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RAW SEWAGE COAGULATION AND AEROBIC SLUDGE DIGESTION

Municipal Environmental Research Laboratory
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RAW SEWAGE COAGULATION AND AEROBIC SLUDGE DIGESTION

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ABSTRACT

Laboratory and full-scale studies were conducted at the Hollywood, Florida, sewage treatment plant to determine the efficiency of chemical coagulation for treatment of raw sewage. Various polyelectrolytes were investigated in laboratory tests and several cationic polyelectrolytes were chosen for field study. A full-scale primary clarifier was converted to a chemical coagulation reactor and clarifier. Polyelectrolyte addition was evaluated at various dosages and mixing speeds in order to achieve maximum solids separation. Unit design deficiencies were noted and evaluated.

The full scale clarifier was unable to duplicate the high treatment efficiencies achieved in the laboratory tests, probably due to a lack of adequate mixing and higher concentration of soluble BOD.

A comparative study of aerobic digestion of primary municipal sewage sludge was also performed at the Hollywood plant. Detention time and loading rate were deliberately varied along with the naturally varying temperature, sludge qualities, seasonal flow, evaporation, and precipitation. Primary and digested sludges were analyzed for reductions in chemical oxygen demand (COD), biochemical oxygen demand (BOD), total solids, total volatile solids, suspended and dissolved solids, alkalinity, pH and oxygen uptake rate. A batch digestion test was compared to the continuous feed tests. Operating conditions were optimized for maximum performance based on behavior of digested sludge on sand beds in terms of filterability, drainability, lack of odor, and nutrient content. Sludges were successfully digested with as little as ten days hydraulic detention. Process monitoring parameters of pH, oxygen uptake rate, and alkalinity were studied and evaluated as being moderately effective. Note was taken of operating difficulties such as foaming, poor sludge metering, and equipment deficiencies. A process design including tank and aerator sizing, and equipment and operating costs was developed for the existing Hollywood plant based on actual operating data. A storm water infiltration model, with an elimination of periodic flow fluctuations, was used to analyze the effects of rainfall on sewage treatment plant inflow.

It was concluded that aerobic sludge digestion provides an excellent method of stabilizing sludge prior to final disposal. An oxygen uptake rate of up to 1.8 mg of O_2/(gm T.S.)(hr) was observed for digestion tests with sludge ages greater than 20 days. Larger uptake rates were observed for digestion tests of 15 days or less detention. Sludge alkalinity was reduced to below 200 mg/l after 15 days and the pH stabilized at near 7.0. The solids content of

the digested sludge was between 4 and 6 percent and further gravity thickening was not practical. Digestion can be conducted in either a batch or continuous flow made with a recommended detention time of 20 days.

This report was submitted in fulfillment of project number 11010FAC under the partial sponsorship of the Office of Research and Development, Environmental Protection Agency.

TABLE OF CONTENTS

FIGURES

FIGURES (Continued)

TABLES

ACKNOWLEDGEMENTS

The funding and support for this project provided by the City Council of the City of Hollywood, Florida, is sincerely appreciated. Mr. Wallace Venrick, City Engineer and Mr. Marshall Bergacker, City Engineer, supplied labor from their departments to accomplish the many tasks of this project. During the project, the entire treatment plant and particularly the aerobic digesters were operated most ably by Mr. Bud Calhoun, Mr. Ernie Atkins, and their staff of plant personnel.

The operation of the pilot plant, laboratory analyses and program direction were provided by the staff of Environmental Science and Engineering, Inc., who also compiled the Progress and Final Project Reports. The aerobic digestion studies were directed by Dr. R. H. Jones who was assisted in the various duties by Messrs. M. K. Hamlin, R. G. Maxwell, and the entire laboratory staff. The final report was prepared by Messrs. T. A. Burnszytnsky and J. D. Crane.

The support given the project by the Office of Research and Development, Environmental Protection Agency, and the understanding help provided by the Project Officer, Mr. Ed Lomasney, are very sincerely appreciated.

SECTION I

CONCLUSIONS

RAW SEWAGE COAGULATION

1. Both laboratory jar tests and laboratory flow-through systems have shown that certain polyelectrolytes are highly effective for raw sewage coagulation. This effect can be explained by the existence of low concentrations of soluble BOD and high concentrations of colloidal BOD in the wastewater tested.

2. The Dorr-Oliver clariflocculator installed in an existing clarifier at the Hollywood sewage treatment plant was unable to duplicate the high treatment efficiencies achieved in laboratory jar tests. This was probably due to a lack of adequate mixing.

3. The most efficient coagulation of sewage was found at or near an electrophoretic mobility of 0.0 u/(sec)(v)(cm). However, significant reductions in BOD and suspended solids were found over a wide range of electrophoretic mobility values.

AEROBIC SLUDGE DIGESTION

1. Aerobic sludge digestion provides an excellent method of stabilizing primary municipal sewage sludge prior to ultimate disposal. It was indicated that waste sludge from an aerobic digester may contain 40 percent less COD, 80 percent less BOD, 11 percent less total solids, and 26 percent less volatile solids concentrations than undigested primary sludge. Actual reductions are higher, but evaporative losses approaching 25 percent reconcentrate the digested sludge.

2. Aerobically digested sludge will dry at a high rate on a sand bed with a good underdrain system. Properly digested sludge may be removed from the bed after four weeks of drying. The sludge should have no objectionable odor during the drying process. The depth of sludge applied to the sand bed was approximately 12 inches.

3. Aerobically digested sludges, dried on a sand bed, have little mineral fertilizer value. Phosphorus values were less than 0.4 percent and Kjeldahl nitrogen less than 3.7 percent by dry weight. Nitrate plus nitrite nitrogen were found at less than 0.8 mg/gm of dry sludge.

4. Aerobically digested sludge for all detention times experienced substantial reductions of waste constituents upon lagooning. Total mass reductions of COD, BOD, total solids, and volatile solids were between 30 and 50 percent within a 70-day lagooning period. Constituent reductions approached zero at 70 days lagooning of batch samples. A potential problem with lagooning of aerobically digested sludge is the possibility of odors.

5. The specific resistance values of aerobically digested sludges were from 25 to 182 times greater than undigested primary sludge. It would therefore appear that aerobically digested sludges are more amenable to mechanical dewatering than anaerobically digested sludges.

6. Digested primary municipal sewage sludge was not amenable to further gravity thickening. The total solids concentrations of the aerobic digester were usually between 40,000 and 60,000 mg/l.

7. Process monitoring parameters could be used to detect gross changes in sludge quality. An oxygen uptake rate up to 1.8 mg of O_2/(gmT.S.)(hr) characterized digestion tests with sludge ages greater than 20 days. Uptake rates of greater than 1.8 mg of O_2/(gmT.S.)(hr) occurred with digestion tests of 15 days or less detention. Alkalinity of aerobically digested sludge was greatly reduced from that of primary sludge. Sludges digested for 15 days or longer had average alkalinities below 200 mg/l. There was a gradual and small rise in the pH of digested sludges from 5.9 to near 7.0 within the digestion periods of this program. Of the three parameters just mentioned, none provide an accurate picture of sludge quality that would relate to behavior on a sand bed or upon filtration without further correlation and testing.

8. Visual parameters of aid to the plant operator are the color and sludge thickness in the digester.

SECTION II

RECOMMENDATIONS

RAW SEWAGE COAGULATION

Further research on coagulation of sewage with polyelectrolytes should only be conducted in treatment systems especially designed to provide adequate mixing and settling conditions with high concentrations of colloidal BOD.

Control systems need to be found which can automatically regulate polyelectrolyte addition to provide optimum coagulation during wide fluctuations of wastewater flow and composition normally found at sewage treatment plants.

New polyelectrolytes should be developed which will provide effective sewage coagulation at a minimum cost, as existing polymer costs are quite high.

AEROBIC SLUDGE DIGESTION

It is recognized that there is a growing trend in this country to provide at least secondary treatment for municipal wastewaters. When primary waste sludges alone, or even combined with waste activated sludges, are to be stabilized prior to final disposal, aerobic digestion should be given serious consideration as a prime alternative. Specific design recommendations are presented in Appendix B.

The operation and maintenance of an aerobic digester is relatively simple and trouble free. Still needing to be determined are rapid physical or chemical tests which would indicate the degree of digestion a sludge has undergone and which could be accurately related to future behavior of the sludge in drying and final disposal. Until such tests are available, design parameters will need to be conservative and allow for overdigestion to produce a given stabilization. These tests should be developed with full- scale aerobic digesters under the rigors and changing conditions of daily operation.

Mechanical equipment should be improved for use with aerobic digesters. Currently, wind driven spray from mechanical mixers coats equipment and surrounding areas. Future designs should include provisions for spray containment.

Accurate determinations of volume change in a large scale digester cannot readily be made. Fouling of measuring devices by detritus or foam blankets precludes the use of most inexpensive devices available. Similarly, sludge transfer mechanisms, particularly under gravity flow, need reliable metering equipment. Such equipment could greatly improve an operator's control over his plant and additionally could be the tools needed to find process monitoring parameters.

In view of the trends toward secondary treatment of municipal wastewaters, it is strongly recommended that a study similar to the one described herein be performed for primary and waste activated or trickling filter sludges combined with an appropriate representation of the various waste activated and trickling filter sludge available.

SECTION III

INTRODUCTION

This research program involving a study of raw sewage coagulation and aerobic sludge digestion originated in 1968 when, as a result of the increasing number of ocean outfalls and the lack of knowledge concerning their effects, the Environmental Protection Agency funded a grant to the city of Hollywood, Florida, to demonstrate new sewage treatment methods. Environmental Science and Engineering, Inc., of Gainesville, Florida, was contracted to perform the necessary research work.

The study of raw sewage coagulation and aerobic sludge digestion was part of the overall project which also dealt with a study of diffusion from the Hollywood ocean outfall and a biological study of the effects of the outfall on the environment. The results of the outfall studies have been published in a separate report.

Financial support for the research effort necessary to accomplish this project was partially provided by an EPA Research and Development Grant (No. 57 (R1)-01-68) of $300,000 which is equivalent to 50 percent or less of eligible project costs. The City of Hollywood provided the balance of the project funding.

THE HOLLYWOOD SEWAGE TREATMENT PLANT

The City of Hollywood Sewage Treatment Plant in Hollywood, Florida, serves a principally residential region with very little industry. The Hollywood region is one of rapid growth and ever expanding population. The City of Hollywood and adjoining communities are situated on coastal land bordered on the east by the Atlantic Ocean. West of the city at distances of 10 to 15 miles from the coast lie extensive freshwater swamps.

The city of Hollywood draws its water from local aquifers. Increasing population demands on these aquifers have led to salt water intrusion along the coast and newer wellfields are being utilized farther inland. The salt water intrusion into the ground water table at the coast has been noticed in the seepage to the city's sewage system. High chloride levels of 3,500 mg/l are common in raw sewage entering the treatment plant. At some locations on the coast, very old and leaking sewer systems experience direct seawater infiltration and thus substantially increase the salinity of the total sewage flow to the sewage treatment plant. A further discussion of sewer line infiltration is contained in Appendix A.

The average plant flow of raw sewage in 1971 was 13.6 million gallons per day. Typical influent concentrations of constituents were biochemical oxygen demand at 130 mg/l, chemical oxygen demand at 340 mg/l, suspended solids at 110 mg/l, and chloride ion at 3,500 mg/l. These values are indicative of a relatively weak sewage generated by residential communities with little industrial input. The topography of the Hollywood area is flat with a low elevation. Sewer flows are at minimum velocities and sewage has often arrived at the plant in an anaerobic state due to long residence times in the sewers. There being no storm sewers in the Hollywood area, storm water and sea water infiltration is collected by the sanitary sewer system. This additional water provides a noticeable dilution of normal sewage constituent concentrations.

At the time of the study the wastewater treatment plant (shown in Figure 1) served solely as a primary solids separation plant. Plant flow was 13.6 MGD with a capacity of 36 MGD. Raw wastewater was initially screened before flowing to grit collectors. The grit collectors could remove a minimum of 95 percent of 100 mesh grit having a specific gravity of 2.65. The plant was equipped with two grit collectors each capable of handling a maximum flow of 40 MGD.

The de-gritted wastewater flowed to a below grade influent pumping station. This pumping station provided the lift necessary to feed the primary clarifiers which were located entirely above ground level. Flow from the pumping station was distributed to the various clarifiers by an elevated distribution box.

The physical plant had nine primary clarifiers; however, only six of these were in use during the research project. The primary clarifiers varied in diameter from 65 feet to 120 feet and in depth from 9 ft. 7 in. to 11 ft. 5 in. The efficiencies of the primary clarifiers in removing solids are presented with the data for each specific test run.

Solids were wasted from the primary clarifiers' sludge well by manual control. Sludge would be pumped from the clarifier to the digester until the operators noticed a lessening in solids from the clarifier. At that time the pumps would be stopped with a relatively light liquid present in the pipes leading to the clarifiers. This light liquid would somewhat dilute the sludge in the next pumping cycle. Progressive cavity sludge pumps from the primary clarifiers were equipped with time clocks and during the program were calibrated against a measured liquid flow.

Sludge digestion facilities consisted of three 75 ft. diameter aerobic digesters with an operating depth of 12.0 feet and individual capacities of 396,345 gallons. Based on normal design criteria for primary sludge of three cubic feet per capita, the aerobic digesters could handle a design population of 53,000. This criterion will be re-evaluated in a later section. Each digester was equipped with a 100 HP floating mechanical aerator capable of providing 3.5 pounds of oxygen per horsepower hour as shown in Figure 2. Based on the results of this study, design recommendations for aerobic sludge digestion are presented in Appendix B.

FIGURE 1: AERIAL VIEW OF HOLLYWOOD SEWAGE TREATMENT PLANT

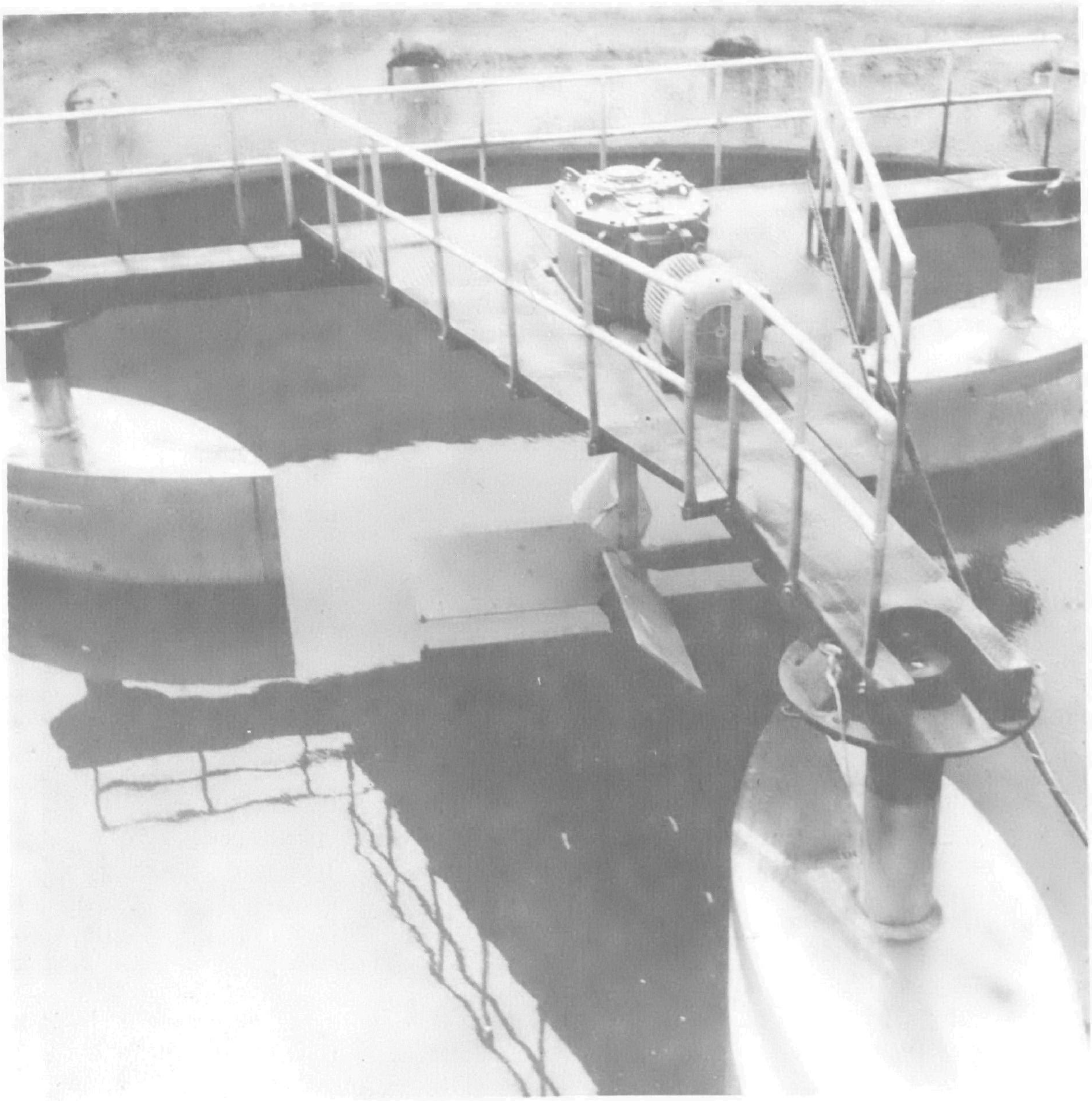

FIGURE 2: FLOATING MECHANICAL AERATOR FOR AEROBIC DIGESTER

Digested sludge was either wasted onto sludge drying beds or dewatered in two experimental centrifuges. Ultimate sludge disposal was in landfill areas.

Septic tank waste was received at a concrete unloading station with a receiving channel equipped with 45° bar screen. The septic tank station's wet well had a liquid capacity of 11,800 gallons and a pump-out capacity of 10,230 gallons. The septic tank raw sludge pump transferred the screened septic tank raw sludge to Digester No. 3 during most of the program except for the last two tests with the permanent plant digesters.

The sewage treatment plant effluent was discharged by gravity flow through a 9,700 foot ocean outfall. The diffusion of the effluent and its biological effects were also subjects of this study and are covered in a separate report.

The primary wastewater treatment plant had recently undergone conversion from a secondary trickling filter plant of lower capacity. At the start of the research effort, conversion of all equipment and the laboratory had not yet been completed. This occasionally resulted in discontinuous operating conditions for the aerobic digesters and a lack of analytical data in the early part of the program. With time, difficulties in plant operations were eliminated and both plant performance and operating data improved.

OBJECTIVES

Raw Sewage Coagulation

Coagulation of raw sewage with polyelectrolytes was one objective of this research and demonstration project. The City of Hollywood sewage treatment plant consisted of only primary sedimentation with final discharge through an ocean outfall. The use of polyelectrolytes to coagulate raw sewage within the primary clarifiers held the potential of significantly increasing treatment efficiency with minimum capital investment. In order to demonstrate the coagulation of raw sewage with polyelectrolytes within a primary clarifier, the necessary modifications were made and equipment installed in an existing 2.0 MGD clarifier, as shown in Figure 3. Results of laboratory and plant scale tests are reported in Section VI.

Aerobic Sludge Digestion

The basic objectives were to study the operation of an aerobic digester processing primary sewage sludge and to provide operating and design data applicable to future aerobic digesters in the treatment of municipal wastewaters. The specific objectives in this project were greatly influenced by the limitation of the project facilities. The City of Hollywood had recently converted an old trickling filter sewage treatment plant to a primary sedimentation plant with an ocean outfall for

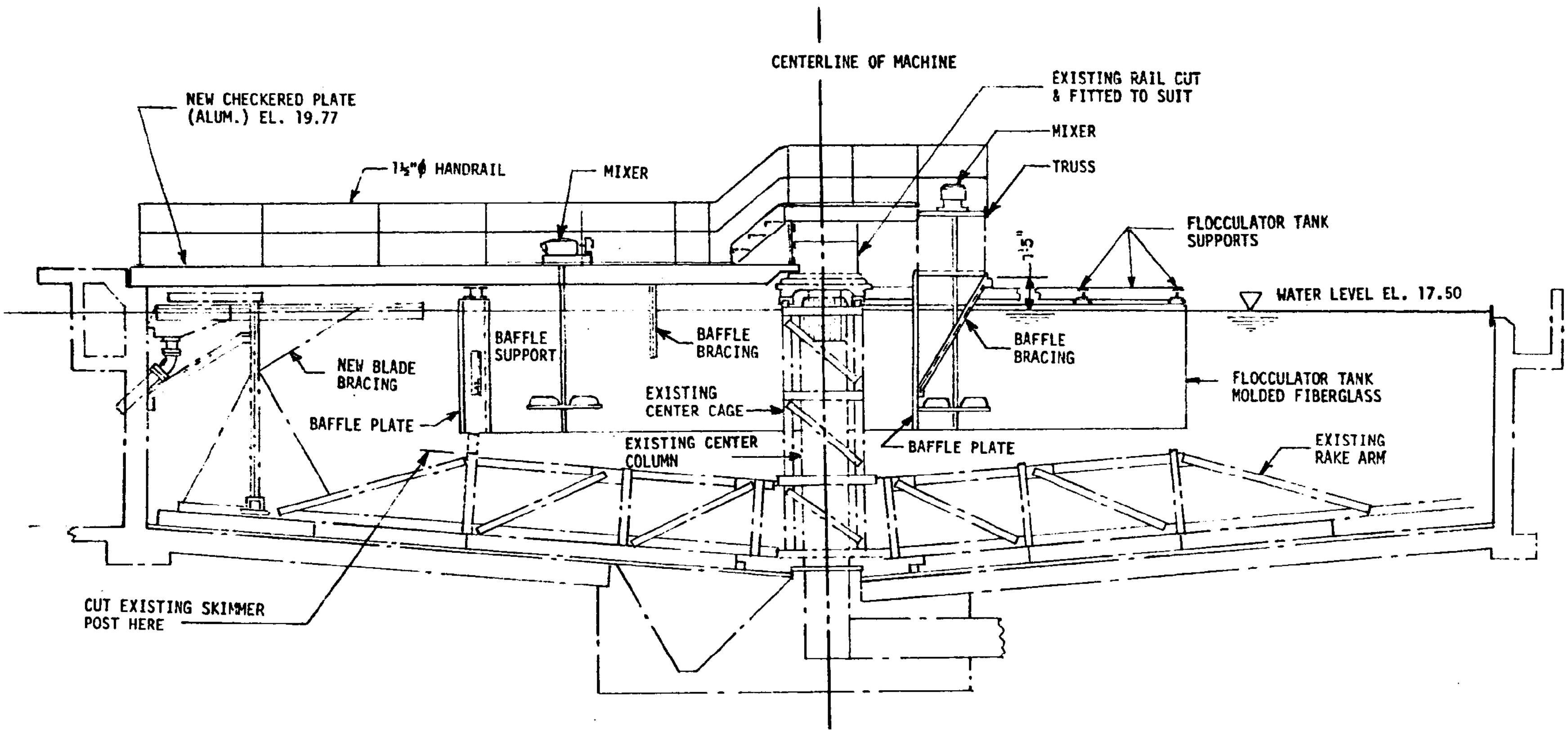

Figure 3. Modified Primary Clarifier with Clariflocculator

the effluent. Some construction work was still proceeding at the inception of this program. Limitations, therefore, had to be imposed on the scope and depth of project objectives in keeping with new, often partially functioning equipment, and a plant staff burdened with the necessity of establishing a properly functioning facility.

The first objective during the project was to get the primary plant and the aerobic digesters operating. During the initial months of the study so much effort went into this task that process control and laboratory analyses were minimally conducted. Valuable information was obtained on general plant operation, equipment performance, and suitability.

The second objective was to experimentally determine the optimum digester operating conditions for maximum performance. Once an operating routine had been established and the equipment shakedown completed, a series of tests was conducted to verify results achieved by previous researchers in pilot and laboratory scale. Detention time was deliberately varied to determine a minimum economical period for sludge stabilization. Digester loading could not be varied except by detention period because of the already thick sludge being pumped from the primary clarifiers.

A third objective was to obtain a basic analytical characterization of the aerobic digestion process. Primary sludge constituents of total solids, volatile solids, suspended solids, pH, chemical oxygen demand, biochemical oxygen demand, alkalinity, and chloride were measured, tabulated, and compared with the resulting sludges in the aerobic digesters. This information provided invaluable design data. It was also helpful in defining the best method of ultimate sludge disposal.

The fourth objective was to provide process control parameters through the analyses and evaluation of sludge constituents. Previous researchers had reported changes in all constituents, particularly alkalinity and pH with increased digestion. This project measured these changes in full-scale digesters under actual operating conditions in order to evaluate their suitability as control tools for the plant operator.

A fifth objective was to evaluate stabilized sludge qualities, both physical and chemical, and to relate them to aerobic digester operating conditions. Sludges were measured for settleability, filterability, odor, drying characteristics on sand beds, and final nutrient content. Such information would enable an evaluation of the final end product of digestion, the stable sludge, with respect to further study steps.

The sixth objective was to provide realistic plant scale operating costs for the aerobic digestion process. Operating economics were determined with a high degree of reliability.

A specially tailored computer program was used to determine the effects of rainfall through sewer line infiltration on total plant flow. Two years of operating data provided a basis upon which a computer separated regular daily and seasonal variations from fluctuations due to storm water infiltration. The results are presented in Appendix A.

SECTION IV

BACKGROUND INFORMATION

Raw Sewage Coagulation

Domestic sewage is composed of a wide variety of both dissolved and suspended organic and inorganic matter. In the past the popularity of chemical treatment of sewage has undergone several cycles of rising and waning. As a sole process for treatment of sewage, chemical treatment possesses the inherent limitation of being less effective for the removal of soluble organic matter than biological processes.

The most frequently used coagulants, salts of iron and aluminum, due to their ability to remove phosphates, are finding ever wider application. The use of synthetic organic polyelectrolytes for wastewater coagulation has been advocated by manufacturers for a number of years. However, little laboratory data and even less full scale data are available on the subject.

Laboratory tests indicated that several cationic polyelectrolytes are capable of effectively coagulating both raw and settled domestic sewage. Figure 4 and Table C1 in the Appendix show the effects of various dosages of Calgon Cat Floc on removal of BOD and suspended solids from the effluent of the Gainesville, Florida, Sewage Treatment Plant grit chamber. Figure 4 shows that initial BOD concentrations could be reduced from 152 mg/l to 19 mg/l, a removal efficiency of 86 percent. Suspended solids were reduced from 130 mg/l to 10 mg/l for a removal efficiency of 92 percent.

Also shown in Figure 4 is the change in electrophoretic mobility with polymer dosage. Electrophoretic mobilities were measured by the use of a Zeta-Meter (Zeta-Meter, Inc.). Initial electrophoretic mobility values of colloidal particles were found to average 1.7 u/(sec)(v)(cm) and these values were increased with increasing dosages of the cationic polymer.

Figure 5 and Table C2 in the Appendix show the effects of various dosages of Cat Floc on removal of BOD and suspended solids from the effluent of a primary settling tank. Initial BOD concentrations were reduced from 170 mg/l to 33 mg/l for a reduction efficiency of 80 percent. Initial suspended solids concentrations were reduced from 80 mg/l to 17 mg/l for a reduction efficiency of 79 percent. Electrophoretic mobility values were changed from 1.8 to + 0.3 u/(sec)(v)(cm).

A comparison of Figures 4 and 5 shows several interesting facts. In Figure 4, BOD and suspended solids removal efficiencies were quite high at low polymer dosages as compared to Figure 5. This is due to the fact

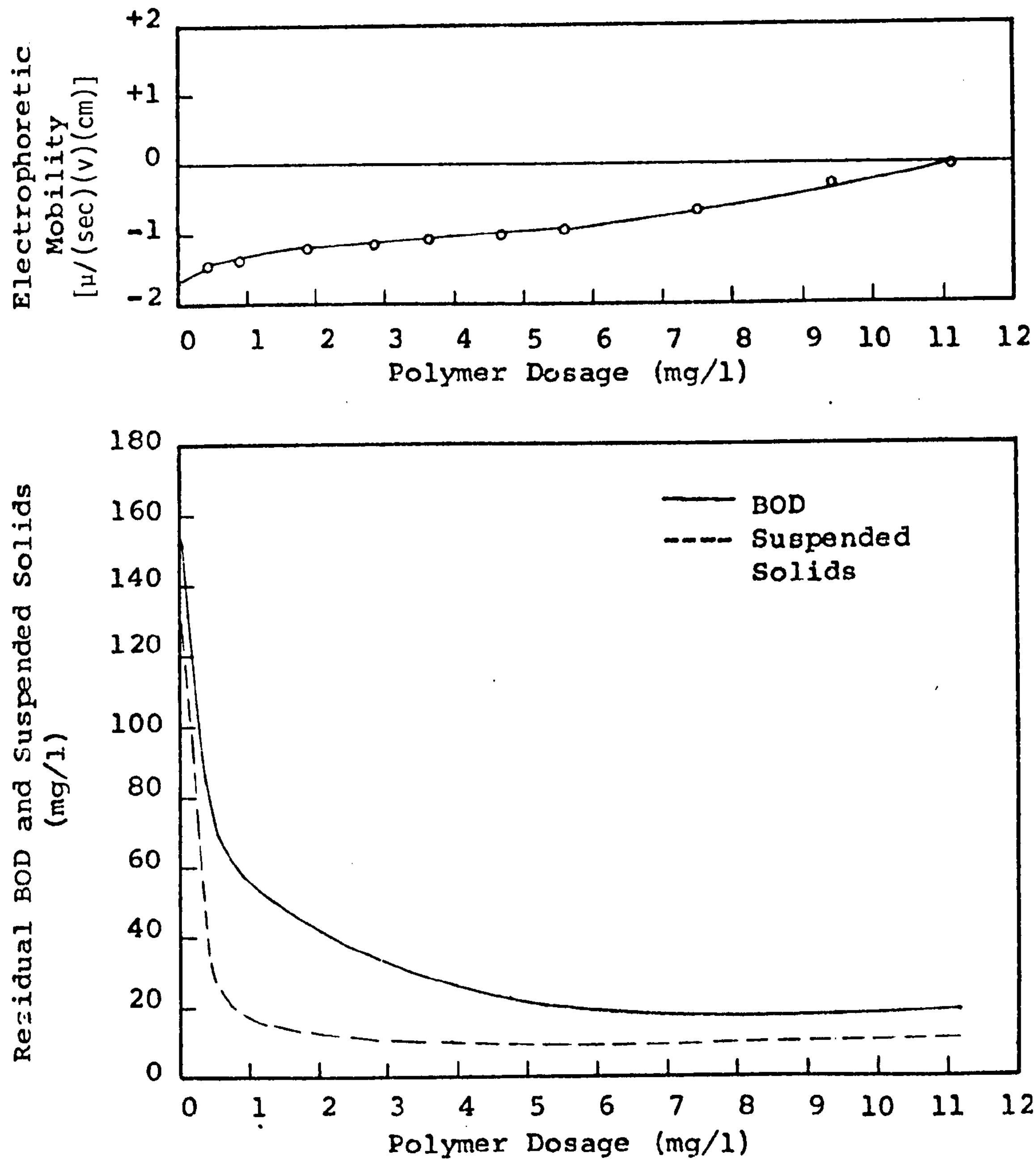

Fig. 4 Effect of Various Dosages of Cat Floc on Removal of BOD and Suspended Solids in Sewage from the Effluent of the Gainesville Grit Chamber.

