PACKED-BED REACTORS FOR CONCENTRATED-WASTE TREATMENT AND ENERGY PRODUCTION

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Project No. A-052-PR
Matching Grant Agreement No. 14-34-0001-9041

FINAL TECHNICAL COMPLETION REPORTP
TO
BUREAU OF RECLAMATION
U.S. DEPARTMENT OF THE INTERIOR
WASHINGTON, D.C. 20240

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SECTION 1

INTRODUCTION

During the past years many nations, including Puerto Rico, have been faced with an urgent pollution problem. This consists of how to effectively and economically treat concentrated wastes such as sewage sludge from municipal wastewater treatment plants, wastewaters from rum distillery plants, from various meat and tuna fish packing and from pharmaceutical and petrochemical plants, etc. Some of these wastes are inadequately treated before being discharged into the receiving waters, and some others, unfortunately, are discharged without any treatment at all [6,42]. The pollution effects resulting from the discharge of such wastes are enormous. Foul odors, fish kills, and stream pollution are common in the vicinity of the wastewater discharging points. An effective and economical way to solve this pollution problem is a cause of concern.

For many years, broad scale application of the anaerobic treatment process had been used for the treatment of the high strength wastewaters mentioned above [25,31].

Treating concentrated wastewaters by the anaerobic digestion process may be more economical as to operating costs than treating them by an aerobic process because the sludge production and the energy input are minimal [5]. However, the big drawback of this process is the long detention time required. In a conventional treatment plant this is on the order of 30 days, thus, a digester of large size is needed

The results of a feasibility study on a bench-scale filter [33] encouraged further investigation of the anaerobic filter process. The objetive of this research project was to study the design parameters of the anaerobic filter process such as organic loadings and hydraulic retention time, and the response of the process in relation to organic matter removal and energy production for a typical condition in Puerto Rico. The research was conducted using a bench-scale unit capable of treating several liters of activated sludge per day. The unit was located at a domestic wastewater treatment plant at the Alturas de Mayaguez development. An extensive monitoring program including both gas and liquid analyses was accomplished for the evaluation of the process.

SECTION 2

LITERATURE REVIEW AND GENERAL THEORY

2.1 PREVIOUS INVESTIGATIONS

The anaerobic filter process has been researched and the findings have been discussed in several published works.

Coulter, Soneda, and Ettinger[7] employed an anaerobic filter filled with rock media to retain solids from an anaerobic digester effluent. They noted that BOD removal was achieved although most of the BOD was removed in the preceding digester.

Young and McCarty[45] developed the upflow anaerobic filter in which the facultative and anaerobic bacterias are contained in a film attached to a rock media to remove the organic matter in the wastes. They observed that for a constant organic loading, COD removal increases as influent COD increases. They noted that the major fraction of the COD was removed in the lower level of the filter, particularly with the higher strength wastes. They also found that high loading rates are possible with little production of biological solids for disposal, power requirements are low, and the methane produced by anaerobic treatment is a useful end product.

Haug et al[34], demostrated that the anaerobic filter could reduce the COD in a sludge from 9500 mg/l to 2300 mg/l at 90°F with a retention time of 2 days.

Rivera[33] evaluated the feasibiblity, for Puerto Rico, of producing methane gas as an energy resource, from city sewage, using the anaerobic filter process. He found that by increasing the liquid flow rate from 94.5 to 157.5 ml/min, a fairly good gas production at the latter flow rate was obtained. At this flow rate, Rivera obtained a total gas production at STP of approximately 1.58 ft^3/Lb TSS removed with an average methane content of about 80% by volume.

Lovan et al.[19], used the anaerobic filter for the treatment of brewery press liquor wastes, and as had Young and McCarty, they found that most of the influent COD was removed in the lower level of the filter.

Szendrey[40], working for a rum distillery in Puerto Rico, used the anaerobic filter for the treatment of the rum slops. He used a downflow model to which the cooled and neutralized rum slops were injected through the top of the filter and passed thru the packed bed reactor prior to discharge. Szendrey found that the process removed approximately 70% or more of the organics in the rum slops. The gas produced in the filter was used to feed the boilers and/or compresed and stored under pressure in a gas holding sphere for future use and to provide a smooth and constant flow of gas to the boilers.

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APPENDIX A

GAS CHROMATOGRAPHIC ANALYSIS

GAS CHROMATOGRAPHIC ANALYSIS

EQUIPMENT

Device	Model/Type
Chromatograph	Perkin-Elmer 900
Column	Porapak N. packed material

CALIBRATING CONDITIONS

Scheme	Setting
Injection Port Temperature	30° C
Column Temperature	55° C
Manifold Temperature	110° C
Hot Wire Detector Temperature	200° C
Hot Wire Control	
Temperature	190° C
Current	275ma
Attenuation	X32
Polarity	+
Carrier Gas	Helium
Carrier Gas Flow Rate	30ml/min
Detention Time	
Air	32 Sec
Methane	55 Sec
Carbon Dioxide	150 Sec

2.2 THEORETICAL CONSIDERATIONS

The complete stabilization of organic matter under anaerobic conditions is carried out through the metabolic activity of a highly specialized group of microorganisms in a molecular oxygen-free environment. For the purpose of simplicity, the anaerobic stabilization of the organic matter could be considered as a two stage process, acid forming and gasification. During acid forming, the organic molecules are broken down into smaller molecules. These molecules are solubilized in order to facilitate absorption through the cell wall[2]. In this stage proteins, carbohydrates, and fats are converted into initial and intermediate products which primarily include fatty acids[21]. The stabilization is completed in the second stage when the fatty acids are mostly converted into methane and carbon dioxide.

Methane is the major component of the gas produced. Its production is independent of the structure of the substrate, and under optimum conditions, the ratio of methane to carbon dioxide depends on the state of the substrate after the oxidation[2].

The most important group of microorganisms during the anaerobic stabilization of organic matter, is bacteria. The acid forming stage occurs under the action of facultative and anaerobic bacteria. However, the ease in growth of the facultative bacteria make them predominate over the strict anaerobes[25]. Various species of Pseudomonas, Flavobacterium, Alcaligenes, Escherichia, and Aerobacter are involved in the acid formation[25]. In the gasification stage, strictly anaerobic bacteria are employed[3]. Most of them belong to the genera Methanobacte-

rium, Methanosarcina, and Methanococcus[25]. Many researchers[3,11,31] refer to those bacteria that take place in the first stage, as acid-producing bacteria, and methane-producing bacteria to those that take place in second stage.

The first stage is characterized by no appreciable reduction in BOD (biochemical oxygen demand), or COD (chemical oxygen demand) of the organic matter in suspension or solution[12]. All that takes place is a chemical rearrangement of the organic molecules, a portion is converted to end products, mostly organic acids, and the remaining into new cells. The gas production stage is thus considered to be responsible for the stabilization of the organic matter. Such stabilization is directly proportional to the quantity of methane produced[33]. However, removals resulting from the occasional formation of hydrogen or reduction of inorganic electron acceptors such as sulfates, nitrates, and nitrites are exceptions to this. Under steady state conditions, the acid forming and gasification stage occur simultaneously in a balanced and synchronized way[9]. Figure 2.1 shows the two stages in the anaerobic stabilization of organic matter. Because of the many variables involved and the complex, interrelated, and mixed biological reactions that take place, [27] the anaerobic stabilization of the organic matter should not be considered as simple as presented here. In addition, the process comprises several species of bacteria and each species has been found to have specific requirements and can metabolize only a relatively limited group of organic compounds.

The major portion of the methane produced in the anaerobic treat-

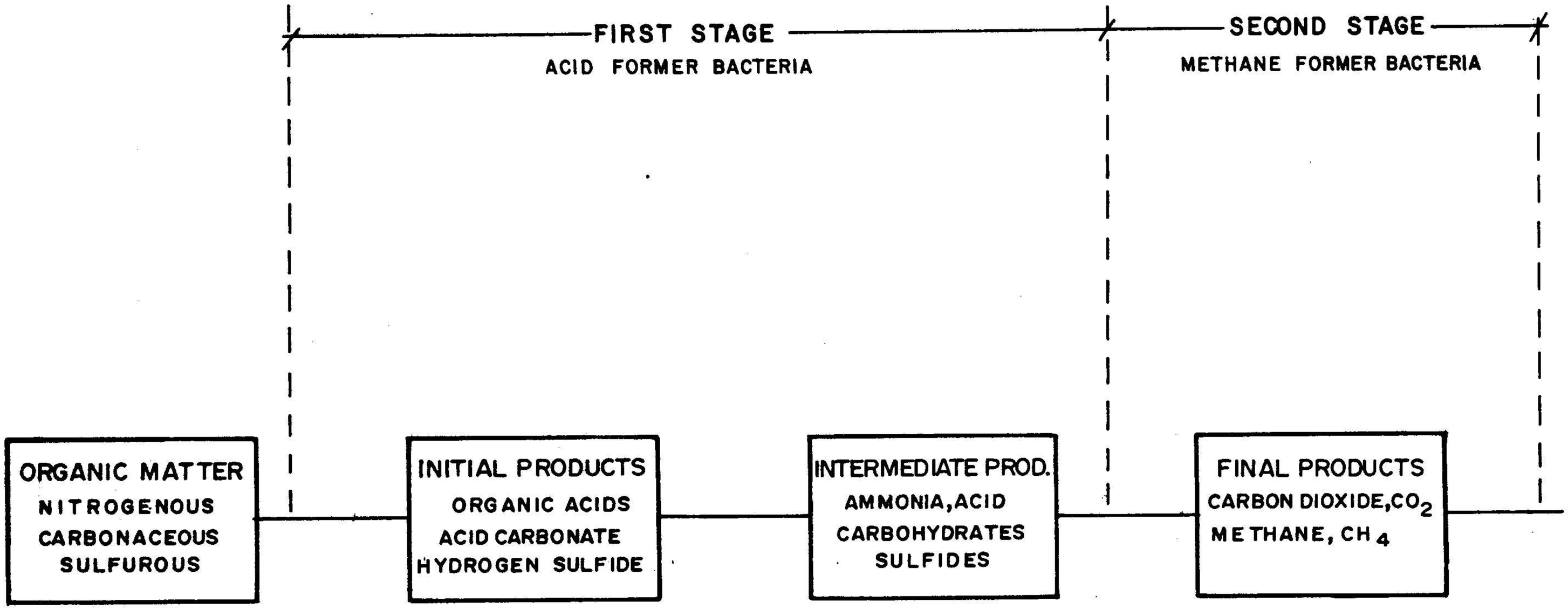


FIG. 2.1 ANAEROBIC STABILIZATION OF ORGANIC MATTER IN TWO STAGES

ment of most wastes results from fermentation of acetic and propionic acids. Approximately 85 percent of the total methane comes from the fermentation of these two acids[21]. About 70 percent results from metabolization of acetic acid, and 15 percent from propionic acid. The remaining appears to result from other sources such as hydrogen and formic acid fermentation[21]. The typical volatile acid intermediates formed during complex organic matter decomposition are acetic, propionic, formic, butyric, and valeric acids. Figure 2.2 shows the pathways by which complex organic matter is converted to methane gas.

Considering methane as an ideal gas, the theoretical volume produce from one pound of COD or BOD_L can be calculated from the oxygen equivalent of methane gas. If 1 lb. (453.6g) of glucose is considered for instance, the methane production is determined from the following analysis:

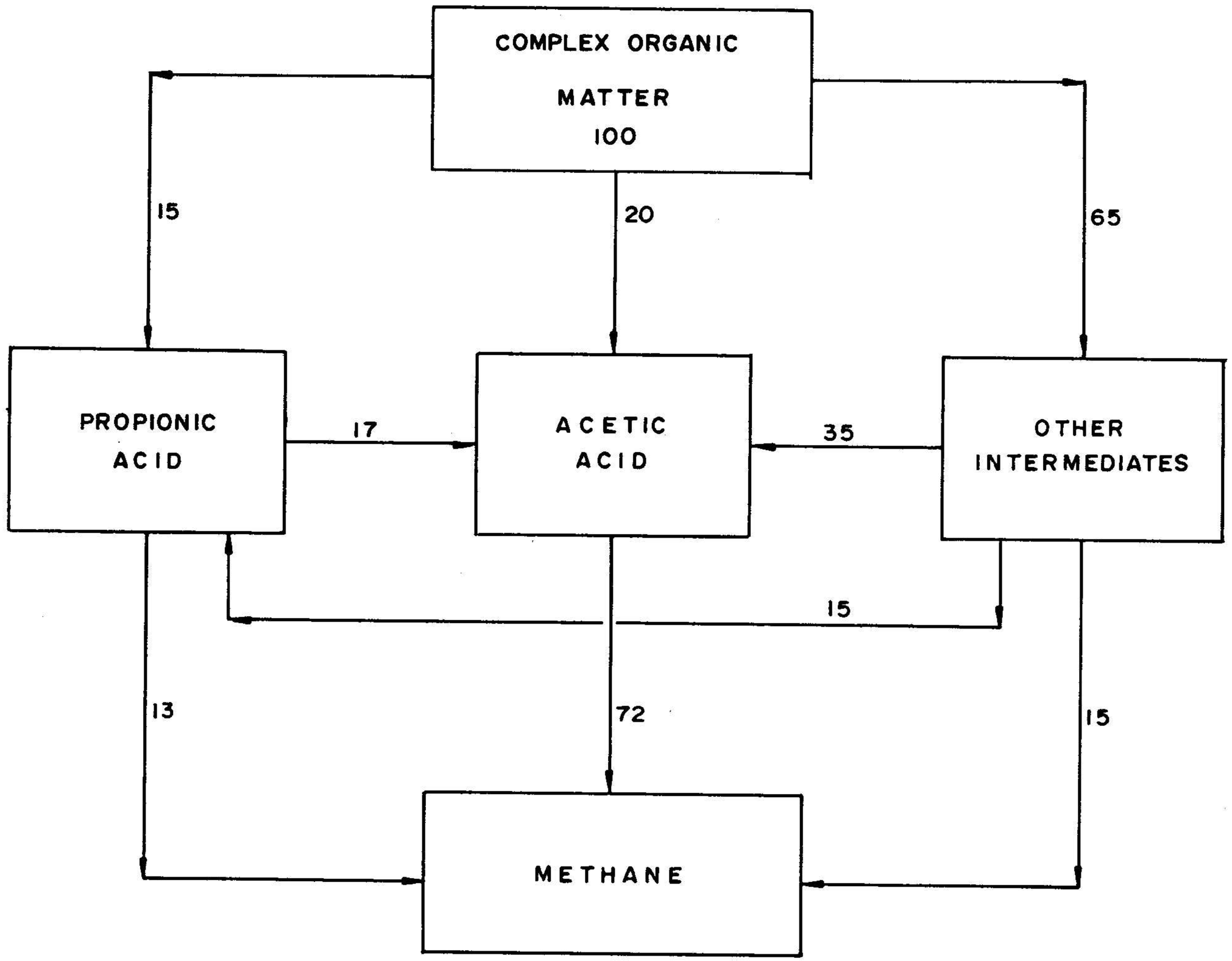
1. Under anaerobic conditions glucose is converted to carbon dioxide and methane as follows:

$$\underset{(180g)}{C_6H_{12}O_6} \longrightarrow \underset{(132g)}{3CO_2} + 3CH_4 \qquad (2\text{-}1)$$

2. The amount of oxygen required to oxidize methane to carbon dioxide and water is:

$$\underset{(48g)}{3CH_4} + \underset{(192g)}{6O_2} + \cdot \longrightarrow 3CO_2 + 6H_2O \qquad (2\text{-}2)$$

From stoichiometric analysis of Equations 2-1 and 2-2, the COD or BOD_L of 1 Lb of glucose is 192/180 Lb, and 1 Lb of glucose yields 48/180 Lb, of methane, so that



NOTES: 1. NUMBERS REPRESENT PERCENTAGE OF WASTE COD CONVERSION
2. INFORMATION OBTAINED FROM REFERENCE NO. 21

FIG. 2.2 FERMENTATION OF COMPLEX ORGANIC MATTER

$$\frac{\text{Lb } CH_4}{\text{Lb } BOD_L} = \frac{48/180}{192/180} = 0.25$$

$$1 \text{ Lb } BOD_L = 0.25 \text{ Lb} \times 453.6 \frac{g}{\text{Lb}} \times \frac{1 \text{ mole}}{16 \text{ g}}$$

$$\times \frac{22.4 \text{ l}}{\text{mole}} \times \frac{1 \text{ cu-ft}}{28.32 \text{ l}} = 5.62 \text{ cu-ft (159 l) of } CH_4 \text{ at}$$

standard temperature and pressure (STP) conditions. STP conditions are defined as the conditions where the temperature and pressure are 32°F (0°C) and 1 atm (101.325 kPa), respectively.

During anaerobic digestion, the kinetics of the slowest stage will control the overall kinetics of waste utilization. This slowest or limiting stage generally is believed to be the methane fermentation[23].

A mixed culture of methane bacteria are responsible for converting the organic acids into methane. Methane-producing bacteria are strictly anaerobes. They have a low rate of reproduction. Most of them are non-motile and are extremely sensitive to changes in pH and temperature[17]. Since the organic acids produced from hydrolysis of complex organic materials results in a depression of the pH as the concentration becomes sufficiently high, it is very important to accurately control the pH. If, because of any environmental condition, the methane bacteria are inhibited, the organic acid concentration will increase, thus, the pH will decrease to such extent that the bacteria culture may be severely affected. In a well-balanced process organic acids are metabolized by methane bacteria as soon as they are produced.

In addition to the excess of volatile fatty acids there are other substances that may affect the efficiency of anaerobic waste stabilization. Heavy metals such as chromium, cadmium, zinc, copper, lead, etc. are generally inhibitory to all bacterial activity[23]. Observation on the effects of copper[24] revealed that a total copper concentration in excess of 200 mg/l is necessary before severe inhibition of bacteria occurs. However, except for chromium, all the heavy metals form insoluble sulfides and are, therefore, likely to be removed from solution and activity by sulfide present in digesting sludge. Ammonia

may also cause inhibitory effects to methane-producing bacteria[22]. It has been found[14] that a total ammonia concentration of 3,000 mg/l at pH of 7.1 partly inhibits the methane bacteria, while 4,000 mg/l cause the complete inhibition of them. An accurate monitoring of the anaerobic waste stabilization should be kept to avoid any substance detrimental to the process.

The knowledge of the kinetics of utilization of the most prevalent volatile fatty acid precursors of methane, i.e., acetic and propionic acids; is a very important element in the development of a rational approach to the analysis and design of anaerobic treatment systems. Toward this end, a summary of what appears to be the most important considerations is discussed herein.

Some researchers [10, 13, 28] have developed empirical expressions to describe biological waste treatment systems. The use of continuous culture growth kinetics have been frequently used in recent years since they provide continuous functions for the description of both substrate-limited and substrate-unlimited growth. Biological waste treatment processes are basically characterized by a heterogeneous microbial population metabolizing complex organic wastes. A description of the net growth rate of microorganisms in a continuous flow, completely mixed anaerobic treatment system, has evolved from observations of microbiological growth in both aerobic and anaerobic treatment systems[1,13,10], pure culture, and batch fed systems [20,28]. This description is expressed as:

$$\frac{dX}{dt} = Y\left(\frac{dF}{dt}\right) - K_d X \qquad (2\text{-}3)$$

where,

$\frac{dX}{dt}$ = microorganism net growth rate per unit volume of reactor, mass/volume-time

$\frac{dF}{dt}$ = rate of waste utilization per unit volume of reactor, mass/volume-time

X = microorganism concentration, mass/volume

Y = growth yield coefficient

K_d = microorganism decay coefficient, time $^{-1}$.

