PARAMETER RESPONSES TO INFLUENT SUSPENDED SOLIDS IN THE ACTIVATED SLUDGE TREATMENT PROCESS

Technical Report

to the

Federal Water Pollution Control Administration

by

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ABSTRACT

The purpose of this research was to observe the effects of influent volatile suspended solids in domestic sewage on volatile solids accumulation and oxygen requirements in the activated sludge treatment process. Four laboratory-scale biological units, each with a different influent suspended solids loading were used to make these observations. Two continuous-flow investigations were performed with the only variable between the two being MLVSS concentration. A batch study was also done in order that various coefficients could be determined.

Volatile solids accumulation was found to vary directly with influent suspended solids loading. It was also found that solids accumulation varied with the MLVSS concentration. However, when the number of viable organisms present was taken into account, this difference was negated. It appeared that influent suspended solids had minimal affect on the oxygen utilization process.

Mathematical models were developed for both volatile solids buildup and oxygen requirements. The coefficients for these models have been developed and are presented.

CONCLUSIONS

The conclusions of this study can be summarized as follows:

(1) For a domestic waste, volatile solids buildup in the activated sludge treatment process varies directly with the amount of influent volatile suspended solids fed to the system.

(2) For this waste, the amount of influent volatile suspended solids degraded at any time is a direct function of the sludge age of the system.

(3) The endogenous respiration coefficient varies with the amount of influent volatile suspended solids.

(4) Increased suspended solids loadings appear to have a minimal affect on process efficiency.

(5) Mixed liquor volatile suspended solids concentration appears to be a poor estimate of the amount of viable organisms present in a system. Care should be used when this parameter is utilized as an estimate of the viable organisms present such that erroneous results do not occur.

(6) It appears that increased suspended solids loadings have minimal affect on the specific oxygen uptake rates.

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SYMBOLS AND ABBREVIATIONS

BOD	Biochemical Oxygen Demand
TOC	Total Organic Carbon
L_{vss}	Organic Loading gm TOC/day/gmMLVSS
s'_o	Total Influent TOC
s'_e	Total Effluent TOC
$s'_{o,r}$	Total TOC Removed
s^*_o	Soluble Influent TOC
s^*_e	Soluble Effluent TOC
$s^*_{o,r}$	Soluble TOC Removed
MLSS	Mixed Liquor Suspended Solids
MLVSS	Mixed Liquor Volatile Suspended Solids
X_v	MLVSS Concentration
$X_{v,n}$	Non-Biodegradable Portion of the MLVSS
$X_{v,b}$	Biodegradable Portion of the MLVSS
ΔX_v	Volatile Solids Accumulation
X_o	Influent Suspended Solids
$X_{o,v}$	Influent Volatile Suspended Solids
t	time
G	sludge age, days
r	Oxygen Uptake Rate mg/l/hr
k_r	Specific Oxygen Uptake Rate mg/l/hr/gmMLVSS
a	mg VSS Produced per mg Organic Substrate Removed

SYMBOLS AND ABBREVIATIONS
(continued)

b   Endogenous Respiration Coefficient, $1/time$

f   Fraction of Influent Volatile Suspended Solids Remaining After Time, G

K_V Degradation Rate of the Influent Volatile Suspended Solids

K' Degradation Rate of the MLVSS

a' mgO_2 Utilized per mg Organic Substrate Removed

b' mgO_2 per mg MLVSS per Unit of Time

1. INTRODUCTION

The successful biological treatment of a domestic
wastewater necessitates a well-designed system which takes
into account all of the parameters affecting such a biological
mass. In order to complete a successful design, the engineer
must have a knowledge of the variables involved and a means
by which to accurately estimate them.

Among the most important factors are two which are
inherent to a biological system; namely, increase in cellular
mass during metabolism of an organic substrate, and oxygen
utilization by the microorganisms during this metabolism.
It is essential that the designer have a close estimate of
these parameters so that efficient sludge handling and
oxygen transfer systems can be designed.

Most investigators to date have limited themselves
to studies which utilize an artificial organic substrate.
While these have provided a good insight into increase in
cellular material and oxygen usage by the organisms, it has
been difficult to scale-up these findings to actual plant
conditions due to the nature of the substrate fed. In
particular, the effect of influent suspended solids on the
system has been neglected. Since most domestic wastewaters
contain some amount of influent suspended solids, it is of
great interest to investigate the affect that these might have
on solids accumulation and oxygen usage.

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1-1   Objectives

The primary objectives of this study were:
a) to observe the volatile solids accumulation when influent
volatile suspended solids are present, b) to modify the
existing solids accumulation model to account for the presence
of these solids and to develop values for the coefficients
of this model, and c) to observe the oxygen usage rate under
the same conditions and to re-evaluate the existing model
to account for the influent solids.

1-2   Scope

Four laboratory activated sludge units were operated
in order that a range of influent volatile suspended solids
could be fed. Volatile solids accumulation was monitored
daily and the mathematical model formulated from these
observations. Similarly, oxygen usage was monitored on each
unit and the oxygen model modified to include the effects of
the influent solids. All experiments were performed at the
Govalle Sewage Treatment Plant in Austin, Texas.

1-3   Study Limitations

The primary limitation of this study is that the
model was developed to include only volatile solids
accumulation. It is a well known fact that many inorganic
materials are present in a domestic sewage and that these
would also make a contribution to the total solids accumulation.

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However, it is extremely difficult to predict the amount and character of these inorganic solids due to the many variables involved. Thus, it was decided not to include their effect in this investigation.

2. LITERATURE REVIEW

2-1   General

The activated sludge process grew out of the idea of
man that he could relieve the obnoxious conditions of wastewater
by blowing air through it. Basically, the process consists of
a group of heterogeneous microorganisms which utilize the
organic waste being treated as a substrate under aerobic
conditions. Air may be supplied to the system in a number of
ways, but this is usually accomplished by injecting air bubbles
into the sludge-liquid mass under turbulent conditions. This
aeration step is normally followed by a solids-liquid separation
in which the organisms flocculate, settle, and are returned to
the aeration chamber with a clarified effluent remaining.

Various factors, if not controlled, can adversely
affect the biological system by upsetting the existing balance.
These factors determine how well the process operates, and
among the most important are pH, temperature, nutrient
availability, and variation in organic loading.

Hydrogen ion concentration, pH, can have a very
pronounced affect on the biological system if it is not limited
to a range of values. This range for most organisms is defined
as 6.0 to 9.0. The inhibitory effects which occur at unfavorable
pH conditions should not be attributed to high hydrogen or
hydroxyl ion concentrations, but rather are a result of the

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ability of the undissociated molecules of acidic and basic substances to enter the cell and cause internal pH changes. (Stanier, et al., 1963) The optimum pH value for most biological systems is 7.0 in which a condition of neutrality exists.

Temperature is another variable which can markedly affect a system. Microorganisms can stand varying degrees of temperature depending on the type of organism under consideration. In general, most organisms increase their reaction rate with an increase in temperature, the upper limit being determined by the ability of the cell constituents, mainly protein and nucleic acids, to withstand thermal attack. In the range of $50^{\circ}C$ to $90^{\circ}C$ these cell constituents are rapidly destroyed with a resulting cell death. (Stanier, et al., 1963) Optimum temperature conditions for most organisms which are involved in the activated sludge process is $30^{\circ}C$.

In order that the microorganisms in the process might flourish and grow, nutrients in sufficient quantity must be available. The most important of these are carbon, nitrogen and phosphorus. Most domestic wastes include substantial amounts of the inorganic and trace inorganic compounds which are necessary for growth. However, there are various wastes, usually industrial in nature, which are sometimes deficient in these vital nutrients. Based on studies performed in this area, minimal quantities of phosphorus and nitrogen required were 0.6 lb P/100 lb BOD removed and 4.0 lb N/100 lb BOD removed,

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which is equivalent to a BOD:N:P ratio of about 150:5:1. (Eckenfelder, 1966)

Of considerable importance in the maintenance of an efficient activated sludge system is the variation in organic loading. Wide variations in daily flow are observed in most domestic wastewater treatment facilities resulting in a changing food microorganism ratio and thus changing removal rates of the organisms. Ford, (1966) in his investigations found that the optimum organic loading range was 0.2 to 0.7 lb BOD/day/lb solids. Values out of this range produced a poor settling floc which is essential in the successful operation of this system. Adams' (1969) work on transient loadings with both industrial and domestic wastes indicated that acclimated activated sludge systems could tolerate variations in organic loading up to a limit which is defined by the individual system without showing any significant increase of effluent soluble organic matter.

2-2   Composition of Influent Suspended Solids

Classification of the pollutional aspects of most wastewaters can be placed in two categories; their state (suspended, colloidal, or dissolved) or their nature (inorganic, organic, gases or living organisms).(Eckenfelder and O'Connor, 1961) The most significant of these in domestic wastewaters are organic content and suspended solids. Most texts characterize a typical domestic wastewater as having between 100-300 mg/l BOD and 100-300 ppm suspended solids. A great portion of

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this BOD is normally contributed by the suspended solids which are present. Hunter and Heukelekian (1965) determined that 60 percent of the volatile solids and 76 percent of the total COD of raw sewage was contributed by the suspended and colloidal organic matter. When settleable solids are excluded, 43 percent of total volatile solids and 62 percent of the total COD are contributed by the remaining fraction. They also determined that the particulate fraction solids are approximately 80 percent organic in nature, while the soluble-fraction solids were 30 percent organic. In agreement with these figures are Takahashi, et al.,(1968) who found that sewage contained approximately 80 percent volatile solids. Kurbiel (1968) stated that approximately 80 percent of the total BOD was contributed by suspended and colloidal solids present.

Heukelekian and Hunter (1960) studied the composition of total solids in sewage. They found that 62 percent of the total solids were soluble in nature with the remainder being suspended. Of the portion which was soluble, 39 percent was volatile, indicating that a very high percentage of the soluble solids were inorganic in nature. However, the suspended matter still contributed approximately 75 percent of the COD measured. These findings are in keeping with the previously mentioned sources.

Based on these figures, it can be concluded that the removal and metabolism of suspended and colloidal matter can account for a great portion of the purification of sewage.

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Of the organics which exist in sewage, most are classified into one of three groups; carbohydrates, proteins and lipids. These are the primary energy sources for the bacteria during synthesis and respiration. Carbohydrates are compounds of high molecular weight which are composed of carbon, hydrogen, and oxygen in a ratio of 1:2:2, and is one of the most readily available metabolic materials.(Bloodgood, 1953) The principal carbohydrate group is the polysaccarides which are more commonly known as the simple sugars and their derivatives. Among these are glucose, dextrose, hexose and cellulose. The important role which they play in the cell function is twofold. First, during metabolism some serve as reserve food materials and are stored in the cell to be used when other available sources are exhausted. Others, such as cellulose, are important in the formation of cellular constituents. Not all carbohydrates exhibit similar degradation rates; for example, cellulose is much more difficult to degrade than a simple sugar such as dextrose, the rate being dependent on the ease of destruction of the bonds which link the molecules together.(Lehninger, 1965)

Proteins are the basic materials which make up a majority of the cellular protoplasm.(McKinney, 1962) These molecules are constructed of amino acids of which there are twenty-five presently known. The importance of proteins in the cell lies in the fact that almost half of the organic matter of the cell is protenaceous in nature.(Stanier, et al.,

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1963) This enables these molecules to play an important role
in most of the physical and structural functions of the cell.
Proteins are also the enzymes which are vital factors in
catalytic cellular reactions.

Closely related to proteins are the lipids. This is
a general term applied to organic compounds which are insoluble
in water. These are usually molecules of moderate size, the
best example of which are the fats. Lipids complex with proteins
forming lypoproteins which are the main constituents of cell
membranes and other cellular components such as the mitochondria
and chloroplasts. In part, the lypoproteins present in cell
membranes are responsible for the selectivity of this cellular
component.(Stanier, et al., 1963)

2-3   Metabolism of Suspended Matter

Since suspended matter represents such a large
portion of the organic material in a domestic waste, a knowledge
of the degradation rates of these particles is important.
Basically, metabolic rates can be described by one of two
theories. Either all materials present in a waste are oxidized
at the same rate, or each sequentially oxidizes at its own rate
with the overall impression being that it is a monomolecular
reaction. The amount of particle dispersion, size of particle
and origin of the sewage all play a major role in the rate at
which these particles are metabolized, but probably the most
important factor in the degradation of both soluble and suspended

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matter is maintenance of an active population in contact with the available substrate and oxygen source.

It has been shown by many investigators that both bacteria and protozoa can metabolize suspended solids.(McKinney, 1968) Protozoa cannot act as quickly as the bacteria with the net result being that they contribute an insignificant amount to the stabilization of suspended organics. The bacterial cells provide the main source of food for the protozoa such that the protozoa play a secondary role in the clarification of sewage.

Takahashi et al., (1968) presented data on the effect of particle size on metabolism. They established that larger size particulates were metabolized at a much slower rate. Protenaceous suspended matter 60μ to 2mm in size were hardly metabolized in a period of 20 hours while particle sizes of 1μ to 4μ were 58 percent metabolized over the same period. In the same experiment, glutamic acid was 80 percent degraded in a period of 2 hours. This is a graphic description of the difference in degradation rates of suspended and soluble organics.

Kurbiel (1968) related particle size degradation rates to oxygen utilization. He theorized that the oxygen utilization rate increased as the particle size decreased. This is based on the fact that smaller particles are easier to degrade; therefore, the microorganisms act on them at a quicker rate. He presented BOD rate constants (k_1) ranging from 0.18 for a raw sewage up to 0.44 for a filtered sample. Also shown was the variability of these rates for samples taken at various locations.

Balmat (1957) presented similar figures based on BOD reaction rates. His values ranged from a value of 0.08 for the larger settleable particles to 0.39 for the soluble portion. He theorized that the rate at which the larger organic particles degraded was limited by the slow rate of hydrolysis, while the soluble organic matter did not have this physical dimunition imposed on it prior to utilization by the bacteria.

Based on these facts, it can be concluded that most authors agree that individual metabolic rates occur when various size particles are present rather than a single rate existing for all sizes.

2-4   Cell Yield and Oxidation

When oxidative biological treatment is employed, organic matter is removed from the wastewater by the micro-organisms present and utilized in one of two ways. Part of the carbon content of the removed organic matter is synthesized to new cells, while the rest is utilized as a source of energy to sustain cell life and to permit synthesis.(Weston and Eckenfelder, 1955) The fact that cellular matter is synthesized when BOD is removed in a biological system has been well documented by many investigators. The amount and weight of this increase has been assumed to include the following factors: a) the weight of influent suspended solids minus the portion which is dissolved during the aeration period and lost in the treated sewage, b) the growth of biological organisms which

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is related to available nutrients and the accessability of the organisms to these nutrients, c) the amount of auto-oxidation which occurs in the plant itself.(Wuhrmann, 1956)

Many different factors are involved in determining the quantity of sludge produced. Probably the most important of these is the type of waste being treated. Some wastes are more difficult to degrade than others resulting in a different sludge production for each. Other factors involved are temperature, sludge age, and mixed liquor volatile suspended solids (MLVSS) concentration.

Many investigators have presented data on the amount of cell yields when various wastes are treated. One of the first studies was done by Ruchhoft et al., (1940) who found that a simple linear relationship existed between the rate of substrate removal and the initial sludge concentration using glucose as the sole carbon source. In later work, Plack and Ruchhoft (1947) reported sludge yields of 65 to 85 percent for carbohydrate wastes.

Sawyer (1956) summarized data from several sources in which the values ranged from 10 to 60 percent conversion of organic acids to new cells and 44 to 64 percent for glucose. Gaudy and Engelbrecht (1963) obtained a cell yield of 60 percent when they used glucose as a substrate. Using the same substrate, McWhorter and Heukelekian (1964) showed that the average cell yield was 31.5 percent. Glucose concentrations of 100 to 10,000 mg/l and seed concentrations up to 100 mg/l were used

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with little variation in cell yields occurring. This indicated that, while cell yields from various sources might vary, these variations were not due to substrate or seed concentration differences.

Busch and Myrick (1960) showed a 49 percent yield which was calculated from an emperical equation describing the synthesis and oxidation of glucose during the growth phase. Servizi and Bogan (1963) based their theoretical cell yield on the premise that it was proportional to the quantity of adenosine triphosphate (ATP) formed per unit of substrate. They ultimately related cell yield to COD and indicated that 0.38g of cells would be produced per gram of COD removed. Schroeder and Busch (1968) have criticized the use of free energy as a growth parameter, however, Burkhead and Mc-Kinney (1969) have analyzed this principle and agree with its use, although indicating that more laboratory data is needed.

In some instances, a biological sludge can undergo oxidation of its own cellular mass. This occurs when the aeration period is extended beyond that required for substrate removal and is defined as endogenous respiration. During this period, the cells oxidize their own tissue and use this as a source of energy for maintenance. Investigations have shown that endogenous respiration occurs concurrently with synthesis at a rate which varies from 5 to 10 percent of the rate of active metabolism. (Eckenfelder, 1956) Some investigators have attempted to utilize this principle to create total

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oxidation systems which in effect would have no sludge accumulation problems and thus, require no wasting.(Porges, et al., 1956; Kountz, 1956) However, the active mass of micro-organisms cannot be completely oxidized due to the presence of inert materials. These have been reported to average about 22 percent of the sludge mass after prolonged aeration.(Kountz, 1956)

Sludge oxidation rates for various wastes have been reported. Hoover et al., (1951) worked with a dairy waste sludge and reported a sludge-oxidation rate of 24 percent per day. A synthetic fiber waste was shown to have an oxidation rate of 11 percent per day, while a combined pulp and papermill wastes was oxidized at a rate of 7 percent per day.(Eckenfelder and McCabe, 1960)

When a domestic sewage is undergoing treatment, sludge oxidation rates can be far different than for those of soluble wastes. Since sewage contains various amounts of suspended solids the oxidation rates of the total sludge mass can be far less than those cited, depending on the degradation rates of the suspended solids. Thus, increase in detention periods should not be expected to show the same results as those exhibited by a waste free of suspended solids. Eckenfelder (1956) reports that 10 to 12 percent per day of the volatile solids from a conventional activated sludge plant were oxidized up to a point where 64 percent of the volatile solids remained.

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Minimal information is available on the oxidation rates of domestic sludge which varies in influent suspended solids and this was one of the objectives of this study.

3. DEVELOPMENT OF MATHEMATICAL RELATIONSHIPS

3-1   Volatile Solids Accumulation

It has been shown that when an organic substrate is fed to a heterogeneous group of microorganisms that an increase in cellular protoplasm occurs. This increase in biological mass is related to the amount of synthesis by the coefficient "a" which is the mgVSS produced/mg organic substrate removed.