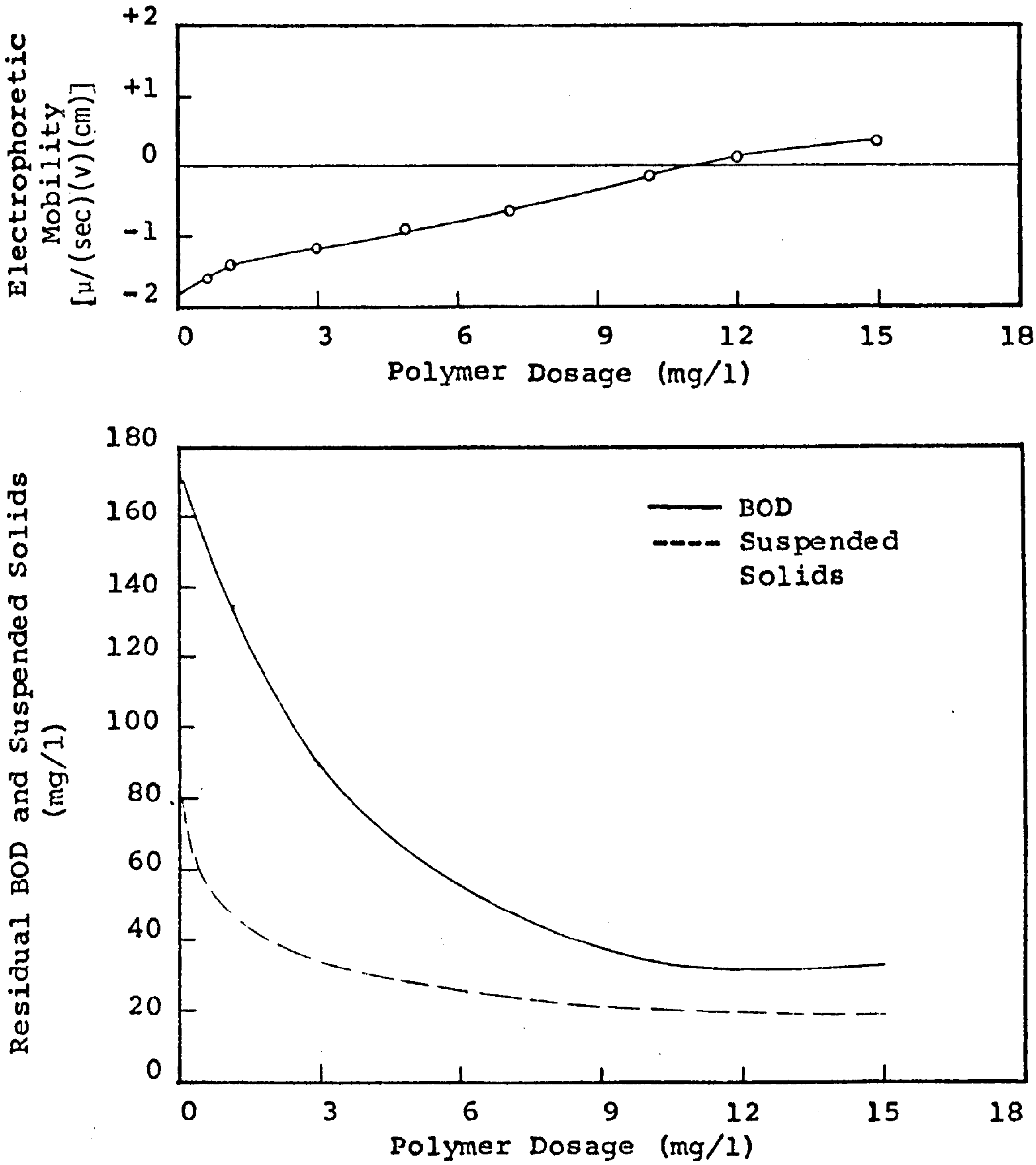

Fig. 5 Effect of Various Dosages of Cat Floc on Removal of BOD and Suspended Solids in Sewage from the Effluent of a Gainesville Primary Settling Tank.

that Figure 4 shows results of coagulation of unsettled raw sewage and Figure 5 shows results of settled sewage. A significant reduction of BOD and suspended solids would have been realized without polymer addition to raw sewage due to sedimentation alone, while little or no reduction would have been realized in the primary settled sample without polymer addition. Polymer dosages cannot be compared because the exact chemical composition of each sample was not determined and varied widely.

In general, the optimum dosage of polymer was that dosage which changed the electrophoretic mobility of domestic sewage from approximately - 1.8 u/(sec)(v)(cm) to approximately 0.0 u/(sec)(v)(cm). The addition of cationic polymer dosages in quantities required to increase the electrophoretic mobility to greater than 0.0 u/(sec)(v)(cm) generally caused a reduction in treatment efficiency as would be expected due to the repulsion of like charges of the colloidal particles.

The high reduction of BOD was due to the high reductions in suspended and colloidal BOD and not to removal of soluble BOD. Laboratory analyses on filtered and unfiltered samples showed that the soluble BOD of the Gainesville sewage was exceedingly low which resulted in high percentage removal of BOD through polyelectrolyte coagulation. Each of the samples tested were grab samples and, therefore, do not necessarily represent the "typical" sewage at the Gainesville sewage treatment plant.

Figure 6 and Table C3 in the Appendix show the effect of various dosages of Cat Floc on removal of BOD and suspended solids in sewage from the effluent of the University of Florida grit chamber. Initial BOD concentrations were reduced from 120 mg/l to 30 mg/l for a reduction of 75 percent. Initial suspended solids concentrations were reduced from 95 mg/l to 0.0 mg/l for a reduction of 100 percent.

Although electrophoretic mobility values were increased from - 1.7 to + 1.1 u/(sec)(v)(cm), there was little reduction in BOD removal efficiencies at the higher mobility levels. Suspended solids removal efficiencies remained highest at approximately 0.0 mobility values, and decreased as mobility values increased above 0.0 u/(sec)(v)(cm).

Figure 7 and Table C4 in the Appendix show the effect of various dosages of Cat Floc on removal of BOD and suspended solids in sewage from the effluent of a University of Florida primary settling tank. BOD concentrations were reduced from 50 mg/l to 5 mg/l for a removal efficiency of 90 percent. Suspended solids concentrations were reduced from 31 mg/l to 2.0 mg/l for a removal efficiency of 94 percent.

Electrophoretic values were increased from-1.9 to + 1.2 u/(sec)(v)(cm). The highest efficiencies for removal of BOD and suspended solids occurred at electrophoretic mobilities of approximately 0.0 u/(sec)(v)(cm).

Results shown in Figures 4 through 7 indicate the high level of treatment efficiency which can be realized by proper coagulation of domestic

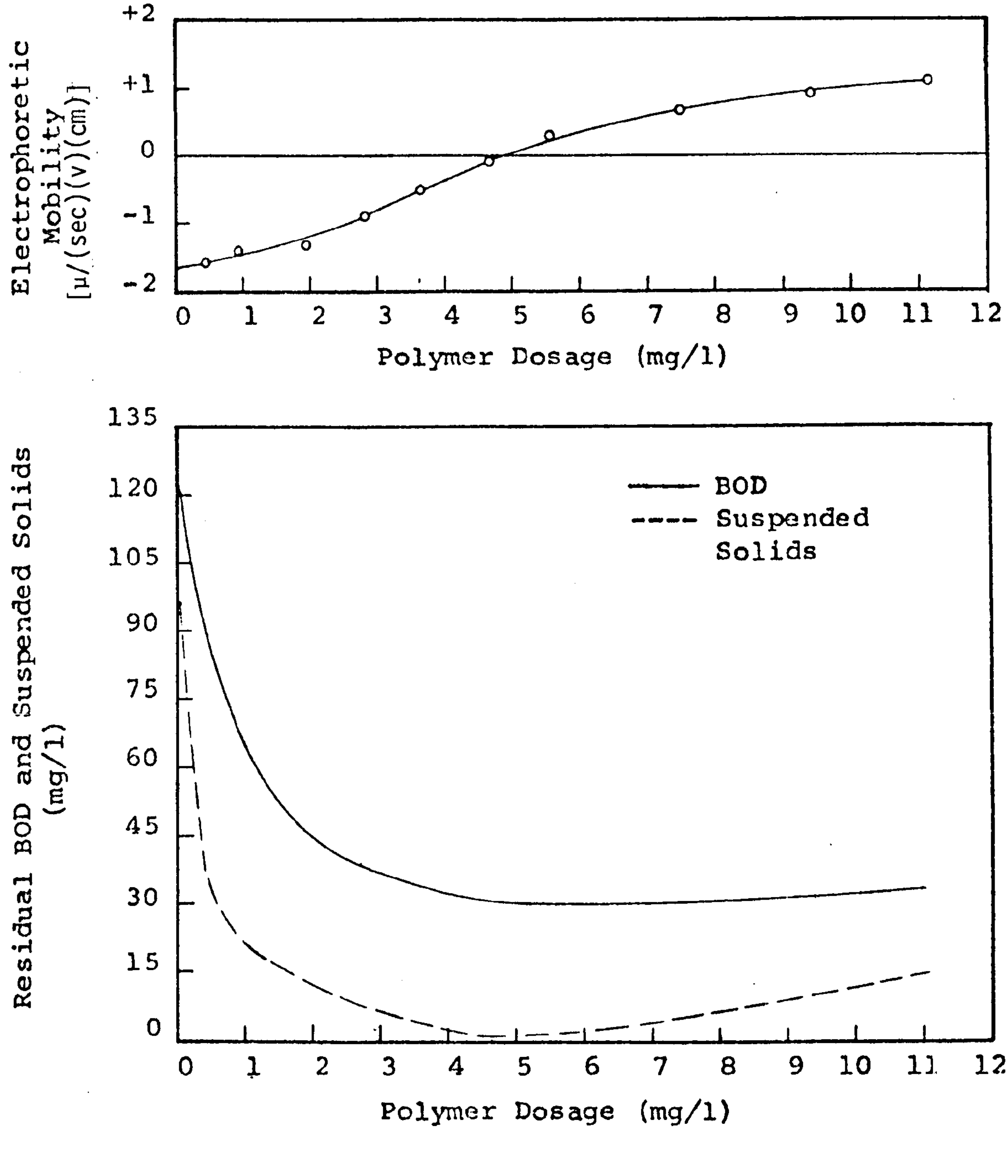

Fig. 6 Effect of Various Dosages of Cat Floc on Removal of BOD and Suspended Solids in Sewage from the Effluent of the University of Florida Grit Chamber.

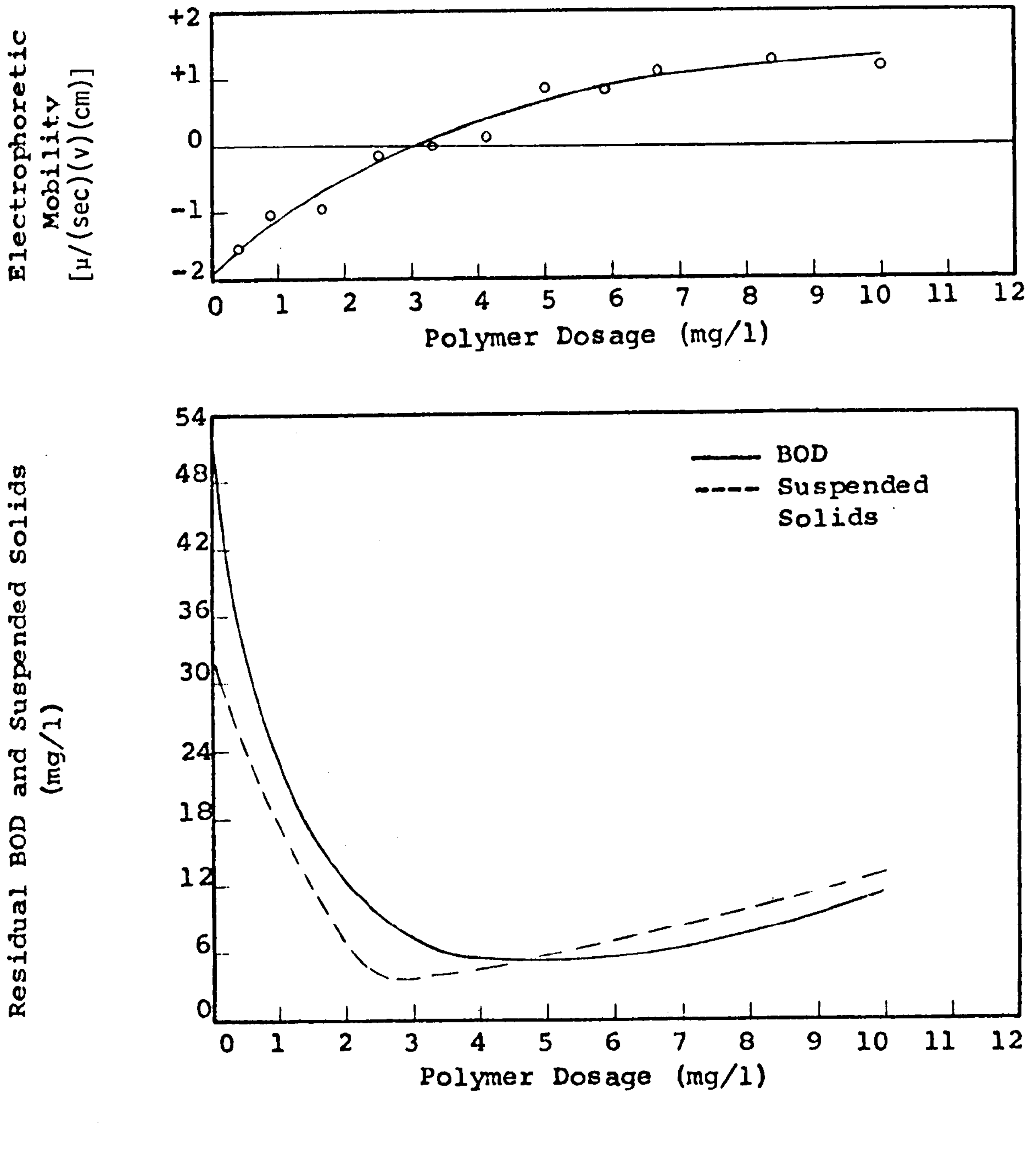

Fig. 7 Effect of Various Dosages of Cat Floc on Removal of BOD and Suspended Solids in Sewage from the Effluent of a University of Florida Primary Settling Tank.

sewage with the cationic polyelectrolyte Cat Floc. Figure 8 and Table C5 in the Appendix show the effect of various concentrations of Dow C-31 (Dow Chemical Company). Figure 9 and Table C6 in the Appendix show the effect of various concentrations of Primafloc C-7 (Rohm and Haas Company) on removal of BOD and suspended solids and changing mobility values from negative to positive values. In general, removal efficiencies were greatest at mobility values of 0.0 u/(sec)(v)(cm).

Perhaps the most important factor in the use of polyelectrolytes for coagulation of sewage is mixing or energy input. A distinction can be made between the terms coagulation and flocculation in order to describe more accurately the basic mechanisms of polymer colloid interactions. Coagulation is defined as being a general kinetic process which obeys the simple Smoluchowski equation. It is brought about by neutralization of the repulsive potential of the electrical double layer, allowing the forces of attraction between particles to bring them together. Flocculation, on the other hand, is visualized as a completely different mechanism whereby colloidal particles are bound together by a bridging mechanism in which adsorption plays the major role.

Assuming that an adequate polymer dosage has been introduced to reduce the repulsive potential of the electrical double layer, i.e., increase the electrophoretic mobility from a negative value to near 0.0 u/(sec)(v)(cm), then it is essential to provide adequate mixing so that individual colloidal particles may come together to form larger particles which will settle from suspension.

Figure 10 shows the effect of revolutions of mixing in a jar test machine on removal of BOD from the effluent of the University of Florida grit chamber. The initial BOD was 120 mg/l, mixing rate 20 rpm, polymer dosage 2.8 mg/l, and electrophoretic mobility 0.0 u(sec)(v)(cm). Figure 11 shows the effect of mixing in the same jar test for the removal of suspended solids. These data are tabulated in Table C7 in the Appendix. Results of these tests simply show that with increased mixing or energy input up to some maximum value, removal efficiencies for BOD and suspended solids increased. Excess mixing led to the limitation of particle size due to sheer forces.

The above laboratory results demonstrated that a domestic sewage with a relatively low concentration of soluble BOD coagulated with cationic polyelectrolytes in a properly designed and operated system with adequate mixing and settling.

Effective use of cationic polyelectrolytes for sewage coagulation has been limited by their low efficiency when attempts have been made to use them in existing sewage plants, the desire being to upgrade the efficiency of an existing treatment system at a minimum capital expenditure. These attempts have almost always resulted in failure

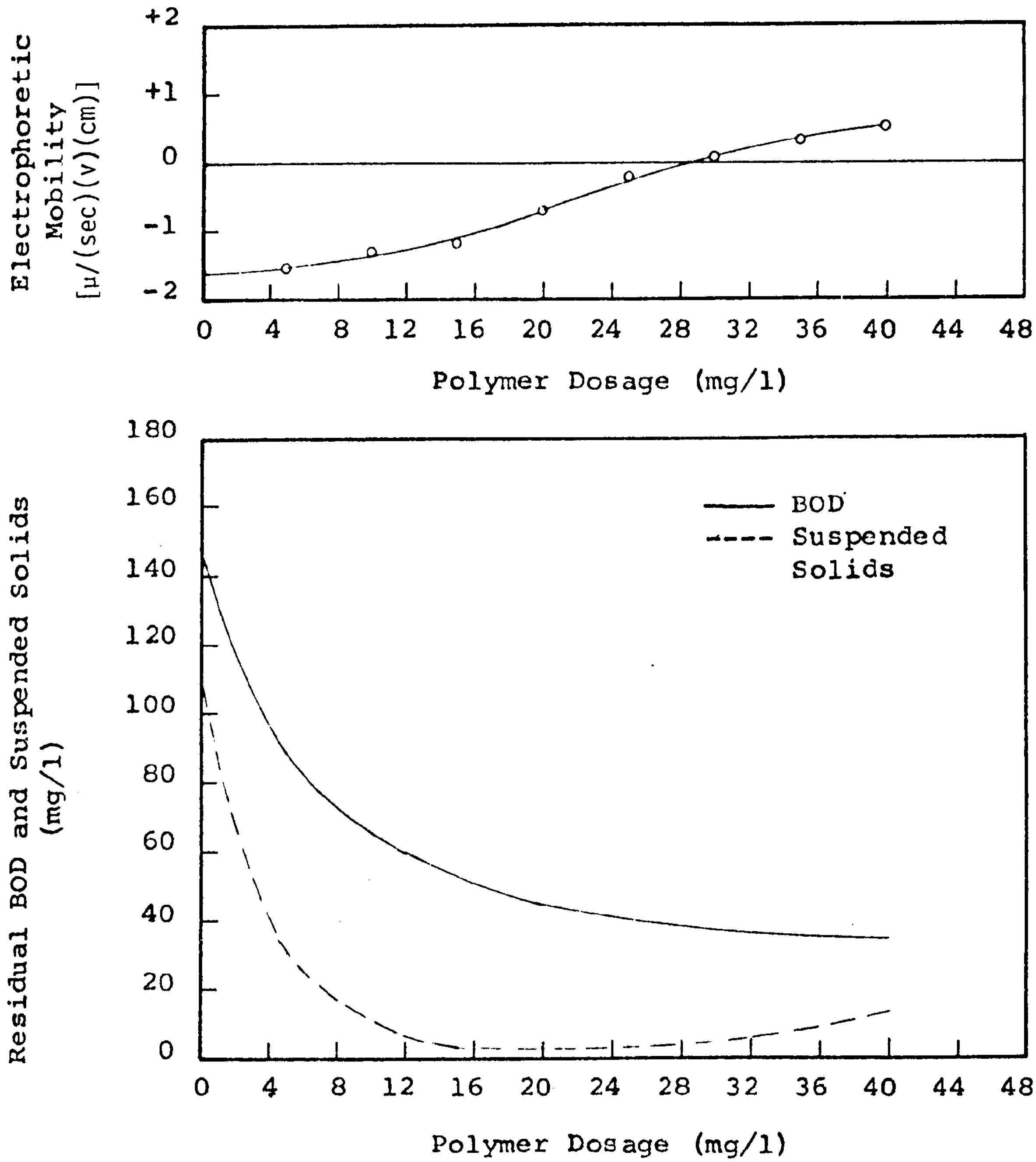

Fig. 8 Effect of Various Dosages of Dow C-31 on Removal of BOD and Suspended Solids in Sewage from the Effluent of the University of Florida Grit Chamber.

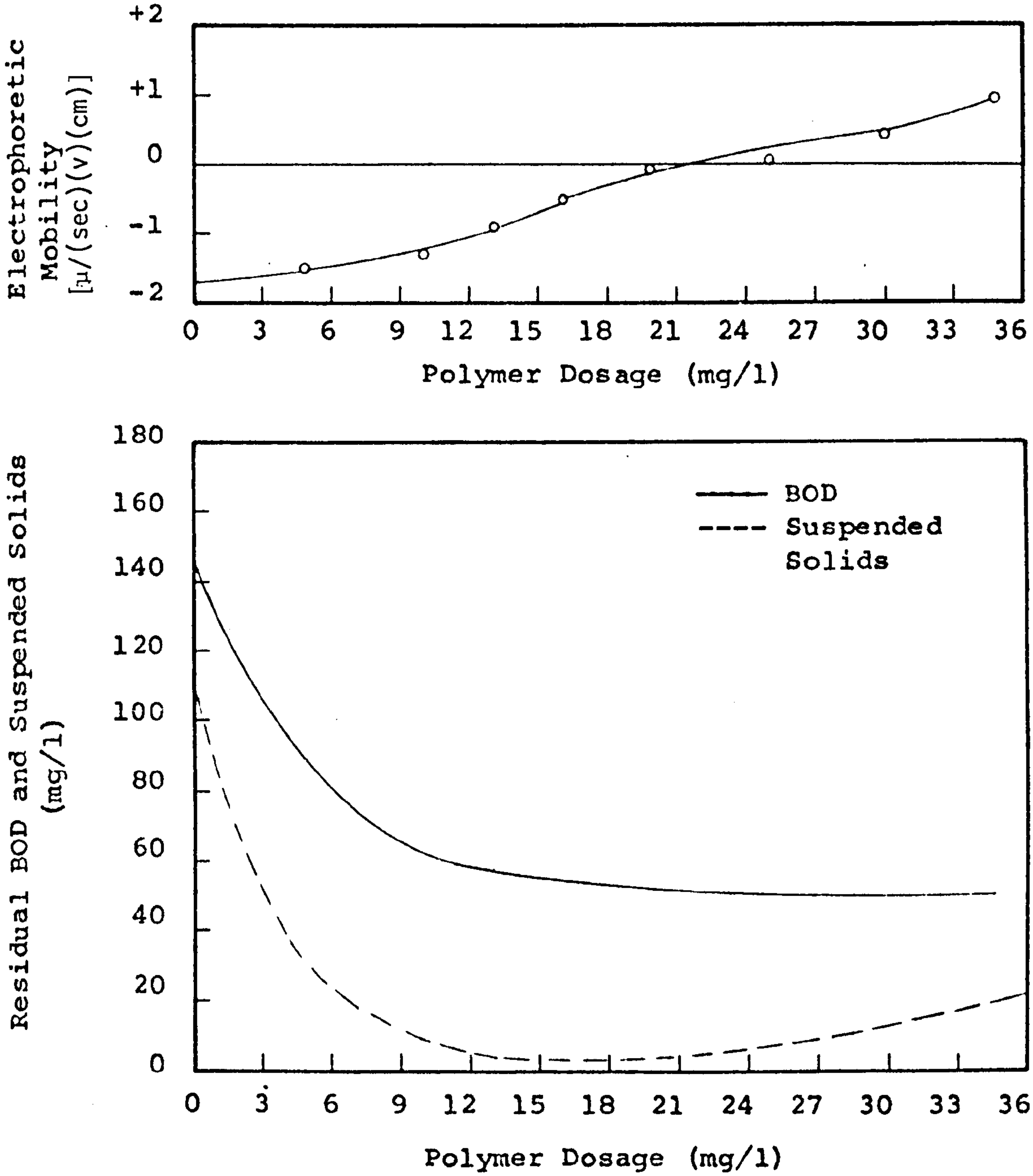

Fig. 9 Effect of Various Dosages of Primafloc C-7 on Removal of BOD and Suspended Solids in Sewage from the Effluent of the University of Florida Grit Chamber.

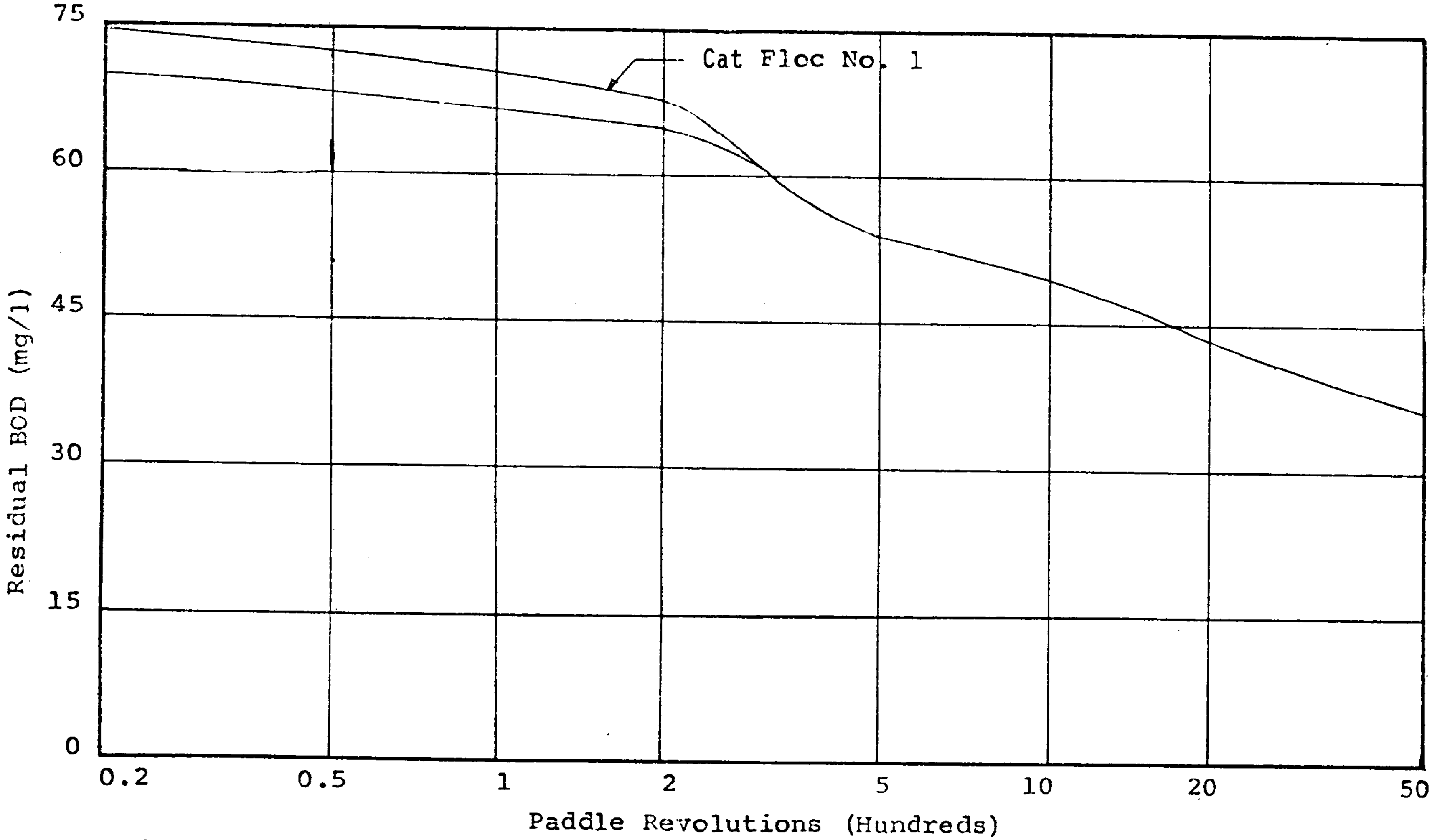

Fig. 10. Effect of Revolutions of Mixing on Removal of BOD from the Effluent of the University of Florida Grit Chamber.

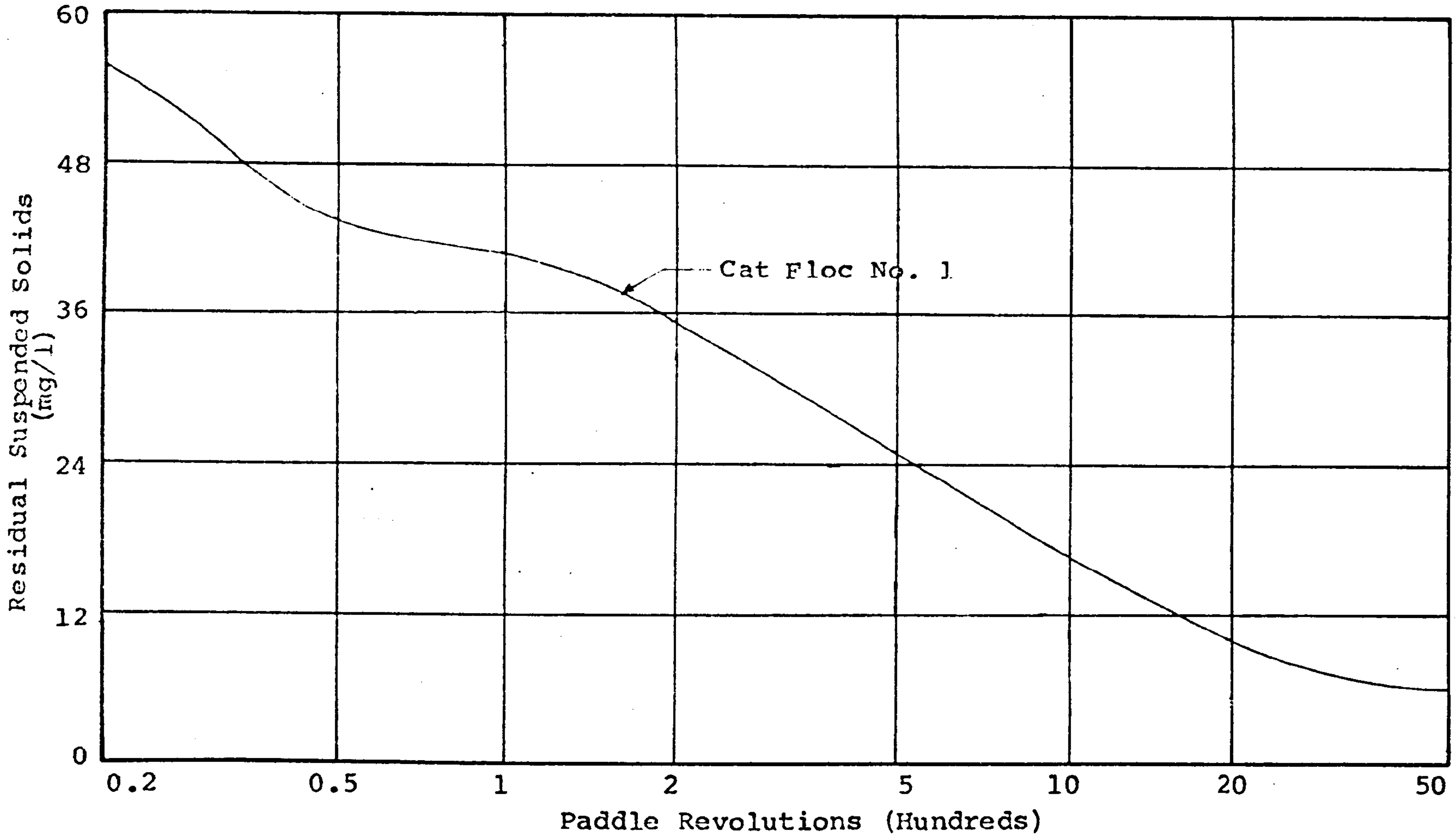

Fig. 11. Effect of Revolutions of Mixing on Removal of Suspended Solids from the Effluent of the University of Florida Grit Chamber.

due to lack of facilities to provide proper mixing conditions required for coagulation. The inefficiency of cationic polyelectrolytes for removal of soluble BOD, and their high costs, have made it uneconomical to design a new sewage treatment plant which would provide proper conditions for effective coagulation.

The use of polyelectrolytes for treatment of domestic sewage in existing plants has been primarily limited to anionic and nonionic polymers whose principal mechanism is flocculation. Flocculation, in which adsorption plays the major role, does not require a high level of mixing for effective coagulation. Flocculation is usually effective for removal of large particles, such as fibers, and ineffective for colloidal removal. Therefore, in sewage treatment plants, efficiency in BOD and suspended solids removal is usually much lower than that which could be achieved if adequate mixing were provided with the use of cationic polymers.