The volumetric rate of waste utilization $(\frac{dF}{dt})$ is related to the waste concentration in contact with the microorganisms by the following expression:

$$\frac{dF}{dt} = \frac{kXS}{K_s + S} \qquad (2-4)$$

where,

S = waste concentration in the reactor, mass/volume

K = maximum rate of waste utilization per unit weight of microorganisms occuring at high waste concentration, time $^{-1}$

K_s = half velocity coefficient equal to waste concentration when $\frac{dF}{dt}$ is equal to one half of the maximum rate, mass/volume.

Equation 2-4 is similar to an expression used by Monod[28] for describing microorganism growth in pure culture systems. Dividing both sides of Egn. 2.3 by X results in an equation that expresses the net growth per unit weight of microorganisms per unit time:

$$\frac{dX/dt}{X} = \frac{Y}{X}\frac{dF}{dt} - K_d \qquad (2-5)$$

where,

$\frac{dX/dt}{X}$ = net specific growth rate

$\frac{dF/dt}{X}$ = specific utilization ratio. In practice, it is commonly known as food to microorganism ratio (F/M). Equation 2-5 is applicable to both the conventional anaerobic treatment process and anaerobic activated sludge or contact process. The conventional process is a completely mixed single flow-through system commonly used in the treatment of municipal wastewater sludges. The anaerobic activated sludge process is a continuous flow process where solids are settled and returned partially or totally to the reactor prior to effluent discharge.

When either process is operated as a continuous flow system a steady state condition can be reached in which the mass of microorganism in the total system will remain constant. For this, it is required that the rate at which the microorganisms are wasted from the system must be equalized to the microorganism net growth rate (dX/dt).

It should be realized that the kinetics for the anaerobic filter are more complicated. The reasons for this will be discussed henceforth.

A very useful parameter results from Equation 2-5, in which the reciprocal of specific growth rate is defined as the mean cell residence time or the biological solids retention time (SRT). It is identified by some authors by the symbol θ_c, so that,

$$SRT = \theta_c = \frac{X}{\Delta X/\Delta T} = \frac{\text{mass of microorganisms in reactor}}{\text{mass of microorganisms wasted per day.}} \qquad (2\text{-}6)$$

Thus, SRT is the average retention time of microorganisms in the waste treatment system and it is analogous to the sludge age concept of the activated sludge process. As in activated sludge processes, as SRT decreases, the concentration of waste in the effluent increases and process efficiency, decreases.

The efficiency of waste treatment is defined as follows:

$$E = \frac{(Si-Se)}{(Si)} \quad 100 \qquad (2-7)$$

where,

E = efficiency of waste treatment, percent

Si = influent waste concentration, mass/volume

Se = effluent waste concentration, mass/volume. For an efficient waste treatment, S_e must be small.

As mentioned before, the quantity of solids wasted daily must equal the net microorganism growth rate, $\frac{\Delta X}{\Delta t} = \frac{Q}{V} X$ (2-8)

where,

Q = daily flow rate

V = volume of the reactor

X = mass of microorganism in the reactor

The theoretical hydraulic retention time (HRT) is defined as

$$HRT = \frac{V}{Q} \qquad (2-9)$$

By sustituting Equation 2-8 and 2-9 in Equation 2-6, it can be seen that SRT = HRT.

In the anaerobic contact process the SRT and HRT are not necessarily the same. They may be varied independently by varying the amount of biological mass waste daily. For the anaerobic filter, the calculation of SRT is very complicated since the microbial population grows attached to the filter media and may remain in the filter for exceptionally high periods of time. An SRT of as much as 100 days was found

by Young and McCarty [45], but it was necessary to open the filter and to examine the quantity and nature of biological growth in order to figure out such information.

When the SRT is reduced to a value at which the microorganisms are washed off from the system at a rate greater than their maximum net specific growth rate, process failure will occur. Under these conditions waste treatment efficiency drops to zero and the effluent waste concentration, Se, becomes equal to the influent waste concentration, S_i. The SRT below which the treatment process fails is known as the minimum SRT (SRTmin) and can be approximated from Equations 2-4 and 2-5 by considering K_d to be negligible:

$$SRTmin = \frac{1}{YK} \left(\frac{K_s + S_i}{S_i}\right) \qquad (2\text{-}10)$$

Thus, the minimum SRT is a function of the fraction of organic waste converted to biological cells, Y, the maximum rate of waste utilization, K, and the raw waste concentration, S_i.

The SRTmin is considered as a very important concept in the design of biological reactors. It indicates a limiting factor below which the process may fail. In practice, a safety factor is commonly used to prevent process failure. This has typically ranged from 2 to 10, so that actual SRT values are from 2 to 10 times greater than SRTmin. In general terms, the greater the SRT the more efficient will be the treatment, but the more expensive. The best practice in the SRT application is decided by the required degree of treatment and good engineering judgment.

Anaerobic wastewater treatment is one of the major biological waste-

water treatment processes in use today. For many years, it has been employed in the stabilization of high strength wastes such as some industrial wastes, and sludge produced by aerobic processes and removed from settling tanks. Conventional anaerobic processes have required long retention times for satisfactory waste stabilization and usually have been uneconomical for the treatment of waste containing less than approximately one percent biologically degradable organic matter [44]. Anaerobic activated sludge and other similar anaerobic contact processes treat low strength wastewater efficiently, but settling and recycling of the effluent solids are necessary to maintain a sufficiently high biological mass for a high treatment performance. For wastes which primarily are soluble, a significant fraction of biological mass may remain dispersed; the biological solids are difficult to settle and recycle, and high treatment efficiencies are therefore, difficult to maintain.

The anaerobic filter is basically a plug flow reactor in which wastes enter at the bottom and flow upward, so that the filter is completely submerged in the waste, but has a limited mixing action. The organic matter is continually being metabolized as it comes into contact with the microorganisms adhered quite readily to the filter media surfaces. For this reason they remain in the filter in large masses allowing efficient waste treatment even at moderate temperatures. By using an upflow model, the organisms tend to remain in the filter increasing both the biological mass, X, as well as the SRT. With the plug flow pattern the concentration of biological solids and organic material, and hence the reaction rate, would be expected to vary throughout the filter with, as established in Subsection 2.1, the greater biological activity

occuring at the lower levels. However, the growth of biological solids and the upward flow of gas through the filter combines with the effects of hydraulic mixing and dispersion to cause a possible significant deviation from ideal plug flow[45].

Comparing the anaerobic filter to the aforementioned biological processes, several advantages in general, stand out. Heating is not required by the anaerobic filter as in most other anaerobic processes to keep a high treatment efficiency, sufficiently high biological mass can be achieved, solid retention time may be greatly reduced, capability to treat relatively low strength wastes, suitability for the treatment of soluble wastes, and very low sludge volume production. Because no aeration equipment is needed, and because of the low hydraulic head loss in the filter, the power requirements could be almost negligible.

The absence of devices for solid separation and return, heating, mixing, and the minimum solid disposal requirements would suggest that the filter also has a number of economical advantages.

Filter gas may represent another advantage, since it can be used in many ways. It may be suitable for engines that drive process blowers, pumps, or electrical generators; for boilers that provide heat to filter wastes and plant buildings; and for incinerator operation[4]. The gas might also be sold to a natural-gas utility company.

The industrial processing of the filter gas is a very important factor that should be considered in any utilization scheme because of quality and efficiency problems. In low concentrations, this gas

contains moisture, hydrogen sulfide, and carbon dioxide, in addition to methane. Removal of moisture may easily be accomplished by a condensation and precipitation process. This is considered the minimum gas treatment acceptable for engine or boiler firing, as long as hydrogen sulfide levels are not excessive[43]. The degree of the gas cleaning process will certainly depend on its final use.

In general, due to the tropical weather conditions existing in Puerto Rico, the ambient temperature normally varies from 75°F (24°C) to 90°F (32°C). This causes the heat requirements for the anaerobic filter process to be significantly reduced. Optimum temperature conditions for the anaerobic treatment of wastes, are in the mesophilic range of 85°F (30°C) to 100°F (38°C) or in the thermophilic range of 120°F (49°C) to 135°F (57°C). However, previous investigations [33,38,39,45] have revealed that organic wastes can be succesfully treated with an anaerobic attached film process when operating at a temperature of 77°F (25°C). This is caused partly by the large mass of microorganisms, required for an efficient treatment, present in the anaerobic filter and the fact that at lower temperatures, film thicknesses and biomass concentrations increase[38]. This phenomenon may suggest that the film system compensates for temperature much more easily than the suspended-growth systems.

SECTION 3

EXPERIMENTAL PROCEDURE

3.1 LOCATION OF STUDY

The study was conducted by means of a pilot plant. The unit was installed at Alturas de Mayaguez Wastewater Treatment Plant facilities, located near Highway PR-2 in the northern part of the City of Mayaguez. Figure 3-1 shows a location map of the site. Alturas de Mayaguez Wastewater Treatment Plant consists, basically, of a small activated sludge treatment plant that essentially treats the domestic wastes from Urbanización Alturas de Mayaguez.

3.2 PILOT PLANT

The pilot plant consists of a bench-scale unit of various components. The major components include: a mixing chamber, the pump system, the anaerobic filter, and the gas collector system. A schematic diagram of the plant is shown in Figure 3.2. In order to avoid damages and to maintain the total control of the entire system, it was housed in a 6ft * 6ft * 9ft (1.83m * 1.83m * 2.74m) plywood house, within which all switches and electrical controls were installed.

3.2.1 The Mixing Chamber

A mixing chamber was provided to maintain a homogeneous mixture of the influent to be fed to the anaerobic filter. It consists of a 55-gallon (208.2 l) container with a vertical motor and a stirrer. The stirrer was composed of a 1/2 inch (1.27cm) diameter pipe connected to the shaft of the motor, and with a twisted piece of sheet metal welded

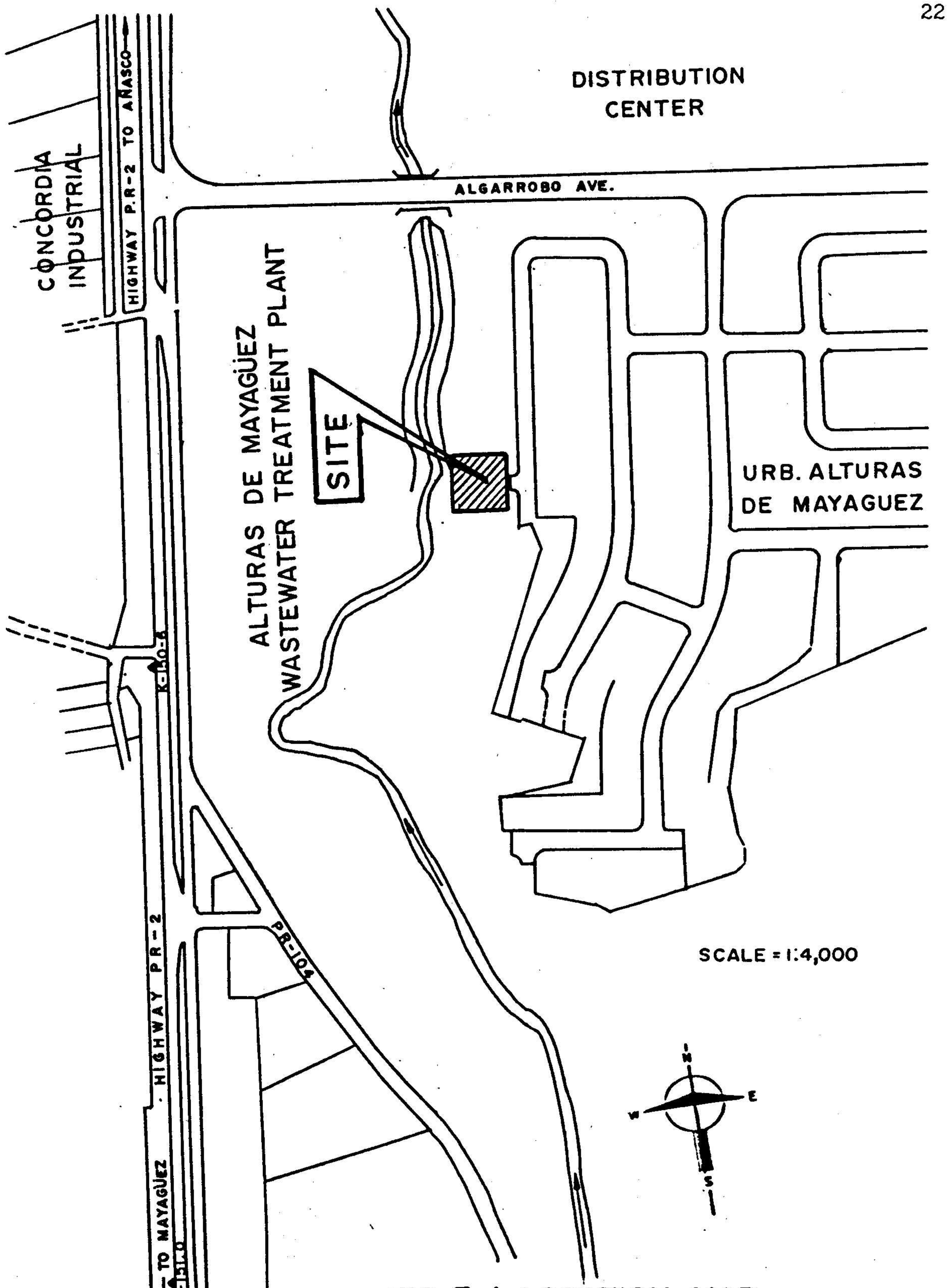


FIG. 3.1 LOCATION MAP

to its end. A Buty Master 1/2 horse-power (372.85 J/sec) and 1725 rpm motor was used. A schematic diagram of the mixing chamber is shown in Figure 3.3.

3.2.2 The Influent Pump System

A Masterflex variable speed drive pump was used to feed the anaerobic filter with the returned activated sludge. The drive unit was combined with a speed controller for changes in flow rates. Both controller and drive unit were fuse protected. The standard pump head with stainless steel rotor assembly attached directly to the drive unit. The controller was equiped with a reversing switch to set the direction of flow, on/off switch with pilot light, a speed control, and a fuse. The capacity range of the pump varies from a minimum flow of 24 ml/min to a maximum flow of 480 ml/min. The pump was connected between the mixing chamber and the anaerobic filter, and it was able to keep a suitable constant flow rate.

A bellows type metering pump with a capacity range of 63 ml/min to 630 ml/min was used to back-up the system. Actually, it was only used when maintenance was required on the Masterflex pump or during emergencies.

3.2.3 The Anaerobic Filter

Schematic diagrams of the anaerobic filter used in this study are shown in Figures 3.4 and 3.5. The filter was constructed of 8-inch (20 cm) diameter and 6ft - 6in (1.981m) tall PVC pipe, having a total effective volume of 2.09 cubic feet (59.18 l) measured on total packed volume basis. The influent was pumped from the mixing chamber to the

