

AEROBIC BIOSTABILIZATION OF A HIGH-STRENGTH
LANDFILL LEACHATE

by

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ABSTRACT

One particularly undesirable aspect of solid waste disposal on land is the contamination of water passing through the landfill site. The potential adverse environmental effects of these "leachates" have been recognized to the extent that their control and treatment is the subject of a great deal of current research in water pollution control.

This study was initiated to investigate the possibility of reducing the amounts of oxygen demanding material in a high-strength landfill leachate by aerobic biological methods, without any prior removal of the heavy metals contained in that leachate. The effect of varying solids detention time was also investigated and the distribution of the heavy metals in the effluents was examined.

Using very high mixed liquor volatile suspended solids concentrations, 8,000 to 16,000 mg/l, and a combination of air and mechanical mixing, anticipated foaming problems were controlled and stable digester operation was maintained at solids detention times as low as 10 days. For influent COD concentrations between 44,000 and 52,000 mg/l, settled effluent COD removal increased marginally from 96.8 to 99.2 percent, as the solids detention time increased from 10 to 60 days. Mixed liquor COD removal similarly increased from 51.5 to 75.7 percent. Increasing the solids detention time from 10 to 20 days, significantly improved the quality of the settled effluent with respect to oxygen demanding material. At solids detention times greater than 20 days, and with influent BOD_5 between 32,000 and 38,000 mg/l, settled effluent BOD_5 averaged 58.1 mg/l, as opposed to settled effluent BOD_5 greater than 125 mg/l when the solids detention time was 10 days or less.

The leachate feed used in these studies contained a variety of

heavy metals including aluminum (41.8 mg/l), cadmium (0.39 mg/l), chromium (1.9 mg/l), copper (0.24 mg/l), lead (1.44 mg/l), nickel (0.65 mg/l), and zinc (223 mg/l). Most of these metals including aluminum, cadmium, chromium, nickel and zinc were almost completely removed by the settling biological floc. Others were associated with the sludge solids to a lesser extent. Analysis of the kinetic parameters associated with the biostabilization process indicated that the high heavy metal concentrations in the mixed liquors inhibited the actual biological removal of oxygen demanding material in the digesters tested. The settling biological floc was found, however, to remove greater than 97 percent of the mixed liquor BOD_5 and greater than 96 percent of the mixed liquor COD when solids detention times were maintained greater than 20 days. Therefore, for best treatment results a solids detention time of at least 20 days is recommended and the food to micro-organism ratio should be kept below 0.15 lb. BOD_5 /lb.MLVSS/day.

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CHAPTER 1

INTRODUCTION

Over the years there has been a substantial increase in the volume of solid waste being generated throughout the world. Although enormous amounts of money have been spent on the development of alternative disposal methods such as incineration, composting and recycling, sanitary landfills and garbage dumps remain the most popular method of disposal for solid wastes.

One of the major problems presented by the operation of a solid waste landfill, particularly in high rainfall climates, is the production of leachate. Leachate is produced when surface or groundwater becomes contaminated as it passes through the layers of refuse in a landfill. If the leachate enters nearby surface or groundwaters, a serious pollution problem may result. The magnitude of the pollution problem will depend largely on the strength and quantity of leachate produced, as well as on the dilution afforded by receiving waters. Table I illustrates the observed variability of leachate strength (1). The quality and quantity of leachate depends on the amount and composition of the refuse, the hydrogeology of the site, the age of the landfill, and the climate. The deleterious effects of leachates on receiving waters has been well documented in the literature (1,2,3).

With the recent popularity of environmental matters, the importance of leachate as a particularly undesirable aspect of solid waste disposal on land has been recognized to such an extent that disposal sites are usually chosen and designed to minimize leachate production. Design precautions entail diversion of surface water from the landfill site, prevention of groundwater contact with refuse, and sealing and sloping the surface to minimize or eliminate precipitation infiltration. This method of control is very effective in arid or semi-arid climates where precipitation is minimal.

TABLE I
COMPOSITION OF TYPICAL LEACHATES

Parameter	Range of Values or Concentrations* (Landfills and Test Lysimeters)
BOD ₅	9 - 55,000
COD	0 - 90,000
Total Carbon	715 - 22,350
Total Organic Carbon	715 - 22,350
Total Solids	1,000 - 45,000
Total Volatile Solids	1,000 - 23,157
Total Dissolved Solids	0 - 42,300
Acidity	0 - 9,560
Alkalinity	0 - 20,900
Aluminum	0 - 122
Arsenic	0 - 11.6
Barium	0 - 5.4
Beryllium	0 - 0.3
Calcium	5 - 4,000
Cadmium	0 - 0.19
Chloride	34 - 2,800
Chromium	0 - 33.4
Copper	0 - 10
Iron	0.2 - 5,500
Lead	0 - 5.0
Magnesium	165 - 15,600
Manganese	0.06 - 1,400
Mercury	0 - 0.064
Molybdenum	0 - 0.52
Nitrogen - total	0 - 2,406
- NH ₃	0 - 1,106
Nickel	0.01 - 0.80
Phosphorus - total	0 - 154
Potassium	2.8 - 3,770
Sodium	0 - 7,700
Sulphates	1 - 1,826
Sulphides	0 - 0.13
Titanium	0 - 5.0
Vanadium	0 - 1.4
Zinc	0 - 1,000
pH	3.7 - 8.5
Tannin-like compounds	78 - 1,278
Colour (chloroplatinate)	0 - 12,000
Odour	not detectable to terrible

* all values except those for pH, colour and odour are in mg/l.

However, many landfill sites are located in areas where precipitation rates are high and where available soil cover material is unsuitable for sealing the landfill against infiltrating precipitation. In addition, urban development has resulted in keen competition for the available lands by all potential users and so less than ideal parcels of land have often been chosen for landfill sites.

The percolation of water through the refuse greatly increases the rate of biochemical stabilization of the landfill and thus decreases the time required for consolidation and settling of the landfill. Although such a landfill site may be used for building construction or recreational purposes much sooner than a sealed landfill, the leachate produced is highly contaminated and must therefore be collected for subsequent treatment.

Collection of the leachate before it enters ground or surface waters can be accomplished by careful landfill design and site selection. The development of suitable treatment methods, however, remains the topic of much current research. This study was initiated to investigate aerobic biostabilization of a high-strength landfill leachate as a means of reducing potential receiving water pollution problems.

CHAPTER 2

GENERAL REVIEW OF AEROBIC BIOSTABILIZATION

2-1 General Process Description

Aerobic processes include activated sludge, trickling filters and aerobic stabilization ponds. The activated sludge process is used almost exclusively in large cities. Trickling filters are often used in small cities and for high-strength, readily biodegradable industrial wastes. Aerobic ponds are used in small cities where large land areas are available. The principles behind all three processes are similar. However, since variations of the complete-mix activated sludge system were used in this study, the following discussion will be directed to that process.

The activated sludge process was developed in England in 1914 and was so named because it involved the production of an activated mass of micro-organisms capable of aerobically stabilizing or decomposing an organic waste. The aerobic environment in an activated sludge aeration basin is maintained by the use of diffused or mechanical aeration. The reactor contents are referred to as the mixed liquor. After the waste is treated in the reactor, the resulting biological mass is separated from the liquid in a settling tank or clarifier. A portion of the settled biological solids is usually recycled, the remaining mass is wasted. A portion of the micro-organisms must be wasted, otherwise the mass of micro-organisms would keep increasing until the system could no longer contain them. The level at which the biological mass should be kept depends on the desired treatment efficiency and other considerations related to growth kinetics. The micro-organism concentrations generally maintained in three types of activated sludge treatment systems are listed in Table II(4).

TABLE II

DESIGN PARAMETERS FOR ACTIVATED SLUDGE PROCESSES

Process Modification	Solids Detention Time, θ_c , Days	Food To Micro- organism Ratio, U, lb. BOD ₅ /lb. MLVSS/Day	Volumetric Loading, lb. BOD ₅ /1000 cu. ft.	Mixed Liquor Volatile Suspended Solids, mg/liter	Recycle Ratio
Conventional	5 - 15	0.2 - 0.4	20 - 40	1,200 - 2,400	0.25 - 0.50
Complete Mix	5 - 15	0.2 - 0.6	50 - 120	2,400 - 4,800	0.25 - 1.00
Extended Aeration	20 - 30	0.05 - 0.15	10 - 25	2,400 - 4,800	0.75 - 1.50

To design and operate an activated-sludge system efficiently, it is necessary to understand the importance of the micro-organisms in the system. In nature, the key role of the bacteria is to decompose organic matter produced by other living organisms. In the activated-sludge process, the bacteria are the most important micro-organisms because they are responsible for the decomposition of the organic material in the influent. In the mixed liquor tank, a portion of the organic waste matter is used by aerobic and facultative bacteria to obtain energy for the synthesis of the remainder of the organic material into new cells. Thus, a portion of the organic matter is oxidized to low energy compounds such as NO_3^- , $\text{SO}_4^{=}$ and CO_2 . The remainder is synthesized into cellular material.

While bacteria are the micro-organisms that actually degrade the organic waste in the influent, the metabolic activities of other micro-organisms are also important in the activated-sludge system. For example, protozoa and rotifers act as effluent polishers. Protozoa consume dispersed bacteria that have not flocculated, and rotifers consume any small biological floc particles that have not settled.

Further, while it is important that bacteria decompose the organic waste as quickly as possible, it is also important that they form a satisfactory floc, which is a prerequisite for the effective separation of the biological solids in the settling unit. It has been observed that as the solids detention or mean cell residence time is increased, the settling characteristics of the biological floc are enhanced. The reason for this is that, as the mean age of the cells increases, the surface charge is reduced and the micro-organisms start to produce extracellular polymers, eventually becoming "encapsulated" in a slime layer. The presence of these polymers and the slime promotes the formation of floc particles that can be removed readily by gravity settling. Typical values of mean cell residence

or solids detention time used in the design and operation of activated sludge processes are also shown in Table II (4).

2-2 Design Equations

In this study the biological solids retention time, θ_c , and the food to micro-organism ratio, U , were used as basic design parameters. Lawrence and McCarty (5) have defined θ_c for completely mixed, no-recycle systems as the reciprocal of the net specific growth rate as follows:

$$\frac{1}{\theta_c} = \frac{Y K S}{K_s + S} - b \quad (1)$$

where Y = growth yield coefficient,

K = maximum rate of substrate utilization per unit weight of micro-organisms, (T^{-1}) ,

S = concentration of substrate surrounding the micro-organisms, (M/L^3) ,

b = micro-organism decay or endogenous respiration coefficient, (T^{-1}) ,

K_s = substrate concentration when $\frac{dS/dt}{X} = \frac{K}{2}$, (M/L^3) ,

$\frac{dS}{dt}$ = rate of microbial substrate utilization per unit volume, and

X = microbial mass concentration or mixed liquor volatile suspended solid, MLVSS, concentration, (M/L^3) .

An expression for the mixed liquor microbial mass concentration, X , can be derived for steady-state conditions by performing a substrate mass balance on the reactor. The equation is as follows:

$$X = \frac{Y(S_0 - S_1)}{1 + b\theta_c} \quad (2)$$

where S_0 = influent waste concentration, (M/L^3) , and

S_1 = effluent waste concentration, (M/L^3) .

The parameters, Y , b , K and K_s were determined using the results of a preliminary "extended aeration" efficiency study and then, equations 1 and

2 were used to predict the performance of the units at lower solids detention times.

2-3 Factors Affecting Aerobic Biostabilization

Application and study of aerobic treatment methods over a number of years have demonstrated that certain factors may have favourable or unfavourable effects on aerobic digestion. Since the process is carried out by a highly diverse group of micro-organisms, certain optimum conditions must be maintained during digestion. Among the factors most often considered in designing an aerobic stabilization process are pH, temperature, oxygen requirements, nutrient requirements, and waste toxicity. Because an understanding of the factors that effect the process was necessary in order to design and successfully operate the digesters, the most important factors were examined.

- (a) pH and Alkalinity - To maintain a stable, biological population, the pH should be maintained between 6.5 and 9.0. Values outside of this recommended range may inhibit the growth of aerobic bacteria or even cause their destruction. As the organic waste is decomposed and oxidized, $\text{SO}_4^{=}$, NO_3^- and CO_2 may be formed resulting in a pH drop. For this reason it is recommended that the influent waste should contain 0.5 lb. of alkalinity per lb. of BOD_5 to be removed. If sufficient alkalinity is not present in the influent, it may be necessary to add buffering agents to maintain the pH in the desired range.
- (b) Temperature - The temperature dependence of the biological reaction-rate constant is very important in assessing the overall efficiency of a biological treatment process. Temperature not only influences the metabolic activities of the microbial population, but also has

a profound effect on such factors as gas transfer rates and the settling characteristics of the biological solids. The temperature effect on the reaction rate of a biological process is usually expressed in the following form:

$$\frac{K_T}{K_{20}} = \phi^{(T-20)} \quad (3)$$

where K_T = reaction rate at $T^{\circ}\text{C}$,

K_{20} = reaction rate at 20°C ,

ϕ = temperature-activity coefficient, and

T = temperature, $^{\circ}\text{C}$.

For activated sludge processes, ϕ varies between 1.00 and 1.03.

From these relatively low values of the temperature-activity coefficient, it is evident that relatively large temperature changes would be required to significantly affect treatment efficiency.

- (c) Oxygen Requirements - To maintain aerobic conditions in the reactor, the dissolved oxygen level must be kept above 1-2 mg/litre. In addition, the air supply rate must be adequate to satisfy the BOD of the waste, to satisfy the endogenous respiration of the sludge organisms, and to provide adequate mixing. For food to micro-organism ratios greater than 0.3, the air requirements amount to 500 to 900 cubic feet per lb. of BOD_5 removed. At lower food to micro-organism ratios, endogenous respiration, nitrification and prolonged aeration periods increase air use to 1,200 to 1,800 cubic feet per lb. of BOD_5 removed. A minimum air flow of approximately 3 cubic feet per minute per foot of tank length is required to maintain adequate mixing and to avoid solids deposition (4).

(d) Nutrient Requirements - If any biological system is to function properly, nutrients required by the micro-organisms must be available in adequate amounts. Nitrogen and phosphorus are the nutrients required in highest concentrations. Since these materials may be absent in some wastes, it is important to know the amounts which may have to be added. Sawyer (6) established a ratio of nitrogen to phosphorus to BOD_5 which should be maintained if aerobic micro-organisms are to function effectively. He cited $BOD_5:N$ ratios ranging from 17:1 to 32:1 and $BOD_5:P$ ratios ranging from 90:1 to 150:1 as being adequate. These ratios have been adjusted through usage to $BOD_5:N:P$ of 100:5:1 and have generally resulted in satisfactory performance.

(e) Waste Toxicity - Because the incoming waste is more or less uniformly dispersed in a complete-mix reactor, it can, in comparison to the conventional, plug-flow, activated sludge reactor, more easily withstand shock loads of organic and toxic materials. For this reason, a complete-mix reactor was chosen for this study.

The term toxic, however, is very relative and the concentration at which any substance is toxic or inhibiting to aerobic digestion may vary from a fraction of a mg/l to several thousand mg/l. At some low concentrations, stimulation of activity is usually achieved. This stimulatory concentration may range from a fraction of a mg/l for heavy metals to over a hundred mg/l for sodium and calcium salts. As the concentration is increased above stimulatory concentrations, the rate of biological activity begins to decrease. A point is then reached where inhibition is apparent and the rate of biological activity is less than that achieved in the absence of the substance. Finally, at some high concentration, the biological activity may

approach zero.

Micro-organisms have the ability to adapt to some extent to the inhibitory concentration of most substances. The extent of adaptation, however, is also relative. In some cases the activity after acclimatization may approach that obtained in the absence of the inhibitory substance, while in other cases, the level of activity will remain much lower than that obtained in the absence of inhibitory substances.

Barth et al. (7) conducted a comprehensive study on the effects of heavy metals on a conventional activated sludge process. However, their study involved only four metals, namely chromium, copper, nickel and zinc. During each run, an experimental pilot-plant unit and a control unit receiving no metal were compared. The metal was added continuously to a constant sewage feed of the experimental unit. Two weeks of acclimation were allowed before data on the quality of the final effluent were collected. This time interval was required for the metal concentration in the activated sludge to build up to a condition of operating equilibrium. The final effluent from both units was assayed daily for BOD, COD, suspended solids and turbidity. The run for any selected metal dosage was continued for 60 days to obtain sufficient data. The values for the two units were then compared as frequency distribution curves and the continuous doses of each metal that will give significant reduction in aerobic treatment efficiency were thus determined. Their results are summarized in Table III (7).

TABLE III
CONTINUOUS DOSE OF METAL THAT WILL GIVE SIGNIFICANT
REDUCTION IN AEROBIC TREATMENT EFFICIENCY

Metal	Concentration in Influent Waste mg/l
Chromium (VI)	10
Copper	1
Nickel	1 to 2.5
Zinc	5 to 10

In addition, mixed doses of the four metals were applied at different concentrations, so as to investigate possible synergistic effects. The results of these studies showed that the activated sludge phase of a biological treatment plant can tolerate, in the influent sewage, chromium, copper, nickel and zinc, up to a total heavy metal concentration of 10 mg/l. Either singly or in combination, heavy metal concentrations of this magnitude caused only a 5 percent reduction in overall plant efficiency (7).

In addition Kampf (8), a German researcher, has developed a 3-stage method for examining the effect of toxic compounds on activated sludge. Based on measurements of oxygen consumption using the Warburg respirometer, stage 1 measures the direct inhibition of respiration by toxic substances. Stage 2, which examines the recovery of the sludge and the duration and intensity of harmful effects after the toxic load has been interrupted, measures the inhibition of respiration in sludge from a parallel stage 1 sample after mixing with fresh nutrient solution. Stage 3, used to indicate the toxicity of the substrate after contact with the activated sludge,

measures the inhibition of respiration in fresh sludge when exposed to a toxic solution separated from a stage 1 sample by centrifuging. The method has been used to examine the effects of magnesium and aluminum. Only high concentrations of magnesium affected oxygen consumption. Concentrations of about 2,850 mg of magnesium chloride per litre were practically harmless, while the highest concentration tested, 20,000 mg/litre, inhibited respiration by about 25 percent, and the original rate of respiration was restored rapidly when the sludge was separated and exposed to fresh nutrient solution. The respiration rate of activated sludge was, however, inhibited by aluminum (as sulphate) in concentrations of 100 mg per litre, but the micro-organisms became acclimatized after several hours. In the second stage, even after long periods of contact, the separated sludge regained its respiratory activity slowly, provided the concentration of aluminum was not significantly higher than 160 mg per litre. The highest concentration of aluminum tested, 320 mg per litre, caused irreversible damage.

Neufeld and Hermann (9) investigated the effect of mercury, cadmium and zinc on acclimated activated sludge. Using shock doses of 30, 100, 300 and 1,000 mg/l of each metal, they found that it was possible to maintain a thriving culture of activated biota in the presence of levels of mercury, cadmium and zinc that are much higher than previously thought possible. Kinetic parameters were evaluated at several heavy metal concentrations. For cadmium and zinc, the maximum rate of substrate utilization per unit weight of micro-organisms, K , was found to be virtually constant until a threshold concentration of metal in the sludge, about 25 mg/l of cadmium or 8 mg/l of zinc, was reached. Beyond this threshold, K

decreased linearly when plotted relative to metal in the floc, mg/gm VSS, on log-log paper. No threshold effect was observed in the case of mercury and it was concluded that mercury affects the metabolic rate in a way that may be totally counteracted by increasing the concentration of organic substrate.

- (f) Detention Time - Detention time, which is closely related to loading rate expressed in terms of the food to micro-organism ratio, has been shown to affect the efficiency of aerobic biostabilization. As detention time decreases, the loading rate increases. As the detention time decreases, an increasing percentage of bacteria is removed each day with the effluent. Eventually a limiting detention time is reached when the bacteria are being removed from the system as fast as they can reproduce themselves. This minimum solids detention time can be predicted, if Y , b , K , K_s and S_0 are known using the equation (5):

$$\frac{1}{\theta_c \text{ min.}} = \frac{Y K S_0}{K_s + S_0} - b \quad (4)$$

Using the results of a preliminary study at "safe" conservative detention times, the minimum solids detention time can be predicted and detention times in the final efficiency study can then be set above the predicted minimum.

2-4 Heavy Metal Removal by Activated Sludge

The completely mixed, aerobic biological treatment process has been shown to have a capability for long-term removal of heavy metal ions that is superior to anaerobic processes (7,10). Barth et al. (7) investigated the removal of chromium, copper, nickel and zinc by activated sludge. Their results are summarized in Table IV (7). It was also found that the effects

of the metals on the mixed liquor are apparent even in the 1 to 2 mg/l range. During five years of study, no bulking was encountered in the metal fed system. The floc in the final settler settled quickly while control units frequently bulked. Table V (7) shows the effects of a combination of the four metals on the volatile solids content of the mixed liquor.

TABLE IV
DISTRIBUTION OF METALS THROUGH THE ACTIVATED SLUDGE PROCESS
(CONTINUOUS DOSAGE)

Percent of Metal Fed	Outlet	Cr (VI) (15 mg/l)	Cu (10 mg/l)	Ni (10 mg/l)	Zn (10 mg/l)
	Primary Sludge	2.4	9	2.5	14
	Excess Activated Sludge	27	55	15	63
	Final Effluent	56	25	72	11
	Metal Unaccounted for	15	15	11	12
	Average Efficiency of Process in Removing Metal	44	75	28	89
	Range of Removal Efficiencies	18-58	50-80	12-76	74-97

TABLE V
EFFECTS OF METALS ON MIXED LIQUOR SOLIDS

Analysis	Mixed Liquor From			
	Control Unit	Metal Mixture 8.9 mg/l	Metal Mixture 4.9 mg/l	Metal Mixture 2.0 mg/l
Percent Volatile Solids	66.7	57.9	61.3	63.8

Moulton and Shumate (11) indicated that over a long period, an acclimated, activated sludge system retained 80 to 85 percent of the influent copper fed to it at a concentration of 50 mg/l. Jackson et al. (12) in a survey of metals removal by activated sludge, listed reports of copper removals ranging from 54 to 93 percent, chromium removals from 10 to 100 percent, and zinc removals from 60 to 100 percent. Total influent metal concentrations for this report, however, were less than 10 mg/l.

Neufeld and Hermann (9) also investigated the uptake of mercury, cadmium and zinc by acclimated activated sludge. Using shock doses of 30, 100, 300 and 1000 mg/l of each metal, they investigated the metal distribution between the settled sludge and clear supernatant versus time. Mercury, cadmium and zinc were removed rapidly from aqueous solution by the biological floc. Although eventual equilibrium was achieved after about 2 weeks of contact, no significant increase in the percent metal removal could be observed after 3 hours of contact. At doses up to 300 mg/l, after 3 hours, 95 percent of the mercury, 73 percent of the cadmium, and 53 percent of the zinc were removed on the biological floc.

Using slug doses up to 25 mg/l of cadmium, copper, lead and nickel in a synthetic waste feed, Cheng et al. (13) also studied the heavy metal uptake by acclimated sludge with time. It was found that under aerobic conditions, metal uptake by the biomass is characterized by a very rapid phase of 3 to 10 minutes followed by a long-term, slow-phase, uptake. At lower metal concentrations, metal was concluded to be taken up by the biofloc through the formation of metal-organic complexes. At higher metal concentrations, metal ion precipitation from solution may occur in addition to sludge uptake. The high molecular weight exocellular polymers of the biofloc, which include polysaccharides, proteins, ribonucleic acid, and

deoxyribonucleic acid, provide many functional groupings that may act as binding sites for the metals.

Cheng et al. (13) found that metal uptake by the biomass depends on several factors, including pH and the concentration of organic matter and metals present in the system. Higher initial concentrations of metal ions or mixed liquor volatile suspended solids increase the overall uptake. In general, the uptake capacity increases with increasing pH, up to a value at which metal hydroxide precipitation occurs. Among the metals studied, the preferred order of uptake by activated sludge, with average percent removal in brackets, was found to be lead (90%) > copper (89%) > cadmium (80%) > nickel (58%) at mixed liquor volatile suspended solids concentrations between 1600 and 1800 mg/l.

The large-scale accumulation of heavy metals by activated sludge, with its subsequent removal in the secondary clarifier, would therefore appear to offer a very promising method of treating landfill leachate.

2-5 Previous Studies of Biological Treatment of Landfill Leachate

A study by Poorman (14) was established to investigate the possibility of reducing the amounts of oxygen demanding material in leachate by anaerobic digestion without any prior removal of heavy metals. The effects of varied detention time and changing characteristics of the leachate were also studied. BOD₅ removals ranging from 80 to 96 percent were achieved for detention times ranging from 5 to 20 days and influent BOD₅'s ranging from 11,000 to 16,000 mg/l. COD removals ranged from 65 to 79 percent for influent values ranging from 23,000 to 33,000 mg/l. A variety of metals including aluminum, cadmium, chromium, copper, lead, mercury, nickel and zinc were present in the leachate. Their concentrations covered a broad range with zinc being the highest at 65 mg/l. The anaerobic digestion

process was not adversely affected by these metals. Some of the metals, notably aluminum, cadmium, mercury, nickel and zinc, were essentially completely associated with the sludge, while others were primarily associated with the settled effluent.

Boyle and Ham (15) investigated the biological treatability of landfill leachate with total solids concentrations between 4,000 and 7,800 mg/l. Processes evaluated in the laboratory included anaerobic and aerobic biological treatment of leachate, aerobic treatment of selected combinations of leachate and domestic wastewater in a simulated activated sludge treatment plant, and anaerobic followed by aerobic polishing treatment of leachate. Anaerobic treatment of raw leachate was most promising, providing greater than 90 percent BOD reduction for hydraulic detention times greater than 10 days at temperatures in the range of 23° to 30°C. Temperature was found to greatly affect the anaerobic stabilization of leachate in the range of 23° to 11°C. A temperature coefficient of 1.111 was estimated for BOD removal rates in laboratory vessels. Aerobic polishing of anaerobic effluents produced a more stable effluent suitable for surface water discharge. Aerobic treatment also proved to be promising, resulting in BOD removals in excess of 90 percent and COD removals greater than 80 percent at approximately 23°C and at loadings of less than 30 lb.BOD₅/day/1,000 cu. ft. BOD removal dropped to 80 percent as the loading was increased to 87 lb.BOD₅/day/1,000 cu.ft. and COD removal dropped to 74 percent at a food to micro-organism ratio of about 0.25 mg BOD₅/mg MLVSS/day. Serious foaming problems were encountered throughout the study, even though an anti-foam solution was added to the aerobic units. When the food to micro-organism ratio exceeded 1.5, sludge bulking problems were also encountered. No metal analyses were given and no effort was made to determine the metal distribution in the mixed liquor effluents.

Additional laboratory studies indicated that leachate could be added to domestic wastewater in an "extended aeration" activated sludge plant at a level up to 5 percent by volume (leachate COD = 10,000 mg/l) without seriously impairing effluent quality. At greater than 5 percent by volume, leachate additions resulted in greatly increased effluent BOD and COD, increased oxygen uptake rates, and poorer mixed liquor settling.

