primary treatment subsystem) for different values of the influent suspended waste concentration, x_3^f . A one dimensional exhaustive search technique is used for checking the absolute minimum among the multiple relative minima.

In this optimization study, the depths of the primary clarifier and secondary clarifier, are both fixed at 10 ft. The concentration of recycled sludge, $x_2^r + x_3^r$, is fixed at 10,000 ppm. The numerical values used for the parameters are as follows:

$$\mu_{m_1} = 0.1 \text{ hr}^{-1}$$

$$K_s = 100 \text{ ppm}$$

$$Y_1 = 0.5 \text{ microbes ppm/BOD ppm}$$

$$k_d = 0.002 \text{ hr}^{-1}$$

$$\beta_3 = 0.00001 \text{ hr}^{-1} \text{ ppm}^{-1}$$

$$Y_3 = 0.5 \text{ microbes ppm/suspended waste}$$

$$p = 2.1$$

$$\alpha = 0.5$$

$$\gamma = 0.74$$

$$C_1 = 0.5 \text{ BOD ppm/microbes ppm}$$

$$C_2 = 0.2 \text{ BOD/suspended waste}$$

$$C_d = 20 \text{ BOD ppm}$$

$$q = 3 \text{ MG/day}$$

4.5 RESULTS AND DISCUSSION

The results of optimization are presented in Figs. 5 through 14.

In general, the optimal degree of primary treatment depends on the

concentration and masking characteristics of the influent suspended waste, as well as the concentration of the soluble influent substrate.

Figures 5 and 6 show the variation of optimal primary clarifier detention time T_p with respect to the inlet suspended waste concentration x_3^f with the masking effect coefficient h_3 as parameter. Figure 5 is for the case without addition of a flocculent while in Fig. 6 a flocculent has been added. It can be seen from both figures that the optimal T_p increases with an increase in x_3^f when $h_3 = 1.0$ or 2.0 . For the case without masking effect, i.e. $h_3 = 0.0$, the optimal primary clarifier detention time is zero for the whole range of concentration of inlet suspended waste. Figure 5* indicates that the optimal value of T_p increases from 0.50 hr to 2.26 hr (about 350%) when x_3^f increases from 100 ppm to 300 ppm for $h_3 = 2.0$ and $x_1^f = 500$ ppm in the case without flocculent. Figure 6 shows that the optimal value of T_p increases from 0.75 hr to 4.60 hr (about 500%) if flocculent is added. The change in the optimal value of T_p with respect to x_3^f is greater in the case with flocculent than in the case without flocculent. Figures 5 and 6 show that the optimal value of T_p also increases as h_3 increases. When the masking coefficient is large, the change in the optimal value of T_p with respect to x_3^f is greater than when the masking effect coefficient is small. A comparison of Figs. 5 and 6 shows that the optimal primary clarifier detention time in the case with flocculent is greater than that in the case without flocculation. Since the operating cost of

* Voshell's model cannot predict the actual performance of the primary clarifier in the region where the detention time of the primary clarifier is less than 0.5 hr. This region is represented by the dotted line in Fig. 5.

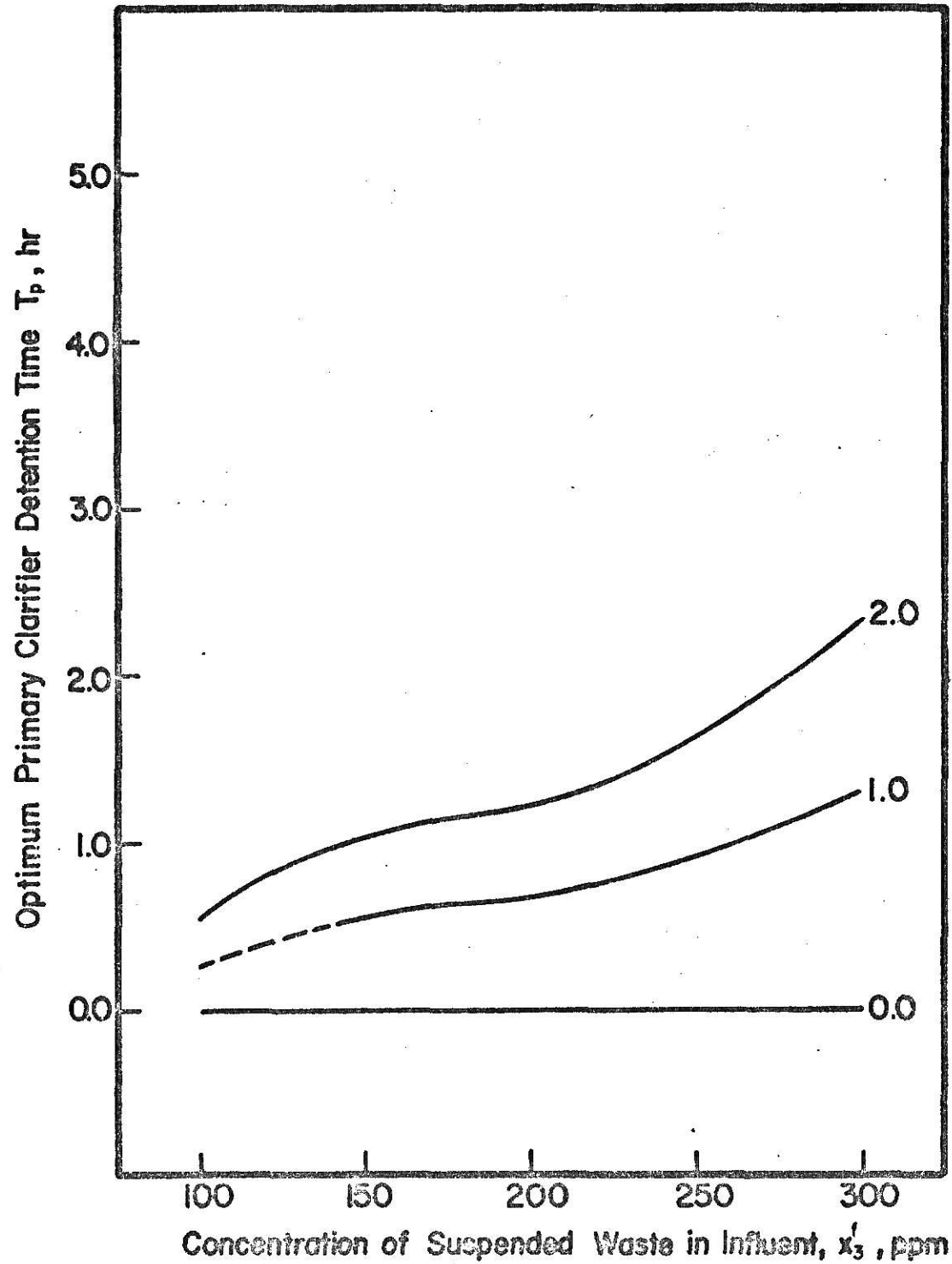


Fig. 5. Variation of Optimum T_p with x'_3 for $x'_1 = 500$ ppm with h_3 as parameter (No flocculent added).