Aerobic Sludge Digestion

A considerable amount of research effort has been expended in converting soluble and fine suspended matter into insoluble and readily settleable solids which may be removed by standard physical separation processes. While the subsequent stabilization or elimination of collected sludges from the wastewater treatment systems has long been a neglected field, anerobic sludge digestion is not an intrinsically new or unique process. Basic bio-oxidation lagoons convert soluble and some insoluble organic matter into carbon dioxide, water, and cell matter. In the extended aeration process, retention times of the wastes are sufficiently long that initial organic solids and newly created activated sludge solids are biologically converted under aeration to carbon dioxide and water, although in practice the extended aeration process experiences a slow buildup of inert matter that must eventually be wasted.

In the aerobic sludge digestion process and in the preceding examples, the underlying principle of sludge digestion is the auto-oxidation of biological material. When deprived of a food source, microorganisms undergo endogenous respiration in a continuing process of digestion that produces carbon dioxide, water, and fewer cells than at the start of digestion. Eventually the self destruction of biological matter reaches an irreducible minimum and the sludge is said to be stabilized. A stable sludge has a minimum of organic or volatile solids but retains many of its original inorganic nutrients. Stable sludges are relatively free of odor, are more acceptable to final disposal on land or in the ocean, and often have characteristics of easier handleability.

Aerobic digestion differs from other aeration processes in that primary settled solids and waste activated solids, separated from the main wastewater stream, are concentrated and aerated in a separate reactor. Advantages of the aerobic sludge digestion process include the smaller volumes of liquid that need to undergo the extended aeration process, and the reduced capital resulting from those smaller volumes. Other advantages claimed for the aerobic digestion process are ease and simplicity of operation, the highly stable nature of the end product, and improvements in the ease of handling the digested sludges.

In order to provide reasonable comparisons between various batches of data on the aerobic digestion of sludges, a common language with common sets of parameters which may be transferred from one data group to another needs to be employed. Previous work in this field has been scattered in scope and has resulted in inconsistent terminology. Differing waste characteristics have complicated most comparisons. The data on sludge characteristics at least provide performance goals as well as some basis for comparison against other processes.

Eckenfelder[1], studying aerobic digestion of domestic sewage activated sludge in a batch process at 25°C, achieved a reduction in chemical oxygen demand of 48 percent in 7 days; a 48.7 percent reduction in total suspended solids; and a 38.3 percent reduction in total suspended solids. Carpenter and Blosser[2] achieved a 14.5 percent reduction in volatile solids after 30 days batch digestion at 30°C with waste activated boardmill sludges.

Jaworski, Lawton, Rohlich[3] performed continuous feed studies on a mixture of primary and waste activated domestic sludges. At 20°C they reported a 44 percent volatile solids reduction with a 30 day hydraulic detention time and 46 percent volatile solids reduction after 60 days retention time. The loading rate during the test varied with detention period due to a fixed reactor volume and feed concentration. More than 600 mg/l of nitrate nitrogen was reported after 60 days retention time.

Malina and Burton[4] recorded a 43 percent reduction in volatile solids in a continuous feed process treating primary domestic sludge. The hydraulic retention time of 15 days was achieved with a sludge loading rate of 0.14 $lb/(ft^3)(day)$ at 35°C.

Nature of Waste

The performance of an aerobic digester depends on several independent variables, of which the designer has little control. The nature of the original waste processed in the sewage treatment plant is paramount in a determination of sludge treatability. A 12 percent reduction in volatile solids with aerobic digestion of activated sludge from domestic wastes at 20°C and 12 days aeration was observed by Carpenter and Blosser[2]. Also at 20°C, they found 7 percent reductions in 27 days and 9 percent reductions in 19 days with activated sludge from boardmill wastes and de-inking wastes, respectively. A laboratory study by Barnhart[5] demonstrated markedly differing volatile solids reductions for several types of wastes. Reductions of volatiles achieved at 8 days aeration were 29 percent with mixed pulp and paper waste; 42 percent with biochemical wastes; 46 percent with domestic sewage; and 60 percent with textile and domestic wastes.

Sludge Age

Sludge age has been reported to be a good indicator of expected volatile solids reductions for any particular waste, but researchers have been inconsistent in defining their terminology. Work done by Norman[6] at the University of Wisconsin described a semi-logarithmic correlation between percent volatile solids reduction and sludge age. Increasing sludge age caused increased reductions. Norman defined sludge age to be the ratio of the weight of volatile solids in the digester to the weight of volatile solids added daily. In essence his report gave a mathematical fit to the statement that with increased treatment time, the rate of volatile solids reduction decreases exponentially.

The common definition of sludge age relates to the theoretical detention time of any particle of solid matter in the activated sludge process. Loehr[7] indicated that sludge with a high incoming sludge age will experience a lower reduction in volatile solids than a sludge with a low age. This was attributed to a previous partial oxidation of the older sludge in the activated sludge system. An application of this observation may be made in explaining the differences in oxygen demand between raw settled sludge and aerated activated sludge. The fresh raw sludge must first undergo synthesis of biomass and this raises oxygen requirements in the aerobic digester, according to Loehr, by a factor of six.

Detention Time

Most researchers agree that most of the volatile solids reduction in an aerobic digester occurs within the first 15 days. A typical set of data[8] relating volatile solids reductions to detention time at 20°C reads as follows: 10 percent reduction at 2 days, 24 percent at 5 days, 41 percent at 10 days, 43 percent at 15 days, and 46 percent at 60 days. Doubling digester volume from 15 days detention to 30 days detention would substantially increase capital costs while providing, in this case, approximately a 1 percent decrease in volatile solids content.

Very tentative research work conducted by Bruemmer[9] on the use of oxygen enriched air for sludge digestion indicated that sludge stabilization could occur in a shorter period of time using oxygen. However, the data indicate eventual equal levels of BOD stabilization.

In batch tests conducted on municipal waste activated sludge, Reynolds[10] achieved better than 50 percent reduction in volatile solids in less than 6 days aeration. This represented stabilization of most of the biodegradable material present.

Kehr[11] further substantiated the more rapid stabilization of waste activated sludges by reporting that the oxygen uptake rate was minimal after 5 days digestion in a batch test. Dryden, et. al.,[12] reported a 25 percent per day reduction in volatile suspended solids during the aerobic digestion of pharmaceutical waste activated sludge.

Reaction Temperature

Another factor involved very heavily in aerobic digester performance is the temperature at which reaction takes place. For long detention periods of approximately 60 days and for short detention periods of less that 5 days, temperature differences do not appear to affect volatile solids reductions[3]. Reactions may be considered essentially complete at 60 days for any temperature between 15°C and 35°C, while reaction rates below 5 days detention are so rapid as to be unaffected by temperature. At intermediate detention times, typical volatile solids removals reported for several temperatures were 45 percent at 35°C, 41 percent at 20°C, and 32 percent at 15°C, all at 8 days[3]; and 11.4 percent at 20°C and 13.7 percent at 30°C over a period of 25 days[2]. From this data it would appear that increased temperatures are extremely beneficial to the efficiency of the aerobic digestion process, but it has been reported[7] that high temperatures on the order of 60°C are not as effective in improving aerobic digestion of sludges. An optimum temperature would appear to lie near 30 to 35°C with the exact temperature used in an actual plant depending on the economics of artificially heating the aerobic digester.

Loading Rate

The final design parameter which affects aerobic digester performance is the loading rate or rate of application of fresh feed per unit volume of digester. The loading rate is not an independent variable in that it will be determined by incoming volatile solids concentration in the sludge liquor and also by the design retention period which fixes the aerobic digester tank volume. Most investigators have used a fixed loading rate determined by volumetric detention time and thus have reported optimum loading rates on the order of 0.10 lbs volatile solids/(ft^3 of digester) (day) which roughly corresponds to 12 to 15 days retention time. In the study by Malina and Burton[4], loading rates were varied from 0.10 to 0.14 lbs/(ft^3)(day) with a 15 day retention period. At 35°C the higher loading rate was associated with a 43.2 percent volatile solids reduction as compared to 33.3 percent at the lower rate. Further comparable data is lacking of effects of loading rates on aerobic digester performance, but an upper limit would eventually be reached due to mixing and oxygen transfer limitations. The exact loading rate would still be beyond the direct control of the plant designer or operator due to the previously mentioned reasons.

Oxygen Uptake

Reliable data on oxygen uptake rates are generally unavailable for aerobic digestion of sludges. Research work to date has included oxygen supply rates to fixed volume containers, but with little mention of oxygen transfer methods or efficiencies. Various uptake rates have been measured for endogenous respiration of sludge with values ranging from 2 to 10 mg O_2/(hr)(gm VSS) depending on the nature and age of the sludge. Since a 400 percent variation in oxygen uptake rate will make a considerable difference in the sizing of aeration equipment for the digester, it is necessary to measure specific rates for individual sludges prior to design.

Sludge Dewatering

Previous investigators have not reported methods used for digested sludge thickening or discussed difficulties encountered with such operations. Brief discussions have been presented of supernatant decanting or centrifugation with no reliable supporting figures. Research has usually been conducted with a 2 to 5 percent concentration of sludge transported directly to a dewatering process. Irgens and Halvorson[13] did report, however, that aerobically digested raw sludge settled poorly but that settleability increased to excellent when waste activated sludge was added to the digestion process.

Liquid drainage from aerobically digested sludge is different from that obtained with anaerobically digested sludge. Randall and Koch[14] reported that aerobically digested waste activated sludge demonstrated more rapid drainage in a sand bed with a higher percentage of drainable water. Drainage and drying were both improved when dissolved oxygen levels were kept above 1.0 ppm and by increased retention time. Dreier and Obma[8] agreed with Lawton and Norman[15] that increased digestion periods were desirable for improved liquid - solids separation and suggested a minimum retention period of 10 days. It has also been reported[16] that aerobic treatment of an anaerobically digested sludge greatly improves the filterability of the product sludge.

Supernatant

The supernatant obtained from either decantation or centrifugation of aerobically digested sludge is of sufficiently fine quality that basic plant performance is not upset when the supernatant is reintroduced to the headworks. Biological oxygen demand values of supernatant have been consistently reported to be less than 100 mg/l -- with a single high value of 240 mg/l found by Vararaghavan[17]. Chemical oxygen demand values have ranged below 700 mg/l. Malina and Burton[4] achieved reductions of 70 to 82 percent in COD using a continuous feed apparatus on primary sludge with a 15 day retention period. Research in batch operations has been conducted on waste activated sludge and combinations of waste activated sludge and primary waste sludge for varying detention times (10, 15, and 60 days). As a result, direct comparison between specific values becomes difficult and almost meaningless in view of the fact that reductions depend so heavily on the original nature and source of the raw sewage.

Process Monitors

Certain effluent parameters, in addition to BOD, COD, and solids, which may be of use in monitoring process conditions are alkalinity, pH, and nitrate content of the supernatant or mixed sludge. Values for these parameters have been duplicated in batch studies by various researchers with some supporting evidence on the applicability of these values to continuous feed processes.

Researchers have consistently reported gradual or no decline in alkalinity with retention times up to 15 days, and more rapid declines in alkalinity thereafter up to 60 days. This has been attributed to removal of CO_2 and subsequent buffering capacity during the aeration process. Inasmuch as the greater majority of endogenous respiration with its concomitant release of CO_2 occurs during the first 15 days of retention time, minimal reduction in alkalinity is expected during that period. As an example, Dreier and Obma[8] reported alkalinities of 510 mg/l at starting, 560 mg/l after 15 days, and 81 mg/l after 30 days of digestion.

Figure 12 taken from Viraraghewan[17], shows the close relationship between alkalinity reduction and volatile solids reduction at various detention times. Figure 13 shows a similar comparison from a report by Dreier and Obma[8].

In batch aerobic digestion of waste activated or primary sludges, the pH of the system undergoes an increase during the period of most active digestion and thereafter the pH decreases to values in the vicinity of 5.0 after approximately 60 days. The pH increase is presently not explained, but the subsequent decrease, occurring after major digestion is completed, may be attributed to two causes: the ever increasing rise in nitrate ion reported by most researchers to occur after most of the volatile solids have been destroyed, and the decreasing alkalinity with resultant loss of buffering capacity, again occurring after the major portion of endogenous respiration has transpired. Figures 12 and 13 clearly show more than a coincidental relationship between reduction of volatile solids and sludge pH.

In their continuous feed digestion studies on primary sludges, Malina and Burton[4] maintained a retention period of 15 days, which has been reported to be nearly optimum for major digestion to be completed. Their mixed sludge pH was 8.0 compared to a feed pH of 6.2. This result negates the fears of other researchers who have felt that the pH of 5.0 obtained after 60 days digestion was too low for effective aerobic digestion. Most treatment units would be operated at shorter retention periods than 60 days and concomitantly higher pH levels.

Nitrate and nitrite forms of nitrogen increase in concentration with progressive detention times as ammonia and organic forms decrease. The increased quantities of nitrates offset the losses in volatile acids due to aerobic digestion and account for decreases in sludge pH with extended digestion periods. Figure 14 taken from a report by Dreier and Obma[8], demonstrates the increasing concentrations of nitrate and nitrite ions with time and, in comparison with Figure 13, relates these concentrations to decreasing pH and alkalinity.

Full-scale Performance

One of the few investigations concerning full-scale aerobic digestion was conducted by Ahlberg and Boyko[18]. The aerobic digestion processes

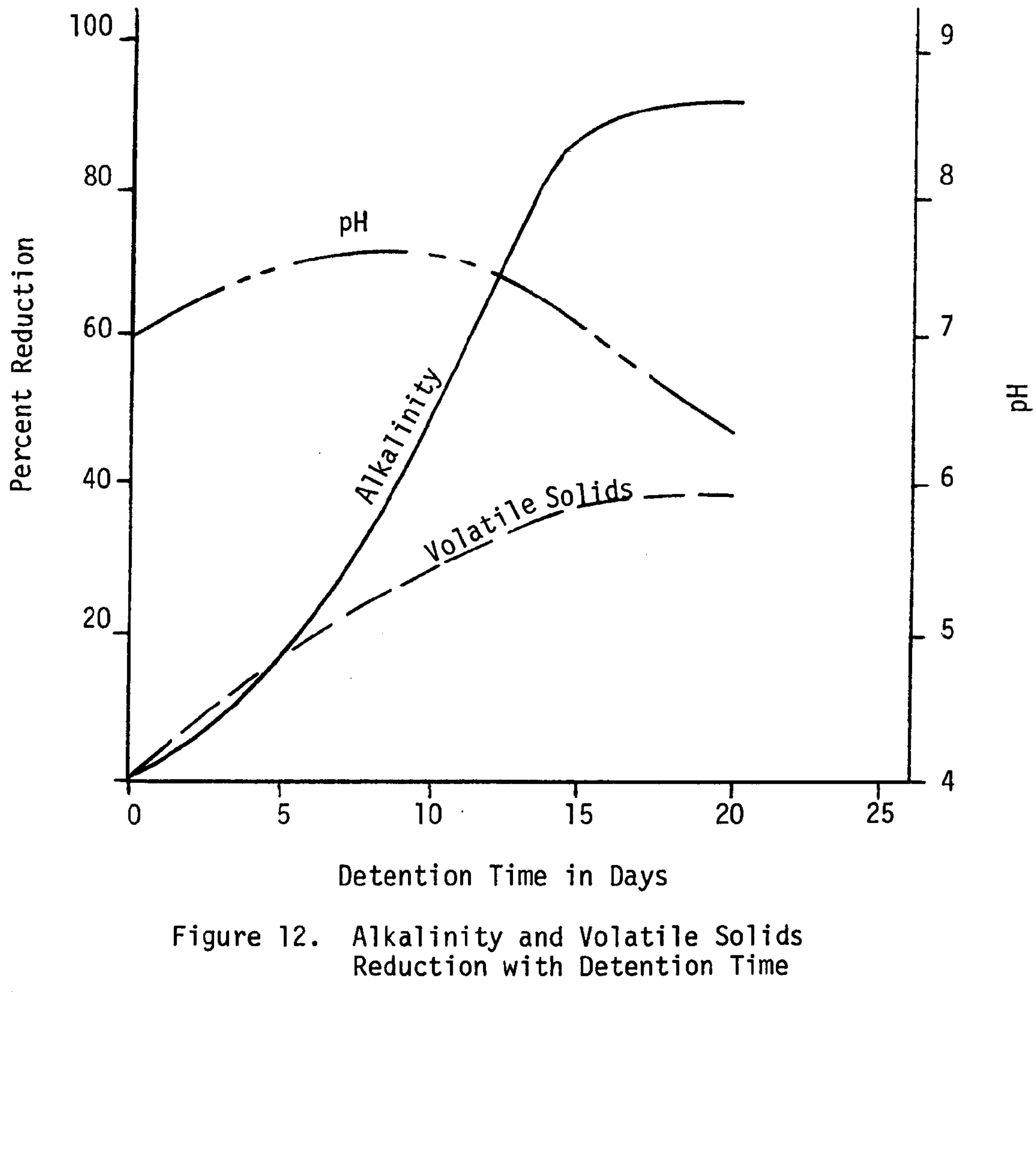

Figure 12. Alkalinity and Volatile Solids Reduction with Detention Time

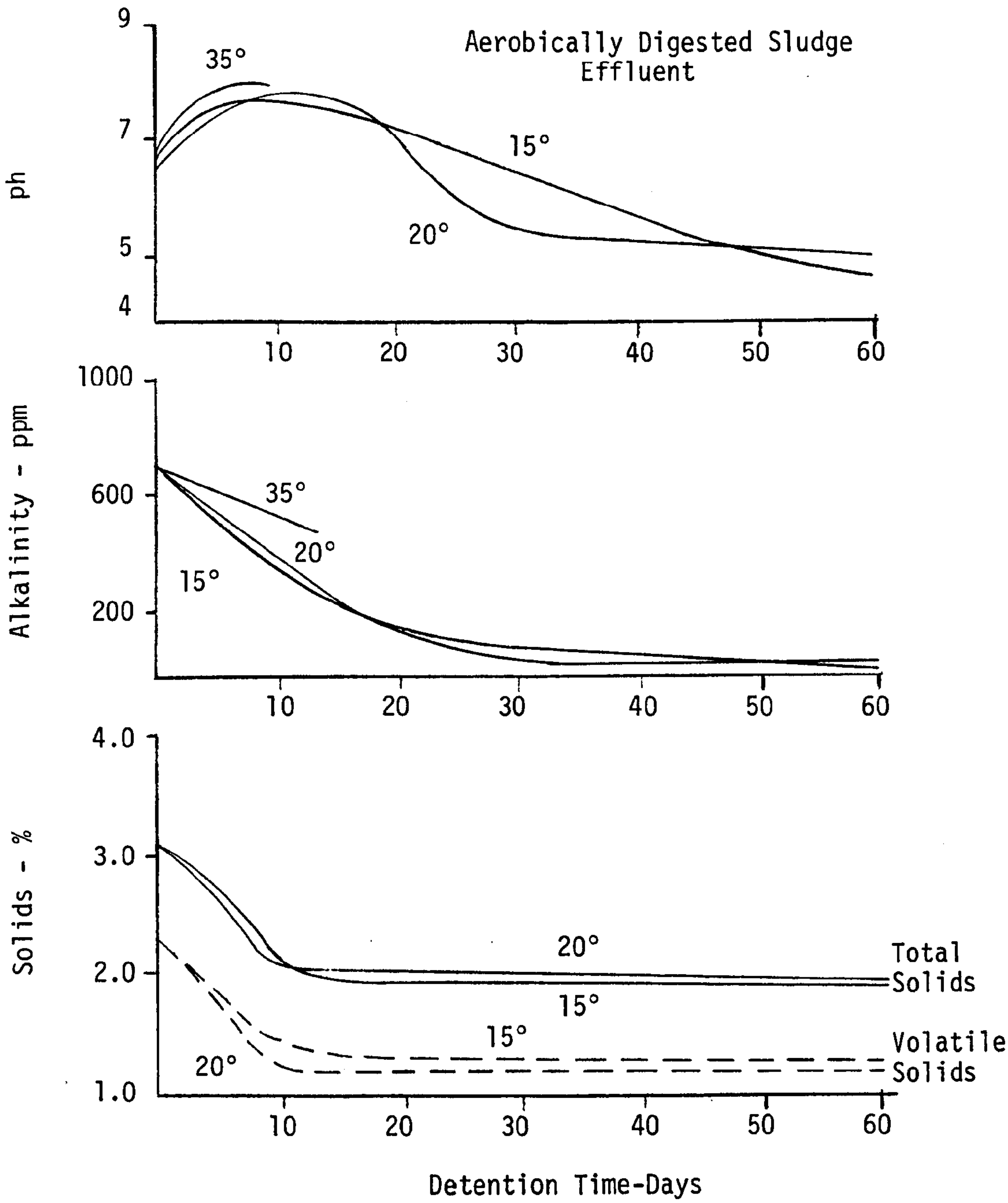

Figure 13. Solids, Alkalinity and pH vs. Detention Time

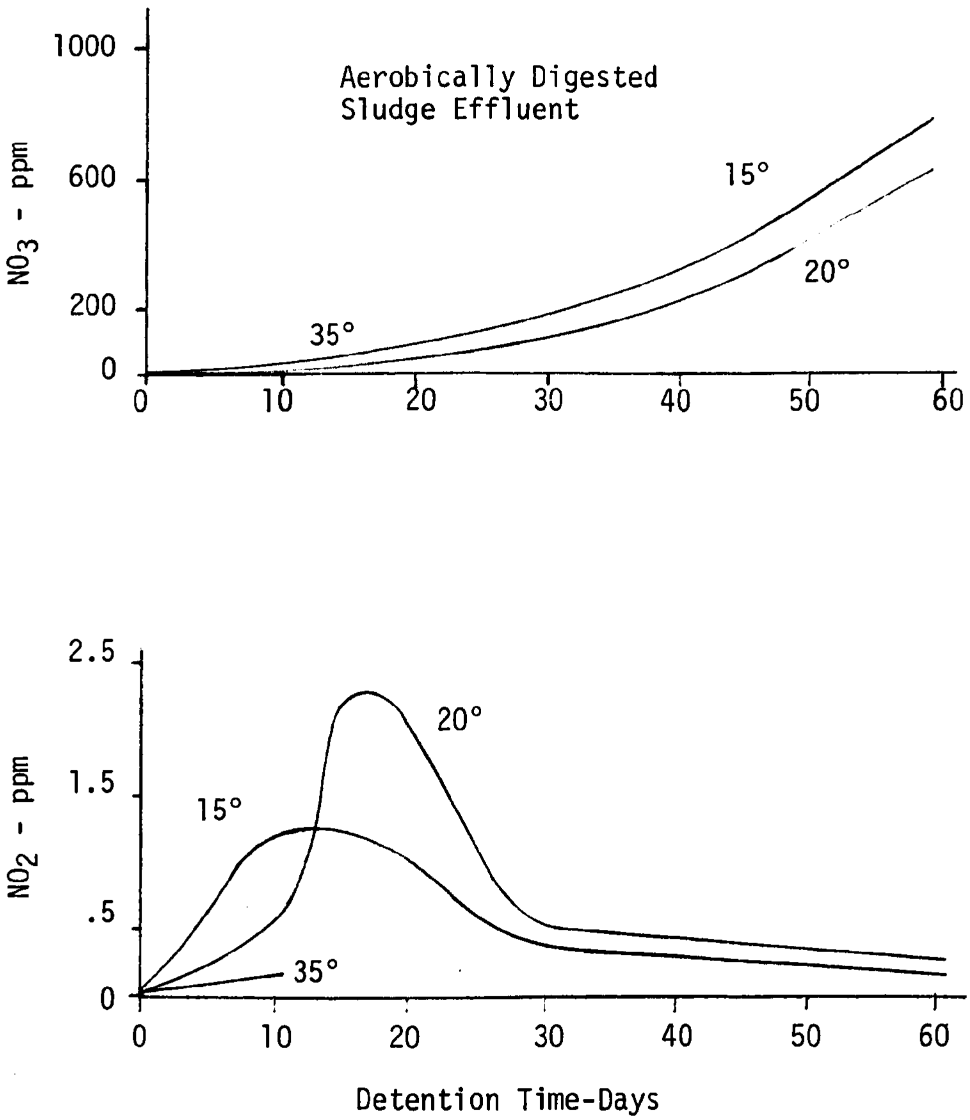

Figure 14. Increase in Nitrate-Nitrite Nitrogen During Aerobic Digestion of a Mixture of Raw and Waste Activated Sludges

at 7 treatment plants in Ontario were evaluated. All 7 processes utilized diffused air.

It was concluded that the aerobic digestion process is capable of producing a stable sludge and a supernatant low in organics. Nutrient return from the digesters represented less than 5 percent of the total plant nutrients.

Operational problems included poor settleability in some cases due to low DO levels and high solids concentrations. Foaming at high temperatures and icing at low temperatures were observed to occur.

SECTION V

PROCEDURES

RAW SEWAGE COAGULATION

Laboratory Selection of Polyelectrolytes

It was necessary to select effective polyelectrolyte coagulants for full scale testing at the City of Hollywood. This was accomplished by sending letters to manufacturers requesting polymer samples to be evaluated. As a result, seventy-eight samples representing cationic, anionic, and nonionic polymers were received. A list of those polymers evaluated may be found in Appendix D.

Evaluation of polymers was done by the standard jar test procedure using raw sewage from the Hollywood treatment plant. Rapid mixing was performed at a speed of 100 rpm for 20 minutes, followed by slow mixing at 20 rpm for 20 minutes, then 30 minutes of settling. Efficiency of each polymer for coagulating raw sewage was determined by measuring the change in light transmission with a Klett Photometer for various dosages. The original intent was to use a Zeta Meter to determine the electrophoretic mobility during each jar test so that polymer dosages could be properly controlled. However, attempts at using the Zeta Meter proved unsuccessful, as the high ionic concentrations of the Hollywood sewage caused turbulence in the cell. The high ionic concentrations resulted from sea water infiltration into sewer lines which caused chloride concentrations to approach 7,000 mg/l.

Extensive laboratory coagulation studies indicated that the following 14 polymers gave the best results under laboratory conditions:

1. Betz Poly Floc 1175
2. Betz Poly Floc 1100
3. Calgon Cat Floc
4. Calgon Coagulant Aid #25
5. Dow Purifloc C-31
6. Garratt - Callahan 72A
7. Garratt - Callahan 73
8. Garratt - Callahan 78S
9. Ionic Chemical NC - 720
10. Nalco 607
11. Nalco 610
12. National Natron 86
13. Rohm and Haas C-7
14. Herco Floc 828

Sufficient quantities of the six most highly effective polymers were purchased to conduct full scale plant coagulation tests; these included:

1. Betz Poly Floc 1175
2. Betz Poly Floc 1100
3. Calgon Cat Floc
4. Calgon Coagulant Aid #25
5. Rohm and Haas C-7
6. Herco Floc 828

Coagulation Unit

An existing 65 foot diameter clarifier was modified in an attempt to provide the necessary mixing and settling for effective coagulation. Laboratory tests had shown that coagulation could be achieved by eliminating long term rapid mixing, and utilizing only slow mixing followed by sedimentation. The Dorr-Oliver clariflocculator was selected as being the most suitable for installation in an existing clarifier.

Figure 3 presented a detailed drawing of the modified clarifier. A fiberglass baffle, 35 feet in diameter and 6.0 feet deep, was installed as shown. Agitation was supplied by three 2-H.P. variable speed mixers. At a nominal flow rate of 1.0 MGD, the theoretical detention time in the slow mix section was approximately one hour. The lack of bottom in the fiberglass baffle allowed direct flow from the slow mix section to the sedimentation section of the clariflocculator. Special mixing blades were utilized in an attempt to prevent mixing outside of the baffled area. The hydraulic surface loading rate on the sedimentation section at 1.0 MGD flow was 420 gal/(ft^2)(day).

Polyelectrolyte feed solutions were made in one of two 1,000 gallons tanks. Agitation was provided by a 1.0 H.P. Lightning Mixer. Dilutions of 1.0, 0.5, or 0.25 percent were utilized as feed solutions, depending upon the required dosage of a particular polymer to be fed. Polymer solutions were fed by a variable capacity Wallace and Tiernan positive displacement pump directly into the influent line to the clariflocculator. A sample of the polyelectrolyte solution was used to conduct a laboratory jar test to determine the optimum polymer dosage. Flow through the clariflocculator was regulated to 1.0 MGD and recorded on a Hershey Sparling flow recorder.

After start up, the system was allowed to stabilize for several hours before automatic sampling equipment was used for collecting composite samples of the influent raw sewage and coagulated and settled effluent. Each test normally was conducted for a minimum of 24 hours. The composited samples were analyzed for BOD, COD, and suspended solids.

AEROBIC SLUDGE DIGESTION

Operating Conditions

The operating conditions of the aerobic digesters were varied to obtain the best possible performance from those units. The variable parameters at the operator's control were digester volume, controlled by depths varying between 8 feet and 12 feet, and digester loading rates which could be applied to 1, 2, or 3 digesters.

A pilot scale digester was employed to perform tests at loading rates that could not be achieved in the full-scale digester. The digester was converted from a 480 gallon activated sludge aeration tank. Due to excessive liquid splashing from the compressed air aerators, the maximum volume at which the digester could be operated was 350 gallons. The pilot scale digester was fed manually on a daily basis.

The test conditions which were imposed during the research program were partially chosen by trial-and-error in that each test improved upon the deficiencies of the previous test. Certain parameters such as detention time and feeding were anticipated at the start of the program, but could not be defined until the capabilities of the basic plant facilities were studied and evaluated. The following is a list of the test conditions:

1) Test 1 was conducted with two digesters operating in series with each digester having a minimum retention time of 21 days. Sludge feed flow was somewhat variable in that new primary settling tanks were coming on-and off-stream while plant operation was being stabilized. The nominal retention time in the two digesters was, therefore, 43+ days.

2) Test 2 was conducted in a single digester with a varying detention period between 23 and 30 days. Since solids concentration in the digester was maximized, thickening by decanting was not practicable. Feed sludge was added daily and waste sludge was removed as necessary.

3) Test 3 was similar to Test 2 in that a nominal 29 day detention period was used in the aerobic digester. This test came about because equipment failure forced a change in digesters during Test 2. The practice of partially filling a digester with groundwater during startup in order to float the mechanical aerator so disrupted equilibrium test conditions that an entirely separate designation was given to Test 3. Feed sludge was added daily and waste sludge was removed as necessary.

4) Test 4 was a continuous feed aerobic digestion test with an average detention time of 22 days. During Test 4 all plant sludge flow, including septic tank wastes, was added to the digester. The digester was operated to its maximum hydraulic capacity and waste sludge was withdrawn approximately once per week.

5) Test 5 was a continuous feed aerobic digestion test with an average detention period of 15 days. In order to achieve this test condition, all primary plant sludges and septic tank sludges were added to a single digester with an 8 foot sidewall depth operating at minimal hydraulic capacity.

6) Test 6 was a single batch feed digestion test conducted in a 55 gallon drum. This test provided a correlation between the changes in wastewater constituents with increased degree of digestion of a single sludge mass.

7) Test 7 was a 20 day digestion test with a carefully controlled, constant volume daily feed of primary sludge. This test, conducted in the 350 gallon pilot plant, provided a basis of comparison between performance of the pilot plant and the fullscale digester.

8) Test 8 was a 14 day digestion test with a carefully controlled, constant volume daily feed of primary sludge. This test, similar to Test 7, provided a basis of comparison between the pilot plant and the full-scale digester.

9) Test 9 was a 10 day digestion test with a carefully controlled, constant volume daily feed of primary sludge. This test, conducted with the 350 gallon pilot plant, provided a retention period unobtainable in the full-scale digesters due to time and equipment limitation.

10) Test 10, a 5 day retention digestion test with a carefully controlled, constant volume daily feed of primary sludge, was conducted with the 350 gallon pilot plant and provided a retention period unobtainable in the full-scale digesters.

Special studies were carried out on the physical behavior of digested sludges. Sand bed drying of digested sludges was accomplished on the existing standard size sand bed at the treatment plant. Waste sludges from the full scale digester were used to flood a full sand bed to a depth of 17 inches in order to determine whether a greater depth of sludge would dry adequately on the bed. The smaller quantity of sludges available from the pilot scale digester was dried in a restricted sand bed. This was accomplished by sinking a bottomless 55 gallon drum to a depth of six inches into a standard sand bed. Waste sludge would be contained in that drum during the period of drying. All sludges were kept on the sand beds until they had dried, cracked, and were easily handleable by shovel or pitch fork.