At the same time that cellular growth is occurring, a certain portion of the biological mass is undergoing auto-oxidation or endogenous respiration, during which cellular mass is broken down and utilized in maintenance. The amount of cells utilized in endogenous respiration is proportional to the amount of biological solids present and is indicated by the term "b" which has the units of 1/time. Thus, the net solids production over a period of time can be stated as,

$$\Delta X_V = as^*_{o,r} - bX_V \tag{3-1}$$

where: ΔX_V = total VSS produced per unit of time

   a = mgVSS produced/mg organic substrate removed

   $s^*_{o,r}$ = soluble organic substrate removed per unit of time

   b = mgVSS used/mgMLVSS/unit of time

   X_V = average MLVSS over a period of time

Values of the coefficient "a" have been reported by various investigators and they seem to vary with the type of

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waste being treated. It is also important to note that this coefficient also varies with the type of organic measuring parameter (BOD, COD or TOC) which is employed.

If influent suspended solids are introduced along with the soluble substrate being fed to the system the model must be modified to account for that portion of these organic solids which are not degraded in the designated aeration period. The term which relates the amount of influent volatile suspended solids not degraded has been designated as "f" or the fraction of volatile solids which remains. This fraction appears to be a function of the sludge age of the system. Accounting for this factor, the solids production becomes,

$$\Delta X_v = as^*_{o,r} - bX_v + fX_{o,v} \qquad (3\text{-}2)$$

where: ΔX_v = total VSS produced per unit of time

a = mgVSS produced/mg organic substrate removed

$s^*_{o,r}$ = soluble organic substrate removed per unit of time

b = mgVSS used/mg MLVSS/unit of time

X_v = average MLVSS over a period of time

f = fraction of influent volatile suspended solids remaining

$X_{o,v}'$ = total influent volatile suspended solids fed per unit of time

During the degradation of the influent volatile suspended solids a hydrolysis of these particles occurs and it must be recognized that this places an additional soluble

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organic substrate loading to the system. This in turn is utilized by the biomass resulting in additional synthesis and must also be accounted for in the model. Equation 3-2 then becomes,

$$\Delta X_v = a s^*_{o,r} + a((s'_{o,r} - s^*_{o,r})(1-f)) - bX_v + fX_{o,v} \qquad (3-3)$$

where: $s'_{o,r}$ = total organic substrate removed per unit of time

The term $(s'_{o,r} - s^*_{o,r})$ represents that portion of the organic substrate which is contributed by the influent volatile suspended solids while, (1-f) indicates the amount which is hydrolyzed over the aeration period. Thus, the product of the two is an estimation of the contribution of the $X_{o,v}$ to the soluble organic substrate loading.

Equation 3-3 is now the model from which an accurate prediction of volatile solids accumulation can be made assuming that correct values of the coefficients "a", "b" and "f" can be obtained.

3-2   Oxygen Model

An analysis similar to that employed in the derivation of the solids accumulation model can now be employed to predict total oxygen utilization in an activated sludge system. It has been shown that the total oxygen requirements in a biological system are related to that needed for synthesis and also the oxygen utilized during endogenous respiration. Therefore, it can be stated that the oxygen requirements for such a system are,

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$$O_2/t = a's^*_{o,r} + b'X_v \qquad (3\text{-}4)$$

where:
O_2/t = total oxygen utilized per unit of time

a' = mgO_2 used/mg organic substrate removed

$s^*_{o,r}$ = soluble organic substrate utilized per unit of time

b' = mgO_2/mg MLVSS per unit of time

X_v = MLVSS concentration

The term which relates the amount of oxygen utilized in synthesis is designated as a' in Equation 3-4 and has the units of mgO_2 utilized/mg organic substrate removed. The amount of oxygen required in endogenous respiration is related to the amount of biological mass present and is represented by the term b' which has the units of 1/time.

If influent volatile suspended solids, $X_{o,v}$ were introduced into this system they would hydrolyze over a period of time thus introducing additional soluble substrate to be removed. This in turn would require that additional oxygen be utilized in metabolizing this added load. The model would then become,

$$O_2/t = a's^*_{o,r} + a'((s'_{o,r} - s^*_{o,r})(1-f)) + b'X_v \qquad (3\text{-}5)$$

where:
$s^*_{o,r}$ = soluble organic substrate removed per unit of time

$s'_{o,r}$ = total organic substrate removed per unit of time

f = fraction of influent volatile suspended solids which are not degraded

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The relationship now contains an expression to account for the amount of volatile suspended solids which are hydrolyzed and utilized as substrate during the period of time the sludge is under aeration.

4. EQUIPMENT AND EXPERIMENTAL PROCEDURES

Observation of sludge accumulation in an activated sludge treatment plant was the primary purpose of this study. Continuous-flow activated sludge units, each with a different influent suspended solids loading, were fed domestic sewage and samples obtained daily. Batch units were used in the auto-oxidation studies.

4-1   Continuous Aeration Units

The continuous units used in this investigation were constructed of plexiglass and mounted on a movable table. Both aeration and settling chambers were combined in a single unit separated by an adjustable baffle. This unit eliminates scale-up problems found in horizontal-flow clarifiers by providing an upflow clarification basin. (Busch, 1962) A maximum of eight liters and a minimum of three liters aeration volume could be obtained by adjusting the effluent weir.

Air was supplied by a one hundred psi compressed air source through diffuser stones. This air flow was regulated to approximately ten psi and was found adequate in maintaining a minimum dissolved oxygen content in the aeration chamber while insuring complete mixing. The air was passed through a bottle water trap to clean the air stream of any oil or particulate matter which commonly occurs in compressed air

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systems. This also enabled the air to be presaturated with water such that evaporation losses were minimized.

Waste was fed to the units from four twenty gallon galvanized containers by means of two variable speed sigmamotor pumps. Each pump fed two units since this was the maximum load each could handle and still deliver reproducible flows. Different flow rates through one pump could be obtained by using variable size tubing or by partially clamping one of the feed lines. Flow rates were determined by measuring influent and effluent volumes over various time intervals. Results of these studies indicated that evaporation losses were negligible.

Since fresh sewage was obtained daily, it was unnecessary to refrigerate the influent sample. Organic studies were run to determine the amount of sample degradation over a 24 hour period and these results showed that it was negligible for the purposes of this study. Suspended solids in the influent were kept in suspension through the use of continuous duty constant-speed mixers. These proved to be highly efficient in maintaining a constant suspended solids loading to the units.

The operating temperature observed varied in the range of $23^{\circ}C \pm 2^{\circ}C$ and all tubing and air hoses used were of the tygon variety. A schematic diagram of the laboratory apparatus is shown in Figure 4-1.

4-2   Batch Aeration Units

The batch units were the same as those used in the

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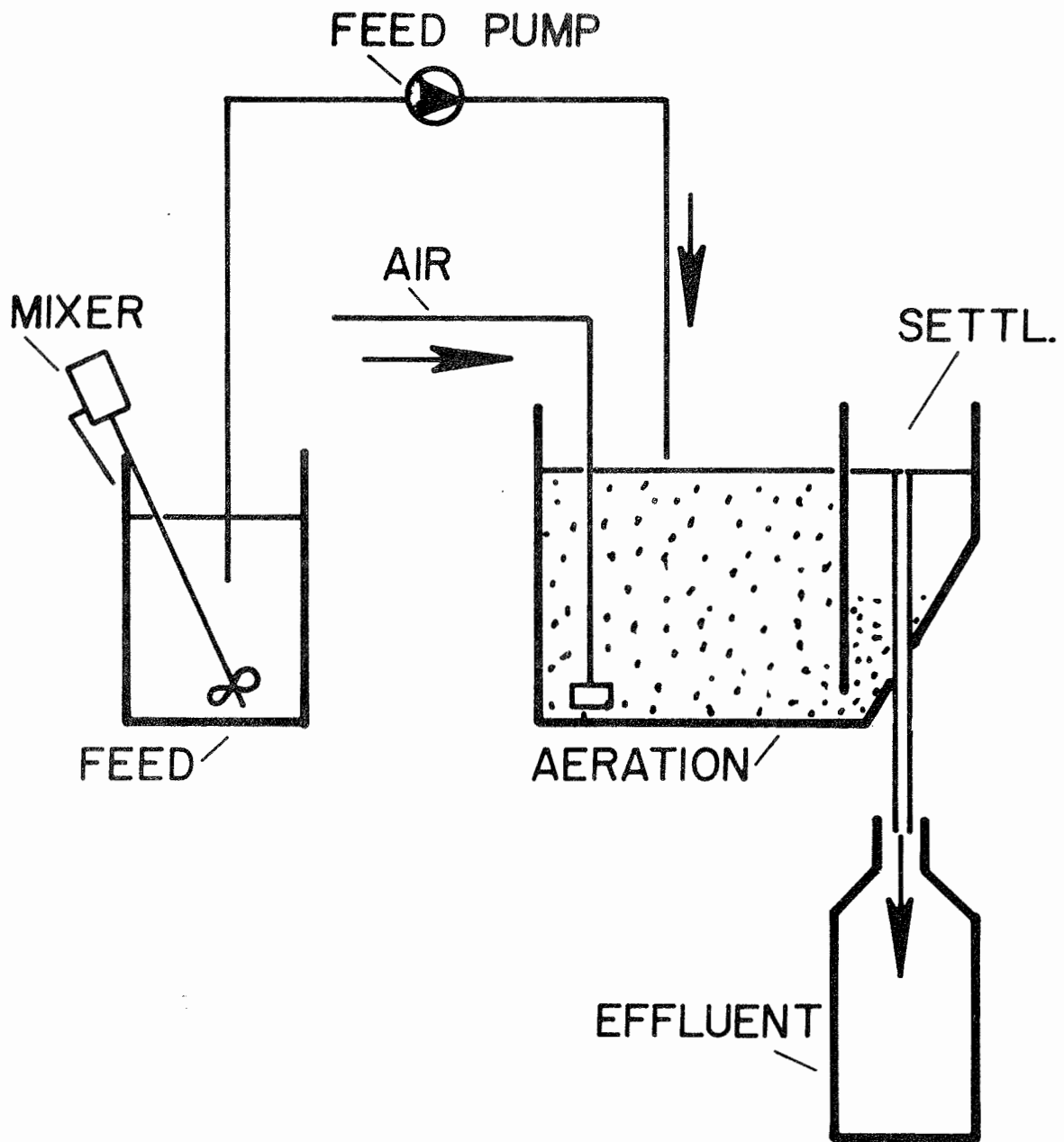
FIG. 4-I. LAB-SCALE ACTIVATED SLUDGE
UNIT FLOW DIAGRAM

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continuous study with one exception. The plexiglass baffle
was removed from the units to provide one aeration chamber from
which the study could be made. The aeration technique was the
same as that used in the continuous study.

4-3   Experimental Procedure

The basic scope of the experiments encompassed the
following: 1) to observe the effects of various influent
volatile suspended solids loadings on the volatile solids
accumulation in the activated sludge process; 2) to measure
the rate of influent volatile suspended solids degradation
so that the proposed model could be utilized to predict
volatile solids accumulation; 3) to observe the oxygen uptake
so that oxygen utilization could be determined.

The domestic wastewater was obtained from the Govalle
Sewage Treatment Plant in Austin, Texas, and all experiments
were conducted at this site. This waste has shown to be
typical of municipal wastewaters in every respect. The sample
was taken daily from the effluent weir of a pre-settling
chamber in the plant. Collection of the waste at the same time
each day eliminated variable loadings to the units. Because
the sample was obtained from the effluent of a settling tank,
it was relatively free of the larger suspended solids particles
which were settleable and could serve as a base to which solids
could be added to attain the desired levels. The solids
which were added to this base were collected from a tap in

the sludge line of the same tank so, in essence, the solids removed were replaced, but at a controlled level.

Four influent volatile suspended solids levels were employed. The original sample, which was low in suspended solids, served as a control. To this sample sludge solids were added and approximately 200 mg/l, 400 mg/l and 600 mg/l of suspended solids were maintained in the respective units. These solids were kept in suspension by the previously described mixers, and the mixture fed to the continuous units.

Activated sludge seed was obtained from the Govalle Treatment Plant and although no acclimation was needed, the units were allowed to stabilize for a period of three days. Once this was done, sludge buildup was observed.

The procedure for measuring the accumulation was as follows. The mixed liquor volatile suspended solids (MLVSS) level in each tank was determined. The unit was then allowed to run for a period of 24 hours and the MLVSS again observed. The difference plus the effluent suspended solids was assumed to be the accumulation for that day. Sludge was then wasted down to the original level and the procedure repeated. This buildup was observed in two separate sets of experiments, each with a different initial MLVSS concentration. Each experiment was run for a period of about one month so that the effects could be observed over a considerable length of time.

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Daily samples were taken from each unit on both the influent and effluent and analyzed for total and volatile suspended solids, pH, and total organic carbon (TOC). The pH and total and volatile suspended solids content of the aeration tank were monitored daily. Periodically the five-day biochemical oxygen demand (BOD), sludge volume index, sludge settling velocity, and oxygen uptake were also measured to insure that no drastic changes were occurring in each system. All organic determinations were made on both total and filtered samples.

The same basic procedure was used in the batch experiments. Four units were arranged such that four different influent suspended solids loadings were fed. The sewage and suspended solids were of the same type as those used in the continuous units. The basic procedure involved obtaining an activated sludge seed from the Govalle Plant, adding sewage plus the required suspended solids load and measuring the auto-oxidation rate of the resulting sludge. MLVSS was determined daily for each unit and the experiment was terminated when it appeared that the MLVSS level had stabilized and only inert and non-biodegradable material remained. This occurred after a period of eight days. TOC, BOD and oxygen uptake were determined in the first 24 hours of this experiment in order that the system could be monitored while the organic substrate was being utilized.

5. LABORATORY ANALYSES

Any changes in the activated sludge units were noted by daily monitoring of influent and effluent quality. TOC, BOD and suspended solids determinations were used to characterize the raw and treated waste streams. Oxygen uptake, sludge volume index, and sludge settling velocity were indications of any change within the system itself.

5-1   Sample Preparation and Storage

Samples for TOC and BOD were taken from both the influent and effluent containers at the prescribed sampling times. Upon obtaining the samples, a portion was saved for total analysis and the rest filtered through glass filters in order that filtered samples could also be obtained. These were then placed in polyethelene bottles and stored at $4^{o}C$ until analysis.

5-2   Solids Determination

Influent and effluent solids for each unit were analyzed for both volatile and total content by the Gooch crucible method using glass filters as described in Standard Methods. (1965) A 25-ml sample was used employing a wide tip pipette for measurement. The baffle was raised for complete tank mixing before the sample was withdrawn, with a 10-ml sample being collected. This determination was used

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to calculate the amount of sludge accumulation each day and also to compute the amount of daily wasting needed. Thus, the biological solids were kept constant, eliminating this as a process variable.

5-3   Total Organic Carbon

Total organic carbon (TOC) was run as an indication of the loading to each unit. The instrument used was the Beckman Carbonaceous Analyzer Model 915. This instrument utilizes two channels, one to determine total carbon and the other to measure inorganic carbon. The difference between these two values is the amount of total organic carbon present. Standards composed of acetic acid dissolved in CO_2-free distilled water were used to calibrate the total organic carbon channel, while a mixture of sodium carbonate and sodium bicarbonate calibrated the inorganic channel. TOC as well as BOD were run on both total and filtered samples. Total TOC samples were blended before analysis to facilitate the accuracy of this determination.

5-4   Biochemical Oxygen Demand

Biochemical Oxygen Demand (BOD) was determined by using the dilution technique presented in Standard Methods. (1965) Duplicates of each sample were run at two dilutions.

5-5   Oxygen Uptake

Oxygen uptake rates were obtained by using a Precision Scientific Galvanic Cell Oxygen Analyzer which

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utilized a galvanic cell arrangement to measure the current
produced in the reduction of the oxygen. This analyzer
employs a cylindrical-shaped lead anode surrounding a rod-
shaped silver cathode. The cell was connected to a recorder
which automatically plotted the depletion of dissolved oxygen
against time. The slope of this line was assumed to be the
total oxygen uptake rate, (mg oxygen/liter/hour). The specific
oxygen uptake rate was obtained by dividing the total uptake
rate by the biological solids in the aeration chamber, (mg
oxygen/hour/gm MLVSS). Specifically, the procedure was as
follows: a) a BOD bottle was filled with mixed liquor from
the aeration unit, b) the oxygen probe was placed in the
bottle without trapping any air bubbles inside, c) the contents
were stirred by a magnetic stirrer and d) the uptake measured.
Calibrations using the Winkler Method were performed before
each use and the membrane was replaced weekly to minimize
erroneous results. To guard against errors introduced by
temperature effects, the probe was calibrated at the temperature
at which the sample analysis would be performed.

6. EXPERIMENTAL RESULTS

6-1   General

This study involved three main laboratory phases.
The first two were continuous-flow studies with four lab-scale
activated sludge units. From these studies, the long-term
effects of influent suspended solids on solids buildup and oxygen
were observed.

The third phase involved a batch study from which
the magnitude of some of the coefficients in the mathematical
model were determined.

Results of each experiment are presented in the
following discussion.

6-2   Continuous Run #1

The main objective of the continuous-flow experiments
was to minimize the process variables between each unit, such
that influent volatile suspended solids would be the only
parameter affecting solids accumulation and oxygen usage. It
was thus attempted to have the MLVSS concentration and the
organic loading as close to equal in each unit as was possible.

6-2.1 Mixed Liquor Concentration

Table 6-1 presents the data on the MLSS and MLVSS
concentration over the period of this run. The MLVSS values
ranged from a value of 2130 mg/l for Unit #1 up to a concentra-
tion of 2400 mg/l for Unit #4. These were considered close

enough to effectively eliminate the MLVSS concentration as a
major variable among the units. Values of MLSS and MLVSS are
also shown calculated in grams. An aeration volume of eight
liters was used in making this conversion.

Table 6-1. Mixed Liquor Concentration
            Continuous Unit #1

Unit	MLSS (mg/l)	MLVSS (mg/l)	MLSS (gm)	MLVSS (gm)	Volatile (%)
1	2580	2130	20.7	17.0	83
2	2740	2260	21.9	18.1	83
3	2970	2400	23.8	19.2	81
4	2880	2400	23.0	19.2	83

The volatile solids in each unit averaged from
81-83 percent. These agree with the commonly reported value
of 80 percent for most biological sludges.

6-2.2 Organic Loading

In a further attempt to minimize the effects of
other variables, it was necessary to keep the organic loading
to each unit at approximately the same level. It should be
mentioned that the primary organic parameter utilized in this
study was TOC, due to the ease with which these values are
obtained. BOD values were determined at various intervals and
are presented in the appendix.