Cook and Foree (16) investigated aerobic biostabilization of a medium-strength ($BOD_5 = 9,500$ mg/l, $COD = 17,500$ mg/l) sanitary landfill leachate. Their study was designed to determine the susceptibility to treatment of a typical sanitary landfill leachate by aerobic biological methods, to evaluate treatment processes for polishing of the effluents from aerobic biological treatment, and to perform a chemical and physical characterization of the leachate and treated effluents. To accomplish these objectives, laboratory scale treatment units (2 litre volume) were operated under various organic loading, nutrient addition and pH conditions, and their performance was evaluated by analytical testing. The results of this study indicated that aerobic biological treatment was a very effective means of stabilizing a "typical" sanitary landfill leachate. The best operational conditions were found to be a detention time of 10 days (COD loading = 98.5 lb. $COD/day/1,000$ cu.ft.), which resulted in a $MLVSS$ concentration of $4,400$ mg/l or greater (food to micro-organism ratio = 0.216 lb. $BOD_5/lb.$ $MLVSS/day$) in the completely mixed, no recycle, systems evaluated. With these two operational conditions, COD stabilization efficiency of greater than 97 percent was accomplished. The BOD_5 of the settled effluent was reduced to less than 26 mg/l (99.7 percent removal), indicating almost complete biological stabilization. A stable microbial population was established and maintained. The mixed liquor was characterized by very

good settling properties and efficient nutrient removal was accomplished. The obnoxious odour of the raw leachate was completely removed and a pH above 7.6 was maintained in each unit. Aerobic biological treatment units with detention times of 2 days and 5 days failed as indicated by sharply increasing effluent COD concentrations and sharply decreasing MLVSS concentrations. This failure was predicted by theoretical determinations. The removal of only three metals was examined. The iron concentration in the raw leachate was 240 mg/l. All of the 10 day units had less than 10 mg/l of iron remaining in their settled effluent. This large iron removal was attributed mainly to chemical precipitation at the high pH maintained in the 10 day units. The calcium concentration in the raw feed was 1,200 mg/l. Less than 430 mg/l remained in any of the settled effluents from the 10 day units. As the pH in these 10 day units increased from 7.6 to 8.4, the calcium concentration in the settled effluents dropped from 430 mg/l to 20 mg/l. The magnesium concentration in the raw leachate was 170 mg/l. This concentration was not significantly reduced because the pH in the biological treatment units was not high enough to cause precipitation of the magnesium as magnesium hydroxide.

The effluent polishing results showed that activated carbon was very effective in reducing the residual COD (by approximately 40 percent), organic carbon and colour. The use of bleach was effective in colour removal, but had little effect on COD.

2-6 Summary

Aerobic digestion is sensitive to a number of factors and should therefore be designed with these in mind. Optimum nutrient requirements and suitable operating temperatures for aerobic micro-organisms have been well established and can readily be satisfied. pH may also be controlled

through the addition of buffers and acids or bases. Enough oxygen must be supplied to keep the reactors aerobic. If loading rates are kept low enough, aerobic biostabilization is a very effective means of stabilizing a medium-strength landfill leachate. The effect of increased heavy metal concentrations in a strong landfill leachate, on the aerobic treatment efficiency at various detention times, must, however, be examined and the degree to which these heavy metals may be concentrated in the settled sludge must be determined.

CHAPTER 3

RESEARCH RATIONALE AND EXPERIMENTAL DESIGN

The development of methods of satisfactorily treating landfill leachates is a major goal of an on-going research program currently being conducted at the University of British Columbia. As part of that research program, anaerobic digestion, chemical treatment and peat treatment have been investigated by research personnel in the Department of Civil Engineering. To complete the investigation of the most obvious treatment alternatives, this study was initiated to determine the treatability of landfill leachate by aerobic digestion.

Although the composition of landfill leachate varies widely, previous studies have shown that invariably, leachate has very high BOD values, as well as numerous heavy metals of varying concentration. Because the presence of large amounts of oxygen demanding materials is a major concern, especially in rivers with fish, BOD reduction must be the prime goal of any leachate treatment process. For this reason all forms of biological treatment must be considered. The effects of heavy metals on the process and their distribution in the resulting sludge and liquid effluents are also of vital interest and therefore require investigation.

Although the presence of heavy metals is generally believed to cause more problems during aerobic digestion than during anaerobic digestion, advantages claimed for aerobic digestion as compared to anaerobic digestion include (4):

- (a) volatile-solids reduction approximately equal to that obtained anaerobically;
- (b) lower BOD concentrations in supernatant liquor;
- (c) production of an odourless, humus-like, biologically stable end product

that can be disposed of easily;

- (d) production of a sludge with excellent dewatering characteristics;
- (e) recovery of more of the basic fertilizer values in the sludge;
- (f) fewer operational problems; and
- (g) lower capital cost.

The major disadvantage of the aerobic digestion process appears to be the higher power cost associated with supplying the required oxygen.

The purposes of this study were to determine the susceptibility to treatment of a high-strength, landfill leachate by aerobic biological methods, to determine where and to what extent metals in the leachate might be concentrated, and to characterize the settled effluents obtained from the aerobic biostabilization process.

The study was carried out in three phases. The acclimatization-metal removal study was designed to produce an acclimatized microbial population for use in the subsequent aerobic biostabilization efficiency studies and to study the long-term, metal removal capacity of the settling biological floc. The aerobic biostabilization efficiency studies were designed to determine the effect of increasing solids detention time and organic loading on treatment efficiency and metal removal. Based on estimates of the steady state mixed liquor volatile suspended solids levels, solids detention times were selected to give organic loadings in the range recommended for extended aeration. Using the results of this "extended aeration" efficiency study, the minimum solids detention time for the system was predicted and the solids detention times to be used in the "shorter detention time" efficiency study were then set above this predicted minimum. At the conclusion of each phase of the study, settled effluents were collected for metal analysis and subsequent characterization.

CHAPTER 4

SYSTEM DESIGN AND EXPERIMENTAL PROCEDURE

4-1 Design of the Treatment System

The investigation of the theory of aerobic biostabilization and previous attempts at aerobically treating landfill leachate (15,16) provided the basic information needed to design the system. It was decided that a single stage bench scale system would be used to evaluate the aerobic biostabilization of high-strength landfill leachate, because of its simplicity and ease of operation. After investigating previous models used in similar studies, it was decided to use three digesters each of 10 litres capacity. This decision was based on the fact that: (1) they were readily available in the laboratory, (2) similar units had successfully been used in previous studies, and (3) leachate volumes available were insufficient to use larger digesters. The digesters were made from large glass bottles. The bottom of each bottle was removed and the necks were fitted with large rubber stoppers. The stoppers were secured using heavy stainless steel wire but no wire was allowed inside the digesters, thus preventing any unknown additions of metal to the digester contents. A porous glass, coarse-bubble, air diffuser was fitted in the bottom of each digester and air was provided for each unit from the laboratory compressed air system.

Because of the high concentrations of metals in the leachate feed, foaming problems were anticipated. To control foaming, while maintaining adequate mixing, it was felt that a combination of air and mechanical mixing should be employed in the digesters. Consequently, an adjustable clamp was placed on the air line to each digester to control air flow and an electric driven stirrer was provided in each digester to ensure uniform distribution of food and micro-organisms. Mixing speeds were set approximately equal in

all three digesters and air flow rates were adjusted to maintain aerobic conditions while minimizing foaming. A schematic of these digesters is shown in Figure 1.

To contain any foam which might be produced during the study, it was decided to use only 4.5 litres of mixed liquor, thus allowing for about 8 inches of foam in each digester. An antifoam agent* was also tested for toxicity to the biological system. Various doses of the antifoam agent were added to test units, but even in very large doses the oxygen uptake rates of test and control units remained equal after several hours. Foaming problems, however, never reached the proportions anticipated and it was necessary to add the antifoam agent to only the highest loaded digester tested.

Since the conventional activated sludge process is not significantly influenced by small temperature changes, and since the reactors were to be operated during the summer, it was felt that temperature controls were not necessary. The temperature of the mixed liquors was measured frequently throughout the study and found to vary between 21° and 25°C. The temperature of the mixed liquor appeared to be affected more by the air flowrate through the digester than by the ambient air temperature, decreasing as the air flowrate increased.

4-2 Leachate Source and Characteristics

The leachate used as feed in this study was generated from a lysimeter constructed at the University of British Columbia, as part of an ongoing program to characterize landfill leachates and monitor variations in their composition with time, rainfall rate, cover material and other parameters. The program was initiated by Dr. R.D. Cameron, of the Department of

*Dow Corning antifoam emulsion DB-31.

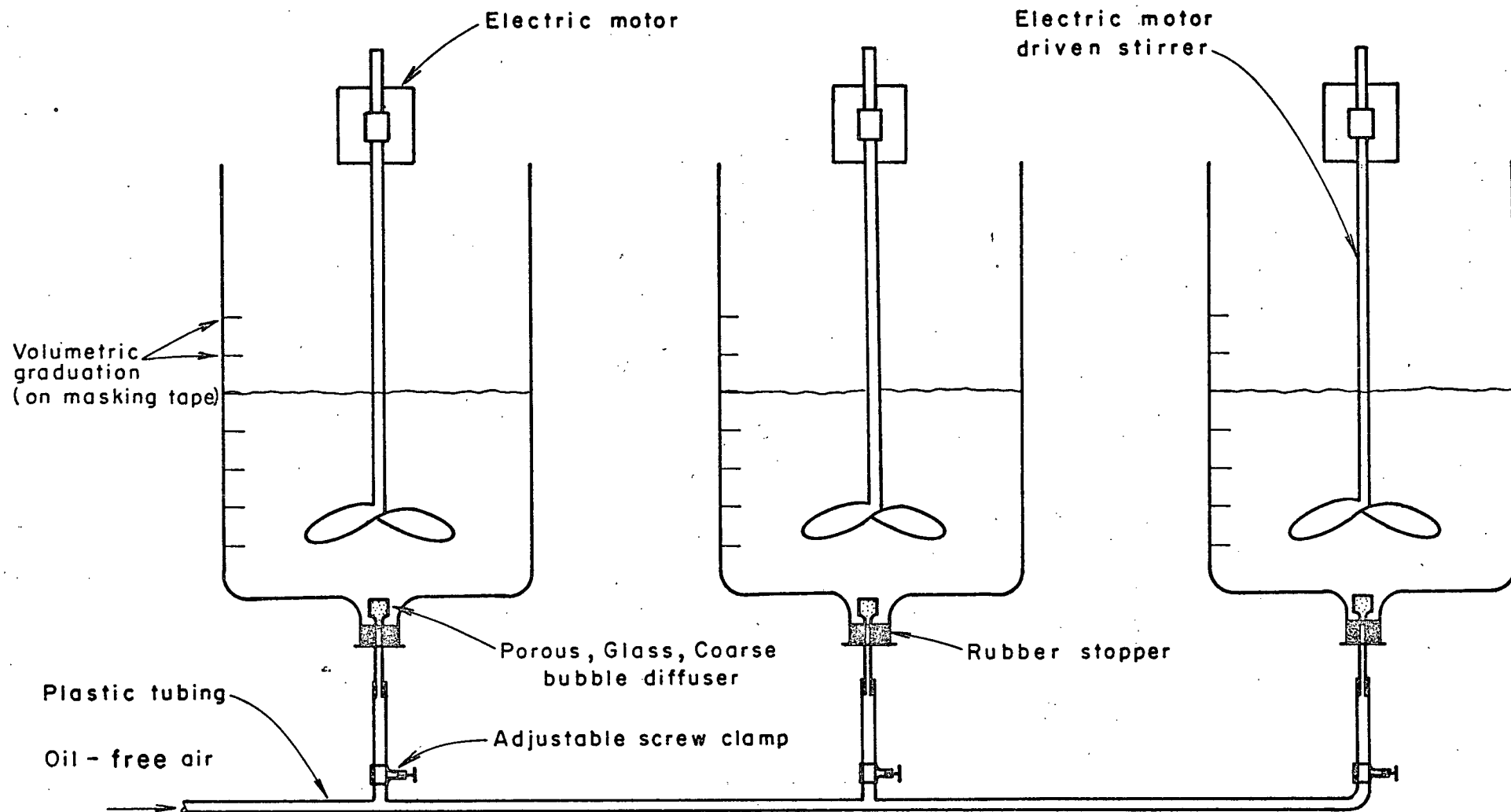


Figure 1 SCHEMATIC OF LABORATORY AEROBIC DIGESTERS

Civil Engineering, U.B.C.

Details of the lysimeter are:

- (1) Dimensions - 14 feet deep, 4 feet in diameter
- (2) Cover material - 2 feet of hog fuel
- (3) Total weight of garbage - 3420 lbs.
- (4) Depth of garbage - 8 feet
- (5) Weight (density) before final cover - 884 lb./cubic yard (wet)
- (6) Rainfall rate - 15 inches per year
- (7) Moisture content - 34.7%
- (8) Percentage composition of garbage:

Food waste - 11.8

Garden waste - 9.8

Paper products - 47.6

Cardboard - 5.4

Textiles - 3.6

Wood - 4.7

Metals - 8.7

Glass and ceramics - 7.0

Ash, rocks and dirt - 1.4

Total - 100

Leachate from this lysimeter was collected weekly, returned to the lab and stored at 4°C. The 4°C temperature has been found adequate to minimize changes in leachate composition. Samples were mixed every 4 weeks to produce a composite sample, which was analysed by technicians in the laboratory as part of the leachate characterization research program. Composite samples were then mixed for use in this study and stored in 20 l polyethylene bottles at 4°C.

120 litres of high-strength landfill leachate were thus collected over a five month period for use in the aerobic biostabilization study.

One 20 litre bottle was selected for use in the acclimatization-metal removal study. Its composition is shown in Table VI. As the acclimatization-metal removal study drew to an end, the remaining 100 l of leachate were mixed to form a large composite which was used throughout the treatment efficiency studies. The composite was pumped into 20 l polyethylene bottles and again stored at 4°C to minimize biological activity before feeding. The composition of the composite leachate sample is also shown in Table VI.

4-3 pH Control

Because the pH of the leachate was well below 6.5, it was felt that pH control might be necessary. At the start of the acclimatization-metal removal study, the pH of the leachate feed, prepared in 2 litre batches, was therefore adjusted to approximately 7.2 using calcium hydroxide. The pH of the mixed liquor was monitored daily. In 9 days the pH of all mixed liquors rose from 7.2 to greater than 8.3 and thus, pH adjustment of the leachate feed was stopped. From day 10 on in the acclimatization study and all through the efficiency studies, only nutrients were added to the leachate feed and no attempt was made to control the pH of the mixed liquors.

4-4 Nutrient Balance

In order to maintain a $BOD_5:N:P$ ratio of 100:5:1, additional nitrogen and phosphorus were required. Several chemicals were considered for this purpose. A mixture of mono-basic ammonium phosphate $((NH_4)H_2PO_4)$ and di-ammonium phosphate $((NH_4)_2HPO_4)$ was selected because it supplied both nitrogen and phosphorus in forms suitable for utilization by aerobic

TABLE VI
COMPOSITION OF LEACHATE FEED USED DURING STUDY

Parameter	Concentration mg/l During Acclimatization- Metal Removal Study	Concentration mg/l During Efficiency Studies
BOD ₅	42,000	36,000
COD	58,000	48,000
Total Carbon	18,400	15,400
Total Inorganic Carbon	16	11
Total Solids	34,900	26,600
Total Volatile Solids	21,500	17,800
Total Dissolved Solids	34,500	25,700
Acidity	6,600	5,640
Alkalinity	10,200	7,640
Aluminum	60.2	41.8
Arsenic	4.1	3.6
Barium	1.3	0.7
Beryllium	trace	trace
Boron	7.40	7.30
Calcium	1,924	1,394
Cadmium	0.43	0.39
Chloride	1,650	1,620
Chromium	2.3	1.9
Copper	0.17	0.24
Iron	1,260	960
Lead	1.79	1.44
Magnesium	378	310
Manganese	46.0	41.0
Mercury	0.012	0.012
Nitrogen - total	1,370	1,080
- NH ₃	938	725
Nickel	0.61	0.65
Phosphorus - total	22.2	19.8
Potassium	1,610	1,060
Sodium	1,720	1,250
Sulphates	1,020	1,070
Zinc	227	223
Tannin-like compounds	943	578
pH*	5.09	5.02

*not in mg/l

micro-organisms and it was felt that pH of the leachate feed could be buffered around 7.2 by selection of the proper molar ratios of these two salts. An exact ratio of 5:1 for N:P could, however, not be achieved using these two salts, so a $BOD_5:N$ ratio of 20:1 was aimed for in establishing required nutrient additions. Since the analysis of the leachate feed used in the acclimatization-metal removal study was not complete when the study began, nutrient additions were estimated from previous lab analyses on the 4-week composite samples. Similarly, the analysis of the composite leachate feed used in the efficiency studies was not complete when these studies began. Therefore, the same amounts of each salt were added during the first half of the efficiency study ("extended aeration" efficiency study). Nutrient additions were then reduced during the final half of the efficiency study ("shorter detention time" efficiency study). The resulting nutrient additions and $BOD_5:N:P$ ratios are shown in Table VII.

TABLE VII
NUTRIENT ADDITIONS AND $BOD_5:N:P$ RATIOS DURING STUDY

Study Phase	Ammonium Phosphate Addition, mg/l	Di-Ammonium Phosphate Addition, mg/l	$BOD_5:N:P$ Ratio in Leachate Feed
Acclimatization-Metal Removal Study	630	2,900	100:4.85:2.05
"Extended Aeration" Efficiency Study	630	2,900	100:6.37:3.12
"Shorter Detention Time" Efficiency Study	---	1,462	100:5:1.3

4-5 Metal Concentrations

No attempt was made to modify metal concentrations. It was felt that the best approach would be to use leachate as produced and observe the effects of the very high metal concentrations on the efficiency of the aerobic biostabilization process.

4-6 Acclimatization-Metal Removal Study

This phase of the research program was designed to produce an acclimatized microbial population for use in the aerobic biostabilization efficiency studies and to study the long-term, metal removal capacity of the settling biological floc.

To set "safe" hydraulic detention times for use in this study, it was necessary to evaluate a number of conventional design parameters. Boyle and Ham (15) found aerobic treatment of landfill leachate promising when loadings were kept below 30 lb.BOD₅/day/1,000 cubic feet. Cook and Foree (16) found, however, that BOD removals were still excellent when loadings were increased to about 100 lb.COD/day/1,000 cubic feet, provided food to micro-organism ratios were kept relatively low (around 0.22 lb.BOD₅/lb.MLVSS/day). For this reason, the volumetric BOD and COD loading rates and food to micro-organism ratios, assuming a MLVSS concentration of 4,000 mg/l, were evaluated at a number of convenient hydraulic detention times. With a hydraulic detention time of 45 days, COD loading was anticipated to be about 81 lb.COD/day/1,000 cubic feet resulting in an initial food to micro-organism ratio of about 0.23 lb/BOD₅/lb.MLVSS/day. Thus, a 45 day hydraulic detention time was set for the highest loaded digester and hydraulic detention times for the other two digesters were conveniently set at 60 and 90 days. Since no suspended solids were to be withdrawn during the acclimatization study, the solids detention times in all three units were equal to the length of that study.(56 days).

- (a) Start Up - About 15 l of waste activated sludge were obtained from the Central Sewage Treatment Plant in Squamish, B.C., some 40 miles north of Vancouver. The Squamish Sewage Treatment Plant is a "package activated sludge treatment" plant treating a mixture of domestic and light industrial waste. A survey of "package activated sludge treatment" plants in the Vancouver area had shown it to produce the most suitable activated sludge for use in this study.

The mixed liquor volatile suspended solids concentration in the sludge sample was determined and enough sludge was then placed in each digester to provide 4.5 l of mixed liquor with a volatile suspended solids concentration of 3,960 mg/l. The required volumes of leachate feed with nutrients added and pH adjusted to about 7.2 were then added to each digester: 100 ml to Digester D, 75 ml to Digester E, and 50 ml to Digester F. The total volume in each digester was then adjusted to 4.5 l using distilled water. Air flow was initiated and adjusted in each digester using the adjustable clamps on the air lines. Stirrers in each digester were then turned on and stirring speeds set approximately equal.

- (b) Digester Operation and Testing - At 24 hour intervals the water lost by evaporation was replaced with distilled water. The sides of the digesters and the stirrers in each digester were scraped to remove all adhering micro-organisms, which were thus returned to the mixed liquor and then the contents were completely mixed. The oxygen uptake rate in each digester was then measured at 20°C* using 3.0 ml of mixed liquor, which was subsequently returned to the diges-

* using a YSI Model 53 Biological Oxygen Monitor and a Haake Constant Temperature Circulator, Model FJ.

ter from which it was obtained. After the oxygen uptake rate in each digester had been determined, the air and stirrers in all three digesters were shut off and the biological flocs were allowed to settle. The settling time required to obtain an adequate volume of clear supernatant increased as biological solids accumulated in the digesters, but the digesters were never allowed to sit more than an hour without air. After settling, the required volume of clear supernatant was withdrawn from each digester using volumetric pipettes: 100 ml from Digester D', 75 ml from Digester E', and 50 ml from Digester F'. Volumes of leachate feed equal to the volumes removed were then added to each digester. Air to the digesters was turned back on and the stirring speeds were again set equal. The pH of the settled effluent from each digester was measured and recorded. Every 5 days the total solids concentrations in the settled effluents were determined. The BOD_5 's of the settled effluents were determined every 7 days.

As indicated, leachate feed for these units was prepared in 2 litre volumes and stored at $4^{\circ}C$ until needed. pH adjustment on the initial feed caused a great portion of the metals to settle out of the leachate feed. When the pH of all 3 units climbed to greater than 8.3 after 9 days of operation, the pH adjustment of the leachate feed was discontinued. The addition of nutrients alone still caused a portion of the metals to settle out of the leachate. Thus, throughout this study, feed was brought out of the refrigerator, allowed to warm up for about an hour to reduce any temperature shock to the system and then thoroughly mixed just prior to the daily feeding.

After 56 days, 500 ml of mixed liquor were withdrawn from each digester. 100 ml of each mixed liquor were digested for metal

analysis following the recommended EPA method (17) and the balance was allowed to settle. Clear supernatants were then withdrawn for metal analysis.

4-7 Aerobic Biostabilization Efficiency Studies

Solids tests near the end of the acclimatization-metal removal study indicated MLVSS levels in Digesters D, E, and F of approximately 11,800, 10,900 and 7,600 mg/l respectively. While these MLVSS levels are greatly in excess of the recommended range for activated sludge processes, no attempt was made to significantly reduce the biological solids concentrations because:

- (1) the biological flocs still settled well,
- (2) the settled effluents had very low BOD₅ and greatly reduced metal concentrations,
- (3) Cook and Foree (16) credited their high MLVSS levels (>4,400 mg/l) with helping control and reduce the foaming problem, and
- (4) it was felt that the biological solids levels would drop to suitable levels if there was not enough food in the leachate feed to maintain such high MLVSS concentrations.

Again, to set "safe" solids detention times for use in the first half of these efficiency studies, volumetric BOD and COD loading rates and anticipated food to micro-organism ratios were calculated. Assuming a maximum MLVSS concentration of 10,000 mg/l, a 30 day solids detention time resulted in a food to micro-organism ratio of about 0.12, a BOD loading rate of about 75 lb.BOD₅/day/1,000 cubic feet and COD loading of about 102 lb.COD/day/1,000 cubic feet. The COD loading was therefore very close to the maximum recommended by Cook and Foree (16) and the food to micro-organism ratio was expected to remain in the range recommended for extended

aeration and below the range for conventional complete mix activated sludge treatment (see Table II). A solids detention time of 30 days was therefore set for the highest loaded digester, Digester D, in the first half of the aerobic biostabilization efficiency studies. Solids detention times for Digesters E and F were then set at 45 and 60 days respectively, to cover the range of food to micro-organism ratios recommended for extended aeration, 0.05 to 0.15 lb.BOD₅/lb.MLVSS/day.

- (a) Digester Operation and Testing - At 24 hour intervals, the water lost by evaporation was replaced with distilled water, the sides and stirrers in each digester were scraped, and the oxygen uptake rate at 20°C was determined for each digester. The required volumes of mixed liquor were then withdrawn from each digester using large-tip-opening, bacteriological pipettes: 150 ml from Digester D, 100 ml from Digester E, and 75 ml from Digester F. Volumes of leachate feed equal to the volumes of mixed liquors removed were then added to each digester. The pH of the mixed liquor from each digester was measured and recorded. Every 3 or 4 days, the MLSS concentration, MLVSS concentration and total solids concentration in the mixed liquor effluent were determined. The BOD₅ of the mixed liquor and settled effluents were determined every 7 days. These parameters were used to determine when steady state operation was achieved.

After 30 days, settled effluents from each digester were collected daily and composited for subsequent effluent characterization. After 35 days, 200 ml of mixed liquor were withdrawn from each digester. 100 ml of each mixed liquor were wet-ash digested following the recommended EPA procedure (17). Small samples of each mixed liquor were then withdrawn for COD analysis and the balance of the samples was allowed to settle. The settled effluents

were then collected for metal analysis. The analytical procedures employed for all tests used in this study are outlined in the thirteenth edition of Standard Methods (18) and further explained in Chemistry for Sanitary Engineers (19). Metal concentrations were determined using a Jarrell-Ash MV 500 Atomic Adsorption Spectrophotometer.

- (b) Transition to "Shorter Detention Time" Study - Analysis of the MLVSS concentration and mixed liquor BOD_5 data collected during the "extended aeration" efficiency study, predicted a minimum solids detention time of 6.46 days (see Appendix E). Activated sludge treatment plants are usually designed with solids detention times 3 or 4 times the predicted minimum. Therefore, because considerable personal judgment was involved in the selection of the kinetic parameters used to determine the minimum solids detention time, and because foaming problems were still anticipated at shorter detention times, a solids detention time of 10 days was set for the highest loaded digester. Detention times of 20 and 30 days, approximately 3 and 4 times the predicted minimum, were then chosen for the remaining units. To minimize the shock to any unit, it was decided to gradually increase the loading on each and to make the highest loaded digester in the "extended aeration" efficiency study, the highest loaded digester in the "shorter detention time" efficiency study. Therefore, over the next 7 days, the volume of mixed liquor withdrawn and leachate feed added to each unit was gradually increased: from 150 ml per day to 450 ml per day for Digester D, from 100 ml per day to 225 ml per day for Digester E, and from 75 ml per day to 150 ml per day for Digester F.

- (c) "Shorter Detention Time" Efficiency Study - The same daily procedure used in the "extended aeration" efficiency study was employed during this study. Briefly, each day, after replacing water lost by evaporation and measuring the oxygen uptake rate in each digester, the required volumes of mixed liquor were withdrawn from each digester: 450 ml from Digester A, 225 ml from Digester B, and 150 ml from Digester C. Volumes of leachate feed equal to the volumes of mixed liquor withdrawn were then added to each digester.

The pH of the mixed liquor from each digester was measured and recorded daily. Every 3 or 4 days the MLSS concentration, MLVSS concentration and total solids concentration in the mixed liquor were determined. The BOD_5 of the mixed and settled effluents was determined every 7 days. However, because there was some evidence of inhibition in the mixed liquor BOD_5 tests and because those test results were very erratic, the COD of the mixed and settled effluents was determined every 3 or 4 days initially, and every 7 days after steady state operation was achieved.

