

EFFECTS ON ANAEROBIC DIGESTION
OF EMPLOYING
POLYELECTROLYTES AND FERRIC CHLORIDE
AS AIDS TO
CLARIFICATION OF DOMESTIC SEWAGE

by

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A B S T R A C T

The advent of high molecular weight polyelectrolytes has stimulated research into their use for BOD reduction in primary and secondary treatment and as sludge dewatering aids in vacuum filtration and centrifugation. Since many of these products have not been approved for use in domestic water supplies because of their possible toxicity to humans, it was felt that they may be toxic to the microorganisms in anaerobic digestion, activated sludge or other biological treatment processes. This research evaluates effects on the anaerobic digestion process.

Three continuously mixed laboratory scale anaerobic digesters were operated at $32 \pm 1^{\circ}\text{C}$ with a 30 day hydraulic and solids retention time. Digester number one served as a control and received sludge obtained by sedimentation of domestic sewage without the use of coagulants; number two received sludge obtained using 14 mg/l of a cationic Hercules Incorporated polymer, Hercofloc 814.2, as the coagulant; and number three received sludge obtained using 30 mg/l of ferric chloride as the primary coagulant and 1 mg/l of Hercofloc 836.2 as a coagulant aid. Waste stabilization calculations, based on influent and effluent BOD, COD, and VS results and on methane production, failed to indicate any toxicity or physical inability of anaerobic microorganisms to penetrate the flocs formed as a result of the addition of coagulants as aids to sewage sedimentation. Calculations of waste stabilization from BOD_5 , BOD_L ,

COD, and VS results indicated treatment efficiencies of approximately 81, 70, 62 and 59 percent, respectively, for all three digesters.

Results of pH, alkalinity, and volatile acids testing of digester effluents and total gas production from the digesters did not indicate unbalanced treatment due to the presence of coagulants. pH and alkalinity results were, however, consistently higher in the digesters receiving chemically coagulated sludge than in the control digester, signifying a greater buffering capacity against digester upset.

The effluent from digester number two was observed to settle more rapidly and leave a clearer supernatant than effluent from either of the other digesters. Subsequent Buchner funnel vacuum filtration tests produced values of specific resistance for effluents from digesters one and three that were 18 times greater than the values obtained for the number two effluent. Although the results were for the mixed digester contents rather than for the settled portion of the effluent, they indicate that little or no additional conditioning would be required prior to vacuum filtration dewatering of effluent from digester number two.

A limited number of jar tests and settling column tests using a weak to medium strength domestic sewage, produced BOD₅ and COD removal efficiencies of 50 to 70 percent using 30 mg/l of FeCl₃ in combination with 0.5-1.0 mg/l of anionic Hercofloc 836.2. Similar efficiencies were achieved using 6-14 mg/l of either of the cationic Hercofloc polymers, 812 or 814.2, as the sole coagulant.

An economic analysis was carried out comparing the total annual costs of primary and activated sludge treatment methods. Capital costs were amortized over a twenty-five year period at 10 percent per annum and were added to operation and maintenance costs to obtain total costs. The results of this analysis indicated that the maximum economic dosages of Hercofloc 814.2 added continuously to primary plants operating at capacity are 14.9, 10.2, and 6.6 mg/l for 1, 10, and 100 mgd plants, respectively. Similarly for ferric chloride and 0.5 mg/l of Hercofloc 836.2, the corresponding economic dosages of FeCl_3 are 51, 34, and 21.5 mg/l. These dosages are based on the assumption that an adequate degree of treatment can be obtained by chemical precipitation.

Within the limitations of the economic analysis and based on jar test results, it was concluded that use of Hercofloc 814.2 as an aid to primary clarification of domestic sewage is not an economically attractive alternative to providing activated sludge treatment unless an adequate degree of treatment can be achieved at dosages somewhat less than 14 mg/l. On the other hand, use of ferric chloride and Hercofloc 836.2 was found to be economically attractive for plants in the 1-10 mgd range.