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Both soluble and total TOC values were collected over the period of the study, since it was necessary to know the contribution to the total TOC by the influent solids. Table 6-2 contains data on the total organic loading. The loading factors, L_{VSS}, varied from 0.21 to 0.24 which are sufficiently close to eliminate loading as a significant variable between units. These

Table 6-2. Total Organic Loading Parameters
Continuous Run #1

Unit	S'_o (mg/l)	S'_e (mg/l)	Removal (%)	MLVSS (gm)	L_{VSS} $\left(\dfrac{gmTOC/day}{gm\ MLVSS}\right)$	Flow (l/day)
1	125	23	82	17.0	0.21	27.8
2	150	29	81	18.1	0.22	27.1
3	178	22	88	19.2	0.23	25.5
4	195	26	87	19.2	0.24	23.3

equal loadings were obtained by reducing the flow as the influent suspended solids increased from Unit #1 to Unit #4. This was necessitated by an increase in total TOC as the influent solids increased.

It is interesting to note the increase in process efficiency as the solids loading was raised. This was caused by the effluent solids in Units #1 and #2 being higher than in Units #3 and #4 resulting in a higher effluent TOC. A poorer settling sludge was probably the cause of more solids being passed to the effluent in Units #1 and #2.

A record of soluble TOC values is presented in Table 6-3. The amount of soluble material fed to each unit was almost constant and this seems reasonable since the base sewage fed to each unit was the same. The removal efficiency of each plant seems rather low, however, the low s_o^* value must

Table 6-3. Soluble Organic Loading Parameters Continuous Run #1

Unit	s_o^* (mg/l)	s_e^* (mg/l)	Removal (%)
1	40	14	65
2	36	14	61
3	41	15	63
4	42	13	70

be taken into account before making any observations. Actually, the effluent values are about as low as could be expected in these types of units, so it is the influent TOC value which makes these appear to be low efficiency units.

6-2.3 Influent Suspended Solids

Since the MLVSS concentration and organic loading to each unit were effectively equal, it was possible to vary the influent suspended solids among the units so that its effect on solids accumulation and oxygen usage could be observed. Table 6-4 indicates the range of values used varied from 117 mg/l for Unit #1 up to 510 mg/l for Unit #4. The volatile portion,

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$X_{O,V}$, which is of primary concern in this study, averaged about 88 percent, indicating that a large portion of the suspended solids fed to each unit were organic in nature.

Table 6-4. Influent Suspended Solids
Continuous Run #1

Unit	X_O (mg/l)	$X_{O,V}$ (mg/l)	Volatile (%)
1	136	117	86
2	280	247	88
3	410	362	88
4	574	510	89

6-2.4 Solids Accumulation

The volatile solids buildup was observed in each unit and the average values for the run are reported in Table 6-5. These were obtained by daily measuring the buildup in the aeration chamber and adding to it any effluent solids, thus obtaining the total volatile solids buildup, ΔX_V, for that particular day.

As can be seen in Table 6-5, the volatile solids buildup increased as the influent volatile solids increased. This is graphically illustrated in Figures 6-1 and 6-2. It is also important to note that as the influent solids changes the sludge buildup changes in a similar pattern. The strong influence which influent volatile solids has on the total volatile solids accumulated over a period of time is obvious.

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FIG. 6-1. VOLATILE SOLIDS ACCUMULATION AND INFLUENT VOLATILE SUSPENDED SOLIDS
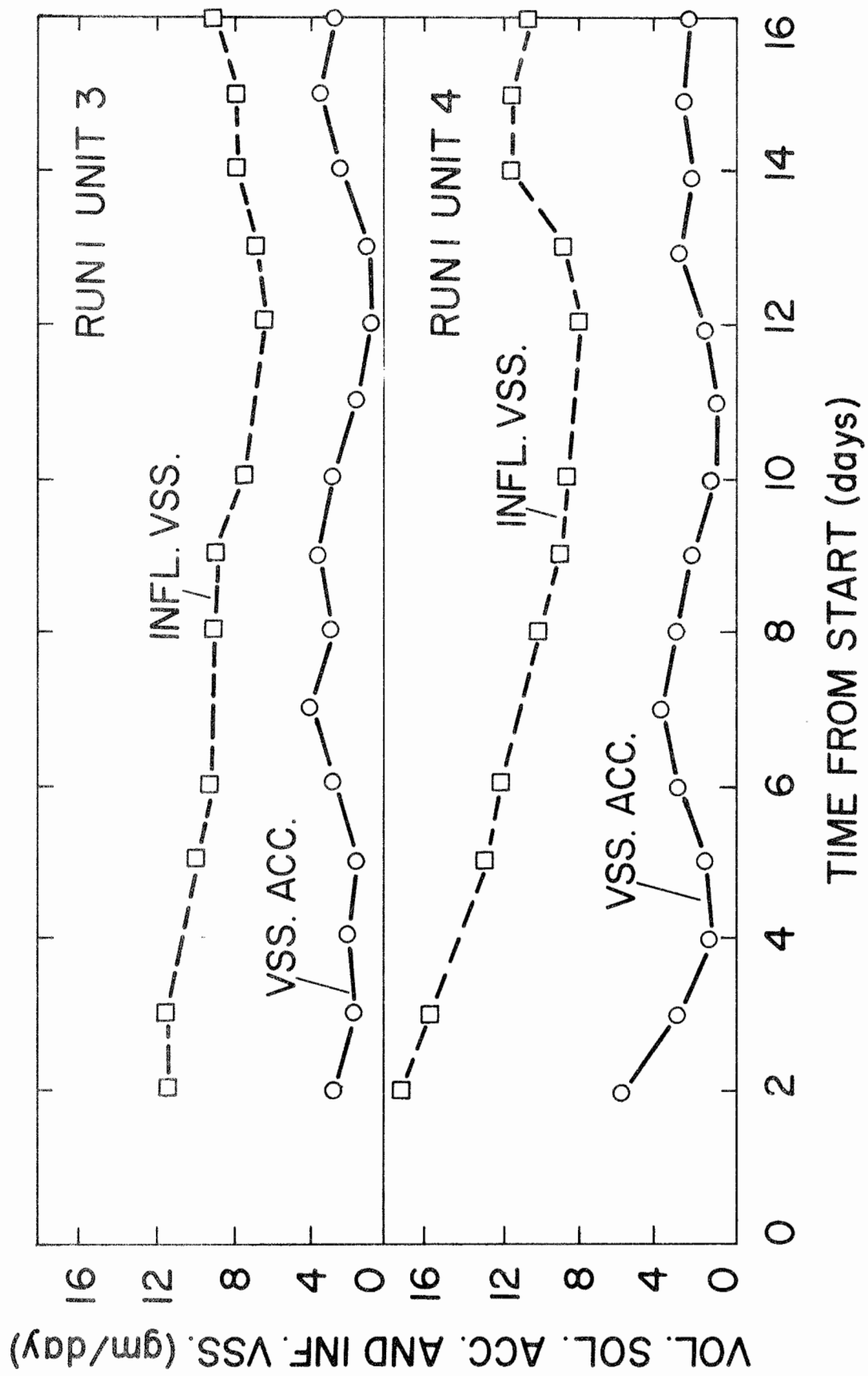
FIG. 6-2. VOLATILE SOLIDS ACCUMULATION AND INFLUENT VOLATILE SUSPENDED SOLIDS

Table 6-5. Average Volatile Solids Buildup
Continuous Run #1

Unit	ΔX_V(aeration) (gm/day)	Eff.Solids (gm/day)	ΔX_V (gm/day)	$X_{0,V}$ (gm/day)
1	0.89	0.67	1.56	3.26
2	1.64	1.02	2.66	6.70
3	2.43	0.43	2.86	9.21
4	2.75	0.58	3.33	12.30

The points plotted in Figures 6-1 and 6-2 represent those calculated by utilizing the statistical method of weighted averages as presented in Fair and Geyer (1954). By doing so any irregularities which were introduced by the random sampling used and also caused by the small size of the units were eliminated. The actual raw data points can be found in the appendix.

6-2.5 Oxygen Relationships

The specific oxygen uptake rates, k_r, remained approximately constant for all of the units involved in this study. Table 6-6 shows the relative magnitude of k_r for each unit. Since the organic loading to each unit was the same, it is to be expected that the oxygen utilized should be approximately the same, an indication that the sludge activity in each unit was also equal. It appears that at similar loadings, the influent suspended solids have a minimal effect on the

Table 6-6. Oxygen Uptake Parameters
          Continuous Run #1

Unit	r (mg/l/hr)	MLVSS (mg/l)	k_r ($\frac{mgO_2/hr}{gm\ MLVSS}$)
1	40.6	2010	20.2
2	44.3	2150	20.7
3	43.5	2200	20.1
4	40.1	2100	19.5

amounts of oxygen utilized. One should also anticipate that if the loadings had been allowed to increase with increasing suspended solids, that the oxygen utilization rate would also increase due to the added organic loading placed on the system by the influent solids.

6-3   Continuous Run #2

The only difference between Runs #1 and #2 was the mixed liquor volatile suspended solids concentration carried in the aeration chamber. It was desired to see whether, under the same organic and influent suspended loadings as existed in Run #1, the MLVSS concentration had any effect on the amount of solids accumulated.

6-3.1 Mixed Liquor Concentration

Table 6-7 shows the average MLSS and MLVSS concentrations for each of the units in Run #2. These values are about 800 to 1000 mg/l greater in MLSS concentration than

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were used in Run #1. Again the variation between units is considered negligible and the volatile solids averaged about 80 percent.

Table 6-7. Average Mixed Liquor Concentrations
Continuous Run #2

Unit	MLSS (mg/l)	MLVSS (mg/l)	MLSS (gm)	MLVSS (gm)	Volatile (%)
1	3499	2760	27.9	22.1	79
2	3540	2779	28.3	22.2	79
3	3740	2995	29.9	23.9	80
4	3680	2946	29.4	23.6	80

6-3.2 Organic Loading

Since the type of sewage and amount of suspended solids fed to each unit were approximately the same as used in Run #1, the organic loading, L_{VSS}, showed a decrease in this run due to the increase in biological solids. Table 6-8 indicates the amount of total TOC fed and the loading factors which were computed. These ranged from 0.16 to 0.21 for Run #2 and were considered to have no significant effect between units. Just as in the first run, the flow had to be lowered as influent solids increased to equalize the loading.

Soluble TOC was also monitored and the results shown in Table 6-9 closely correlate with those of Run #1. This is because the same sewage was used in both runs.

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Table 6-8. Total Organic Loading Parameters
Continuous Run #2

Unit	s'_o (mg/1)	s'_e (mg/1)	Removal (%)	L_{VSS} $(\frac{gmTOC/day}{gmMLVSS})$	Flow (1/day)
1	116	20	83	0.16	19.7
2	145	28	81	0.18	19.5
3	177	26	85	0.20	18.7
4	204	35	83	0.21	17.4

Again it appears that the removal efficiency of the soluble matter was low, but this occurred for the same reason as in Run #1.

Table 6-9. Soluble Organic Loading Parameters
Continuous Run #2

Unit	s^*_o (mg/1)	s^*_e (mg/1)	Removal (%)
1	42	16	66
2	44	16	63
3	42	17	58
4	45	18	59

6-3.3 Influent Suspended Solids

Influent suspended solids were also considered the main variable between units in Run #2. It was attempted to add the same amount of solids to each unit in this run as were added in Run #1. Table 6-10 contains the values of $X_{o,v}$

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for Run #2. It appears that an excellent correlation of Runs #1 and #2 was obtained in this aspect. The values in the first

Table 6-10. Influent Suspended Solids Continuous Run #2

Unit	X_o (mg/l)	$X_{o,v}$ (mg/l)	Volatile (%)
1	134	113	84
2	273	228	84
3	425	352	83
4	535	458	86

run ranged from 117 to 510 mg/l which are close to the range of 113 to 458 mg/l observed in this phase. The percent influent volatile solids again appear to have the high organic content which was exhibited in Run #1.

6-3.4 Volatile Solids Accumulation

Volatile solids accumulation was again monitored in this experiment and the results are shown in Table 6-11. It is interesting to note that the volatile solids accumulated in this phase were considerably higher than in Run #1, indicating a dependence of ΔX_v on the MLVSS concentration. It again appears that volatile solids buildup was also dependent on the influent volatile suspended solids loading. Chronological data for the period of the experiment are shown in Figures 6-3 and 6-4. These curves exhibit a similar pattern to those
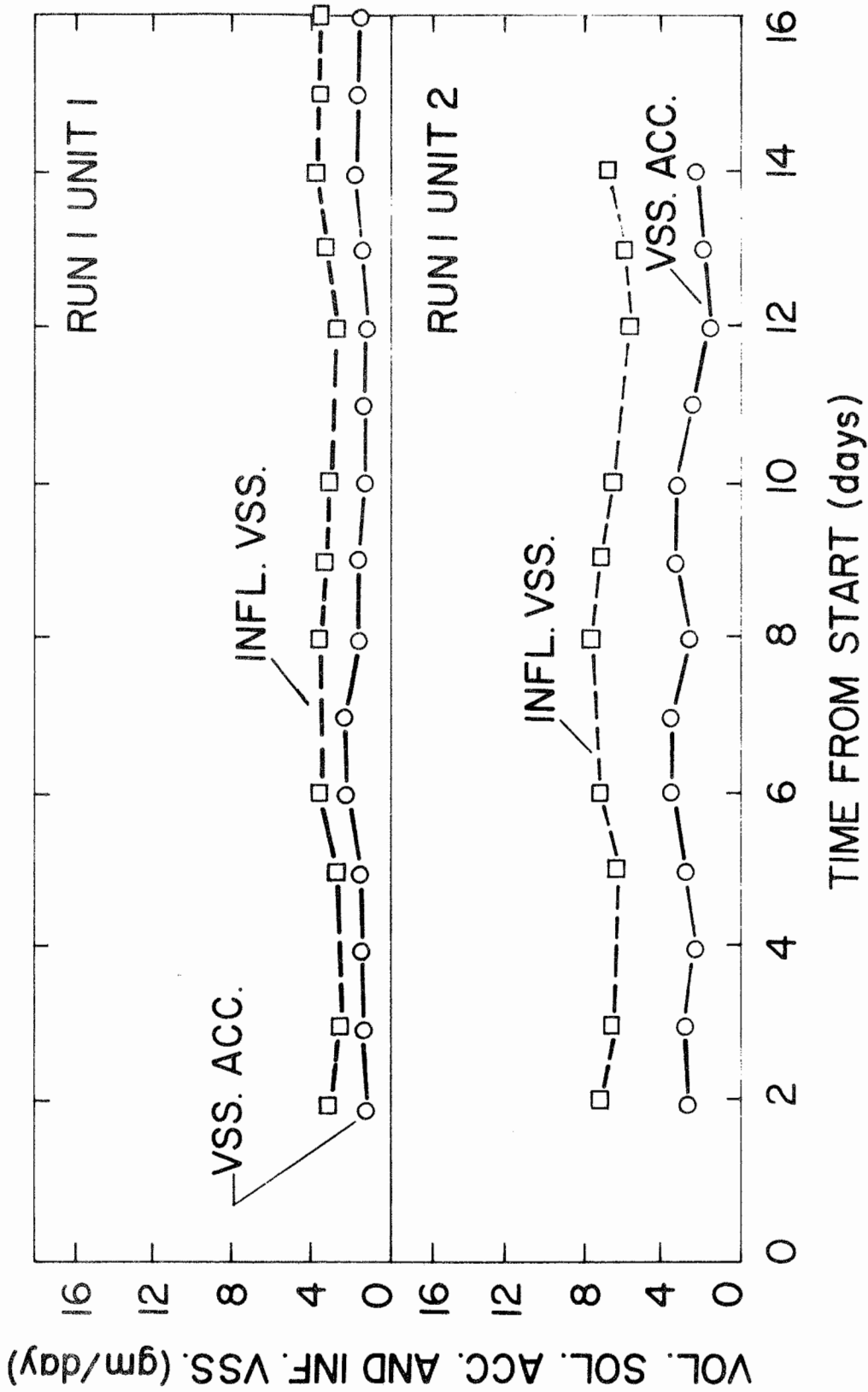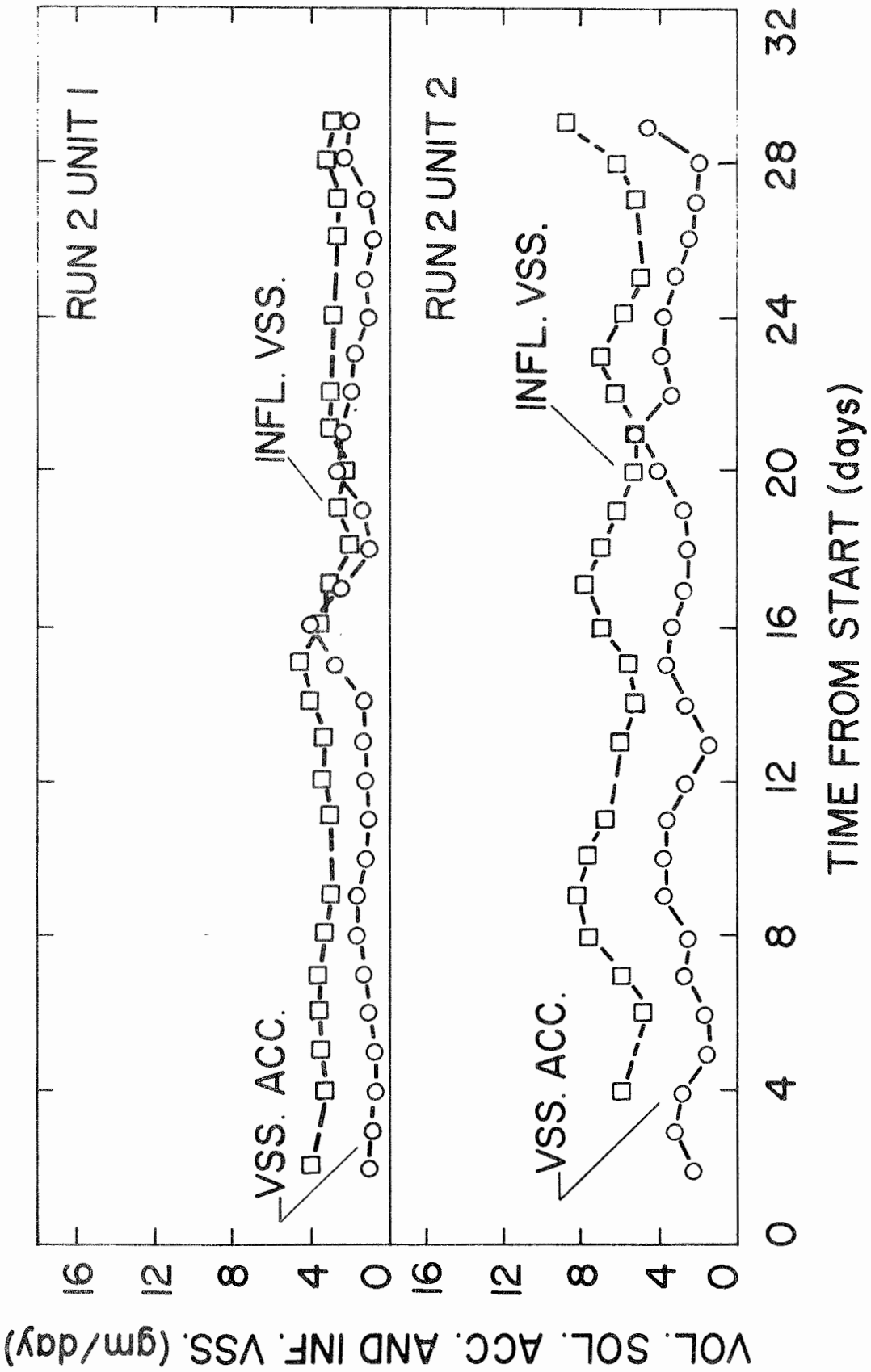
FIG. 6-3. VOLATILE SOLIDS ACCUMULATION AND INFLUENT VOLATILE SUSPENDED SOLIDS
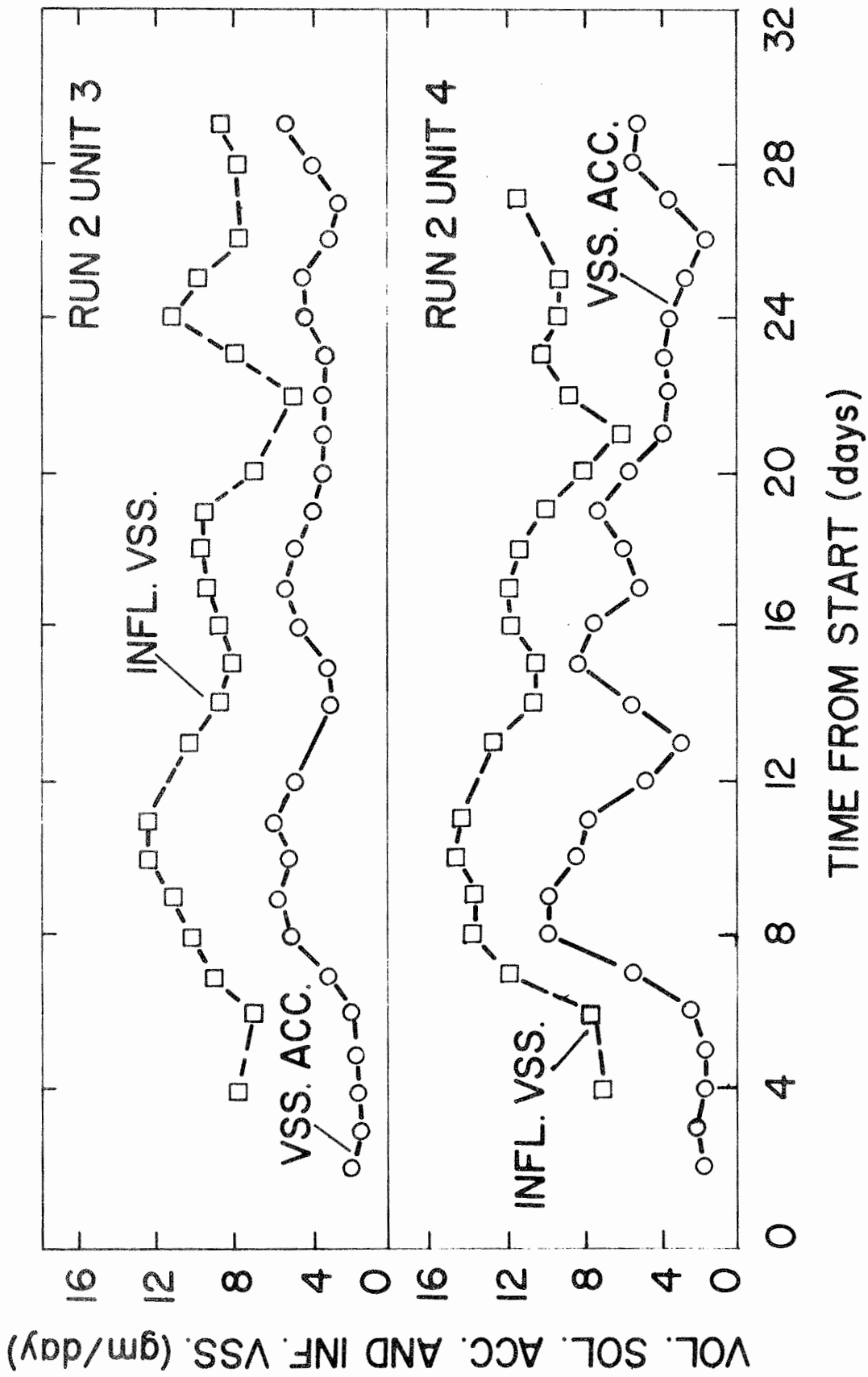
FIG. 6-4 VOLATILE SOLIDS ACCUMULATION AND
INFLUENT VOLATILE SUSPENDED SOLIDS