Simulated lagooning studies were also carried out with the aerobically digested sludges. Four gallon plastic waste cans were filled with sludge at the end of a digestion test and placed in an open area exposed to the natural elements. Four liter containers were also filled with the same sludge and placed in the air conditioned laboratory for comparative purposes. The sludges were then observed over a period of time and finally chemically analyzed at the end of the test program.

Sampling and Analyses

Sludge samples for chemical analyses were normally collected three times per week. Six single samples were composited over a 24 hour period because, in most of the waste streams, automatic sampling equipment could not handle the solids content.

Refrigeration was the standard means of sample preservation for all analyses except nutrient content. Basic analyses were conducted at the test site during the day of the sampling. Nutrient analyses were performed in the Gainesville laboratories of Environmental Science and Engineering, Inc.

Samples to be analyzed for nutrient content were preserved with mercuric chloride and sulfuric acid in addition to being refrigerated. The nutrient samples were then shipped by bus to Gainesville. It was inevitable that some samples were delayed in shipment and arrived both warm and in an anaerobic state.

With the exception of the automated analyses discussed below, analyses for waste constituents and qualities were conducted in accordance with the 12th and 13th Editions of Standard Methods for the Examination of Water and Wastewater, published jointly by the American Public Health Association, the American Water Works Association, and the Water Pollution Control Federation.

Nitrate and nitrite nitrogen and total ortho-phosphorous phosphate analyses were performed on the Technicon Auto-Analyzer. The automated procedure for nitrate plus nitrite uses hydrogen sulfate and a copper catalyst to reduce nitrates to nitrites. The nitrites are then treated with sulfanilamides under acidic condition to produce a diazo compound which reacts with N-1 naphthylethylenediamine di-hydrochloride to form a soluble dye. The samples are prefiltered with a coarse filter to prevent clogging of capillary tubes in the Auto-Analyzer and diluted to stay within the working range of the method. Control tests have indicated salinity to not be an interfering factor. The analysis for nitrate nitrogen involves reaction of the nitrates with brucine sulfate and sulfanilic acid in an acidic solution to form a measurable colored complex. The samples for nitrate ion are also prefiltered by a coarse filter and diluted to the working range of the Auto-Analyzer. Total phosphate is measured by digesting polyphosphate forms with ammonium persulfate in an autoclave. Then analyses proceed as for orthophosphorous. Orthophosphorous reacts with ammonium molybdate to form molybdophosphoric acid which is subsequently reduced with aminonaphtholsulfonic acid to a molybdenum blue complex. Filtration of the raw sample is practiced only after any digestion in the autoclave.

Specific Resistance

The specific resistance of the digested sludges was measured during the study by means of the Buchner Funnel technique. In this procedure specific sludge volume is placed in the funnel, a cake allowed to form on the filter by gravity flow, and a vacuum of 20 in. Hg applied to the cake. The volume of filtrate collected per unit time is recorded, forming the basis for further calculation.

Carman, as discussed by Coackley[19], has shown that filtration in the case of compressible filter cakes is:

$$\frac{dV}{d\theta} = \frac{PA^2}{u(rcV + RmA)} \qquad (1)$$

V = volume of filtrate, ml
θ = time, sec
p = pressure, inches Hg
A = filtration area, cm^2
u = filtrate viscosity, poises
r = specific resistance, sec^2/gm
c = weight of solids/unit volume of filtrate, gm/ml
Rm = initial resistance of a unit area of filtering surface

The specific resistance, r, is numerically equal to the pressure difference required to produce a unit rate of filtrate flow of unit viscosity through a unit weight of cake.

Integration of Equation 1 yields:

$$\theta = \frac{urc}{2PA^2} \cdot V^2 + \frac{uRm}{PA} \cdot V \qquad (2)$$

or

$$\frac{\theta}{V} = \frac{urc}{2PA^2} \cdot V + \frac{uRm}{PA}$$

i.e.,

$$\frac{\theta}{V} = bV + a$$

If $\frac{\theta}{V}$ is plotted against V, a straight line of slope b is obtained where

$$b = \frac{urc}{2PA^2}$$

To calculate the specific resistance, it is necessary to obtain adequate data to plot $\frac{\theta}{V}$ against V so that b may be measured. Once slope b has been determined and the other variables are known, the specific resistance may be calculated from the equation:

$$r = \frac{2bPA^2}{uc}$$

Data Reduction

During the course of the program, voluminous amounts of data were collected on waste flows, constituent concentrations, and sludge qualities. Presentation of massive repetitive data and assimilation of this data would be time consuming and of marginal value. Therefore, in most instances, average data figures are used and special note is taken of unusual operating conditions.

With the exception of a brief period during the beginning of this program, when laboratory facilities were not yet completed, detailed analyses were conducted of most of the waste streams on a three times per week basis. These analyses permitted the definition of a "settling-in" period for each test and a stabilized operating period thereafter. In the presentation of the data, average results from each test were used. The averaged data covers only the stabilized operating condition of the digesters. Noticeable trends or specific oddities in daily data are mentioned in the presentation.

While daily feed to the digesters was measured by means of time clocks on calibrated progressive cavity sludge pumps, there was no accurate way to measure volumes of the gravity flow of sludge wasted from the digester. An attempt was made to measure volumetric changes within the digester itself in order to relate such changes to evaporation, rainfall, and sludge wasting, first by using a float mechanism as pictured in Figure 15. However, this mechanism became rapidly fouled with coarse solids and sludge and became unuseable. The second attempt at measuring wasted sludge volume involved the installation of verticle sight tubes at the sides of the digesters. These sight tubes were filled with clear water, could be blown out with each use, and were to give an indication of water level within the digester. In a special experiment the sight tubes were found to have a minimum precision of greater than one inch of water level. Since a one inch change in the digester represented 2,780 gallons of sludge or approximately 15 percent of the daily feed to the digesters, the sight tubes were discarded as too inaccurate. Fouling of the inside of the digester surface from spray and foam prevented accurate measurement of digester liquid level directly. No other satisfactory method of sludge volume measurement was provided in this program.

A special computer program was used to analyze the daily sewage flow data and compare them with daily rainfall statistics. This program was able to separate surge flows due to stormwater infiltration from daily and seasonal variations in domestic wastewater discharge. With the aid of this program, any municipality providing detailed daily plant flow records and detailed rainfall information could accurately estimate the amount of storm water infiltration in both sanitary and combined sewer systems. A discussion of the program is presented in Appendix A.

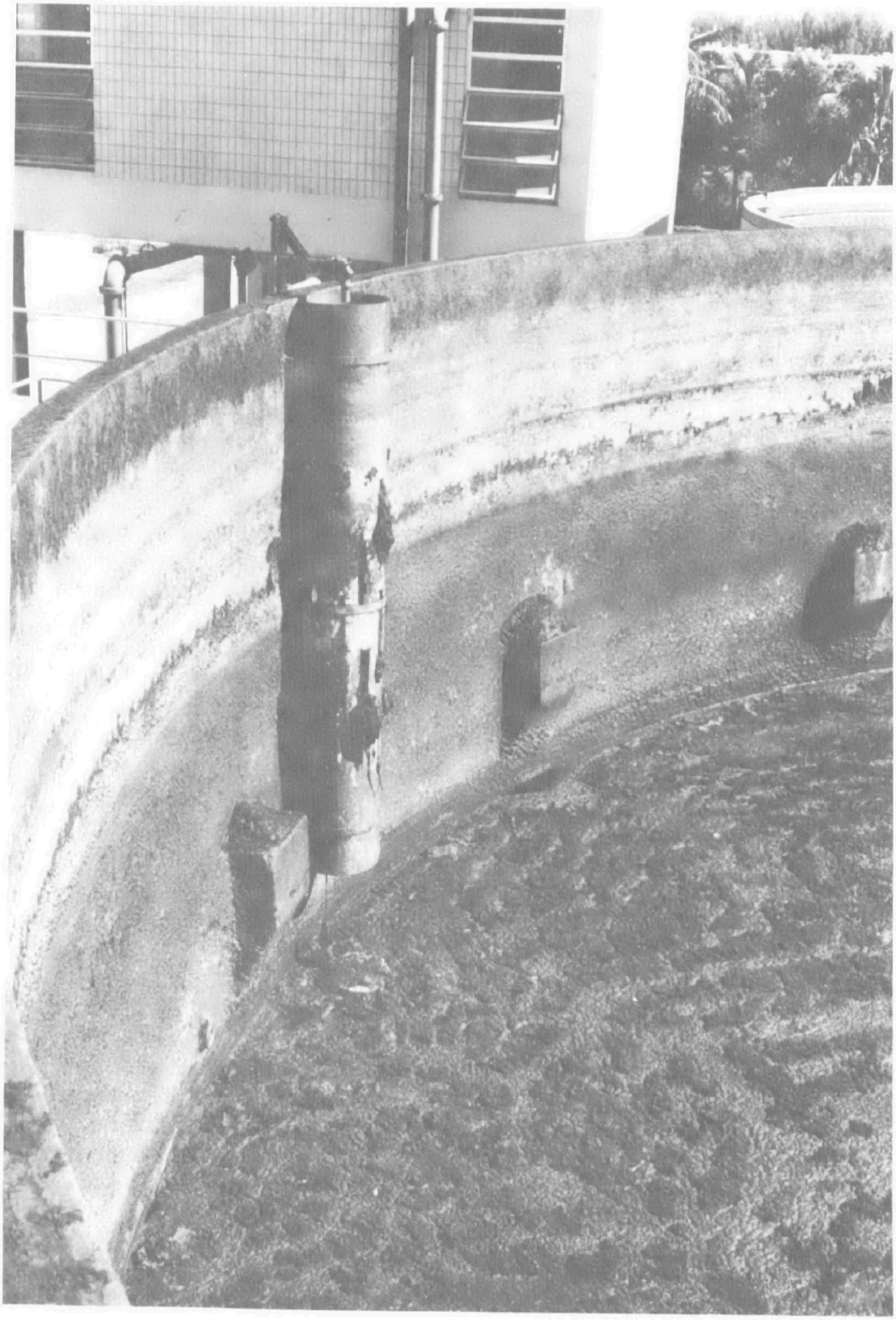

FIGURE 15: FOULED DIGESTER LIQUID LEVEL INDICATOR

SECTION VI

STUDY RESULTS

RAW SEWAGE COAGULATION

Initial Tests

Prior to full scale tests, a laboratory jar test was conducted to determine optimum polymer dosage. In July 1970, the first full scale raw sewage coagulation experiments were conducted. Flow through the coagulation unit was limited to 1.0 MGD and an initial dosage of 5 mg/l of Cat Floc was utilized. It was immediately obvious that excessive mixing velocities caused any settled sludge to be resuspended and remixed with the incoming sewage. Therefore, little or no coagulation treatment efficiency was realized (see Table 1).

Two steps were taken to alleviate the mixing problem, one was to raise the mixing blades to a point where their zone of influence did not include the settled sludge and the other was to order new gears for the mixing equipment in order to reduce its rpm range.

Before the new gears were obtained, another series of coagulation tests were conducted with Cat Floc and Calgon Coagulant Aid #25. In all of these tests it was found that mixing velocities were still too high and that sludge was being resuspended from the bottom. Toward the end of 1970 the mixing equipment had been modified as recommended by the Dorr Oliver Research Department. Mixing blades had been set at optimum height and the new gears installed to lower the rpm of the mixing equipment.

Laboratory coagulation tests conducted at the Hollywood sewage plant showed that the sewage could be effectively coagulated with a variety of cationic polymers; however, the Dorr-Oliver Clariflocculator was unable to duplicate the laboratory results before or after modifications were made to the coagulation unit. Typical results of laboratory coagulation of the Hollywood sewage are shown in Table 2. Rohm and Haas C-7 cationic polymer at a dosage of 20 mg/l was used to obtain the maximum BOD reduction of 70 percent. The maximum COD reduction of 69 percent occurred at a polymer dosage of 40 mg/l and the maximum suspended solids reduction of 99 percent occurred at a polymer dosage of 50 mg/l.

Full scale plant tests at a flow of 1.0 MGD were conducted with the coagulation unit. Tests were conducted over several 24 hour periods

TABLE 1

CHEMICAL ANALYSES OF COAGULATION UNIT

Date	Flow (mgd)	Polymer	BOD INF (mg/l)	BOD EFF (mg/l)	COD INF (mg/l)	COD EFF (mg/l)	Sus. Solids INF (mg/l)	Sus. Solids EFF (mg/l)
6/ 9/70	0.89	None	-	-	186	124	165	69
7/12/70	1.0	None	98	95	193	152	81	41
7/13/70	1.0	Cat Floc 10 mg/l	83	75	109	101	65	40
7/14/70	1.0	Cat Floc 5 mg/l	124	103	170	145	-	-
7/15/70	1.0	Cat Floc 5 mg/l	76	70	164	148	77	55
7/21/70	2.2	None	85	53	145	52	-	-

TABLE 2

LABORATORY JAR TESTS

JAR	POLYMER* DOSE (mg/l)	BOD (mg/l)	COD (mg/l)	SS (mg/l)
Mixed	0	119	414	186
Settled	0	86	261	94
2	10	79	225	64
3	20	36	171	14
4	30	42	207	8
5	40	42	126	4
6	50	46	135	2

* Rohm and Haas C-7

TABLE 3

FULL SCALE COAGULATION TEST

TEST	POLYMER* DOSE (mg/l)	COD (mg/l)	BOD (mg/l)	SS (mg/l)
Influent	0	274	116	112
Effluent before test	0	145	110	28
Effluent after test	30	118	108	19

*Rohm and Haas C-7

with composite samples being collected from both the influent and effluent. Typical results of these tests are shown in Table 3. Results show that the BOD was reduced by only 7.0 percent, the COD by 57 percent, and the suspended solids by 83 percent. The actual increase over plain sedimentation was 2.0 percent for BOD, 10.0 percent for COD, and 9.0 percent for suspended solids. These treatment efficiencies were far below that achieved in the laboratory.

Continuous Flow Laboratory Studies

Since full scale coagulation studies at Hollywood could not duplicate laboratory results, further laboratory studies were conducted to determine how the Hollywood plant facilities could best be modified. The tests were done primarily to determine if poor results of polymer coagulation on a plant scale basis, when compared to laboratory tests, were mainly due to poor or improper mixing conditions. A laboratory scale coagulation-flocculation-clarification unit with a one gallon per hour capacity was assembled. Primary settled sewage was obtained at the University of Florida sewage treatment plant in Gainesville, Florida. A reservoir of this feed water was maintained in a large plastic container. From there, a submerged centrifugal pump delivered the feed water at 63 ml/min to a 400 ml rapid mix plastic chamber. Polymer addition was employed to coagulate the sewage solids. Calgon Cat-Floc was added because of previously successful experience with this product. A positive displacement diaphragm pump delivered 123 ml/hr of the polymer solution to the rapid mix chamber. The energy to the rapid mix was provided at first by a single air pump and later by two air pumps. Water from the rapid mix overflowed into a 1/2 gallon slow mix chamber where a flat paddle type stirrer rotated at 20 rpm. Retention time was approximately 6.3 minutes in the rapid mix and 30 minutes in the slow mix. A siphon tube was used to gently transport the flocculated mixture to the 5 gallon sedimentation basin where finished effluent was collected as overflow.

At startup, all containers except the basic feed reservoir were filled with tap water. The primary sewage gradually displaced the tap water and, as it had been preserved for several hours by refrigeration, the primary sewage was several degrees colder. The temperature difference manifested itself in the clarifier where the coagulation sewage displaced the tap water in plug flow from the bottom to the top.

A standard jar test apparatus was used to find the optimum dosage of polymer for the sewage in question. Results were as follows:

Polymer Dosage (mg/l)	Light Absorbance on Klett Photometer
0	100
Tap Water	66
2	86
4	80
6	82
8	86
10	89

Since the best results were obtained at levels of 4 and 6 mg/l, a dosage of 5 mg/l was chosen for the continuous feed test. It should be noted, however, that the heaviest, most readily settled floc occurred at 8 mg/l of polymer. The following is a summary of the results of the continuous feed experiment using 5 mg/l of Cat-Floc as a coagulant:

Time	Klett Reading on Effluent	Comments
9:00 a.m.	Feed = 95, Tap = 63	Start Feed
9:30		Floc forming in slow mix
10:00	65.0	Distinct floc in clarifier
10:30		No change
11:00	63.0	Added second air supply to rapid mix
11:30		Greater floc size in slow mix
12:00 p.m.	65.0	Large floc in slow mix
12:30 p.m.		No change
1:00	63.0	No change
1:30		No change
2:00	63.5	No change
2:30		No change
3:00	73.0	Tap water displaced in clarifier
3:30	73.5	Good separating floc
4:00	73.0	No change

Floc formed by increasing energy input to the rapid mix was noticeably larger. In all cases, this floc was relatively light and easily disturbed by water currents. Results of the laboratory study showed that polyelectrolytes could coagulate raw sewage on a continuous flow basis. The three principal requisites of good operation were 1) high energy input to the rapid mix to obtain a good dispersal of polymer and the formation of pinpoint floc; 2) adequate energy input and detention time in the slow mix to build up floc; and 3) provision of adequate detention time and quiescent conditions in the final clarifier to provide effective liquid-solid separation.

The deficiencies in the Hollywood treatment plant were determined to be a lack of high energy input for rapid mix before entering the Dorr-Oliver clariflocculator. Provisions were made to modify the system so that approximately 15 minutes of rapid mixing could be provided to the sewage before it entered the coagulation unit. Polymer addition was moved to a point upstream of an existing distribution box.

Modification of the distribution box consisted of the addition of an air header and compressor which hopefully would provide the energy input and detention time required for rapid mixing prior to discharge into the existing slow mix unit.

Final Coagulation

Further full scale coagulation tests were conducted after modifications were made to provide rapid mix prior to the Dorr-Oliver clariflocculator. The results of several 24-hour tests using Cat-Floc at various coagulant dosages are shown in Table 4. Little if any improvement in treatment efficiency was experienced. Several other experiments were conducted with other polymers and a wide range of polymer dosages, but the results were similar to previous tests with essentially no increase in treatment efficiencies. Due to the inability of the full scale unit to duplicate laboratory results, coagulation studies were terminated. Since the existing facility could not be modified to provide the mixing conditions necessary to achieve efficient raw sewage coagulation, further coagulation studies with the existing facilities would have been unproductive.

AEROBIC SLUDGE DIGESTION

The operating rationale at the Hollywood Sewage Treatment Plant was to construct an aerobic digester feeding and aerating schedule that utilized existing equipment and personnel from one test to another. First the most conservative operating factors were chosen,then, by trial and error, the operating factors were modified to achieve optimum digester performance. Occasionally equipment would fail during a test and the test would have to be restarted. The end result of varying test conditions and digesters was a collection of independent trials providing parametric comparisons of the effects on aerobic digestion.

The ultimate standard of performance for the aerobic digestion process is a stabilized, odor free,and manageable waste sludge. In this project, waste sludge quality was determined by its behavior on a sand drying bed and by the filterability of the sludge. These parameters were not measured for all tests. The original tests in the program were to establish a minimum theoretical detention time for sludge digestion based on analyses of chemical constituents. As lower detention times were approached, sludge quality was also included in the observations of the program. Certain chemical parameters, such as pH and alkalinity, were monitored and compared with process performance.

TEST 1 -- 43+ DAY DIGESTION

The first trial conducted at the Hollywood Sewage Treatment Plant was begun before all construction work at the plant had been completed.

TABLE 4

COAGULATION OF RAW SEWAGE WITH CAT FLOC

Test No.	Polymer Dose (mg/l)	BOD (mg/l)	Supernatant COD (mg/l)	SS (mg/l)
1	1	124	384	88
2	3	125	360	66
3	5	134	261	84
4	10	147	310	80
Raw Sewage	-	130	374	80

Therefore, necessary changes in flows due to equipment malfunction, equipment installation, and an occasional error provided variable detention periods for this test. The basic concept at that time was to treat the primary settled sludge by two-stage series digestion. The digesters were prepared for operation by filling them two-thirds full of groundwater and then adding sludge on a daily basis. Digester 1 commenced operation on March 24, 1970, and Digester 2 was filled two-thirds with groundwater on April 1, 1970. This particular test was terminated on January 6, 1971. During much of this period measurements of liquid volumes to the digesters were based on changes in the liquid levels in the digesters. These values were often difficult to determine because of heavy surface foam and fouling of indicator devices. The flow data commencing on November 1, 1970, were determined by reading time clocks mounted on the progressive cavity pumps feeding the digesters. The time clocks were calibrated against measured pump outputs.

During the test period, feed to the digesters varied from a low of 5,000 gallons per day to a high of 35,000 gallons per day with volumes equal to the raw feed being transferred from Digester 1 to Digester 2 on a daily basis. Hydraulic detention in both Digesters 1 and 2 varied from a low of 22.2 days to a high of 208 days.

The detention time in Digester 2 was considered to be nominal because during the first part of the test (until November 1, 1970) decanting for sludge thickening was necessary because of the initial two-thirds groundwater charge. Decanting provides for a sludge residence time longer than simple hydraulic detention calculations can estimate. Measurements of decanted volumes were too sporadically recorded to permit accurate determinations of residence time. This, combined with natural solids reduction due to digestion, made estimations of exact sludge residence time in Digester 2 extremely difficult.

Some flow changes to the digesters were deliberately initiated to alter conditions within the digester. A criterion of overloading in Digester 1 was the measure of dissolved oxygen in the mixed sludge. When the D.O. fell below 1.0 ppm, fresh feed sludge would be diverted to Digester 2 until the D.O. was increased in Digester 1. This condition happened several times during the test and was not alleviated until it was recognized that the floating mechanical aerators were not producing their rated horsepower. Adjustment of the aerators by the manufacturers terminated most difficulties of low dissolved oxygen levels in the digesters.

A second factor which forced flow variations was foaming. Heavy and thick layers of foam, as illustrated in Figure 16, decreased aerator efficiency in the digester and temporarily forced a lower overall digester feed flow to reduce the loading. This was done by wasting undigested primary sludge.

FIGURE 16: FOAMING ON AEROBIC DIGESTER

Feed Sludge Quality. The samples collected for subsequent analyses were of practical necessity: 6 individual samples composited over a 24-hour period, 3 times weekly. The feed qualities were analyzed from the start of the program but, due to the length of this particular test period and the two month period during which no analyses occurred, the average feed sludge conditions presented in Table 5 are for the period of stable conditions of the digester only. Influent BOD varied from 8,000 to 16,000 mg/l in November and December of 1970. The values for COD, total solids, and total volatile solids varied from 38,000 to 78,000 mg/l, 44,000 to 81,000 mg/l, and 35,000 to 55,000 mg/l, respectively. These values are indicative of a heavy or well concentrated sludge being withdrawn from the primary sedimentation basins. The COD to BOD average ratio was 5.2:1 and the total solids to total volatile solids average ratio was 1.4:1.

Digester Mixed Liquor. During the first day of operation, each digester was filled two-thirds full of groundwater in order to utilize the floating aerators. Daily feeding with primary sludge gradually displaced the groundwater, particularly in Digester 2 where decanting was practiced until steady state operation was achieved. From initiation of the analyses, a gradual increase in the sludge liquor constituent concentrations, as the original groundwater was being displaced in the digester, could be detected. Total solids reached a 4 percent concentration in September, 1970. Since a 4 percent solids concentration in the aerobic digester was considered the minimum achievable with primary sludge, this value was chosen as the point of stabilization of the digester. At the termination of this particular test, the solids concentration had crept to 5.7 percent. The average values for digester constituents are presented in Table 5.

From November 9 through January 6, there were 5 days out of 59 when the dissolved oxygen level in Digester 1 dropped below 1.0 mg/l and the feeding of primary sludge directly to Digester 2 was necessitated. The average dissolved oxygen level in Digester 1 was 4.5 mg/l and in Digester 2 was 5.1 mg/l.

The temperature of a mechanically aerated digester is to some extent dependent on ambient weather conditions. Temperatures in Digester 1 varied between 10°C and 24°C for an average of 17.6°C, while the temperatures in Digester 2 varied from 9°C to 21°C for an average of 16.6°C. The pH in both digesters only varied from a low of 6.6 to a high of 8.0. The average pH for each digester was 7.4.

TABLE 5

AVERAGE CONSTITUENT REDUCTIONS THROUGH TWO STAGE DIGESTION

(mg/l)

Liquor	COD	BOD	Total Solids	Total Volatile Solids
Primary Sludge	61,086	11,786	58,060	41,076
Digester 1 Mixed Liquor	40,460	2,202	47,619	27,843
Digester 2 Mixed Liquor	33,332	926	48,511	25,510
Total Percent Reduction in 1	34	81	18	32
Total Percent Reduction in 2	11	11	-2	6
Total Percent Reduction	45	92	16	38

Chloride levels in the digesters were relatively high due both to the initial filling of the digesters with chloride bearing groundwater and to sewer line infiltration by brackish and ocean waters. The average chloride level in Digester 1 was 6,800 mg/l as Cl^- and in Digester 2 was 7,800 mg/l as Cl^-.

The total solids content of Digester 1 averaged 47,619 mg/l for an 18 percent reduction over the feed sludge. The total solids increased in Digester 2 to an average of 48,511 mg/l for a net reduction of 16 percent over the feed sludge. It is felt that the differences between digesters are insignificant and may possibly be due to difficulties in obtaining a representative sample. Evaporation in Digester 2 could increase concentrations of constituents more rapidly than digestion removes them. There was an overall reduction of 38 percent in total volatile solids through the two digesters with Digester 1 accounting for 32 percent at 27,843 mg/l average total volatile solids. Digester 2 achieved a further 6 percent reduction to 25,510 mg/l average total volatile solids. There was a reduction in suspended solids between the two digesters from 36,029 mg/l to 34,513 mg/l. Volatile suspended solids experienced a similar magnitude reduction from 24,734 mg/l in Digester 1 to 20,703 mg/l in Digester 2.

Digester 1 provided a 34 percent reduction in chemical oxygen demand to 46,460 mg/l. Digester 2 further reduced the COD by an overall 11 percent to an average 33,332 mg/l. The 45 percent total reduction in COD is substantial and compares well with the total reduction in BOD of 92 percent, keeping in mind that increased biodegradation usually increases the COD to BOD ratio. The COD to BOD ratio was 36:1. The BOD of the mixed sludge in Digester 1 averaged 2,202 mg/l and in Digester 2 averaged 926 mg/l.

Oxygen Uptake. A common indicator of biological activity is the oxygen uptake rate of the mixed liquor. Besides providing comparative values of low or high activities, the uptake rate furnishes a measure of the aeration equipment necessary for an aerobic digester at any temperature. Figure 17 relates the volumetric oxygen uptake rates measured during November and December, 1970, against temperature. Figure 18 relates the oxygen uptake rates for the same period per weight of total solids in the digesters as a function of temperature. This eliminates variation in uptake due to fluctuating solids and biomass in the digesters. Too few data points are available for an exact relationship between uptake and temperature; however, an upward trend in oxygen uptake with

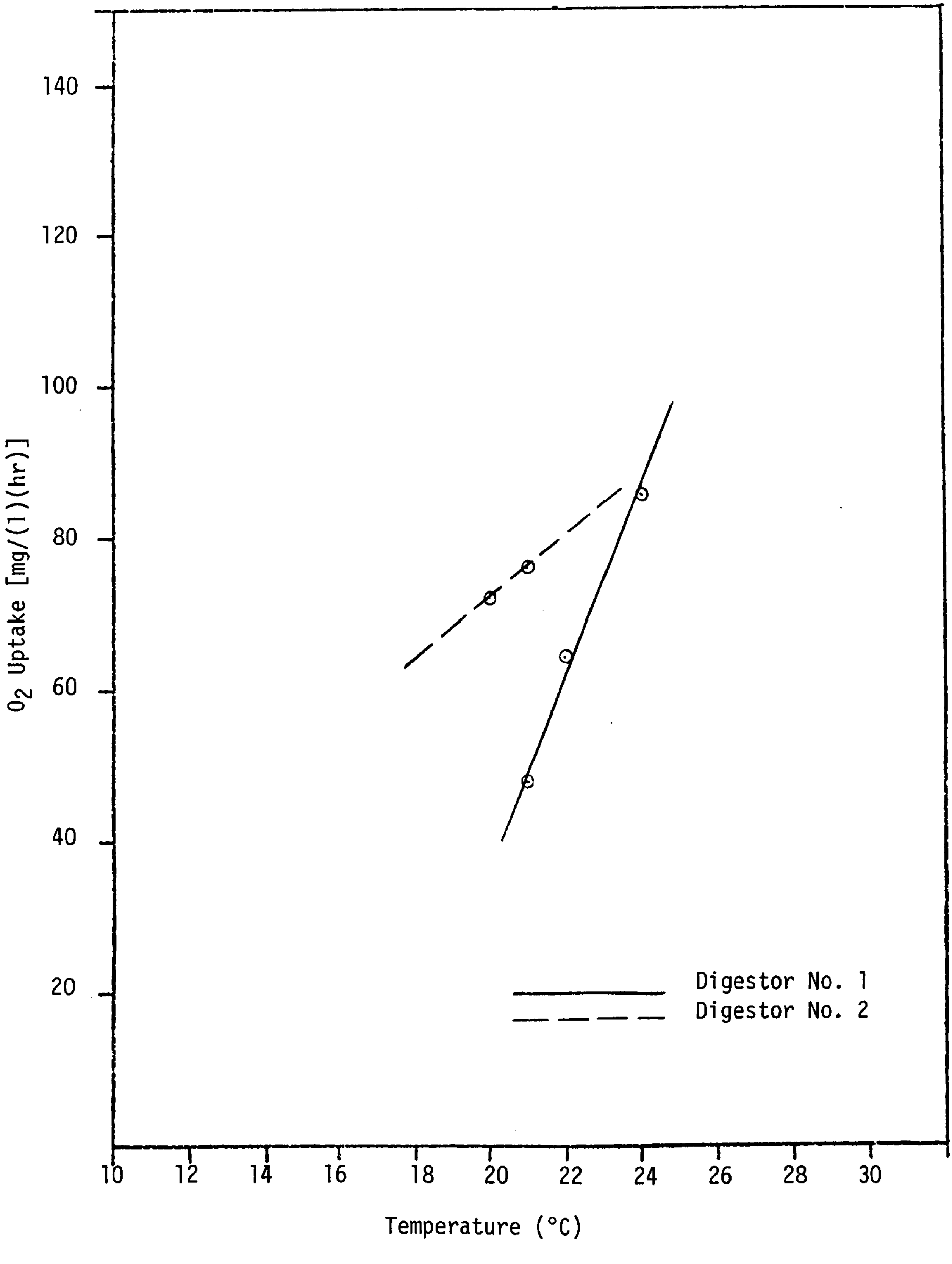

Figure 17. O_2 Uptake Ràte, 2-Stage Digestion
43+ Day Detention

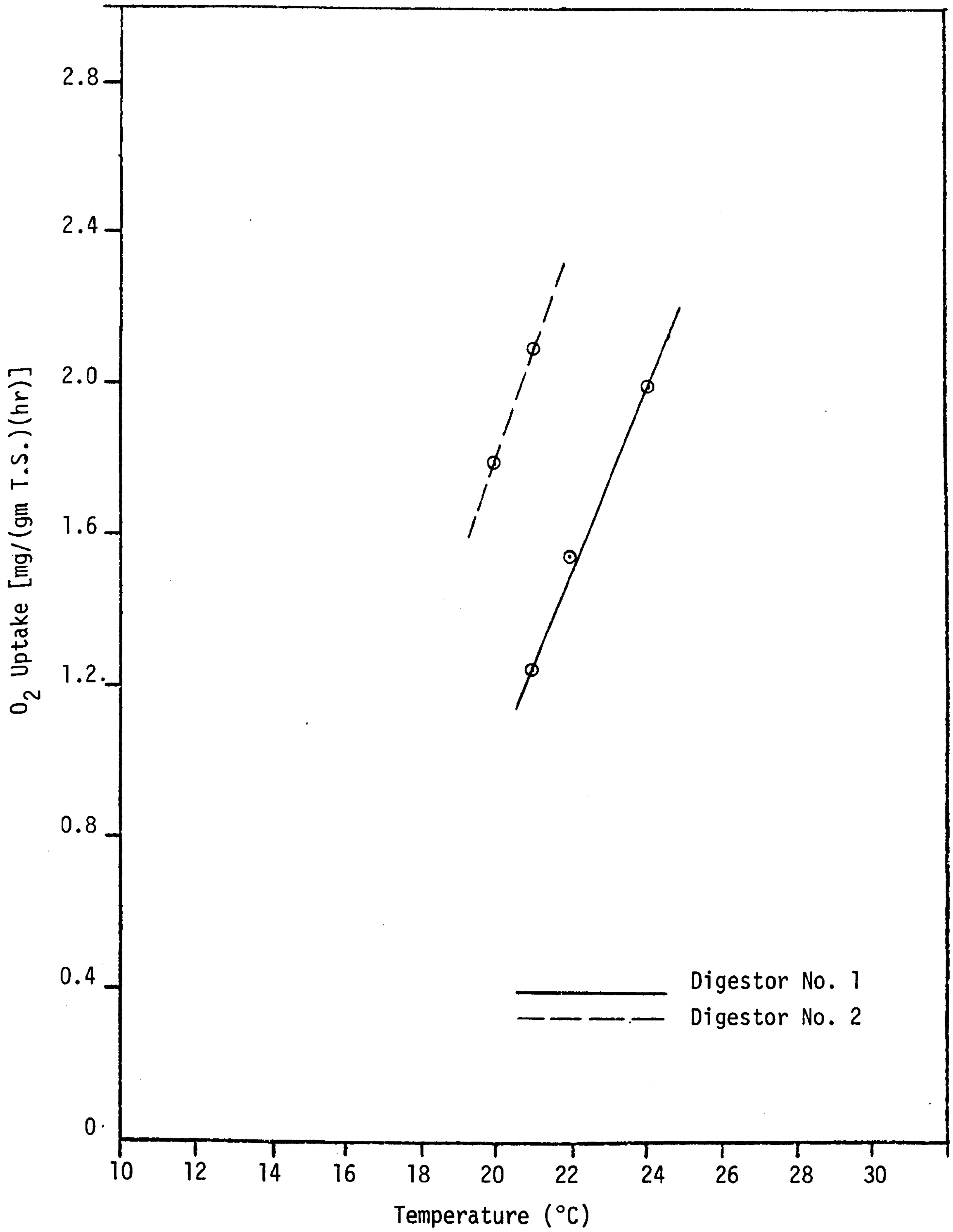

Figure 18. O_2 Uptake Rate, 2-Stage Digestion, 43+ Day Detention

increasing temperature is noted. Oxygen uptake in Digester 1 ranged from 47 to 86 mg/(l)(hr), and in Digester 2 from 72 to 76 mg/(l)(hr). Presented on a mass basis, the oxygen uptake rates were between 12 and 20 mg/(gm T.S.)(hr) in Digester 1 and 18 and 21 mg/(gm T.S.)(hr) in Digester 2.