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CHAPTER 1

INTRODUCTION

1.1 General

The advent of high molecular weight, long-chain polyelectrolytes has stimulated research into their use in sewage treatment for removal of organic solids in primary and secondary treatment and as sludge dewatering aids in vacuum filtration and centrifugation. Polymers are also under investigation as primary coagulants or coagulant aids for removal of solids and organic colour from water supplies and in water softening.

Because of possible adverse physiological effects to humans stemming from the use of polymers in public water supplies, the U.S. Environmental Protection Agency approves some polymers for this use, but sets limits upon dosages for those polymers which are approved.

The research reported on herein stems from a concern about possible toxicity to microbial life in anaerobic digesters, activated sludge and trickling filter plants. Coagulation and settling tests during studies on sludge dewatering at the University of Washington indicated that polyelectrolytes had a toxic effect on the bacterial life in the supernatant liquor [1].

The scope of this study was limited to determination of the effects on the anaerobic digestion process of the chemical sludge obtained by the coagulation and sedimentation of a domestic sewage employing polyelectrolytes and ferric chloride as coagulants.

1.2 History of Chemical Treatment

The use of chemicals in sewage treatment is not a new concept, the advent of polyelectrolytes has merely served to stimulate interest in their use.

Chemical precipitation was tried in Paris, France in 1740 and was popular in England between 1857 and 1880, when interest waned due to the introduction of biological treatment [2].

In the United States, chemical precipitation was popular for about 35 years prior to 1910. Interest waned between 1910 and 1928 and revived around 1929, apparently due to development of the Laughlin process [2]. The following statement by Enslow [3] in 1935 attests to the popularity of chemical treatment at that time:

"Today there are 50 or more American plants completed, under construction, or definitely planned, in which chemical precipitation alone or in combination with biological processes is being, or will be, employed. In addition, there are not less than 14 such plants proposed, 12 to employ chemical treatment alone and 2 to use it for assisting biological processes."

By 1959, the construction of sewage treatment plants based solely on chemical precipitation had declined but chemical treatment as an aid to other processes was on the increase [2].

1.3 Theory of Chemical Precipitation

Chemical precipitation, or physical-chemical treatment as the process is also known, is a process by which clarification of sewage is attained by the addition of chemical substances to

promote coagulation and flocculation of suspended colloidal matter. In order to understand chemical precipitation, it is necessary to understand the nature of sewage colloids.

The size range of colloidal particles is arbitrarily defined as one millimicron to one micron. A dispersion of such particles in a liquid is called a "sol".

A dispersion of particles of larger size, called a "suspension", will clarify itself by gravity settling in a reasonable length of time. A dispersion of particles of smaller size, called a "solution", is little affected by coagulants.

Colloids are either hydrophobic (little affinity for water) or hydrophilic (great affinity for water). Generally, inorganic colloids are hydrophobic and organic colloids are hydrophilic. The organic colloids found in domestic sewage are mainly hydrophilic.

Colloids of both types also possess an electrical charge. The colloids usually found in wastewaters are characterized by a zeta potential of -15 to -20 millivolts [4]. The strong mutual repulsion induced by a high zeta potential contributes to the stability of poor sedimentation characteristics of a "sol".

Before colloids can be removed from the wastewater, the "sol" must first be destabilized, followed by flocculation to generate large particles. Destabilization can be accomplished by:

1. The addition of a strong cationic electrolyte such as ferric chloride to lower the zeta potential,

permitting the van der Waals attractive forces to become effective.

2. The addition of cationic electrolyte in the presence of sufficient alkali resulting in the formation of positively charged hydrous oxides. These insoluble complexes become adsorbed on the colloids.
3. The addition of sufficient cationic polyelectrolyte to lower the zeta potential resulting in the forces of attraction between the polymer and colloids becoming large enough for bridging to occur.
4. Mutual coagulation of cationic and anionic polymers in the system.
5. Agglomeration of negative colloids with an anionic or nonionic polyelectrolyte.
6. Entrapment of wastewater colloids and other suspended matter by the flocs formed by the above processes.