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Table 6-11. Volatile Solids Buildup
Continuous Run #2

Unit	ΔX_v(aeration) (gm/day)	Eff.Solids (gm/day)	ΔX_v (gm/day)	$X_{o,v}$ (gm/day)
1	1.10	0.45	1.55	3.2
2	1.95	1.29	3.24	6.4
3	2.47	0.97	3.44	9.5
4	3.32	1.15	4.47	11.5

observed in Run #1 in that they show the definite influence
which $X_{o,v}$ has on the total ΔX_v. Here again, moving averages
are plotted to eliminate error.

6-3.5 Oxygen Relationships

The specific oxygen uptake rate was significantly
lower in Run #2 than in the first continuous experiment.

Table 6-12. Oxygen Uptake Parameters
Continuous Run #2

Unit	r (mg/l/hr)	MLVSS (mg/l)	k_r ($\frac{mgO_2/hr}{gmMLVSS}$)
1	38.0	2890	13.1
2	43.8	2900	15.0
3	46.2	3190	14.5
4	41.1	2950	14.0

While k_r remained relatively constant between units, the range shown in Table 6-12 of 13.1 to 15.0 $mgO_2/hr/gmMLVSS$ was lower than the 19.5 to 20.7 $mgO_2/hr/gmMLVSS$ of Run #1. The reason for this lies in the fact that the organic loading in Run #2 was less than the initial run, therefore, the biological mass present had to work less to metabolize the same amount of material, resulting in less oxygen utilized.

6-4   Summary of Continuous-Flow Data

The basic differences between the continuous flow experiments can be summarized in the following manner:

(1) The MLSS and MLVSS concentrations varied from Run #1 to Run #2 in order that any effects which the mixed liquor concentration had on sludge buildup could be observed. Values of MLVSS for Run #1 varied from 2130 to 2400 mg/l as compared to 2760 to 2946 mg/l for Run #2. The percent volatile solids averaged about 81 percent.

(2) The amount of organic matter fed to each unit was the same in both experiments, however, since the MLVSS differed between runs, the loading factors for each run were not equal. Values of L_{VSS} for Run #1 varied from 0.21 to 0.24, while the range for Run #2 was 0.16 to 0.21. Average total TOC removal efficiencies were about 85 percent. Figure 6-5 shows the effect of influent suspended solids on the total TOC measured. This plot illustrates the increase in organic matter as influent solids increases. It also shows how close

45
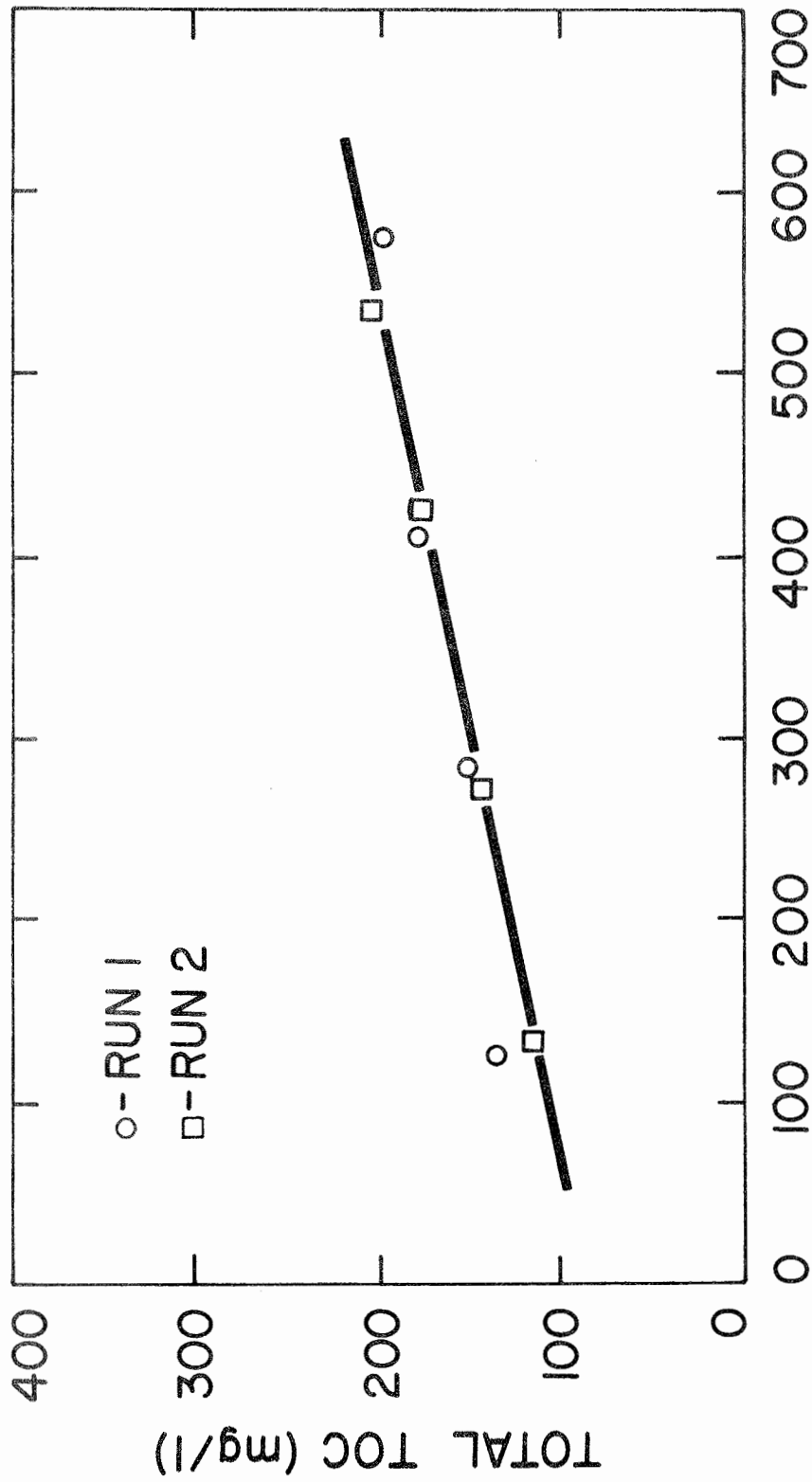
FIG.6-5. INFLUENT SUSPENDED SOLIDS AND
TOTAL TOC

the influent solids and total TOC values were for each continuous
run.

Soluble TOC values for each run compared favorably.
Influent soluble TOC values for both runs averaged about 40 mg/l
while the effluent was about 16 mg/l. Soluble TOC removal
efficiencies ranged from about 60 to 70 percent.

(3) Influent suspended solids fed in both runs were
approximately the same for each unit. Influent volatile suspended
solids, $X_{o,v}$, values ranged from 117 to 510 mg/l for Run #1 and
from 113 to 458 mg/l for Run #2. Figures 6-1 and 6-2 indicate
the daily values of $X_{o,v}$ for Run #1 and Figures 6-3 to 6-4 show
these values for Run #2.

(4) Volatile solids accumulation differed from the
first to the second run. This indicates that the MLVSS
concentration influences ΔX_V, since this was the only variable
between the two runs. If this effect is cancelled by dividing
ΔX_V by the MLVSS concentration, the volatile solids buildup in
each run is approximately equal for each unit, providing that
the influent solids loading to each unit is approximately the
same. Figure 6-6 shows the effect of dividing by X_V and also
shows how the volatile solids buildup increases with influent
volatile suspended solids.

Figures 6-1 through 6-4 show the daily variation of
volatile solids buildup and also the effects of influent solids
on ΔX_V.

47
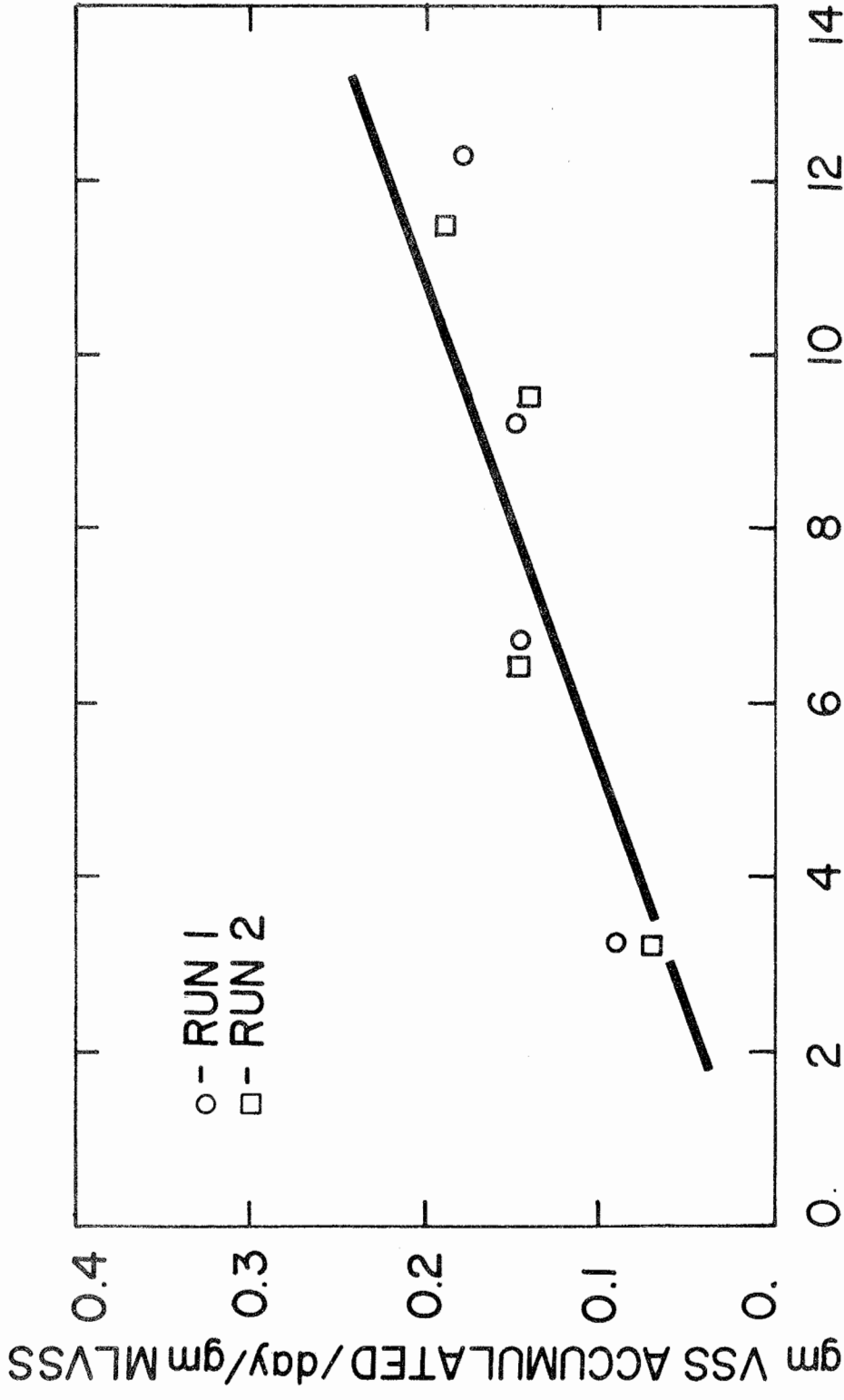
FIG. 6-6. VOLATILE SOLIDS ACCUMULATION WITH INFLUENT VOLATILE SUSPENDED SOLIDS

(5) Specific oxygen uptake rates, k_r, were different for each of the continuous-flow phases. More oxygen per organism was utilized in Run #1 because the organic loading in this phase was greater and the organisms required more oxygen to remove all of the organic material. Values of k_r for Run #1 varied from 19.5 to 20.7 $mgO_2/hr/gmMLVSS$ while in Run #2 the range was 13.9 to 14.8 $mgO_2/hr/gmMLVSS$. Specific oxygen uptake rates did not vary with increases in the influent suspended solids, indicating that this variable does not affect the oxygen utilization process. It would seem that the only affect which influent suspended solids would have on a unit would be to increase the organic loading, thereby requiring more oxygen to completely assimilate the substrate. It was impossible to observe this phenomenon in these continuous phase experiments since the loading to each unit was approximately equal.

6-5   Batch Run

The purpose of the batch phase was to develop values for the coefficients "b" and "f" of Equation 3-3, so that the model could be used to predict volatile solids buildup under any condition.

6-5.1 Development of Coefficient "f"

In order that the coefficient "f", defined as the amount of volatile solids remaining after a period of time, can be computed, the degradation rate of the influent volatile suspended solids must be obtained. It is postulated that "f"

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is directly related to the sludge age of the system, G, since the period of time which the solids are under aeration determines the amount of $X_{O,V}$ which will hydrolyze and thus be degraded. This can be stated as,

$$f = 10^{-K_V G} \qquad\qquad (6\text{-}1)$$

where: f = percent of influent volatile suspended solids remaining

K_V = degradation rate constant of the influent volatile suspended solids

G = sludge age of the system

Four laboratory batch units were used in this phase, each with a different $X_{O,V}$, and the degradation of the sludge mass monitored over a period of time. Figures 6-7 and 6-8 show the degradation of the MLVSS in each unit over a number of days. As these figures show, it took about eight days for each unit to stabilize, indicating that auto-oxidation was complete and only non-biodegradable solids remained after this period of time. Since we were only concerned with the bio-degradable portion, the final amount of non-biodegradables were subtracted from each point in Figures 6-7 and 6-8 so that the biodegradable degradation rates could be determined. The final non-biodegradable portion of the MLVSS for each unit as determined is shown in the following table, along with the influent volatile suspended solids loading for each unit.