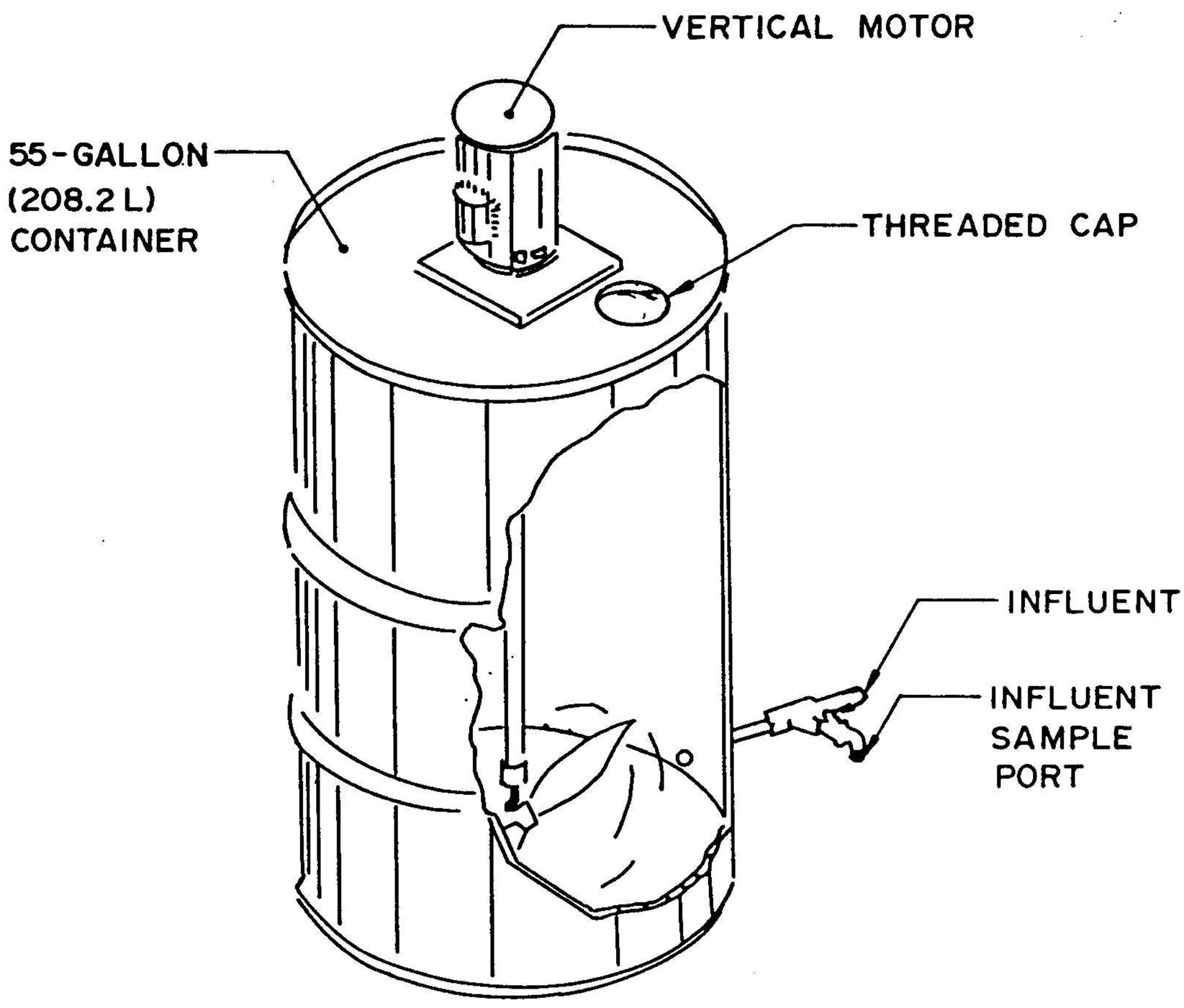


FIG. 3.3 SCHEMATIC DIAGRAM OF THE MIXING CHAMBER

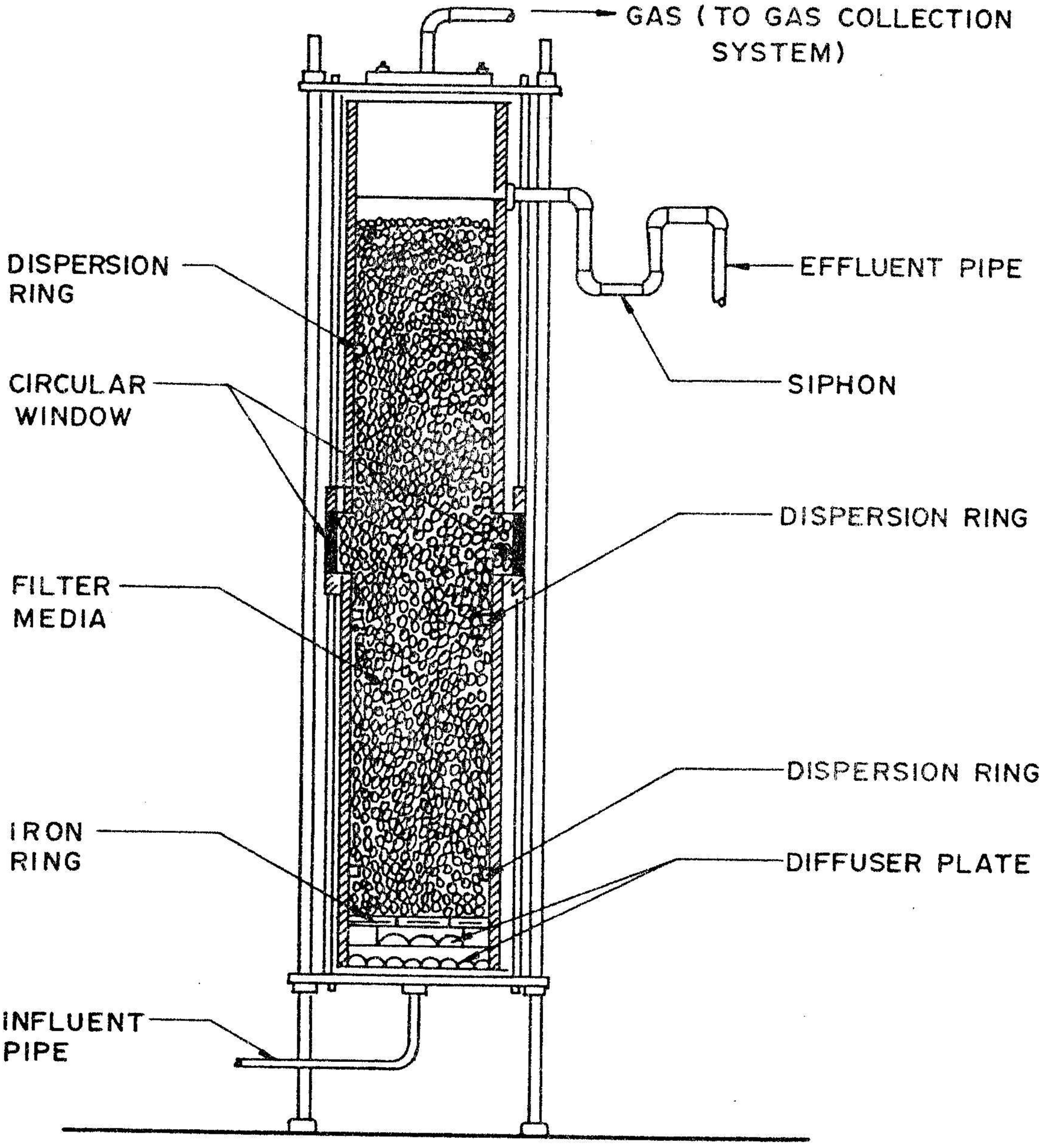


FIG. 3.4 SCHEMATIC FRONT-VIEW OF THE ANAEROBIC FILTER

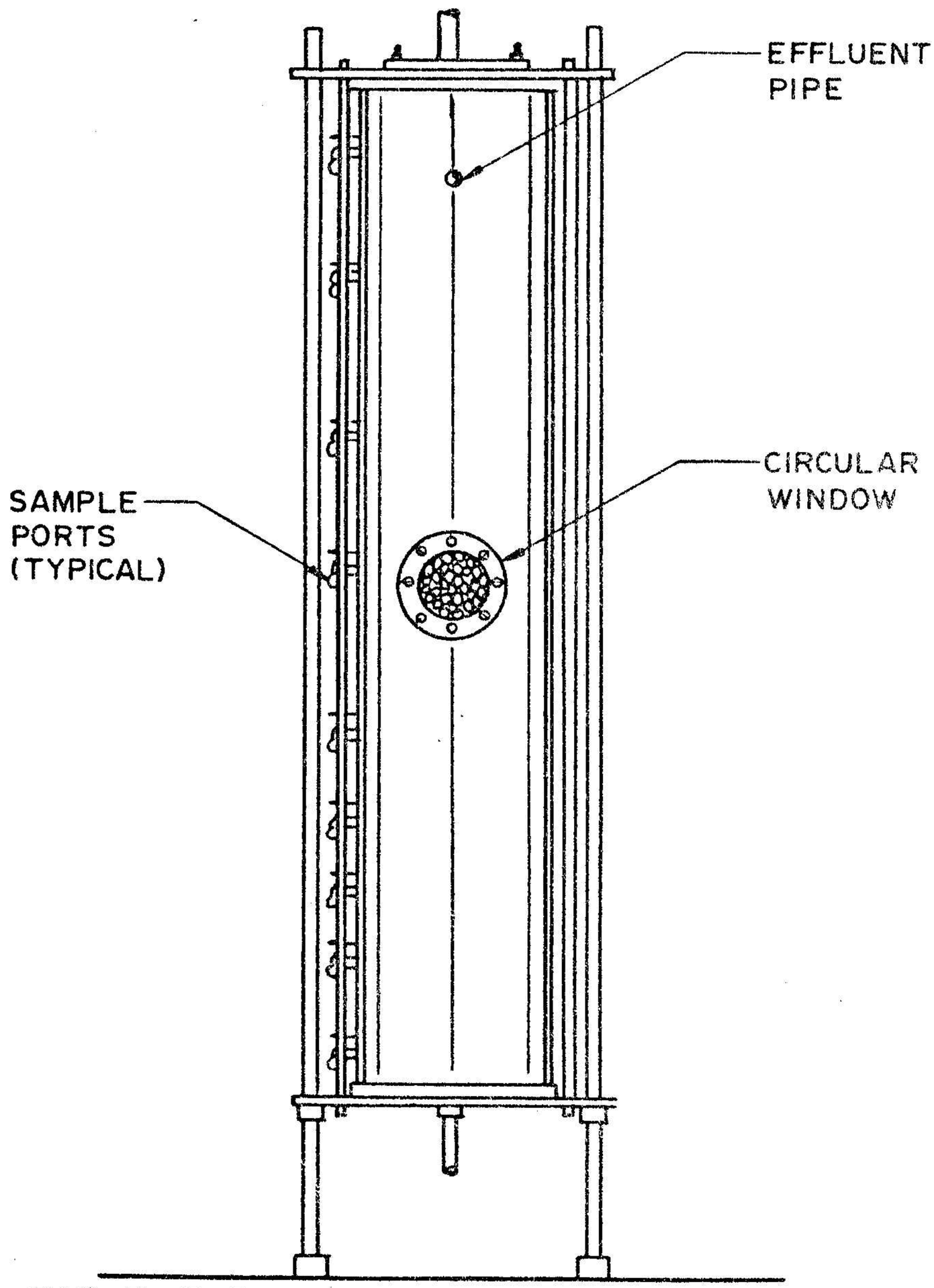


FIG. 3.5 SCHEMATIC SIDE-VIEW DIAGRAM OF THE ANAEROBIC FILTER

filter through a 1/2 inch (12.70mm) diameter ductile iron pipe, which was then reduced to a 1/4 inch (6.35mm) diameter tygon line connected to the bottom of the column. The wastes were distributed across the bottom and moved upward through the bed of the filter media, so that the filter was completely submerged. A diffuser plate was placed at the base of the filter to disperse the waste evenly across the bottom. Nine sample ports were installed throughout the height of the column. The first five were installed at 6-inch (15.24cm) intervals, and the rest at 1 foot (0.305m). To prevent short circuiting of the wastes through the large void spaces formed at the filter media-column boundary, three dispersion flat rings were placed at three different points along the filter.

Six feet (1.829m) of the column were filled with 1/2 inch (1.27cm) diameter unglazed ceramic Raschig ring packing. They were approximately 1/2 inch (12.70mm) long and about 1/4 inch (6.35 mm) internal diameter. One inch (2.54 cm) of the remaining six inches (15.24 cm) was used for the diffuser plate, and the other five inches (12.70 cm) were allowed for the final separation of the liquid and the gaseous effluents at the top of the column.

The completed filter had a void volume of 1.35 cubic feet (38.23 1). The filter effluent was passed through a siphon to assure the complete separation of the gas produced from the liquid. The gas produced in the process was collected through a 1/4 inch (6.35 mm) diameter tygon line connected to the top of the filter.

Two small circular windows were located at the middle of the col-

umn to enable observation of how the solids became atached to the filter media.

3.2.4 The Gas Collection System

The total gas production from the process was measured and collected in the gas collection system shown in Figure 3.6. The gas collection system was composed of 2-1 gallon (3.79 1) glass collector bottles connected to each other, by a 1/2 inch (1.27 cm) diameter acid resistant tygon tube, and placed at different elevations. The bottles contained a 5% sulfuric acid solution that was displaced from the first collector bottle to the second bottle as the gas entered from the filter. The sulfuric acid solution was used to minimize the possible gas absorption by the liquid phase. The gas collector bottle was calibrated to measure the total gas production. A few drops of methyl orange for color purposes were added to the acid solution, so that easy and accurate reading of the liquid level could be taken. Continuous liquid flow was kept from the first collector bottle (gas collector) to the second (liquid transfer bottle). The total volume of gas produced was assumed to be equal to the liquid volume displaced from the first bottle to the second. The liquid transfer bottle was kept under atmospheric pressure by providing two 1/4 inch (6.35 mm) holes at the rubber stopper. The volume of the gas collected was measured by equalizing the liquid levels from both collectors, so that the pressure of the gas collected was the same as atmospheric. Then, the atmospheric pressure was measured by means of a mercury differential manometer. At this time the atmospheric temperature was measured and assumed to be equal to the collected gas temperature. The volume of the gas produced in the process was measured on a daily basis and expressed in ml/day at STP conditions.

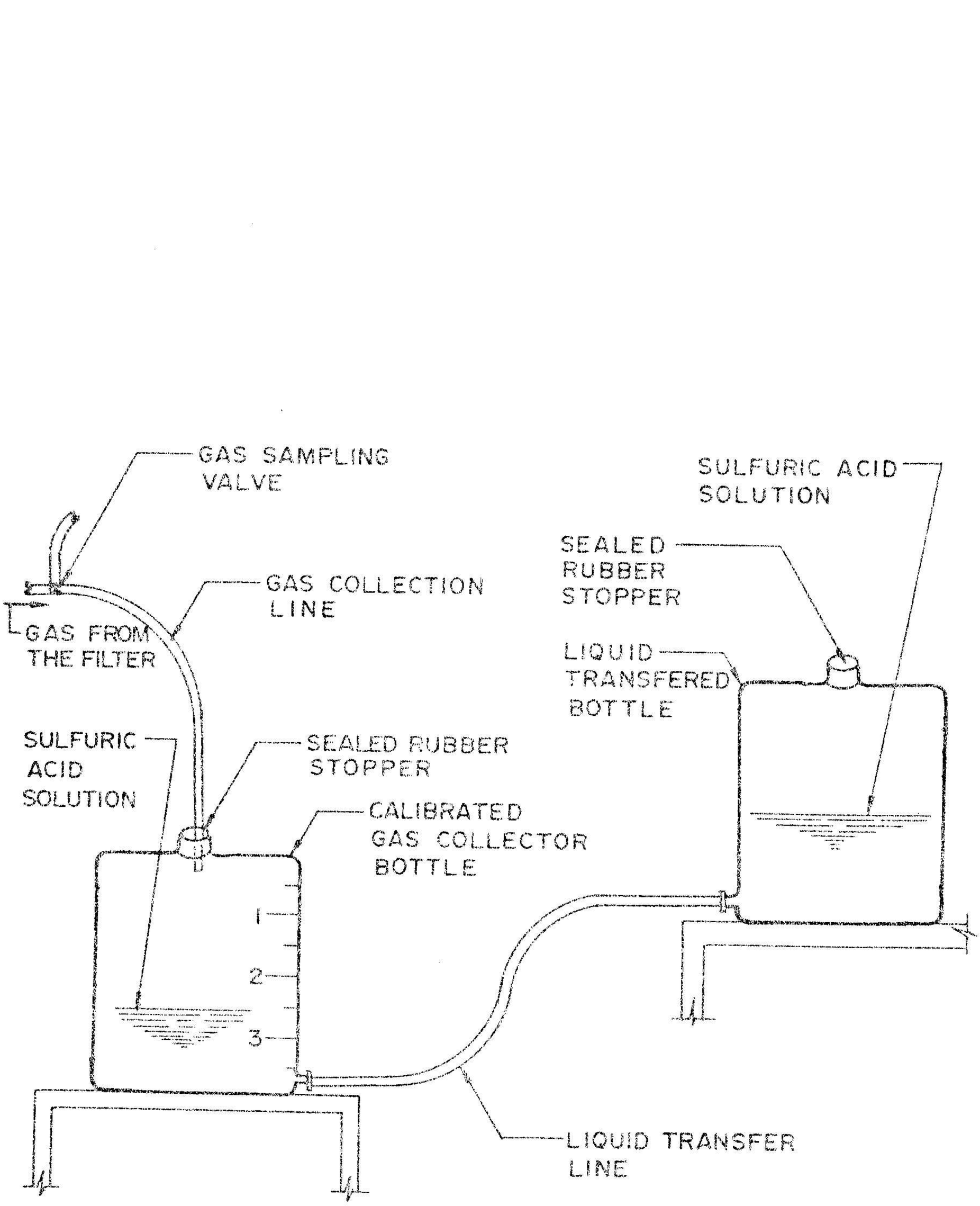


FIG. 3.6 GAS COLLECTION SYSTEM

Sporadic checks for leak detection were carried out on the entire system using a soap solution.

3.3 START-UP OPERATION

The study was conducted from January 1978 to March 1979. However, the filter operational activities began in early June 1978. From October 1978 to December 1978 no data could be collected due to serious filter plugging.

The filter was first seeded with approximately 5 gallons (18.91 l) of anaerobic digested sludge from the Añasco Wastewater Treatment Plant to assure a population of methane-forming microorganisms. Since the feed material used in the study was essentially the same under which bacteria were originally growing, not too long an acclimation period was required. However, a period of three weeks was allowed for the total acclimation of the microorganisms. After the first two weeks, the system was producing a fairly constant amount of gas. Immediately after, a very low flow rate of feed material was pumped into the filter to acclimate the bacteria to a continuous flow-through condition. After the three-week period, active microbial mass attachments developed on the filter media. Upon completion of one month of start-up operations, the system had reached equilibrium conditions. This was evidenced by the stabilization of the gas production to a suitable constant rate.

After a period of operation at a given flow rate, a steady-state removal efficiency was obtained. When the flow rate to the filter was changed, an additional period of about 15 days was required to reach a

new steady-state condition.

3.4 FEED MATERIAL

The feed material was obtained from Alturas de Mayaguez Wastewater Treatment Plant. It was drawn off from the returned activated sludge flow. A filter-ended hose was introduced in the plant flow splitter box to convey the feed material to the mixing chamber. This had to be done at time intervals depending on the flow rate at which the anaerobic filter was operated. By filtering the feed material before pumping it into the filter, those large particles that may cause clogging problems were removed. However, this practice also removed that portion of the COD caused by the materials retained in the hose filter. Except for this, no other changes in COD concentration were intentionally done to the feed material. The influent COD applied to the filter depended, therefore, on the performance of the full scale wastewater treatment plant.

3.5 EXPERIMENTAL ANALYSES

This study required the observation of the anaerobic filter under various operating conditions. Each condition was allowed for a period of time. The column was operated under three liquid flow rate conditions, for which three different hydraulic retention times resulted. The influent organic load was measured in terms of the influent COD. No control had been exercised on the influent COD. The returned activated sludge was pumped from the full scale treatment plant without changes in its constituent concentrations, except for that discussed in Subsection 3.4. Thus, the strength of the feed material depended

only on the performance of the treatment plant. Consequently, several organic loadings were obtained depending on the returned activated sludge characteristics and the operating flow rate. For each flow rate condition, a complete monitoring program was conducted, The design and operating parameters as determined from this experimental study are discussed hereinafter.

3.5.1 Liquid Analysis

The analyses carried out in this study were performed in accordance with Standard Methods[36]. Analyses on influent and effluent liquid samples included: COD, total solids (TS), total volatile solids (TVS), total suspended solids (TSS), alkalinity, and pH. These samples were collected in 300-ml plastic bottles. The influent samples were collected from the influent sampling port located in the line between the mixing chamber and the influent pump as shown in Figure 3.2. The effluent samples were withdrawn from the effluent discharge pipe (Figure 3.2). Both influent and effluent samples were taken just before they were carried to the laboratory. The samples for COD were preserved by adding sulfuric acid until the pH was less than 2. They were analyzed within the following five days after their collection. The samples for alkalinity were kept refrigerated at 0°C and the test was run within the next 24 hours after their collection. The samples TS, TSS, and TVS were preserved at 0°C and no more than five days elapsed between the date of sample collection and date of testing.

Measurements for the liquid flow rate were performed on a daily basis. Temperature and pH were measured on-site, and also on a daily

basis.

There were some occasions where the influent pH decreased below 6.5. On those occasions the pH was neutralized by adding lime. .The lime was added into the mixing chamber until a neutral pH was reached.

3.5.2 Gas Analysis

The total gas production was measured on a daily basis. The gas composition was determined by gas chromatography. The gas sample was collected in a 4.7 liter capacity teflon gas sampling bag. An on/off valve located at the center of the sampling bag was fitted to the 1/4 inch (6.35mm) diameter tygon gas sampling valve (Fig. 3.6) to collect the sample. At that moment, measures were taken to avoid the entrance of air into the bag. Figure 3.7 shows a schematic diagram of the gas sampling bag.

A Perkin-Elmer Gas Chromatograph-Model 900 was used for gas analysis, The calibrating conditions of the chromatograph and the packing material used are described in Appendix A.