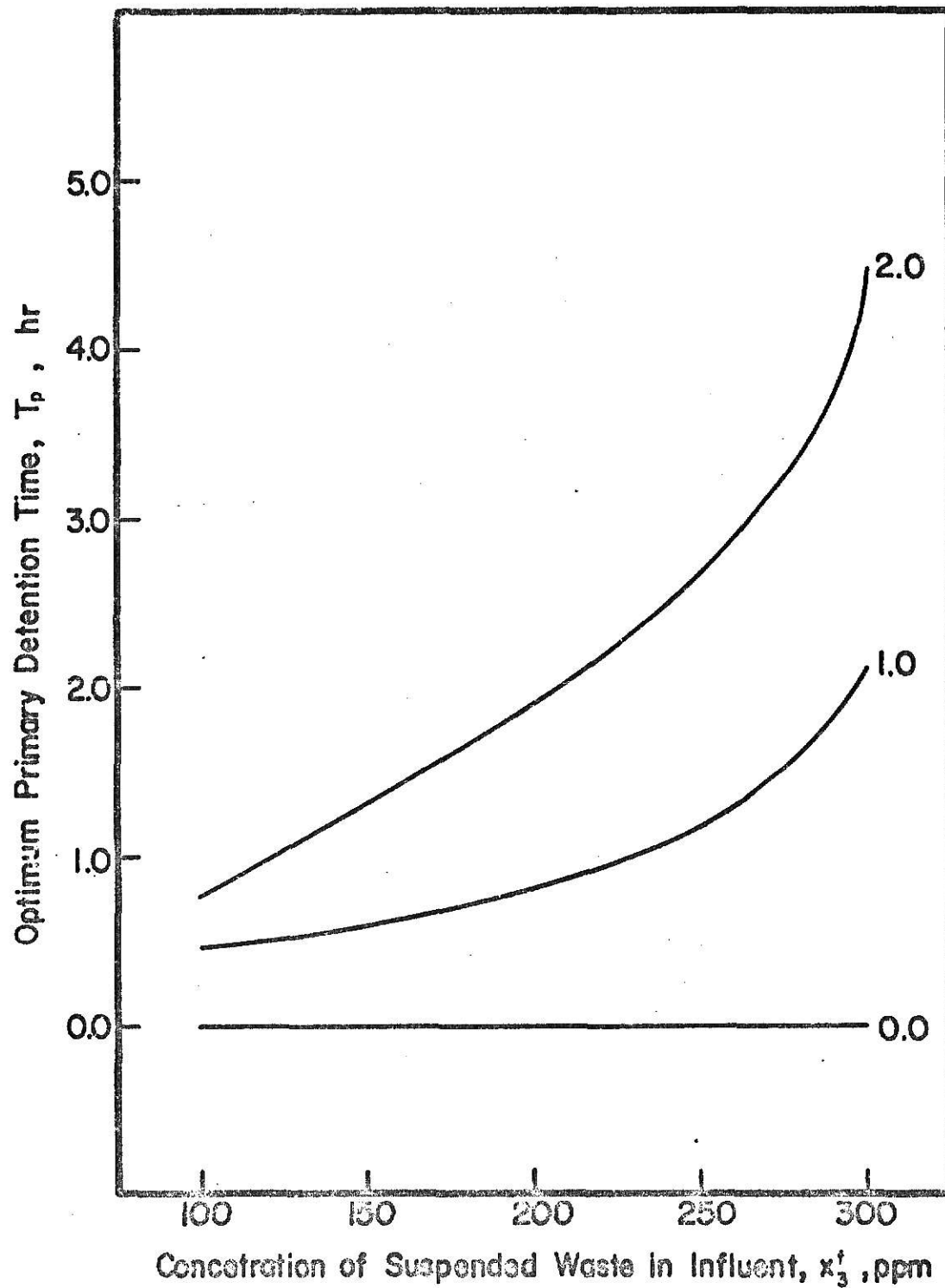


Fig. 6. Variation of Optimum T_p with x'_3 for $x'_1 = 500\text{ppm}$ with h_3 as parameter (Flocculent added) .

adding flocculent is not considered, the optimization results are properly reflecting the relative effectiveness of the two systems based solely on their capital costs. Because the clarifier with flocculent can remove suspended solids very efficiently, a larger system is indicated to take proper advantage of the good separation characteristics of this part of the total system. For example, when $h_3 = 1.0$ and $x_3^f = 300$ ppm, $x_{3p}^e = 139$ ppm without flocculent addition and $x_{3p}^e = 43$ ppm with flocculent addition.

The effect of influent soluble substrate concentration on the variation of the optimal clarifier holding time with respect to x_3^f is shown in Fig. 7. Figure 7 shows the variation of the optimal value of T_p with respect to x_3^f . The parameters are masking effect coefficient h_3 and soluble substrate concentration x_1^f . It can be seen that the optimal value of T_p increases with an increase in x_1^f in case $h_3 = 2.0$, while the optimal value of T_p is not affected with the increase in x_1^f in case $h_3 = 0.0$. It can also be observed that the change in the optimal value of T_p with respect to x_3^f is more revealing when x_1^f is higher. For example, the optimal value of T_p increases from 0.75 hr to 4.75 hr (about 530%) when x_3^f increases from 100 ppm to 300 ppm for $x_1^f = 500$ ppm and $h_3 = 2.0$. While the optimal value of T_p increases from 0.60 hr to 2.80 hr (about 367%) correspondingly for $x_1^f = 300$ ppm and $h_3 = 2.0$. Generally the computation results also indicate that the change in the optimal value of T_p with respect to x_3^f is substantial when the masking effect coefficient is large.

Figure 8 shows the variation of the optimal total construction cost C_T with respect to x_3^f with h_3 as parameter. Both the flocculation and

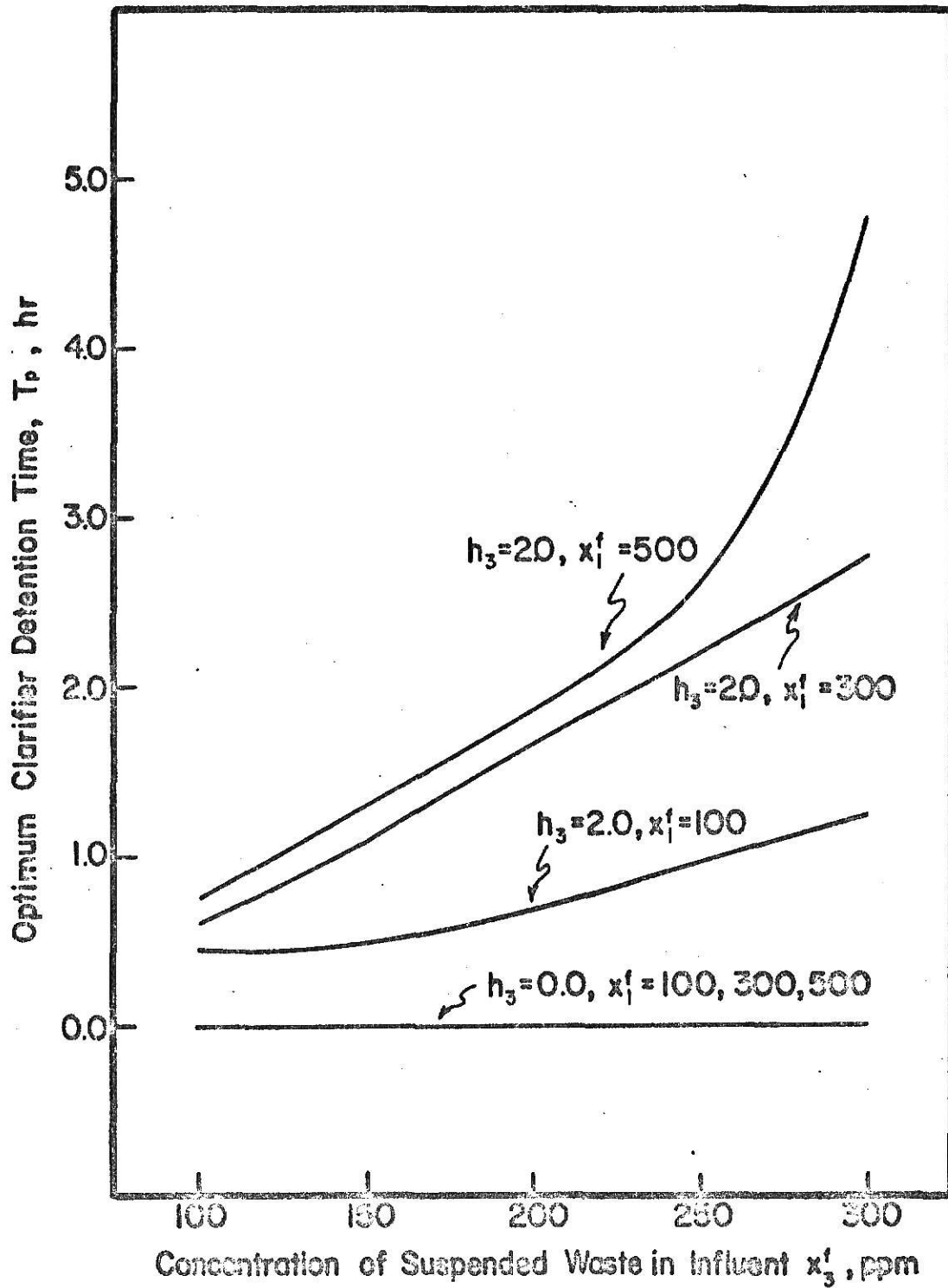


Fig. 7. Variation of Optimum T_p with x'_3 with h_3 and x'_1 as parameters (Flocculent added) .