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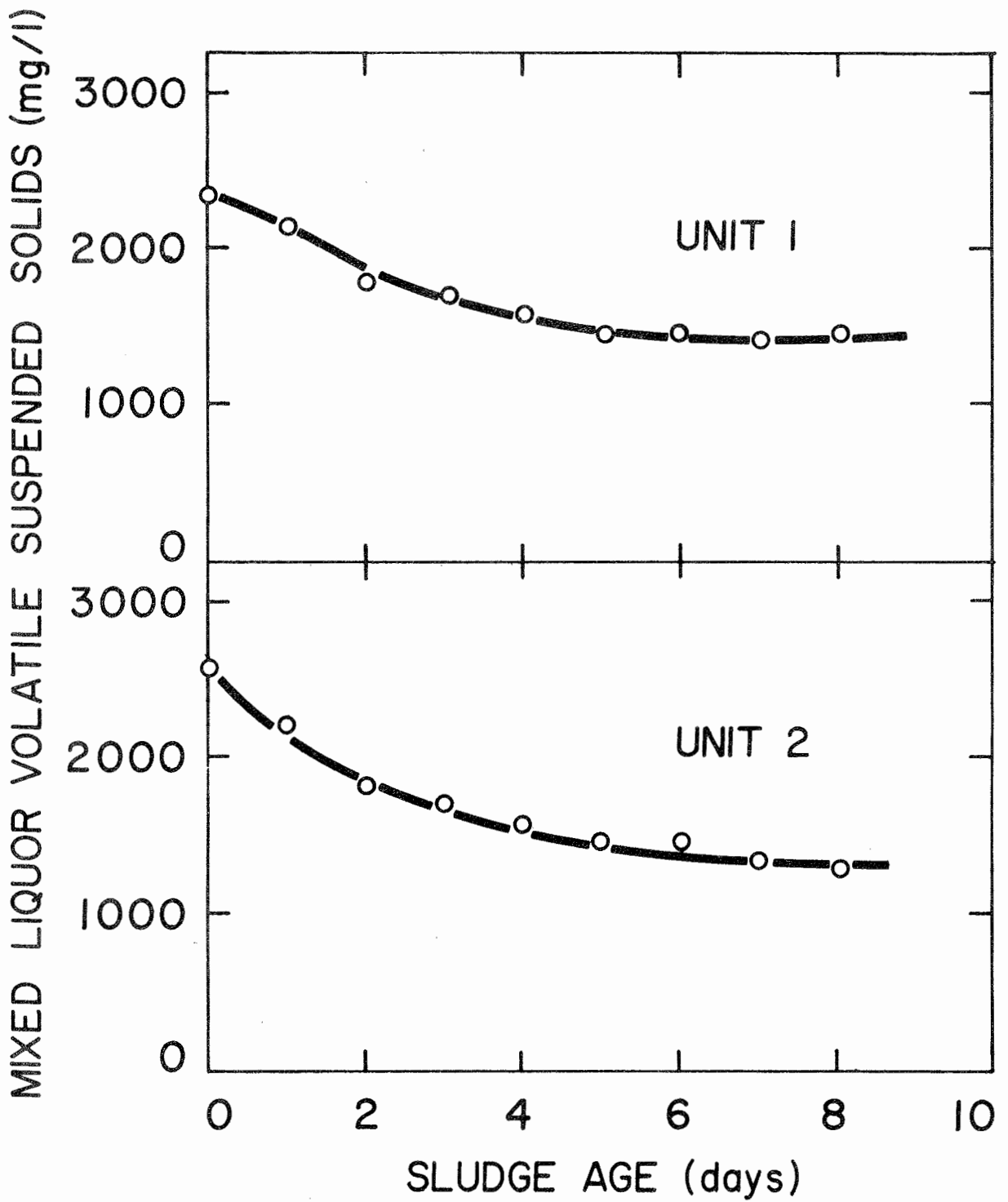
FIG. 6-7. DEGRADATION OF MLVSS
IN BATCH STUDY
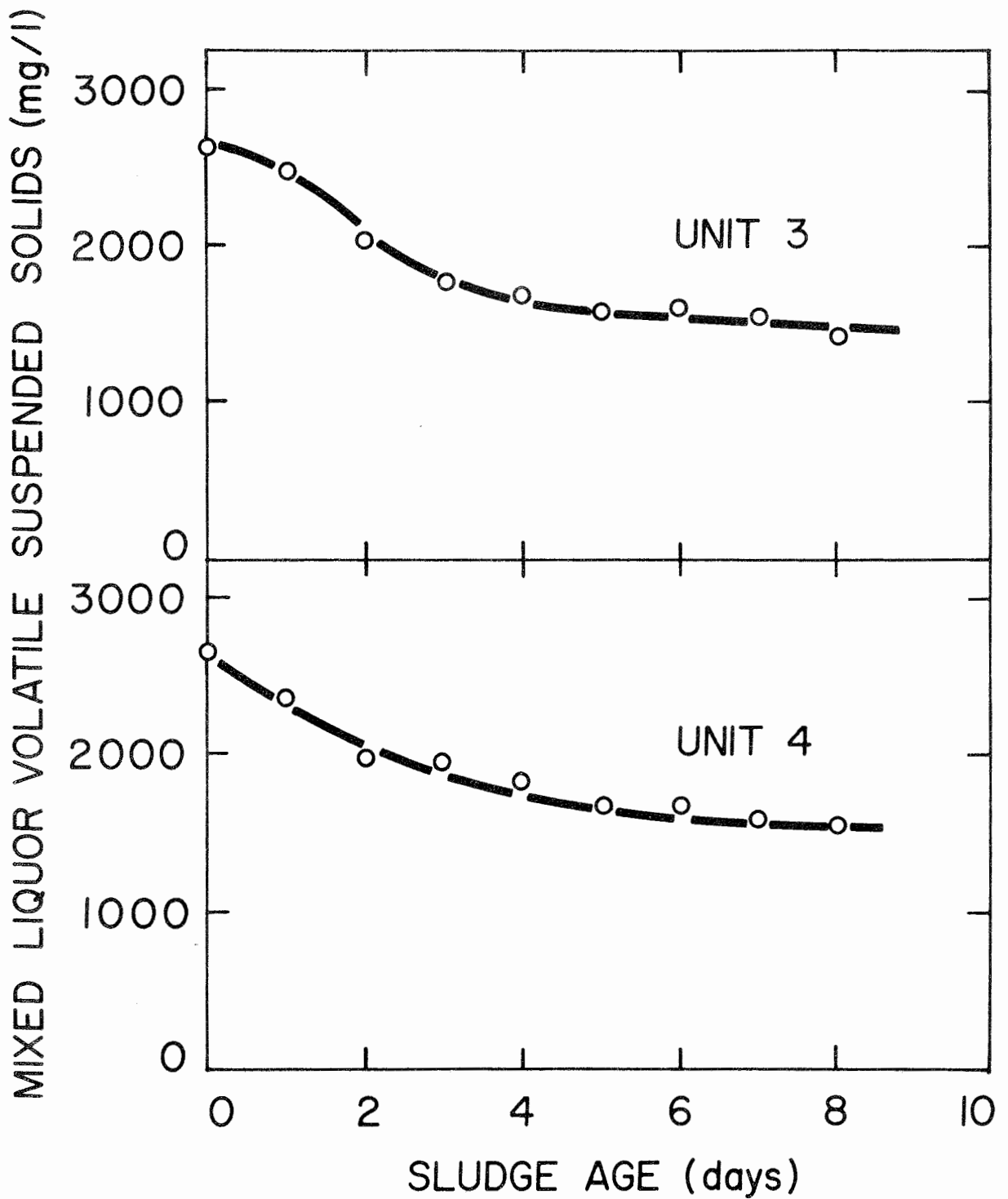
FIG. 6-8. DEGRADATION OF MLVSS
IN BATCH STUDY

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Unit	1	2	3	4
$X_{v,n}$ (mg/l)	1450	1300	1400	1500
$X_{o,v}$ (mg/l)	92	230	420	880

These values were subtracted from the total MLVSS concentration, X_v, to yield the biodegradable portion, $X_{v,b}$ and are presented in Table 6-13. From these values, Figure 6-9 was plotted and the degradation rate for each unit was determined. Table 6-14 presents the degradation rates of the biodegradable MLVSS, K', obtained from this plot. The variation of K' with influent volatile suspended solids is shown in Figure 6-10. Close examination of this plot indicates that K' decreases with

Table 6-13. Biodegradable MLVSS
Batch Study

Time (days)	Unit 1 (mg/l)	Unit 2 (mg/l)	Unit 3 (mg/l)	Unit 4 (mg/l)
0	900	1255	1185	1130
1	705	900	1085	860
2	335	510	610	475
3	285	405	350	450
4	140	265	280	335
5	0	175	175	190
6	–	0	200	190
7	–	–	–	–

increasing volatile solids up to a point where as more volatile solids are added, there is no change in the degradation rate of the mixture. It can then be stated that the MLVSS and the $X_{o,v}$ which were added are degrading at the same rate. This then

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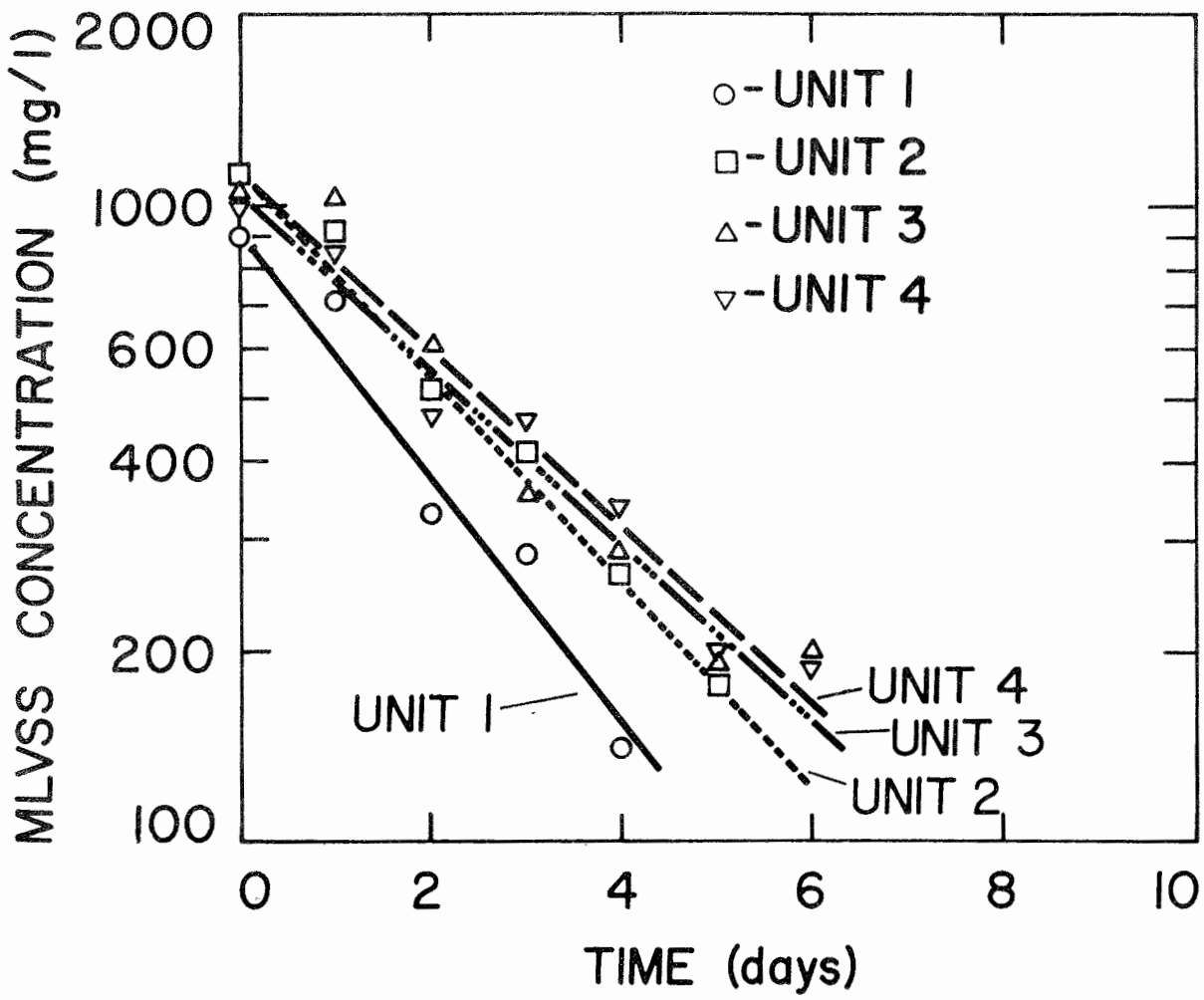
FIG.6-9. DETERMINATION OF MLVSS
DEGRADATION RATES

Table 6-14. Biodegradable MLVSS
Degradation Rates, K'
Batch Study

Unit	K'	$X_{o,v}$ (mg/l)
1	0.188	92
2	0.175	230
3	0.145	420
4	0.146	880

yields the degradation rate of the influent volatile suspended solids, K_v. An inspection of Figure 6-10 shows this parameter to have a value of 0.14. Substituting this value into Equation 6-1 yields,

$$f = 10^{-0.14G} \qquad (6-2)$$

where: f = percent of influent volatile
              suspended solids remaining

         G = Sludge age of the system

From this relationship, a value of "f" can be determined when the sludge age of a system is known. Figure 6-11 presents a plot of values of "f" for a range of sludge ages. This plot was developed through use of Equation 6-2.

6-5.2 Determination of Coefficient "b"

The endogenous respiration coefficient, b, can also be determined by utilizing the information given in Figure 6-9. This can be easily seen using the following analogy:
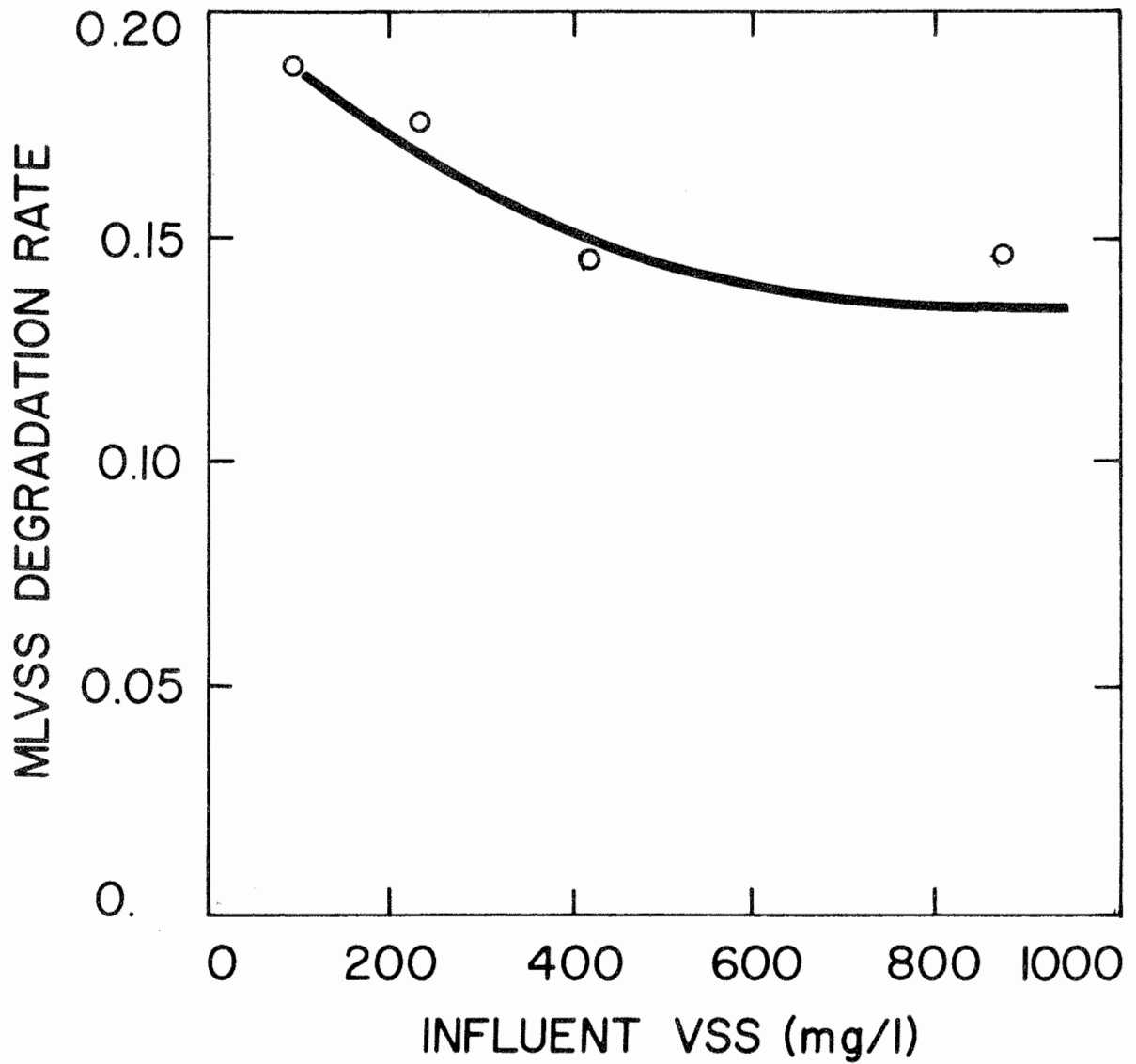
FIG.6-10. MLVSS DEGRADATION AND
INFLUENT VSS