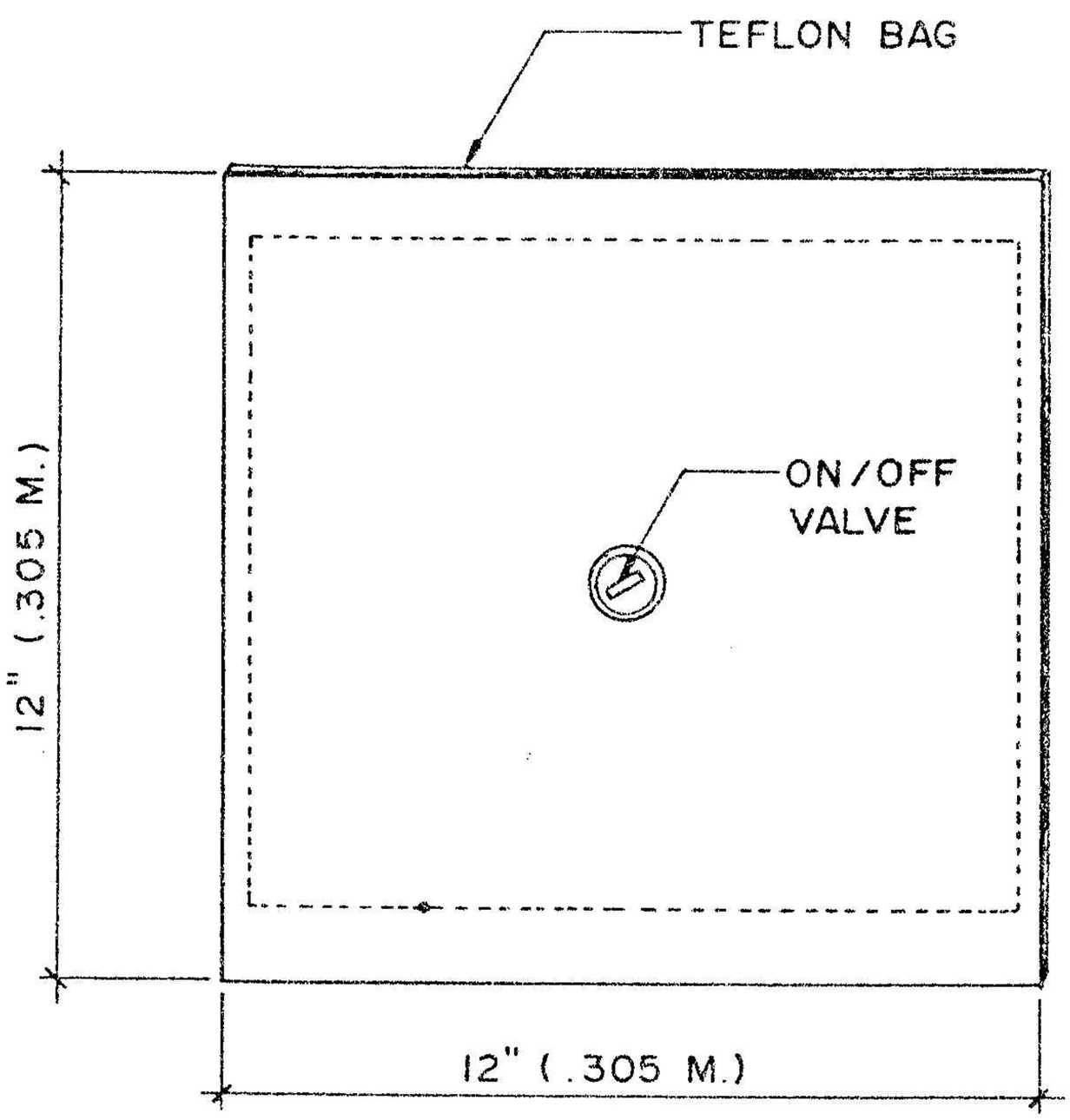


FIG. 3.7 GAS SAMPLING BAG

SECTION 4

DISCUSSION OF RESULTS

In this chapter the results obtained are interpredted relative to the adequacy of the design of the experimental units, the analytical measurements made, and the selection of wastes and loading to represent actual waste treatment situations. In additions, the filter performance is summarized with emphasis on the major operational characteristics of the filter. General physical-chemical characteristics of the feed material and the effluent quality at each condition studied are shown in Tables 4.1 thru 4.4.

TABLE 4.1

PHYSICAL-CHEMICAL CHARACTERISTICS OF FEED MATERIAL AND EFFLUENT QUALITY AT 92 l/d FLOW RATE CONDITION

SAMPLE	pH		COD mg/l		TS mg/l		TVS mg/l		TSS mg/l	
	I	E	I	E	I	E	I	E	I	E
Jun 30/78	7.1	6.7	1497	1263	2040	1527	1329	937	1600	1100
Jul 6	6.7	6.7	1510	1276	1841	1749	1175	1043	1465	1364
Jul 16	6.7	6.6	1716	1293	1830	1435	935	756	1180	1162
Jul 21	6.7	6.8	1884	1661	2662	1736	1242	1139	2460	1220
Jul 22	6.6	6.8	2181	1760	2630	1795	1414	1195	2580	1454
Jul 31	6.7	6.8	4776	3097	3855	4973	2487	2332	3830	3730
Aug 3	6.9	6.8	3433	3089	3960	3916	2536	2392	4540	3172
Aug 8	6.8	6.9	2737	2190	3247	3008	2072	2200	4120	2406
Aug 13	6.8	6.8	2920	2847	4025	3458	2578	2271	3976	2836
Aug 14	7.0	6.9	2980	2799	4597	4079	2607	2906	4345	3222
Aug 16	6.6	6.7	4706	2643	4004	2761	2428	1807	3700	2220
Aug 22	6.8	6.8	3254	1473	8522	2949	3557	1900	7560	2440
Sep 6	6.7	6.8	4667	4567	6873	5248	3747	3382	6100	4980
Sep 7	6.7	6.8	4500	3967	8829	5529	2777	3410	8240	4560
Sep 10	6.8	6.8	5074	4572	8397	6590	5458	4328	8312	5074
Sep 12	6.7	6.8	5647	5176	8012	7107	4422	4614	7947	5330
Sep 13	6.7	6.8	5608	5333	9033	6479	4486	4255	8060	5377

Note: I = Influent

E = Effluent

TABLE 4.2
PHYSICAL-CHEMICAL CHARACTERISTICS OF FEED MATERIAL AND EFFLUENT QUALITY AT 158 l/d FLOW RATE CONDITION

SAMPLE	pH		COD mg/l		TS mg/l		TVS mg/l		TSS mg/l	
	I	E	I	E	I	E	I	E	I	E
Jan 22/79	7.0	6.9	6164	5697	6714	6250	4675	4375	6437	5780
Jan 27	6.7	6.7	5967	4984	7266	6071	4600	4350	7225	5539
Jan 28	6.8	6.7	6230	5769	9012	6766	5125	4925	8700	6174
Jan 29	6.7	6.8	5769	5308	6647	6641	4500	4367	6365	6267
Jan 30	6.9	7.0	6154	5385	7916	5913	5300	4033	7577	5600
Jan 31	6.8	6.8	6538	5623	7134	8166	4100	4767	6567	6700
Feb 14	6.6	6.7	5922	5389	7109	7466	3525	3425	6675	6800
Feb 15	7.0	7.0	5821	5298	6688	6413	2975	3150	6025	5950

Note: I = Influent

E = Effluent

TABLE 4.3

PHYSISICAL-CHEMICAL CHARACTERISTICS OF FEED MATERIAL AND EFFLUENT QUALITY AT 180 l/d FLOW RATE CONDITION

SAMPLE	pH		COD mg/l		TS mg/l		TVS mg/l		TSS mg/l	
	I	E	I	E	I	E	I	E	I	E
Mar 2/79	7.0	6.9	7905	7747	7922	8867	4470	5215	7209	6500
Mar 3	7.0	6.9	10356	8063	8584	8647	5124	4826	8400	8267
Mar 7	6.7	6.8	8063	7036	7308	7183	3642	4009	6504	6967
Mar 8	7.1	7.0	7610	6514	9320	8520	5498	5004	8697	7753
Mar 9	7.0	7.0	7589	6451	9787	7858	5774	4621	9133	7137
Mar 10	7.1	6.8	7431	7115	6812	7868	3237	4627	5995	7600
Mar 11	7.0	7.0	7194	6259	7683	9753	4088	5949	7433	9067
Mar 12	6.8	6.9	7510	6403	6278	6625	3073	3896	5587	5454
Mar 13	7.1	7.1	5771	5136	7341	6359	3567	3600	6833	6067
Mar 18	7.1	7.0	5771	4822	6509	5057	3533	3200	5967	4833
Mar 19	7.1	7.0	4427	3715	5550	6416	2750	3025	4625	5325
Mar 20	7.1	7.0	4506	3557	5717	4397	3000	2800	5675	4125
Mar 22	7.0	6.9	3478	3399	3820	4353	2500	2500	3500	3775
Mar 24	7.2	7.1	3715	2846	3600	3366	1925	2025	3175	3250
Mar 25	7.1	7.1	3162	3083	4842	3117	2050	1975	4125	2800

Note: I = Influent

E = Effluent

TABLE 4.4

ALKALINITY OF FEED

FLOW RATE OF 92 l/d		FLOW RATE OF 158 l/d		FLOW RATE OF 180 l/d	
Sample	Alkalinity mg/l as $CaCO_3$	Sample	Alkalinity mg/l as $CaCo_3$	Sample	Alkalinity mg/l as $CaCo_3$
Jun 30/78	148	Jan 22/79	152	Mar 2/79	277
Jul 6	122	Jan 27	190	Mar 3	257
Jul 16	144	Jan 28	238	Mar 7	217
Jul 21	132	Jan 29	184	Mar 8	209
Jul 22	144	Jan 30	215	Mar 9	212
Jul 31	216	Jan 31	250	Mar 10	206
Aug 3	200	Feb 14	166	Mar 11	202
Aug 8	176	Feb 15	204	Mar 12	263
Aug 13	166			Mar 13	227
Aug 14	156			Mar 18	245
Aug 16	132			Mar 19	188
Aug 22	128			Mar 20	191
Sep 6	216			Mar 22	182
Sep 7	212			Mar 24	194
Sep 10	194			Mar 25	165
Sep 12	180				
Sep 13	220				

4.1 EXPERIMENTAL DESIGN

The proper use of the basic kinetics of continuous culture growth discussed in Subsection 2.2 for describing biological growth and organic removal in continuous flow completely mixed system, required a number of assumptions for the incorporation of these expressions into the anaerobic filter process. The results of such assumptions could not always be verified by the information presently available. The accuracy of the equations to describe the actual organic removal characteristics of the anaerobic filter process is, therefore, highly dependent upon the possible errors that these assumptions contribute to.

Basic to the application of the equations was the assumption of ideal plug flow in the absence of any biological activity or mixing by gas upflow. In addition, the biological growth coefficients were assumed constant. Actually, the filter was sensitive to changes in any of these coefficients, but they were not accurately known. There is no doubt they were somewhat variable because of the inherent variability of heterogeneous biological culture. Microbial culture predominance can continually shift as a result of changes in waste strength and constituents, pH, temperature, and other environmental factors.

A physical limitations-free system was considered. However, physical factors may be the most serious limitations to the applicability of the filter. These include but are not limited to biological mass transport and solids accumulation, waste channeling and short circuiting, and substrate gradient effect.

There is almost no doubt that the accumulation of biological solids and entrapped gas bubbles may reduce the filter effective volume available for waste treatment. For considerably high solids contained wastes, the active solids would probably not be mixed uniformly due to the limited mixing action in the filter and physical clogging of some of the void spaces. Closely related to the accumulation of biological solids is the channeling effect. Channeling is considered to further reduce the effective filter volume in proportion to gas flow. In laboratory-scale filters, channels may be visually observed through the walls of the filters.

In general, when the effect of biological mass transport is considered, the effect of channeling is neglected and biological solids are assumed to be transported equally from all parts of a volume element of the filter. However, with serious chanelling this assumptions would not be valid and the fraction of biological mass subject to transport could be expected to vary with the packing and flocculating characteristics of the solids. The fraction of biological solids subject to transport would be expected to be higher for lightly dispersed growth than for well flocculated or attached growth.

4.1.1 The Laboratory Filter

The selection of the 1/2 inch (1.27cm) diameter Raschig rings used in the experimental filter was to provide more surface area per unit volume for biological growth. Many researches have been conducted with the anaerobic filter using stones as filter media [12,17,19,21,23,45] and satisfactory results have been obtained. However, they provide less sur-

face area per unit volume than the Rasching rings and the plastic media. Additionally, small stones might not permit solids transport and could result in serious plugging of the void spaces. Also, the accumulated solids might not be as readily removed from the filter for disposal. On the other hand, larger stones might result in severe channeling of the waste through the larger void spaces. The rate of solids washout could also increase due to the more direct path of waste flow, resulting in a lower SRT and a lower filter efficiency.

In practice, the void volume of Rasching rings-filled filters might be lower than that measured for the laboratory filters because of the presence of grit and other debris. A corresponding reduction in filter efficiency could result.

Although biological growth eventually became attached to the inside walls of the column, the effect was not considered to seriously affect filter performance. The amount of wall growth would probably no be greater than that which would have become attached on an adjacent layer of filter media.

The provision of a large enough filter diameter, relative to the Rasching ring size was a basic concern of the laboratory filter design since geometric distortion of the filter performance would be minimized.

4.1.2 Analytical Measurements

Throughout the experimental phase of this study, the biochemical oxidation of the organic matter was considered to be completed with the formation of methane gas. Consequently, the gas production was normally

used as a measure of filter performance.

To determine if the high solids concentrations in the effluent must be considered as an additional organic load to the system receiving the filter effluent, spot check tests of soluble COD were performed during the first flow rate condition. These indicated that the COD of the effluent solids was much higher than the soluble effluent COD. Therefore, they must actually be considered as an additional organic load to the receiving system. Their presence also indicated an incomplete biochemical conversion of the organic matter. The results of these tests are shown in Table 4.5. This situation was presumably repeated in all the three flow rate conditions as the high effluent solids concentrations were common for all of them. Effluent solids separation will have to be considered in full scale wastewater treatment systems when treating domestic activated sludge at high loading rates.

The COD removal efficiencies listed in Table 4.6 show that for all the conditions studied, the treatment efficiency was linearly related to filter organic loading. The resulting curves are shown in Figure 4.1. They were fit by the linear regression method. The correlation coefficients were -0.69, -0.68, and-0.68 for the 92 l/d, 158 l/d, and 180 l/d flow rate conditions,respectively. This indicates that efficiencies of treatment decreased with an increase in organic loading for steady-state removal of COD. Waste loading appears to be a very significant factor in the resulting treatment efficicency. This condition was also observed by Young and McCarty[44] when treating both protein-carbohydrate and volatile acid wastes. They found that at a given loading the higher strength

TABLE 4.5

EFFLUENT QUALITY AND TREATMENT EFFICIENCY DURING 92 l/d FLOW RATE CONDITION

Sample	Influent COD mg/l	Loading LbCOD/1000Ft^3/d	Influent TSS mg/l	EFFLUENT QUALITY TSS mg/l	COD - mg/l Total	COD - mg/l Soluble Organic	PERCENT REMOVAL Total COD	PERCENT REMOVAL TSS
Jul 6/78	1510	147	1465	1364	1276	46	15	7
Jul 31/78	4776	464	3830	3730	3097	96	35	3
Aug 8 /78	2737	266	4120	2406	2190	53	20	42
Aug 13/78	2920	283	3976	2836	2847	84	3	29
Aug 16/78	4706	457	3700	2220	2643	142	44	40
Aug 22/78	3254	316	7560	2440	1473	129	55	68

Note: kg/m^3/d × 62.428 = Lb/1000 ft^3/d

TABLE 4.6

FILTER ORGANIC LOADING AND TREATMENT REMOVAL EFFICIENCIES FOR EACH CONDITION STUDIED

FLOW RATE OF 92 l/d			FLOW RATE OF 158 l/d			FLOW RATE OF 180 l/d		
Sample	Filter Load Lb COD/ $10^3 Ft^3/d$	COD Removal %	Sample	Filter Load Lb COD/ $10^3 Ft^3/d$	COD Removal %	Sample	Filter Load Lb COD/ $10^3 Ft^3/d$	COD Removal %
Jun 30/78	145	16	Jan 22/79	1028	8	Mar 2/79	1498	2
Jul 6	147	15	Jan 27	995	16	Mar 3	1963	22
Jul 16	167	25	Jan 28	1039	7	Mar 7	1528	13
Jul 21	183	12	Jan 29	962	8	Mar 8	1442	14
Jul 22	212	19	Jan 30	1026	12	Mar 9	1438	15
Jul 31	464	35	Jan 31	1091	14	Mar 10	1409	4
Aug 3	333	10	Feb 14	988	9	Mar 11	1364	13
Aug 8	266	20	Feb 15	971	9	Mar 12	1423	15
Aug 13	283	3				Mar 13	1094	11
Aug 14	289	6				Mar 18	1094	16
Aug 16	457	44				Mar 19	839	16
Aug 22	316	55				Mar 20	854	21
Sep 6	453	2				Mar 22	659	2
Sep 7	437	12				Mar 24	704	23
Sep 10	492	10				Mar 25	599	2
Sep 12	548	8						
Sep 13	544	5						

Note: $Kg/m^3/d \times 62.428 = Lb/1000\ Ft^3/d$

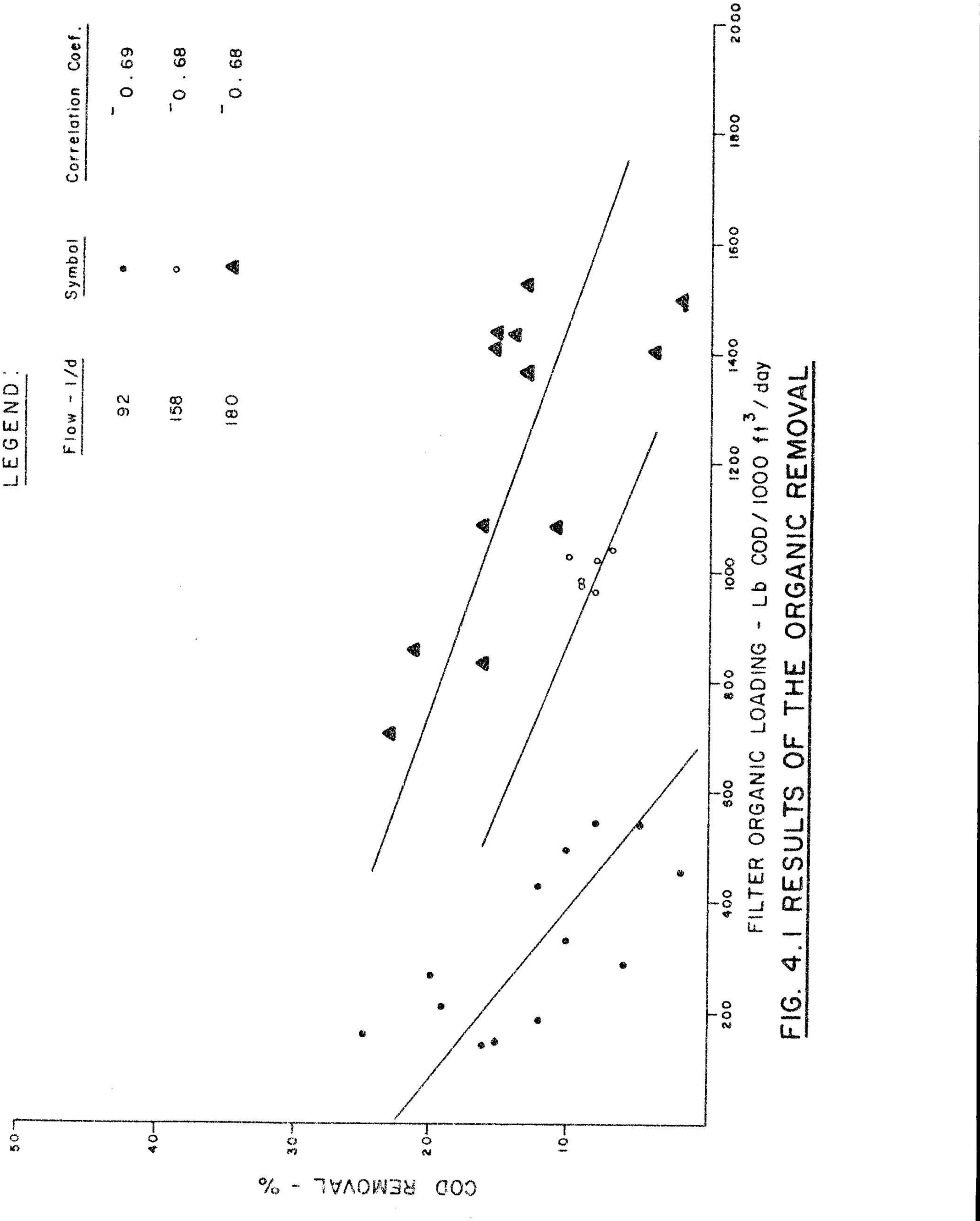


FIG. 4.1 RESULTS OF THE ORGANIC REMOVAL

wastes result in higher removal efficiency. In addition, the resulting linear relationship between the influent and effluent COD's (Figures 4.2 thru 4.4) corroborates that the activity of the filter in removing organic materials was entirely a function of the concentration of the organic load applied. The curves were fit by the linear regression method. The correlation coefficient for each of the curves were 0.91, 0.67, and 0.97, respectively. The fact that this coefficient resulted to be near ±1 for 92 1/d and 180 1/d flow rate conditions and about one third lower for the 158 1/d condition can be explained as due to the sampling and/or testing procedures. El-Shaffie and Bloodgood[12] using Metrecal (vanilla flavor) as the feed material for a multiple upflow anaerobic filter system, also found a linear relationship between influent and effluent COD's.