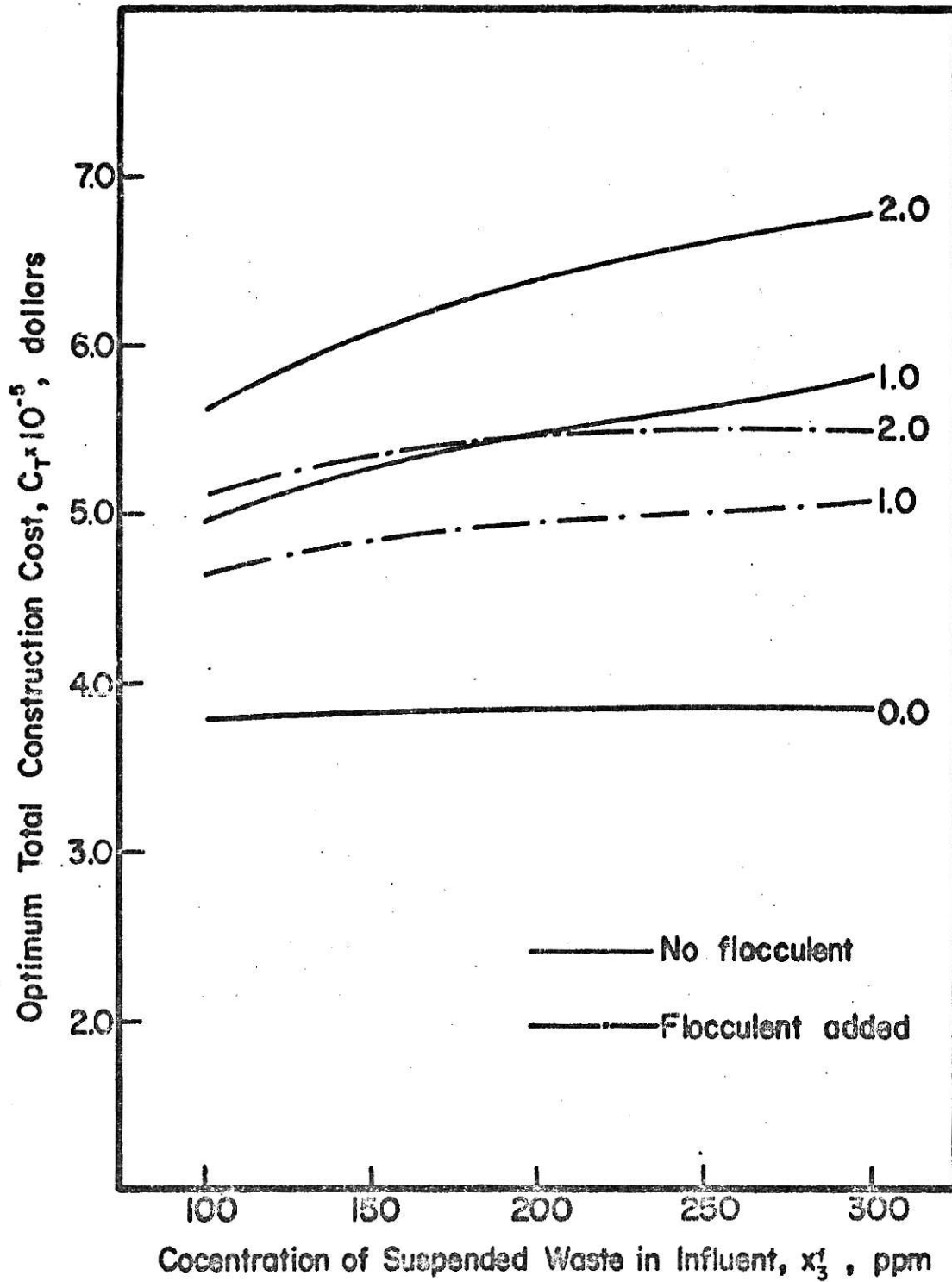


Fig. 8. Variation of optimum C_T with x'_3 for $x'_1 = 500\text{ppm}$ with h_3 as parameter .

nonflocculation are compared. It can be seen that the optimal value of C_T increases with an increase in x_3^f when $h_3 = 1.0$ or 2.0 . For the case without the masking effect, i.e. $h_3 = 0.0$, the optimal value of C_T only increases slightly due to the increase in x_3^f . When x_3^f increases from 100 ppm to 300 ppm in the case without flocculation, the optimal value of C_T increases from 5.60×10^5 dollars to 6.80×10^5 dollars for $h_3 = 2.0$; increases from 4.95×10^5 dollars to 5.80×10^5 dollars for $h_3 = 1.0$; increases from 3.75×10^5 dollars to 3.85×10^5 dollars for $h_3 = 0.0$. Generally the change in the optimal value of C_T with respect to x_3^f is greater when the masking effect coefficient is larger. It can also be observed that the optimal value of C_T in the case with flocculation is less than that in the case without flocculation except when $h_3 = 0.0$.

The difference in the optimal value of C_T between the flocculating and nonflocculation cases is greater when the masking effect is larger. For instance, the difference is about 1.30×10^5 dollars for $h_3 = 2.0$ and is about 0.60×10^5 dollars for $h = 1.0$ at $x_3^f = 300$ ppm and $x_1^f = 500$ ppm. In addition, there is no difference between the flocculating and non-flocculation cases at $h_3 = 0.0$. This implies that the reduction in the optimal total construction cost by flocculation is substantial when the masking effect is large.

Figures 9 and 10 show the variation of the optimal primary clarifier construction cost C_p with respect to the inlet suspended waste concentration x_3^f with the masking effect coefficient h_3 as parameter. Figure 9 is for the case with flocculation and Fig. 10 without flocculation. Both figures indicate that in the absence of masking effect, the optimal primary clarifier construction cost remains fixed at zero for the whole