56
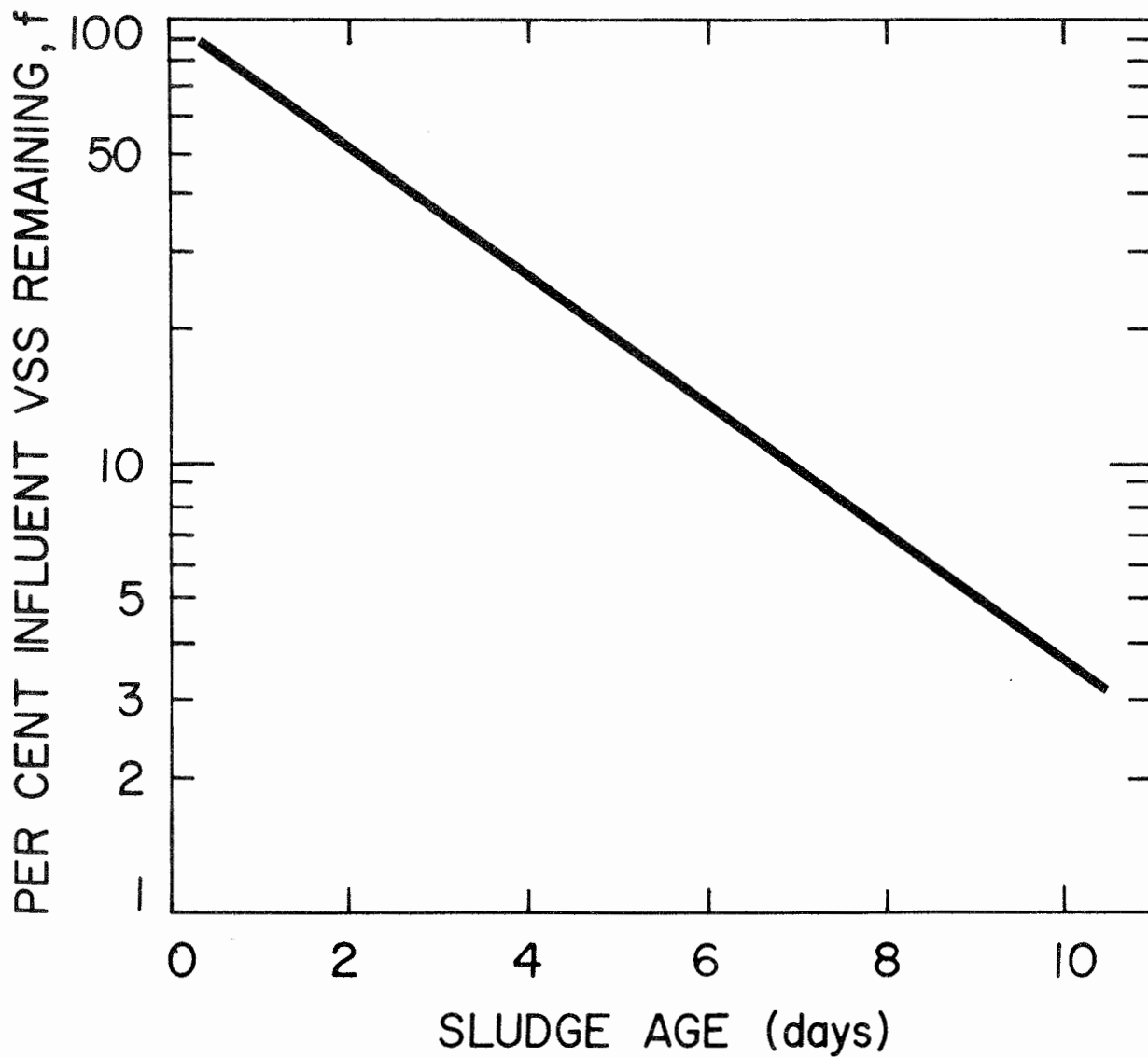
FIG. 6-11. COEFFICIENT "f" AND SLUDGE AGE

$$\frac{X_1}{X_O} = 10^{-K't} \tag{6-3}$$

where: X_O = initial solids concentration

X_1 = solids concentration after time, t

K' = solids degradation rate

t = time

If $t = 1$ day Equation 6-3 becomes,

$$\frac{X_1}{X_O} = 10^{-K'} \tag{6-4}$$

This is the fraction of solids remaining after one day. Since "b" is the fraction oxidized per day we can say,

$$b = (1 - \frac{X_1}{X_O}) \tag{6-5}$$

Utilizing Equation 6-5, values of "b" were determined at each influent volatile suspended solids loading in the batch study. These values are presented in Table 6-15. Values of "b" were then plotted against influent volatile suspended solids to

Table 6-15. Determination of Coefficient "b" Batch Study

Unit	K'	$1/10^{K'}$	b (/day)	X_O,v (mg/l)
1	0.188	0.65	0.35	92
2	0.175	0.67	0.33	230
3	0.145	0.72	0.28	420
4	0.146	0.72	0.28	880

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determine the amount of variation with this parameter. This is
shown in Figure 6-12 and indicates that there is a variation of
the endogenous respiration coefficient with $X_{o,v}$. This is
reasonable since the amount of volatile solids remaining after
any period of time is also dependent on the amount of influent
volatile suspended solids present.

The magnitude of the calculated values of "b" are
quite high when compared to other reported values. However,
it must be recognized that this coefficient was determined by
using only the biodegradable portion of the MLVSS and thus, the
coefficient applies to only biodegradable solids. Since it is
not always possible to determine $X_{v,b}$, Figures 6-7 and 6-8
can give a reasonable estimate of the biodegradable portion
of a biological sludge. Based on these plots, it appears that
an average of 45 percent of the sludge was biodegradable.

6-6   Summary of Batch Study

The data obtained in the batch study phase of this
investigation can be summarized as follows:

(1) The coefficient "f" was determined and was
found to vary according to the relationship shown by Equation 6-1.
This coefficient varies with the sludge age and also the
influent volatile suspended solids degradation rate, K_v. The
value of K_v was determined to be 0.14.

(2) The endogenous respiration coefficient was
also determined and it was found to vary with influent volatile

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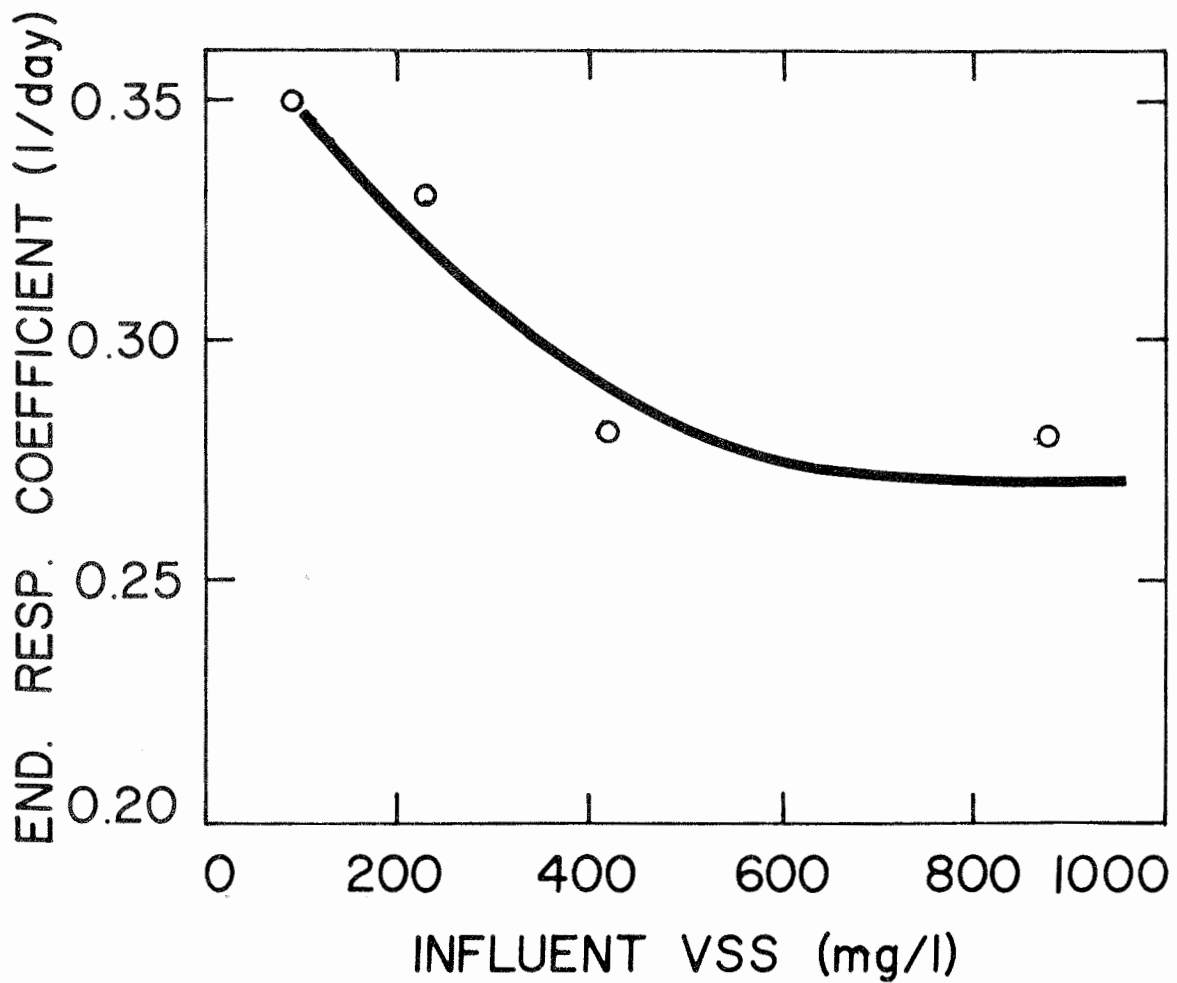
FIG. 6-12. ENDOGENOUS RESPIRATION
COEFF. AND INFLUENT VSS

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suspended solids according to the relationship described in Figure 6-12. The coefficients determined should only be applied to the biodegradable portion of a biological sludge. A good estimate of this biodegradable portion was determined to be 45 percent.

6-7   Determination of Coefficient "a"

In order to compute the amount of cellular material produced when organic substrate is utilized, it will be necessary to return to the volatile solids buildup model. As was previously stated,

$$\Delta X_V = as^*_{o,r} + a((s'_{o,r} - s^*_{o,r})(1-f)) - bX_V + fX_{o,v} \quad (3-3)$$

where: ΔX_V = total VSS produced per unit of time

a = mg VSS produced/mg organic substrate removed

$s^*_{o,r}$ = soluble organic substrate removed per unit of time

$s'_{o,r}$ = total organic substrate removed per unit of time

f = fraction of influent volatile suspended solids remaining

b = mg VSS/mgMLVSS/unit of time

X_V = average MLVSS over a period of time

$X_{o,v}$ = influent volatile suspended solids fed per unit of time.

Inspection of Equation 3-3 reveals that the only variable which was not computed or experimentally determined from the continuous flow and batch studies is the coefficient "a".

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Therefore, by substituting the known experimental parameters
and solving the equation for "a", values for this coefficient
can be obtained. This has been done and the figures are
presented in Table 6-16. The values of "a" presented vary from
one run to the other, and at first impression this would seem
to indicate that this coefficient varies with the MLVSS concen-
tration, however, closer inspection reveals that "a" cannot
vary since the same amount of cells produced per unit of substrate
removed has to remain constant. Therefore, the difference must
lie in some other term of the mathematical model.

It was previously found that dividing ΔX_V by the
MLVSS concentration eliminated any discrepancy there was in
solids buildup from Run #1 to Run #2. (Figure 6-6) If the
coefficient "a" is also divided by the MLVSS concentration,
the difference again disappears and "a" becomes constant in
both runs. This is shown in Figure 6-13. Therefore, it appears
that the discrepancy lies in the fact that X_V is used as the
measure of viable organisms present.

Wuhrmann (1964) has presented data on the variation
of viable organisms as MLSS concentration increases and these
figures are presented below. The percentage of viable

MLSS (mg/l)	0	600	3300	6000
% Active	100	96	74	58

organisms decreases as MLSS concentration increases. Using
X_V as a measure of viable organisms, assumes that the percentage

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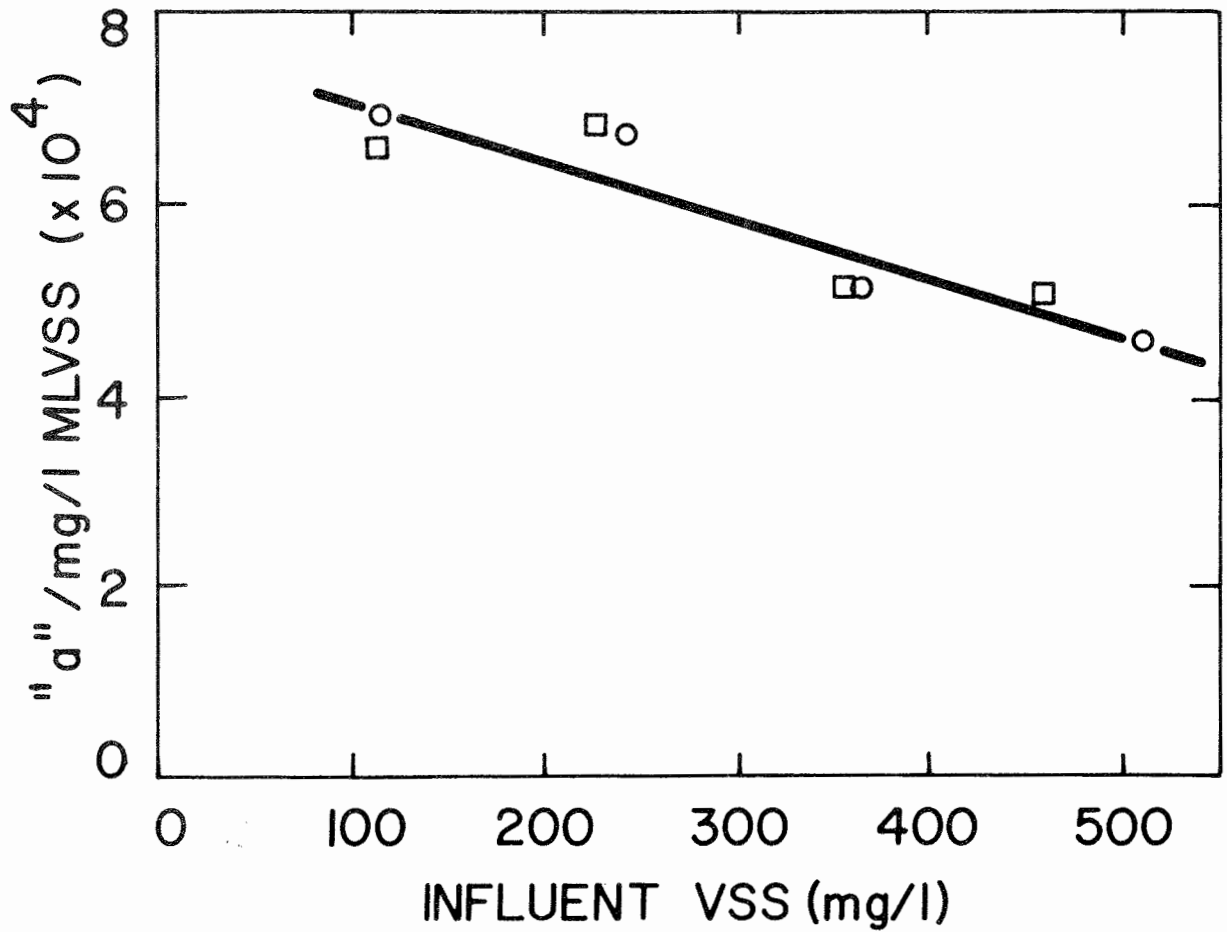
FIG. 6-13. COEFFICIENT "a" AND
INFLUENT VSS

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Table 6-16: Computation of Coefficient "a"
Continuous Runs #1 and #2

Run	Unit	X_v (g/day)	X_v (g)	G (days)	f	b (1/day)	$S^*_{o,r}$ (g/day)	$S'_{o,r}$ (g/day)	$X_{o,v}$ (g/day)	Computed "a"
1	1	1.56	17.0	10.90	0.03	0.345	0.72	2.84	3.26	1.27
	2	2.66	18.1	6.80	0.11	0.316	0.60	3.29	6.70	1.50
	3	2.86	19.2	6.70	0.12	0.296	0.66	3.96	9.21	1.22
	4	3.33	19.2	5.77	0.15	0.278	0.68	3.95	12.3	1.10
2	1	1.55	22.1	14.20	0.011	0.346	0.85	2.72	3.20	1.80
	2	3.24	22.2	6.85	0.110	0.320	0.78	3.29	6.40	1.89
	3	3.44	23.9	6.94	0.106	0.296	0.64	4.06	9.50	1.52
	4	4.47	23.6	5.29	0.182	0.282	0.66	4.24	11.50	1.48

of viable organisms remains the same as X_V increases and as
is shown, this is not true. Therefore, in order to compute
the exact amount of volatile solids produced, it seems that the
actual number of viable organisms should be used instead of an
estimate.

In making this observation based on the data of
Wuhrmann, it is realized that the data he presents is for only
one sludge age. It must be recognized that the number of viable
organisms will also change as the sludge age changes. This
analogy is valid when applied to the experimental results of
this study only because the sludge ages of the units being
compared are approximately equal.

6-8   Computation of Coefficients a' and b'

Based on the oxygen data collected in the continuous-
flow phase, it is possible to obtain estimates of the coefficients
a' and b' by plotting the oxygen model, Equation 3-5.

$$O_2/t = a' s^*_{o,r} + a'((s'_{o,r} - s^*_{o,r})(1-f)) + b'X_V \quad (3-5)$$

where: O_2/t = total oxygen utilized per unit
                        of time

           a'   = mgO_2 used/mg organic substrate
                        removed

           $s^*_{o,r}$ = soluble organic substrate utilized
                        per unit of time

           $s'_{o,r}$ = total organic substrate removed
                        per unit of time

           f   = fraction of influent volatile
                        suspended solids which are
                        not degraded

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$$b' = mgO_2/mgMLVSS/unit\ of\ time$$

$$X_V = MLVSS\ concentration$$

Compilation of the variables of Equation 3-5 give the values
shown in Table 6-17. A plot of these values is shown in
Figure 6-14 from which estimates of a' and b' are obtained.

Table 6-17. Correlation of Oxygen Uptake Data
Continuous Runs #1 and #2

Run	Unit	$\dfrac{O_2/t}{X_V}$ $\left(\dfrac{gmO_2/day}{gm\ MLVSS}\right)$	$\dfrac{s^*_{o,r}+(s'_{o,r}-s^*_{o,r})(1-f)}{X_V}$ $\left(\dfrac{gmTOCrem/day}{gmMLVSS}\right)$
1	1	0.485	0.170
	2	0.496	0.178
	3	0.483	0.202
	4	0.467	0.197
2	1	0.314	0.118
	2	0.360	0.130
	3	0.348	0.150
	4	0.336	0.148

From this figure, a' = 2.45 and b' = 0.020 on a TOC basis.
It must be realized that these are average values for the
experiments which were performed and it could be possible
to obtain different values if drastically different conditions
prevailed. However, since these values were compiled over a
wide range of influent solids loadings, it is probable that the
above estimates of a' and b' would be accurate under normal
operating conditions.