Profiles of the daily influent and effluent COD's are illustrated in Figures 4.5 thru 4.7.

In anaerobic conditions, microorganisms can reduce sulfates by utiliazing them as hydrogen acceptors. Through this reaction organic COD of the wastes is oxidized, but methane is not a product. In this case, because of the nature of the domestic activated sludge used as feed, the reduced methane production cause by the sulfate contents in the waste was considered as negligible due to the low sulfate concentration typicaly found in such a waste. However, for wastes containing high sulfate concentrations (200 mg/l) this difference could be significant. Nitrates and nitrites would produce similar results if present in high concentrations in the wastes.

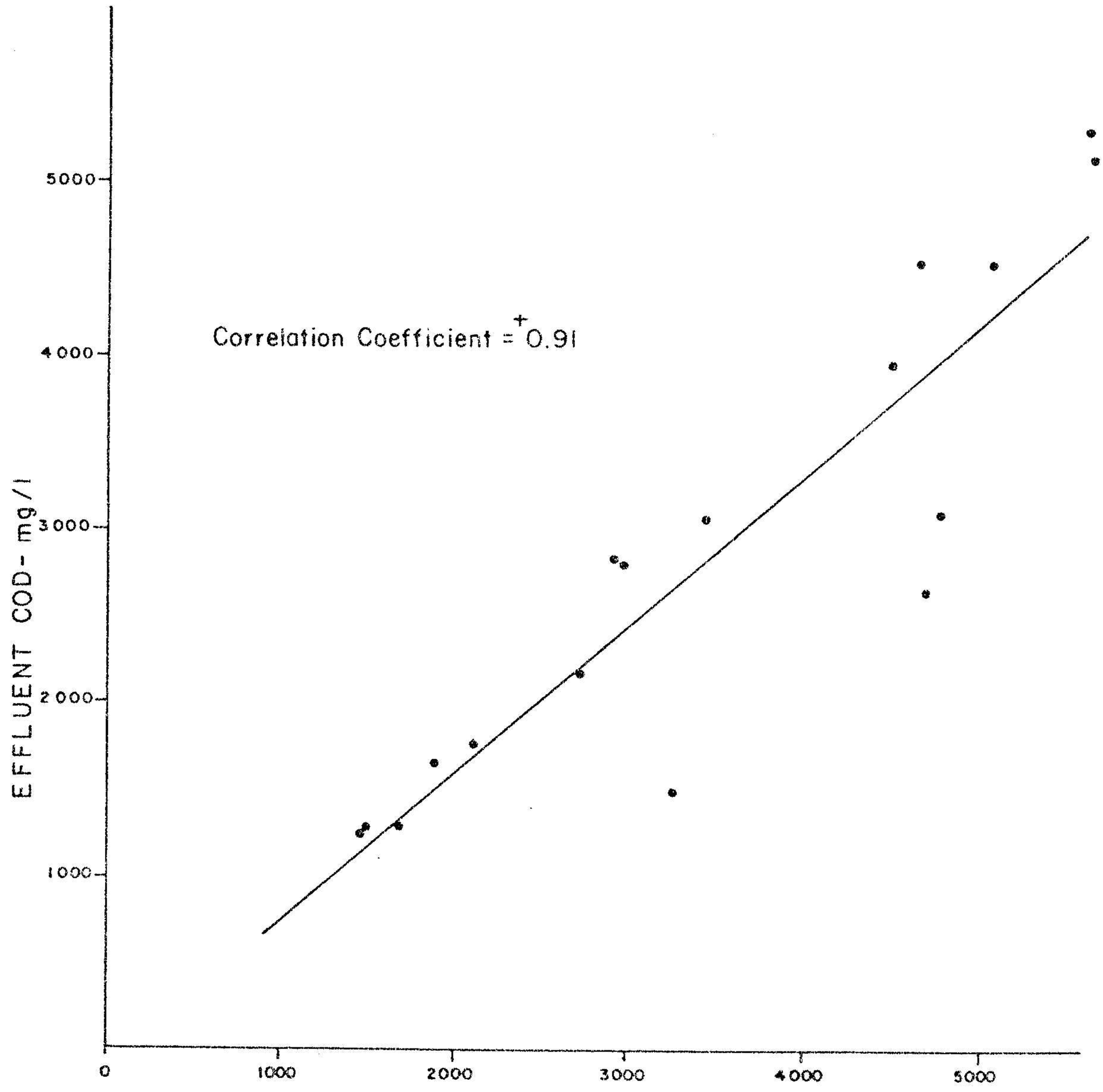


FIG. 4.2 RELATION BETWEEN INFLUENT AND EFFLUENT COD AT LIQUID FLOW RATE OF 92 l/d

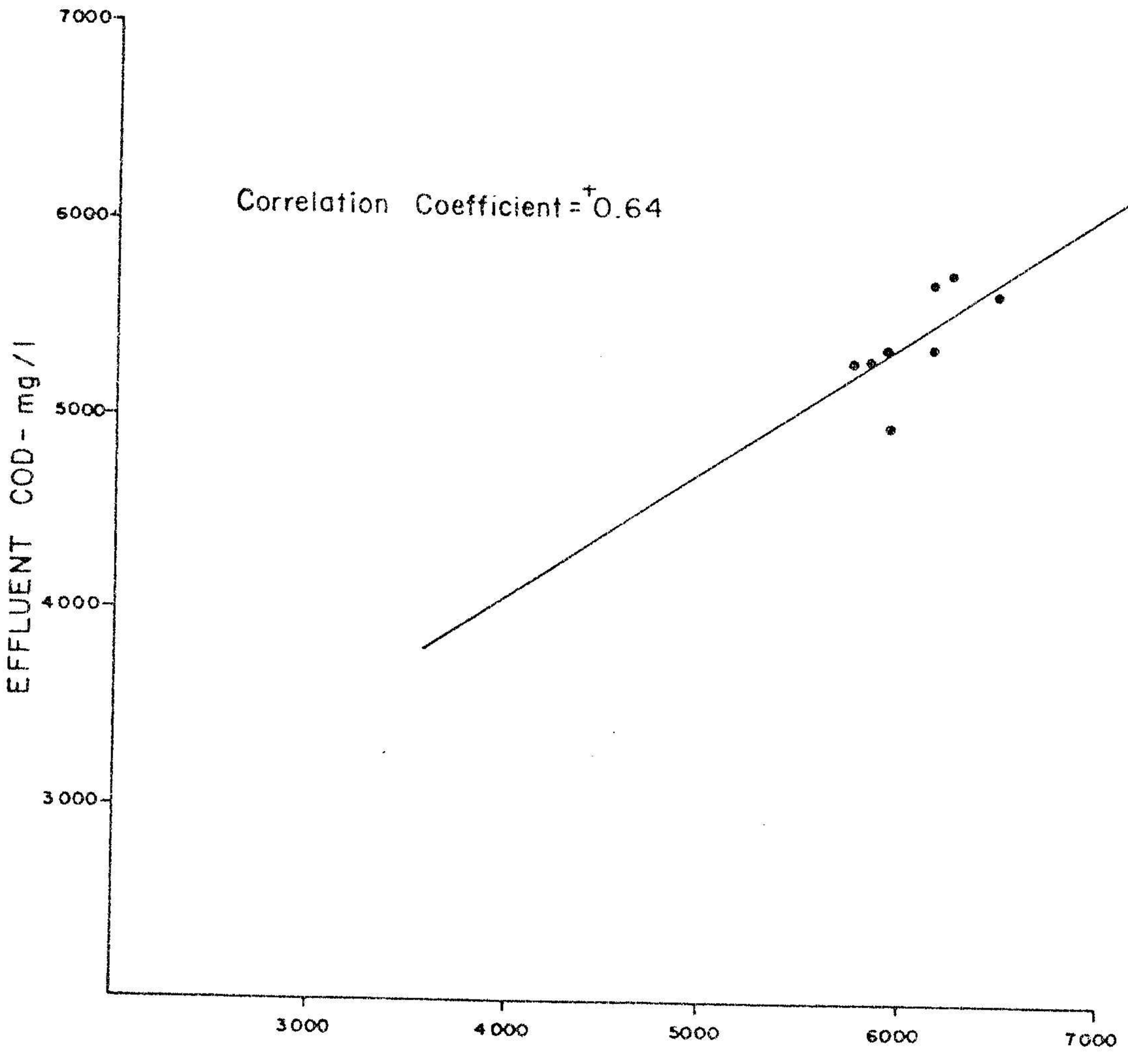


FIG. 4.3 RELATION BETWEEN INFLUENT AND EFFLUENT COD AT LIQUID FLOW RATE OF 158 l/d

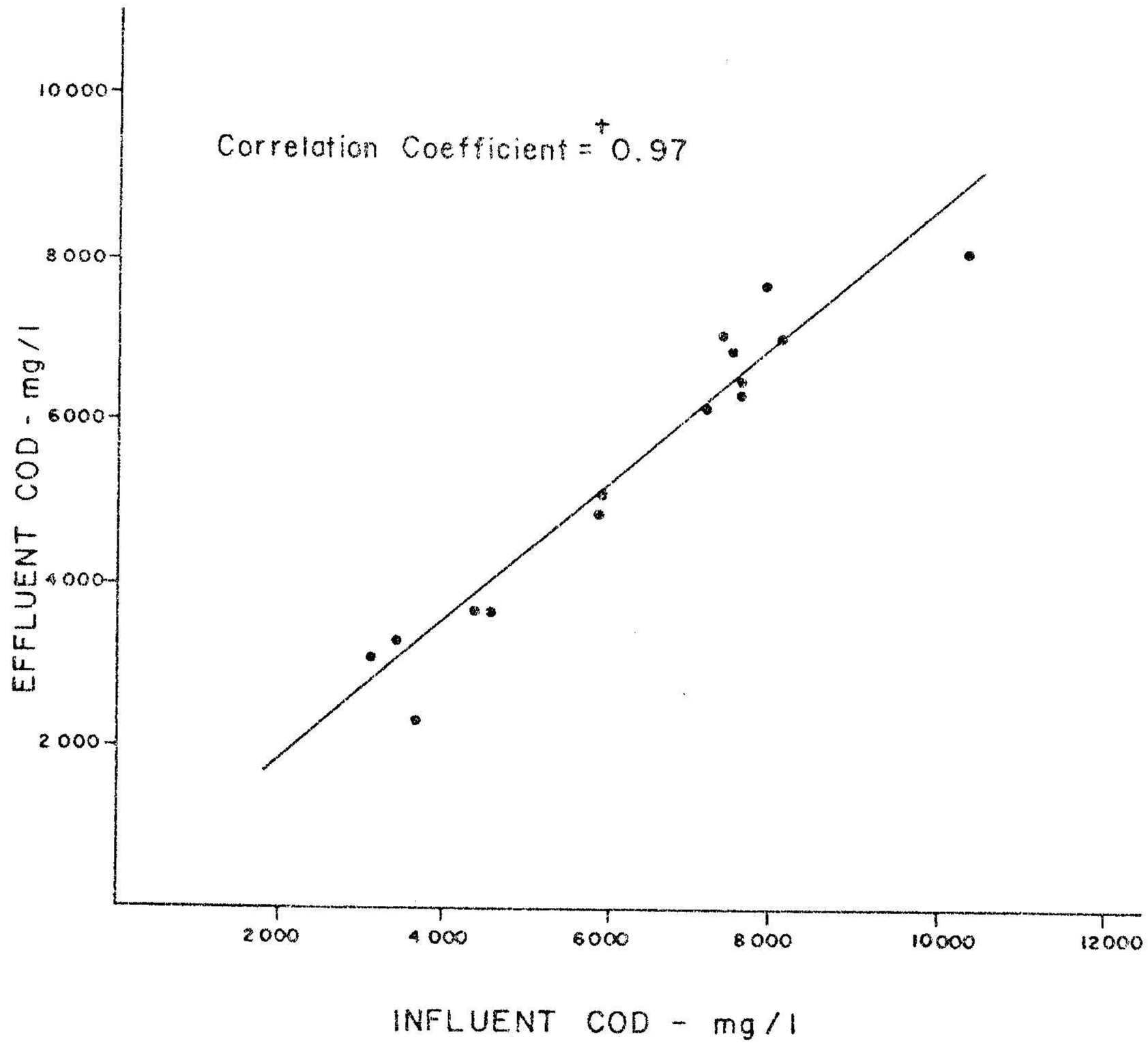


FIG. 4.4 RELATION BETWEEN INFLUENT AND EFFLUENT COD AT LIQUID FLOW RATE OF 180 l/d

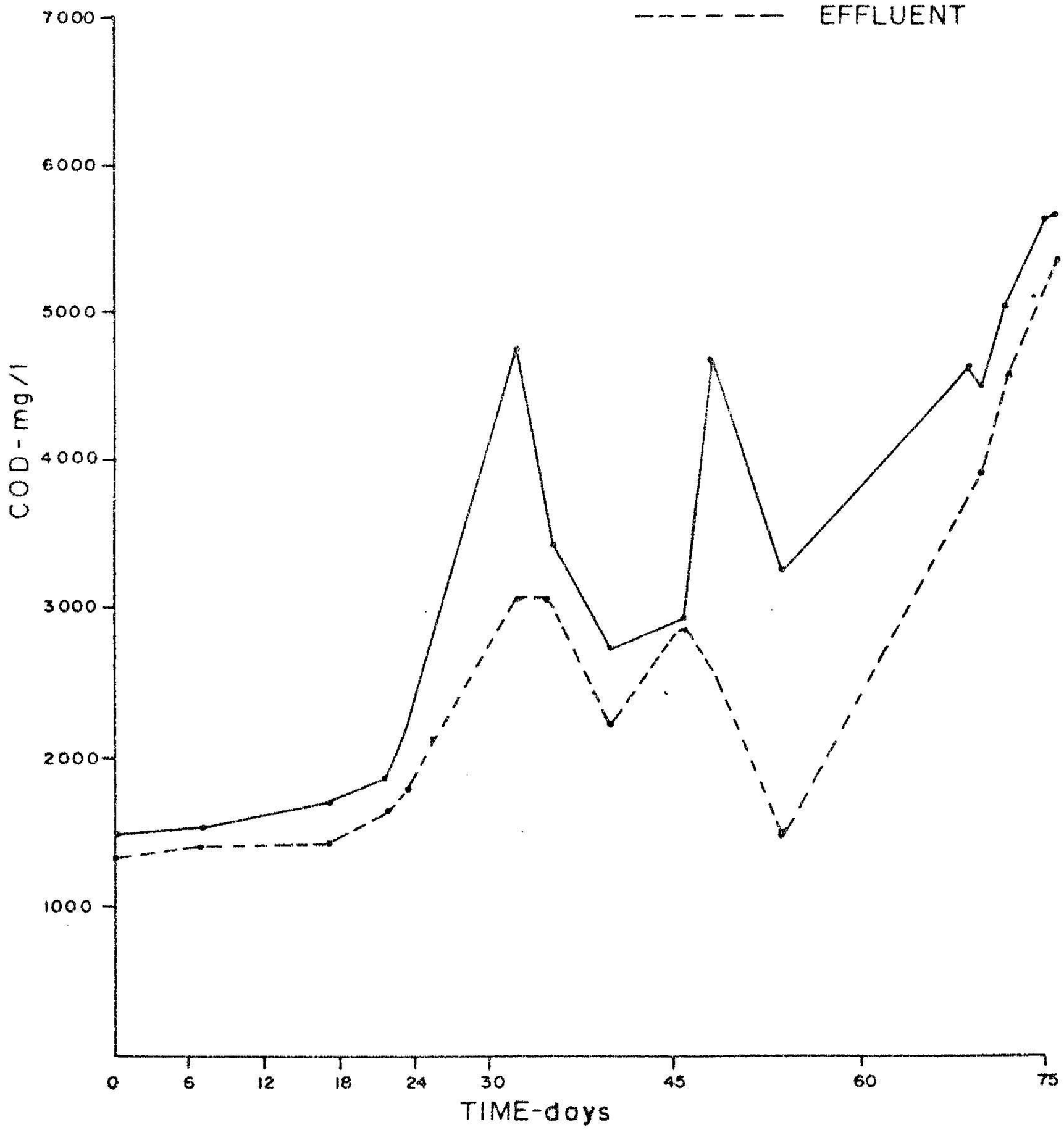


FIG.4.5 COD CONCENTRATIONS AT FLOW RATE OF 92 l/d

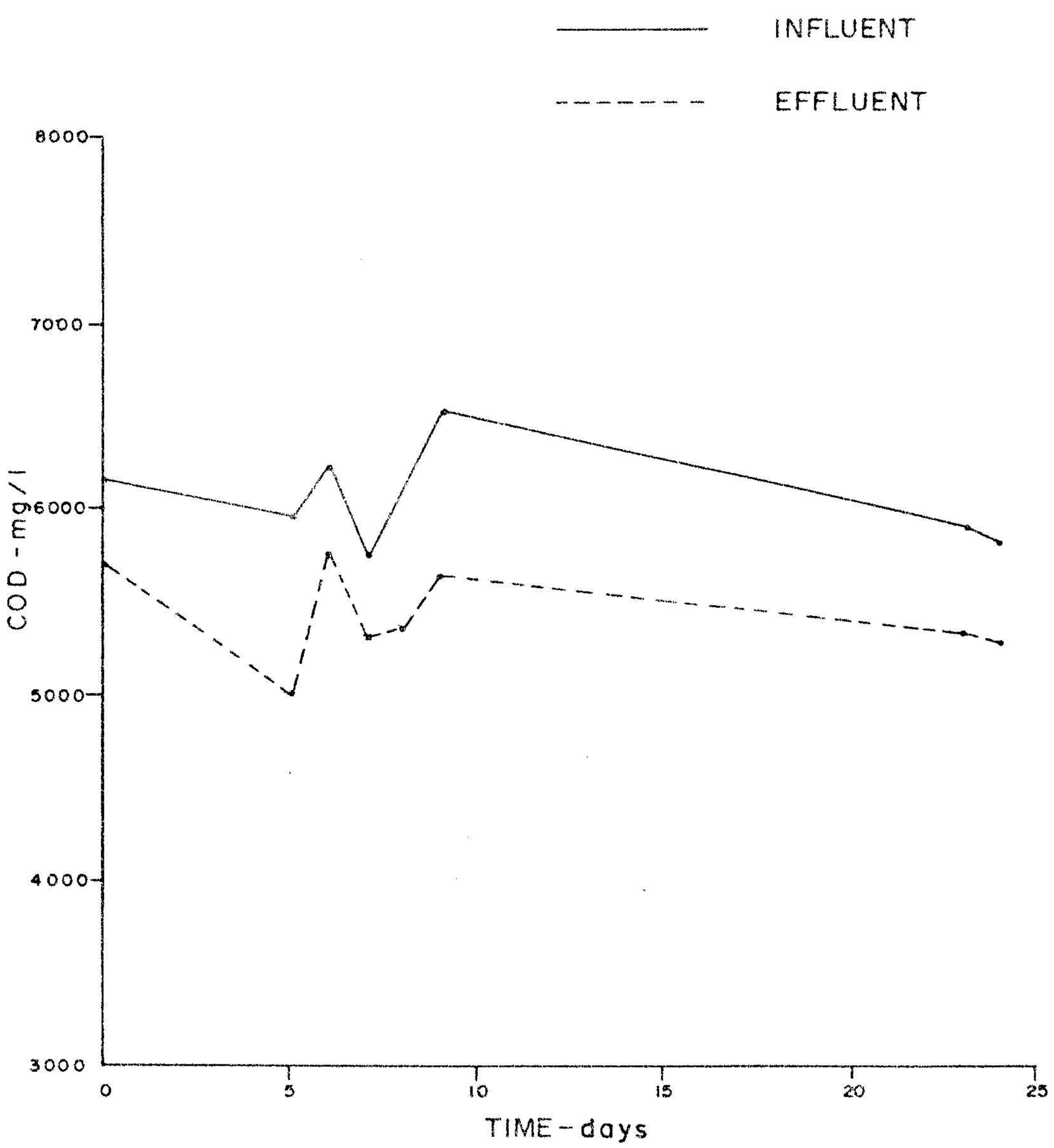


FIG.4.6 COD CONCENTRATIONS AT FLOW RATE OF 158 l/d

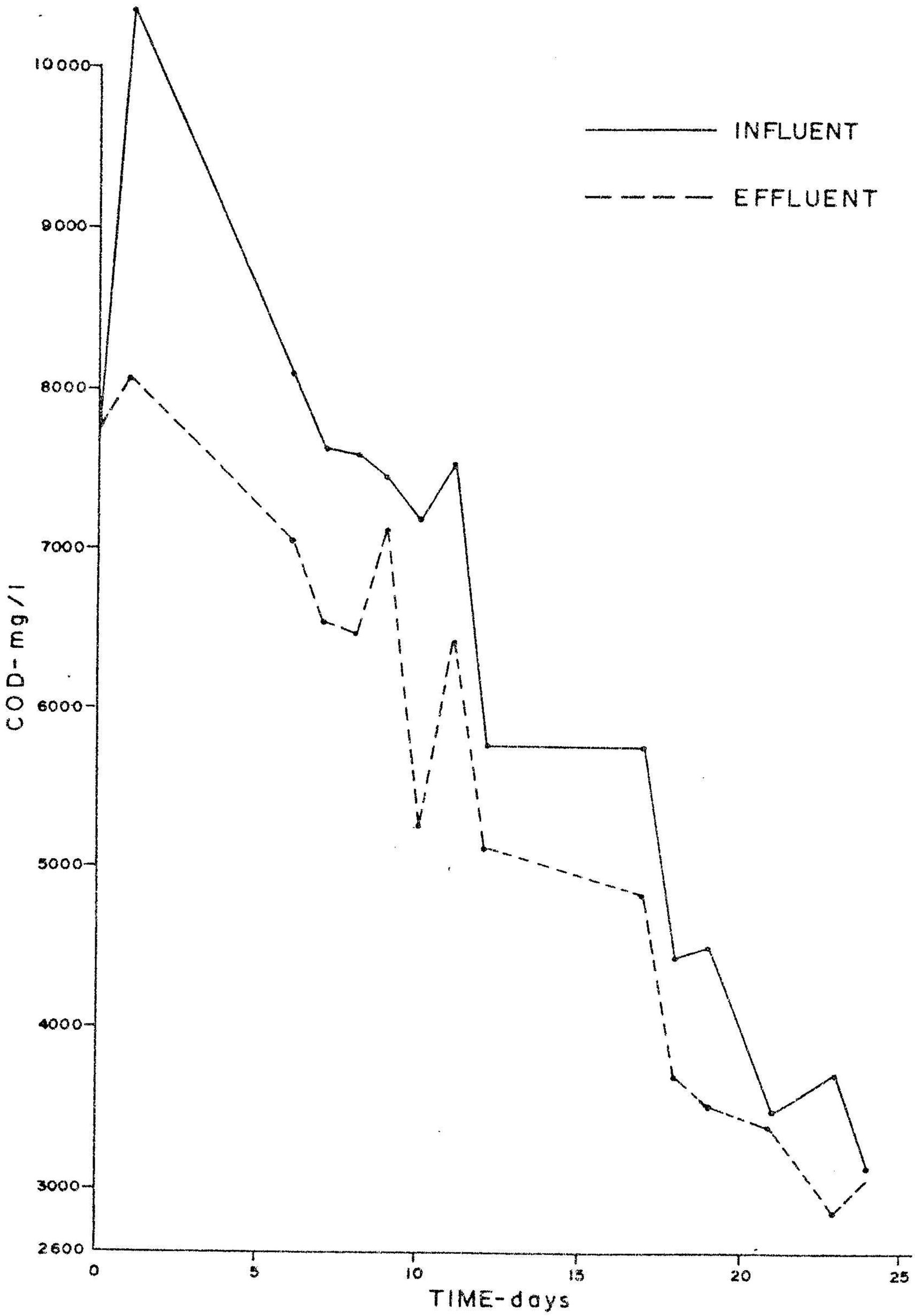


FIG. 4.7 COD CONCENTRATIONS AT FLOW RATE OF 180 l/d

4.1.3 Selection of the Waste and Loadings

4.1.3.1 Wastes

The returned activated sludge was selected because it represents the highest strength waste in a domestic wastewater treatment plant-activated sludge type.

In addition, the anaerobic treatment of municipal sludges including their handling is a very significant component of the municipal wastewater treatment plants representing nearly 50% of the total plant cost.