After 35 days, 100 ml of each mixed liquor was digested for metal analysis (17). One litre of each mixed liquor was then withdrawn for settling tests and the settled effluents were collected for metal analysis and characterization.

4-8 Summary

A long, careful, acclimatization period produced mixed liquors with very high volatile suspended solids concentrations. Prudent selection of solids detention times for the "extended aeration" efficiency study resulted in stable operation within 3 weeks, as indicated by the mixed liquor BOD_5 and VSS concentrations. A short transition period to shorter detention

times resulted again in stable operation, at these new detention times, within 3 weeks. Well balanced and stable aerobic biostabilization efficiency studies were conducted for 35 days for these two sets of digesters. The high suspended solids levels and the combination of air and mechanical mixing effectively controlled foaming and only at the lowest detention time tested was it necessary to add a chemical antifoam agent.

CHAPTER 5

DISCUSSION OF RESULTS

5-1 Removal of Oxygen Demanding Material

- (a) BOD₅ Removal - It was originally intended to use BOD₅ data throughout the study to indicate the efficiencies of the units tested.

Figure 2 shows the BOD's of the mixed liquors and settled effluents as a function of the solids detention time. Figure 3 shows the percent BOD₅ removal as a function of the solids detention time. From these two figures, it can be seen that the mixed liquor BOD₅ data were very erratic, varying randomly from 2,040 to 3,680 mg/l. Throughout the study, the mixed liquor BOD₅ concentrations determined, using the standard BOD₅ test, indicated BOD₅ removals ranging from 89.3 to 93.7 percent. While such high levels of treatment would be very encouraging, the reliability of the BOD₅ test on a waste containing such high heavy metal concentrations is very questionable.

Table VIII shows typical BOD₅ test results for the mixed liquor effluents from Digesters A, B and C, as well as one set of BOD₅ test results for the leachate feed. As the dilution factor decreases, the calculated BOD₅ of each sample decreases. This trend is indicative of biological inhibition. At dilutions greater than 2 times the greatest dilution used for the determination of the mixed liquor BOD₅, the same inhibition may be observed in the leachate feed results. Since metal concentrations in the mixed liquors were very close to those in the leachate feed, it is highly probable that

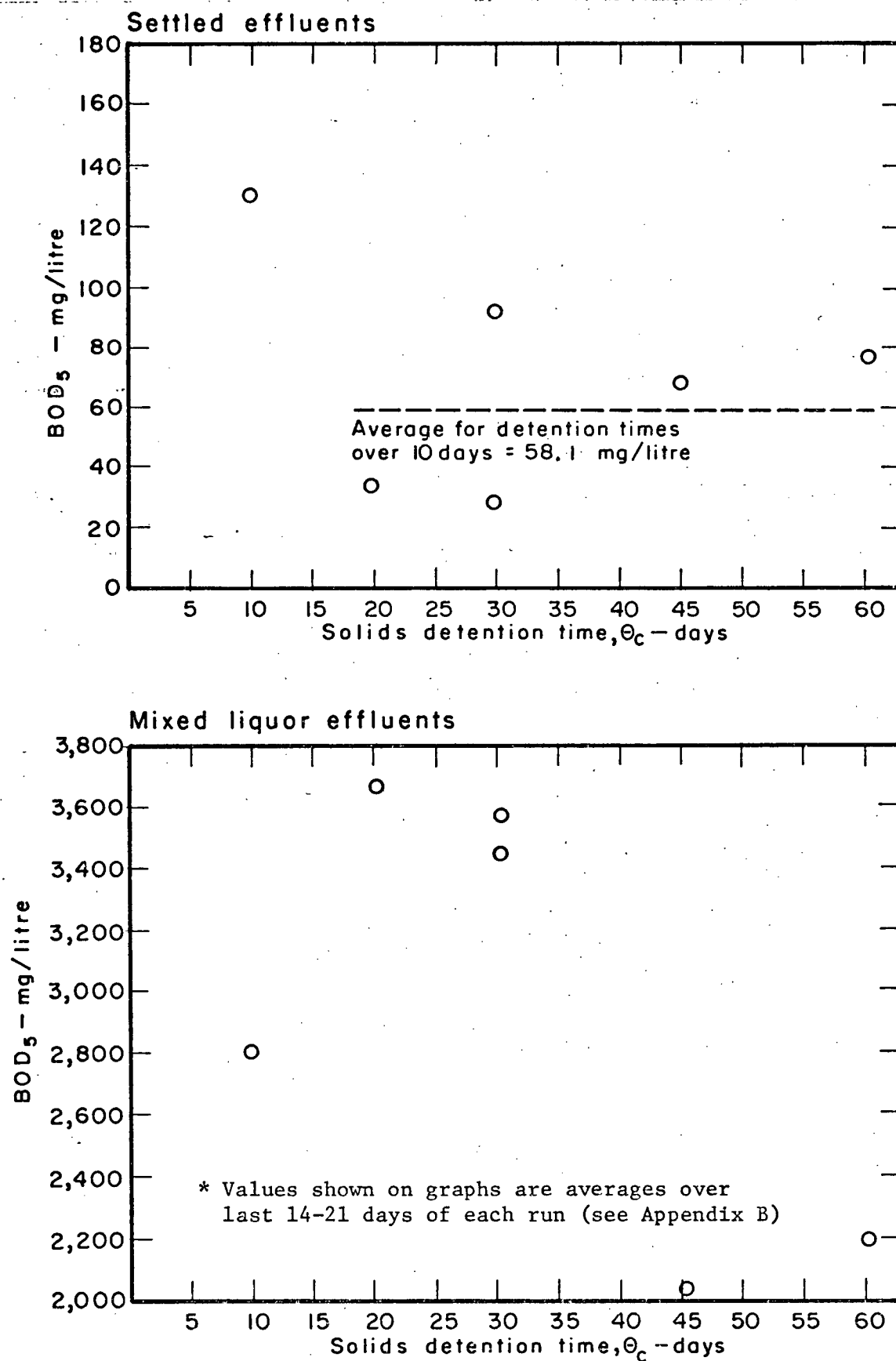


Figure 2 BOD_5 OF MIXED LIQUORS AND SETTLED EFFLUENTS
vs SOLIDS DETENTION TIME

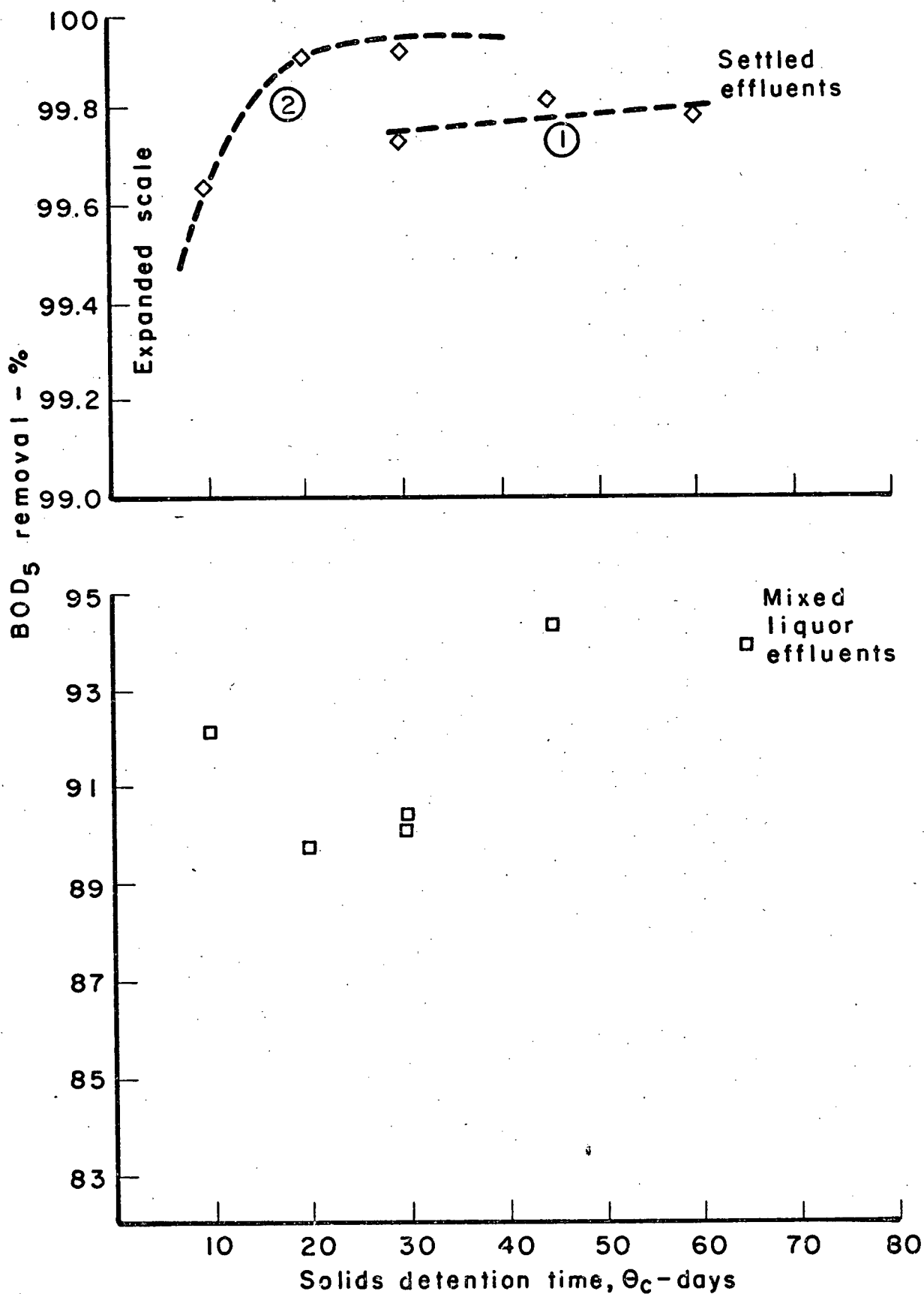


Figure 3 PERCENT BOD₅ REMOVALS vs SOLIDS DETENTION TIME

TABLE VIII

TYPICAL BOD₅ TEST RESULTS FOR MIXED LIQUOR EFFLUENTS

FROM DIGESTERS A, B AND C, AND FOR LEACHATE FEED

Sample Source	ML of Sample in 300 ML BOD Bottle (Dilution Factor in Brackets)	Dissolved Oxygen Depletion mg/l	BOD ₅ mg/l Accepted Average
Mixed Liquor Effluent from Digester A $\theta_c = 10$ days	0.10 (3,000:1)	1.38	4,140
	0.20 (1,500:1)	2.20	3,300
	0.30 (1,000:1)	2.94	2,940
	0.30 (1,000:1)	3.03	3,030
	0.50 (600:1)	4.54	2,724
	0.70 (429:1)	5.40	2,320
			} 2,998
Mixed Liquor Effluent from Digester B $\theta_c = 20$ days	0.10 (3,000:1)	1.47	4,410
	0.20 (1,500:1)	2.60	3,900
	0.30 (1,000:1)	3.50	3,500
	0.30 (1,000:1)	3.60	3,600
	0.50 (600:1)	4.73	2,838
	0.70 (429:1)	5.82	2,494
			} 3,667
Mixed Liquor Effluent from Digester C $\theta_c = 30$ days	0.10 (3,000:1)	1.70	5,100
	0.20 (1,500:1)	2.52	3,780
	0.30 (1,000:1)	3.40	3,400
	0.30 (1,000:1)	3.50	3,500
	0.50 (600:1)	4.69	2,814
	0.70 (429:1)	5.85	2,507
			} 3,560
Leachate Feed	0.010 (30,000:1)	0.97	29,100
	0.020 (15,000:1)	2.23	33,450
	0.020 (15,000:1)	2.28	35,100
	0.030 (10,000:1)	3.52	35,200
	0.040 (7,500:1)	3.72	27,900
	0.050 (6,000:1)	3.96	23,600
			} 34,580

heavy metal inhibition of biological activity resulted in the observed highly variable BOD₅ test results. Since the metals concentrations and BOD₅ of the settled supernatants were very low, it was believed that the metals and a large percentage of the BOD₅ of the mixed liquors, were bound to the biological floc. Since no method could be found to remove the inhibiting heavy metals without removing biological solids and hence BOD₅, dilution offered the only feasible method of obtaining reliable BOD₅ test results for the mixed liquors.

In the standard BOD₅ test, an oxygen depletion of at least 0.50 mg/l is required for statistical reliability. Blanks of the BOD dilution water used, generally had oxygen depletions between 0.15 and 0.30 mg/l after 5 days. Higher dilutions of the mixed liquor effluents resulted in highly variable results with oxygen depletions very close to 0.50 mg/l. The high variability at these higher dilutions may have been due to sampling variability or to the oxygen depletion of the BOD dilution water, as observed in blank tests. Nevertheless, since higher dilutions did not give consistent, statistically-reliable results, and since the trend indicated in Table VIII was not always observed with all mixed liquor samples, the BOD₅ values obtained using dilution factors between 1,000:1 and 1,500:1 were accepted for the mixed liquor effluents. However, because of the problem in obtaining consistent, statistically-reliable BOD₅ results, without any evidence of biological inhibition, it was decided that COD results would be used to indicate the efficiency of the units tested.

The BOD₅ of the settled effluents was very low; with average effluent BOD₅'s ranging between 27.1 and 128.9 mg/l. Several dilutions of each settled effluent were used in the BOD₅ tests

and no evidence of inhibition was apparent in the results. If the mixed liquor BOD_5 results are accepted, the settling biological floc removed an average of 97.5 percent of the mixed liquor BOD_5 . The actual percent removal by the settling biological floc is probably even higher. Overall, better than 99.6 percent of the influent BOD_5 was removed in all settled effluents. As shown in Figure 3, two curves may be drawn through the percent BOD_5 removal data for settled effluents. Curve 1 was the BOD_5 data for settled effluents from Digesters D, E and F. During this study, the mixed liquor was allowed to settle for about a half an hour before settled effluent samples were withdrawn for BOD_5 analysis. Curve 2 uses the BOD_5 data for settled effluents from Digesters A, B and C. During this study, the mixed liquor was allowed to settle for at least an hour before settled effluent samples were withdrawn for BOD_5 and COD analysis. The extra time was required to obtain adequate volumes of settled effluent for both test procedures. As can be seen in both Figures 2 and 3, the longer settling time resulted in greater overall BOD_5 removal and lower settled effluent BOD_5 . For detention times over 20 days, the BOD_5 of the settled effluents averaged 58.1 mg/l.

Because the settling biological floc was observed to remove a very large percentage of both the mixed liquor BOD_5 and solids, it was suspected that the very low settled effluent BOD_5 might be due to an absence of micro-organisms in the settled effluent. For this reason, BOD_5 tests were periodically conducted on settled effluent samples using unseeded BOD dilution water and BOD dilution water seeded with enough domestic sewage to cause an oxygen depletion of

about 0.50 mg/l after 5 days. Typical results from these tests are shown in Table IX. As only the BOD₅ of settled effluent from Digester A was significantly increased by seeding the BOD dilution water, the BOD₅ of all settled effluents was determined using unseeded BOD dilution water. The values reported in following tables and figures and in Figures 2 and 3 are the results of BOD tests using unseeded BOD dilution water.

TABLE IX
COMPARISON OF BOD₅ TEST RESULTS ON SETTLED EFFLUENTS
USING UNSEEDED AND SEEDED BOD DILUTION WATER

Settled Effluent Source Digester	A $\theta_c =$ 10 days	B $\theta_c =$ 20 days	C $\theta_c =$ 30 days	D $\theta_c =$ 30 days	E $\theta_c =$ 45 days	F $\theta_c =$ 60 days
Effluent BOD ₅ , mg/l - using unseeded BOD dilution water	162.6	32.4	27.1	83.2	65.9	77.0
- using seeded BOD dilution water	208.6	28.7	24.9	88.2	68.9	79.5

- (b) COD Removal - Because it was originally intended to use BOD₅ data throughout the study to indicate operational stability and removal efficiencies, the COD of the mixed liquors and settled effluents from Digesters D, E and F was checked only at the end of the "extended aeration" efficiency study. During the "shorter detention

time" efficiency study, the COD of both the mixed liquors and settled effluents from Digesters A, B, and C was monitored. Figures 4 and 5 show the COD of the mixed liquors and settled effluents, respectively, during that study. From these figures, it can be seen that the COD results on mixed liquor effluents were more variable than the COD results on settled effluents. However, considering the very high mixed liquor suspended solids levels in these units (20,500 to 25,000 mg/l) and the resulting sampling problems, the observed variability of the mixed liquor COD test results is neither surprising nor excessive.

The mixed liquor and settled effluent COD results over the last 14 to 17 days were averaged. COD tests were also conducted on the mixed liquor and settled effluents from Digesters D, E, and F at the end of the "extended aeration" efficiency study. Figure 6 shows the COD of the mixed liquors and settled effluents as a function of the solids detention time. The COD of the influent leachate averaged 48,250 mg/l. This high COD was substantially reduced. The COD of both the mixed liquors and settled effluents decreased with increasing solids detention time. The settling biological floc removed an average of 96.4 percent of the mixed liquor COD. At solids detention times less than 20 days, however, settled effluent COD rose very sharply. Settled effluent COD at solids detention times greater than 20 days was less than 600 mg/l.

Figure 7 shows the percent COD removal as a function of the solids detention time. Mixed liquor COD removal increased from 51.5 to 75.7 percent as the solids detention time was increased from 10 to 60 days. Settled effluent COD removal increased slightly from 96.8