From the preceding discussion it may be inferred that chemical precipitation of domestic sewage is a well understood science. In fact, the coagulation processes are not well understood, and a "trial-and-error" procedure - the jar test - is still one of the most widely used methods of evaluating coagulants and determining optimum dosages. Thus, in-plant control of chemical treatment is particularly difficult for

domestic wastewaters, since both the strength and amount of waste fluctuate throughout the day.

1.4 Efficiency of Removal of Organics by Chemical Precipitation

The conventional methods of treatment used in recent years have been termed "primary" and "secondary" treatment.

The expression "primary treatment" means removal of suspended solids by gravity settling with discharge of the liquid portion or supernatant. "Secondary treatment" customarily includes primary sedimentation plus additional aerobic biological treatment of the supernatant and secondary sedimentation before discharge of the effluent supernatant.

Treatment efficiencies normally expected from primary sedimentation are 25-35 percent removal of 5-day, 20°C Biochemical Oxygen Demand (BOD) and 50-60 percent removal of suspended solids (SS). For the most efficient biological processes, removal efficiencies of approximately 90 percent of both BOD and SS can be achieved.

As soluble organics are little affected by coagulants, chemical precipitation can be expected to remove only 65-85 percent of BOD [3,5], but SS removals approaching 90 percent should be possible. However, higher BOD and SS removal efficiencies have been reported for chemical precipitation processes when followed by an effluent polishing step.

One such process, the Guggenheim process, employed ferric sulphate and lime as coagulants followed by zeolite ion ex-

changers. BOD and SS removals averaging 90 percent and 97 percent, respectively, were reported [5]. Excluding the ion exchange step, however, monthly average BOD reduction ranged between 76 and 86 percent over a seven month period. Chemical dosages were high with ferric sulphate ranging from 19.5 to 38.5 mg/l as Fe and lime from 31.6 to 52.9 mg/l as CaO.

1.5 Why Use Chemical Precipitation?

Although it has been shown in the previous section that chemical precipitation is capable of achieving only an "intermediate" degree of treatment, there are several instances in which its use may be advantageous. These are:

1. Where plain sedimentation is normally sufficient but receiving water limitations necessitate better treatment at times.
2. Where seasonal variations occur in the volume of sewage treated and degree of treatment required.
3. Where an intermediate degree of treatment between plain sedimentation and secondary biological treatment is all that is required.
4. Where the area for plant location is restricted.
5. Where it is necessary to help out an existing plant, primary or secondary, which is overloaded.
6. Where it is necessary to treat certain industrial wastes or domestic sewage containing a significant portion of industrial wastes which are inhibitory to biological processes.

1.6 Advantage of Polyelectrolytes in Chemical Treatment

The principal advantages in using polyelectrolytes are the significant reductions in the quantity of chemical sludge which must be handled and in the quantity of chemical coagulant which must be handled. Early investigators found that quantities of lime in excess of 100 mg/l as CaO were often required in conjunction with metal salts to obtain efficient treatment [5]. A fraction of a part per million of anionic polyelectrolyte has been found to effectively replace lime as a coagulant aid.

When used as primary coagulants, cationic polymers have been found to be 10 to 15 times as effective as metal salts for the destabilization of sewage colloids [4].

1.7 Objectives of the Research

The principal objective of the research undertaken was to investigate the possible toxicity of polyelectrolytes in anaerobic digestion. In addition, it was anticipated that these coagulant aids might have a physical effect on anaerobic digestion either through physical interference with mixing due to the size and weight of the flocculated particles formed or through the inability of the organisms to penetrate and stabilize the large flocs formed. It was intended, therefore, that the research look at both the physical and biological aspects of the anaerobic digestion of chemically precipitated wastes.

CHAPTER II

EXPERIMENTAL METHODS

2.1 General

The research detailed in this report includes results of the following laboratory investigations:

1. Jar tests were performed to evaluate several polymers as primary coagulants or as coagulant aids for the clarification of domestic wastewater.
2. Three laboratory scale, model digesters were operated - one with wastewater solids obtained using no coagulants, the second with wastewater solids obtained using a cationic polymer as the coagulant, and the third with wastewater solids obtained using ferric chloride as the primary coagulant and an anionic polymer as a coagulant aid.
3. A Buchner funnel assembly was used to evaluate the dewaterability of the digested sludges by vacuum filtration.