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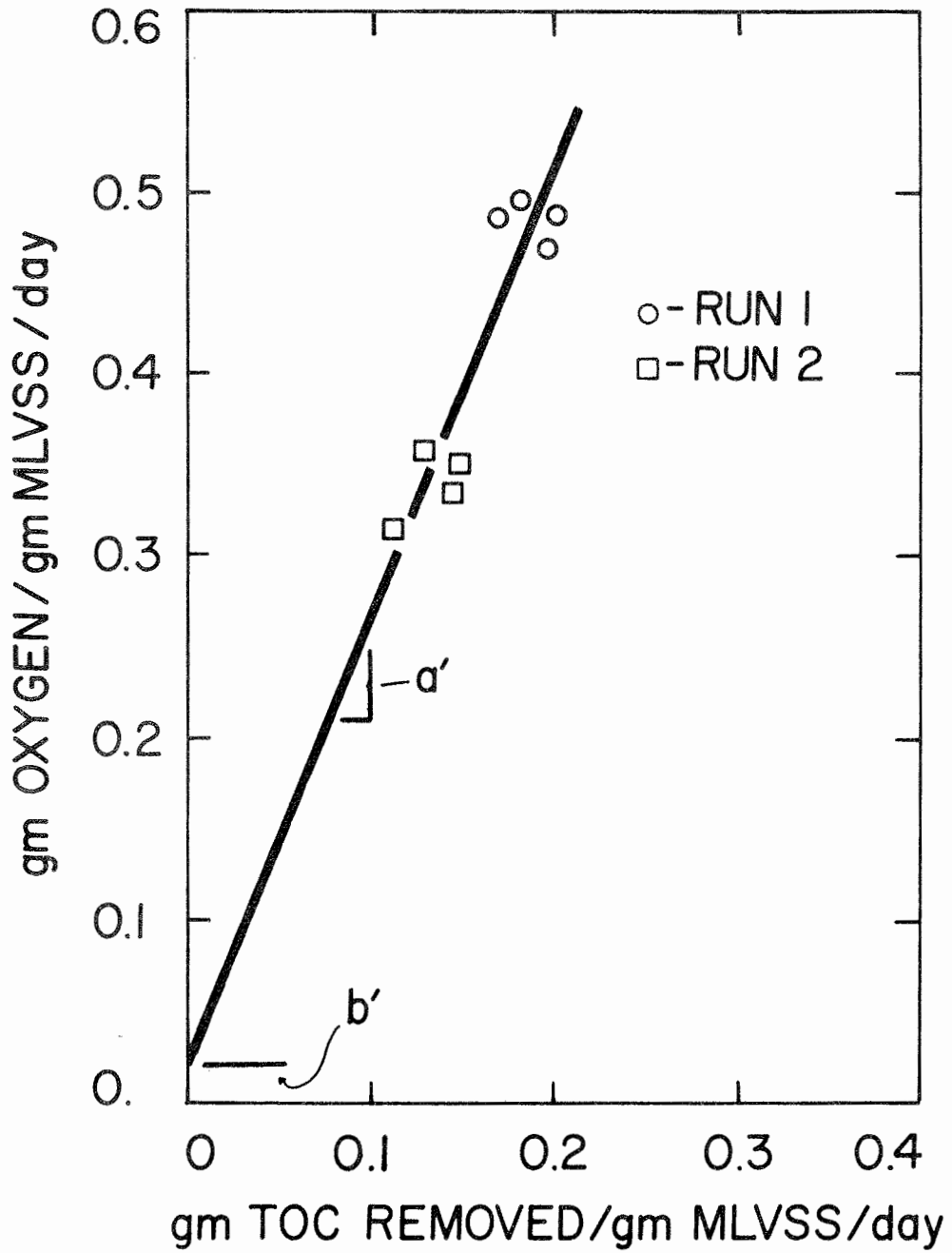
FIG. 6-14. DETERMINATION OF
COEFFICIENTS a′ AND b′

7. DISCUSSION

The main purpose of this study was to develop the volatile solids buildup and oxygen requirement mathematical models so that the effects of influent volatile suspended solids on these relationships could be accounted for. It was also desired to obtain values for the coefficients of the models so that they could be effectively utilized under actual field conditions.

Since these objectives have been accomplished in the previous discussion, it is now of prime importance to insure that the design engineer has a firm grasp on the methodology required to utilize these relationships in actual field design. Probably the best way to demonstrate this is by an actual solved example of a theoretical design condition.

7-1   Example Problem

Estimate the volatile solids buildup and oxygen requirement for an activated sludge treatment plant with the following conditions:

$$X_v = 2500 \text{ mg/l}$$
$$X_{o,v} = 200 \text{ mg/l}$$
$$\text{Flow} = 100,000 \text{ gpd}$$
$$\text{Detention Time} = 4 \text{ hours}$$
$$\text{Total TOC} = 125 \text{ mg/l}$$
$$\text{Soluble TOC} = 40 \text{ mg/l}$$
$$\% \text{ Removal} = 90 \text{ percent}$$

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(1) Volatile Solids Accumulation

Utilizing Equation 3-3.

$$\Delta X_v = a s^*_{o,r} + a((s'_{o,r} - s^*_{o,r})(1-f)) - bX_v + fX_{o,v}$$

where: ΔX_v = total VSS produced per unit of time

a = mg VSS produced/mg organic substrate removed

$s^*_{o,r}$ = soluble organic substrate removed per unit of time

$s'_{o,r}$ = total organic substrate removed per unit of time

f = fraction of influent volatile suspended solids remaining

b = mg VSS oxidized/mg MLVSS/unit of time

X_v = average MLVSS over a period of time

$X_{o,v}$ = total influent volatile suspended solids fed per unit of time

Converting known values to a flow basis,

$$\text{Flow} = 100,000 \text{ gpd}$$

$$\Delta X_v = 2500\text{mg/l} \times 100,000\text{gpd} \times 3.79\text{liters/gal} \times \frac{4}{24}$$

$$\Delta X_v = 1.58 \times 10^5 \text{g} \times 2.21 \times 10^{-3}\text{lb/g}$$

$$\Delta X_v = 350 \text{ lb}$$

$$X_{o,v} = 200 \text{ mg/l} \times 100,000\text{gpd} \times 3.79 \text{ l/gal}$$

$$= 7.6 \times 10^4 \text{g/day} \times 2.21 \times 10^{-3}\text{lb/g}$$

$$X_{o,v} = 168 \text{ lb/day}$$

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$$s^*_o = 40\text{mg/l} \times 100{,}000 \text{ gal/day} \times 3.79 \text{ l/gal}$$

$$s^*_o = 1.52 \times 10^4 \text{g/day} \times 2.21 \times 10^{-3}\text{lb/g}$$

$$s^*_o = 33.3 \text{ lb/day}$$

$$s^*_{o,r} = 33.6 \times 0.90$$

$$s^*_{o,r} = 30.3 \text{ lb/day}$$

$$s'_o = 125\text{mg/l} \times 100{,}000 \text{ gal/day} \times 3.79 \text{ l/gal}$$

$$s'_o = 4.73 \times 10^4 \text{g/day} \times 2.21 \times 10^{-3}\text{lb/g}$$

$$s'_o = 105 \text{ lb/day}$$

$$s'_{o,r} = 105 \times 0.90$$

$$s'_{o,r} = 94.5 \text{ lb/day}$$

Estimates of the coefficients must now be made. Since it is improbable that the design engineer will have access to the amount of viable organisms present, X_v will be used in the model and the discrepancy introduced by using this term will be accounted for in the selected value of "a". Using Figure 6-13 a value of a/X_v is obtained which will eliminate the difference in sludge accumulation caused by using X_v as an estimate of viable organisms. From Figure 6-13,

$$a/X_v = 6.1 \times 10^{-4}$$

For
$$X_v = 2500\text{mg/l}$$

$$a = 6.1 \times 10^{-4} \times 2500$$

$$a = 1.52$$

Selection of the coefficient "b" can be made from Figure 6-12. From this plot, $b = 0.324$/day. It must be

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remembered that this coefficient applies only to the biodegradable MLVSS and if X_v is used, it must be multiplied by 0.45 to obtain $X_{v,b}$.

Since the sludge age of the system is not known, an estimate must be made so that ΔX_v can be computed. Once ΔX_v is computed, the sludge age can be calculated and the solids buildup can be readjusted for the true sludge age. Assuming a value of 4 days for the sludge age, "f" can be determined from Figure 6-11. At this sludge age, f = 0.27 which indicates that 27 percent of $X_{o,v}$ remains after a 4 day period.

Substituting these values in Equation 3-3 yields,

$$\Delta X_v = as^*_{o,r} + a((s'_{o,r} - s^*_{o,r})(1-f) - bX_v + fX_{o,v}$$
$$= 1.52(30.3) + 1.52(94.5 - 30.3)(1-0.27) - 0.345 (350)(0.45) + 0.27(168)$$
$$= 46.2 + 71.5 - 54.3 + 45.3$$
$$\Delta X_v = 108.7 \text{ lb/day}$$

Computing the actual sludge age,

$$G = \frac{X_v}{\Delta X_v}$$
$$G = \frac{350}{108.7}$$
$$G = 3.23 \text{ days}$$

Therefore, the original estimate of 4 days was in error and ΔX_v must be recomputed. For G = 3.23 days, f = 0.35 and recomputing ΔX_v yields,

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$$\Delta X_V \;=\; 1.52(30.3)+1.52(94.5-30.3)(1-0.35)-$$
$$0.345(350)(0.45)+0.35(168)$$

$$=\; 46.2 + 63.6 - 54.3 + 58.7$$

$$\Delta X_V \;=\; 104.9 \text{ lb/day}$$

A check on the sludge age shows,

$$G \;=\; \frac{350}{104.9}$$

$$G \;=\; 3.31 \text{ days}$$

This adjusted value is assumed to be close enough to the
second assumption. Therefore, the sludge age of this system
is 3.23 days and has an average daily volatile solids buildup
of 104.9 lb/day.

(2) Oxygen Requirement

In a similar manner, the oxygen requirement can be
computed. Using the average values of a' and b' as 2.45 and
0.020/day and substituting in Equation 3-5 gives,

$$O_2/t \;=\; a's^*_{o,r}+a'((s'_{o,r}-s^*_{o,r})(1-f))+b'X_V$$

$$=\; 2.45(30.3)+2.45(94.5-30.3)(1-0.35)+0.02(350)$$

$$=\; 74.2 + 102.2 + 7.0$$

$$O_2/t \;=\; 183.4 \text{ lb/day}$$

Therefore, facilities must be designed to handle an
average volatile solids buildup of approximately 105 lb/day
and to provide 183 lb of oxygen per day to the microorganisms.

7-2   Interrelationships of Coefficients

One problem remains to be considered, that of errors
which could be introduced if the coefficients chosen were not

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of the correct magnitude. In other words, what would happen if the design engineer did not have access to the plots generated in this study?

The first coefficient analyzed will be "f", or the fraction remaining after a certain sludge age. An inspection of Equation 3-3 shows that an incorrect value of "f" does not cause an error of large magnitude in the final ΔX_V calculation. This is because both "f" and (1-f) are accounted for in the equation. A wrong value for "f" will be compensated by the (1-f) term. However, it must be remembered that each of these terms is multiplied by a different factor and therefore must still be considered.

If the endogenous respiration coefficient, "b", was also incorrectly selected, little error would again occur, due to the small magnitude of this value. An error of 50 percent in the estimation of "b" in Example 1, incorporates only a 15 percent error in the final ΔX_V value. It must be realized however, that if this error in selection rises much above 50 percent it could then significantly affect the final answer.

It appears that an error in the estimate of the value of the coefficient "a" could cause the most damage. A 50 percent variation of "a" causes about a 60 percent error in the final ΔX_V calculation. Therefore, it is important that a good estimate of this value be obtained. It should be noted that the value of a = 1.52 used in Example 1 is comparable to those reported in previous soluble substrate studies, thus,

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if the design engineer were to base his estimate on previously published figures, he would come reasonably close to the desired value.

APPENDIX A

Continuous Run #1

Influent and Effluent Soluble TOC
(mg/1)

Date	Unit 1 Inf.	Unit 1 Eff.	Unit 2 Inf.	Unit 2 Eff.	Unit 3 Inf.	Unit 3 Eff.	Unit 4 Inf.	Unit 4 Eff.
1/22	39	—	34	—	41	—	40	—
1/23	—	—	—	—	—	—	—	—
1/24	42	26	48	20	41	18	42	15
1/25	30	20	39	20	32	17	29	—
1/26	—	—	—	—	—	—	—	—
1/27	34	18	37	18	46	16	49	15
1/28	41	16	42	17	48	14	43	14
1/29	—	15	—	15	—	19	—	12
1/30	58	21	49	18	49	29	49	—
1/31	39	13	34	13	38	15	33	16
2/1	31	14	19	16	36	12	24	18
2/2	—	—	—	—	—	—	—	—
2/3	30	—	31	9	34	8	45	8
2/4	48	5	42	—	42	10	49	12
2/5	38	11	36	13	40	11	42	16
2/6	29	7	10	10	37	—	37	—
2/7	—	—	—	—	—	—	—	—
2/8	—	8	—	13	—	14	—	14
2/9	—	—	—	—	—	—	—	—
2/10	42	6	42	8	31	15	50	11
2/11	58	7	47	10	53	11	57	14
2/12	37	16	33	16	53	14	39	10
Avg.	40	14	36	14	41	15	42	13

APPENDIX A-2

Continuous Run #1

Influent and Effluent Total TOC
(mg/l)

Date	Unit 1		Unit 2		Unit 3		Unit 4	
	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.
1/22	84	-	141	-	147	-	105	-
1/23	-	-	-	-	-	-	-	-
1/24	81	36	139	39	311	19	213	21
1/25	86	58	107	58	163	33	314	-
1/26	-	-	-	-	-	-	-	-
1/27	79	24	138	24	159	16	172	22
1/28	182	26	172	26	190	22	191	20
1/29	-	22	-	22	-	35	-	24
1/30	156	23	234	23	213	30	238	29
1/31	135	19	116	19	143	18	177	20
2/1	75	27	87	20	222	17	203	20
2/2	-	-	-	-	-	-	-	-
2/3	99	8	123	12	135	8	179	15
2/4	181	7	178	11	218	16	223	11
2/5	281	21	184	32	212	20	281	23
2/6	107	15	166	20	103	16	149	-
2/7	-	-	-	-	-	-	-	-
2/8	-	15	-	37	-	27	-	24
2/9	-	-	-	-	-	-	-	-
2/10	122	21	121	32	118	21	121	26
2/11	127	23	214	48	172	19	229	45
2/12	75	26	130	42	170	43	142	60
Avg.	125	23	150	29	178	22	195	26

APPENDIX A-3

Continuous Run #1

Influent Suspended Solids
(mg/l)

Date	Unit 1		Unit 2		Unit 3		Unit 4	
	Total	Volatile	Total	Volatile	Total	Volatile	Total	Volatile
1/22	92	92	188	188	372	372	672	624
1/23	136	136	340	328	508	484	924	864
1/24	132	94	280	220	612	508	800	692
1/25	104	56	252	188	448	352	572	468
1/26								
1/27	156	156	336	320	392	372	692	644
1/28	140	120	272	244	392	344	396	356
1/29								
1/30	168	128	368	296	480	396	504	428
1/31	164	124	272	228	344	280	432	368
2/1	68	68	204	204	272	260	324	320
2/2								
2/3	128	100	236	188	296	232	488	416
2/4	188	172	308	280	428	380	624	552
2/5	124	108	260	216	312	268	600	516
2/6	124	124	240	224	388	360	516	472
2/7	176	168	364	336	496	448	504	448
Avg.	136	117	280	247	410	362	574	510
% Vol.	86		88		88		89	

APPENDIX A-4

Continuous Run #1

Oxygen Uptake Summary

Date	Unit 1 r (mg/l/hr)	MLVSS (mg/l)	k_r ($\frac{mgO_2/hr}{gmMLVSS}$)	Unit 2 r (mg/l/hr)	MLVSS (mg/l)	k_r ($\frac{mgO_2/hr}{gmMLVSS}$)
1/25	41.2	2070	19.9	51.4	2410	21.3
1/27	46.7	1910	24.3	46.7	1900	24.3
1/28	43.0	1940	22.1	41.7	1970	21.8
1/30	30.8	1640	18.8	44.6	1850	24.1
1/31	38.2	2040	18.7	43.4	2330	18.6
2/1	47.1	2120	22.2	49.8	2300	21.6
2/4	31.1	2070	15.0	33.8	2080	16.2
2/5	37.7	2190	17.2	37.7	2010	18.8
2/6	41.9	2040	20.5	37.0	2260	16.3
2/7	53.0	2150	24.6	58.6	2260	25.9
2/8	39.5	2030	19.4	43.8	2330	18.8
Avg.	41.1	2010	20.2	44.3	2150	20.7

Date	Unit 3 r (mg/l/hr)	MLVSS (mg/l)	k_r ($\frac{mgO_2/hr}{gmMLVSS}$)	Unit 4 r (mg/l/hr)	MLVSS (mg/l)	k_r ($\frac{mgO_2/hr}{gmMLVSS}$)
1/25	46.3	2470	18.7	42.4	2310	18.3
1/27	41.6	1930	21.5	41.6	1920	21.6
1/28	40.4	1890	22.7	36.7	1800	23.9
1/30	44.6	1930	23.1	42.0	2040	20.6
1/31	45.2	2290	19.7	41.7	2280	18.3
2/1	44.3	2770	15.9	41.5	2010	20.6
2/4	36.7	2360	15.6	33.8	2290	14.8
2/5	40.2	2040	19.7	40.2	2230	18.0
2/6	41.9	2110	19.8			
2/7	53.0	2420	21.9	39.0	2040	19.2
2/8	44.9	2010	22.3	41.6	2100	19.8
Avg.	43.5	2200	20.1	40.1	2100	19.5

APPENDIX A-5

Continuous Run #1

Solids Correlations
(mg/l)