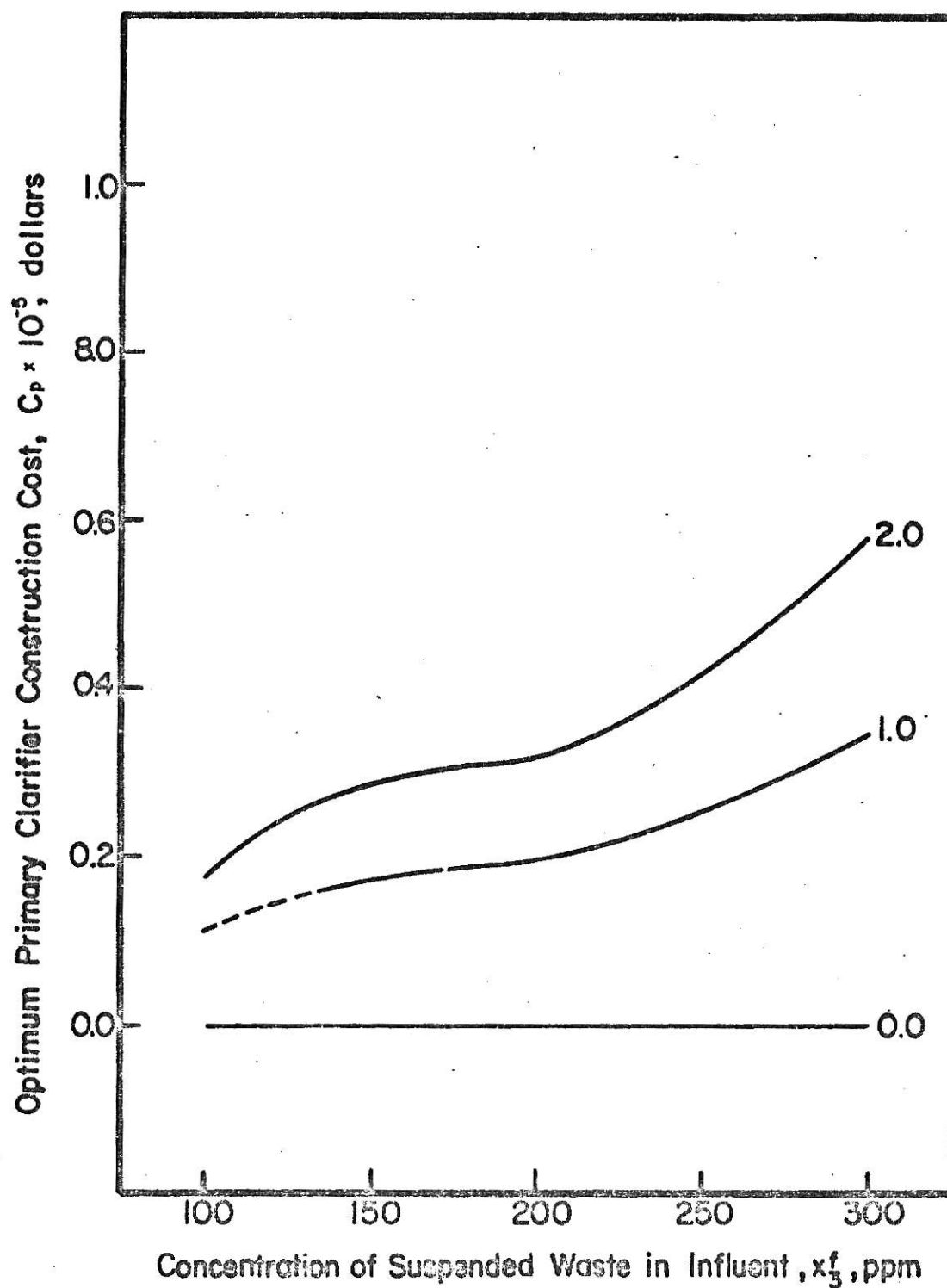


Fig. 9. Variation of optimum C_p with x_3^f , for $x_1^f = 500\text{ppm}$ and with h_3 as parameter (No flocculent added) .

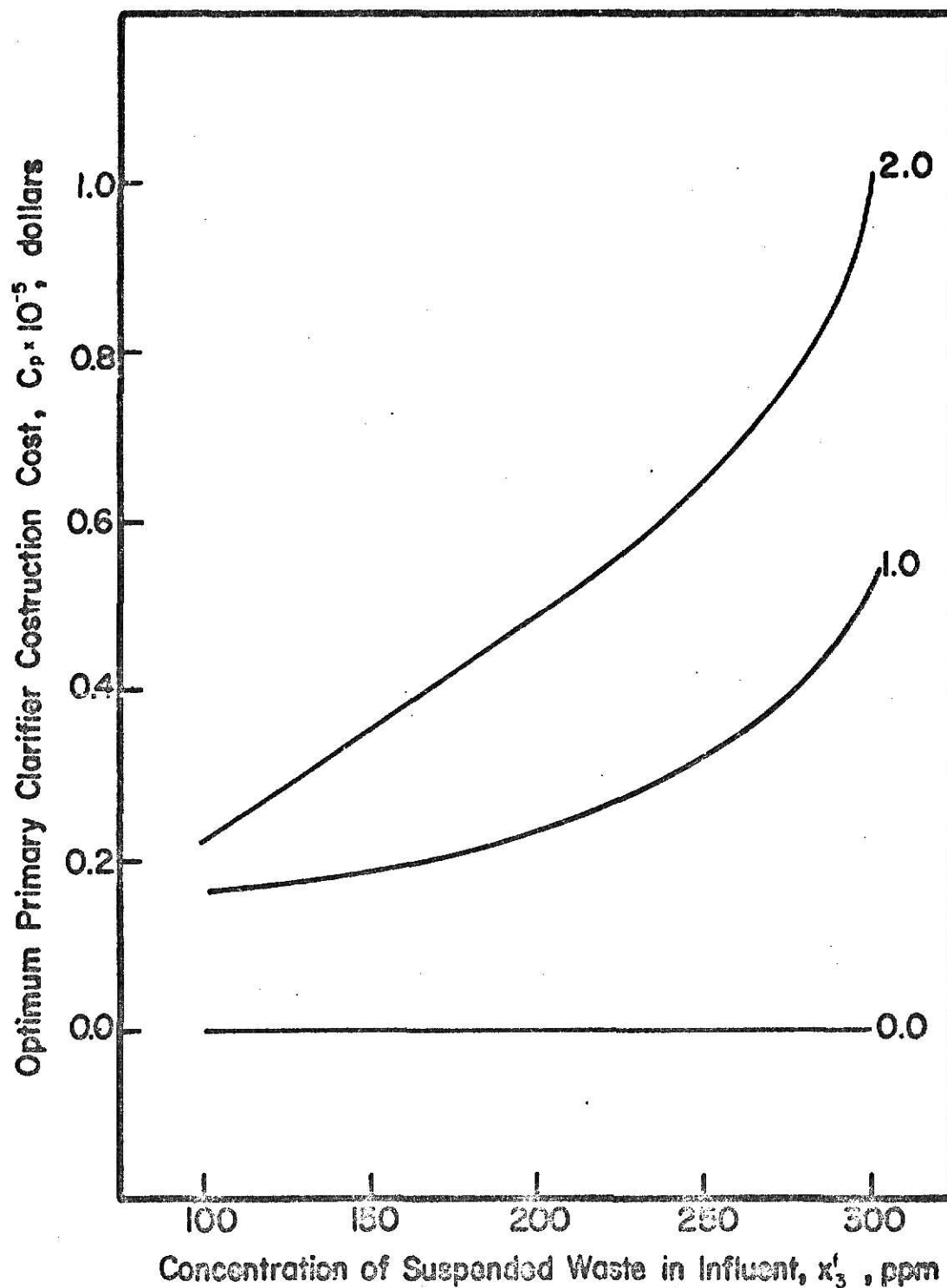


Fig. 10. Variation of optimum C_p with x'_3 for $x'_1 = 500$ ppm with h_3 as parameter (Flocculent added).

range of inlet suspended waste concentration. Furthermore, increases in both x_3^f and h_3 result in increases in the optimal value of C_p . For example, Fig. 10 shows that C_p increases from 2.20×10^4 dollars to 1.10×10^5 dollars (an increase of approximately 400%) when x_3^f increases from 100 ppm to 300 ppm for $h_3 = 2.0$, while C_p increases from 1.60×10^4 dollars to 5.40×10^4 dollars (an increase of approximately 237%) for $h_3 = 1.0$. It can be seen that the change in C_p with respect to x_3^f is greater in the case with flocculation than in the case without flocculation. For instance, Fig. 9* indicates that the optimal primary clarifier cost increases from 1.70×10^4 to 5.70×10^4 dollars (an increase of approximately 235%) when x_3^f increases from 100 ppm to 300 ppm for $h_3 = 2.0$ and $x_1^f = 500$ ppm in the case without flocculation. Figure 10 shows that the optimal primary clarifier cost increases from 2.20×10^4 dollars to 1.10×10^5 dollars (an increase of approximately 400%) for the corresponding case with flocculation. A comparison of Figs. 9 and 10 shows that the optimal primary clarifier construction cost in the case with flocculation is greater than that in the case without flocculation.