The treatment of the municipal returned activated sludge provided information concerning the problems associated with high solids wastes. The experimental results indicated a high solids effluent concentration which affected the filter removal efficiency. Frequent filter plugging evidenced that wastes with high solids contents could present a problem for continued filter operation. This is in accordance with Jennet & Dennis[15], who observed no net removal for wastes containing solids. Similarly, Young & McCarty[45], and Chian & De Walle[5] observed that for high solids producing wastes, a high solids accumulation resulted which required occasional solids wasting to avoid severe filter plugging and subsequent problems for continued filter operation.

Profiles of the influent and effluent TSS contents are shown in Figures 4.8 thru 4.10

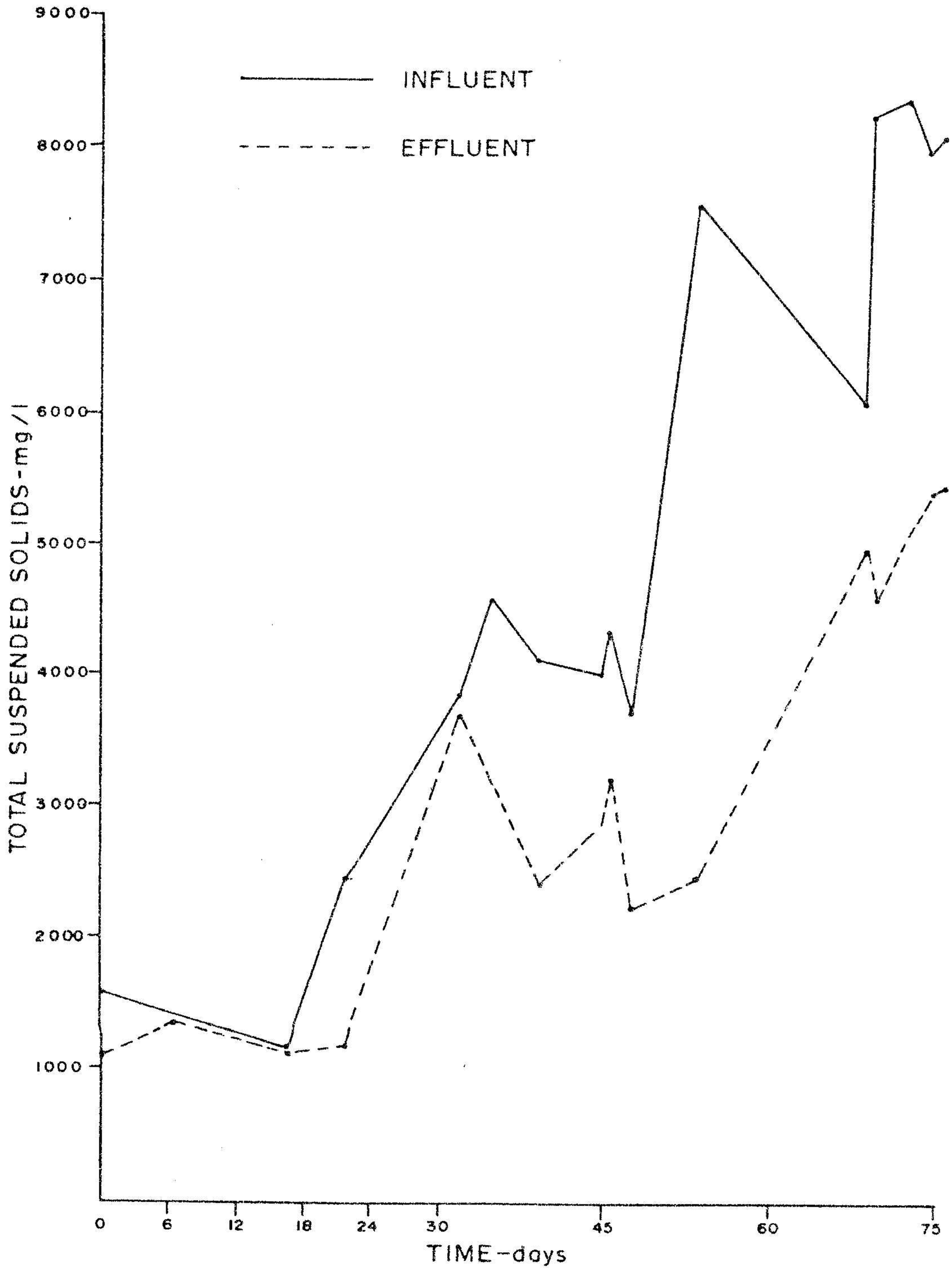


FIG. 4.8 TOTAL SUSPENDED SOLIDS AT FLOW RATE OF 92 l/d

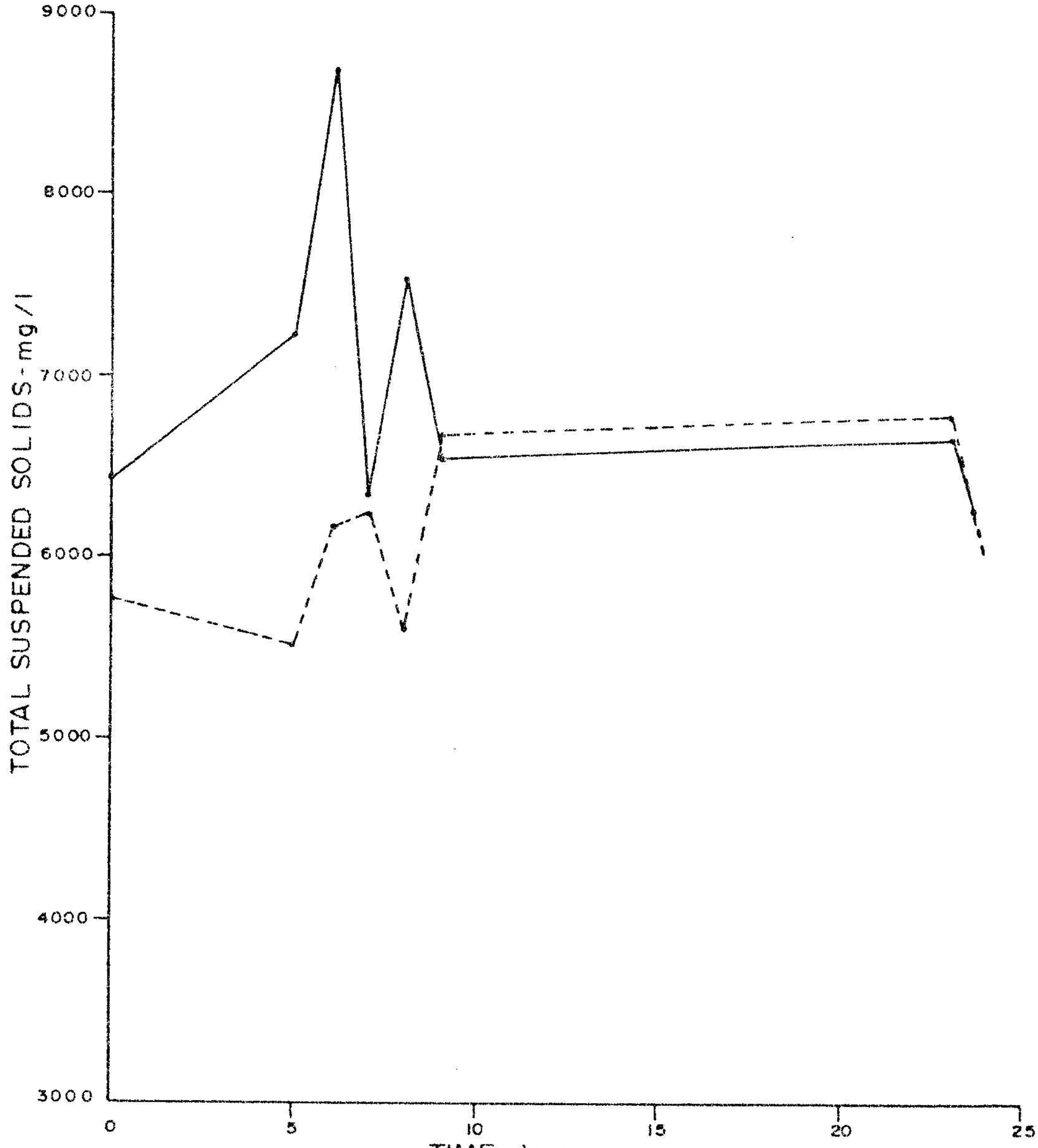


FIG. 4.9 TOTAL SUSPENDED SOLIDS AT FLOW RATE OF 158 l/d

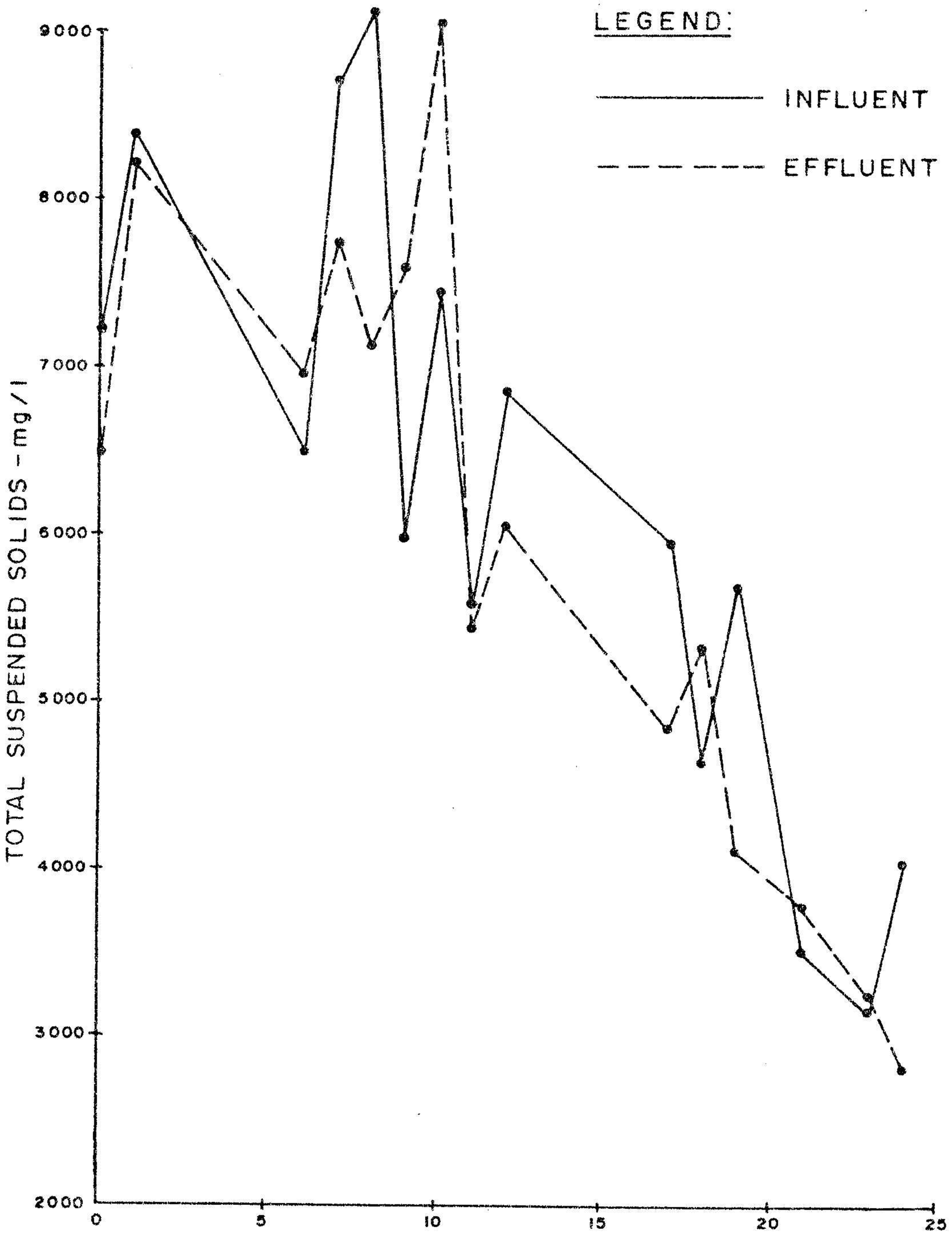


FIG. 4.10 TOTAL SUSPENDED SOLIDS AT FLOW RATE OF 180 l/d

4.1.3.2 Loadings

As previously discussed, the organic loadings applied to the filter depended on the performance of the full scale treatment plant. The organic loadings are expressed in terms of pounds of COD per day per 1000 cubic feet of total filter volume. Table 4.6 shows the organic loadings applied to the filter for each flow rate condition.

4.2 PERFORMANCE OF THE ANAEROBIC FILTER PROCESS

4.2.1 Organic Removal Efficiency

The organic contents in the filter effluent resulted to be relatively high in all of the three conditions studied. This was essentially caused by several factors that affected the performance of the process. Such factors are discussed here.