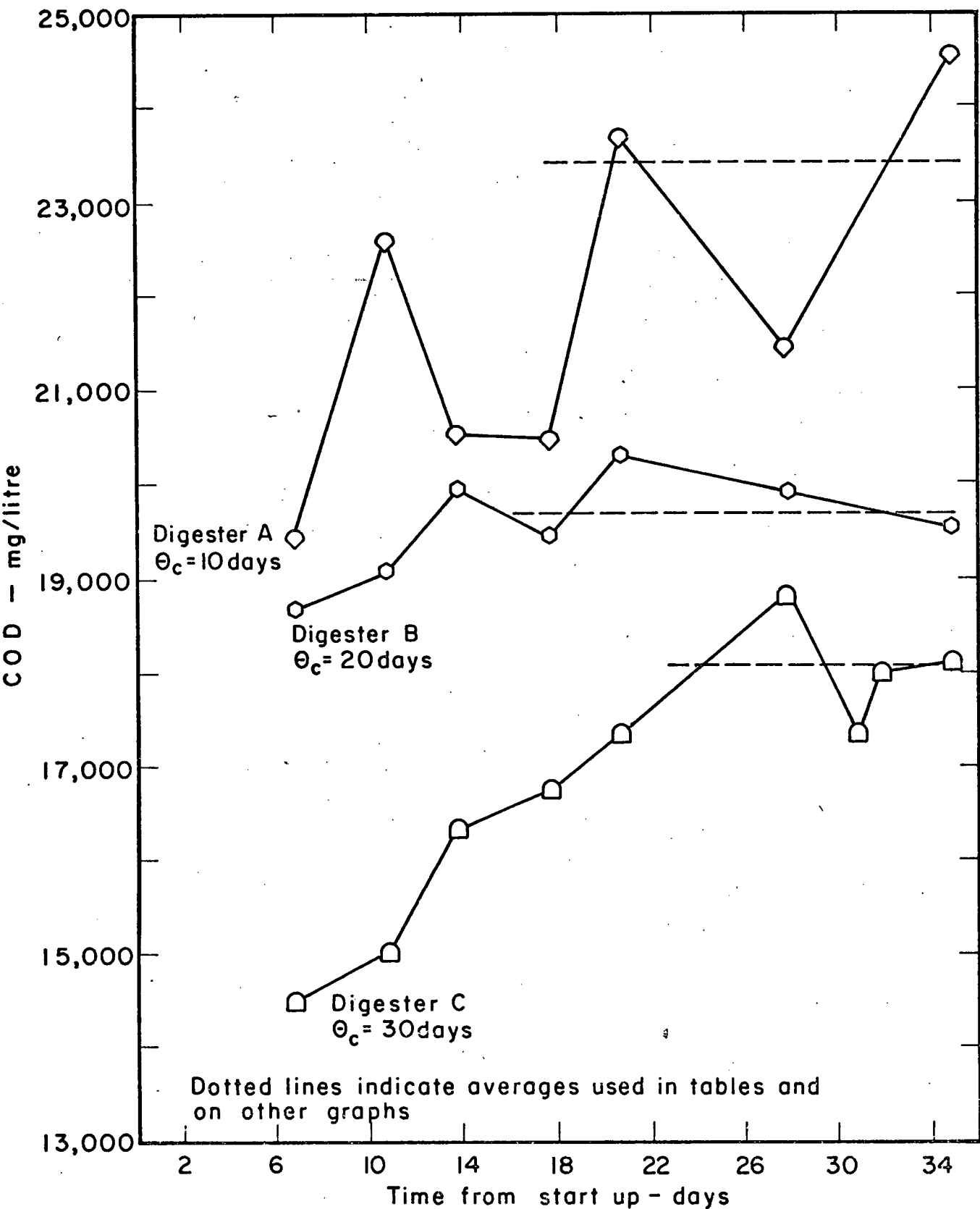


Figure 4 COD OF MIXED LIQUORS DURING "SHORTER DETENTION TIME" EFFICIENCY STUDY

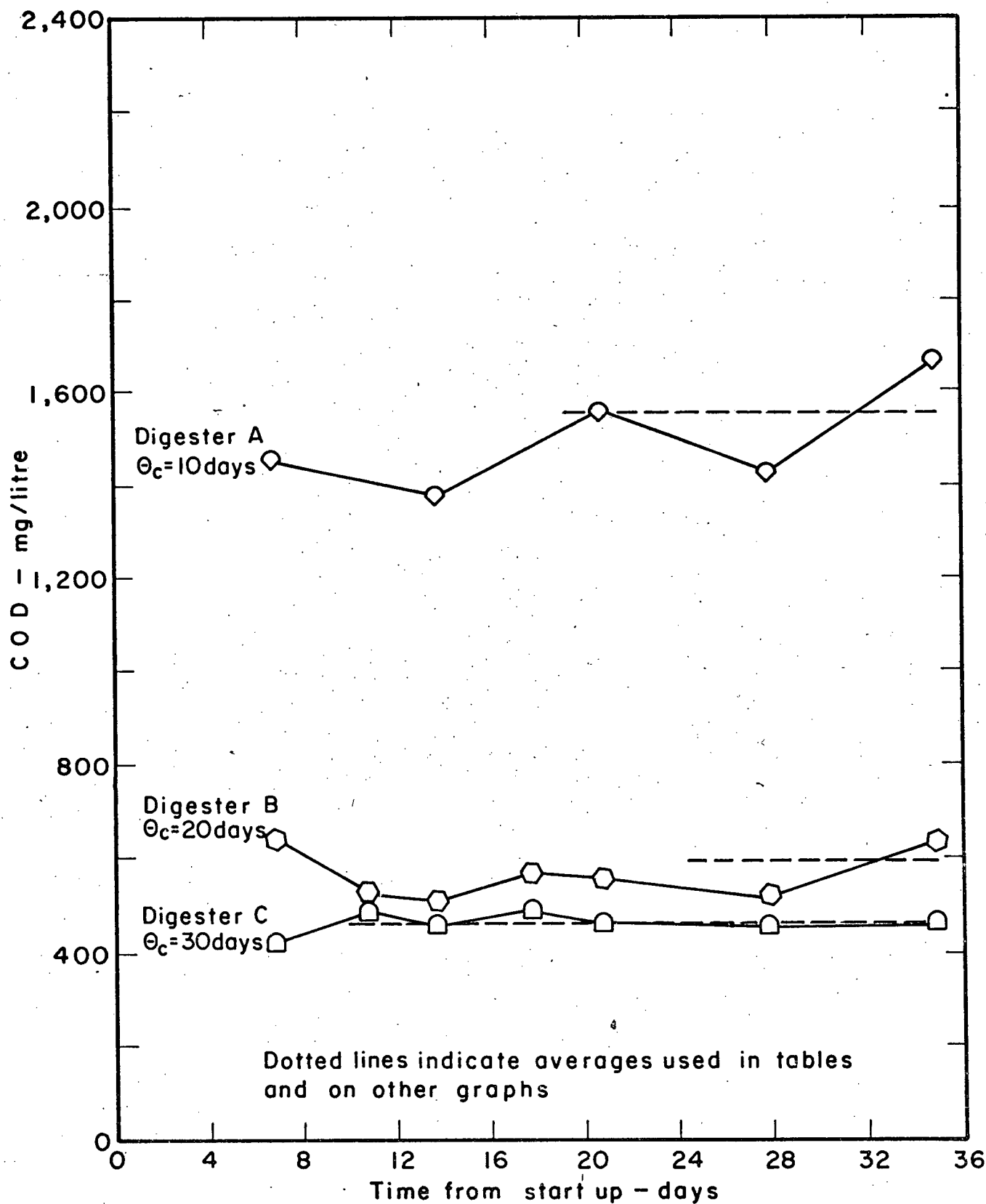


Figure 5 COD OF SETTLED EFFLUENTS DURING "SHORTER DETENTION TIME" EFFICIENCY STUDY

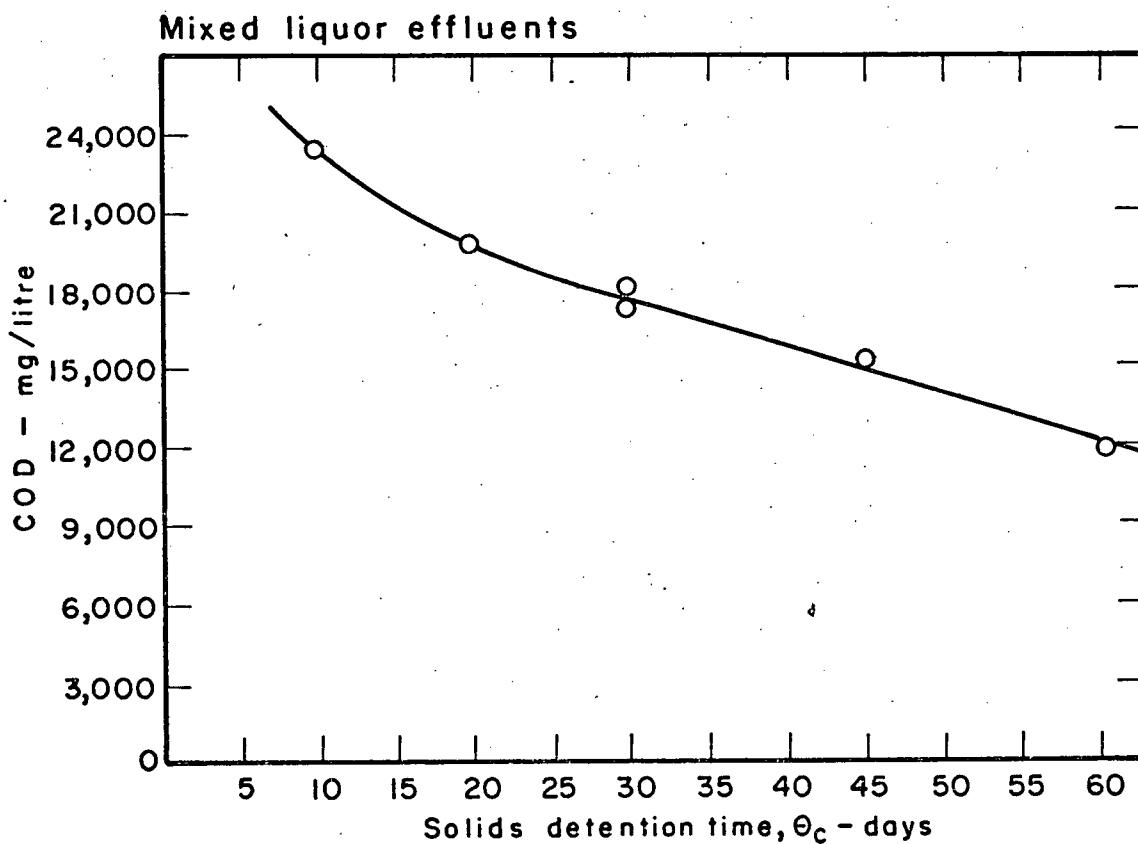
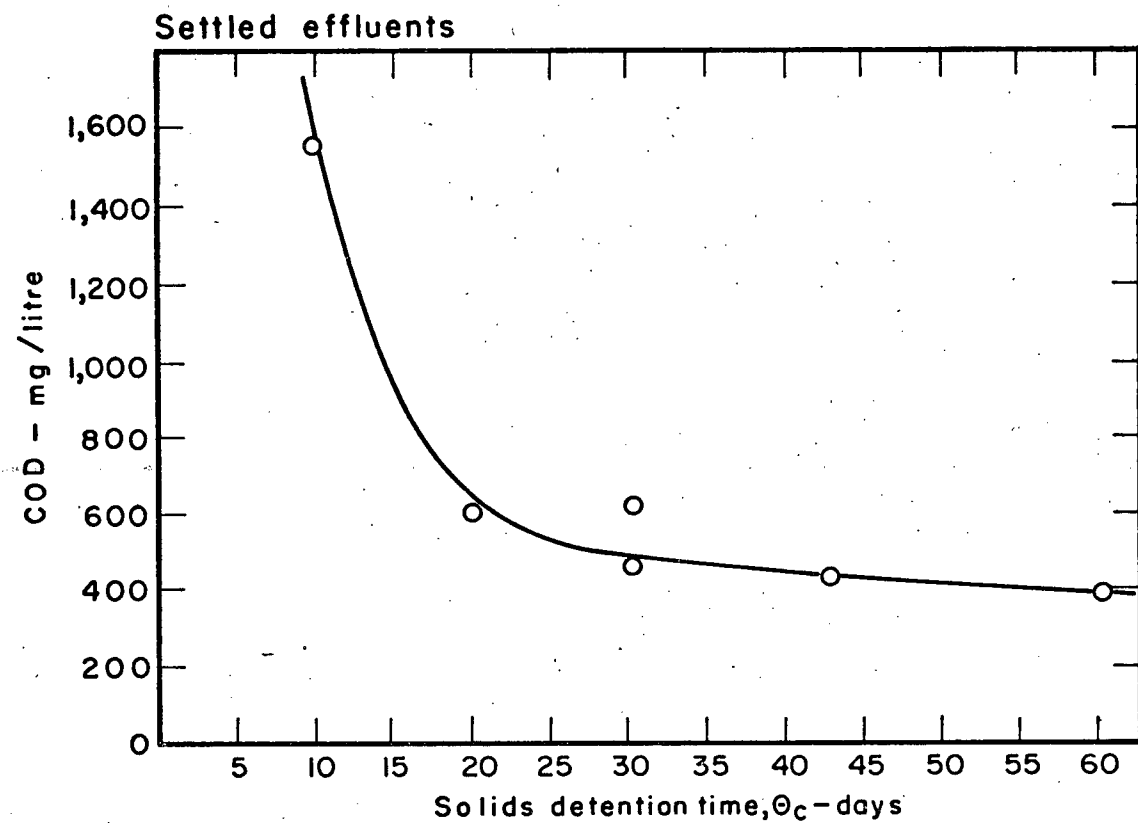


Figure 6 COD OF MIXED AND SETTLED EFFLUENTS vs SOLIDS DETENTION TIME

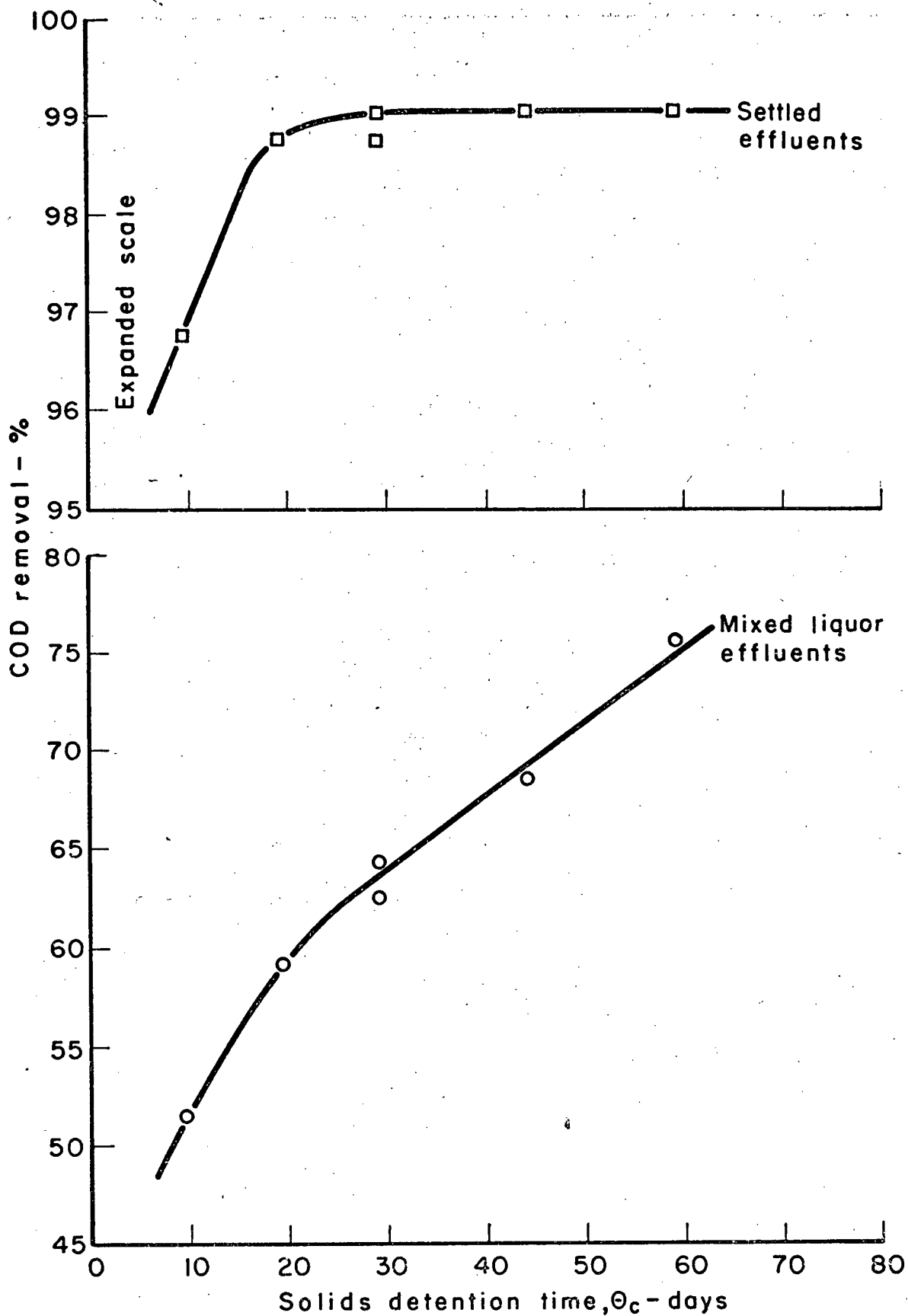


Figure 7 PERCENT COD REMOVALS vs SOLIDS DETENTION TIME

to 99.2 percent as the solids detention time increased from 10 to 60 days. At solids detention time greater than 20 days, settled effluent COD removal was greater than 98.7 percent. It has been generally observed that the settling characteristics of the biological floc are enhanced as the solids detention time increases (4). As the mean age of the cells in each digester increases, the micro-organisms in the biological floc produce more extracellular polymers and eventually become "encapsulated" in a slime layer. It appears, therefore, that the presence of these extracellular polymers and the slime layer promote both BOD and COD removal, when very high volatile suspended solids levels are maintained. In the 10 day solids detention time unit, the settling biological floc removed 93.5 percent of the mixed liquor COD. In the 20 day solids detention time unit, the settling biological floc removed 97.0 percent of the mixed liquor COD. A decrease of better than 800 mg/l in settled effluent COD therefore resulted from increasing the solids detention time from 10 to 20 days.

Because very high volatile suspended solids concentrations were maintained in all six digesters, a look at COD removal as a function of the food to micro-organism ratio is desirable both for design purposes and for a comparison of the results with those obtained by other researchers. Figure 8 shows the COD of the mixed liquor and settled effluents as a function of the food to micro-organism ratio. The COD of the mixed liquor and settled effluents increases as the organic loading or food to micro-organism ratio increases. As the food to micro-organism ratio is increased, the incremental rise in settled effluent COD increases, while the incremental increase in mixed liquor COD decreases. These contrasting curves probably

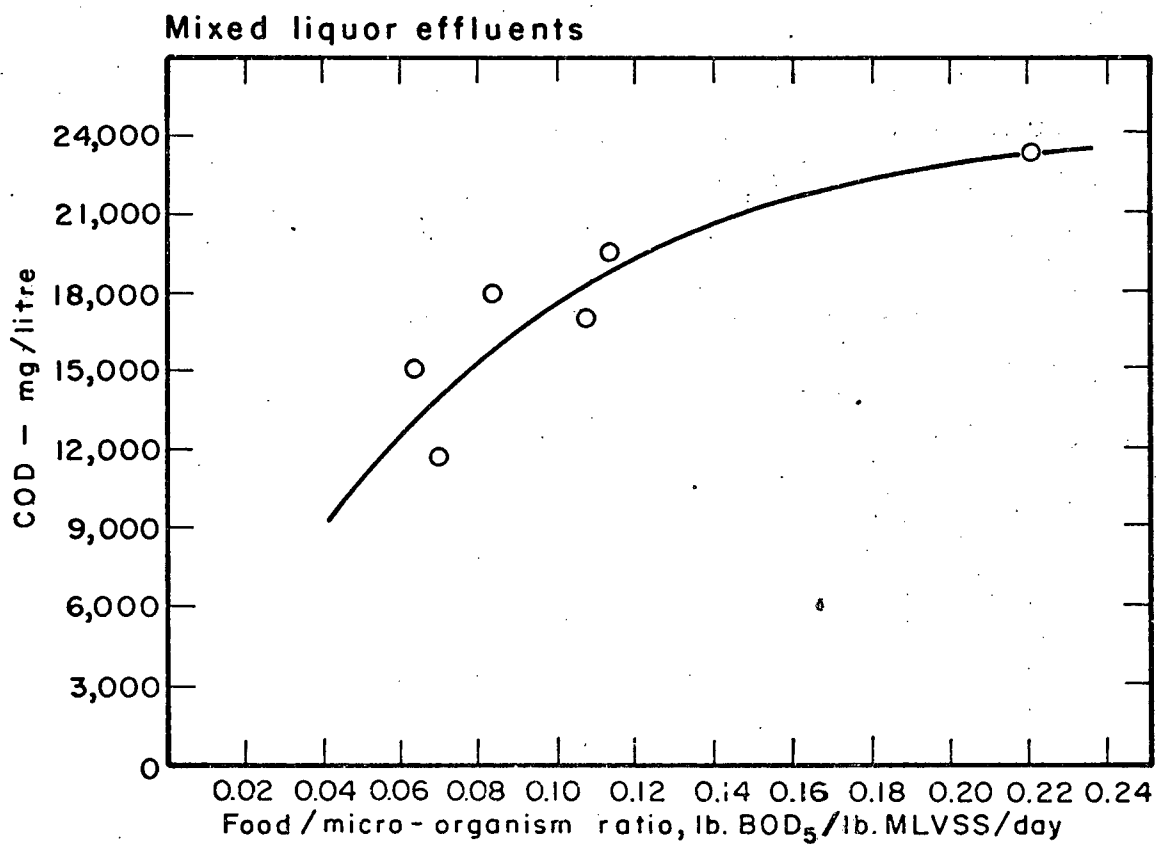
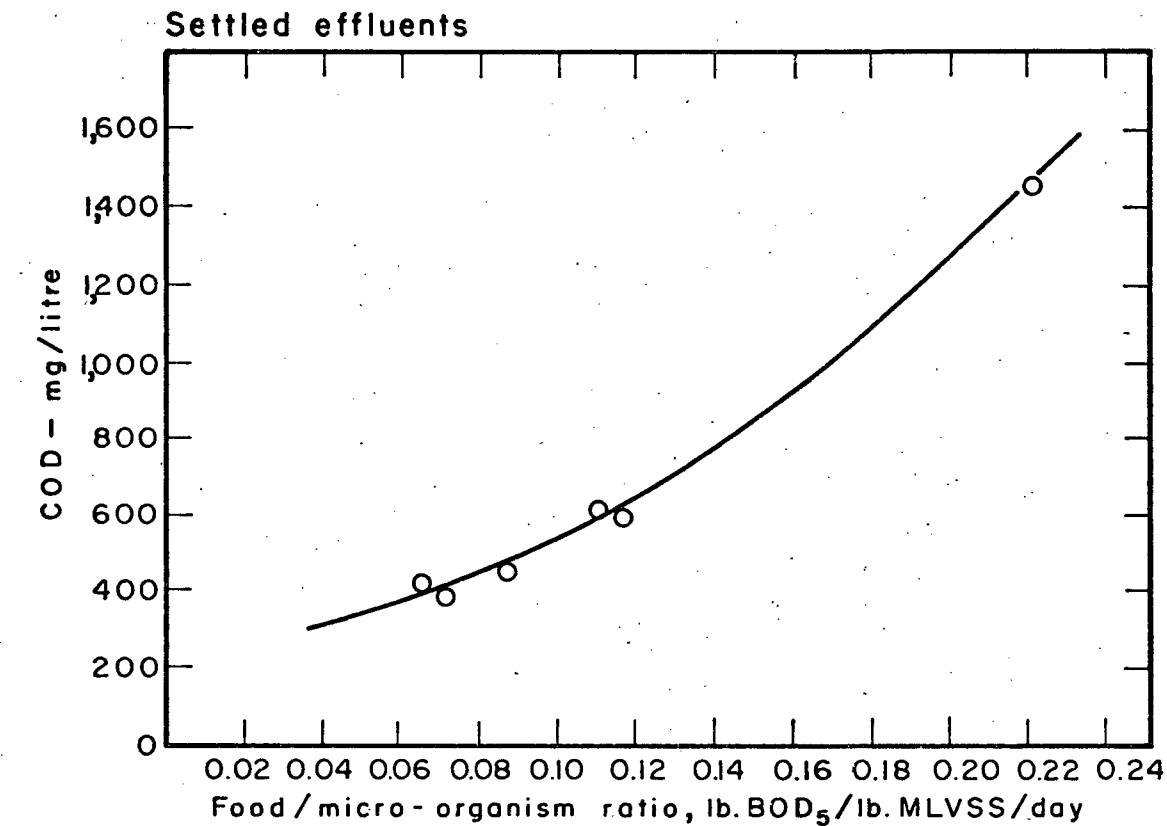


Figure 8 COD OF MIXED AND SETTLED EFFLUENTS vs FOOD TO MICRO-ORGANISM RATIO

indicate that the quality of the settled effluent is affected more by the sludge age (θ_c) than by the food to micro-organism ratio.

Figure 9 shows the percent COD removal for both the mixed liquor and settled effluents as a function of the organic loading. The percent COD removal decreases with increasing food to micro-organism ratio. At food to micro-organism ratios less than 0.12 lb.BOD₅/lb.MLVSS/day, better than 59 percent of the influent COD is removed in the mixed liquor and better than 98 percent of the influent COD is removed in the settled effluent. As the food to micro-organism ratio increases to greater than 0.20 lb.BOD₅/lb.MLVSS/day, the percent COD removal decreases rapidly. This trend was also observed by Boyle and Ham (15) and Cook and Foree (16), even though lower strength landfill leachates were used in their studies.

- (c) Organic Carbon Removal - Total carbon in the raw leachate averaged 15,400 mg/l, of which 15,389 mg/l was organic carbon and 11 mg/l was inorganic carbon. The total carbon and total inorganic carbon in the settled effluents from Digesters A, B, and C were determined* as part of the settled effluent characterization program. The results are summarized in Table X. From these results, it is apparent that a large amount of organic matter was removed from the settled effluents of all units. The removal of organic carbon increased rapidly as the solids detention time increased from 10 to 20 days. Removal of organic carbon was greater than 98 percent at solids detention times, (θ_c), greater than 20 days, and thus confirmed the observed COD removal efficiencies.

*using a Beckman Model 915-A Total Organic Carbon Analyser.

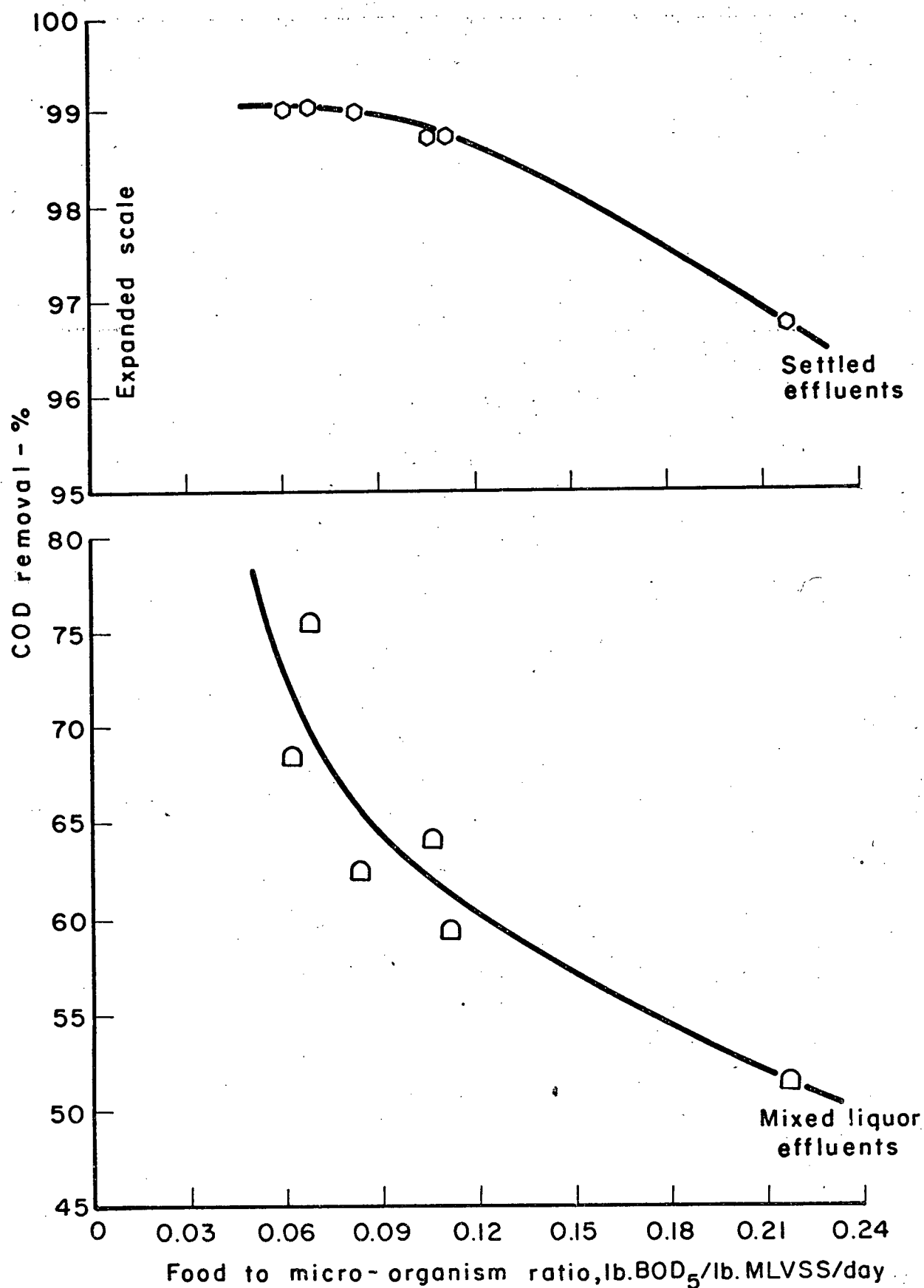


Figure 9 PERCENT COD REMOVALS vs FOOD TO MICRO-ORGANISM RATIO

TABLE X
ORGANIC CARBON REMOVAL DURING
"SHORTER DETENTION TIME" EFFICIENCY STUDY

Settled Effluent Source Solid Detention Time, days	Raw Leachate --	Digester A 10	Digester B 20	Digester C 30
Total Carbon, mg/l	15,400	933	513	454
Total Organic Carbon, mg/l	15,389	683	268	221
Total Inorganic Carbon, mg/l	11	250	245	233
Percent Organic Carbon Removal	--	95.6	98.3	98.6

Total inorganic carbon in the leachate feed was only 11 mg/l. Total inorganic carbon in the settled effluents, however, varied between 230 and 250 mg/l. This increase in effluent inorganic carbon, results from the biodegradation of organic carbon to carbon dioxide and water. As carbon dioxide was formed by the destruction of organic materials in the leachate feed, a portion of the released gas dissolved in the mixed liquor water and was converted to carbonate and bicarbonate metallic salts. The high pH maintained in these units (8.5 - 8.8) would promote both the formation of insoluble carbonates, such as calcium carbonate, and the release of gaseous carbon dioxide to the atmosphere. It is therefore likely that this narrow range of total inorganic carbon concentrations is caused by saturation of the settled effluents with soluble carbonate and bicarbonate metallic salts.

5-5-2 Volatile Suspended Solids

The mixed liquor total solids, total suspended solids, and volatile suspended solids were monitored during the efficiency studies. The results

of those tests are illustrated in Appendix A. All 3 parameters generally reached steady state values within 4 weeks of startup. Although the suspended solids levels maintained in all units were several times the recommended levels for activated sludge systems, the mixed liquors settled well and the settling biological floc removed a large percentage of the mixed liquor COD and BOD₅. Steady state MLSS concentrations ranged from 14,500 mg/l to 25,000 mg/l. An average 64 percent of these suspended solids were volatile. The mixed liquors settled quickly to produce sludges with total suspended solids concentrations around 45,000 mg/l. Settling was essentially complete after 2 hours.

Figure 10 shows the steady state mixed liquor volatile suspended solids concentrations as a function of the solids detention time. The steady state MLVSS concentration decreases as the solids detention time increases. As previously discussed, increasing the solids detention time from 10 to 20 days increased the removal of mixed liquor COD by the settling biological floc, from 93.5 to 97.0 percent. At solids detention times greater than 20 days, the settling biological floc consistently removed between 96.5 and 97.5 percent of the mixed liquor COD even though the MLVSS concentrations steadily decreased. This fact supports the previously drawn conclusion that solids detention time or sludge age is very important in determining settled effluent composition, and that increasing the solids detention time from 10 to 20 days significantly improves the quality of the settled effluent.

The very low settled effluent organic carbon, COD, and BOD₅ indicate that highly stabilized microbial masses existed in all units. Microscopic examination of the mixed liquors confirmed the presence of various forms of bacteria, protozoa, fungi and rotifers in all units. Fungal growth was

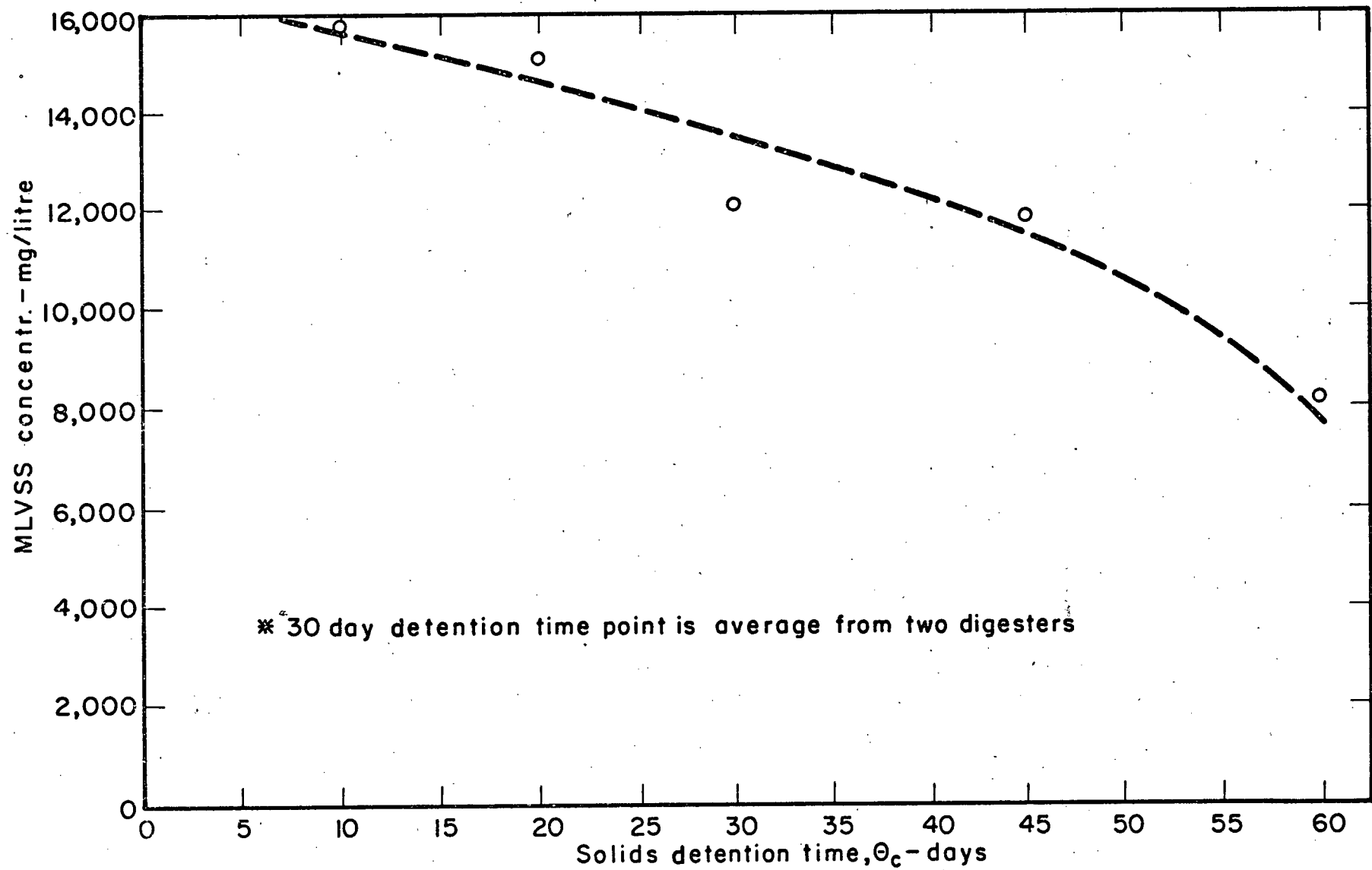


Figure 10 STEADY STATE MIXED LIQUOR VOLATILE SUSPENDED SOLIDS CONCENTRATIONS vs SOLIDS DETENTION TIME

very limited and thus did not adversely affect the settling characteristics of the biological flocs. A large number of free-swimming ciliates were observed. Since free-swimming ciliates use much more energy than fixed or stalked protozoa, and therefore require much more food, these microscopic examinations confirm the observed high mixed liquor BOD₅ and COD concentrations.