Figure 11 shows the variation of the optimal second stage construction cost $I(x_{3p}^e, 2)$ with respect to x_3^f with h_3 as parameter. In the case without flocculation (solid line), the optimal second stage construction cost increases with an increase in x_3^f . While in the case with flocculation, $I(x_{3p}^e, 2)$ exhibits maxima when the masking effect is appreciable. The existence of such maxima is due to the fact that a larger primary clarifier is needed for the optimal design of the

*The dotted line in Fig. 9 represents the region where Voshel's model cannot predict the actual performance of the primary clarifier.

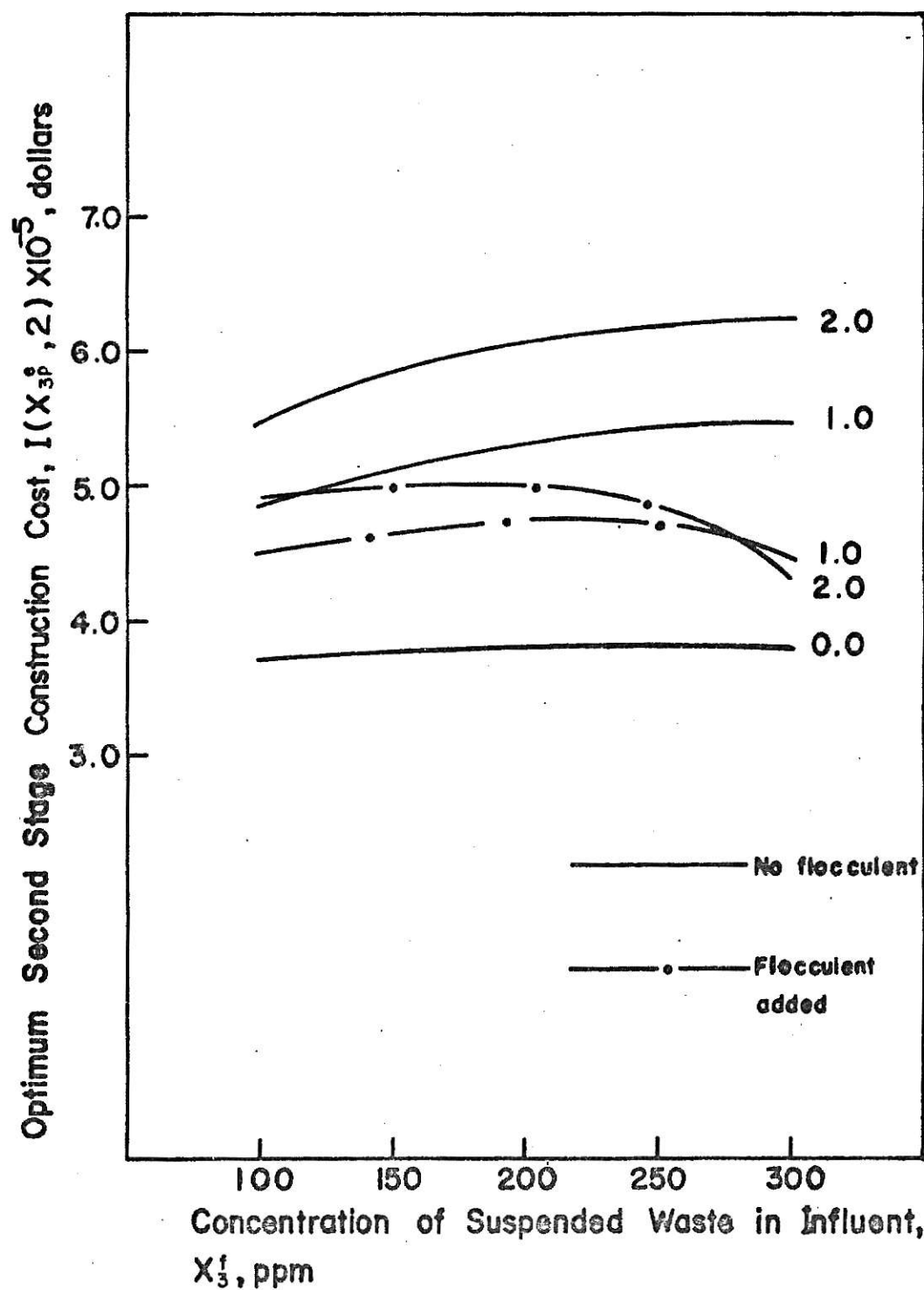


Fig. II . Variation of optimum $I(x_{3p}^*, 2)$ with x_3^f for $x_1^f = 500$ ppm with h_3 as parameter .

total system when the influent suspended waste concentration is high, masking effect is significant, and flocculation is employed. It can also be observed that the optimal second stage construction cost $I(x_{3p}^e, 2)$ in the case with flocculation is less than that in the case without flocculation except when $h_3 = 0.0$. The difference in the optimal second stage construction cost due to use of a flocculating agent is greater when the masking effect is larger. For instance, the difference is about 2.0×10^5 dollars for $h_3 = 2.0$ and is about 1.0×10^5 dollars for $h_3 = 1.0$ at $x_3^f = 300$ ppm and $x_1^f = 500$ ppm.

Figure 12 exhibits the variation of the optimal primary clarifier construction cost C_p with respect to the influent suspended waste concentration x_3^f . The parameters are masking effect coefficient h_3 and influent soluble substrate concentration x_1^f . The computational results as illustrated in Fig. 12 indicate C_p increases with an increase in x_1^f and remains fixed at zero when no masking effect exists. It can be observed that the change in the optimal value of C_p with respect to x_3^f is larger when x_1^f is higher. For example, C_p increases from 0.22×10^5 dollars to 1.10×10^5 dollars (an increase of approximately 400%) when x_3^f increases from 100 ppm to 300 ppm for $x_1^f = 500$ ppm and $h_3 = 2.0$, while C_p increases from 0.19×10^5 dollars to 0.69×10^5 dollars (an increase of approximately 250%) correspondingly for $x_1^f = 300$ ppm and $h_3 = 2.0$.

Figure 13 shows the variation of the optimal suspended waste concentration in the primary clarifier effluent x_{3p}^e with respect to the influent suspended waste concentration x_3^f with the masking effect coefficient as a parameter. It can be observed that the optimal value of