Primary Plant Performance. During the period of this test, the raw sewage to the treatment plant contained an average of 122 mg/l of BOD, 166 mg/l of COD, and 122 mg/l of suspended solids. Analytical difficulties during this period may have given low values for chemical oxygen demand. After primary separation, the plant effluent contained 112 mg/l of BOD, 150 mg/l of COD, and 75 mg/l of suspended solids.

TEST 2 -- 23 TO 29 DAY DIGESTION. On January 7, 1971, the two stage digestion test was terminated. The second stage digester was taken out of operation and subsequently, all waste sludge from Digester 1 was discharged to either sand beds or, more often, to the ocean outfall. The second major test in the program consisted of primary sludge going to Digester 1 only. The second test commenced on January 7, 1971, and terminated on May 6, 1971. Because a full digester was used at the start of this test, stable operating conditions may also be assumed to have started on January 7, 1971. During the first two months of the test, septic tank sludge was added to Digester 1 because other facilities for septic tank sludges were temporarily out of order. After March 1, 1971, septic tank sludge was no longer added to Digester 1. The average flow to Digester 1 during the first two months of aeration was 17,170 gpd for a 23 day theoretical detention period. For the subsequent two months the average flow as 13,760 gpd for a theoretical detention period of 29 days. Daily flow variations of primary sludge were small, ranging from 13,420 gpd to 19,970 gpd in the first two months, and from 8,390 gpd to 21,350 gpd with the majority of the flows falling between 9,490 gpd and 17,790 gpd in the second two months. Decanting was not practiced at any time.

Feed Sludge Quality. The feed sludge quality during this test did not change appreciably from the previous test. Table 6 presents averaged primary sludge parameters. These values have not been adjusted for the change in quality due to addition of septic tank sludge during a two month period. Total averaged COD, BOD, total solids, and total volatile solids values were 65,700 mg/l, 16,240 mg/l, 60,036 mg/l, and 44,905 mg/l, respectively. The septic tank sludge qualities had much lower constituent concentrations at 43,508 mg/l, 6,205 mg/l, 33,685 mg/l, and 21,439 mg/l for COD, BOD, total solids, and total volatile solids, respectively.

TABLE 6

AVERAGE CONSTITUENT REDUCTIONS AT 23-29 DAYS DIGESTION

Constituents, (mg/l)

Liquor	COD	BOD	Total Solids	Total Volatile Solids	Suspended Solids	Volatile Suspended Solids	Chloride	pH	Dissolved Oxygen	Temp. ^oC
Raw Sludge	65,700	16,240	60,036	44,905	-	-	-	-	-	-
Mixed Liquor	53,800	4,910	58,334	39,111	49,351	34,854	6,666	6.5	2.5	20
% Reduction	18%	70%	3%	13%	-	-	-	-	-	-

As explained below, effects from septic tank sludge additions are minor.

Digester Mixed Liquor. The digester in this test had been full from a previous test at a 30 day theoretical detention condition. Since feed water quality and test conditions did not change significantly from the first test to the second, it was decided to continue with a full digester. Therefore, stabilized conditions and analytical data commenced on the first day of the test.

Table 6 shows that only BOD was substantially reduced to a mixed liquor value of 4,910 mg/l. Other comparable reductions were COD to 53,800 mg/l, total solids to 58,334 mg/l, and total volatile solids to 39,111 mg/l. The total solids concentration is high and approaches the practical limit of solids content in an aerobic digester from mixing, thickening, and oxygen transfer considerations. A good portion of the total solids in this digester (greater than 1 percent) are soluble salts from seawater intrusion to the sewer system.

Suspended solids averaged 49,351 mg/l, which was close to the total solids content. In view of the high level of chloride ion in the digester (6,666 mg/l), it is apparent that the majority of the true sewage waste constituents are in suspended solids. This is further substantiated by the volatile suspended solids level of 34,854 mg/l, which was close to the total volatile solids level.

The average temperature in the digester during the test was 20° C with a range from 11°C to 25°C. The average pH was 6.5 with a low of 6.2 and a high of 7.0. Dissolved oxygen levels varied from 0.3 to 7.8 mg/l but on most days fell between 0.5 and 5.0 mg/l with an average of 2.5 mg/l.

Oxygen Uptake. The oxygen uptake rate of the aerobic digester varied slightly as shown in Figure 19. Figure 20 correlates uptake rate to total solids. The highest rate recorded was 1.8 mg/(gm T.S.)(hr) and the lowest was 1.1 mg/(gm T.S.) (hr) with a noticeable increase with increasing temperatures.
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Primary Plant Performance. During the period of this test, the Hollywood Sewage Treatment Plant was receiving a raw sewage with an average of 128 mg/l of BOD, 340 mg/l of COD, and 109 mg/l of suspended solids. The average plant effluent contained 119 mg/l of BOD, 314 mg/l of COD, and 84 mg/l of suspended solids.

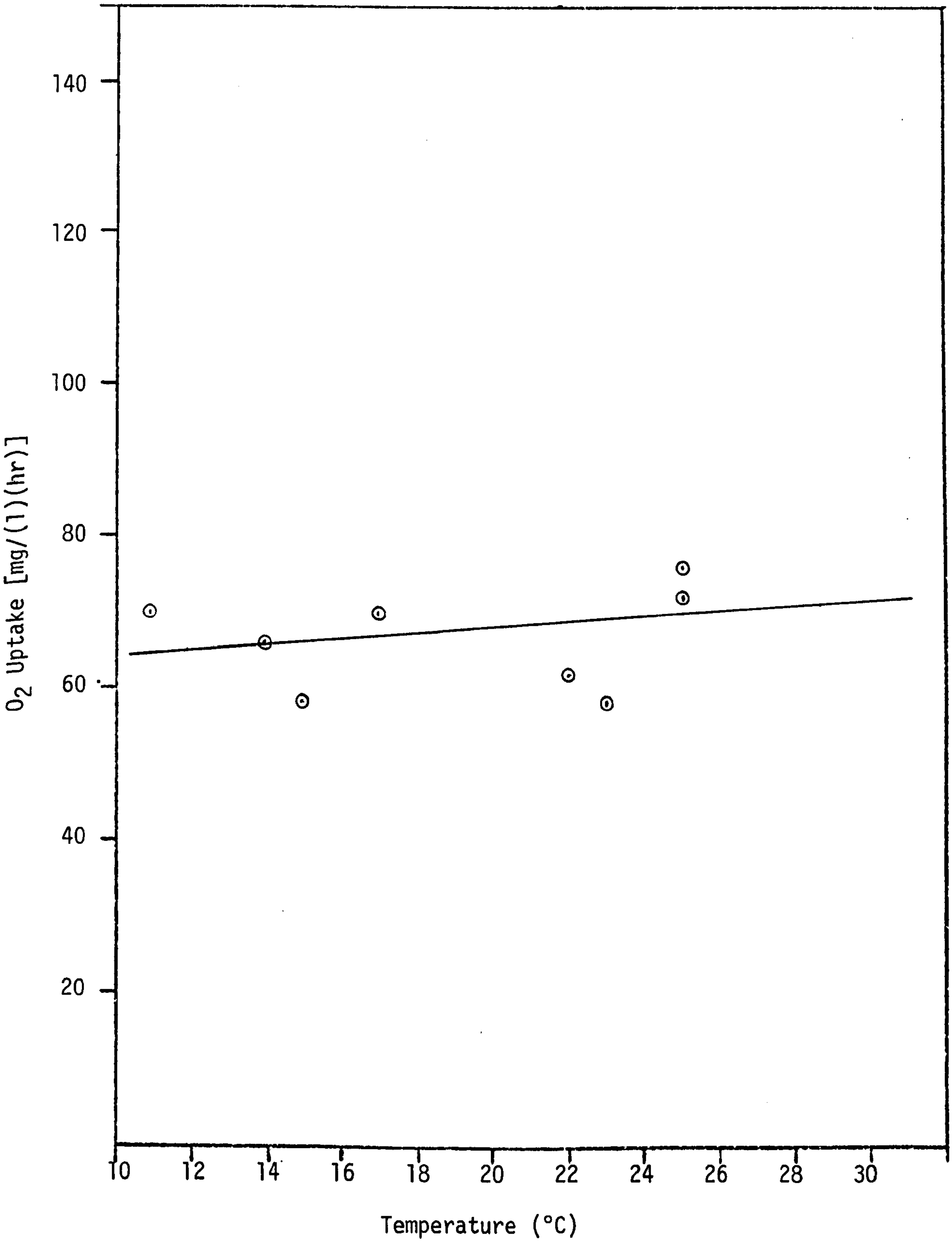

Figure 19. O_2 Uptake Rate (mg/l/hr)
24-30 Day Digestion

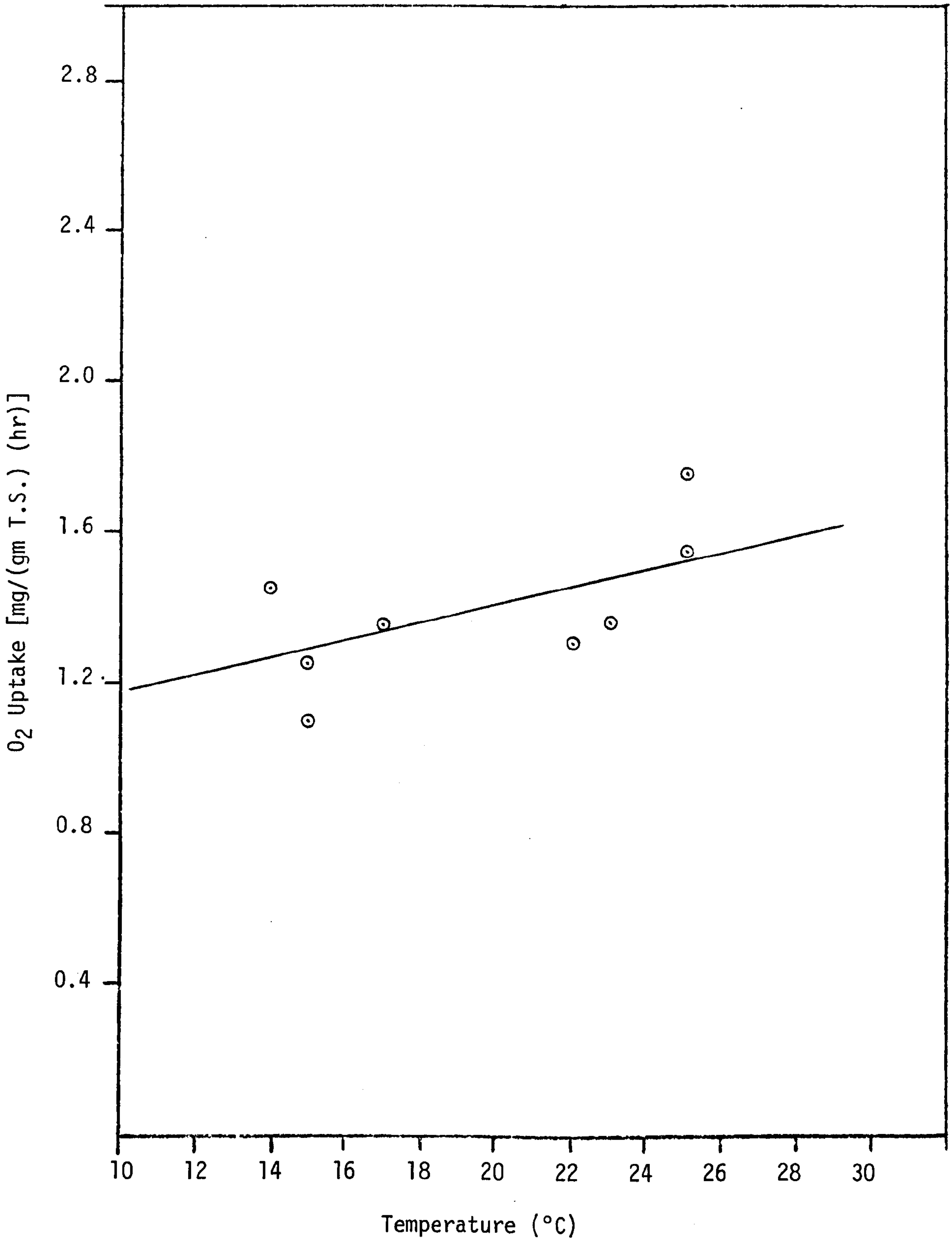

Figure 20. O_2 Uptake Rate [mg/(gm T.S.)(hr)], 24-30 Day Digestion

TEST 3 -- 29 DAYS DIGESTION. A mechnical failure in Digester 1 forced a continuation of the previous test in a new digester. Changing digesters involved partially filling the new digester with groundwater to float the mechnical aerators. Thus, test conditions were so disrupted that the following test must be considered independently. In this particular case, some mixed liquor from Digester 1 had been pumped to Digester 2 with the groundwater. Thus, stabilization was achieved more quickly.

Flow Data. Sludge feed to the digester for Test 3 commenced on May 7, 1971, and terminated on July 31, 1971. Average feed to the digester was 13,570 gpd with a daily low of 8,300 gpd and a high of 18,970 gpd. The great majority of flows fell between 11,100 gpd and 15,420 gpd. The average detention period was 29 days. Whenever maximum capacity was reached, 2.5 feet of mixed sludge was wasted from the digester. This occurred approximately once per week. Decanting was not considered practical due to the density of the mixed sludge and to jar test results which indicated poor settleability.

Feed Sludge Quality. Table 7 gives the average values for analyses completed on the feed sludge to the digester. During this test the average COD to BOD ratio was 4.8:1. The total solids varied widely from 45,380 mg/l to 74,860 mg/l, averaging 6 percent solids. Suspended solids averaged 50,593 mg/l, thus indicating that a significant portion of the total solids could be attributable to the "salt" content of the incoming sewage. The total volatile solids concentration varied from 35,068 to 57,058 mg/l and constituted a large portion of the total solids. Volatile suspended solids analyses indicated that most of the volatile matter collected in primary separation was insoluble. The alkalinity of the incoming sludge was a relatively high 1,293 mg/l, while the average pH was 5.9.

Digester Mixed Liquor. Averaged values of mixed sludge constituent concentrations are also presented in Table 7, with the percentage reduction obtained for each constituent. Dissolved oxygen concentration of the mixed sludge averaged 1.6 mg/l during the test. While the dissolved oxygen dropped as low as 0.3 mg/l, the digester never became anaerobic. The average digester temperature was 26°C and ranged from 23 to 27°C. The pH hardly varied during this test from the average value of 6.5, which represented an increase over the feed sludge pH of 5.9. Reductions in COD and BOD were 42 percent and 83 percent, respectively. The COD to BOD ratio changed from 4.8:1 in the feed to 16:1 in the digested sludge. Total suspended solids and volatile solids concentrations

TABLE 7

AVERAGE CONSTITUENT REDUCTIONS AT 29 DAYS DIGESTION

Constituents, (mg/l)

Liquor	COD	BOD	Total Solids	Total Volatile Solids	Suspended Solids	Volatile Suspended Solids	Alkalinity	Chloride	pH	Dissolved Oxygen	Temp. °C
Primary Sludge	65,851	13,841	60,780	46,718	50,593	42,492	1,293	5,250	5.9	-	-
Mixed Liquor	37,952	2,368	47,580	28,340	35,637	25,259	-	6,268	6.5	1.6	26
Percentage Reduction	42	83	22	39	30	41	-	-19	-	-	-

varied little during the test, although significant reductions of solids were obtained when compared to feed study values.

Chloride content in the digesters varied from a high of 7,250 mg/l three weeks after the beginning of this test to a low of 5,650 mg/l at the termination.

Primary Plant Performance. Collected data indicated that the performance of the primary treatment plant was marginal at best. Influent suspended solids of 103 mg/l were reduced to an effluent of 72 mg/l. Incoming BOD of 124 mg/l was a low value for typical municipal wastewater; however, the Hollywood sewage system serves very few industries and heavy groundwater and ocean water infiltration dilutes the sewage flow. Primary plant effluent contained an average of 113 mg/l of BOD. Influent COD averaged 288 mg/l while the effluent contained 311 mg/l. The apparent increases in COD values may be due to sampling deficiencies in that the influent and effluent samples were collected concurrently, and there exists a time lag of several hours between influent and effluent points. The effluent samples could include a high COD waste that would be missed by the influent sampler.

TEST 4 -- 22 DAY DETENTION. An analysis of the data from Test 3 indicated that the digester was not necessarily being utilized to its fullest capacity. Therefore, all primary sludges which had been diverted to another experimental digester, including septic tank sludges, were now added to the digester treating the main body of the waste. The digester was still maintained up to maximum liquid capacity of 12.0 feet and the theoretical detention time of sludges in the digester was 22 days.

The 22 day digestion test commenced on August 1 and terminated on November 4, 1971, when equipment failure occurred. The average flow to the digester during this test was 18,459 gallons per day with a single low of 9,490 gallons per day and a high of 27,220 gallons per day. The majority of the daily flow values fell between 23,330 and 14,230 gallons per day. Septic tank sludges were added intermittently. The monthly totals were averaged with the accumulated daily flows to obtain an overall daily average. Digested mixed liquor was wasted approximately once weekly.

Feed Sludge Quality. Test 4 commenced with a full digester from a previous test that had been operating at a 29 day digestion period. The basic change in the new test was the increase in feed sludge flow and the addition of septic tank sludges. Careful review of the individual sample analyses of the digester mixed liquor in the 22 day retention test produced no noticeable changes with time in any of the monitoring parameters except alkalinity, which gradually increased. For these reasons, stabilized test conditions more arbitrarily assumed to start with the first day of sampling and all data from that period was included in the averages.

The feed sludge characteristics presented in Table 8A are indicative only of the primary sewage sludge and do not include septic tank sludges. Separate analyses were not conducted on septic tank sludges during the test. Previous tests had indicated that a reduction in primary sludge constituent concentrations of approximately 2 percent would result from the addition of septic tank sludges. Table 8B presents the expected feed sludge characteristics based on a theoretical 2 percent change due to septic tank sludges. A comparison of Tables 8A and 8B, shows little difference in the overall removal percentages for the various applicable categories. Since the corrections for septic tank sludge qualities were principally an arithmetic exercise in extrapolation from earlier tests and the data on primary sludges have a much more concrete basis, and because the differences in the final outcome are small, the following discussion pertains to the main flow of primary sludge only.

The chemical oxygen demand of the primary sludge varied between 31,000 mg/l and 84,000 mg/l with an average of 51,260 mg/l. The biological oxygen demand averaged 12,030 mg/l with a low of 4,500 mg/l and a high of 22,500 mg/l. The COD to BOD ratio was 4.3:1. Variations in total, suspended, and volatile suspended solids were from 24,572 to 61,746, 19,032 to 53,388, and 28,817 to 31,478 mg/l, respectively.

The alkalinity of the feed sludge was relatively high at 1,060 mg/l. This value was not due to intrusion into the sewer system of seawater, which has an alkalinity on the order of 100 mg/l. The chloride level in the feed sludge remained comparatively high at 4,535 mg/l. The pH of the feed sludge varied between 5.9 and 6.4.

Digester Mixed Liquor. The digester maintained relatively stable during the period of the test. Tables 8A and 8B present the average constituent concentration and values in the digester and the percentage reductions from the feed source. Since the addition of septic tank sludges into the calculation creates at most one percentage point difference in removal efficiencies, the discussion will include the primary sewage sludge only.

Chemical oxygen demand was reduced by 46 percent while BOD experienced a greater reduction of 84 percent. The resulting COD to BOD ratio for the digested sludge was 14:1. Total solids reductions were not as great as that of suspended solids. Total volatile solids, the principal measure of digestion completeness, were reduced by 36 percent. The volatile suspended solids declined by 41 percent. The change in alkalinity from 1,060 mg/l to 176 mg/l was quite substantial. The chloride content changed little with digestion.

TABLE 8

AVERAGE CONSTITUENT REDUCTIONS AT 22 DAYS DIGESTION

TABLE 8A

Average Constituent Reductions at 22 Days Digestion Based On Primary Sludge Analyses

Constituents (mg/l)

Liquor	COD	BOD	Total Solids	Total Volatile Solids	Suspended Solids	Volatile Suspended Solids	Alkalinity	Chloride	pH	Dissolved Oxygen	Temp. °C
Primary Sludge	51,260	12,030	44,818	31,478	35,463	28,817	1,060	4,535	6.1	-	-
Mixed Liquor	27,701	1,940	36,211	20,200	25,466	16,940	176	4,320	6.9	3.5	26
% Reduction	46	84	19	36	28	41	83	-	-13	-	-

TABLE 8B

Average Constituent Reductions at 22 Days Digestion Based on Primary Sludge Analyses Adjusted for Septic Tank Sludges

Constituents (mg/l)

Liquor	COD	BOD	Total Solids	Total Volatile Solids	Suspended Solids	Volatile Suspended Solids	Alkalinity	Chloride	pH	Dissolved Oxygen	Temp. °C
Feed Sludge	50,235	11,790	43,922	30 848	34,754	28,240	-	-	-	-	-
Mixed Liquor	27,701	1,940	36,211	20,200	25,466	16,940	176	4,320	6.9	3.5	26
% Reduction	45	84	18	35	27	40	-	-	-	-	-

Dissolved oxygen was maintained at a high average of 3.5 mg/l and never dropped below 1 mg/l. Temperature in the digester ranged from 22°C to 28°C during the test.

Nutrients. Primary feed sludge was also analyzed to determine its nutrient content prior to entering the digester. During the test period, primary sludge contained an average of 408 mg/l Kjeldahl nitrogen, 0.4 mg/l nitrate nitrogen, and 233 mg/l total phosphorus. The BOD to nitrogen ratio was 101:1 and the BOD to phosphorus ratio was 220:1. Corresponding nutrient levels in the digester liquor were 1,434 mg/l Kjeldahl nitrogen, 1.2 mg/l nitrate nitrogen, and 215 mg/l total phoshporus.

Oxygen Uptake. Temperatures during the test varied from 22°C to 28°C. Figure 21 indicates only slightly increasing oxygen uptake rates with increasing temperature. Similarly, Figure 22, which expresses uptake rate per mass of solids, also does not present a definitive relationship. The oxygen uptake rate per mass of solids plotted against time in Figure 23 reveals a high utilization rate of approximately 28 mg/(gm)(hr) during the first 30 days of the test and a low rate of approximately 17 mg/(gm)(hr) during the last 30 days of the test.

Primary Plant Treatment The primary sewage treatment plant performed better than average during this test period. Plant operation was improved and equipment failures became less frequent. Suspended solids removal in the primary clarifiers and grit chambers averaged 34 percent, chemical oxygen demand was reduced by 13 percent, and dropped by 16 percent.

TEST 5 -- 15 DAY DETENTION This test was conducted immediately following the 22 day test. All primary and septic tank sludges were added to a single digester which operated at a reduced volume of 330,000 gallons and had an average hydraulic detention period of 14.7 days with an average daily feed rate of 22,525 gallons. This test commenced on November 8, 1971, and terminated March 15, 1972.

Feed Sludge Quality Feed sludge analyses were conducted 3 days weekly on a composite of 6 samples per day. The septic tank sludges were not included in the sampling; however, it has been shown that their contribution is negligible and may be omitted. Table 9 presents the averaged daily feed sludge analyses of samples taken during this test. The chemical oxygen demand varied between 27,400 and 113,000 mg/l. The BOD ranged from 5,400 to 26,900 mg/l, and the COD to BOD ratio was 4:1.