5-3 Metal Removal and Distribution

The metal distribution within the mixed liquor effluent was examined at the end of both sets of efficiency studies. In addition, the overall metal removal by the settling biological floc was examined during the acclimatization-metal removal study. The distribution of metals within the mixed liquor effluent and the metal removal efficiency of the biological floc were of special interest for three reasons:

- (1) They can provide information needed to decide on a satisfactory method of sludge disposal.
- (2) Any need for additional treatment of the settled effluents to remove heavy metals can be identified.
- (3) Depending on where the heavy metals are concentrated, the possibility of toxicity can be assessed.

- (a) Acclimatization-Metal Removal Study - To study the long-term metal removal capacity of the settling biological floc, the total solids concentration in the settled effluents was monitored. Since no biological solids were removed, hydraulic detention time was used as the basis of this study. Figure 11 shows the total solids concentration of the settled effluents from the three digesters, as a function of the time from start up. From Figure 11 it is evident that the total solids concentration in the settled effluents in-

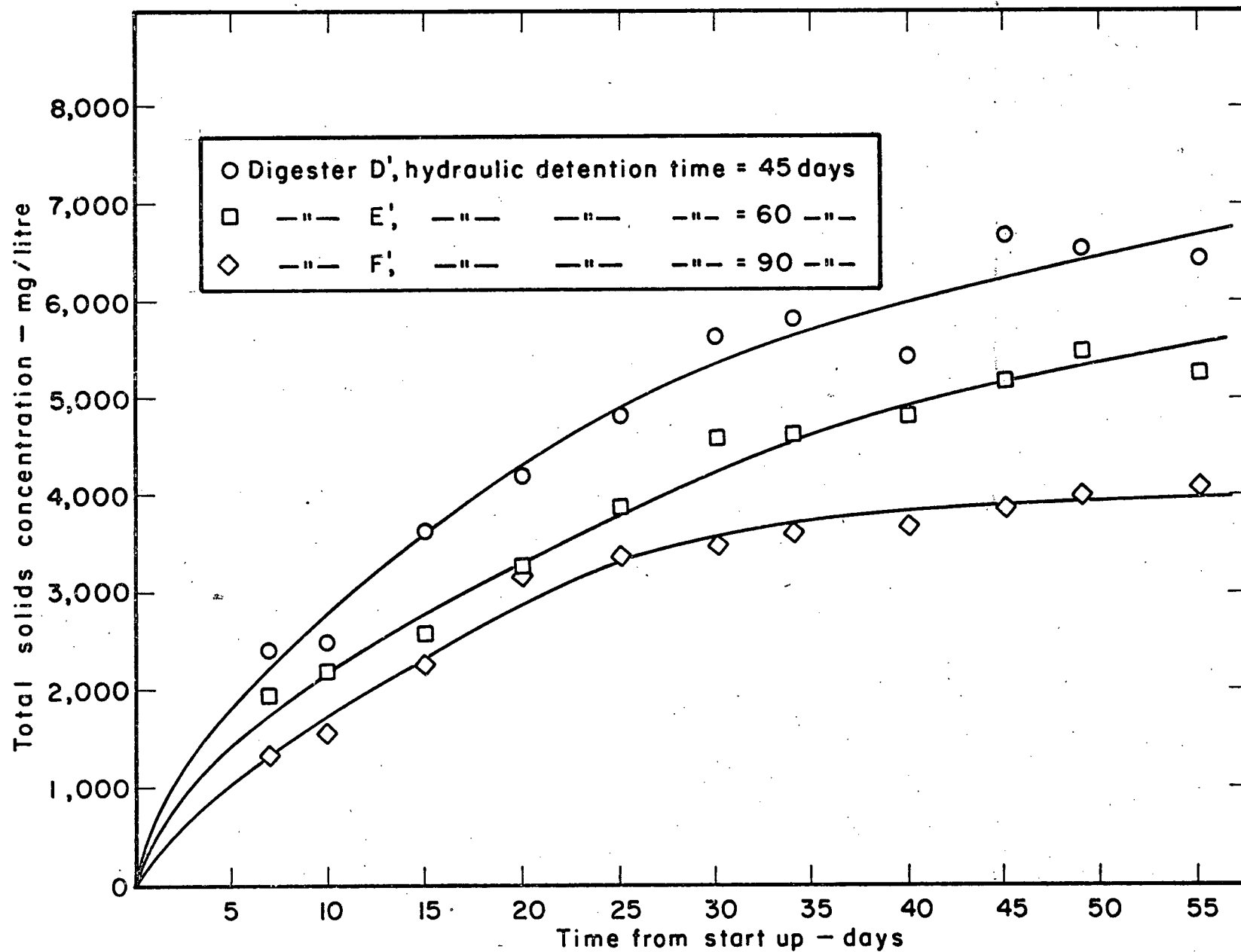


Figure 11 EFFLUENT TOTAL SOLIDS CONCENTRATION DURING ACCLIMATIZATION-METAL REMOVAL STUDY

creases as the hydraulic detention time decreases. Similarly, it was found that the BOD_5 of the settled effluents increased as the hydraulic detention time decreased (see Appendix B) even though the MLVSS concentrations increased with decreasing hydraulic detention time. After 30 days, the total solids concentrations in the settled effluents began to level off. After 56 days of operation, biological solids had accumulated in the digesters to the extent that it was difficult to obtain the required volumes of clear supernatant from Digesters D and E, even after one hour of settling. At this time samples of the mixed liquors and settled effluents from each digester were collected for metal analysis. The mixed liquor samples were "wet-ash" digested, following the recommended EPA procedure (17). However, when the digested samples were filtered prior to metal analysis, considerable particulate matter was observed on the filters. To check the efficiency of the digestion process for metal recovery, and to check the accuracy of the subsequent metal analysis, a material balance was developed, using the results of the total solids concentration tests on the settled effluents. In developing this material balance, it was assumed that:

$$\left[\begin{array}{l} \text{the net} \\ \text{influent} \\ \text{metal} \\ \text{concentration} \end{array} \right] = \left[\begin{array}{l} \text{metal} \\ \text{concentration} \\ \text{in leachate} \\ \text{feed} \end{array} \right] - \left[\begin{array}{l} \text{metal} \\ \text{concentration} \\ \text{in day 56} \\ \text{settled effluent} \end{array} \right] \times \frac{\left(\begin{array}{l} \text{weighted average total} \\ \text{solids concentration} \\ \text{throughout study} \end{array} \right)}{\left(\begin{array}{l} \text{total solids concentra-} \\ \text{tion in day 56} \\ \text{settled effluent} \end{array} \right)}$$

The concentration of each metal ion expected in each mixed liquor was then determined by multiplying the net influent metal concentration to each digester by 56 days and dividing by the respective

digesters hydraulic detention time. The ratio of the analysed mixed liquor metal concentration to that determined by this mass balance was then used to check the metal analysis and metal recovery using the "wet-ash" digestion process.

The large number of substances in leachate and their possibly high concentrations, can produce interferences resulting in errors in the determination of influent metal concentrations. When the many insoluble metal-sludge complexes which might be formed, are considered, the possibility of full metal recovery by any sludge digestion process is very slight. In light of these problems and the simplicity of the material balance applied, it was decided that the metal distribution results would be considered acceptable if application of the material balance accounted for between 90 and 110 percent of the influent metal. To meet this criterion, it was found necessary to use nitrous oxide-acetylene flames for aluminum, calcium, iron, and manganese analyses. The air-acetylene flame, normally employed in atomic absorption analysis for metals, was used for all other metals. These procedural modifications for metal analysis were similarly employed in the metal analyses performed at the end of each efficiency study.

The results of the metal analyses and the application of the simple material balance, along with influent concentrations, are shown in Table XI. Applying the acceptability criterion previously mentioned, it can be seen from the last column in Table XI that none of the averages for any metal lie very far outside the acceptable range. Cadmium, chromium, iron, and magnesium recovery were, however, rather low. When the digesters were taken apart at the end of the study, large clumps of metal were found settled below the coarse-

TABLE XI

METAL DISTRIBUTION AT END OF ACCLIMATIZATION-METAL REMOVAL STUDY

Metal	Dig- ester	Influent Concentration mg/l	Mixed Liquor Concentration mg/l	Settled Effluent Concentration mg/l	Percent of Metal Associated With Sludge Solids	Concentration Expected in Mixed Liquor (From Material Balance) mg/l	Percent of Influent Metal Accounted For
Aluminum	D	60.2	75.0	0.4	99.47	74.5	100.6
	E		58.0	0.0	100	56.2	103.2
	F		40.3	0.0	100	37.4	107.6
Cadmium	D	0.43	0.430	0.02	95.35	0.517	83.7
	E		0.360	0.01	97.22	0.395	91.3
	F		0.240	0.00	100	0.267	89.9
Calcium	D	1,924	2,140	194	90.93	2,224	96.5
	E		1,670	130	92.21	1,720	97.2
	F		1,140	127	88.86	1,138	100.1
Chromium	D	2.3	2.43	0.07	97.11	2.81	86.4
	E		1.85	0.05	97.29	2.12	87.1
	F		1.30	0.04	96.92	1.42	91.7
Iron	D	1,260	1,300	11.4	99.12	1,557	83.6
	E		940	11.7	98.75	1,168	80.6
	F		765	17.8	97.67	775	98.7

/continued..

TABLE XI continued ...

Metal	Dig- ester	Influent Concentration mg/l	Mixed Liquor Concentration mg/l	Settled Effluent Concentration mg/l	Percent of Metal Associated With Sludge Solids	Concentration Expected in Mixed Liquor (From Material Balance) mg/l	Percent of Influent Metal Accounted For
Lead	D	1.79	2.02	0.44	78.22	1.84	108.0
	E		1.58	0.39	75.32	1.42	110.0
	F		1.05	0.29	72.38	0.98	106.0
Magnesium	D	378	276	159.0	42.39	331.4	88.3
	E		240	115.4	51.92	277.2	89.5
	F		179	87.4	51.17	195.1	93.1
Manga- nese	D	46.0	50.4	1.3	97.48	56.1	90.1
	E		38.8	0.7	98.20	42.5	91.5
	F		26.0	0.6	97.69	28.3	91.8
Nickel	D	0.61	0.667	0.090	86.51	0.674	99.1
	E		0.495	0.090	81.82	0.506	98.1
	F		0.350	0.055	84.29	0.351	99.7
Potassium	D	1,610	1,043	1,020	2.21	1,111	96.6
	E		880	862	2.05	938	96.2
	F		678	662	2.06	698	98.0
Zinc	D	227	252	7.6	96.19	275.8	91.6
	E		200	5.5	97.25	208.2	96.1
	F		142	7.7	94.57	137.7	103.0

bubble diffusers. Tests with a magnet indicated that those clumps were primarily iron, but they probably also contained other metal precipitates. This observation could account for many of the low mixed liquor metal concentrations determined in this phase of the study.

Examination of Table XI indicates that most of the metals checked are associated with the sludge solids. These metals may be precipitated, adsorbed to the biological floc, or dissolved in the liquid fraction of the sludge, but they would be removed from the final clarifier with the settled sludge. Better than 95 percent of the mixed liquor aluminum, cadmium, chromium, iron, manganese, and zinc were removed by the settling biological flocs. Between 70 and 95 percent of the mixed liquor calcium, lead, and nickel were associated with the sludge solids.

Between 42 and 52 percent of the mixed liquor magnesium was removed by settling. It is likely that the high pH maintained in the three digesters caused a portion of the influent magnesium salts to precipitate and subsequently to settle out of the mixed liquor with the settling biological flocs.

Less than 3 percent of the mixed liquor potassium was removed by the settling biological flocs. Potassium passes right through the biological treatment system. The mixed liquor potassium remained virtually completely dissolved and associated with the liquid fraction of the mixed liquor. Similar results would be expected for sodium.

From the fifth column in Table XI it can also be seen that the concentration of any particular metal in the settled effluent generally decreases with increasing hydraulic detention time. This trend,

however, is due to the decreasing mixed liquor metal concentrations.

The MLVSS concentrations in digesters D', E', and F', were approximately 11,800, 10,900 and 7,600 mg/l respectively. From the sixth column of Table XI it is evident that increasing MLVSS concentrations did not increase the metal removal by the settling biological flocs and similarly, that increasing hydraulic detention time did not significantly improve metal removal by the settling biological flocs. Solids detention times in all units were equal, as no biological solids were removed during this study. These results are, therefore, consistent with the results observed in the removal of oxygen demanding material.

From the fourth column of Table XI it may be noted that daily settling resulted in mixed liquor metal concentrations in Digester D' exceeding those in the leachate feed. Since metal removal by the settling biological flocs remained consistently high in all of the units tested, no limit could be set on the metal removal capacity of the settling biological floc. It is clear from these results, however, that a settling, activated sludge floc may effectively be used as a physical treatment method for good removal of very high concentrations of a number of metals. The fact that most heavy metals are concentrated in the sludge means, however, that a great deal of care must be taken in disposing of that sludge.

- (b) Efficiency Studies - The concentrations of metals in the mixed liquor and settled effluents from all three digesters were determined at the end of each set of efficiency studies. Table XII shows the results of those metal analyses along with the influent leachate metal concentrations. From the fourth column it can be seen that mixed liquor

TABLE XII
METAL DISTRIBUTION AT END OF EFFICIENCY STUDIES

Metal	Dig- ester	Influent Concentration mg/l	Mixed Liquor Concentration mg/l	Settled Effluent Concentration mg/l	Percent of Metal Removed By Settling Biological Floc
Aluminum		41.8			
	A		41.00	1.02	97.51
	B		40.60	0.64	98.42
	C		36.60	0.31	99.15
	D		38.40	0.31	99.19
	E		38.40	0.00	100
	F		37.60	0.00	100
Cadmium		0.39			
	A		0.384	0.012	96.88
	B		0.388	0.009	97.68
	C		0.352	0.005	98.58
	D		0.374	0.010	97.33
	E		0.369	0.008	97.83
	F		0.334	0.005	98.50
Calcium		1,394			
	A		1,394	28.0	97.99
	B		1,392	20.6	98.52
	C		1,200	20.8	98.27
	D		1,630	84.0	94.85
	E		1,640	63.8	96.11
	F		1,160	75.0	93.53
Chromium		1.9			
	A		1.87	0.14	92.51
	B		1.85	0.06	96.76
	C		1.78	0.06	96.63
	D		1.85	0.06	96.76
	E		1.78	0.04	97.75
	F		1.38	0.04	97.10
Iron		960			
	A		980	13.6	98.61
	B		973	2.9	99.70
	C		887	1.45	99.84
	D		888	1.45	99.84
	E		847	0.50	99.94
	F		782	0.10	99.99

/continued..

TABLE XII continued ...

Metal	Dig- ester	Influent Concentration mg/l	Mixed Liquor Concentration mg/l	Settled Effluent Concentration mg/l	Percent of Metal Removed By Settling Biological Floc
Lead		1.44			
	A		1.39	0.28	79.85
	B		1.22	0.20	83.61
	C		1.10	0.16	85.45
	D		1.35	0.22	83.70
	E		1.12	0.14	87.50
	F		1.06	0.11	89.62
Magnesium		310			
	A		306	139	54.57
	B		289	91	68.51
	C		244	85	65.16
	D		278	112	59.71
	E		244	96	60.65
	F		193	98	49.22
Manganese		41.0			
	A		40.50	1.73	95.73
	B		36.10	0.68	98.12
	C		32.50	0.45	98.62
	D		38.60	0.45	98.83
	E		34.30	0.18	99.47
	F		27.70	0.11	99.60
Nickel		0.65			
	A		0.640	0.190	70.31
	B		0.640	0.180	71.87
	C		0.640	0.120	81.25
	D		0.620	0.150	75.80
	E		0.620	0.150	75.80
	F		0.540	0.080	85.19
Potassium		1,060			
	A		828	690	16.67
	B		792	715	9.72
	C		710	660	7.58
	D		744	680	8.60
	E		716	615	14.11
	F		762	570	15.18
Zinc		223			
	A		197.3	1.81	99.08
	B		183.4	1.42	99.23
	C		160.3	0.60	99.63
	D		215.4	0.86	99.60
	E		179.1	0.25	99.86
	F		137.1	0.17	99.88

calcium concentrations at the end of the "extended aeration" efficiency study exceeded those in the leachate feed. Those calcium concentrations, however, are less than those in the leachate feed used in the acclimatization-metal removal study (1,924 mg/l) and therefore, indicate that calcium concentrations in the mixed liquor were dropping to approach those in the new leachate feed. All other mixed liquor metal concentrations were less than or equal to those in the leachate feed. In the highest loaded units in each study, the mixed liquor metal concentrations were very close to those in the leachate feed. As the loading rate decreases in each set, the concentration of metal in the mixed liquors decreases, as would be expected. Since the same units were used in each study, the metal concentrations in each "shorter detention time" digester more closely approach the metal concentrations in the leachate feed, than do those in the same digesters during the "extended aeration" efficiency study.

Table XIII summarizes the digester operating parameters and the resulting metal removal efficiencies. As in the acclimatization-metal removal study, the settling biological flocs removed better than 95 percent of the mixed liquor aluminum, cadmium, chromium, iron, manganese and zinc. Mixed liquor calcium and lead removal efficiencies increased slightly in most digesters during the efficiency studies, while average mixed liquor nickel removal decreased slightly.

Between 49 and 68 percent of the mixed liquor magnesium was removed with the settling biological solids. It is very likely that the slightly higher pH's maintained during the efficiency studies account for this slight improvement in magnesium removal over that

TABLE XIII

SUMMARY OF METAL REMOVAL BY SETTLING BIOLOGICAL FLOC DURING EFFICIENCY STUDIES

Digester Solids Detention Time, Days	A 10	B 20	C 30	D 30	E 45	F 60
Steady-State MLSS Concentration,mg/l	24,250	22,650	20,800	19,550	20,300	14,300
Steady-State MLVSS Concentration,mg/l	16,100	15,100	13,500	10,590	11,880	8,100
Percent of Mixed Liquor Metal Concentrations Removed by Settling Biological Floc:						
Aluminum	97.51	98.42	99.15	99.19	100	100
Cadmium	96.88	97.68	98.58	97.33	97.83	98.50
Calcium	97.99	98.52	98.27	94.85	96.11	93.53
Chromium	92.51	96.76	96.63	96.76	97.75	97.10
Iron	98.61	99.70	99.84	99.84	99.94	99.99
Lead	79.85	83.61	85.45	83.70	87.50	89.62
Magnesium	54.57	68.51	65.16	59.71	60.65	49.22
Manganese	95.73	98.12	98.62	98.83	99.47	99.60
Nickel	70.31	71.87	81.25	75.80	75.80	85.19
Potassium	16.67	9.72	7.58	8.60	14.11	15.18
Zinc	99.08	99.23	99.63	99.60	99.86	99.88

observed in the acclimatization-metal removal study.

Table XIII also shows that only between 7.6 and 16.7 percent of the mixed liquor potassium was associated with the sludge solids. While potassium removal during the efficiency studies increased over that observed in the acclimatization-metal removal study, the results still indicate that potassium passes right through the activated sludge treatment process and that it remains almost completely associated with the liquid fraction of the mixed liquor.

From the efficiency study results and those observed at the end of the acclimatization-metal removal study, it may be concluded that the order of mixed liquor metal removal by the settling biological floc, with average percent removal in brackets, is as follows:

aluminum (99.3) and iron (99.3) > zinc (98.4) > manganese (98.2)
> cadmium (97.7) > chromium (96.5) > calcium (94.6) > lead
(81.7) > nickel (79.2) > magnesium (55.9) > potassium (8.7).

The percent removal for all metals is generally considerably higher than that observed by other researchers (9,11,12,13). The higher pH and volatile suspended solids levels used in this study could account for this increased metal removal by the settling biological floc, although it may be observed from Table XIII that decreasing MLVSS concentrations from 16,100 to 8,100 mg/l did not adversely affect the mixed liquor metal removal by the settling biological floc. Indeed, it may be observed that in most cases, the percent metal removal in Digester A represents the lowest value in any unit tested. This trend again suggests that increasing the solids detention time from 10 to 20 days, or higher, significantly improves the settling characteristics of the biological solids, with subsequent higher BOD₅, COD, organic carbon, and metal removal by the settling

biological floc.

5-4 Settled Effluent Characterization

The leachate feed to all units during the efficiency study was very dark green in colour, with a fairly strong obnoxious odour. Settled effluents from all the units tested was light brown to yellow in colour. The obnoxious odour of the raw leachate was almost completely removed. The settled effluents from the efficiency study digesters are further characterized in Table XIV. Also shown in Table XIV are the influent leachate concentrations and the proposed B.C. Pollution Control Board guidelines for specific discharges (1). Where no numbers are shown for a specific settled effluent, the test was not performed due to a shortage of the sample.

- (a) Oxygen Demanding Material - As previously discussed, the removal of oxygen demanding material from the settled effluents was excellent. Increasing the solids detention time from 10 to 20 days, significantly improved the quality of the settled effluent with respect to oxygen demanding material. For solids detention times greater than 20 days, the BOD_5 of the settled effluents averaged 58.1 mg/l and the COD of the settled effluent remained less than 625 mg/l. It is evident from these results that the BOD_5 of the settled effluents may satisfy regulatory agency requirements, if adequate settling time is allowed in the final clarifier.
- (b) Solids - The total solids concentrations in the settled effluents generally decreased with increasing solids detention time. Again, the total solids results indicate that increasing the solids detention time from 10 to 20 days or higher significantly improves the effluent quality. Although the sample volumes obtained were

TABLE XIV

CHARACTERISTICS OF LEACHATE FEED AND SETTLED EFFLUENTS FROM AEROBIC
BIOSTABILIZATION EFFICIENCY STUDIES

Characteristics (all, except pH, in mg/l)	Leachate Feed	Digester A	Digester B	Digester C	Digester D	Digester E	Digester F	P.C.B. (1) Requirements
BOD ₅	36,000	128.9	32.4	27.1	90.8	65.7	74.9	45
COD	48,000	1,547	594.2	456.4	610.4	427.8	385.5	
Total Carbon	15,400	933	513	454	-	-	-	
Total Organic Carbon	15,389	683	268	221	-	-	-	
Total Solids	26,600	6,050	5,200	4,980	5,160	4,870	4,450	6.5-8.5
pH	5.02	8.80	8.73	8.50	8.80	8.74	8.60	
Acidity	5,640	0.0	0.0	0.0	0.0	0.0	0.0	
Alkalinity	7,640	1,320	1,210	1,080	857	728	542	
Aluminum	41.8	1.02	0.64	0.31	0.31	0.00	0.00	0.5
Arsenic	3.6	-	-	-	0.26	0.26	0.26	0.05
Cadmium	0.39	0.012	0.009	0.005	0.010	0.008	0.005	0.005
Calcium	1,394	28.0	20.6	20.8	84.0	63.8	75.0	0.10
Chromium	1.9	0.14	0.06	0.06	0.06	0.04	0.04	
Iron	960	13.6	2.9	1.45	1.45	0.50	0.10	
Lead	1.44	0.28	0.20	0.16	0.22	0.14	0.11	
Magnesium	310	119	91	85	112	96	98	150
Manganese	41.0	1.73	0.68	0.45	0.45	0.18	0.11	0.05
Nickel	0.65	0.19	0.18	0.12	0.15	0.15	0.08	0.3
Potassium	1,060	690	715	660	680	615	570	0.5
Selenium	0.450	-	-	-	0.036	-	-	
Zinc	223	1.81	1.42	0.60	0.86	0.25	0.17	

/continued...

TABLE XIV continued...

Characteristics (all, except pH, in mg/l)	Leachate Feed	Digester A	Digester B	Digester C	Digester D	Digester E	Digester F	P.C.B. (1) Requirements
Total Nitrogen*	1,770 1,390	29.4	23.9	13.4	70.4	39.4	22.9	15.0
Total Phosphorus*	868 362	12.0	5.46	3.11	32.4	25.8	20.3	4.5

*nutrient additions to the leachate feed were decreased during the "shorter detention time" efficiency study.

not sufficient to accurately determine the suspended solids concentrations in the settled effluents, tests showed that suspended solids concentrations in all settled effluents were low (less than 100 mg/l), but may, in many cases, exceed Pollution Control Board requirements. For this reason some form of effluent polishing may be necessary.

- (c) pH, Alkalinity and Acidity - pH was checked daily. The results are illustrated in Appendix C. Because pH fluctuated considerably, the values shown in Table XIV are approximate averages over the last 15 to 20 days of each study.

The pH of the leachate feed was 5.02, probably primarily the result of organic acids produced in the landfill. The pH in all digester units was maintained at greater than 8.5. These relatively high pH values undoubtedly aided in the precipitation of many metals such as iron, calcium and magnesium.

The acidity of the leachate feed was completely destroyed, indicating that the organic acids were neutralized. The alkalinity of the leachate feed was also substantially reduced. The alkalinity of the settled effluents decreases with increasing solids detention time. This trend is probably caused by the adsorption of precipitated metal carbonates by the biological floc (carbonate is one form of alkalinity) and by the production of organic acid in each digester. As the solids detention time increases, more of the organic matter in the leachate feed should be utilized and thus the alkalinity of the settled effluents should decrease with increasing solids detention time.

- (d) Metals - The metal concentrations in the leachate feed are signifi-

cantly reduced, but the settled effluents still do not satisfy the effluent requirements set by the Pollution Control Board. Metal concentrations in the settled effluent generally decrease with increasing solids detention time, as do the mixed liquor metal concentrations at the end of each study. A solids detention time of only 10 days is required to satisfy the P.C.B. effluent requirements for magnesium and nickel, while solids detention times of at least 30 days are required to satisfy those requirements for cadmium, chromium and zinc. Even with the sludge age as long as 60 days, and mixed liquor metal concentrations significantly less than those in the leachate feed, the Pollution Control Board effluent standards for arsenic, lead and manganese cannot be met. For this reason, some form of effluent polishing should be developed. Carbon adsorption or ion exchange columns would appear to be most promising for metal removal in these low concentration ranges.