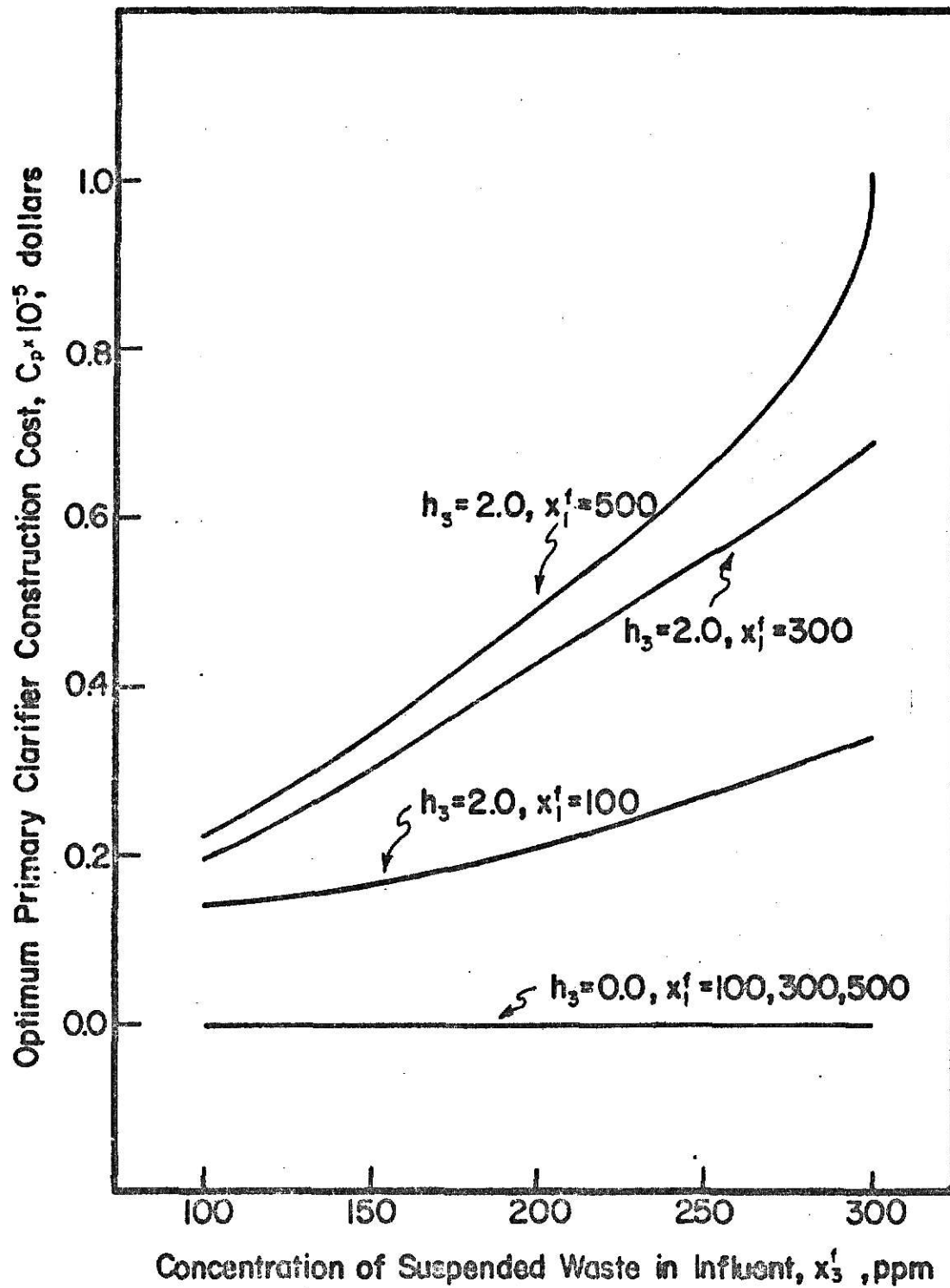


Fig.12. Variation of optimum C_p with x_3^f with h_3 and x_1^f as parameter (Flocculent added).

x_{3p}^e decreases as the masking effect coefficient increases. Furthermore, in the absence of a masking effect, the optimal x_{3p}^e is equal to x_3^f , because the optimal primary clarifier detention time is zero in this case.

Figure 14 exhibits the variation of the optimal value of x_{3p}^e with respect to x_3^f with both h_3 and x_1^f as parameters. When no masking effect exists, x_{3p}^e is invariant with respect to x_1^f . In addition, the computational results, as illustrated in Fig. 14, indicate that the optimal value of x_{3p}^e is reduced by an increase in x_1^f in the presence of the masking effect. Generally, it can be said that the decrease in x_{3p}^e caused by the increase in x_1^f is enhanced when the masking effect coefficient is increased.

4.6 CONCLUSIONS

The results of this study indicate that the optimal detention time of the primary clarifier increases as the concentration or masking characteristics of the influent suspended waste is enhanced. This is to be expected; the masking effect caused by suspended waste in the aeration tank has been known to inhibit the removal of soluble substrates. A larger primary clarifier is also needed when the concentration of soluble substrate is higher, because of the masking effect.

In addition, the results indicate that the optimal primary clarifier detention time in the case with flocculent is greater than that in the case without flocculation. The reduction in the optimal total construction cost by flocculation is substantial when the masking effect is large. The optimal second stage construction cost in the case with flocculent is less than that in the case without flocculation except when no masking effect exists.

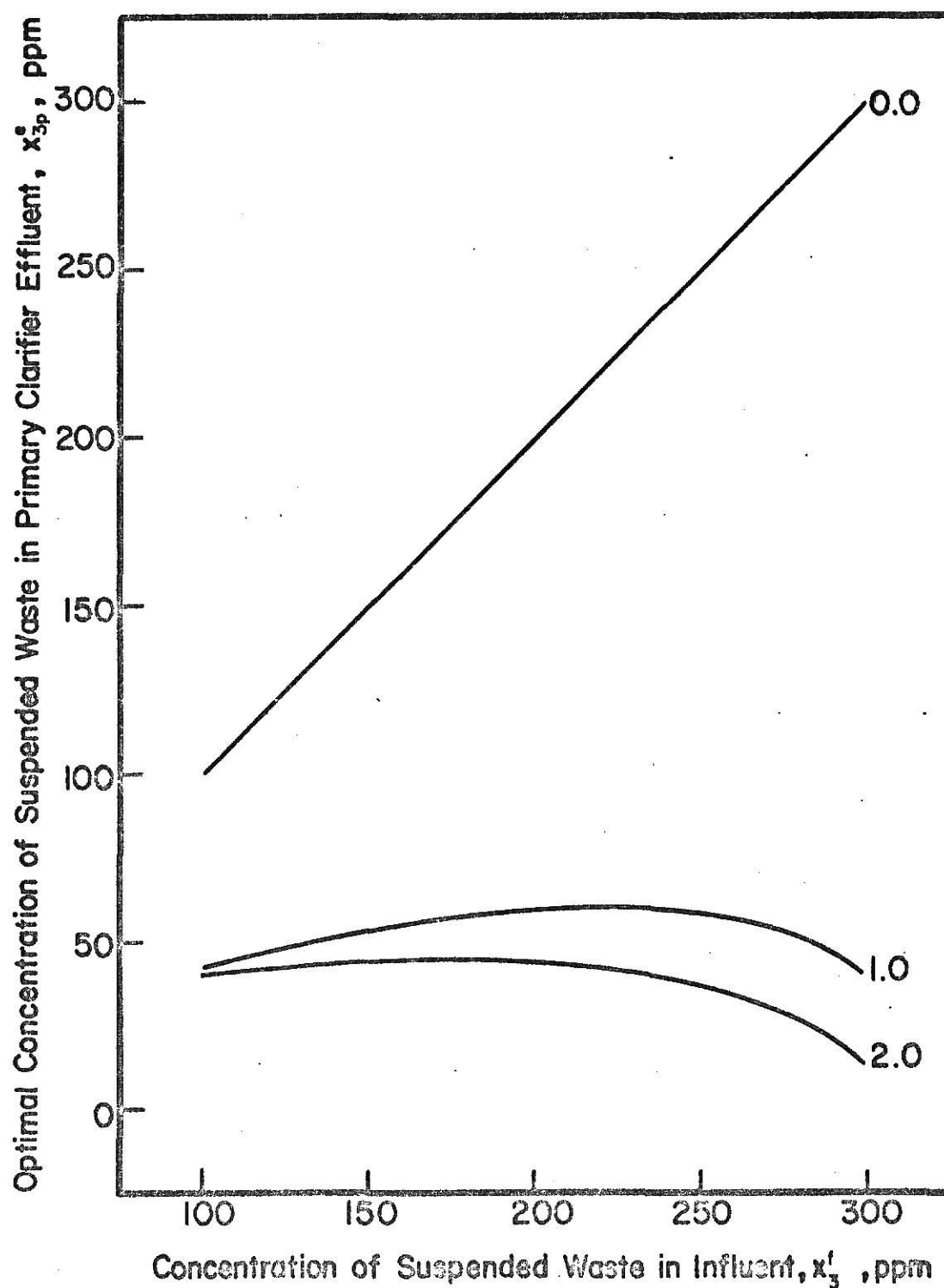


Fig.13. Variation of optimal x_{3p}^o with x_3^i for $x_1^i = 500$ ppm with h as parameter (Flocculent added).