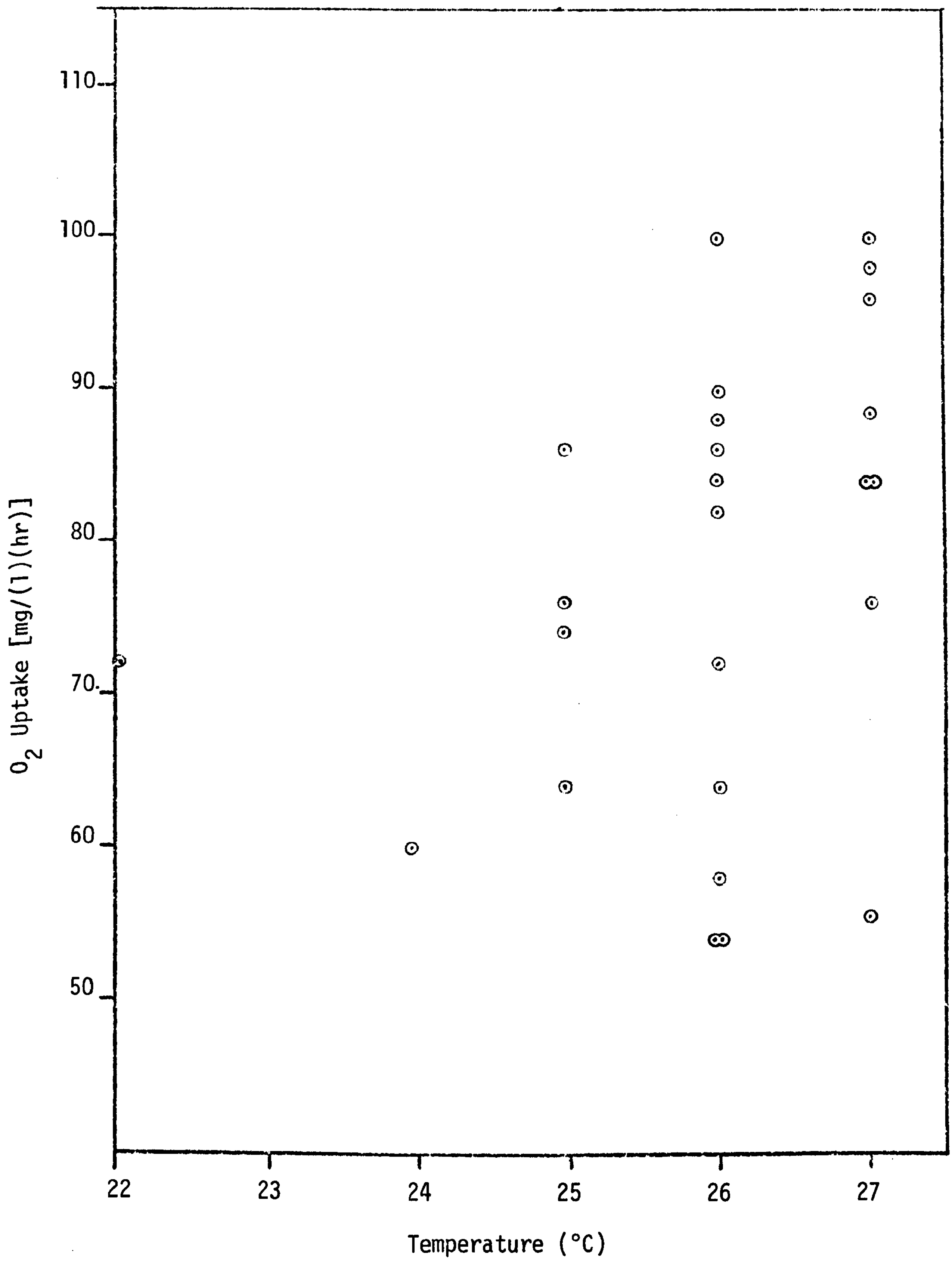

Figure 21. O_2 Uptake Rate [mg/(1)(hr)], 22 Day Digestion

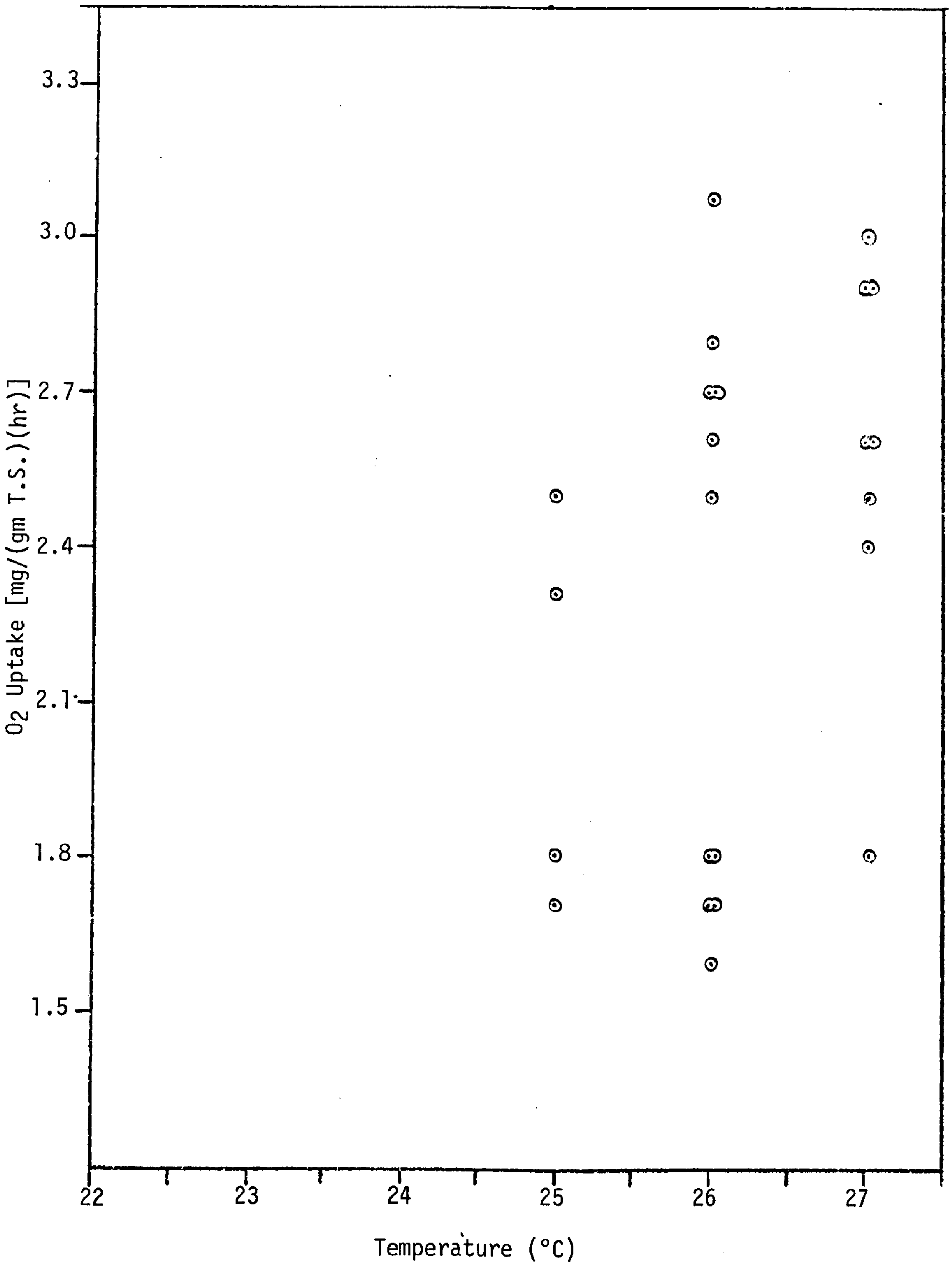

Figure 22. O_2 Uptake Rate [mg/(gm T.S.)(hr)]
22 Day Digestion

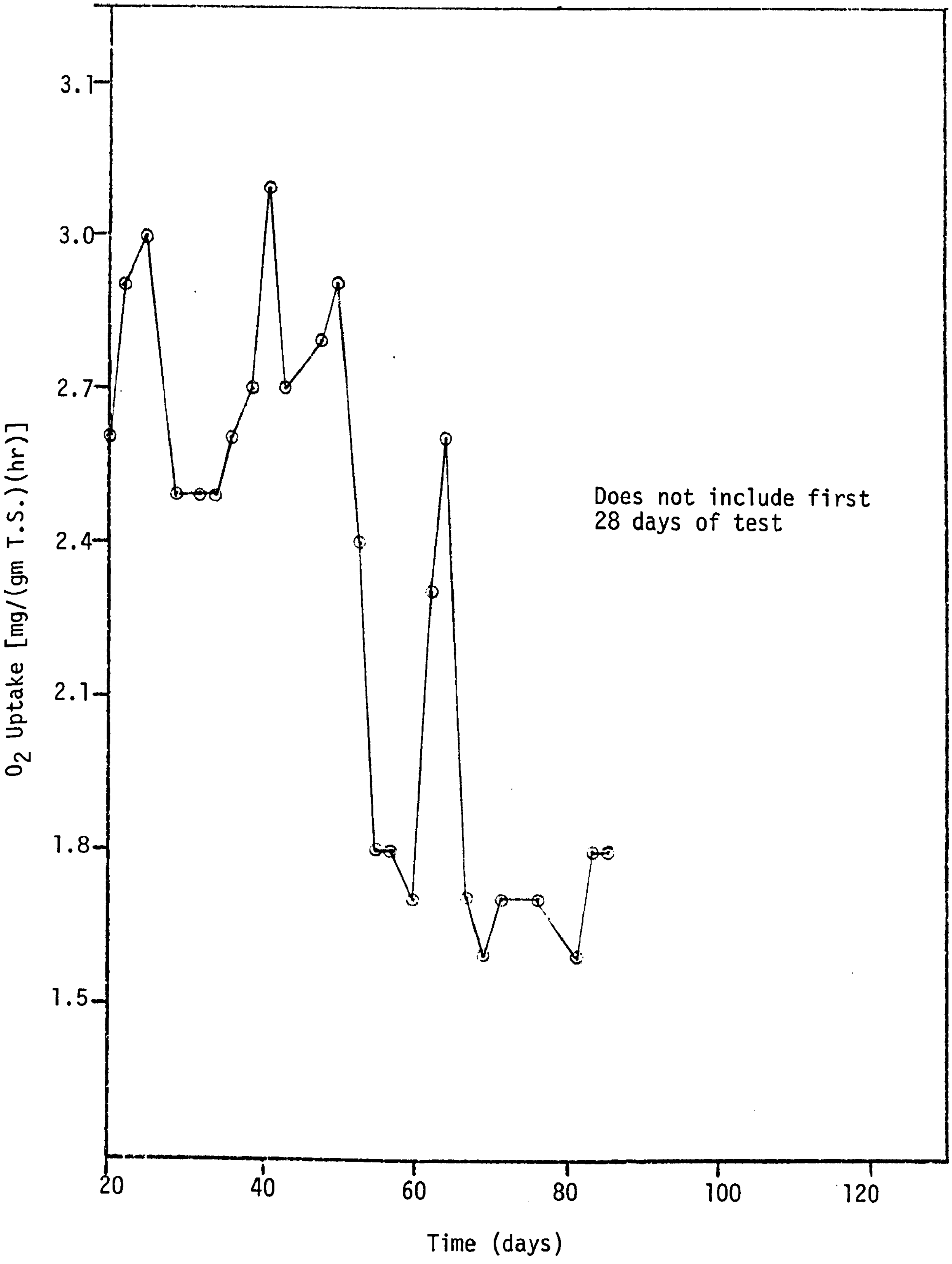

Figure 23. O_2 Uptake Rate [mg/(mg T.S.)(hr)]
22 Day Digestion

TABLE 9

AVERAGE CONSTITUENT REDUCTIONS AT 15 DAYS DIGESTION

Constituents, (mg/l)

Liquor	COD	BOD	Total Solids	Total Volatile Solids	Suspended Solids	Volatile Suspended Solids	Alkalinity	Chloride	pH	Dissolved Oxygen	Temp. °C.
Primary Sludge	63,842	15,994	48,916	36,025	39,536	33,110	1,156	-	5.7	-	-
Mixed Liquor	45,567	5,068	45,959	31,745	38,677	28,312	170	4,277	6.4	2.1	23
Percentage Reduction	29	68	6	12	2	14	85	-	-	-	-

Total solids ranged from 27,554 mg/l to 65,284 mg/l, while suspended solids fell between 21,244 mg/l and 55,034 mg/l. Volatile solids ranged between a low of 18,314 mg/l and a high of 51,418 mg/l. Volatile suspended solids varied from 12,014 mg/l to 40,923 mg/l.

Digester Mixed Liquor To permit stabilization of the digester without unduly affecting performance results, the first 4 weeks of data were discarded. Values included in the averages for digester constituent concentrations in Table 9 were taken only after the digester total solids had risen to 4 percent and appeared to have stabilized. The COD of the feed sludge was reduced by 29 percent and the BOD was reduced by 68 percent. The COD to BOD ratio changed to 9:1. Total solids decreased by only 6 percent but this is offset somewhat by evaporation losses in the digester. Suspended solids decreased by only 2 percent. Total volatile solids were reduced by 12 percent while volatile suspended solids experienced a 14 percent reduction. Alkalinity surprisingly decreased by 85 percent from 1,156 mg/l to 170 mg/l, and the pH increased to 6.4 from 5.7. Dissolved oxygen was maintained at an average of 2.1 mg/l and never dropped lower than 0.7 mg/l. The temperature in the digester varied from 19°C to 26°C.

Oxygen Uptake Rate The oxygen uptake rate was measured at regular intervals during this test and the resulting data are presented in Figures 24 and 25 as a function of temperature. It may be seen that there is little correlation of oxygen uptake rate to temperature. The oxygen uptake rate varied from 86 mg/ (l)(hr) [1.82 mg/(gm)(hr)] to 140 mg/(l) during the initial two weeks of the stabilized test period, but subsequently the rates remained consistently near to 1.0 mg/(l)(hr).

Sludge Dewatering Aerobically digested sludge from the 15 day detention test was placed on a sand bed on January 19, 1972, at a depth of 17 inches. By April 7, 1972, there were 2.75 inches of dried cake on the sand bed. In the interim period the sand bed was exposed to a cumulative total of 6.7 inches of rainfall. During the first four weeks of drying there was a disagreeable odor in the immediate vicinity of the sand bed. Subsequently, no odor was noticed from the drying sludge, except for an earth odor after periods of rainfall. An analysis of the dried sludge from the sand bed revealed the concentrations of phosphorus, Kjeldahl nitrogen, and NO_X nitrogen to be 3.9 mg/gm, 33.4 mg/gm, and 0.023 mg/gm, respectively.

In measuring the filterability of the aerobically digested sludge, specific resistance was determined by means of the Buchner Funnel test. The specific resistance of sludge digested for a 15 day detention period was 5.5×10^8 sec^2/gm.

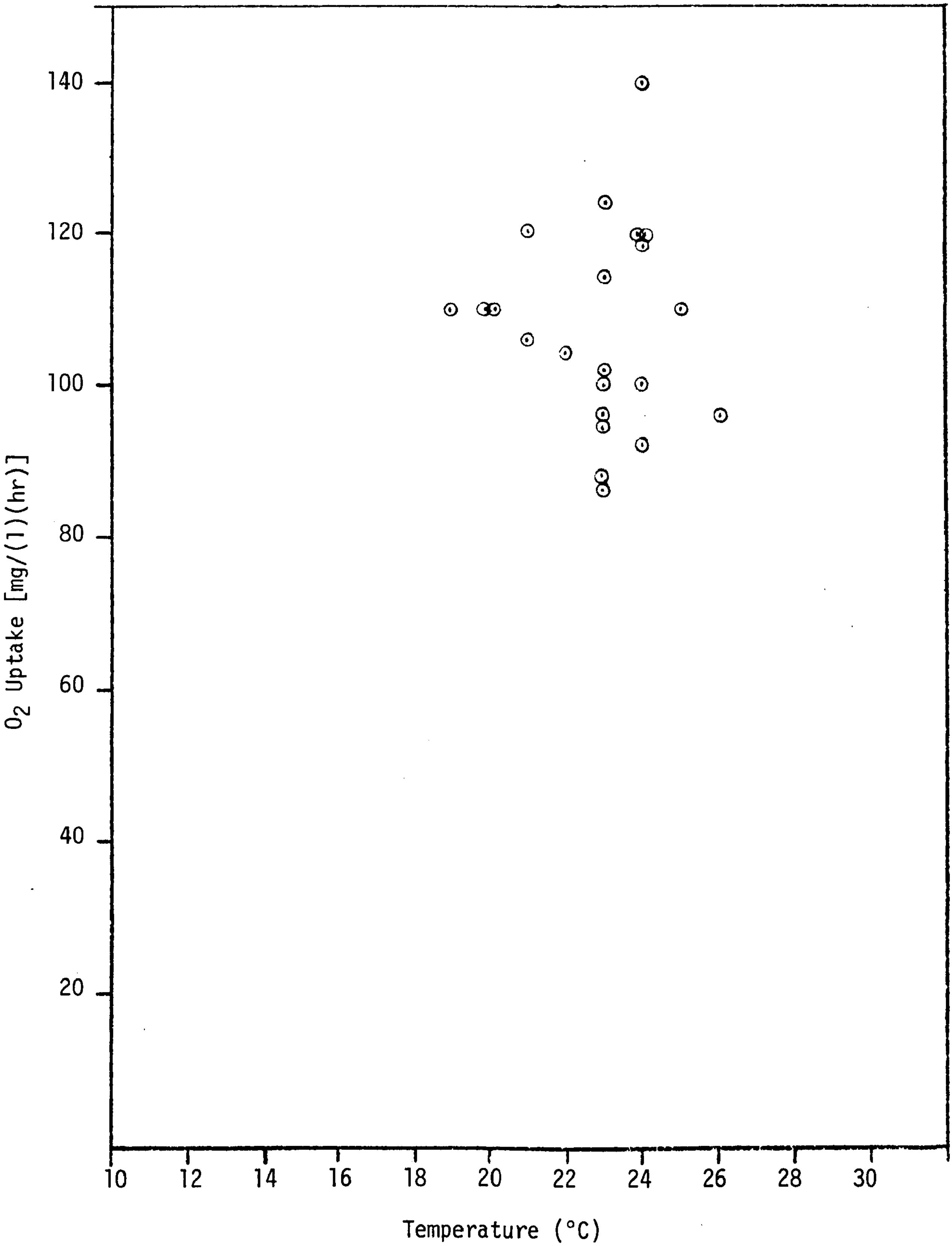

Figure 24. O_2 Uptake Rate [mg/(l)(hr)], 15 Day Digestion

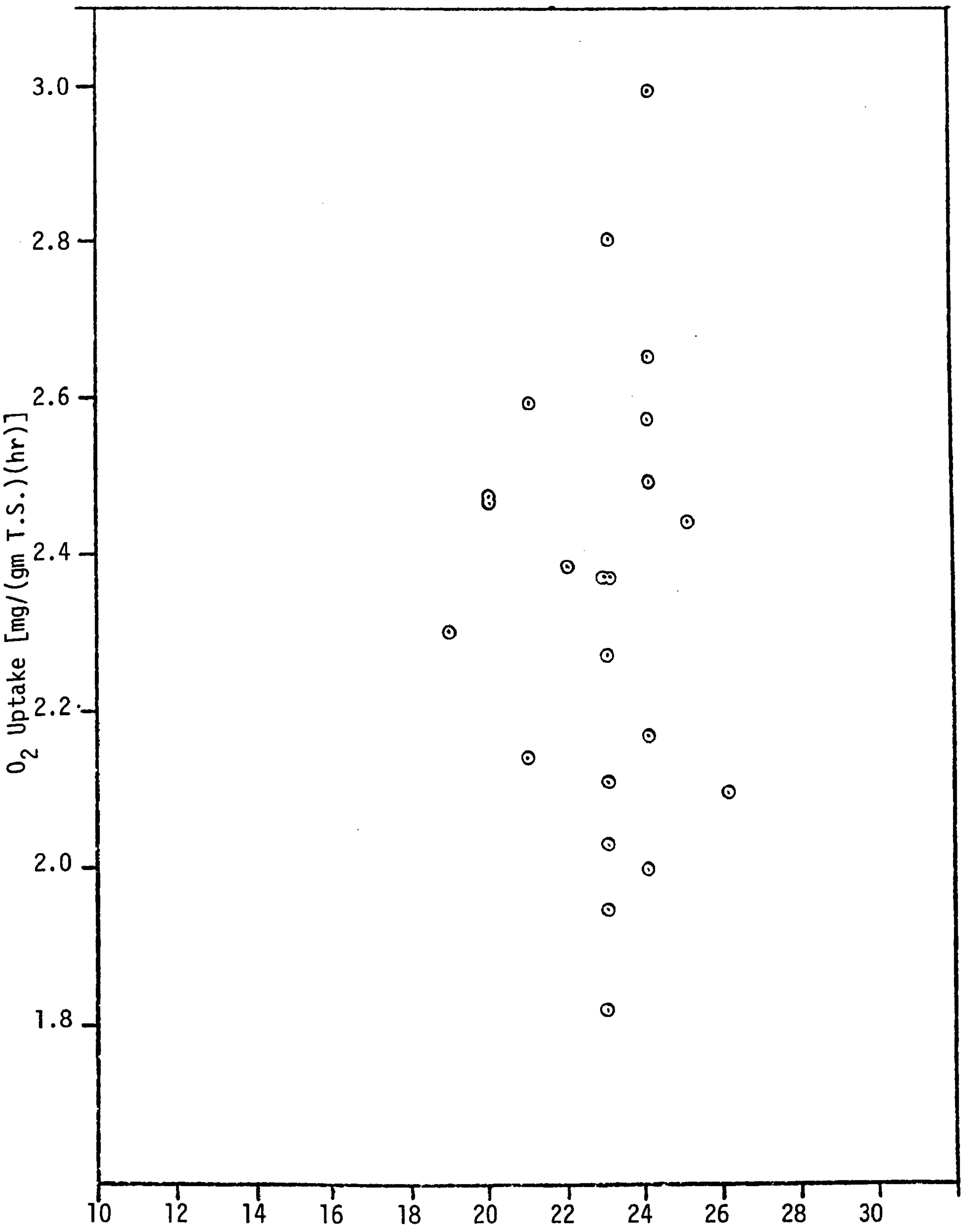

Figure 25. O_2 Uptake Rate [mg/(gm T.S.)(hr)], 15 Day Digestion

Plant Performance Much of the original equipment shakedown had been completed by the time of this test and the primary plant performance had noticeably stabilized. The influent suspended solids of 110 mg/l had been reduced by 35 percent; the biochemical oxygen demand of 141 mg/l had been reduced by 16 percent; and, the chemical oxygen demand reduced 14 percent from 416 mg/l.

TEST 6 -- BATCH DIGESTION On August 4, 1971, a 55 gallon aerobic digester was filled with sludge directly from the primary clarifier and subjected solely to aeration for a period of 23 days. Measurements were taken of the sludge constituents to provide a basis of comparison between batch and continuous aerobic digestion. Table 10 presents the analytical results. There was a definite decrease with time of all the sludge constituents except for chloride which varied about the 4,500 mg/l concentration and was not expected to change. The dissolved oxygen was supplied by an air compressor of fixed output. Dissolved oxygen levels fell from 7.0 mg/l, near the beginning of the test, to 0.5 mg/l during the time of maximum decrease in total volatile solids. By the 23rd day of digestion the oxygen content of the batch had risen to 7.8 mg/l.

All comparisons of sludge constituents hinge on the reduction of volatile solids with time of digestion. Figure 26 presents the reduction in total volatile solids and in biochemical oxygen demand with time. The steepest declines occurred between the 2nd and the 10th day and between the 12th and 14th day of digestion. Relatively stable conditions persisted after the 14th day. A maximum reduction of 63 percent was achieved for total volatile solids after 23 days of aeration. The rapid slowdown in the reduction rates for volatile solids and biochemical oxygen demand after the 14th day of aeration indicates that little biodegradable material remained.

Total and suspended solids also experienced maximum decreases during the first 14 days of aeration. Table 10 shows that after 14 days aeration, most constituent concentrations remained stable with erratic fluctuations that could be attributed solely to the difficulties of obtaining representative sludge samples for analyses.

The oxygen uptake rate of the digesting sludge varied from a high of 114 mg/l at the beginning to an average of 17 mg/l(hr) during the last 11 days of the test. The oxygen uptake rate measured 50 mg/(l)(hr) at the 14th day of operation and fell to 14 mg/(l)(hr) two days later. In terms of oxygen uptake per mass of solids, during the first 14 days of operation the rate varied from 4.5 to 3.1 mg O_2/(gm T.S.)(hr).

Figure 27 depicts the change in alkalinity and pH with respect to time during the batch digestion test. The pH experienced a gradual increase from 6.5 to 8.0 over 23 days. Alkalinity was gradually reduced from 700 mg/l to 240 mg/l, with the majority of the reduction occurring during the first 12 days of operation.

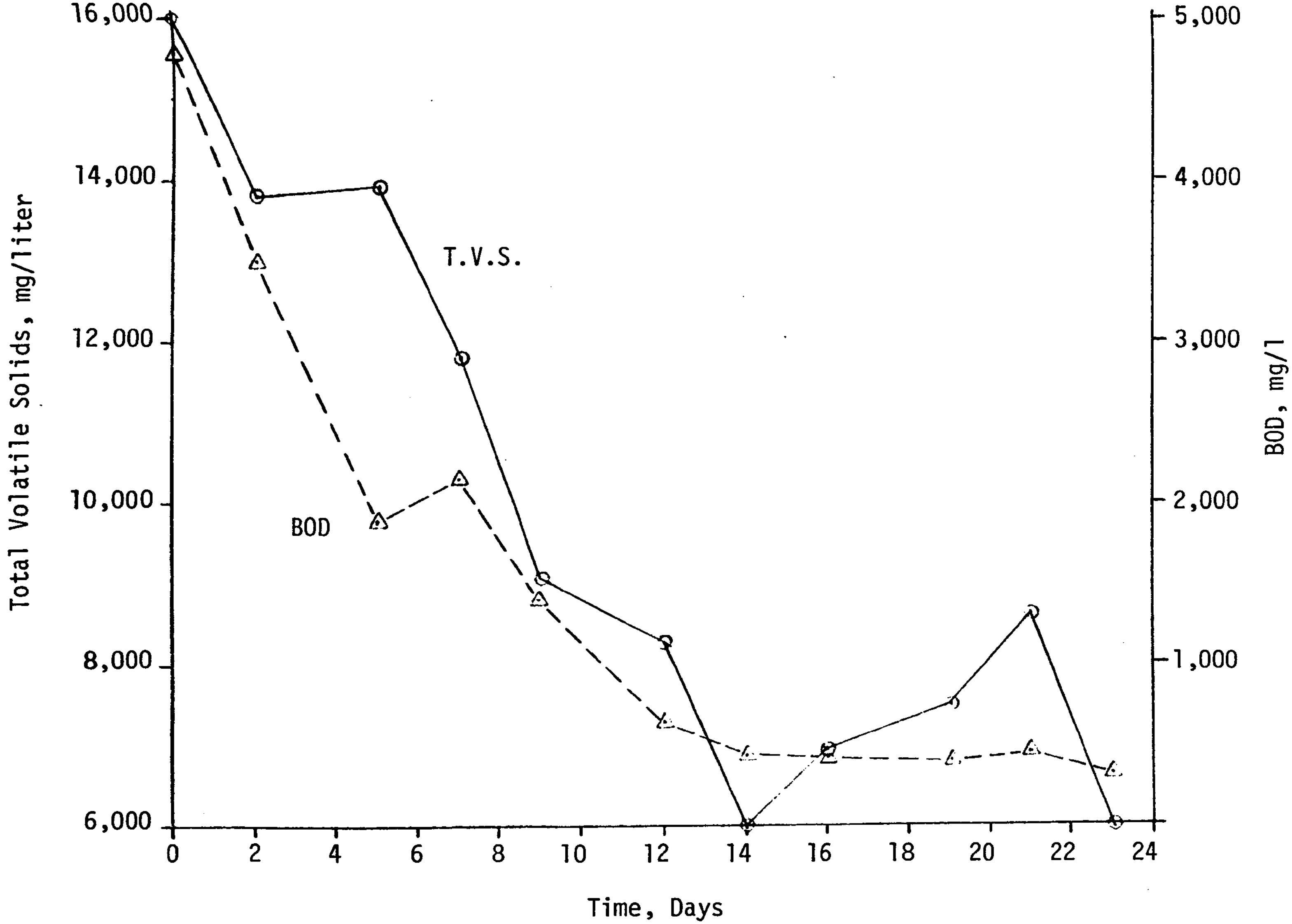

Figure 26. Biological Degradation with Time, Batch Digestion Test

TABLE 10

CHEMICAL ANALYSES OF AEROBIC DIGESTION BATCH TEST

DATE	D.O. (mg/l)	TEMP °C	pH	Cl^- (mg/l)	ALK (mg/l)	BOD (mg/l)	COD (mg/l)	TS (mg/l)	TVS (mg/l)	SS (mg/l)	VSS (mg/l)	O_2* UPTAKE	O_2** UPTAKE
8/04/71	-	-	6.5	4,950	700	4,800	23,000	25,378	16,074	12,702	11,726	114	4.5
8/06/71	7.0	27	7.4	4,250	400	3,500	14,000	21,888	13,784	12,760	11,068	54	2.5
8/09/71	3.4	28	7.3	-	850	1,900	17,100	23,610	13,940	11,466	10,760	70	3.0
8/11/71	1.9	25	7.2	4,450	550	2,150	13,700	20,754	11,792	9,342	8,980	74	3.6
8/13/71	0.5	26	7.4	-	560	1,425	10,350	19,098	9,064	8,812	6,932	-	-
8/16/71	4.9	27	7.4	-	340	675	10,300	16,282	8,296	6,934	5,836	50	3.1
8/18/71	3.4	27	7.5	3,850	420	465	8,000	14,578	5,932	5,504	3,796	14	1.0
8/20/71	5.5	27	7.7	4,100	340	465	8,660	15,774	7,034	6,672	5,134	14	0.9
8/23/71	7.6	27	8.0	-	300	420	9,150	17,598	7,536	8,114	4,336	28	1.6
8/25/71	7.9	27	7.9	5,100	320	470	9,230	18,774	8,646	7,576	7,238	12	0.6
8/27/71	7.8	26	8.0	4,050	240	335	7,280	15,042	5,984	5,670	3,812	18	1.2

*O_2 Uptake expressed in mg/(liter)(hour).

**O_2 Uptake expressed in mg/(gm T.S.)(hour).

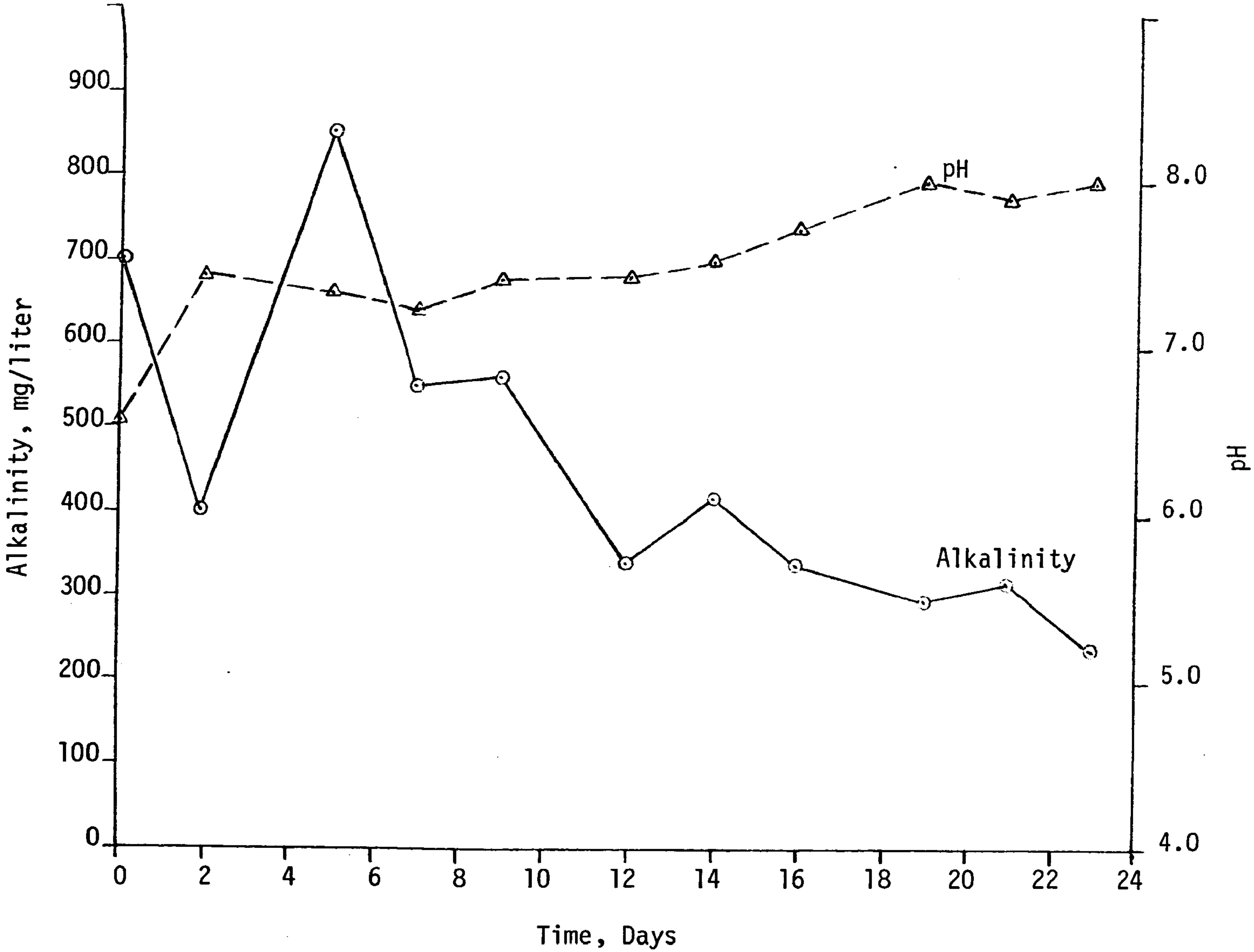

Figure 27. Alkalinity and pH vs. Time
Batch Digestion Test

TEST 7 -- 20 DAY DETENTION A small pilot plant was used to establish test conditions and obtain data that could not be scheduled into the program with the large digester. While there were 3 digesters available to the program, there was sufficient feed to operate only one large digester. A series of tests were conducted to provide correlation between the large and small digesters and to approximate full digestion at 20 days retention. The pilot scale digester, a converted activated sludge plant with a 480 gallon aeration compartment, experienced such vigorous aeration and splashing that the unit could only be operated at a 350 gallon volume. The aerobic digester was fed 17.5 gallons of primary sludge per day. The test lasted 30 days.

Feed Sludge Quality The primary sludge fed to the pilot scale digester was of the same source and quality as fed to the full-scale digester at 15 day digestion. Septic tank wastes were not included. A common set of constituent analyses served both digesters. Table 11 presents the averaged feed sludge qualities for the 20 day digestion test.

The chemical oxygen demand varied from 46,000 mg/l to 113,000 mg/l while the biochemical oxygen demand ranged between 8,400 mg/l and 26,900 mg/l. The COD to BOD ratio of the feed sludge was 4.1:1. Both total and volatile solids concentrations deviated little from their averages. Suspended solids varied between 3 and 5 percent. Volatile suspended solids also stayed near the average of 36,300 mg/l and indicated that the bulk of organic matter was in suspended form. Alkalinity of the primary sludge was 1,200 mg/l. The pH showed little variation from the average of 5.6.

Digester Mixed Liquor Total test duration was one month; however, the first 10 days of data were discarded to allow for stablization of digester operation. Table 11 presents the averaged digester mixed liquor constituent concentrations and the percentage reduction in those concentrations from the feed sludge.

Both chemical oxygen demand and biochemical oxygen demand were significantly reduced while total solids were only slightly decreased. Since no decanting of supernatant was practiced during the test, solids would be expected to increase with losses of water in evaporation and spray. Therefore, it appears that reductions in solids due to digestion just matched the reduction of water in the digester. Suspended solids increased slightly. Total volatile solids averaged a 15 percent decrease while volatile suspended solids were reduced by 17 percent.

The original alkalinity was decreased by 84 percent in the mixed liquor to a concentration of 190 mg/l, although the pH increased slightly to 6.5 mg/l.

TABLE 11

AVERAGE CONSTITUENT REDUCTIONS AT 20 DAYS DIGESTION

Constituents, (mg/l)

Liquor	COD	BOD	Total Solids	Total Volatile Solids	Suspended Solids	Volatile Suspended Solids	Alkalinity	pH	Dissolved Oxygen	Temp. °C
Primary Sludge	74,050	17,880	51,475	39,070	42,505	36,300	1,200	5.6	-	-
Mixed Liquor	38,340	3,740	51,178	33,134	42,841	30,024	190	6.5	4.0	24
Percentage Reduction	48	79	1	15	-1	17	84	-	-	-

Neither dissolved oxygen nor temperature varied significantly during the test.

Oxygen Uptake Rate During the stabilized portion of the test the oxygen uptake rate averaged 84 mg/(l)(hr) or 1.6 mg/(gm T.S.)(hr). Lack of sufficient data prevented a correlation between digester temperature and the oxygen uptake rate of the mixed sludge.

Sludge Dewatering An evaluation of the practicality of any sludge treatment process must include information on sludge dewatering and final disposal. The Buchner Funnel test was performed on aerobically digested sludge withdrawn from the digester during the last day of operation. The calculated specific resistance found by this test was 1.7 x 10^9 $(sec)^2$/gm.

An experiment in sand bed drying of the digested sludge was also conducted. An initial sludge depth of 12 inches was placed over a 3.1 $(ft)^2$ section of a large sand bed. Within the first week of drying the depth dropped to 2 inches but little volume change was observed in the subsequent weeks of the test. Initial surface cracking appeared on the sludge cake within the second week, and at the end of 4 weeks the cake was sufficiently dry for removal from the sand bed. There was no objectionable odor from the sand bed at any time during the test. Rainfall during the period totaled 2.6 inches. The dried sludge contained 4 mg/gm of total phosphorus, 37 mg/gm of Kjeldahl nitrogen, and 0.016 mg/gm of NO_x nitrogen.