- (e) Nutrients - Using the lower leachate feed concentrations in Table XIV as a guideline, it would appear that a solids detention time of at least 30 days is necessary to obtain settled effluent nitrogen and phosphorus concentrations less than the maximums allowed by regulating agencies. However, since the mixed liquor BOD₅ in all units was still fairly high, micro-organisms in those digesters were not given enough time to use all the nutrients supplied. Reducing nutrient additions during the "shorter detention time" efficiency study improved the quality of the settled effluents with respect to nutrient concentrations, without adversely affecting the biological efficiency of those digesters. It may be concluded, therefore, that nutrient additions to the leachate feed were excessive and that those additions might be substantially reduced, thus

lowering the cost of leachate treatment.

Cook and Foree (16) have shown that it is possible to aerobically treat a medium-strength landfill leachate with a $BOD_5:N:P$ ratio of 100:3.95:0.18 without any significant reduction in aerobic biostabilization efficiency. Without nutrient additions, the leachate feed used in these efficiency studies would have had a $BOD_5:N:P$ ratio of 100:2.02:0.55. Since much of the ammonia in the leachate feed may have been stripped out of the high pH mixed liquors by air bubbling through the digesters, it may have been necessary to add nitrogen in some form to the leachate feed. However, since reduced nutrient additions to the leachate feed might result in satisfactory nitrogen and phosphorus levels in the settled effluents, without any significant reduction in treatment efficiency, the nitrogen and phosphorus requirements for aerobic biostabilization of such "nutrient-deficient" wastes should be more thoroughly investigated.

5-5 Kinetic Parameters and Efficiency Predictions

The results of the "extended aeration" efficiency study were used to determine the kinetic parameters associated with aerobic biostabilization of this high-strength landfill leachate. These kinetic parameters were then used to predict the minimum solids detention time for leachate treatment (see Appendix E) and "safe" solids detention times were then chosen for the "shorter detention time" efficiency study. The kinetic parameters thus determined are summarized in Table XV. For comparison, the kinetic parameters determined by Cook and Foree (16) for the treatment of a medium-strength landfill leachate, and those commonly used in sewage treatment plant design (4) are also presented.

TABLE XV

KINETIC PARAMETERS DETERMINED FROM
"EXTENDED AERATION" EFFICIENCY STUDY DATA

Kinetic Parameter	Range of Values Normally Employed in Sewage Treatment Plant Design (4)	Value Determined For a Medium-Strength Landfill Leachate (16)	Value Determined From This "Extended Aeration" Efficiency Study Data
Y	0.40-0.67 mgVSS/mgBOD ₅	0.4 mgVSS/mgCOD	0.332 mgVSS/mgBOD ₅
b	0.05-0.09 day ⁻¹	0.05 day ⁻¹	0.0025 day ⁻¹
K	3.0-6.0 mgBOD ₅ /mgVSS/day	0.60 mgCOD/mgVSS/day	0.75 mgBOD ₅ /mgVSS/day
K _s	20-200 mgBOD ₅ /l	175 mgCOD/l	21,375 mgBOD ₅ /l

Since the BOD₅ data from the "extended aeration" efficiency study showed a great deal of scatter, when plotted to determine these kinetic parameters, considerable personal judgment was involved in obtaining the estimates shown in Table XV. Biological inhibition made accurate determination of mixed liquor BOD₅ impossible. However, that inhibition was not always evident in the "extended aeration" efficiency study BOD₅ tests. Attempts to analyse the COD data from the "extended aeration" efficiency study proved even more unsatisfactory, as even greater scatter prevented any reliable estimation of these kinetic parameters. Thus, although the accuracy of the parameter values appearing in Table XV is somewhat questionable, an analysis of those values should give some insight into what is happening in the digesters.

The low growth yield coefficient, Y, indicates that only 0.332 mg of biological suspended solids were produced for each mg of BOD₅ destroyed. This low value may be the result of underestimating the mixed liquor BOD₅ or of biological inhibition caused by the high mixed liquor, heavy metal concentrations.

The endogenous respiration or auto-oxidation coefficient, b , is also very low. The micro-organisms in the mixed liquor enter the endogenous growth phase only when the food concentration in the mixed liquor is too low to maintain logarithmic growth. During endogenous respiration, cells utilize the protoplasm of similar micro-organisms to obtain energy for growth. The BOD_5 of all mixed liquors in the "extended aeration" efficiency study exceeded 2,000 mg/l and therefore, there was no need for auto-oxidation to occur. This fact is reflected by the very low value of b .

The maximum rate of substrate utilization per unit weight of micro-organisms, K , is lower than normally observed in domestic sewage treatment plants. The low value of K indicates biological inhibition, probably due to the very high heavy metal concentrations in the mixed liquor.

K_s indicates the substrate (BOD_5) concentration when the rate of substrate utilization per unit weight of micro-organisms is one half the maximum, K . K_s has been observed to vary with the type of waste. As the complexity of the waste increases or as the biodegradability of the waste decreases, K_s increases. Here the very high value again indicates biological inhibition, and suggests that very high MLVSS concentrations are necessary to get reasonable reductions in the influent leachate BOD_5 .

Although these estimates of the kinetic parameters may not be very accurate, they may be used to predict the behaviour of the digesters as the solids detention time is decreased. Use of these parameters in equation (2), as presented in section 3-2, predicts a maximum MLVSS concentration of 11,900 mg/l. The fact that all MLVSS concentrations in the "shorter detention time" efficiency study exceeded this predicted maximum would indicate that the predicted value of the growth yield coefficient is low. Nevertheless, the kinetic parameter estimates were then used in equation (1), to predict the mixed liquor BOD_5 . A comparison of the experimentally determined

and predicted mixed liquor BOD₅ values is presented in Table XVI. Using higher estimates of the growth yield coefficient would result in lower predicted mixed liquor BOD₅ concentrations.

TABLE XVI

MIXED LIQUOR BOD₅ DURING "SHORTER DETENTION TIME" EFFICIENCY STUDY

Di- gester	Solids Detention Time, Days	Experimentally Determined		Predicted Values	
		Mixed Liquor BOD ₅	% Removal	Mixed Liquor BOD ₅	% Removal
A	10	2,805 mg/l	92.15	17,700 mg/l	50.5
B	20	3,676 mg/l	89.72	6,250 mg/l	82.5
C	30	3,582 mg/l	89.98	3,790 mg/l	89.3

The predicted mixed liquor BOD₅ in Digester C is very close to the experimentally determined value. However, this would be expected as data from a similar 30 day solids detention time unit was used to estimate the kinetic parameters. As previously discussed, heavy metal inhibition prevented any accurate determination of mixed liquor BOD₅. The predicted values in Table XVI, however, indicate the general trend which should have been observed and the value of increasing the solids detention time from 10 to 20 days or higher. Trends similar to that indicated by the predicted values of mixed liquor BOD₅ were observed in the mixed liquor COD and settled effluent BOD₅ and COD results.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6-1 Conclusions

- (1) Aerobic biostabilization is an effective means of stabilizing a high-strength landfill leachate. Using very high mixed liquor volatile suspended solids concentrations (8,000 to 16,000 mg/l), stable digester operation can be maintained at solids detention times as short as 10 days, provided food to micro-organism ratios are kept below 0.22 lb.BOD₅/lb.VSS/day.
- (2) For influent COD concentrations between 44,000 and 52,000 mg/l, settled effluent COD removal increases slightly from 96.7 to 99.1 percent as the solids detention time is increased from 10 to 60 days. Mixed liquor COD removal similarly increases from 51.5 to 75.7 percent as the food to the micro-organism ratio decreases from 0.22 to 0.06 lb.BOD₅/lb.VSS/day.
- (3) For influent BOD₅ concentrations between 32,000 and 38,000 mg/l, settled effluent BOD₅ removal greater than 99.6 percent is possible at solids detention times greater than 10 days.
- (4) For influent organic carbon concentrations between 15,250 and 15,550 mg/l, settled effluent removals of greater than 95 percent may be expected when food to micro-organism ratios are maintained less than 0.22 lb.BOD₅/lb.VSS/day.
- (5) The settling biological floc removes greater than 97 percent of the mixed liquor BOD₅ and greater than 96 percent of the mixed liquor COD when high volatile suspended solids concentrations (8,000 to 16,000 mg/l) are maintained in the mixed liquor.

- (6) Increasing the solids detention time from 10 to 20 days increases the removal of mixed liquor COD by the settling biological floc from 93.5 to 97.0 percent and significantly improves the quality of the settled effluents with respect to oxygen demanding material. At solids detention times greater than 20 days, settled effluent BOD₅ averaged 58.1 mg/l.
- (7) Most of the metals in the mixed liquor were removed by the settling biological floc. pH's greater than 8.5 were maintained in all units tested without any pH adjustment to the leachate feed. The high pH values undoubtedly aided metal removal, as did the high MLVSS concentrations.

Better than 95 percent of the mixed liquor aluminum, cadmium, chromium, iron, manganese and zinc were removed by the settling biological floc. Better than 90 percent of the mixed liquor calcium and around 80 percent of both the mixed liquor lead and nickel were associated with the sludge solids. On the average, however, only 56 percent of the magnesium in the mixed liquor was removed by settling, and better than 90 percent of mixed liquor potassium remained in the settled effluents.

Even though the leachate used in this study contained very high concentrations of various heavy metals, there was no indication of instability attributable to these metals. This indicates that, for a high-strength waste, containing relatively high concentrations of metals, a biological community can be acclimated and result in a stable system.

Since all of the heavy metals are not completely concentrated in the sludge solids, additional treatment is necessary to remove

the metal remaining in the settled effluents. In addition, because a high percentage of the metals is associated with the sludge, the latter should be disposed of in a manner such that the pollution potential of these metals is minimized.

- (8) Analysis of kinetic parameters indicates that the heavy metals in the mixed liquors seriously inhibited the biological efficiency of the units tested and suggests that very high mixed liquor volatile suspended solids concentrations may be necessary to obtain reasonable mixed liquor BOD₅ reductions.
- (9) The very high mixed liquor metal concentrations inhibited biological activity in the BOD₅ tests to the extent that it was impossible to obtain accurate mixed liquor BOD₅ results. For this reason, COD removal and/or organic carbon removal should be used to characterize the efficiency of biological treatment processes, when the feed to such systems contains high concentrations of inhibiting heavy metals.
- (10) BOD₅:N:P ratios of 100:5:1 or better were used in the efficiency studies and proved satisfactory. Analyses of the nutrients in the settled effluents indicated, however, that the nitrogen and phosphorus additions to the leachate feed were excessive and might be substantially reduced without adversely affecting treatment efficiency.

6-2 Recommendations for Future Studies

Since very little work has been done on the use of aerobic biostabilization as a method of treating landfill leachate, additional studies are necessary. These should include:

- (1) An investigation into methods of disposing of the sludge, so as to

minimize the pollution potential of the heavy metals.

- (2) An investigation of additional treatment methods for effluent polishing, to reduce the heavy metal concentrations and residual oxygen demanding material in the settled effluents.
- (3) An investigation of the nitrogen and phosphorus requirements of aerobic micro-organisms in the digestion process.
- (4) An investigation of the efficiency of aerobic biostabilization of a high-strength landfill leachate when much of the heavy metals are removed by prior chemical treatment of the leachate.