Date	Unit 1		Unit 2		Unit 3		Unit 4	
	MLSS	MLVSS	MLSS	MLVSS	MLSS	MLVSS	MLSS	MLVSS
1/22								
1/23	3200	2620	3660	2995	3350	2625	3530	2795
1/24	2900	2305	3030	2405	3580	2795	3770	2910
1/25	2710	2210	2940	2390	3715	3050	3055	2430
1/26	2310		2300		3445		3560	
1/27								
1/28	2410	1985	2640	2165	2725	2285	2555	2145
1/29	2420	1930	2690	2195	2680	2225	2645	2120
1/30			2310	1810	2295	1905	2465	2045
1/31	2215	1855	2725	2250	2590	2220	2690	2300
2/1	2545	2095	2870	2335	3005	2530	3195	2590
2/2	2430	1960	2505	2110	2840	2125	2390	2175
2/3		1960		2325		2185		2175
2/4	2335	2210	2885	2235	2650	2480	2605	2510
2/5	2705	2225	2765	2095	2990	2375	2995	2100
2/6	2675	2135	2555	2245	2845	2180	2490	1930
2/7	2575	3250	2665	2155	2550	2725	2290	2465
2/8	2720		2625		3275		2910	
Avg.	2580	2130	2740	2260	2970	2400	2880	2400
% Vol.	83		83		81		83	

APPENDIX A-6

Continuous Run #1

Daily Amount of Sludge Wasting

Date	Unit #1 (liters)	Unit #2 (liters)	Unit #3 (liters)	Unit #4 (liters)
1/22	0.06	0.34	1.16	2.37
1/23	0.61	0.55	0.68	1.85
1/24	0	0	0.59	0
1/25	0	0	0	0
1/26	0	0	0	0
1/27	0.55	1.74	2.16	2.52
1/28	0	1.49	2.10	2.10
1/29	0	0.35	0.21	0
1/30	1.66	1.20	1.84	1.62
1/31	0.41	1.20	1.38	1.72
2/1	0	0	0	0
2/2	0	0	0	0
2/3	0.85	1.18	0.97	2.43
2/4	0.95	1.04	0.74	1.29
2/5	0.25	0.62	1.97	0
2/6	0.68	-	0.49	0
2/7	0.71	-	1.34	2.35
Avg.	0.395	0.65	0.92	1.07

APPENDIX A-7

Continuous Run #1

MLVSS Concentration at Sludge Wasting

Date	Unit #1 (mg/l)	Unit #2 (mg/l)	Unit #3 (mg/l)	Unit #4 (mg/l)
1/22	2630	3060	2830	3280
1/23	2390	2480	2920	3290
1/24	—	—	3120	—
1/25	—	—	—	—
1/26	—	—	—	—
1/27	2060	2430	2640	2370
1/28	—	2420	2560	2440
1/29	—	1850	1930	—
1/30	2070	2650	2510	2560
1/31	2150	2340	2770	2900
2/1	—	—	—	—
2/2	—	—	—	—
2/3	2070	2510	2380	2310
2/4	2350	2390	2600	2730
2/5	2260	2180	2710	—
2/6	2230	—	2250	—
2/7	2360	—	3030	2890
Avg.	2257	2531	2636	2752

APPENDIX A-8

Continuous Run #1

Effluent Suspended Solids
(mg/l)

Date	Unit 1		Unit 2		Unit 3		Unit 4	
	Tot.	Vol.	Tot.	Vol.	Tot.	Vol.	Tot.	Vol.
1/23	45	37	103	95	28	22	50	47
1/24	32	24	50	44	17	14	13	11
1/25	65	62	55	51	8	6	∞	∞
1/26	∞	∞	∞	∞	∞	∞	∞	∞
1/27	102	88	116	108	17	13	35	31
1/28	50	42	30	26	35	32	40	36
1/29	3	1	35	25	44	40	17	14
1/30	25	22	25	17	25	22	28	24
1/31	15	10	25	15	18	13	30	25
2/1	30	26	15	12	15	10	15	12
2/2	∞	∞	∞	∞	∞	∞	∞	∞
2/3	10	7	8	6	14	9	25	19
2/4	18	11	25	20	13	9	23	19
2/5	23	19	50	46	35	28	25	22
2/6	10	5	23	19	4	2	∞	∞
2/7	12	8	50	44	19	16	23	20
2/8	5	3	51	44	20	15	38	35
Avg.	29	24	44	38	21	17	28	24
% Vol.	83		87		82		86	

APPENDIX A-9

Continuous Run #2

Influent and Effluent Soluble TOC
(mg/l)

Date	Unit 1 Inf.	Eff.	Unit 2 Inf.	Eff.	Unit 3 Inf.	Eff.	Unit 4 Inf.	Eff.
2/25	48		48		43		50	
2/26	34	16	39	18	44	21	38	19
2/27	35	20	37	18	32	23	32	23
3/3	31	11	33	13	34	13	28	16
3/5	52	20	50	16	47	17	53	19
3/6	38	16	40	15	43	18	49	17
3/11	24	8	27	10	25	10	30	12
3/19	47	14	52	17	41	17	62	21
3/20	66	14	62	16	58	17	60	18
3/26	44	18	40	21	40	21	39	19
3/27	38	18	56	18	49	19	49	17
Avg.	41.5	15.5	44.0	16.2	41.5	17.6	44.5	18.1

APPENDIX A-10

Continuous Run #2

Influent and Effluent Total TOC
(mg/1)

Date	Unit 1 Inf.	Eff.	Unit 2 Inf.	Eff.	Unit 3 Inf.	Eff.	Unit 4 Inf.	Eff.
2/25	240	∞	236	∞	200	∞	206	∞
2/26	104	24	132	31	155	34	250	31
2/27	110	36	112	36	232	31	250	31
2/28	100	30	112	40	120	44	140	47
3/1	123	30	119	30	120	28	142	27
3/2	∞	∞	∞	∞	∞	∞	∞	∞
3/3	179	∞	132	∞	140	∞	176	∞
3/4	232	13	276	26	282	20	294	112
3/5	232	29	238	34	286	34	288	155
3/6	117	24	150	24	214	31	274	71
3/7	120	17	115	19	235	35	200	27
3/8	89	20	93	21	152	24	164	27
3/9	66	16	102	17	120	20	164	20
3/10	95	25	143	19	197	20	148	21
3/11	82	14	126	16	166	16	164	18
3/12	110	15	146	29	166	24	206	26
3/13	106	13	142	39	168	28	196	27
3/14	62	12	108	29	132	29	189	30
3/15	38	7	95	43	124	21	213	19
3/16	65	19	104	20	210	16	130	19
3/17	92	17	92	27	134	20	176	21
3/18	194	16	224	38	222	23	218	19
3/19	130	23	210	30	174	27	288	38
3/20	114	17	144	17	224	20	204	19
3/21	126	29	196	40	182	27	274	32
3/22	94	26	132	47	156	26	216	42
3/23	76	18	108	20	122	20	106	21
3/24	96	20	140	20	188	34	210	21
3/25	66	18	142	26	148	18	210	19
3/26	∞	19	∞	33	168	33	222	25
3/27	∞	20	∞	22	∞	29	∞	18
Avg.	116	20	145	28	177	26	204	35

APPENDIX A-11

Continuous Run #2

Influent Suspended Solids
(mg/l)

Date	Unit 1		Unit 2		Unit 3		Unit 4	
	Total	Volatile	Total	Volatile	Total	Volatile	Total	Volatile
2/26	236	200	220	184	452	408	400	356
2/27	124		132		364		372	
2/28	160	132	344	288	388	316	360	284
3/1	108	92	96	64	192	148	220	172
3/3	128	128	304	248	500	420	660	576
3/4	148	124	320	276	484	388	656	568
3/5	144	132	356	300	452	396	580	488
3/6	140	128	316	280	544	476	716	628
3/7	144	104	264	216	624	500	680	564
3/8	128	108	272	228	392	328	584	504
3/10	184	144	240	188	456	352	532	416
3/11	128	84	208	160	328	236	420	332
3/12	164	164	332	284	432	356	636	560
3/13	168	168	316	288	364	312	492	432
3/14	140	124	292	236	436	382	452	384
3/15	104	76	284	230	484	380	520	416
3/16	96	84	216	168	324	264	424	368
3/17	20	20	144	132	72	72	76	76
3/18	144	96	340	240	376	248	532	412
3/19	120	88	404	296	648	596	576	440
3/20	128	108	192	172	308	260	372	300
3/21	152	120	284	210	380	288	516	416
3/22	124	96	196	144	344	276	408	408
3/24	132	100	332	256	408	284	672	532
3/25	132	96	316	252	468	372	808	124
3/26	132	132	376	340	728	640	708	608
3/27	88	88	288	260	520	452	1092	944
Avg.	134	113	273	228	425	352	535	458
% Vol.	84		84		83		86	

APPENDIX A-12

Continuous Run #2

Oxygen Uptake Summary

	Unit 1				Unit 2	
Date	r (mg/l/hr)	MLVSS (mg/l)	k_r ($\frac{mgO_2/hr}{gmMLVSS}$)	r (mg/l/hr)	MLVSS (mg/l)	k_r ($\frac{mgO_2/hr}{gmMLVSS}$)
2/27	55.7	3220	17.3	52.3	2980	17.5
3/2	38.6	2890	13.4	43.8	2900	15.0
3/4	34.0	2520	13.5	37.8	2190	17.3
3/6	60.4	2710	22.2	54.1	2750	19.7
3/8	40.0	2800	14.3	45.7	2900	15.7
3/11	42.8	3020	14.2	46.2	2870	16.1
3/14	36.0	3020	11.9	46.2	3010	15.3
3/16	37.4	2890	12.9	41.4	2820	14.7
3/18	30.9	2680	11.5	49.4	2910	17.0
3/20	28.0	3010	9.3	42.0	3390	12.3
3/24	38.0	2890	13.1	41.9	2900	14.4
3/25	24.2	2980	8.1	24.2	3220	7.5
Avg.	38.0	2890	13.1	43.8	2900	15.0

	Unit 3				Unit 4	
	r (mg/l/hr)	MLVSS (mg/l)	k_r	r (mg/l/hr)	MLVSS (mg/l)	k_r
2/27	52.3	3170	16.5	49.0	2600	18.8
3/2	44.2	3190	13.8	44.0	3000	14.7
3/4	41.6	2720	15.3	26.5	2350	11.3
3/6	60.4	3520	17.1	58.7	3200	18.3
3/8	48.2	3190	15.1	38.2	2870	13.3
3/11	52.8	3280	16.1	46.2	3290	14.1
3/14	45.1	3000	15.0	41.5	2900	14.3
3/16	46.2	3190	14.5	39.7	2900	13.7
3/18	49.4	3310	14.9	43.2	3010	14.4
3/20	39.2	3390	11.6	36.4	3200	11.4
3/24	47.3	3360	14.0	41.1	2950	14.0
3/25	27.2	2930	9.3	27.2	3080	8.8
Avg.	46.2	3190	14.5	41.1	2950	14.0

APPENDIX A-13

Continuous Run #2

Solids Correlations
(mg/l)

Date	Unit 1		Unit 2		Unit 3		Unit 4	
	MLSS	MLVSS	MLSS	MLVSS	MLSS	MLVSS	MLSS	MLVSS
2/26	3715	3050	3610	2885	3640	2955	3980	3195
2/27	3865	3160	3710	2965	3820	3050	3265	2585
2/28	3300	2670	3065	2445	3250	2615	3160	2525
3/1	3240	2570	2890	2255	3335	2635	3060	2365
3/3	3155	2505	2770	2180	3220	2540	3075	2400
3/4	3180	2495	2820	2170	3275	2565	3030	2365
3/5	3270	2585	2925	2310	3540	2805	3165	2500
3/6	3340	2680	3260	2540	3990	3215	3640	2925
3/7	3545	2825	3820	3010	4115	3475	4240	3420
3/8	3310	2635	3580	2815	3730	3015	3615	2940
3/10	3595	2845	3755	2965	4420	3615	4350	3420
3/11	3855	2980	3605	2765	3840	2995	3895	3130
3/12	3580	2895	3585	2935			3840	3235
3/13	3805	3040	3955	3190	3950	3150	4025	3430
3/14	4050	3210	3845	3100	3995	3235	3920	3225
3/15	3130	2480	3855	3095	3655	2940	3510	2925
3/16	3080	2470	3605	2855	3570	2900	4235	2505
3/17	3100	2425	3790	2980	3630	2960	3840	3140
3/18	3235	2455	3490	2815	3975	3210	3385	2735
3/19	3395	2660	3640	2840	3885	3255	3665	2880
3/20	3730	2860	3995	3065	4005	3165	3785	2980
3/21	3605	2810	3590	2800	3855	3035	3730	2905
3/22	3710	2930	3515	2720	3770	2940	3865	2990
3/24	3645		3800		4015		4020	
3/25	3635	2870	3920	2985	3695	2860	3775	2915
3/26	3780	2890	3670	2775	3865	2975	3940	3060
3/27	3535	2730	3595	2755	3850	2945	3705	2890
3/28	3615	2800	3605	2830	3565	2810	3730	2960
Avg.	3499	2760	3540	2779	3740	2995	3680	2946
% Vol.	79		79		80		80	

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APPENDIX A-14

Continuous Run #2

MLVSS Concentration at Sludge Wasting

Date	Unit #1 (mg/l)	Unit #2 (mg/l)	Unit #3 (mg/l)	Unit #4 (mg/l)
2/26	3220	2980	3170	2600
2/27	—	—	—	—
2/28	—	—	3370	3120
3/1	—	—	—	—
3/2	—	—	—	—
3/3	2520	2190	2720	—
3/4	2650	2430	2910	2650
3/5	2710	2750	3520	3200
3/6	2940	3270	3900	3930
3/7	2570	2950	3060	3200
3/8	2880	3260	4130	4300
3/9	—	—	—	—
3/10	3020	2870	3280	3290
3/11	2910	3090	—	3560
3/12	3170	3380	3210	3960
3/13	3590	3230	3480	3730
3/14	2570	3130	3210	3050
3/15	—	—	3130	3860
3/16	2440	3130	2960	3650
3/17	2680	2910	3310	3010
3/18	2750	3130	3280	3040
3/19	3010	3390	3390	3200
3/20	2860	2990	3200	3070
3/21	3080	2990	3150	3280
3/22	—	—	—	—
3/23	—	—	—	—
3/24	2980	3220	2930	3080
3/25	3100	2970	3150	3410
3/26	2800	3010	3230	3100
3/27	2890	3090	3050	3230
Avg.	2879	3052	3210	3282

APPENDIX A-15

Continuous Run #2

Daily Amount of Sludge Wasting

Date	Unit #1 (liters)	Unit #2 (liters)	Unit #3 (liters)	Unit #4 (liters)
2/26	0.30	0.08	0.50	0.09
2/27	0	0	0	0
2/28	0	0	0.21	0.36
3/1	0	0	0	0
3/2	0	0	0	0
3/3	0.16	0.15	0.91	0
3/4	0.42	0.79	0.52	0.91
3/5	0.18	0.93	1.36	1.37
3/6	0.63	1.27	1.74	2.08
3/7	0	0.73	0.24	1.30
3/8	0.26	1.45	2.00	2.70
3/9	0	0	0	0
3/10	0.21	0.42	1.40	0.78
3/11	0.08	0.80		1.43
3/12	0.65	0.90	0.55	2.14
3/13	1.69	0.65	1.12	2.17
3/14	0.56	0.18	1.32	0.66
3/15	0	0	1.17	1.43
3/16	0.10	0.77	0.72	2.23
3/16	1.34	0.52	0.48	1.46
3/18	0.52	1.48	0.67	0.84
3/19	0.80	1.06	1.06	1.20
3/20	0.28	1.01	0.83	0.89
3/21	0.78	1.17	1.07	1.41
3/22	0	0	1.75	0
3/23	0	0	0	0
3/24	0.59	1.17	0.38	0.86
3/25	1.08	1.05	0.89	1.62
3/26	0.40	1.36	1.41	1.08
3/27	0.50	1.35	1.26	1.31
Avg.	0.383	0.642	0.77	1.01

APPENDIX A-16

Continuous Run #2

Effluent Suspended Solids
(mg/l)

Date	Unit 1 Tot.	Vol.	Unit 2 Tot.	Vol.	Unit 3 Tot.	Vol.	Unit 4 Tot.	Vol.
2/26	18	14	45	42	67	62	35	31
2/27	25	23	62	58	53	48	70	59
2/28	38	34	168	156	60	53	100	82
3/1	19	16	100	92	37	33	50	46
3/2	-	-	-	-	-	-	-	-
3/3	-	-	-	-	-	-	-	-
3/4	24	20	40	35	38	31	160	142
3/5	25	23	34	28	35	29	350	300
3/6	30	27	25	21	42	37	134	126
3/7	8	6	21	18	50	44	30	25
3/8	38	33	30	26	42	36	24	18
3/9	-	-	-	-	-	-	-	-
3/10	52	48	14	10	123	17	28	23
3/11	14	10	18	14	30	24	26	22
3/12	14	10	40	37	32	28	35	30
3/13	8	4	95	70	40	35	36	30
3/14	10	7	43	39	59	52	50	44
3/15	12	10	100	94	35	30	25	18
3/16	19	16	50	40	48	41	24	18
3/17	42	37	103	88	110	103	40	34
3/18	5	3	95	73	25	20	19	15
3/19	24	19	40	36	35	30	54	47
3/20	10	7	23	17	15	11	15	10
3/21	8	6	40	35	32	27	12	9
3/22	12	10	99	73	18	14	16	12
3/23	-	-	-	-	-	-	-	-
3/24	10	8	16	12	23	19	13	9
3/25	9	7	20	16	55	51	16	13
3/26	18	15	53	48	48	41	21	17
3/27	11	9	15	13	38	33	34	27
Avg.	19.3	16.2	53.3	45.8	41.3	36.3	55.4	46.4
% Vol.	84		86		86		84	

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APPENDIX A-17

Batch Study

Decrease in Mixed Liquor Concentration
(mg/1)

Time (days)	Unit 1 MLSS	Unit 1 MLVSS	Unit 2 MLSS	Unit 2 MLVSS	Unit 3 MLSS	Unit 3 MLVSS	Unit 4 MLSS	Unit 4 MLVSS
0	2795	2350	3080	2555	3115	2585	3095	2630
1	2555	2155	2670	2200	2930	2485	2665	2630
2	2165	1785	2200	1810	2415	2010	2385	1975
3	2000	1735	2060	1705	2130	1780	2280	1950
4	1880	1590	1825	1565	2055	1680	2155	1835
5	1720	1465	1790	1475	1850	1575	1990	1690
6	1730	1470	1760	1500	1970	1600	2010	1690
7	1720	1420	1650	1340	1880	1530	1910	1570
8	1690	1450	1530	1300	1630	1400	1770	1500

X_i (mg/1)   106   265   465   965

$X_{i,v}$ (mg/1)   92   230   420   875

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