2.2 Evaluation of Polyelectrolytes

Jar tests were conducted using a Phipps-Bird jar test apparatus capable of simultaneously stirring six samples at speeds up to 100 revolutions per minute (rpm).

Each polymer was prepared in accordance with the manufacturer's directions. A stock solution of 1.0 or 0.5% was prepared and was stable for one or two weeks. From the stock solution a working solution of 0.1 or 0.5% was prepared each day. A 1.0% working solution of ferric chloride was used.

One liter samples of fresh raw sewage were arranged in the jar test apparatus with one sample as a control. Mixing of the contents at 100 rpm was initiated before the addition of coagulants. Following the addition of coagulants at various concentrations, the system was mixed at 100 rpm for one minute. When two coagulants were added, rapid mixing at 100 rpm proceeded for one minute after each coagulant was added.

The addition of coagulants was followed by a flocculation period of three minutes with mixing at 30 rpm.

After flocculation, mixing was slowed to 5 to 10 rpm for a dynamic settling period. Observations such as size and type of floc and their settling characteristics were recorded.

Initially, visual observations were used to evaluate the various polymers and ferric chloride. However, after it had been determined that ferric chloride in combination with some anionic polymers and that some cationic polymers appeared to yield satisfactory results, final selection of coagulants and of coagulant dosages was based on COD or BOD tests of the jar supernatants after five minutes of settling.

2.3 Evaluation of Effects on Anaerobic Digestion

Three model digesters were constructed of acrylic plastic for use in the laboratory. Low temperature heating tapes wrapped around the digesters and switched on and off by means of a thermo-couple maintained the contents of the digesters at $32 \pm 1^\circ\text{C}$. The digester contents were continuously mixed by motor-driven stainless steel paddles at a rate sufficient to keep organic solids in suspension. Some inorganic particles settled out. During addition and withdrawal of sludge, the mixing speed was increased to suspend all solids.

Raw sludge was added to each digester at the rate of 250 ml per day, and digested sludge was withdrawn simultaneously. The working capacity of each digester was 7.5 liters, therefore hydraulic and solids retention times were 30 days.

All digester gases were passed through gas sampling tubes fitted with rubber nipples in order that samples could be withdrawn for composition analysis by gas chromatography. Each gas sampling tube was followed by a simple bubbler apparatus which prevented possible backflow of atmospheric air into the sampling tubes and digesters. These were followed by horizontal acrylic tubes filled with water saturated with digester gas which were used to measure the quantity of gas produced by displacement and collection of the water. The configuration of the tubes was such that the maximum back-pressure on the digester was about 2-inches of water. Towards the end of the experimental period a single Gallenkamp Model GF-052 wet gas meter was obtained, and this was used for both gas quantity

measurements on a rotation basis and as a check against the water displacement method.

Figure 1 shows the layout of a digester and ancillary apparatus.

The following digestion parameters were measured.

1. Influent raw sludge - total and volatile solids, BOD, COD, total iron.
2. Effluent digested sludge - pH, volatile acids, alkalinity, total and volatile solids, BOD, COD, total iron.
3. Digester gas - amount and composition.

Long-term BOD tests were performed on samples of influent and effluent sludges to determine the relationship between 5-day and ultimate carbonaceous biochemical oxygen demand (BOD_L).

Laboratory analyses were performed according to procedures in "Standard Methods" [6]. For gas chromatographic analyses of digester gas composition, a 16-foot by one-eighth inch diameter stainless steel column was used, packed with 8-feet of 50-80 mesh Poropack Q and 8-feet of 50-80 mesh Poropack R. The gas chromatograph was a Hewlett-Packard Model 5752B.