CHAPTER 7

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CHAPTER 8

APPENDICES

APPENDIX A

SOLIDS TESTS RESULTS DURING STUDIES

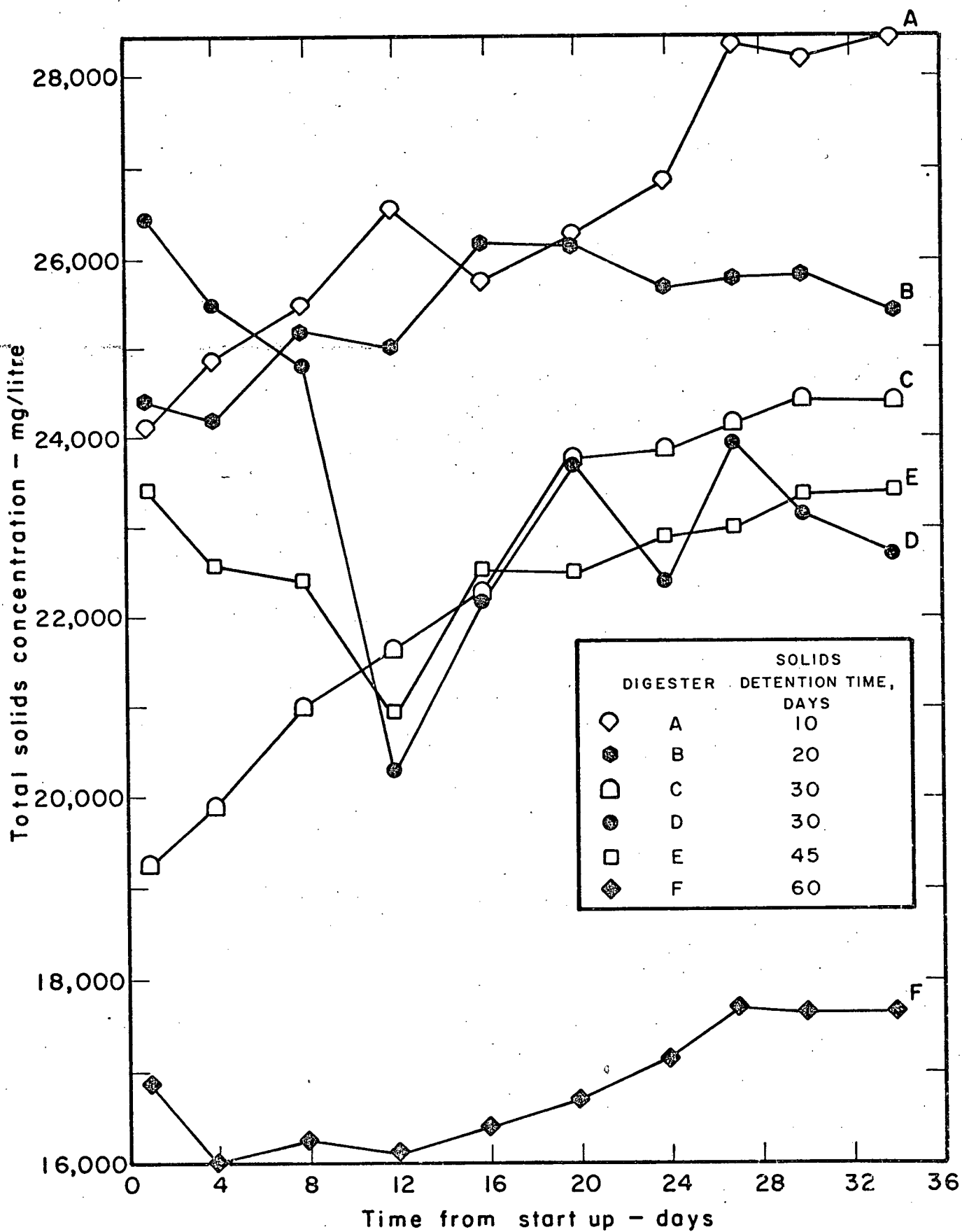


Figure 12 MIXED LIQUOR TOTAL SOLIDS CONCENTRATIONS vs TIME FROM START UP

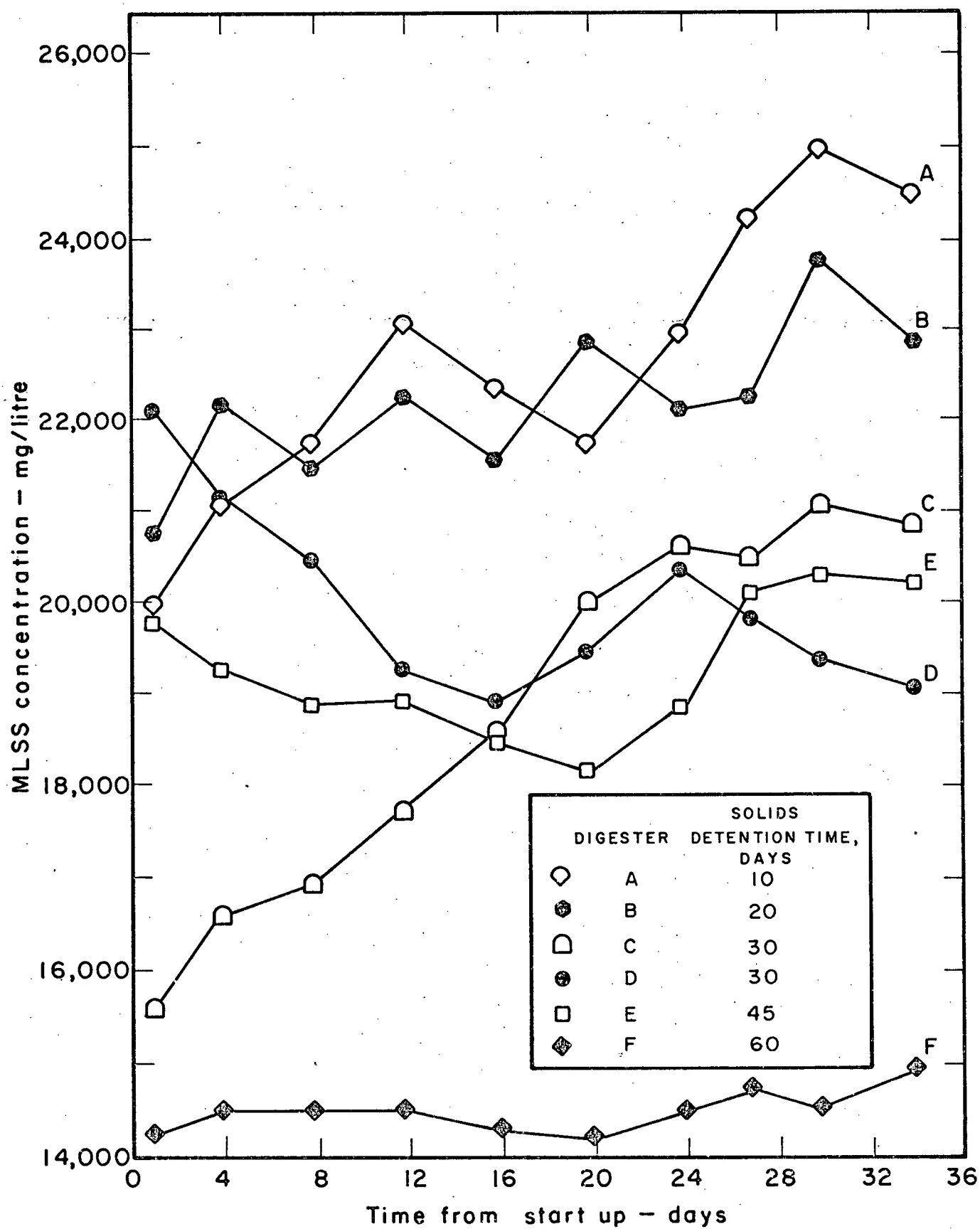


Figure 13 MIXED LIQUOR SUSPENDED SOLIDS CONCENTRATIONS vs TIME FROM START UP

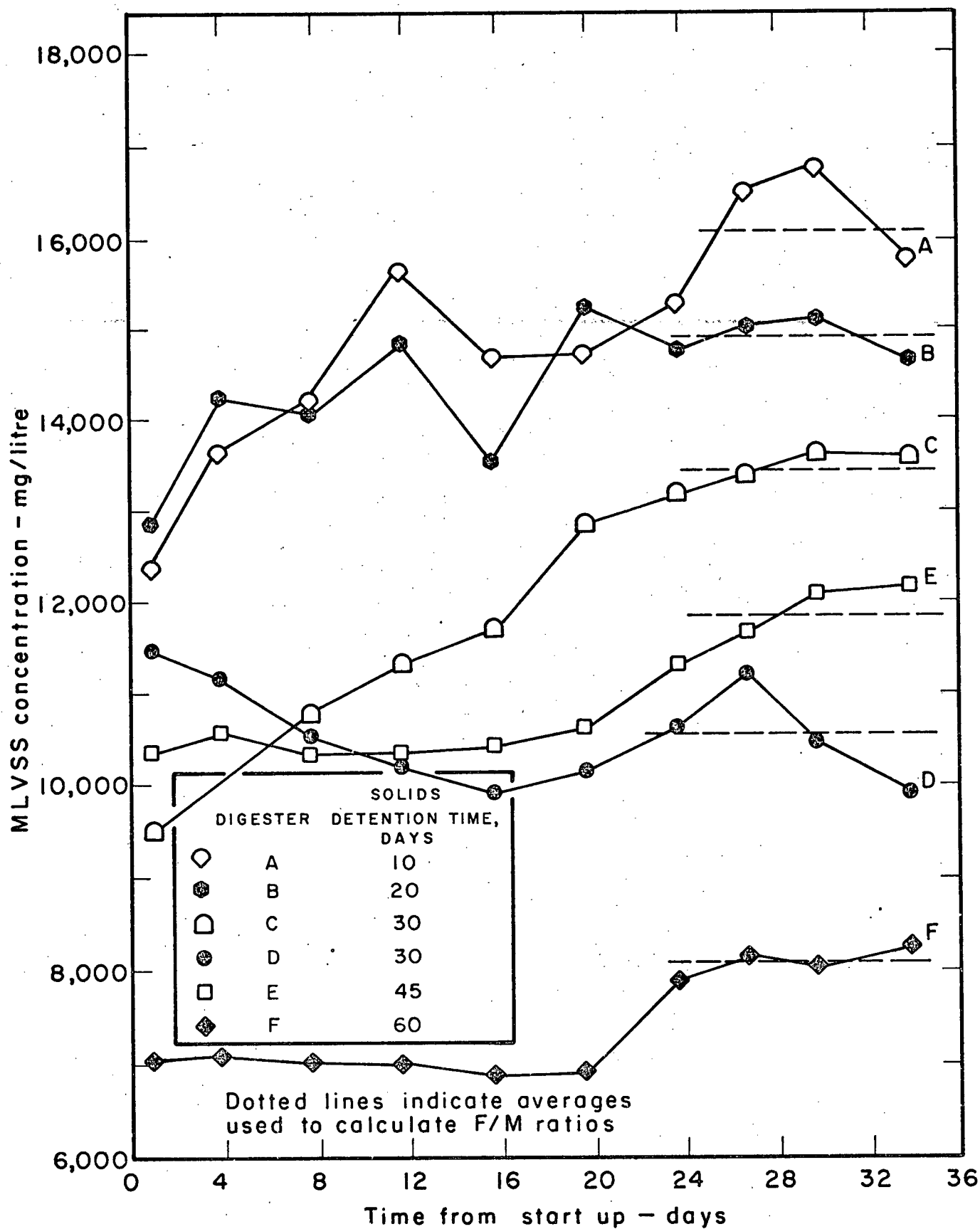


Figure 14 MIXED LIQUOR VOLATILE SUSPENDED SOLIDS CONCENTRATIONS vs TIME FROM START UP

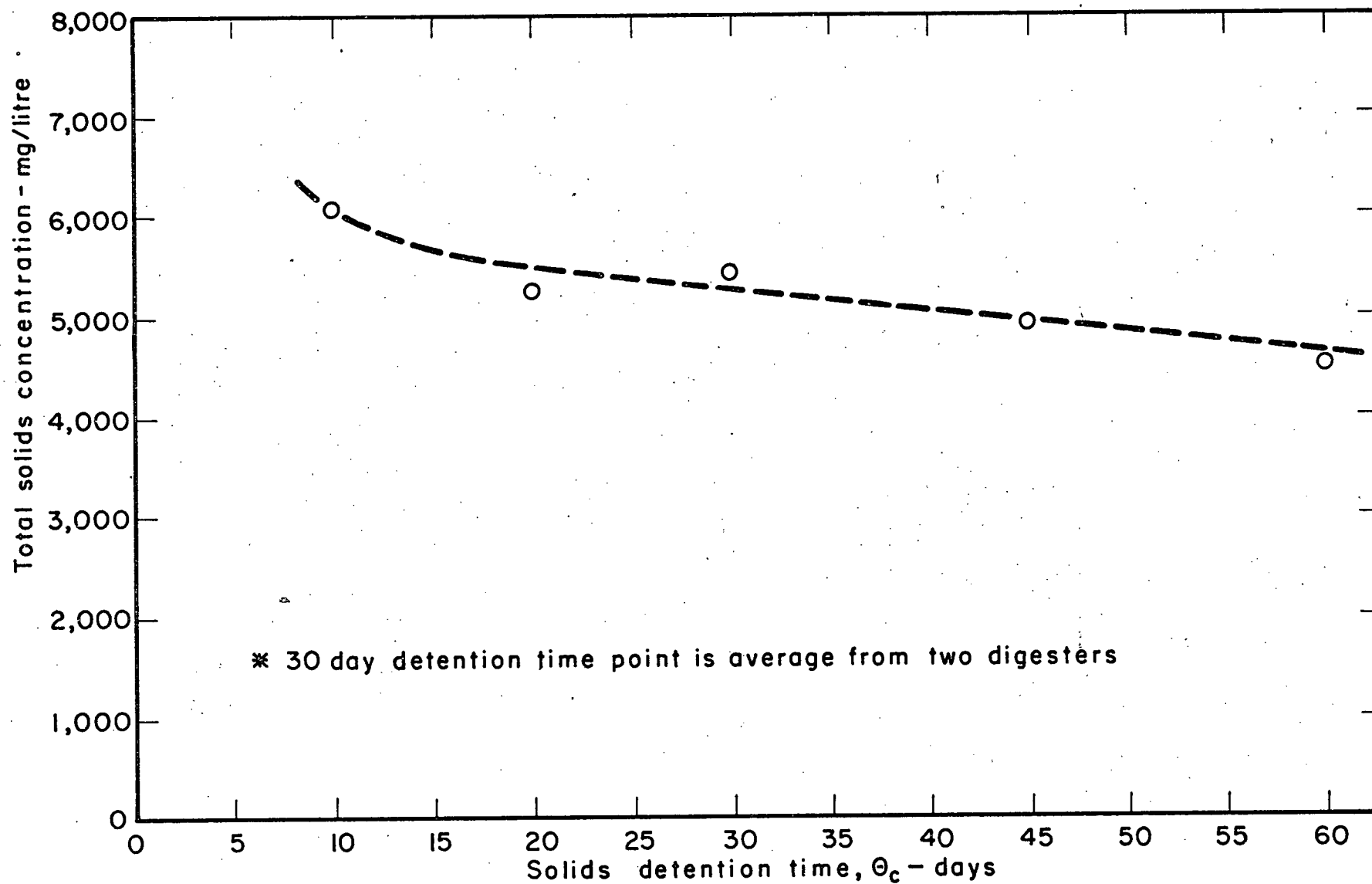


Figure 15 SETTLED EFFLUENT TOTAL SOLIDS CONCENTRATION vs SOLIDS DETENTION TIME

APPENDIX B

BOD₅ TEST RESULTS DURING STUDIES

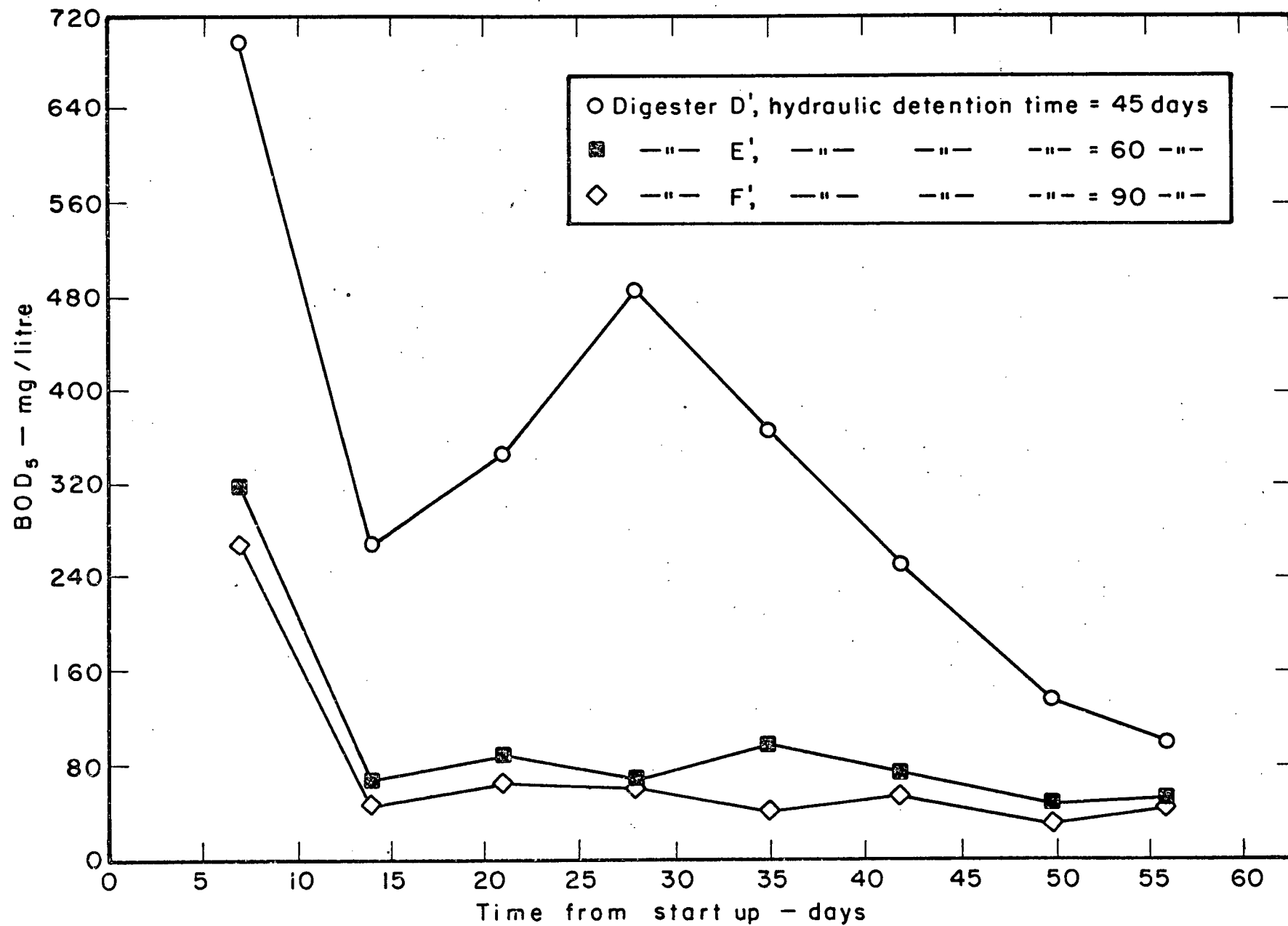


Figure 16 BOD₅ OF SETTLED EFFLUENTS DURING ACCLIMATIZATION STUDY

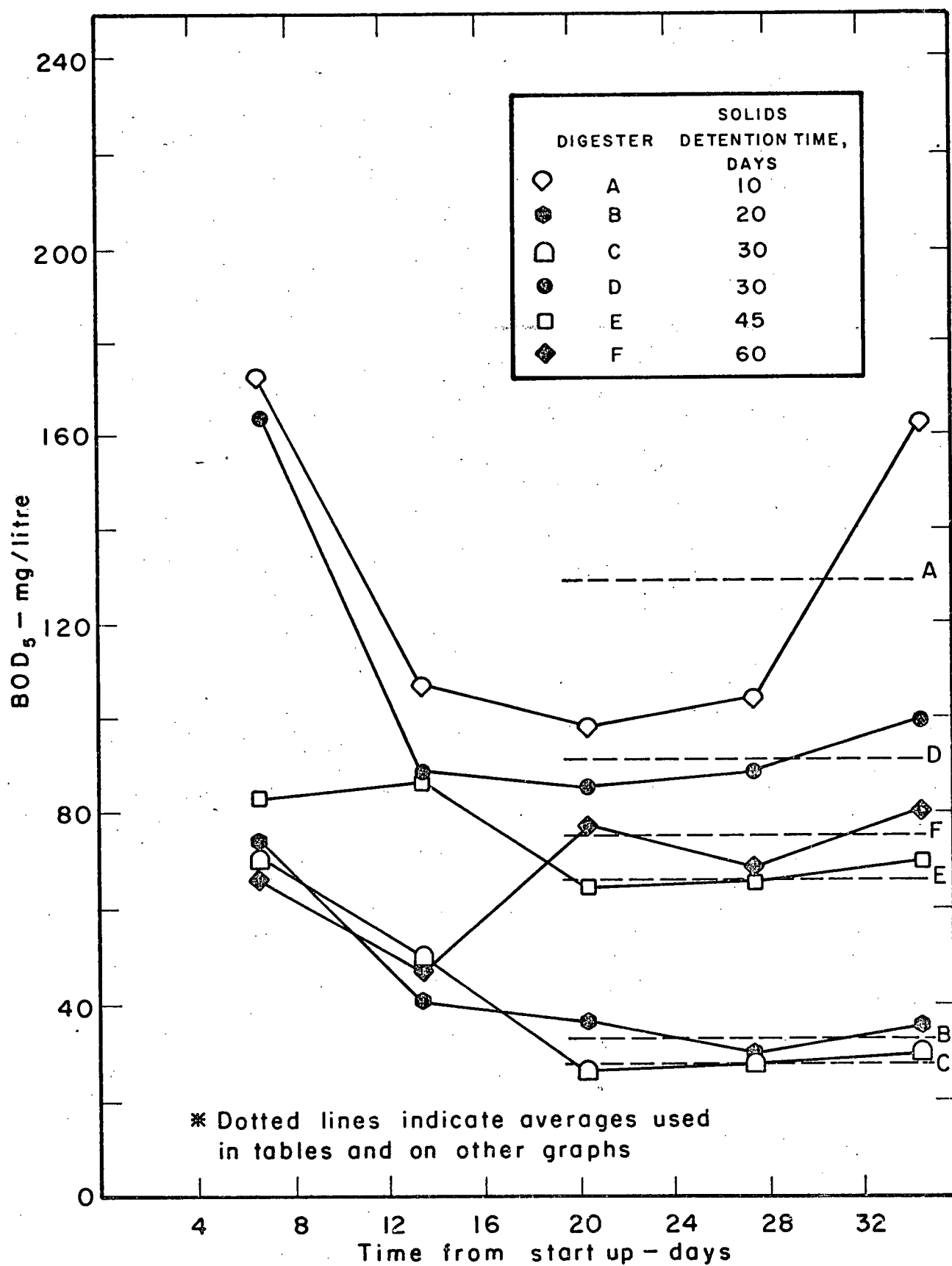


Figure 17 BOD₅ OF SETTLED EFFLUENTS DURING EFFICIENCY STUDIES

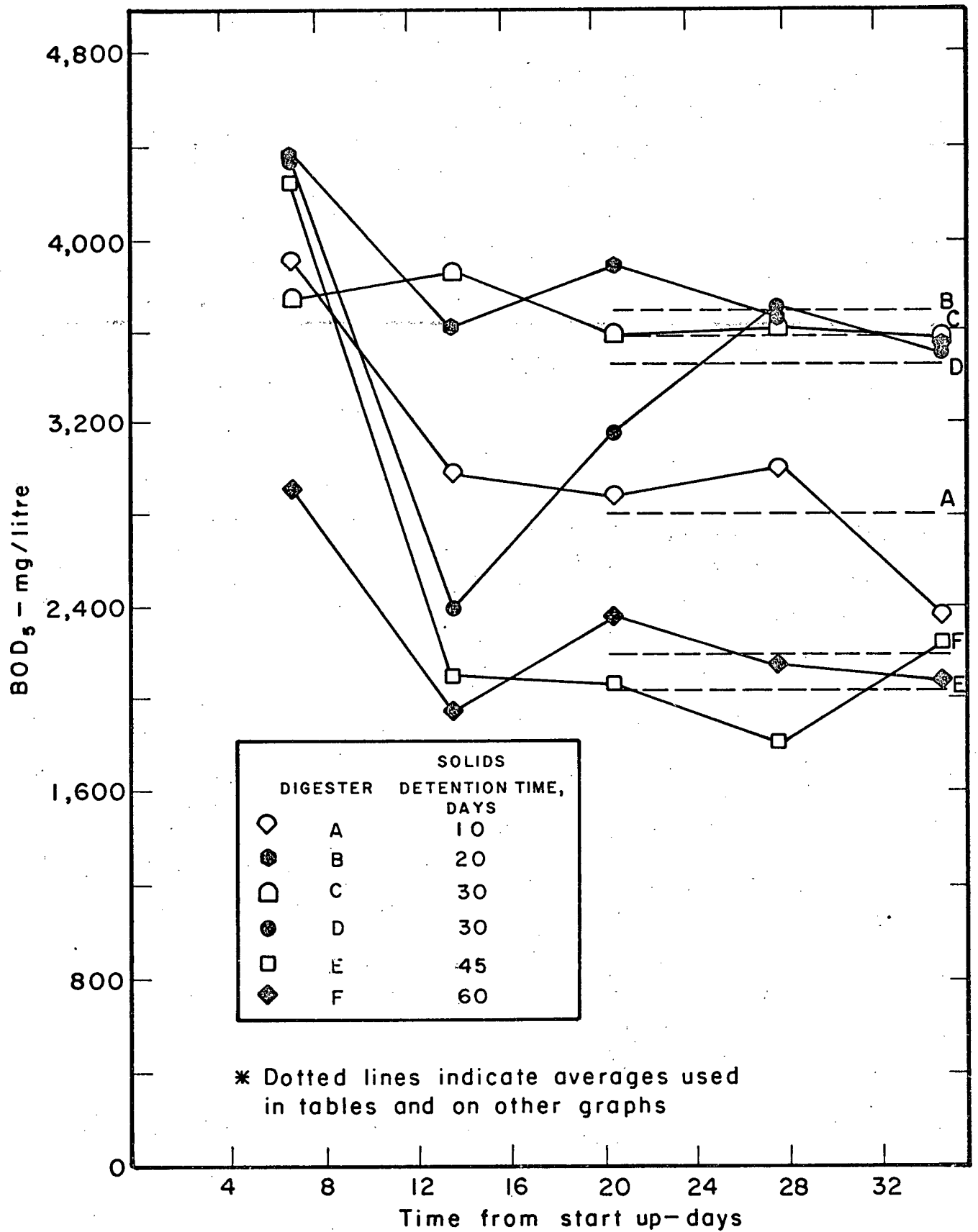


Figure 18 BOD₅ OF MIXED LIQUORS DURING EFFICIENCY STUDIES

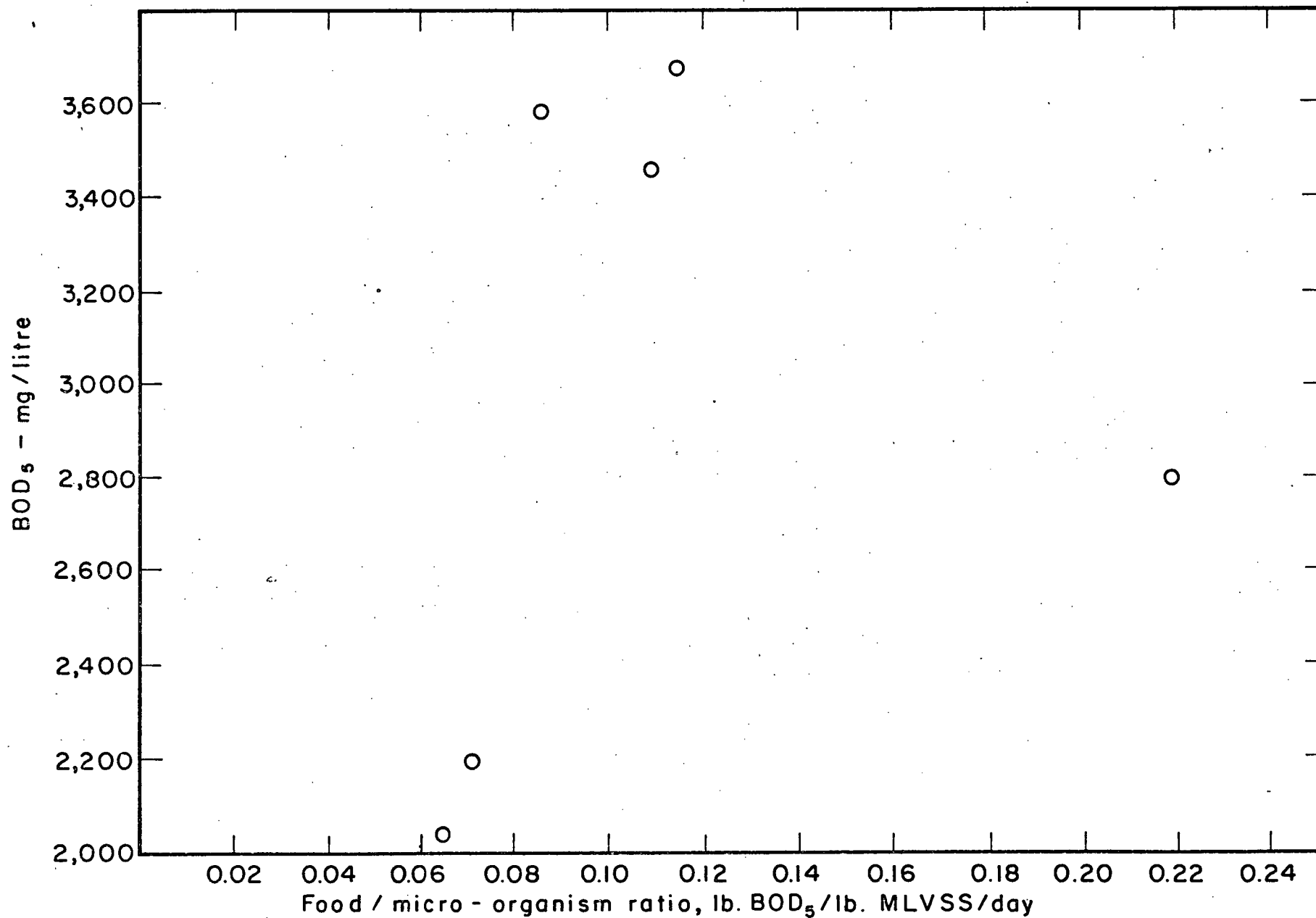


Figure 19 BOD₅ OF MIXED LIQUORS vs FOOD TO MICRO-ORGANISM RATIO

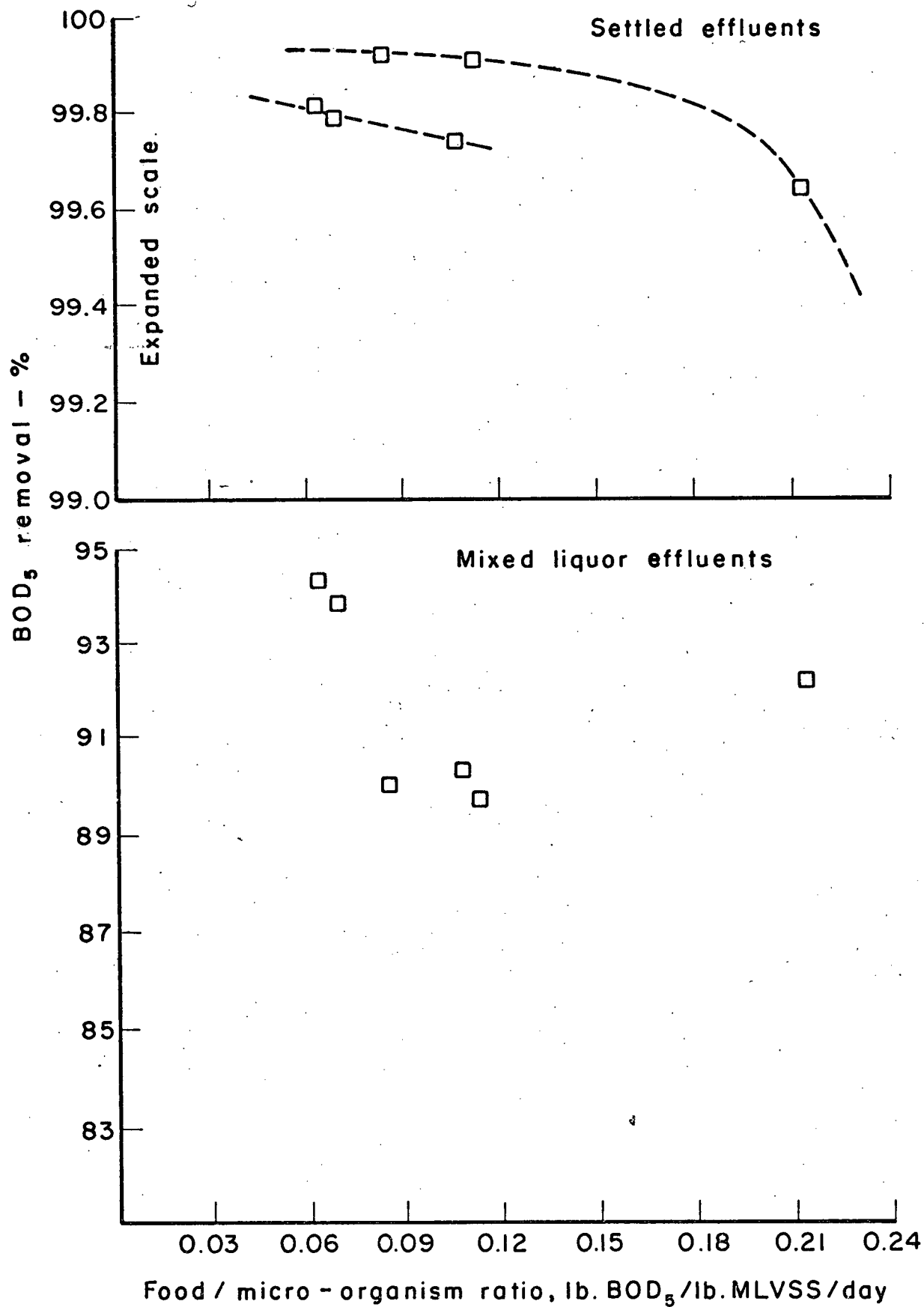


Figure 20 PERCENT BOD₅ REMOVAL vs FOOD TO MICRO-ORGANISM RATIO

APPENDIX C

pH OF EFFLUENTS AND MIXED LIQUORS

DURING STUDIES

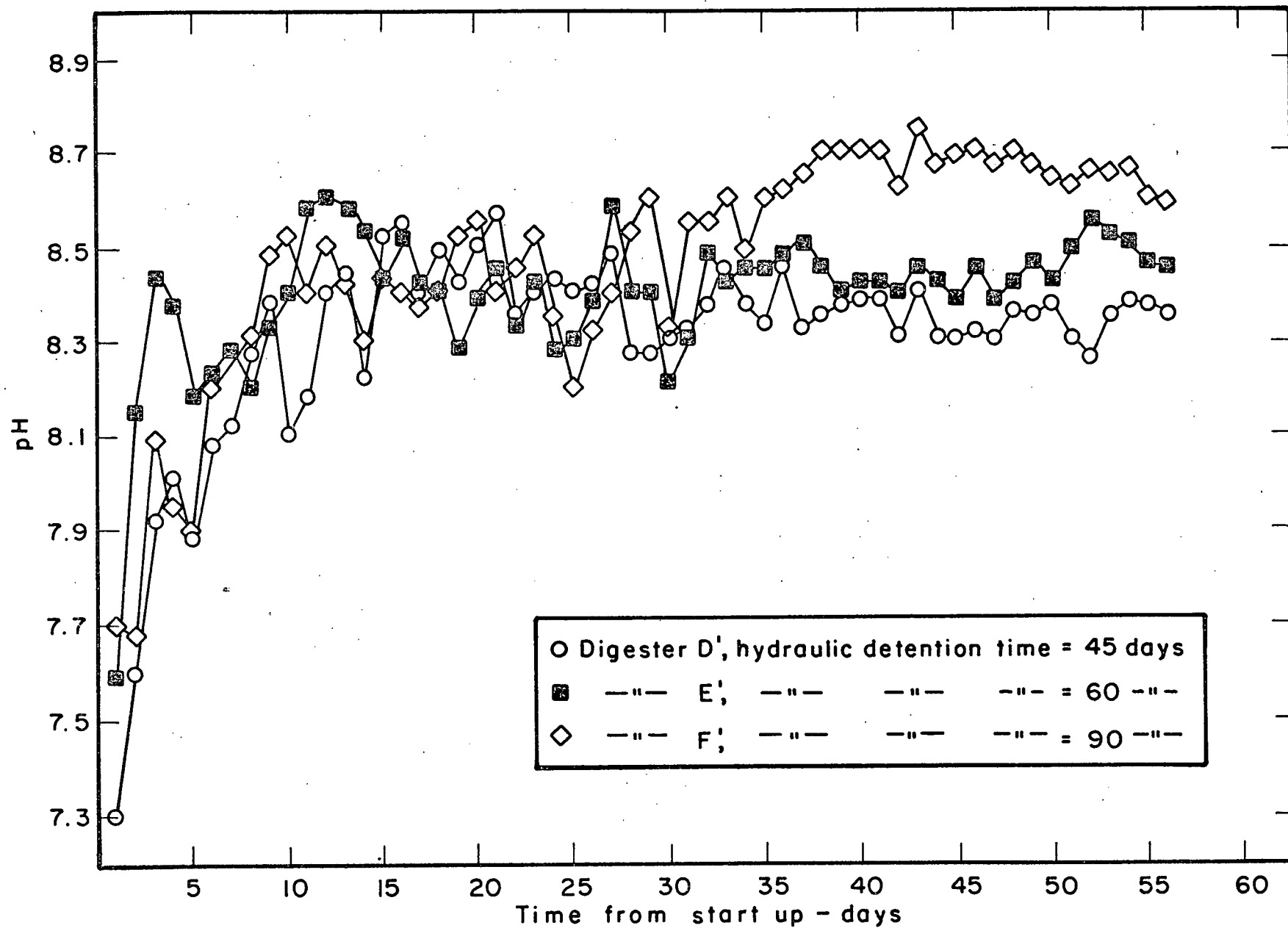


Figure 21 pH OF SETTLED EFFLUENTS DURING ACCLIMATIZATION STUDY

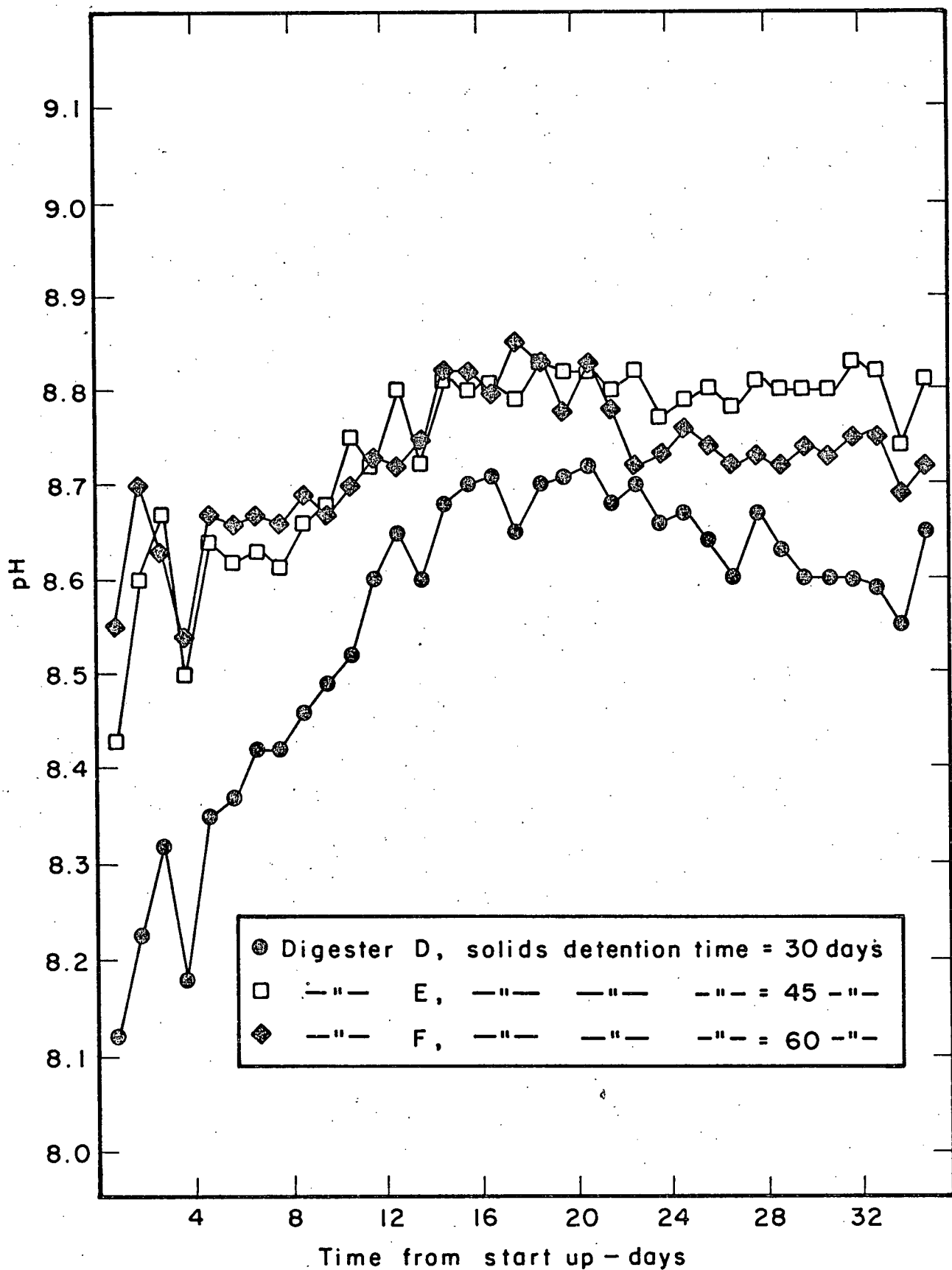


Figure 22 pH OF MIXED LIQUORS DURING "EXTENDED AERATION"
EFFICIENCY STUDY

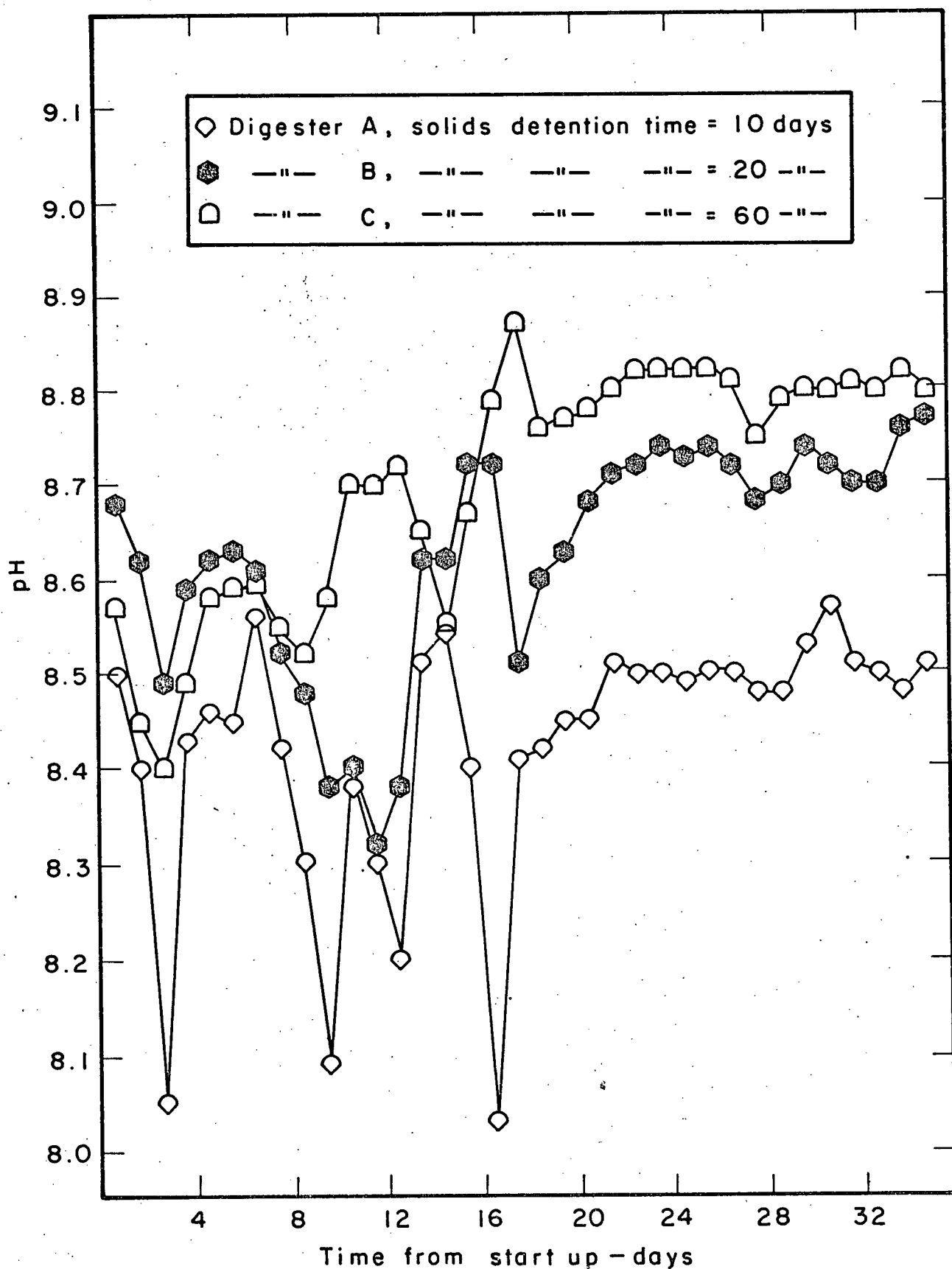


Figure 23 pH OF MIXED LIQUORS DURING "SHORTER DETENTION TIME" EFFICIENCY STUDY

APPENDIX D

OXYGEN UPTAKE RATES DURING STUDIES

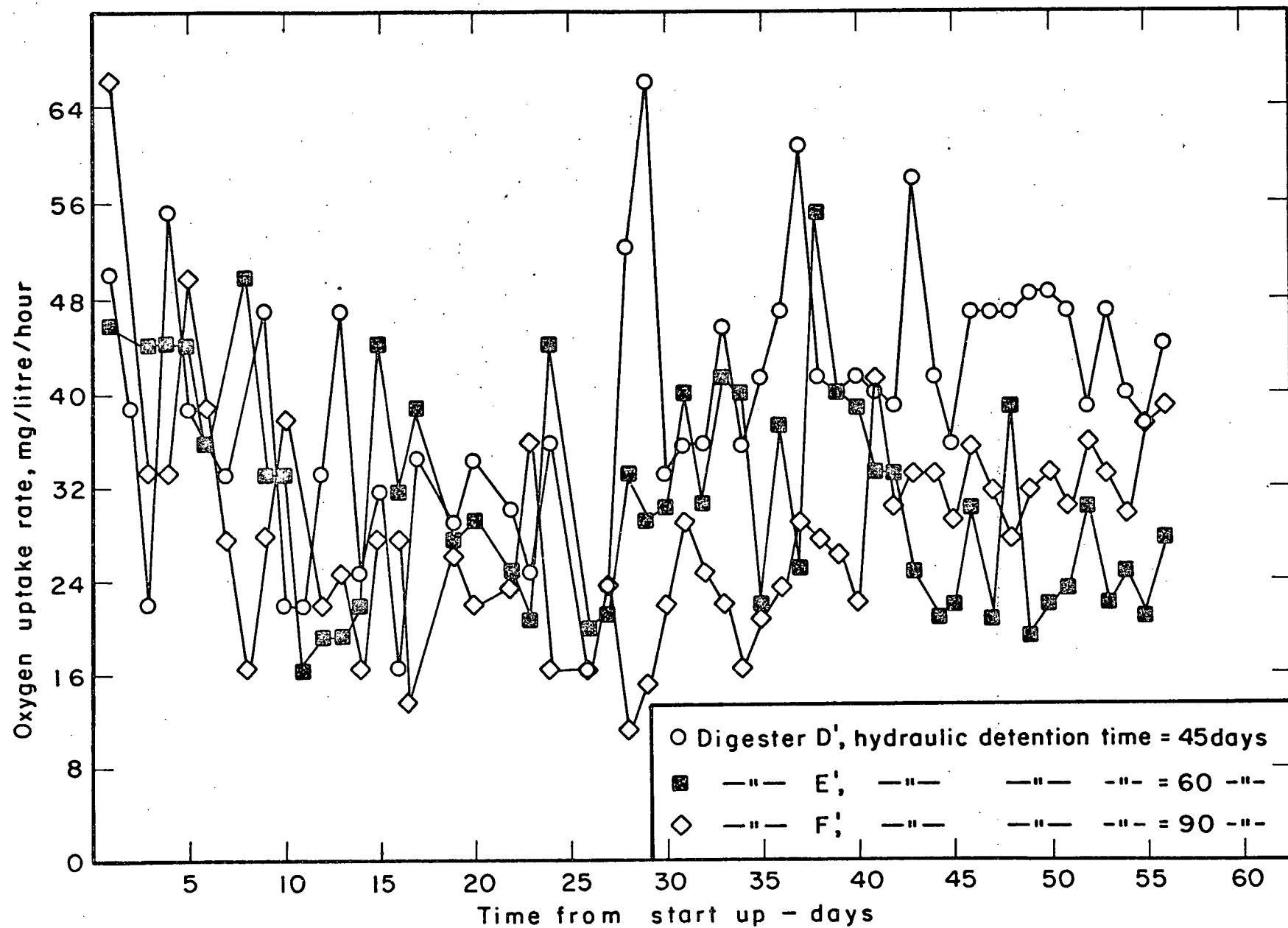


Figure 24 OXYGEN UPTAKE RATES DURING ACCLIMATIZATION STUDY

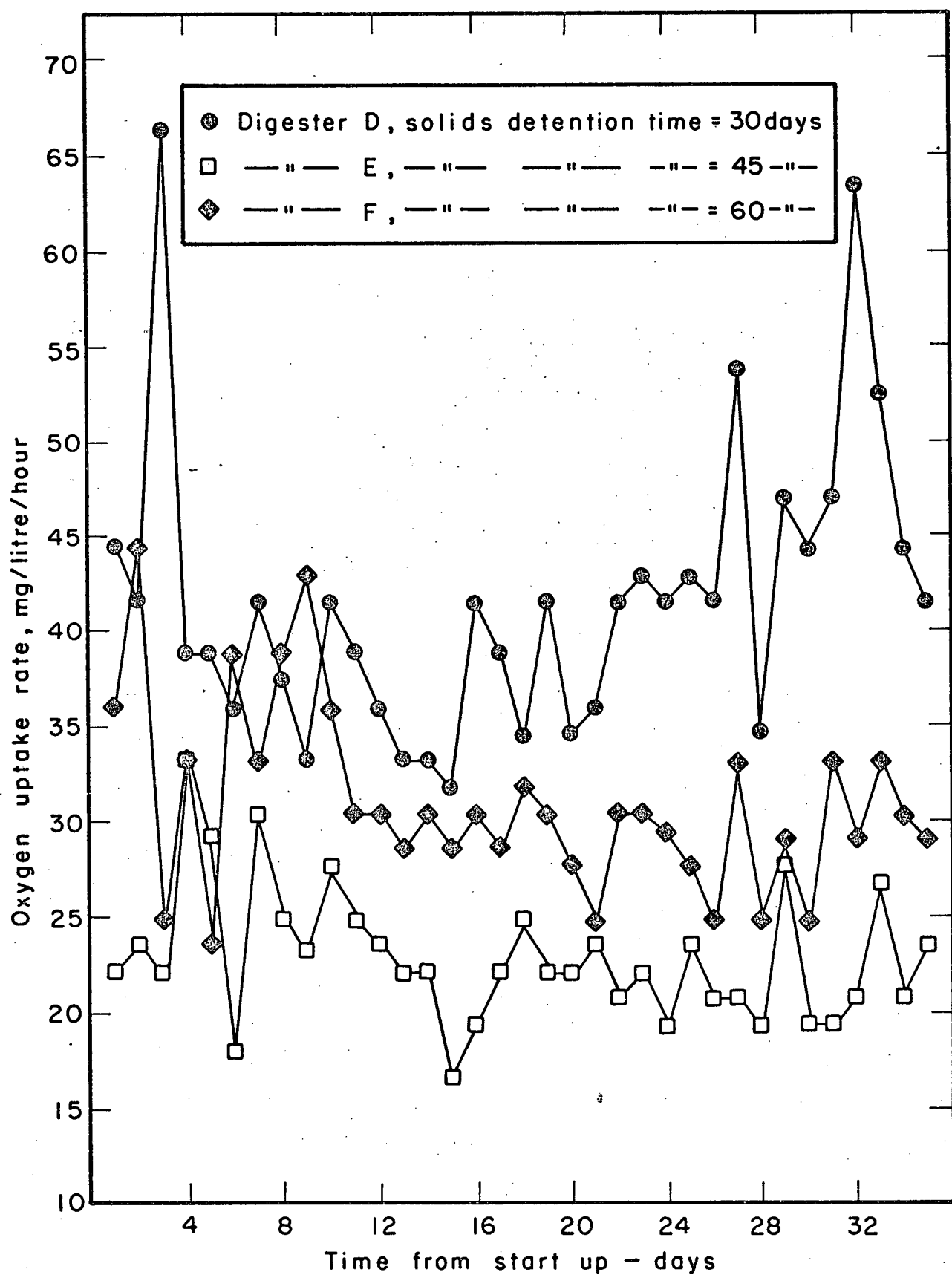


Figure 25 OXYGEN UPTAKE RATES DURING "EXTENDED AERATION" EFFICIENCY STUDY

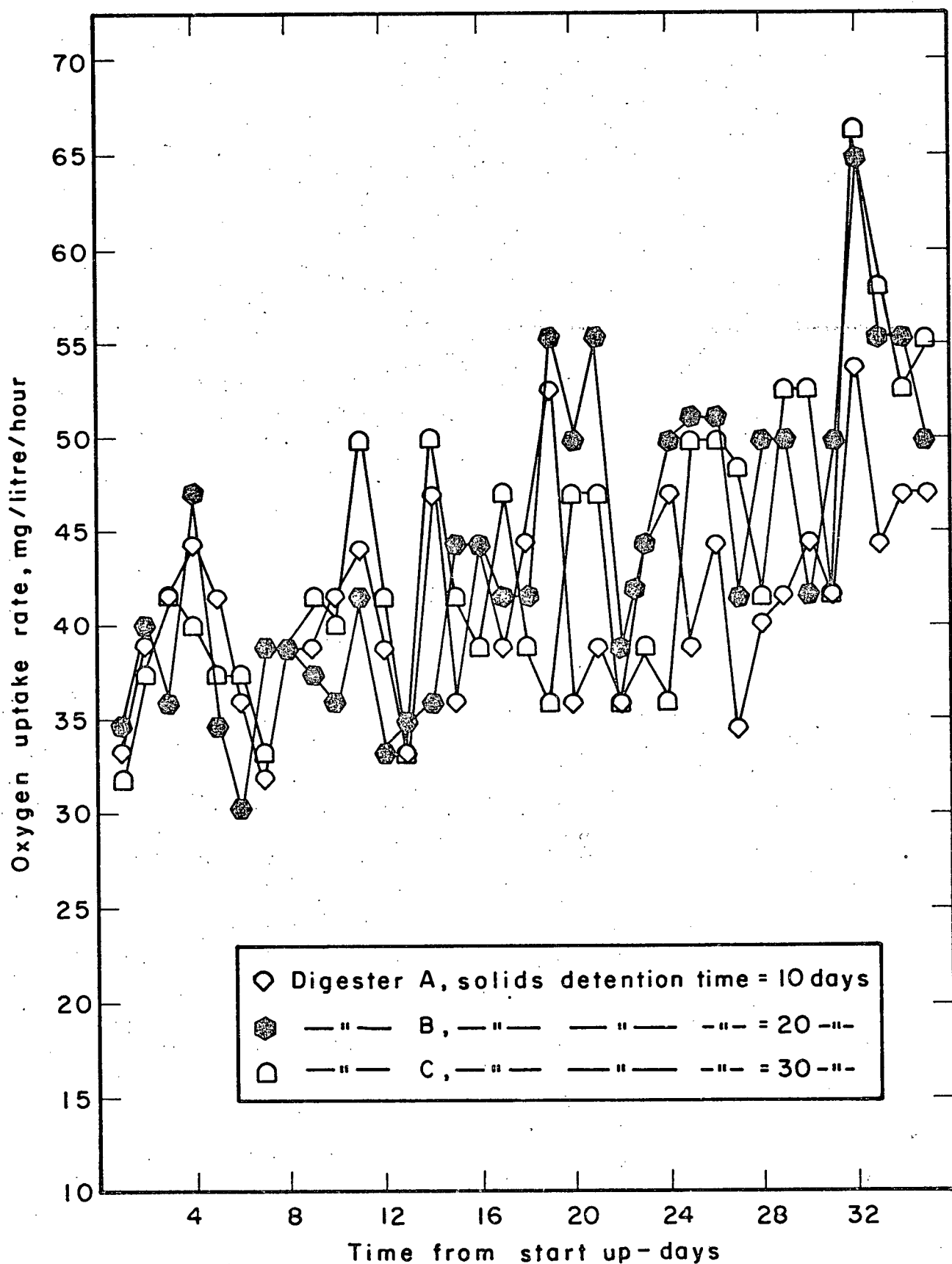


Figure 26 OXYGEN UPTAKE RATES DURING "SHORTER DETENTION TIME" EFFICIENCY STUDY

APPENDIX E

DETERMINATION OF KINETIC PARAMETERS FROM
"EXTENDED AERATION" EFFICIENCY STUDY DATA

Determining K and K_s

$$\text{Rate of food utilization } \frac{\Delta S}{\Delta t} = \frac{S_o - S_1}{\theta_c}$$

$$\text{It can be shown that: } \frac{\Delta S}{\Delta t} = \frac{K \times S_1}{K_s + S_1} \quad [\text{MONOD EQUATION}]$$

$$\text{Rearranging the above equation: } \frac{(\Delta S / \Delta t)}{X} = \frac{K S_1}{K_s + S_1}$$