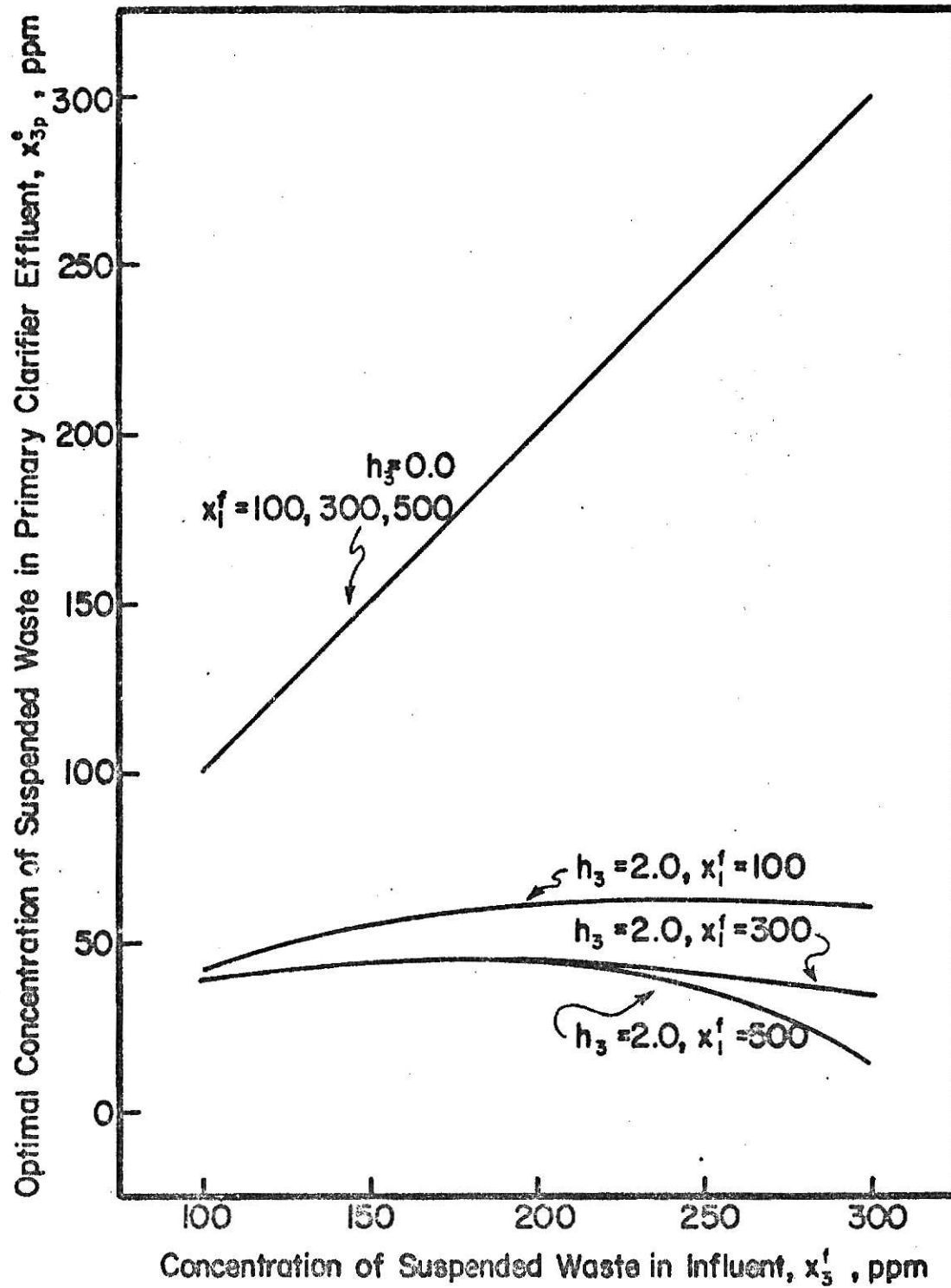


Fig. 14. Variation of optimal x_{3p}^e with x_3^i with h_3 and x_1^f as parameters (Flocculent added) .

The dynamic programming technique can be effectively used in the optimization study of the activated sludge process, in which the system can be easily divided into several serial discrete stages such as primary treatment, secondary treatment, and tertiary treatment.

The primary clarifier has many other advantages, such as damping a dynamic change in the influent load and reducing the operating cost. However, it also has some disadvantages, e.g., degradation of the settling characteristics of microbes in the secondary clarifier. These advantages and disadvantages cannot be directly explained by the model employed here, even though the present model predicts the necessity of the primary clarifier under practical condition in contrast to all the well known conventional models for waste treatment plants.

4.7 NOMENCLATURE

A_p	Surface area of the primary clarifier, ft^2 .
A_s	Surface area of the secondary clarifier, 1000 ft^2 .
C_1	Conversion coefficient for microbes, BOD ppm/microbes ppm.
C_2	Conversion coefficient for suspended waste, BOD ppm/suspended waste ppm.
C_A	Construction cost of the aeration vessel, \$.

C_d	Effluent quality criterion, BOD ppm.
C_p	Construction cost of the primary clarifier, \$.
C_{Rp}	Construction cost of the recycle pump, \$.
C_s	Construction cost of the secondary clarifier, \$.
C_T	Construction cost of the total treatment system, \$.
h_3	Masking effect coefficient, dimensionless.
H	Height of secondary clarifier, ft.
$I(x_{3p}^e, 2)$	Second stage optimal construction cost, \$.
k_d	Endogenous rate coefficient, hr^{-1} .
K_s	Saturation constant of soluble substrate, ppm.
$l(x_3^f, T_p, 1)$	First stage (primary clarifier) construction cost, \$.
p	Specific constant for secondary clarifier, dimensionless.
q	Volumetric flow rate of influent waste water, MGD.
r	Sludge recycle ratio, dimensionless.
S	Object function (performance criterion), \$.
T_A	Aeration chamber detention time, hours.
T_p	Primary clarifier detention time, hours.
T_s	Secondary clarifier detention time, hours.
V_A	Aeration chamber volume, MG.
V_p	Primary clarifier volume, MG.
V_s	Secondary clarifier volume, MG.
$\underline{u}$	Control (decision) vector.
U	Set of constraints for control vector.
w	Sludge wasting ratio, dimensionless.
$\underline{x}$	State vector.
X	Set of constraints for state vector.

x_1	Concentration of soluble substrate, ppm.
x_2	Concentration of microbes, ppm.
x_3	Concentration of suspended waste, ppm.
Y_1	Yield coefficient of soluble substrate, microbes ppm/BOD ppm.
Y_3	Yield coefficient of suspended waste, microbes ppm/suspended waste ppm.
α	Specific coefficient for secondary clarifier, dimensionless.
β_3	Removal rate coefficient of suspended waste, 1/hr·microbes ppm.
γ	Specific constant for secondary clarifier, hr^{-1} .
μ_{ml}	Maximum specific growth rate of microbes on soluble substrate, hr^{-1} .

4.7.1 Superscripts

0	Influent to aeration tank from mixing point.
1	Effluent from aeration tank.
e	Effluent from clarifier overflow.
f	Feed or inflow to primary clarifier.
r	Secondary clarifier underflow and recycle flow.

4.7.2 Subscript

p	Effluent from primary clarifier
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APPENDIX 4-1

Derivation of Functional Equation

The minimum cost function, $I(\underline{x}(k), k)$, can be mathematically defined as

$$I(\underline{x}(k-1), k) = \underset{j=k, k+1, \dots, K}{\text{Min}} \underset{\underline{u}(j) \in U}{\text{Min}} \left\{ \sum_{j=k}^K \ell[\underline{x}(j-1), \underline{u}(j), j] \right\} \quad (\text{A-1})$$

where $\ell[\underline{x}(j), \underline{u}(j), j]$ is the cost function of stage j .