The applied organic loadings for each condition are shown in Table 4.6. They ranged as follows: from 145 to 548 Lb COD/1000 ft^3/d (2.3 to 8.9 kg/m^3/d) at a flow rate of 92 l/d (24.3 gal/d), from 962 to 1091 Lb COD/1000 ft^3/d (15.4 to 17.5 kg/m^3/d) at 158 l/d (41.7 gal/d), and from 599 to 1963 Lb COD/1000ft^3/d (9.6 to 31.4 kg/m^3/d) at 180 l/d (47.6 gal/d). All the loadings were calculated on the basis of the gross filter volume. These loadings resulted to be exceptionally high if compared to those used in previous investigations using the anaerobic filter [5,16,19,21,35,38,45]. According to Table 4.6, the situation appeared to be most critical during the 180 l/d (47.6 gal/d) flow rate condition, for which organic loadings over 1500 Lb COD/1000 ft^3/d (24.0 kg/m^3/d) were registered. McCarty[21] using the anaerobic filter for

treating soluble wastes obtained organic removal efficiencies ranging from 74 to 88 percent with an organic loading of 123 Lb COD/1000ft^3/d (2 kg/m^3/d). Data reported by Schroepfer and Ziemke[35] indicated that BOD loading to anaerobic contact processes do not often exceed 200Lb BOD_5/1000 ft^3/d (3.2 kg BOD_5/m^3/d) which corresponds (assuming BOD_5 equals to 65% ultimate BOD or COD) to 308 Lb COD/1000 ft^3/d (4.9 kg COD/m^3/d) with acceptable removals except for high strength wastes and heated digesters. Young and McCarty[44] found that the treatment efficiency of the anaerobic filter process is quite high at the lower loadings but decreases somewhat as loading increases. They obtained BOD_5 removals ranging from about 60 to 98 percent, treating wastes at loadings of 150 Lb BOD_5/1000 ft^3/d (2.4 kg BOD_5/1000 ft^3/d) corresponding to 231 Lb COD/1000 ft^3/d (3.7 kg/m^3/d). Landine et al.[16], obtained a COD removal efficiency ranging from 45.3 to 67.7% when anaerobic filter was loaded in the range of 51.3 to 75.0 Lb COD/1000 ft^3/d (0.8 to 1.2 kg/m^3/d).

However, a comparison between organic loadings and removal efficiencies does not necessarily represent the best indication of the engineering significance of the filter. When comparing the anaerobic filter to aerobic systems, it must be recognized that in the aerobic system as much as 50 percent of the BOD removed may be synthesized into biological solids which require further treatment, thereby decreasing the effective plant loading. Besides, the resulting linear relationship between the influent and effluent COD's in all the three conditions studied (Figures 4.2 thru 4.4), evidences the relationship between the activity of the filter in removing organic matter and the organic load applied. Consequently, the continuous variation of the organic loading rates affected

the performance of the system and hence its organic removal efficiency. Theoretically, the attainment of a constant gas production rate indicates that a constant COD removal efficiency should also be attained, COD removal at steady-state conditions could be interpreted to imply that for a constant influent waste strength and loading, the COD at any point in the filter would remain constant for an indefinite period of time. As shown in Tables 4.1, 4.2, 4.3, and 4.6 such constant influent waste strength and loading have never been applied to the filter at any of the conditions studied. Young[46] investigated the possibility that steady-state condition might actually exist in the anaerobic filter. He found that while constant gas production and COD removal were attained, the individual COD-producing components in the system were in a continuous state of fluctuation. Steady-state conditions, in the strictest sense of the word, are therefore probably never attained in the anaerobic filter. However, for all practical waste treatment applications, steady-state conditions are normally assumed when a stable gas production rate is attained and high relatively stable COD removal efficiencies are achieved. Along with these two parameters, consistently low concentrations of effluent suspended and volatile solids also indicate steady-state conditions, but these parameters are considered to be less reliable because they depend on more variables.

Even though the system allows for certain fluctuations, the data suggest that the considerable variations observed in the filter organic loads jointly with the exceptionally high magnitude of such loads could result in dynamic fluctuations between the individual waste components affecting the system equilibrium and its removal efficiency. Figures

4.5 thru 4.10 show the influent and effluent COD and TSS variations. The variations in the daily gas production can be seen in Figure 4.11. The decreasing tendency of the daily gas production during the 180 l/d flow rate condition shown in this figure was indicative of a decrease in the quantity of organic matter metabolized. This was probably caused by the continuous decrease in the influent COD throughout this flow rate condition period as shown in Table 4.3 . As discussed previously, the activity of the filter in removing organics resulted to be a function of the concentration of the organic matter. In the other two flow rate conditions, however, the tendency of the influent COD was to increase with time, thus the tendency of the gas production was to increase.

On the other hand, during the first flow rate condition, the soluble COD in the feed was determined by filtering the feed and conducting COD test on the filtrate. The COD of the filtrate was compared to the total influent COD resulting in a COD much lower than that of the unfiltered feed. This evidenced that most of the organic contents applied to the filter were in suspended form. This was apparently common in all the conditions studied. Table 4.7 shows the COD of both soluble and suspended organic matter in the feed.

Best COD removal efficiencies were attained at a liquid flow rate of 92 l/d (24.3 gal/d) and an HRT of 10 hours where a maximum removal of 55% was achieved.

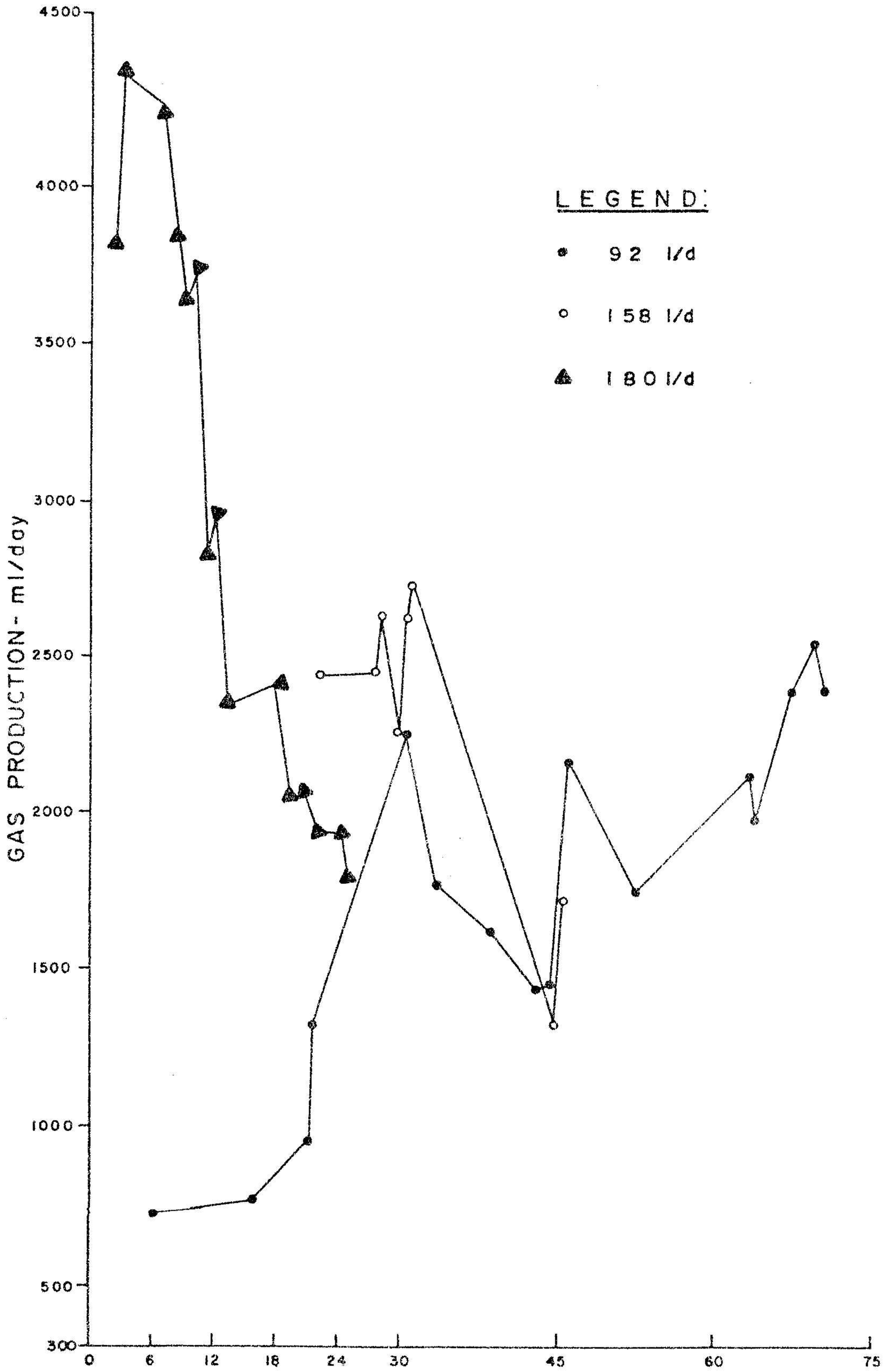


FIG. 4.11 TOTAL GAS PRODUCTION

TABLE 4.7

SOLUBLE AND SUSPENDED ORGANIC CONTENTS IN FEED AT FLOW RATE OF 92 l/d

Sample	TSS mg/l	Total COD mg/l	COD - mg/l Soluble Organic	COD - mg/l Suspended Organic
Jul 6/78	1465	1510	39	1471
Jul 31/78	3830	4776	132	4644
Aug 8/78	4120	2737	95	2642
Aug 13/78	3976	2920	84	2836
Aug 16/78	3700	4706	142	4564
Aug 22/78	7560	3254	123	3131

4.2.2 Biological Solids

Many authors [5,12,15,21,41,45,46] have recognized the ability of the anaerobic filter to retain active biological solids for long periods of time which results in high treatment efficiencies and in an exceptionally low solids production. The total biological solids are composed of the portion attached to the support medium and the portion entrapped between the support particles. However, as was evidenced by the effluent TVS concentrations listed in Tables 4.1 thru 4.3, a high fraction of the biological solids were neither attached nor entrapped by the filter media. This could result in a low organic matter degradation as the contact between the biomass and the organics has not necessarily been accomplished since the biological solids were subject to be washed-off from the filter. Thus, a low COD removal efficiency could result. Unfortunately, there was no experimental evidence that the high concentrations of biological solids in the filter effluent adversely affected the COD removal efficiency.

4.2.2.1 Suspended Solids

As can be seen in Tables 4.1 thru 4.3, the effect of the treatment over the TSS was rather limited, especially at a flow rate of 180 1/d (47.6 gal/d) and a HRT of 4.1 hours where the lowest TSS removal were registered. Best removal efficiencies were obtained at 92 1/d(24.3 gal/d) and 10-hours hydraulic retention time where a maximum removal of 68% was achieved. The effect of the anaerobic filter on the TSS is illustrated in Figures 4.8 thru 4.10.

The resulting solids contents showed that in each of the three conditions studied the influent TSS averaged over 90% of the total solids contents. Of these, approximately 40% were fixed inorganic solids. This resulted in a considerably high TSS contents which was responsible for persistent filter clogging problems. To minimize plugging events, filter influent and effluent lines were cleaned approximately every two days. Plugging events were generally anticipated thru the flow rate monitoring.

Occasional wash-off of solids had been observed. This condition was more evident in the last two flow rate conditions due to the increases in flow rates. In fact, the apparent increase in the effluent TSS shown in Tables 4.2 and 4.3 can be explained as due to the wash off of solids. However, it was difficult to determine the extend to which the effluent solids were being washed off. The rate at which the solids were washed off could not therefore be established.

Although TSS removals have been achieved, the filter effluent TSS concentration was kept relatively high. For all the conditions studied not less than 80% of the total solids present in the effluent were in suspended form. The high effluent TSS concentrations suggested that they were loose instead of attached or trapped by the Raschig rings so that they could easily be removed for further disposal.

Investigations conducted by Young and McCarty[44] showed that the anaerobic filter process was most appropriate for the treatment of completely soluble organic wastes and that small amounts of degradable suspended solids perhaps could be accepted without clogging problems. They also

showed that calloidal suspensions such as starches and dilute milk wastes should be treatable unless coagulation becomes a problem. For high solids producing wastes, they recommended occasional solids wasting to assure continuous operation avoiding severe filter plugging. According to Jennet and Dennis[15], no net removal may be observed for wastes containing solids. Moreover, Jennet and Dennis[15] and Plummer et al.[30], observed that the solids concentration was mainly determined by the HRT.

Treatment limitations would have therefore been expected when treating wastes with a high content of suspended solids by means of the anaerobic filter.

4.2.2.2 Total and Volatile Solids

The influent and effluent TS and TVS concentrations are shown in Tables 4.1 thru 4.3. To simplify the discussion, the solids contents were averaged and listed in Table 4.8. Since the flow rate through the filter was kept constant for a period of time in each of the conditions studied, the values of Table 4.8 represent arithmetic averages.

In all the conditions, the feed resulted in a high solids contents in the effluent. During the first flow rate condition, the average TS concentration was 4962mg/l of which 4707 mg/l or 96% were in suspended form. Of the 4707 mg/l of suspended solids, 57% or 2662 mg/l were volatile solids (TVS). During the second condition the influent TS averaged 7311 mg/l with 95% (6946 mg/l) in suspended form. The TVS concentration averaged 63% of the TSS of 4350 mg/l. During the third condition which was the last flow rate condition studied, the average TS concentration was 6738 mg/l. The TSS concentration average 92% of total

TABLE 4.8

ARITHMETIC AVERAGE OF SOLIDS CONTENTS

FLOW l/d	HRT hr	TS mg/l		TVS mg/l		TSS mg/l	
		Influent	Effluent	Influent	Effluent	Influent	Effluent
92	10.0	4962	3785	2662	2404	4707	3038
158	5.8	7311	6711	4350	4174	6946	6101
180	5.1	6738	6559	3615	3818	6191	5928

solids (6191 mg/l) of which 3615 mg/l (58%) were TVS. For all the conditions, the inorganic solids contents in the influent was about 40% of the TSS. Those high solids concentrations in the feed can be explained as due to the nature of the returned activated sludges generated in the domestic wastewater treatment plants.

The resulting high values of TS and TVS in the effluent suggest that the solids were not well attached or trapped by the support medium. This allowed that considerable biomass concentration measured in terms of TVS was washed-off from the filter.

The fact that the effluent TS and TVS resulted in higher concentrations than the influent TS and TVS can be explained as due to the wash-off condition.

4.2.3 Hydraulic Retention Time

The theoretical HRT in each of the three conditions studied was 5.1, 5.8, and 10.0 hours, respectively. These were calculated on the basis of the filter liquid volume of 1.35 ft^3 (38.2l).

COD and TSS removal efficiencies as a function of the theoretical HRT are shown in Figure 4.12. It can be seen from this figure that COD and TSS removal efficiencies resulted to be directly proportional to the HRT, which was evidenced by the decreases in COD and TSS removals at lower HRT's. Consequently, the portion of the influent COD remaining in the filter effluent resulted to be inversely proportional to the HRT so that, as HRT increases the effluent COD decreases. This means that for high COD removal efficiencies in the anaerobic filter process, the

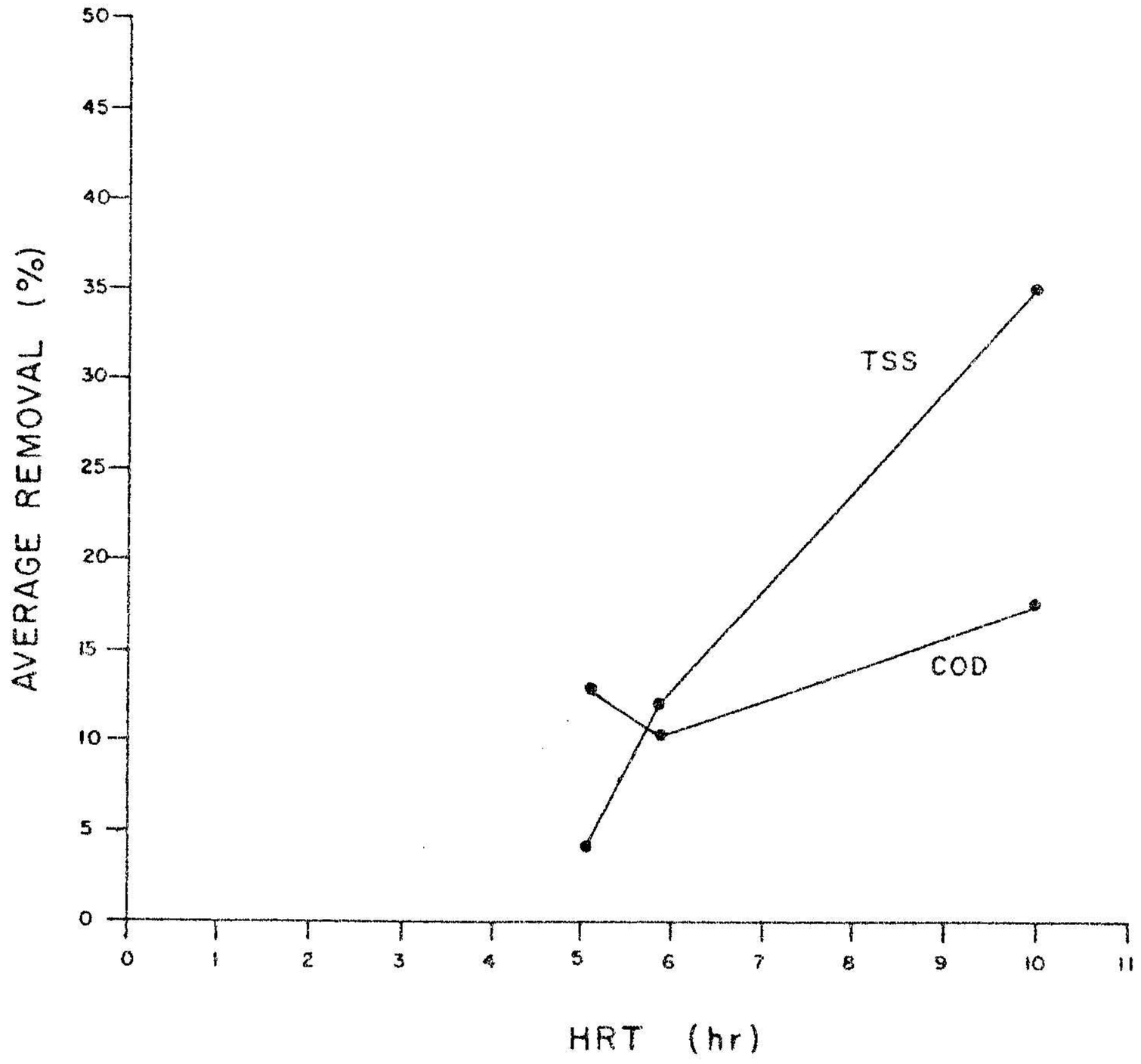


FIG. 4.12 COD AND TSS REMOVAL EFFICIENCIES AS FUNCTION OF THEORETICAL HRT

corresponding HRT should be long enough to assure the organic matter in the wastes get into contact with the bacteria, but short enough to reduce the volume requirements and hence the cost of the filter. Therefore, in terms of effluent quality, the HRT resulted to be the most important operating parameter of the anaerobic filter.

In the anaerobic conventional process, an economical and efficient treatment of the concentrated wastes is obtained with an HRT equals to SRT. An efficient operation of the anaerobic activated sludge process may be performed by controlling the SRT which is achievable through the return of the activated sludge flow. In the anaerobic filter, however, it is very difficult to control the SRT due to the long period of time the microorganisms may remain attached to the medium. Thus, the operation of the system should be controlled by regulating the HRT. From Equation 2-9 it can be seen that since the volume of the filter will remain constant, the HRT may be controlled through the influent flow rate. An increase in the flow rate will result in a decrease in the HRT.

Long HRT's may not be achievable when treating wastes with high concentrations of suspended solids. This is essentially due to the considerable increase in the plugging events in the filter. Such a problem was experienced during the filter start-up operations when a very low flow rate was allowed to acclimate the bacteria to a continuous flow-through condition. Flushing of the influent and effluent lines was required to minimized the plugging events.