Primary Plant Performance Tests conducted with the pilot scale digester were concurrent with the last test in the full-scale digester, i.e. between November 8, 1971, and March 15, 1972. Data for comparable primary plant performance may, therefore, be found in the presentation for Test 5.

TEST 8 -- 14 DAY DIGESTION The pilot plant was also used to obtain data on a 14 day digestion test for correlation with the full-scale digester in this operating range. The aerobic digester was maintained at a 350 gallon volume and was fed 25 gallons of primary sludge daily. Prior to the feeding, 25 gallons of complete mixed sludge were withdrawn to waste. The test lasted 31 days from September 22 through November 22, 1971. The digester had previously been filled with sludge for a "warm up" with a 25 day detention period.

Feed Sludge Quality Averaged results of the feed sludge analyses obtained from the samples collected for the concurrent test in the full-scale digester are presented in Table 12. The daily chemical oxygen demand varied from 27,800 mg/l to 46,000 mg/l. The biochemical oxygen demand gradually increased from 4,500 mg/l to 9,450 mg/l. The COD to BOD ratio was 4.7:1. Total solids fell between 24,572 mg/l and 37,234 mg/l, averaging 29,130 mg/l. Suspended solids changed little. Total volatile solids were about

TABLE 12

AVERAGE CONSTITUENT REDUCTIONS AT 14 DAYS DIGESTION

Constituents, (mg/l)

Liquor	COD	BOD	Total Solids	Total Volatile Solids	Suspended Solids	Volatile Suspended Solids	Alkalinity	pH	Dissolved Oxygen	Temp. °C
Primary Sludge	35,660	7,630	29,130	19,197	22,572	16,560	732	6.2	-	-
Mixed Liquor	15,905	1,080	25,300	13,209	14,733	10,294	250	7.1	4.3	27
Percentage Reduction	55	86	13	31	35	38	66	-	-	-

half of the total solids with a daily average of 19, 192 mg/l. Volatile suspended solids accounted for the bulk of the total solids, with an average concentration of 16,560 mg/l.

Alkalinity of the feed sludge was lower than for most other tests and the pH of the sludge ranged from 6.1 to 6.4.

Digester Mixed Liquor Since the digester had been previously used, it was decided to average performance data over the entire period of the test. Table 12 provides averaged daily mixed liquor constituent concentrations and percentage reductions from the feed sludge.

Oxygen Uptake Rate The oxygen uptake rate of the digester mixed liquor ranged from 34 to 86 mg/(l)(hr) or 1.35 to 3.45 mg/(gm T.S.)(hr). The temperature variation between 25°C and 28°C was too small to provide a meaningful variation in the oxygen uptake rate. The rate was probably more strongly influenced by the nature of the sludge fed for any day. The average uptake rate was 52 mg/(l)(hr) or 2.1 mg/(gm T.S.)(hr).

TEST 9 -- 10 DAY DIGESTION Test 9 was conducted with a 10 day digestion period in an effort to ascertain the minimum acceptable digestion time for the primary sludge at the City of Hollywood. The 350 gallon pilot scale aeration tank was fed 35 gallons per day of primary sludge while a similar amount of mixed liquor was withdrawn prior to each feeding. The test was conducted for a period of 30 days following a 10 day stabilization period. Prior to the test the digester had been used for a 5 day retention test and contents were not removed between tests.

Feed Sludge Quality Both the pilot and plant scale digesters were fed the same sludge. Averaged daily analyses are presented in Table 13. Chemical oxygen demand varied from 40,200 mg/l to 85,700 mg/l, and biochemical oxygen demand varied from 10,650 mg/l to 23,400 mg/l. The COD to BOD ratio was 3.8:1.

Total solids varied by almost 100 percent between 33,916 mg/l and 60,756 mg/l. Suspended solids constituted a large part of the total solids with a large range between 24,926 mg/l and 50,586 mg/l. Volatile solids ranged from 22,508 mg/l to 46,228 mg/l, while volatile suspended solids ranged from 20,860 mg/l to 43,158 mg/l.

Digester Mixed Liquor The mixed liquor constituents were relatively unchanged. The averages of the mixed liquor analyses and the percentage reduction of the various constituents are presented in Table 13. Chemical oxygen demand was reduced by 54 percent and biochemical oxygen demand was reduced by 84 percent. The COD to BOD ratio became 11:1.

TABLE 13

AVERAGE CONSTITUENT REDUCTIONS AT 10 DAYS DIGESTION

Constituents, (mg/l)

Liquor	COD	BOD	Total Solids	Total Volatile Solids	Suspended Solids	Volatile Suspended Solids	Alkalinity	pH	Dissolved Oxygen	Temp. oC
Primary Sludge	52,147	13,690	45,679	32,399	35,816	29,505	1,100	5.9	-	-
Mixed Liquor	24,025	2,188	33,846	20,533	24,822	17,054	240	6.7	3.9	25
Percentage Reduction	54	84	26	37	31	42	78	-	-	-

Oxygen Uptake Rate The oxygen uptake rate varied between 48 mg/(l)(hr) [1.6 mg/(gmT.S.)(hr)] and 76 mg/(l)(hr) [2.5 mg/(gm T.S.)(hr)]. The lower oxygen uptake rates occurring toward the end of the test indicated some relationship of the uptake rates with varying strength or age of sludge. This relationship nullifies the value of temperature-uptake comparisons.

Sludge Dewatering When placed on a sand bed, the digested sludge dewatered rapidly from an initial depth of 12 inches to a final depth of 2 inches within one week. At the end of 4 weeks the sludge could be removed from the bed. There was a disagreeable foul odor from the drying sludge during the 4 weeks; however, rainfall on the sand bed totaled 9 inches over the drying period.

A Buchner Funnel test showed a specific resistance of 6.08 x 10^8 sec^2/gm in the digested sludge.

Dried sludge was removed from the sand bed and analyzed for nutrient content. The following concentrations were measured: 1.2 mg/gm of phosphorus; 17.8 mg/gm of Kjeldahl nitrogen; and 0.065 mg/gm of NO_x nitrogen.

TEST 10 -- 5 DAY DIGESTION Test 10 had the shortest detention time of all tests conducted in the program. The 350 gallon pilot scale digester was fed 70 gallons of primary sludge per day. The same quantity of mixed liquor was removed on a daily basis. This test was conducted for 36 days.

Feed Sludge Quality Table 14 presents a tabulation of averaged daily values for constituents of the feed sludge. The reduction in chemical oxygen demand was 40 percent and the biochemical oxygen demand fell by 80 percent. The COD to BOD ratio increased to 12:1.

Oxygen Uptake Rate The average oxygen uptake rate was 86 mg/(l)(hr) or 2.0 mg/(gm T.S.)(hr). The uptake rate was considerably lower in the beginning when the digester still contained sludge from the 20 day detention test.

Sludge Dewatering Sludge dried as well on a sand bed as in the 10 day digestion test. A 12-inch initial depth of sludge dropped to two inches within one week of drying. Within 4 weeks of drying the sludge was well dried and could be removed from the sand bed. Cumulative rainfall was 5.4 inches. During the first 2 weeks there was a noticeable foul odor from the cake, but by the end of the 4th week the odor had disappeared. Using a digested sludge sample containing 2.7 percent total solids, the measured specific resistance was 2.32 x 10^8 sec^2/gm. When dried sludge was removed from the sand bed, a sample was retained for nutrient analyses. The weight concentrations of nutrients in the dried sludge were 1.21 mg/gm, 16.1 mg/gm, and 0.08 mg/gm for total phosphorus, Kjeldahl nitrogen, and NO_x nitrogen, respectively.

TABLE 14

AVERAGE CONSTITUENT REDUCTIONS AT 5 DAYS DIGESTION

CONSTITUENTS (mg/l)

Liquor	COD	BOD	Total Solids	Total Volatile Solids	Suspended Solids	Volatile Suspended Solids	Alkalinity	pH	Dissolved Oxygen	Temp. °C
Primary Sludge	64,500	16,050	50,670	37,564	40,709	34,305	1,100	5.6	-	-
Mixed Liquor	38,680	3,213	42,420	27,522	33,441	24,159	208	6.5	3.2	26
Percentage Reduction	40	80	16	27	18	30	81	-	-	-

SECTION VII

DISCUSSION OF RESULTS

CONSTITUENT REDUCTIONS Average feed sludge total solids varied, with one exception, in a narrow range between 45,000 mg/l and 61,000 mg/l. Other constituents varied similarly, and except for the 14 day test which had low feed sludge constituent concentrations, all tests were begun with a similar feed.

There was no discernible relationship between initial sludge constituent concentrations and percentage reductions although there was some relationship between initial and final sludge constituent concentrations. Therefore, a basis of percentage reductions was used for data comparison to make the information of the project more universally applicable.

The averaged constituent reductions for each test are presented in Table 15. In comparison with the total mass of available data, it appears that the results of the 23 to 29 day digestion test are atypical, but such performance may be expected at times in a digester. Reductions in chemical oxygen demand ranged from 17 to 55 percent. No direct correlation could be made between COD reduction and digestion period. The high reduction of 55 percent appeared in a 14 day digestion test, while the next to lowest reduction of 29 percent occurred during the 15 day digestion test. The reduction in BOD also could not be correlated with the length of the digestion period. It was reduced by a low 68 percent in the 15 day digestion test, by 86 percent in the 14 day digestion test, and by 92 percent in the 43+ day digestion test.

Difficulties also resulted when an attempt was made to analyze the solids data for a relationship between percent reductions and aeration period. Total solids were reduced from 1 percent in the 20 day digestion tests to 26 percent in the 10 day digestion test. Volatile solids reductions also fluctuated widely between 12 percent at the 15 day digestion test and 39 percent at the 29 day digestion test. Suspended solids decreases varied from minus 1 percent to 35 percent while volatile suspended solids reductions fell between 14 and 42 percent.

It appears from these data that an exact correlation between constituent reduction and period of digestion cannot be made. However, in Table 10, where the results of the batch digestion test are presented, it is obvious that there is a gradual reduction in constituent concentrations with increased digestion time. A clue to the discrepancies in the data, and perhaps even in the uniqueness of the 23 to 29 day digestion test, lies in the differences between the total volatile solids reductions.

TABLE 15

COMPARISON OF AVERAGE CONSTITUENT REDUCTIONS

Digestion Period (days)	Concentration Reduction, %					
	COD	BOD	Total Solids	Volatile Solids	Suspended Solids	Volatile Suspended
43+	45	92	16	38	---	---
23 - 29	18	70	3	13	---	---
29	42	83	22	39	30	41
22	46	84	19	36	28	41
20	48	79	1	15	-1	17
15	29	68	6	12	2	14
14	55	86	13	31	35	38
10	54	84	26	37	31	42
5	40	80	16	27	18	30

During the 20 day digestion test there was a 1 percent reduction in total solids and a 1 percent increase in suspended solids. This compares to a 15 percent reduction in volatile solids and a 17 percent decrease in volatile suspended solids. A major factor that could explain such differences in reductions is evaporation of the digester water, which during a 5, 10, or 40 day period can substantially concentrate the remaining sludge constituents. This could even cause an increase in suspended solids. Varying evaporation rates on sunny, cloudy, or rainy days could affect minor differences in digested sludge concentration and thereby confuse comparisons between reductions and digestion periods. Actual reductions of constituent concentrations were, therefore, probably substantially greater than is presented in the data. Estimated evaporation rates of 20 to 25 percent during a 20 day detention test would reconcentrate remaining sludge constituents and decrease percentage reductions. The lack of readily available sludge metering equipment has been mentioned previously as the reason for comparing constituent concentration rather than total mass changes. Furthermore, the parameters measured in this study are essentially the same ones measured by other treatment plant operators who must relate data to final sludge quality under the same environmental factors encountered in this study, i.e., evaporation, rainfall, and temperature changes.

Other factors also influence differences in the reduction between total solids and volatile solids. Oxidation and digestion of volatile matter are accompanied by the creation of an inert residue which is measured as total solids.

In Test 6, where a single batch of sludge was digested over an extended period, digestion and reduction of constituents were essentially completed within a period of 14 days. The aerobic digestion batch test was conducted under the same conditions of liquid evaporation as were the tests in the pilot and full-scale digesters.

Proceeding under the assumptions that essentially all digestion would be completed by the 14th day of aeration and that subsequent aeration would not significantly change sludge concentrations, the average reductions for all tests between 14 and 43 days digestions were averaged together. The average effluent from an aerobic digester treating primary sewage sludge at and above a minimum hydraulic retention period of 14 days would be 40 percent lower in chemical oxygen demand, 80 percent lower in biochemical oxygen demand, 11 percent lower in total solids, 26 percent lower in volatile solids, 19 percent lower in suspended solids, and 30 percent lower in volatile suspended solids than undigested primary sludge. These averages reflect seasonal changes in population loading, rainfall, and temperature due to the extended test periods involved.

The excessively long detention periods of the 43+ day digestion test were unnecessary in achieving acceptable digested primary sludge. Two-stage digestion as performed in that test was unnecessary except to achieve the long detention period. Two-stage digestion is employed at times in sewage treatment plants that also aerobically digest waste activated sludges.

These sludges frequently have poor settling characteristics and would require large digester volumes for adequate retention periods. A short period of digestion in the first stage of approximately 5 days permits sludge thickening in the second digester which, with decanting or a separate thickening facility, may be constructed at a reduced volume to achieve the same loading rate. The primary digested sludges encountered in this program did not thicken in settling tests and became anaerobic within several hours of the start of such tests. For these reasons, thickening was not practiced in a digester except during some start up periods where there had been an initial charge of groundwater to the digester.

As stated previously, daily feed to the full scale digesters was measured by means of time clocks on the sludge pumps, but there was no accurate way of measuring wasted sludge volumes. Attempts were made to measure volumetric changes within the digester, but were found to be unsatisfactory. Therefore, with the lack of reliable information concerning sludge discharge and rainfall/evaporation effects on the full scale digesters, an attempt was made to develop a mass balance for the pilot plant aerobic digestion studies.

The pilot plant studies consisted of four tests conducted at detention times of 5, 10, 14, and 20 days with a constant reacter volume of 350 gal. A cover was placed over the unit to reduce liquid loss by evaporation and spray. Measurements were made of total solids (TS), total volitile solids (TVS), suspended solids (SS), and volitile suspended soilds (VSS) in the sludge feed and in the reacter.

It would be expected that the reduction of each of the parameters would increase with detention time. In Figure 28 each of the parameters is plotted against detention time, and an increasing reduction is indeed indicated through a detention time of 10 days; however, after 10 days the percent reduction decreases. This would indicate that a concentration effect occured which must be attributed to evaporation loss. It can be assumed that if evaporation could be taken into account and negated, the curves in Figure 28 would have steeper slopes and would not develop negative slopes.

Obviously, since the reactor volume was maintained at 350 gallons in all cases, either the volume of feed or the volume of sludge removal (or both) had to be varied accordingly to compensate for evaporation loss. However, the records indicate merely that 350/t gall were removed and added each day for each test. Unfortunately, it was not anticipated at that point in time that more accurate volume measurements would be desirable.

SLUDGE DEWATERING Sludges resulting from the aerobic digestion of primary sludge were tested and analyzed to determine minimum acceptable digestion times for a stable, odor free waste. Digested sludges were vacuum filtered and the rate of water removal gave an indication of dewatering characteristics. Digested sludges were also placed on sand beds where drying times and odor characteristics were noted. The combined data was used to evaluate a minimum digestion retention time. Additional data was collected on simulated lagooning of single batches of aerobically digested sludge.

Filterability Filterability of digested and undigested sludges was measured to determine which sludges would be more suitable for mechanical dewatering devices. Specific resistance, a quantity calculated from measurements of the liquid volume passing through a filter cake, was used as the comparative index for the various sludges. The specific resistance is numerically equal to the pressure difference required to produce a unit rate of filtrate flow of unit viscosity through a unit weight of cake. Calculated specific resistances for the 20, 15, 10, and 5 day digestion tests were 1.7×10^9 $(sec)^2/gm$, 5.6×10^8 $(sec)^2/gm$, and 2.3×10^8 $(sec)^2/gm$, respectively. The values span one order of magnitude and are substantially less than the specific resistance of primary undigested sludge which was measured to have a specific resistance of 4.2×10^{10} $(sec)^2/gm$. The greatest reduction in specific resistance was by a factor of 182 in the 5 day digestion test and the least measured reduction was by a factor of 25 in the 20 day digestion test.

Studies performed by Jones[20] on the filterability of anaerobically digested sludges provide interesting comparison of data. Anaerobically digested sludge was measured to have a specific resistance of 2.05 $\times 10^{10}$ $(sec)^2/gm$ which is half of the specific resistance of the primary sludges in this study and substantially more than the specific resistances of the aerobically digested sludges. Only with the aid of polymers was Jones able to lower the specific resistance of anaerobically digested sludges to values between 1.53×10^8 $(sec)^2/gm$ and 3.69×10^7 $(sec)^2/gm$.

It would appear that aerobically digested primary sludges are much more amenable to dewatering by filtration than either primary sludges or anaerobically digested primary and waste activated sludges, and that shorter aerobic digestion periods produce sludges with lower specific resistances than do longer periods.

Sand Bed Drying Sand bed drying is one of the most commonly used methods of sludge dewatering due to its simplicity and ease of maintenance. Sand bed tests were conducted on waste sludges from 20, 15, 10, and 5 day digestion tests. Sludge from the 15 day test in the full-scale digester was placed to a depth of 17 inches on a large sand bed. Sludges from the 20, 10, and 5 day digestion tests, conducted in the pilot scale digester, were placed in opened bottom, 55 gallon drums, set at least six inches into a standard, underdrained sand bed. The digester sludge from the 15 day test took approximately 11 weeks to dry to a well cracked cake. The sludge from the 15 day test, however, had experienced relatively low removal of constituents during digestion. Objectionable odors noticed in the immediate vicinity of the sand bed might be attributable to inadequate digestion.

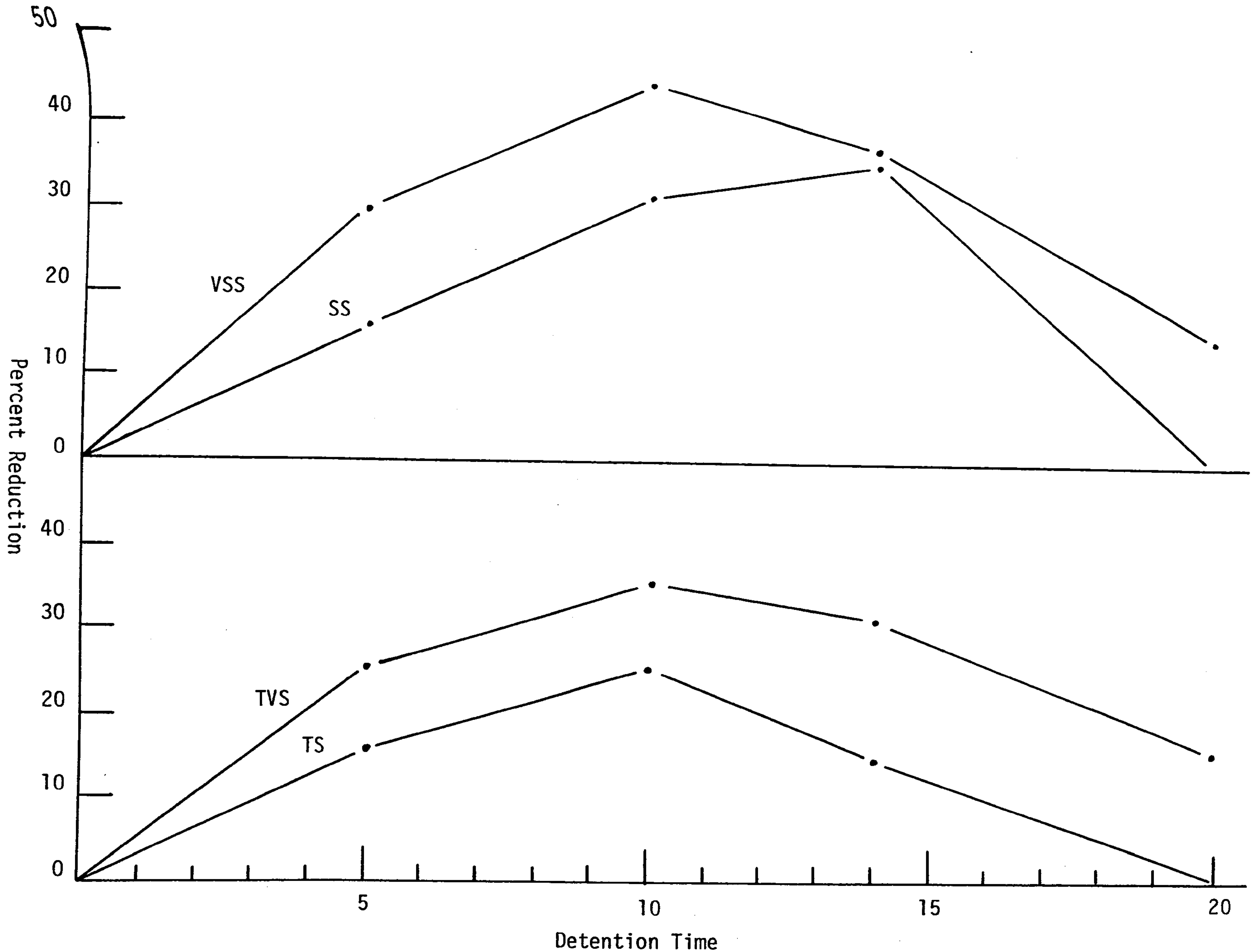

Figure 28. Percent Removal of Solids Versus Detention Time, Pilot Plant Studies

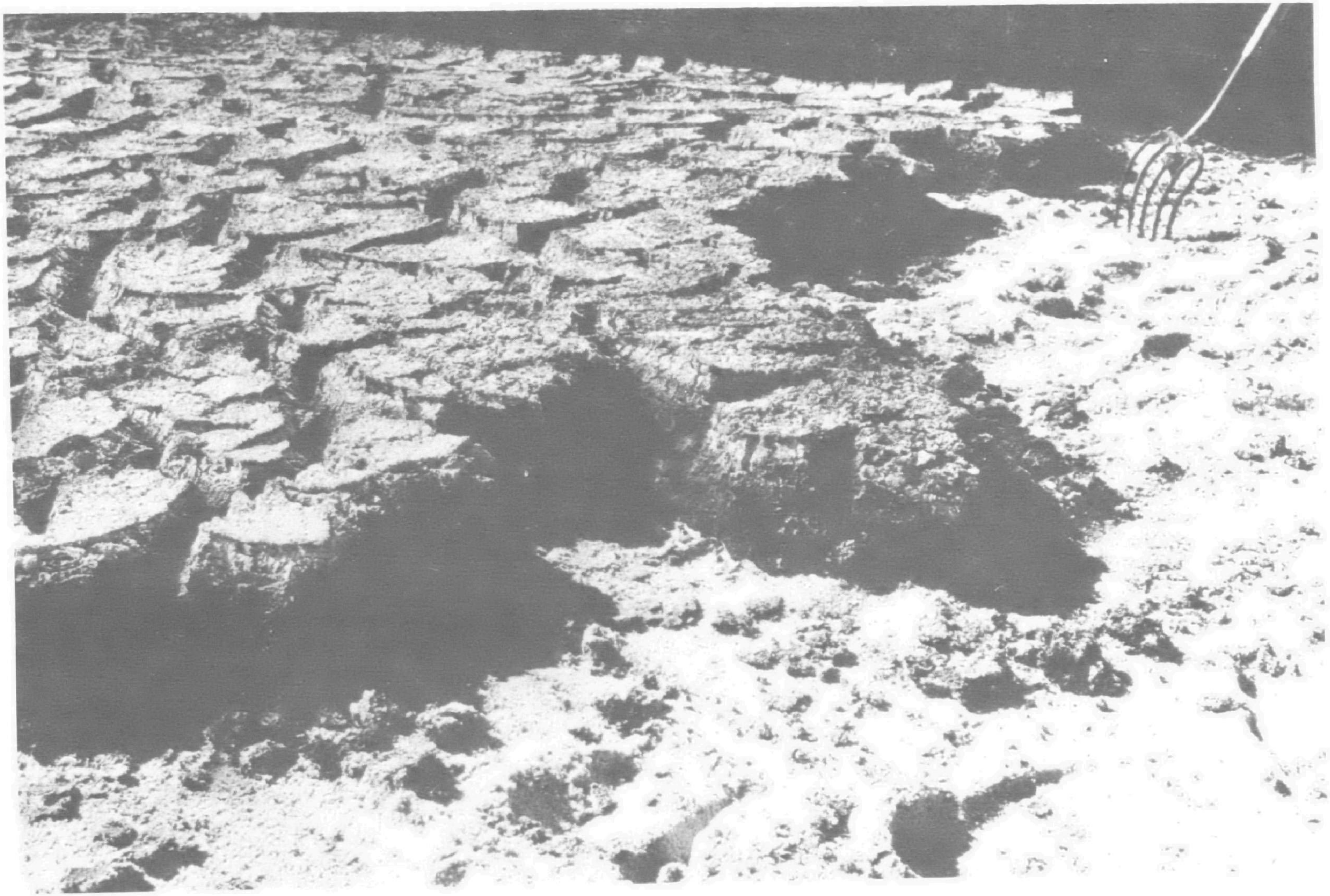

FIGURE 29: A DOUBLE BED OF DRIED, WELL CRACKED AEROBIC SLUDGE

TABLE 16

CHEMICAL ANALYSES OF LAGOONED SLUDGES

Digester Retention	Sample	Days Lagooned	Volume (liter)	Constituents, grams: COD	BOD	Total Solids	Volatile Solids	Suspended Solids	Dissolved Solids	Volatile Dissolved
5 Day	Outdoor	0	15.1	625.3	60.6	663.3	429.2	536.4	144.5	46.3
		70	7.6	367.2	31.8	413.1	230.2	329.0	121.0	20.6
		Decrease		41 %	48 %	38 %	46 %	39 %	16 %	56 %
	Indoor	0	3.5	144.6	14.0	153.3	99.2	124.0	33.5	10.7
		70	1.9	91.8	8.0	107.7	58.6	96.2	30.9	5.2
		Decrease		37 %	43 %	30 %	41 %	22 %	8 %	51 %
10 Day	Outdoor	0	15.1	590.5	40.1	613.5	402.4	506.1	146.9	40.1
		51	10.4	356.0	41.4	438.3	250.8	333.7	125.3	23.7
		Decrease		40 %	-3%	29 %	38 %	34 %	15 %	41 %
	Indoor	0	3.5	136.5	9.3	141.8	93.0	117.0	34.0	9.3
		51	2.5	114.0	10.2	127.8	73.6	104.5	32.2	3.8
		Decrease		16 %	-10 %	10 %	21 %	11 %	5 %	59 %
15 Day	Outdoor	0	15.1	635.9	68.1	702.3	477.0	607.7	167.2	45.6
		70	7.6	418.7	36.3	443.5	261.9	356.9	92.9	20.0
		Decrease		34 %	47 %	37 %	45 %	41 %	44 %	56 %
	Indoor	0	3.5	147.0	15.8	162.3	110.3	140.5	38.6	10.5
		70	2.1	115.0	10.3	124.3	73.0	107.9	25.0	5.0
		Decrease		22 %	34 %	23 %	34 %	23 %	35 %	53 %
20 Day	Outdoor	0	15.1	620.8	49.6	814.7	513.2	672.4	190.1	54.9
		33	16.1	569.5	31.4	643.4	366.5	502.1	136.6	25.4
		Decrease		8 %	37 %	21 %	29 %	25 %	28 %	54 %
	Indoor	0	3.5	143.5	11.5	188.3	118.6	155.4	43.9	12.7
		33	2.7	134.7	9.5	166.0	93.4	140.1	34.5	3.5
		Decrease		6 %	17 %	12 %	21 %	10 %	22 %	73 %

The sand bed drying of pilot plant sludges was performed in a restricted sand bed area due to the small volumes of sludge available from the digester. The sludges from the 20, 10, and 5 day digestion tests dewatered rapidly and could be removed from the sand beds within 4 weeks. Of these three, only the 5 day digestion period sludge exhibited odors in the immediate vicinity of the sand bed and these odors disappeared by the 4th week. In view of the fact that the filterability of the 15 day digestion sludge was similar to that of the other sludges, it is probable that water retention in the 15 day sludge was due to a poor sand bed underdrain system. When allowed to drain rapidly in a vertical and somewhat horizontal direction as in the 55 gallon sand beds, the aerobically digested sludges dewatered very well with as little as a 10 day digestion period.

Chemical analyses of the nutrient value of aerobically digested, sand bed dried sludges indicated very little mineral fertilizer content. Analyses were conducted on the 5, 10, 15, and 20 day digestion sludges. The Kjeldahl nitrogen varied between 16.1 and 36.8 mg/gm of dried sludge. The nitrate forms of nitrogen were from 0.016 to 0.08 mg of N/gm of dry sludge. With the exception of the nitrate and nitrite forms, increased sludge digestion periods resulted in dried sludges of greater nutrient content.

Figure 29 shows a well dried, odor free sludge that was obtained by spreading a double layer of wet sludge on a sand bed.

<u>LAGOONING OF DIGESTED SLUDGES</u> Due to the identical physical behavior of all sludges tested under simulated lagooning, the data from all the lagooning tests have been compiled in this section. At the end of the 5, 10, 14, and 20 day digestion tests, the digested sludges were placed both in containers located outdoors and in others in the laboratory. Observations were made of the sludge condition with passing time and analyses were conducted on the samples at the end of the lagooning tests.

Table 16 presents detailed chemical analyses of the digested lagooned sludges. Lagooning time for each sample varied due to decreasing available time at the end of the program. In all samples except the 20 day digestion outdoor sample, there was a total decrease in liquid volume with a slight corresponding increase in most constituent concentrations. The net effect of lagooning was a reduction in almost all absolute quantities of constituents. Reductions were generally greater for the 5 day digested sludges than for the 10, 15, and 20 day sludges. This is partially due to the longer lagooning period of 70 days on the 5 day test, but also to the fact that 5 day digested sludge has a greater content of unstabilized organic material than do the other sludges.

During the lagooning tests common physical behavior was noted for all the samples, both outdoor and indoor. During the first several days, an inversion resulted in all sludge solids rising to the surface where they hardened and formed a crusty cake. At the very surface of the cake, aerobic decomposition occurred, giving a tan to light brown color to the cake. However, below the surface the sludge cake turned black and within a week, gases producing obnoxious odors broke through and persisted throughout the remainder of the tests. After approximately one week the solids at the bottom of the sludge cake began to fall to the bottom of the container. These solids were light and no compaction was noted at the bottom of the container. Eventually the entire volume of the liquid under the sludge cake was occupied by the light solids. After 45 days of lagooning the surface sludge cake broke up into discrete particles. A considerable amount of obnoxious odor was noted at this time. The sludge at the end of the test was a very black, odorous liquor with finely dispersed solids. Several species of flies were continually attracted to the samples during the test. The flies laid viable eggs and produced many larvae.

The simulated lagooning of aerobically digested sludge indicated that a better reduction of sludge constituents occurred in the outdoor containers than in the laboratory containers. In all probability, external factors such as wind and rain achieved a degree of mixing in the outdoor containers that was absent in the laboratory. Warmer daytime temperatures also occurred in the outdoor samples than in the air conditioned, laboratory samples and provided a stimulus for greater biological activity.

Varying lagoon detention periods confuse a comparison of sludge changes from the lagooning of 20, 15, 10, and 5 day sludges. The two samples of the 15 and 5 day digestion sludges were lagooned for an equal period of time. Table 16 shows little difference in reduction of 5 day sludge constituents and 15 day sludge constituents over a 70 day lagooning period. The comparative reduction for the 5 and 15 day sludge outdoor test are: 41 percent vs. 34 percent of chemical oxygen demand; 48 percent vs. 47 percent of biochemical oxygen demand; 38 percent vs. 37 percent of total solids; 46 percent vs. 45 percent of volatile solids; 39 percent vs. 41 percent of suspended solids; 16 percent vs. 44 percent of dissolved solids; and 56 percent vs. 56 percent of volatile dissolved solids. Slightly greater differences were noted in the indoor lagooned samples for the two retention period tests.