2.4 Significance of Digestion Parameters Monitored

The previously listed digestion parameters measured were used to determine the efficiency of stabilization of organics

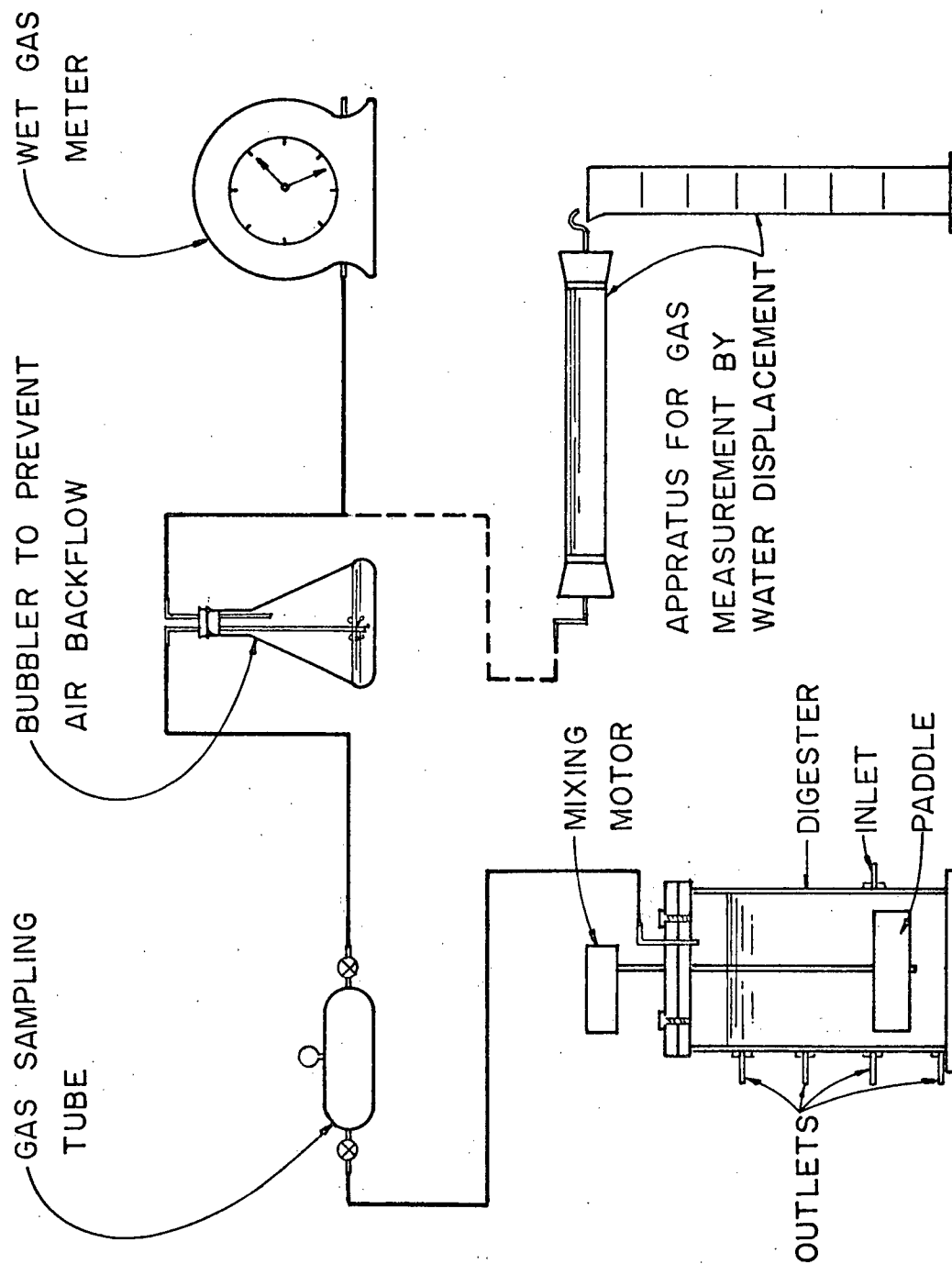


FIGURE I - SCHEMATIC OF DIGESTER
AND ANCILLARY APPARATUS

and as indicators of unbalanced treatment.