$$\text{or } \frac{X}{(\Delta S / \Delta t)} = \frac{K_s}{K} \left(\frac{1}{S_1} \right) + \frac{1}{K}$$

Plotting $\frac{X}{(\Delta S / \Delta t)}$ vs $\frac{1}{S_1}$ should yield a straight line with slope $\frac{K_s}{K}$ and intercept $1/K$.

DIGESTER	θ_c days	X mg VSS/l	S_o mg/l	S_1 mg/l	$\Delta S / \Delta t$ mg/l	$1/S_1$ (10^{-3})/(mg/l)	$\frac{X}{(\Delta S / \Delta t)}$ mg VSS/mg/day
D	30	10,589	35,750	3,454	1,076	0.290	9.85
E	45	11,869	35,750	2,036	750	0.491	15.83
F	60	8,121	35,750	2,194	559	0.456	13.71

The above data is plotted in Figure 27. From that graph it was estimated that:

$$K = 0.75 \text{ mg BOD}_5/\text{mg VSS/day}$$

$$\text{and } K_s = 21,375 \text{ mg/l}$$

Determining Y and b:

A biological solids balance yields the equation:

$$\frac{\Delta X}{\Delta t} = Y \frac{\Delta S}{\Delta t} - bX$$

$$\text{Dividing each side by X: } \frac{(\Delta X / \Delta t)}{X} = Y \frac{(\Delta S / \Delta t)}{X} - b$$

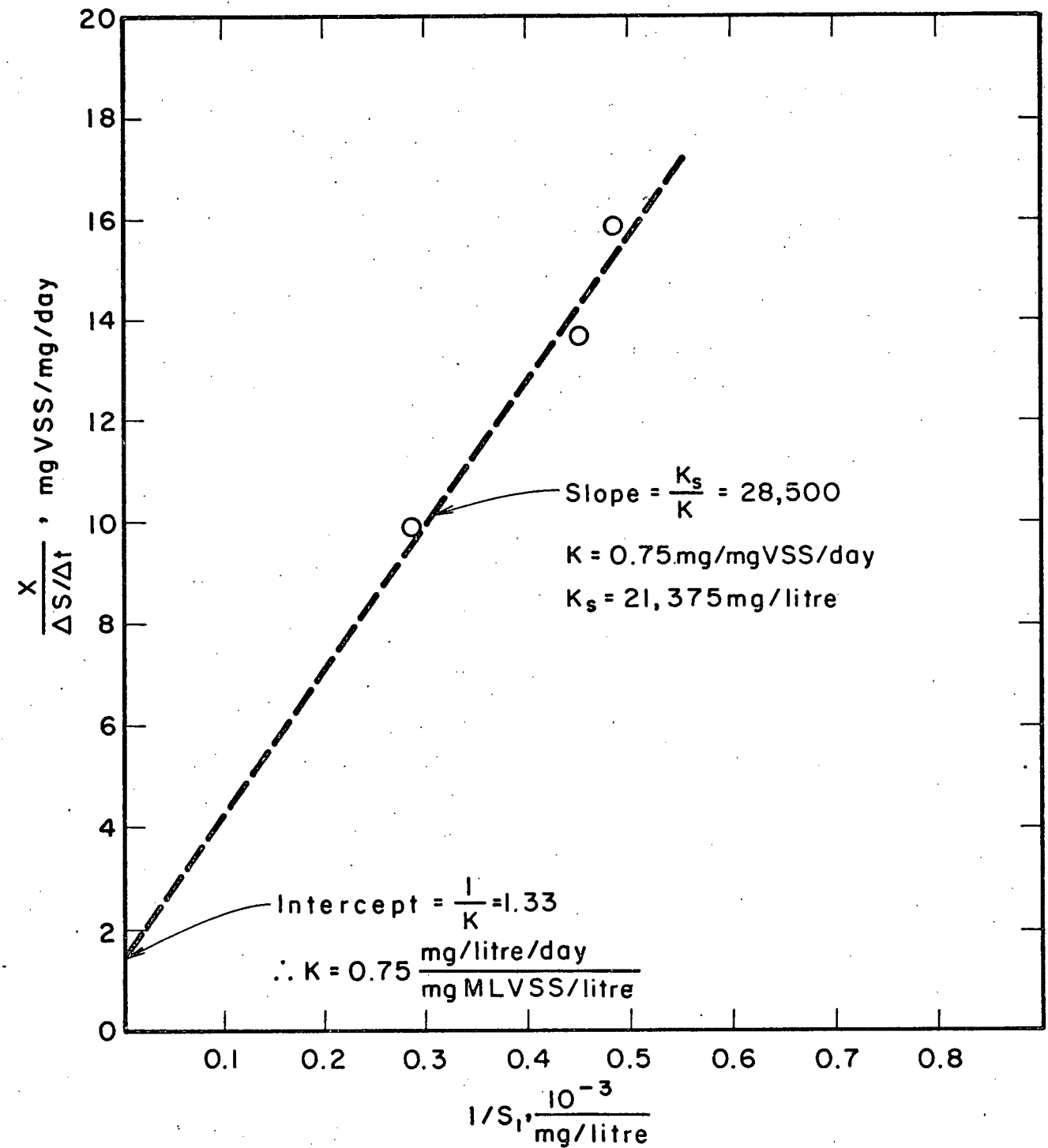


Figure 27 DETERMINATION OF K AND K_s USING BOD₅ DATA FROM "EXTENDED AERATION" EFFICIENCY STUDY

A plot of $\frac{(\Delta X/\Delta t)}{X}$ vs. $\frac{(\Delta S/\Delta t)}{X}$ should therefore yield a straight line with slope Y and intercept, $-b$.

$$\Delta S/\Delta t = \frac{S_o - S_1}{\theta_c}$$

$$\therefore \Delta X/\Delta t = \frac{X_1 - X_o}{\theta_c}$$

Assuming volatile suspended solids concentration in the leachate feed are negligible, $X_o = 0$, then:

$$\Delta X/\Delta t = \frac{X_1}{\theta_c}$$

$$\text{and } \frac{\Delta X/\Delta t}{X} = \frac{1}{\theta_c}$$

DIGESTER	θ_c days	$\frac{\Delta X/\Delta t}{X} = \frac{1}{\theta_c}$ days ⁻¹	X mg VSS/l	S_o mg/l	S_1 mg/l	$\Delta S/\Delta t$ mg/l/day	$\frac{\Delta S/\Delta t}{X}$ mg/mg VSS/day
D	30	0.0333	10,589	35,750	3,454	1,076	0.107
E	45	0.0222	11,869	35,750	2,036	750	0.063
F	60	0.0166	8,121	35,750	2,194	59	0.069

The above data is plotted in Figure 28. From that graph it is evident that the estimated values of Y and b depend a great deal on personal judgement. The "best" values estimated by the author are:

$$Y = 0.332 \text{ mg VSS/mg BOD}_5$$

$$\text{and } b = 0.0025 \text{ day}^{-1}$$

Estimation of Minimum Solids Detention Time:

$$\frac{1}{\theta_c \text{ min.}} = \frac{YK S_o}{K + S_o} - b = \frac{(0.332)(0.75)(35,750)}{21,375 + 35,750} - 0.0025 = 0.155$$

Therefore, minimum solids detention time, $\theta_c \text{ min.} = 6.46 \text{ days}$.

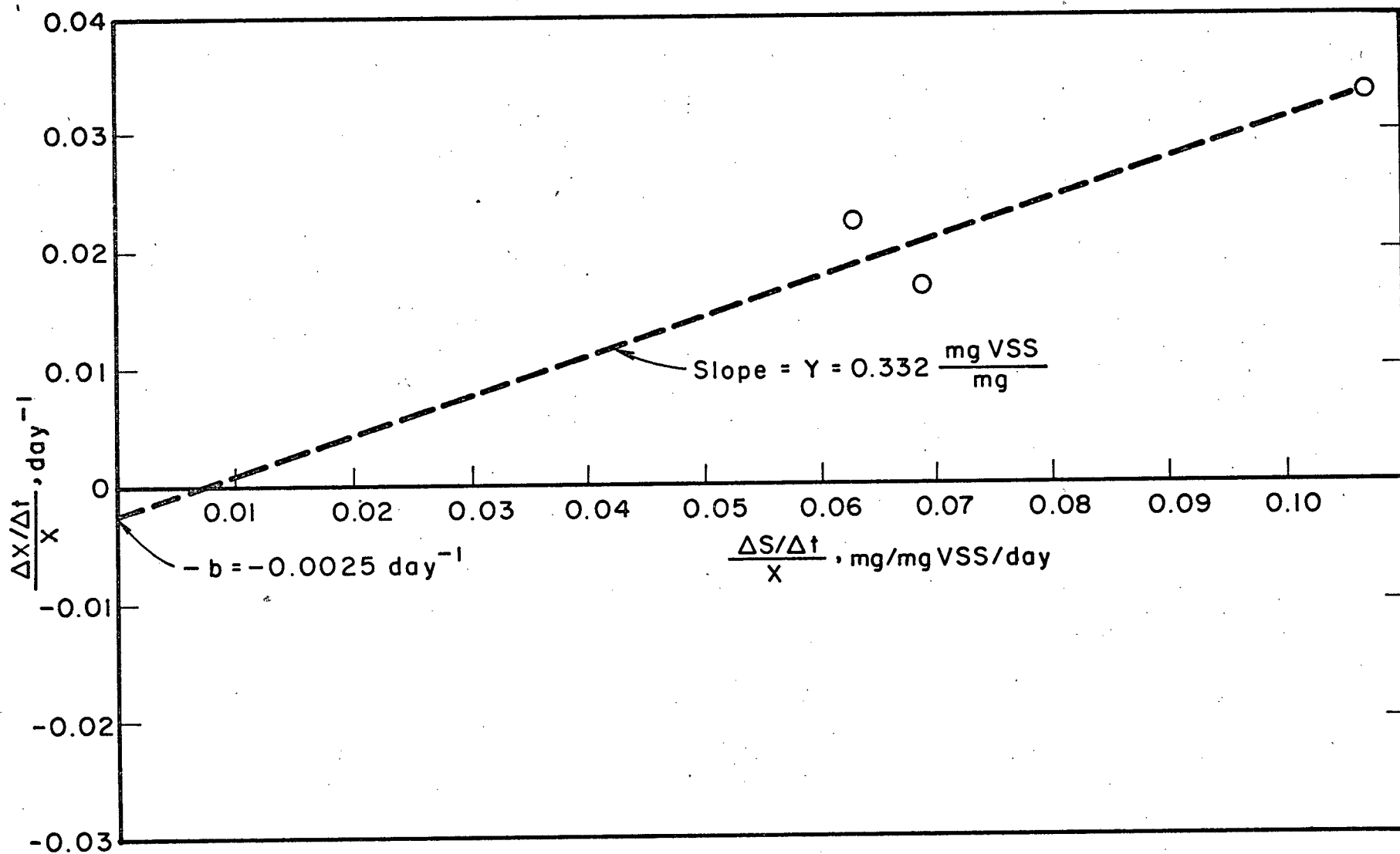


Figure 28 DETERMINATION OF Y AND b USING BOD_5 DATA FROM "EXTENDED AERATION" EFFICIENCY STUDY