Split the summation inside the braces in eq. (A-1) into two parts as follows

$$I(\underline{x}(k-1), k) = \underset{j=k, k+1, \dots, K}{\text{Min}} \underset{\underline{u}(j) \in U}{\text{Min}} \{ \ell[\underline{x}(k-1), \underline{u}(k), k] \\ + \sum_{j=k+1}^K \ell[\underline{x}(j-1), \underline{u}(j), j] \} \quad (\text{A-2})$$

Splitting the minimization operation in eq. (A-2) into two parts, a minimization over $\underline{u}(k)$ and a minimization over $\underline{u}(k+1), \underline{u}(k+2), \dots, \underline{u}(K)$, gives

$$I(\underline{x}(k-1), k) = \underset{\underline{u}(k) \in U}{\text{Min}} \underset{j=k+1, k+2, \dots, K}{\text{Min}} \underset{\underline{u}(j) \in U}{\text{Min}} \{ \ell[\underline{x}(k-1), \underline{u}(k), k] \\ + \sum_{j=k+1}^K \ell[\underline{x}(j-1), \underline{u}(j), j] \} \quad (\text{A-3})$$

It can be seen that the first term in brackets in eq. (A-3) depends only on $\underline{u}(k)$ and not on any $\underline{u}(j)$, $j=k+1, k+2, \dots, K$. Therefore, the minimization over $\underline{u}(j)$, $j > k$, has no effect on this term, and

$$\begin{aligned} & \min_{\substack{\underline{u}(k) \in U \\ j=k+1, k+2, \dots, K}} \min_{\substack{\underline{u}(j) \in U \\ j=k+1, k+2, \dots, K}} \{ \ell[\underline{x}(k-1), k] \} \\ & = \min_{\underline{u}(k) \in U} \{ \ell[\underline{x}(k-1), \underline{u}(k), k] \} \end{aligned} \quad (A-4)$$

The second term in braces in eq. (A-3) does not depend explicitly on $\underline{u}(k)$. However, $\underline{u}(k)$ does determine the state $\underline{x}(k)$ through the system equation

$$\underline{x}(k) = g[\underline{x}(k-1), \underline{u}(k), k]$$

Using this relation and recalling the definition of the minimum cost function from eq. (A-1), then

$$\begin{aligned} & \min_{\underline{u}(k) \in U} \min_{\substack{\underline{u}(j) \in U \\ j=k+1, k+2, \dots, K}} \left\{ \sum_{j=k+1}^K \ell[\underline{x}(j-1), \underline{u}(j), j] \right\} \\ & = \min_{\underline{u}(k) \in U} \{ I[g(\underline{x}(k-1), \underline{u}(k), k), k+1] \} \end{aligned} \quad (A-5)$$

Substituting eqs. (A-4) and (A-5) into (A-3) results in the so-called functional equation of the principle of optimality

$$\begin{aligned} I(\underline{x}(k-1), k) &= \min_{\underline{u}(k) \in U} \{ \ell[\underline{x}(k-1), \underline{u}(k), k] \\ & \quad + I[g(\underline{x}(k-1), \underline{u}(k), k), k+1] \} \end{aligned}$$

CHAPTER 5

CONCLUSIONS AND DISCUSSION

A newly proposed parallel biochemical oxidation kinetic model for soluble substrate and suspended substrate removal in the activated sludge process is considered in the present research. The effect of including a primary clarifier on the performance of the activated sludge process, the influence of suspended solids on the performance of a secondary wastewater treatment system, and the optimization of the overall activated sludge process including both primary and secondary treatments are investigated based on the newly constructed model.

The major features of the newly constructed model, which takes into account the low metabolic rate of suspended substrate and the masking effect of suspended waste, appear to be consistent with the available experimental data. This new model can be effectively used for estimating the optimal size of the primary clarifier in the activated sludge process system. The results show that an increase in the primary clarifier detention time gives rise to an increase in the content of microbes in the mixed liquor inside the aeration tank.

The studies of the influence of suspended solids on the optimal design of the secondary wastewater treatment system reveal that the masking effect due to suspended waste in the aeration chamber is undesirable and that efforts should be made to minimize it. The results also indicated that the masking effect of suspended waste and the feed concentration of soluble substrate to the aeration chamber are two factors which significantly affect the optimal design policies of the secondary wastewater treatment system.

The application of dynamic programming to the optimal design of an overall activated sludge process including a primary clarifier indicates that the optimal detention time of the primary clarifier increases as the concentration or masking characteristics of the influent suspended waste is enhanced. A larger primary is also needed when the concentration of soluble substrate is higher, because of the masking effect. The results also indicate that the optimal primary clarifier detention time in the case with flocculent is greater than that in the case without flocculation. The reduction in the optimal total construction cost by flocculation is substantial when the masking effect is large. The optimal second stage construction cost in the case with flocculent is less than that in the case without flocculation except when no masking effect exists.

In this study, the operating and maintenance costs are not included in the objective function; only the construction cost is considered. The operating and maintenance costs, such as the power cost, labor cost and material cost, may be as important as the construction cost. Inclusion of the operating and maintenance costs in the objective function may predict the optimal results closer to the practical economical optimum. However, this study can be useful in predicting the effect of specific parameters and variables on the performance and design of the system. Further optimization studies, which also take into account the operating and maintenance costs are recommended.

The system considered in the present study does not contain a solid waste handling and disposal subsystem and tertiary treatment subsystem. These two treatment subsystems may account for a large portion of the

total construction cost. In order to optimize the total waste treatment plant, various process models for these subsystems need to be developed and incorporated into the system considered in the present study.

The present model predicts the necessity of the primary clarifier under practical conditions in contrast to other conventional kinetic models. The primary clarifier tends to minimize the dynamic change in the influent to the secondary waste water treatment system. Failures of a treatment plant, e.g., the bulking of activated sludge, and daily variations in treatment plant efficiency are frequently due to variations in waste water flow and composition. Further studies of the dynamics and control of a waste water treatment plant including a primary clarifier are recommended.

ACKNOWLEDGEMENT

The author wishes to express his sincere appreciation to Dr. L. T. Fan for his continued encouragement and guidance during the course of this research and the writing of this thesis.

The experienced advice of Dr. L. E. Erickson and his reading of the manuscript are greatly appreciated. The author wishes to thank Dr. D. A. Wallace for his help in reading the manuscript. The author also wishes to thank Dr. I. C. Kao for his stimulation during the discussion.

This work was made possible through the financial support of Water Quality Office of EPA (Grant 17090 ELL) and Engineering Experiment Station of Kansas State University.

MODELING, SIMULATION AND OPTIMIZATION
OF THE ACTIVATED SLUDGE PROCESS

by

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B.S., National Taiwan University, 1970

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Chemical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1973

Activated sludge processes are widely employed in the field of waste water treatment. Conventionally a primary clarifier has been attached to this process for the removal of suspended solids. However, most of the primary clarifier designs have been based on past experiences rather than on the results of system analysis. An attempt has been made in this research to develop a new approach for the optimal design of the activated sludge process system including a primary clarifier.

A new parallel biochemical oxidation kinetic model, which takes into account the low metabolic rate of suspended substrate and the masking effect of suspended waste, has been constructed based on the available information. The simulation and optimization studies of the activated sludge system have been carried out based on the newly derived kinetic model.

The major features of the newly proposed kinetic model appear to be consistent with the available experimental data. With this new model the optimal size of the primary clarifier in the activated sludge process system is predicted for several values of influent suspended solids concentration.

The studies of the influence of suspended solids on the optimal design of the secondary wastewater treatment system reveal that the masking effect of suspended wastes and the feed concentration of soluble substrate to the aeration tank are two factors which significantly affect the optimal design policies of the secondary wastewater treatment system.

The application of dynamic programming to the optimal design of a primary clarifier followed by an activated sludge process indicates that the optimal detention time of the primary clarifier increases as the concentration or masking characteristics of the influent suspended waste is enhanced.