The HRT's used in this study compare favorably with those used by McCarty[21] in treating synthetic wastes. He used HRT's of 6 and 8 hours. However, much longer HRT's have been used by other investivators depending basically on the waste. Haug et al.[34], used HRT's of 2 and 3 days in an anaerobic filter process treating decant liquor resulting from heat treatment of waste activated sludge. Chian et al.[5] provided HRT's ranging from 3 to 42 days to an anaerobic filter treating high strength acidic wastewater. Jennet and Dennis[15], provided 12 to 48 hours of hydraulic retention to an anaerobic filter treating pharmaceutical wastes. The HRT therefore will depend on the type and nature of the waste. Generally, in a conventional process high strength wastes require longest HRT. However, long HRT's are not necessarily required by the anaerobic filter since microorganisms may remain attached to the filter media for long times resulting in a high treatment efficiency. This may reduce the tank volume requirements and hence, the construction costs.

Although provisions were taken to avoid short circuiting through the biologically reduced filter void volume, the possibility of occurrence may not be neglected. However, a quantitative evaluation of the short circuiting effect could not be performed because of the absence of sufficient information on the operational characteristics of the anaerobic filter.

4.2.4 pH and Alkalinity

Tables 4.1 through 4.3 show the influent and effluent pH in all the conditions studied. The alkalinity provided in the waste to the filter is shown in Table 4.4 .

The alkalinity contents in the feed was apparently not enough to neutralize the drop in pH caused by the excess of volatile fatty acids produced during the hydrolisis stage of organics fermentation. Consequently, the resulting acidic environment could inhibit the methane producing bacterias reducing somewhat the methane production rate and hence the stabilization of the organic matter. Unfortunately, there is no data available to support this.

The alkalinity provided in the feed varied from 100 to 277 mg/l as $CaCO_3$, which is substantially less than that used by other authors. El-Shafie and Bloodgood[12], for instance, used sodium bicarbonate as a buffer at an amount of 6000 mg/l as $NaHCO_3$ and then increased it to 8000 mg/l. Through this, the drop in pH at the first stage of decomposition was prevented. They obtained a total organic removal efficiency of not less than 70.5%. Landine et al.[12], treated potato processing wastewater dosed with sodium bicarbonate to raise the alkalinity to about 3000mg/l. They registered COD removals ranging from 45.3 to 67.7%. Haug et al.[34], feeding the anaerobic filter with decant liquor resulting from heat treatment of waste activated sludge, added approximately 2000mg/l of alkalinity as $CaCO_3$ in the form of sodium bicarbonate. COD and BOD removals averaged 76 and 85 percent, respectively. Finally, Taylor[41] added 1000mg/l of $NaHCO_3$ at an influent COD concentration of 8800mg/l. It should be noted that although the influent pH was always kept around the neutral zone by adding lime in some occasions where the pH dropped below 6.5, the alkalinity provided might not have been sufficient for neutralizing the volatile acids produced in the first stage of the oxidation.

4.2.5 Temperature

No control was exerted over the process temperature. However, the atmospheric temperature was measured on a daily basis. Because of the tropical weather conditions existing in Puerto Rico, the atmospheric temperature registered in the plant surroundings ranged from 75° to 99°F (24° - 37°C) as shown in Tables 4.9 thru 4.11. In 1976, Rivera[33] observed that the temperature in the filter varied approximately from 70° to 80°F (21° to 27°C) in a heat-free anaerobic filter. This relatively high temperature range under which all the three flow rate conditions were studied, obviously mirimized the heat requirements of the process. It is known that the anaerobic treatment of wastes is most efficient at high temperatures, that is, temperature ranging from 85° to 105°F (30° to 41°C). However, good BOD removal efficiencies have been observed in anaerobic systems operated at room temperature [21,38,39,45]. Switzenbaum and Jewell[38] found that the large mass of organisms attached to the medium and the increases in film thicknesses and biomass concentrations at lower temperatures partly caused the system to operates efficiently. Similarly, Young and McCarty[45] observed the ability of the anaerobic filter to retain a large mass of anaerobic microorganisms resulting in an efficient treatment at ambient temperature. Although heating was not strictly required is this filter, first among the possibilities for improving filter performance is to heat the filter and its contents. However, in addition to the extra costs the heating activities would bring, it is clearly understood that the problem of high TSS in the wastes cannot overcome the benefits that heating the filter might bring. It is believed, therefore, that the filter removal efficiency will not signif-

TABLE 4.9

ATMOSPHERIC TEMPERATURE AND PRESSURE CONDITIONS UNDER WHICH GAS MEASUREMENTS WERE CONDUCTED DURING THE 92 l/d FLOW RATE CONDITION

Date	Atmospheric Temp °C	Atmospheric Pressure kPa	Total Gas Production STP ml/day
Jun 30/78	31	135.47	720
Jul 6	30	135.21	721
Jul 16	29	135.10	783
Jul 21	29	135.14	964
Jul 22	30	135.13	1321
Jul 31	32	135.08	2266
Aug 3	33	135.07	1783
Aug 8	30	135.19	1622
Aug 13	30	135.12	1441
Aug 14	29	135.42	1449
Aug 16	27	135.24	2185
Aug 22	34	133.16	1752
Sep 6	35	134.78	2121
Sep 7	37	134.89	1992
Sep 10	35	137.02	2396
Sep 12	28	135.89	2553
Sep 13	28	133.91	2396

Note: 1.8 (^{o}C) + 32 = ^{o}F

kPa x 0.145 = psi

TABLE 4.10

ATMOSPHERIC TEMPERATURE AND PRESSURE CONDITIONS UNDER WHICH GAS MEASUREMENTS WERE CONDUCTED DURING THE 158 l/d FLOW RATE CONDITION

Date	Atmospheric Temp °C	Atmospheric Pressure kPa	Total Gas Production STP ml/day
Jan 22/79	28	129.93	2441
Jan 27	24	135.17	2451
Jan 28	29	134.48	2638
Jan 29	32	134.55	2257
Jan 30	31	134.75	2626
Jan 31	33	134.68	2726
Feb 14	30	134.00	1310
Feb 15	30	137.12	1706

Note: 1.8 (°C) + 32 = °F

kPa x 0.145 = psi

TABLE 4.11

ATMOSPHERIC TEMPERATURE AND PRESSURE CONDITIONS UNDER WHICH GAS MEASUREMENTS WERE CONDUCTED DURING THE 180 1/d FLOW RATE CONDITION

Date	Atmospheric Temp °C	Atmospheric Pressure kPa	Total Gas Production STP ml/day
Mar 2/79	33	135.51	3816
Mar 3	28	135.87	4376
Mar 7	37	135.84	4248
Mar 8	30	135.55	3855
Mar 9	27	135.21	3641
Mar 10	31	135.54	3722
Mar 11	32	134.78	2856
Mar 12	31	134.75	2984
Mar 13	33	134.15	2361
Mar 18	28	134.81	2412
Mar 19	26	134.75	2063
Mar 20	27	134.54	2053
Mar 22	30	135.80	1931
Mar 24	26	134.08	1932
Mar 25	31	134.12	1782

Note: 1.8 (^{o}C) + 32 = ^{o}F

kPa x 0.145 = psi

icantly be improved if the problem of high influent TSS concentration is not first overcome.

For some wastes, sufficient methane may clearly be produced to heat significantly the waste. On the other hand, some wastes are naturally warm and require no heating. Such a condition is very common in the domestic wastewater treatment in Puerto Rico. The wastes used in this study was treated in a natural mesophilic ambient temperature range and in general, required no heating.

If it is compared to the effect caused by the high organic loadings, high organic loading fluctuations, and high TSS concentrations, it is estimated that the effect of the filter temperature operation range has not significantly influenced the biological growth coefficients (Equations 2-3 and 2-4) to cause adverse effects to the treatment efficiency. Though the maximum substrate utilization rate, K, and the half velocity coefficient, K_s, are strongly temperature dependent [18,28] and their variations tend to affect the substrate removal characteristics of the filter. Besides, the variations in the microorganisms growth yield, Y, and decay coefficient, K_d, tend to produce changes in the predictable COD and biological solids accumulations. However, in relative terms it is considered that this phenomena caused less influence in the resulting limited treatment efficiency than the former.

4.2.6 Gas Production

The filter response as indicated by the gas production rates, expressed in STP conditions, resulting after each of the flow rate changes is listed in Tables 4.9 thru 4.11. Figure 4.11 illustrates such responses.

Neither the tables nor the graph include the start-up operation periods provided at each condition. Also excluded are the days in which the filter was found clogged and the days required for the subsequent "recovery" of the filter. Plugging periods have never been more than 24 hours. However, several days were allowed for the recovery of the previous filter operating conditions.

It should be noted, that the flow rate conditions studied were not run at the same time as one might think from the graph. The x-axis represents the period of operation in days of each condition and the starting point represents the day of the month when the condition period began. The exact dates in which the conditions started to be studied and the time ellapsed in each condition can be obtained from Tables 4.9 thru 4.11.

None of the three conditions resulted in a consistent increase of gas production. It was observed that the filter gas production fluctuated day by day as illustrated in Figure 4.11. This has mainly been caused by the irregular waste feeding. A comparison between the variations in gas production rates and the variations in influent COD (Figures 4.5 thru 4.7) suggests that the gas production was affected by the continuous state of fluctuation of the influent COD. In the 92 l/d (24.3 gal/d) flow rate condition, for instance, as the influent COD varied from about 1500 mg/l to approximately 1800 mg/l during the first 24 days, the gas production was limited from about 700ml to approximately 900ml. From day 24 to day 30 the COD of the waste increased from about 1800 mg/l to approximately 5000 mg/l. This variation produced an increase in the gas production from about 900 ml on day 24 to about 2300 ml on day 30. Then

the COD dropped to less than 3000 mg/l on day 40 and so did the gas production rate to about 1600 ml. A similar operational pattern was observed through the rest of the period and also in the other two flow rate conditions. Considering the gas production as an indication of the process performance, it is clear that the activity of the filter in removing organic matter may be significantly affected by the fluctuation in the applied organic loadings. It is recognized, however, that even with uniform feed rates some fluctuations exist[4,46], but these are so insignificant that no considerable effects are produced in the process efficiency.

Moreover, the apparently low alkalinity content could not be sufficient to neutralize the pH decrease during the fatty acids production stage, which could partially inhibit the methane bacterias resulting in a relatively low gas production. On the other hand, in view of the fact that the pH was almost maintained and actually increased as the feed material passed through the system, it can be speculated that there was a loss of methane producers that could not be overcome by the reproduction rate of the gas former. Unfortunately, there is no sufficient data to support this as no volatile acids data could be produced due to a lack of proper material and equipment.

As the considerable high concentration of suspended solids significantly limited the organics conversion, the resulting gas production has consequently been restrained. Similar fluctuation patterns observed in the influent TSS profiles (Figures 4.8 thru 4.10) and in the gas production rates tend to denote the influence of the TSS contents in the filter gas production and therefore on the treatment performance.

Insufficient methane for in/off-plant uses was produced in all the conditions studied. Its rate of production however, changed from condition to condition. Although in the third condition (180 l/d) the highest gas production rate was observed, it was not consistently held during the period of operation. Similarly, the lowest gas production rate was observed during the first condition (92 l/d) but in this condition the gas production rate was also inconsistently held.

In spite of the fact that was in the third condition where the highest amount of gas was produced, it was not the condition where the highest percentage of methane (by volume) was obtained, Table 4.12 shows the percentages by volume of methane produced in each condition. The higher percentage of methane content was observed in the 158 l/d flow rate condition. The chromatographic analysis performed to the produced gas indicated that the gas was a mixture of methane and carbon dioxide only. An increase in the percentage of methane denoted a decrease in the percentage of carbon dioxide. It should be noted that in addition to the methane and carbon dioxide peaks, a very little air peak was also observed on chromatograph's chart. This can be explained as due mainly to deficiencies in the sample collection and/or injection techniques. However, since the percentage of air resulted always to be less than one percent, it was disregarded. The resulting peak areas corresponding to methane and carbon dioxide percentages were measured using a high precision planimeter. Also seen in Table 4.12 is the fact that the lowest percentage of methane occured at the first condition. This could be explained as it was in this condition where the lowest organic loading were applied. However, the percentage of methane in this period has never been less

TABLE 4.12

FILTER GAS COMPOSITION

Date	HRT hrs	Total Gas Production STP ml/day	Methane % by volume	Carbon Dioxide % by volume
Jul 16/78	10.0	783	65	35
Jul 21	10.0	964	70	30
Jul 31	10.0	2266	66	34
Aug 8	10.0	1622	60	40
Aug 14	10.0	1449	62	38
Aug 22	10.0	1752	66	34
Sep 7	10.0	1992	64	36
Sep 13	10.0	2396	63	37
Jan 22	5.8	2441	79	21
Jan 30	5.8	2626	77	23
Feb 15	5.8	1706	65	35
Mar 3	5.1	4376	71	29
Mar 8	5.1	3855	68	32
Mar 12	5.1	2984	69	31
Mar 18	5.1	2412	72	28
Mar 24	5.1	1932	63	37

than 60%. In order to burn a concentration of at least 56% by volume of methane is necessary. Therefore, all the methane produced in the study was able to burn, although a concentration of at least 62% is required to be used as combustible.

Additionally, according to Table 4.13, it was in the first flow rate condition where in general,the highest volume of gas per pound of COD removed was produced, yet it compares unfavorably with theoretical methane production rate of 5.62 cubic feet per pound of COD removed (351 l/g COD removed) discussed in Subsection 2.2. Thus, a comparison between COD removal and methane production indicates that not all the COD removed was converted to gas. This is attributed to the continuous fluctuations of the organic loading rates and the considerably high magnitudes of such loads, and to the significantly high TSS contents.

None of the three conditions studied showed a significant improvement in the organic removal nor in the gas production rate.

4.2.7 Economic Features

Insufficient data are available at this time to perform an accurate economic comparison of the anaerobic filter process to other domestic wastewater treatment process. However, the potential absence of requirements for heating, and the definite absence of aeration equipment would suggest that the filter has a number of economic advantages. Additionally, since the hydraulic head loss in the filter is low, the power requirements could be very limited. Regardless of what the economic advantages would be the big drawback of the filter consists of its limitation to treat wastes with high contents of suspended solids.

TABLE 4.13

TOTAL GAS PRODUCTION AT STP FROM ORGANIC MATTER METABOLIZATION

FLOW RATE OF 92 l/d			FLOW RATE OF 158 l/d		
Date	Total Gas Production ml/d	Total Gas Prod. per Lb COD Removed ft^3/Lb	Date	Total Gas Production ml/d	Total Gas Prod. per Lb COD Removed ft^3/Lb
June 30/78	720	.54	Jan 22/79	2441	.53
Jul 6	721	.54	Jan 27	2451	.25
Jul 16	783	.32	Jan 28	2638	.58
Jul 21	964	.75	Jan 29	2257	.50
Jul 22	1321	.55	Jan 30	2626	.35
Jul 31	2266	.24	Jan 31	2226	.30
Aug 3	1783	.90	Feb 14	1310	.25
Aug 8	1622	.52	Feb 15	1706	.33
Aug 13	1441	3.44			
Aug 14	1449	1.40			
Aug 16	2185	.18			
Aug 22	1752	.17			
Sep 6	2121	3.70			
Sep 7	1992	.65			
Sep 10	2396	.83			
Sep 12	2553	.94			
Sep 13	2396	1.52			

Note: $ft^3/_{Lb} \times 0.0624 = l/g$

TABLE 4.13 (Cont'd.)

FLOW RATE OF 180 l/d		
Date	Total Gas Production ml/d	Total Gas Prod. Per Lb COD_3 Removed ft^3/Lb
Mar 2/79	3816	2.15
Mar 3	4376	.17
Mar 7	4248	.37
Mar 8	3855	.31
Mar 9	3641	.29
Mar 10	3722	1.05
Mar 11	2856	.27
Mar 12	2984	.24
Mar 13	2361	.33
Mar 18	2412	.23
Mar 19	2063	.26
Mar 20	2053	.19
Mar 22	1931	2.18
Mar 24	1932	.20
Mar 25	1782	2.01

Since insufficient methane for in/off-plant uses has resulted, an energy saving and/or marketing analysis would be meaningless.

SECTION 5

CONCLUSION AND RECOMMENDATIONS

The following conclusions can be drawn concerning the performance of the anaerobic filter as determined from this laboratory study:

1. Inability of the anaerobic filter for treating domestic wastewaters containing high concentrations of suspended solids (more than 1000 mg/l) because of the inherent plugging problems. This is applicable to both organic and inorganic solids. Due to the nature of the anaerobic filter, lower concentrations of suspended solids may not presumably be assimilated, either. Therefore, the treatment of sludges from aerobic or anaerobic processes by means of the anaerobic filter seems to be infeasible.

2. The organic loading is a very important design parameter to be controlled during the operation of the anaerobic filter. The activity of the filter in removing organic matter evidenced the dependence on the applied organic loading. The continuous variations of the organic loading rates and the considerably high magnitude of such loads in addition to the high concentration of suspended solids could result in dynamic fluctuations between the individual waste components affecting the steady state condition of the organic conversion process causing that none of the three conditions studied have shown a significant improvement in the organic removal and in the gas production rate. However, occasional COD and TSS removals of 55% and 68%, respectively, were observed at the first flow rate condition of 92 l/d (24.3 gal/d).

3. The portion of the influent COD remaining in the filter effuent appears to be inversely proportional to the theoretical hydraulic retention time for a range of 5.1 to 10 hours. Therefore, that the hydraulic retention time appears to be the most important operating parameter of the anaerobic filter. Its selection depends on the degree of treatment desired as well as on the type and nature of the waste to be treated. For wastewaters containing suspended solids, long hydraulic retention time may not be achievable because of the plugging problems.

4. In a practical sense, the biological solids contained in the filter effluent must be considered as an additional waste load to the system receiving it.

5. Effuent volatile solids concentrations evidenced that a high fraction of the biological solids were neither attached nor entrapped by the filter media.

6. The methane produced from the anaerobic filter treatment of this high suspended solids concentration wastes was not sufficient in volume to represent a potential alternative over a range of in/off plant uses.

7. Not all the COD stabilized in the process was converted to gas. However, the gas produced from the anaerobic treatment of the returned activated sludge results in at least 60% methane by volume but, most of the time over 62% by volume of methane was obtained. Thus, in high methane producing wastes, this may represent a potential alternative to energy saving.

8. The highly possible absence of requirements for heating, the definite absence of aeration equipment, and the low power requirements suggest that the filter has a number of economic advantages over other biological waste treatment processes.

Based on the findings of this study, the following is recommended for future investigation of the anaerobic filter process:

1. The investigation of design modifications in order to make possible the applicability of the anaerobic filter for treating wastewaters containing suspended solids.

2. Pilot plant studies to (a) investigate the design modifications of the filter to operate under a continuous fluctuation of the organic loading with acceptable organic removal efficiencies, (b) determine the effects on the treatment efficiency of accumulated solid wasting, (c) develop better design parameters or to verify the relationships found in this study, (d) define the optimum filter operation conditions where treatment efficiency and methane production rate may be maximized, and (e) obtain more accurate information on the economics of the process.

3. A study of the hydraulics of the filter, including the effects of gas mixing.

4. An evaluation of the plug flow patternbasis of the filter operation.

5. The development of simple procedures to determine and monitor the solid retention time without shutting off the filter.

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