The outdoor lagoon samples of all the various test periods contained similar initial quantities and concentrations of sludge constituents. In view of the fact that these sludges were in an advanced stage of auto-oxidation and probably had similar predominant organisms and chemical compound forms, the data from the 5, 10, 15, and 20 day digestion tests were combined for an analysis of constituent change upon sludge lagooning. The percentage change in absolute quantities of constituents with lagooning time may, therefore, be compared for the various sludges.

Figure 30 shows these changes plotted as a function of time. It appears that the rate of change in organic constituents represented by chemical oxygen demand, biochemical oxygen demand, and volatile solids , tapers to a low value after approximately 70 days of lagooning.

As previously mentioned, lagooning of aerobically digested sludges was accompanied by a surface seal of floating sludge cake while anaerobic decomposition occurred below the sludge cake. Escaping gases from this anaerobic digestion produced noxious odors. It is possible that in a large scale lagoon there would be adequate wind induced turbulence to prevent such a cake from forming and to provide substantial mixing within the lagoon. The possibility exists that such a lagoon would not become anaerobic and/or would not release strong objectionable odors.

MONITORING PARAMETERS Much previous research, particularly that conducted on laboratory aerobic digestion of single sludge batches, has raised the question of finding a process parameter, the monitoring of which would provide the plant operator with information of the efficiency or degree of digestion of the sludge. Process parameters mentioned for possible consideration were pH, alkalinity, and oxygen uptake rate. These parameters may be relatively quickly obtained while others such as reduction of chemical oxygen demand or total volatile solids require more time and elaborate procedures.

This study has monitored pH, alkalinity, and oxygen uptake rates for most of the digestion tests including a reference batch test. It was found that there were definite changes in these indicators between digested and undigested samples. Alkalinity of primary sludge averaged 1,092 mg/l. Sludges digested for 15 days and longer had alkalinities less than 200 mg/l. Individual sample differences did not permit greater differentiation in the alkalinities of samples at specific digestion periods. The batch digestion test provided a gradual if slightly erratic decrease in alkalinity from 700 mg/l in the primary sludge to 340 mg/l at 14 days digestion and 240 mg/l at 24 days digestion. The greatest decrease in alkalinity occurred during the first 14 days of digestion; however, a specific quantitative endpoint associated with a specific degree of digestion could not be chosen.

The pH of all samples increased during digestion. In the batch digestion test the pH increased most rapidly after the first 14 days of digestion and during the first 2 days of digestion when there was a temporary drop in alkalinity. It would appear that there was an initial air stripping of carbon dioxide from the sludge with a concomitant rise in pH, followed by increased biological activity which released additional carbon dioxide, increased alkalinity, and slightly depressed pH, until the 12th day of aeration. The initial pH of most sludges was low and averaged 5.9. The pH of the continuously fed aerobically digested sludges varied between 6.4 and 7.1; however, no correlation could be made between period of digestion and waste sludge pH.

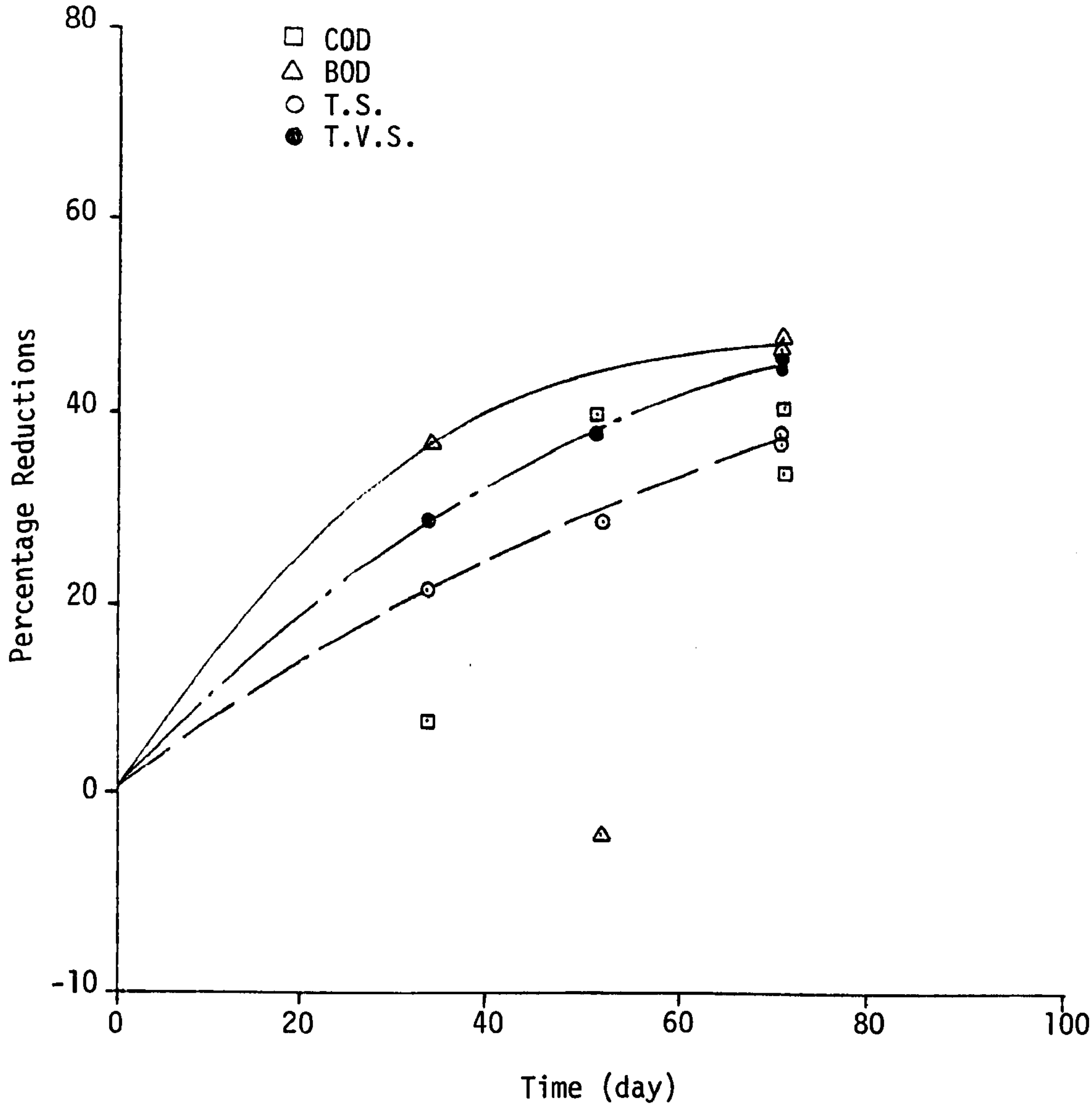

Figure 30. Reduction of Sludge Constituents by Lagooning Outdoor Samples

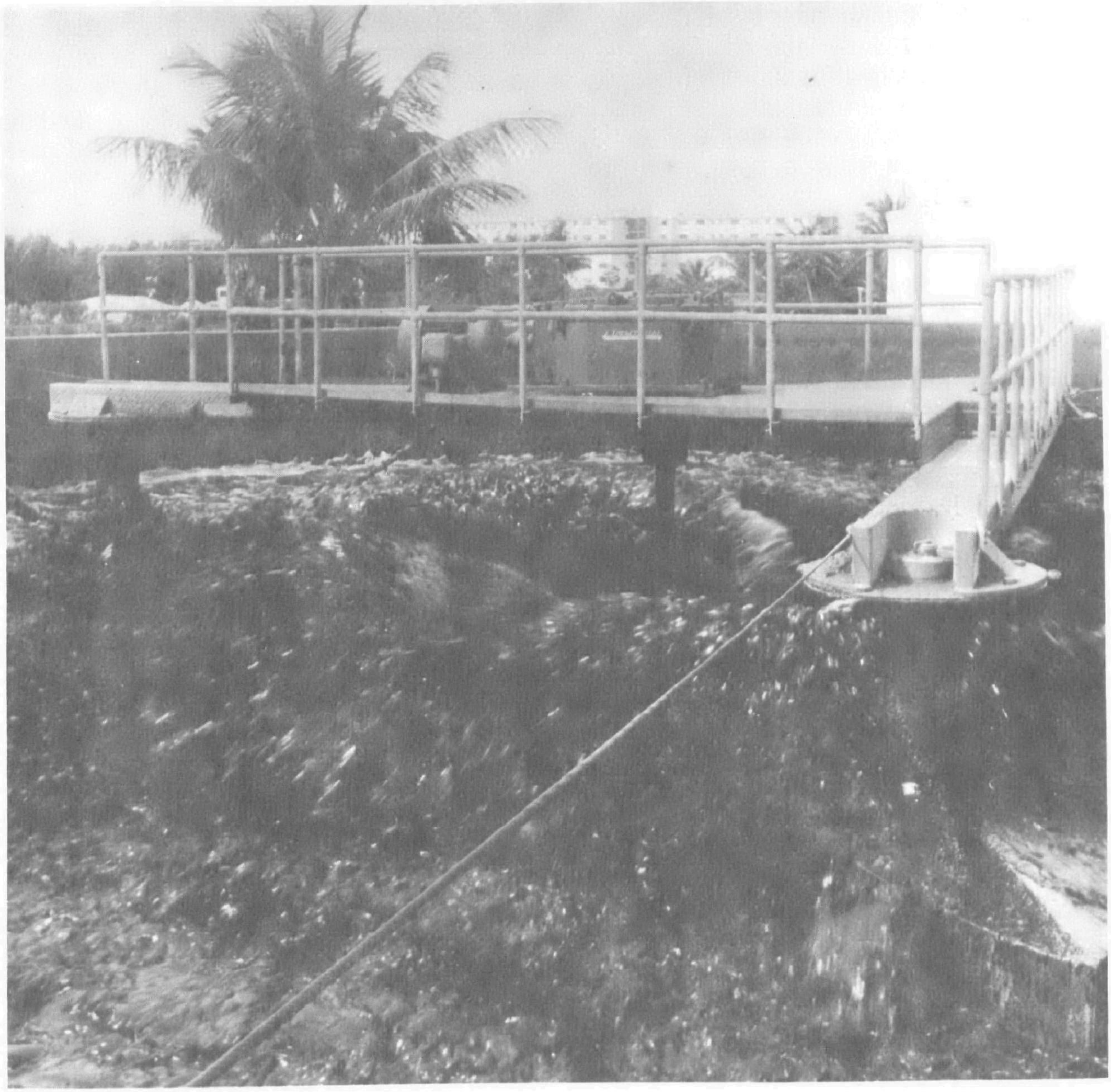

FIGURE 31: A WELL MIXED AEROBIC DIGESTER

Oxygen uptake rate of a digesting sludge reflects the degree of biological activity taking place within the sludge. In the batch test, the oxygen uptake rate was 4.5 mg/(gm T.S.)(hr) on the first day of aeration and fell to 1.2 mg/(gm T.S.)(hr) by the 24th day of aeration with an intermediate low of 0.6 mg/(gm T.S.)(hr) at the 22nd day of aeration. Prior to the 14th day of the test all oxygen uptake rates measured above 2.5 mg/(gm T.S.)(hr) and after the 14th day fell below 1.6 mg/(gm T.S.)(hr). Between the 14th and 24th day of the test there was constant variation in the oxygen uptake rate which was not reflective of the degree of digestion or the period of sludge digestion. In the continuously fed digestion tests the oxygen uptake rate varied between 1.3 and 2.35 mg/(gm T.S.)(hr). While uptake rates of tests of 20 day digestion and longer were below 1.8 mg of O_2/(gm T.S.)(hr) or greater, there was again no exact comparison between the oxygen uptake rate and the degree or period of sludge digestion.

In the continuously fed digestion tests the oxygen uptake rate varied between 1.3 and 2.35 mg/(gm T.S.)(hr). While uptake rates of tests of 20 day digestion and longer were below 1.8 mg of O_2/(gm T.S.)(hr) and of tests of 15 days and less were 1.8 mg of O_2/(gm T.S.)(hr) or greater, there was again no exact comparison between the oxygen uptake rate and the degree or period of sludge digestion.

From the evidence collected in this program it appears that pH, alkalinity, and oxygen uptake rate may provide gross differentiation between raw sludge, partially digested sludge, and completely digested sludge. These parameters cannot provide a fine distinction on the degree of digestion of any sludge, nor could they be related to final sludge filterability or behavior on a sand bed. An evaluation of these parameters and their quantitative values should be performed for each separate aerobic sludge digestion installation.

Certain visual and physical parameters were noted that could help an operator controlling an aerobic digester. The first visual aid recognized was foaming at the surface of the digester. This occurred in the tests of greater than 22 day sludge detention. The foaming was associated with an underloaded digester; however, it gave an appearance of overloading. This was because the surface foam, which was several feet thick, impeded oxygen transfer to the sludge by the mechanical mixer. The sludge, becoming anaerobic black, and foul smelling, gave the impression that the digester was too overloaded for its oxygen transfer capabilities. In contrast to Figure 16 which depicts a foaming digester, Figure 30 presents a properly functioning, well mixed aerobic digester.

Well aerated, aerobic sludges had a light brown color. Anaerobic and near-anaerobic sludges were from dark brown to black in color.

A relative observation of a "too-thick" sludge was usually accompanied by a darkening of the sludge near the digester bottom. This indicates that the sludge is too heavy for proper mixing and should be wasted to a sand bed.

SECTION VIII

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SECTION IX APPENDICES

APPENDIX A

SEWER LINE INFILTRATION

Rainfall and sewer flow were collected on a daily basis during the two year experimental program. This information was fed to a computer where system modeling using discrete transform techniques provided a relatively accurate model of rainfall effects on sewer flow.

The basic model may be expressed as

$$Q_{avg} + Q_{storm} = e^{-0.184} Q_{storm}{-1} + 0.77\ P + Q_{avg}$$

where Q_{avg} = mean sewage flow

Q_{storm} = predicted storm flow for day of rain

$Q_{storm}\ -1$ = measured storm flow for preceding day

and P = precipitation for the day of rain.

This equation is specifically fitted to the City of Hollywood sewage system with its attendant unique conditions of lag time, rainfall frequency, beach front infiltration and general community composition. Careful filtering of the raw data to remove noise and periodic sewage flow variations has produced the constant 0.77 which, when multiplied against precipitation in inches, will result in the daily storm water flow in MGD in the sewage system.

For dry weather flow of 13.6, a 3 inch rainfall would increase the one day flow to 15.9 MGD. This added flow increment of 2.3 MGD then decays at a daily rate of $e^{-0.184}$. As an example of the accuracy of this program a portion of the actual rainfall vs. flow data has been graphically presented in Figure A1. The computer model was then applied to the rainfall and same mean plant flow over a similar period of time. Figure A2 presents the resulting predicted combined sewage flow, less the periodic fluctuations and noise not associated with storm flow. The close match in profiles and magnitude of the sewage flow during the same time period substantiates the validity of the mathematical model.

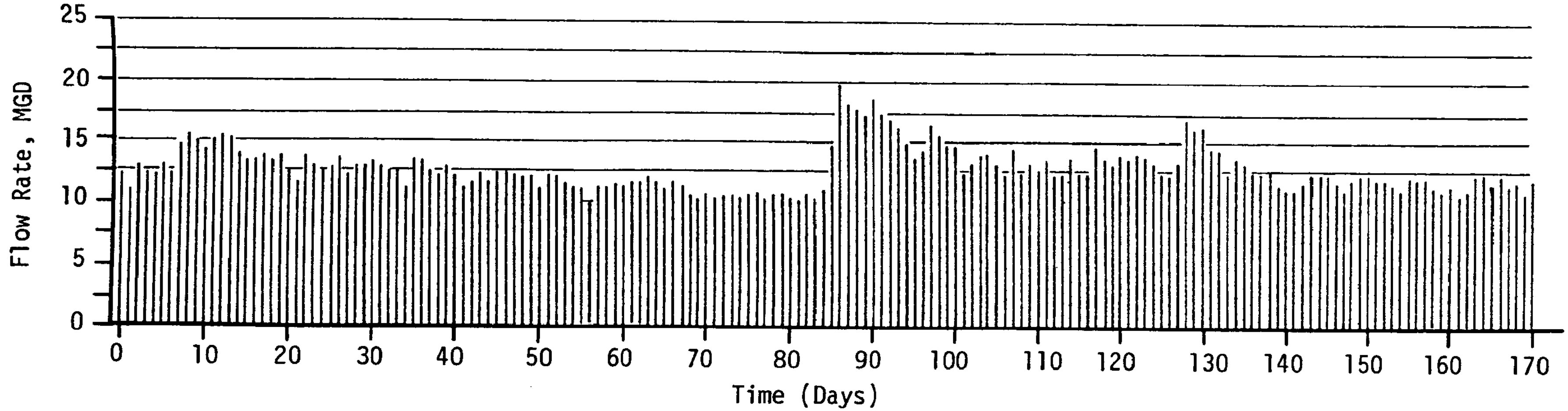

FIGURE A1: Actual Daily Sewage Flow

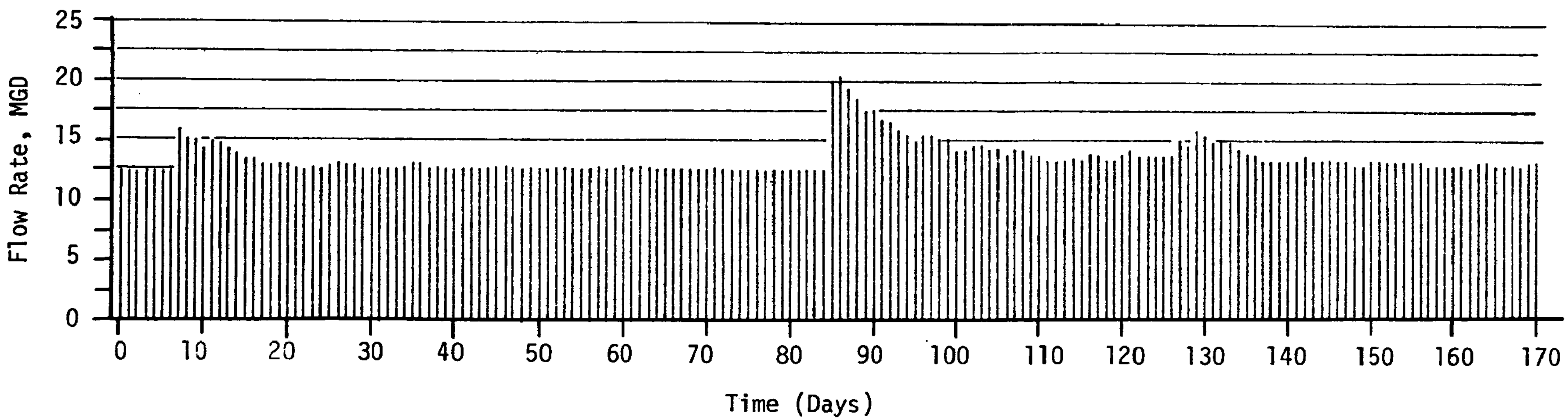

FIGURE A2: Computer Predicted Sewage Flow

APPENDIX B

AEROBIC DIGESTION

System Outline Based on the data collected in this report, an aerobic sludge digestion system would be recommended for serious consideration in any sewage treatment system. Aerobic sludge digestion is a simple process and its component equipment parts would include piping leading to and away from the digester, a plain circular tank as the digester, and a floating mechanical aerator. Special circumstances may dictate the use of rectangular tanks with compressed air aeration. The digester tank should be sized based on hydraulic retention period of the primary sludge. Information gathered in this program indicates a recommended design retention period of 20 days. The BOD loading of the digester would then be a function of the influent sludge concentration. Only the oxygen transfer requirements should be affected by the BOD loading for primary municipal sludge. A high loading would relate to a high uptake rate, and thusly affect the aerator requirements. The principal design consideration is hydraulic retention time.

The peak oxygen uptake rate for the 20 and 22 day digestion tests was measured at 112 mg of O_2/ (1)(hr). In the 396,000 gallon aeration tank at Hollywood this is equivalent to a demand of 370 lbs. of oxygen per hour. The 100 Hp mechanical aerator, used at Hollywood, was rated by the manufacturer to supply 350 lbs. of oxygen per hour. This aerator apparently sufficed because of the average oxygen concentration in the digester during the 22 day test was 3.5 mg/l and at no time did the digester become anaerobic.

System Economics The average wastewater flow at the City of Hollywood Sewage Treatment Plant was 13.6 MGD. The required digester aeration volume for this flow was found to be 396,000 gallons. The following items are assumed:

(1) Site is normal--no high water table or unsuitable soil to be removed,

(2) Digester tank base slab to be placed on existing ground elevation,

(3) Only fine grading involved,

(4) Machine excavation required for footings, etc.

Using this data, a capital cost in May 1972 dollars was calculated for the installation of an aerobic digester at an existing sewage treatment facility. The following items are included in the complete digester:

(1) Excavation
(2) Forms
(3) Concrete
(4) Finishing, float
(5) Curing
(6) Reinforcing steel
(7) Aluminum ladders and rails
(8) 3 hand hoists

(9) Piping and valves	(12) Aerator, 100 Hp, floating
(10) Finishing screens	(13) Electrical controls
(11) Waterstop	(14) Sludge pump

Total cost for installation of this aerobic digester, including contractor's equipment, overhead and profit, is estimated at $130,000. This is approximately one dollar per hundred gallons of main plant flow.

The estimated life of the fixed digester hardware is 30 years, while the aerator and sludge pump have a 15 year estimated life. The total cost of capital equipment over a 30 year period would be $163,189. The yearly cost of this sum amortized over a 30 year period at 7.5 percent interest compounded annually would be $13,817.41. This is equivalent to a cost of 0.28 cents per 1,000 gallons of raw sewage.

Maintenance costs may be assumed at 10 percent of the yearly cost of the aerobic digester. This adds 0.03 cents per 1,000 gallons for a combined capital and maintenance cost of 0.31 cents per 1,000 gallons.

The power requirements for the 100 Hp aerator are 60 kilowatts per hour at a power cost of 0.117 cents per 1,000 gallons. The power requirements for the sludge transfer pump are relatively negligible. The total capital and operating costs exclusive of labor and land for the aerobic digestion process should be less than 0.43 cents per 1,000 gallons at the City of Hollywood. This is equivalent to 0.32 cents per gallon of waste sludge at 4.5 percent total solids concentration.

APPENDIX C

EFFECTS OF VARIOUS DOSAGES

OF POLYELECTROLYTES ON

BOD AND SUSPENDED SOILDS REMOVAL

TABLE C1

EFFECT OF VARIOUS DOSAGES OF CAT FLOC ON REMOVAL OF BOD AND SUSPENDED SOLIDS IN SEWAGE FROM THE EFFLUENT OF THE GAINESVILLE GRIT CHAMBER

Polymer Dosage mg/l	Suspended Solids mg/l	BOD mg/l	Final pH	Electro-phoretic Mobility μ/(sec)(v)(cm)
0.0*	130	152	7.27	-1.7
0.5	18	61	7.32	-1.4
0.9	13	58	7.35	-1.3
1.9	22	50	7.36	-1.2
2.8	20	37	7.36	-1.2
3.7	13	26	7.63	-1.1
4.7	13	24	7.61	-1.0
5.6	12	21	7.59	-0.9
7.5	7	19	7.55	-0.7
9.4	10	18	7.68	0.3
11.2	11	19	7.47	0.0

*Effect of 0.0 polymer dose from raw sample, not a blank.

TABLE C2

EFFECT OF VARIOUS DOSAGES OF CAT FLOC ON REMOVAL OF BOD AND SUSPENDED SOLIDS IN SEWAGE FROM THE EFFLUENT OF A GAINESVILLE PRIMARY SETTLING TANK

Polymer Dosage mg/l	Suspended Solids mg/l	BOD mg/l	Final pH	Electrophoretic Mobility μ/(sec)(v)(cm)
0.0*	80	170	7.42	-1.8
0.5	50	165	7.49	-1.6
1.0	45	135	7.49	-1.4
3.0	53	85	7.47	-1.2
5.0	34	68	7.50	-0.9
7.0	36	55	7.58	-0.7
10.0	28	33	7.62	-0.2
12.0	33	33	7.60	+0.1
15.0	17	35	7.62	+0.3

*Effect of 0.0 polymer dose from raw sample, not a blank.

TABLE C3

EFFECT OF VARIOUS DOSAGES OF CAT FLOC ON REMOVAL OF BOD AND SUSPENDED SOLIDS IN SEWAGE FROM THE EFFLUENT OF THE UNIVERSITY OF FLORIDA GRIT CHAMBER

Polymer Dosage mg/l	Suspended Solids mg/l	BOD mg/l	Final pH	Electro-phoretic Mobility μ/(sec)(v)(cm)
0.0*	95	120	8.50	-1.7
0.5	25	89	..	-1.6
0.9	25	71	..	-1.4
1.9	20	51	..	-1.3
2.8	3	41	..	-0.9
3.7	10	35	..	-0.5
4.7	0	30	..	-0.1
5.6	7	30	..	+0.3
6.6	..	..	..	..
7.5	14	34	..	+0.7
9.4	8	31	..	+0.9
11.2	14	31	..	+1.1

*Effect of 0.0 polymer dose from raw sample, not a blank.

TABLE C4

EFFECT OF VARIOUS DOSAGES OF CAT FLOC ON REMOVAL OF BOD AND SUSPENDED SOLIDS IN SEWAGE FROM THE EFFLUENT OF A UNIVERSITY OF FLORIDA PRIMARY SETTLING TANK

Polymer Dosage mg/l	Suspended Solids mg/l	BOD mg/l	Final pH	Electro-phoretic Mobility μ/(sec)(v)(cm)
0.0*	31	50	7.60	-1.9
0.4	26	34	..	-1.5
0.8	26	21	..	-1.0
1.7	13	17	..	-0.9
2.5	2	9	..	-0.1
3.3	13	5	..	0.0
4.2	17	6	..	+0.2
5.0	14	7	..	+0.9
5.8	15	5	..	+0.8
6.7	13	9	..	+1.1
8.4	12	10	..	+1.3
10.0	10	10	..	+1.2

*Effect of 0.0 polymer dose from raw sample, not a blank

TABLE C5

EFFECT OF VARIOUS DOSAGES OF DOW C-31 ON REMOVAL OF BOD AND SUSPENDED SOLIDS IN SEWAGE FROM THE EFFLUENT OF THE UNIVERSITY OF FLORIDA GRIT CHAMBER

Polymer Dosage mg/l	Suspended Solids mg/l	BOD mg/l	Final pH	Electro-phoretic Mobility μ/(sec)(v)(cm)
0.0*	106	142	8.20	-1.7
5.0	30	89	8.28	-1.6
10.0	15	66	8.48	-1.3
15.0	2	54	8.41	-1.2
20.0	3	49	8.43	-0.7
25.0	2	49	8.42	-0.2
30.0	5	42	8.41	+0.1
35.0	5	37	8.43	+0.3
40.0	17	35	8.43	+0.5

*Effect of 0.0 polymer dose from raw sample, not a blank.

TABLE C6

EFFECT OF VARIOUS DOSAGES OF PRIMAFLOC C-7 ON REMOVAL OF BOD AND SUSPENDED SOLIDS IN SEWAGE FROM THE EFFLUENT OF THE UNIVERSITY OF FLORIDA GRIT CHAMBER

Polymer Dosage mg/l	Suspended Solids mg/l	BOD mg/l	Final pH	Electrophoretic Mobility μ/(sec)(v)(cm)
0.0*	106	142	8.20	-1.7
5.0	34	89	8.25	-1.5
10.0	13	66	8.25	-1.3
13.0	3	58	8.24	-0.9
16.0	5	58	8.18	-0.5
20.0	6	57	8.10	-0.1
25.0	10	57	8.06	+0.1
30.0	9	50	7.96	+0.4
35.0	18	50	7.92	+0.9

*Effect of 0.0 polymer dose from raw sample, not a blank.

TABLE C7

EFFECT OF REVOLUTIONS OF MIXING ON REMOVAL OF BOD AND SUSPENDED SOLIDS IN SEWAGE FROM THE EFFLUENT OF THE UNIVERSITY OF FLORIDA GRIT CHAMBER; POLYMER USED: CAT FLOC

Mixing Rate 20 RPM			Polymer Dosage 2.8 mg/l	
No. of Revolutions	Suspended Solids mg/l	BOD mg/l	Final pH	Electrophoretic Mobility μ/(sec)(v)(cm)
0*	116	120	8.29	-1.9
20	57	75	. .	0.0
50	43	73	. .	0.0
100	41	71	. .	0.0
200	35	66	. .	0.0
500	25	54	. .	0.0
1,000	17	50	. .	0.0
2,000	10	44	. .	0.0
5,000	6	36	. .	0.0

*Raw sample with no polymer added not a blank.

APPENDIX D

LIST OF POLYMERS

TABLE D1

LIST OF POLYELECTROLYTES EVALUATED

COMPANY	POLYMER
Calgon Corporation P. O. Box 1346 Pittsburg, PA 15230	Cat Floc Coagulant Aid 25
Allstate Chemical Company Box 3040 Euclid, Ohio 44117	All-Flok #16
National Starch and Chemical Corp. 1700 West Front Street Plainfield, N.J. 07063	National Natron 86 National Resyn 3285
Garratt-Callahan 111 Rollins Road Millbral, California 94031	72 A 73 74 74 B 74 D 74 E 78 C 78 F 78 G 78 H 78 I 78 J 78 S 78 CF 78 FH 76 76 A 76 C
The Dow Chemical Company Abbott Road Center Midland, Michigan 48640	Purifloc C-31 Purifloc C-32 N-11 N-12 N-17 A-21 A-22

TABLE D1

LIST OF POLYELECTROLYTES EVALUATED
(Continued)

COMPANY	POLYMER
Kelco Company 8225 Aero Drive San Diego, California 92123	KNW-10433-49 2N-8551-29 KL-3859-49
Nalco Chemical Company 6216 W. 66th Place Chicago, Illinois 60638	675 610 635 607 603
Betz Laboratories, Inc. Gillingham and Worth Streets Philadelphia, Pa.	Poly Floc 1100-A Poly Floc 1100 Poly Floc 1120 Poly Floc 1130 Poly Floc 1120-A Poly Floc 1130-A Poly Floc 1150-L Poly Floc 1160-L Poly Floc 4D Poly Floc 1160 Poly Floc 1150 Poly Floc 1175 Poly Floc 1170
Ionic Chemical Company	NI-701 NC-720 NI-700 NA-710
Dearborn Chemical Division W. R. Grace & Company Merchandise Mart Plaza Chicago, Illinois 60654	Aquafloc 415 Aquafloc 412 Aquafloc 410

TABLE D1

LIST OF POLYELECTROLYTES EVALUATED
(Continued)

COMPANY	POLYMER
The Mogal Corporation 20600 Chagrin Boulevard Cleveland, Ohio 44122	Mogal Co-091 Mogal Co-983 Mogal Co-984
Rohm and Haas Company Independence Mall West Philadelphia, Pa. 19105	C-7 C-3 A-10 C-5 C-6
Dubois Chemical Company	540 545 532
Stein, Hall, and Company, Inc. 605 Third Avenue New York, N.Y. 10016	M-295

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EPA-600/2-75-049		

4. TITLE AND SUBTITLE	5. REPORT DATE
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15. SUPPLEMENTARY NOTES

16. ABSTRACT

Laboratory and full-scale studies were conducted at the Hollywood, Florida, sewage treatment plant to determine the efficiency of chemical coagulation for treatment of raw sewage and aerobic digestion of primary sewage sludge.

While various polyelectrolytes produced high treatment efficiencies in the laboratory, these efficiencies could not be achieved in full-scale tests due to inadequate mixing and higher soluble BOD concentrations.

Sludges were successfully digested aerobically with as little as ten days detention. An oxygen uptake rate of up to 1.8 gm O_2/(gm T.S.)(hr) was observed for sludge ages greater than 20 days. The recommended detention time of 20 days produced a solids content between 4 and 6 percent.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
*Sludge digestion Waste treatment Waste water *Sewage treatment Sludge disposal *Aerobic processes *Sludge drying	*Wastewater treatment *Sewage coagulation Sludge treatment Sewer infiltration Municipal sewage *Aerobic digestion	13B

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