Parameters which indicate unbalanced treatment are increases in volatile acids and in CO_2 content of digester gas and decreases in pH, total gas production and BOD, COD or volatile solids reduction. Efficiency of organic removal is determined from measurements of influent and effluent COD, BOD and volatile solids. Methane production also serves as a parameter for estimation of waste stabilization.

Unbalanced treatment can be either of a temporary nature or prolonged. Factors which may cause a temporary imbalance are sudden changes in temperature, organic loading, or the nature of the waste. As the first two factors were controlled, the only factor of minor concern was a change in the nature of the waste at the start of addition of the experimental sludge. However, no problems were expected as any temporary imbalance could be handled by pH control and by reducing feeding rates to allow time for the bacterial population to adjust.

A prolonged imbalance may be caused by the introduction of toxic materials to the digesters, by an extreme drop in pH, or by slow bacterial growth during startup. Since pH could be controlled by the addition of lime or sodium bicarbonate, and since the digesters were operated for several months before the addition of the experimental sludges, a prolonged imbalance could be used as an indicator of toxicity.

It was believed that the parameters measured would also be sufficient to differentiate between microbial inhibition and

physical inability of micro-organisms to penetrate and stabilize the large flocs formed during sedimentation.

The bacterial population in an anaerobic digester consists of two main groups of bacteria. These are a group of facultative and anaerobic bacteria known collectively as "acid forming bacteria" and a group of obligate anaerobes known collectively as "methane fermenting bacteria". In the digestion process, the "acid formers" mainly convert complex organics to organic fatty acids (volatile acids). The "methane formers" convert these organic acids mainly to methane and carbon dioxide.

Of the two groups of bacteria, the "methane formers" are the most sensitive to changes in their environment. Thus, when toxicity is present, it is this group which is affected, resulting in unbalanced treatment. The "acid formers" continue to function, resulting in an increase in volatile acids and a decrease in pH. The decreased activity of the "methane formers" results in decreased waste stabilization and a resulting decrease in methane production. Therefore total gas production decreases and the ratio of CO_2 to CH_4 increases.

In the event of a physical inability of microbes to penetrate the large flocs, it was anticipated that the "acid formers" would be affected, resulting in a decrease in waste stabilization and total gas production without changes in the other parameters which indicate unbalanced treatment.

2.5 Selection of Coagulants for Evaluation of Effects on Anaerobic Digestion

For the following reasons it was decided to use ferric chloride in conjunction with an anionic polymer in one digester and a cationic polymer in the other.

1. Only cationic polymers were found to be effective as primary coagulants. Although a few cationic polymers were reasonably effective, all were believed to be acrylamide-based polymers and without additional information about the functional groups which account for their ionic nature, it was felt that no useful purpose would be served by testing more than one of them.
2. Ferric salts were the most successful and most widely-used coagulants during early experimentation with chemical precipitation [5]. At that time there were conflicting statements that iron salts both improve and retard anaerobic digestion, but little concrete data was presented to substantiate either claim [3,5].
3. Ferric chloride required an anionic polymer as a coagulant aid for effective agglomeration of the small flocs formed. The small quantities of polymer required were not expected to be toxic as some anionic acrylamide-based polymers have been approved for use in public water supplies at dosages up to 1 mg/l. However, the possibility

of the polymer acting synergistically with ferric chloride or with some other component of sewage sludge could not be discounted.

On the basis of the jar test results, cationic Hercofloc 814.2 was selected for use as a primary coagulant at a dosage of 14 mg/l. 30 mg/l of ferric chloride as the primary coagulant followed by 1 mg/l of anionic Hercofloc 836.2 as a coagulant aid were also selected.

As the primary objective of the research was the evaluation of effects on digestion, no attempt was made to select economical dosages of coagulants. Dosages were selected to be slightly in excess of practical requirements for effective coagulation.

2.6 Procedure Used to Obtain Raw Sludge for Anaerobic Digesters

In order to obtain raw sludge for the laboratory digesters with approximately the same characteristics as could be expected from an operating physical-chemical plant, two acrylic settling columns were utilized. Each was 12-inches in diameter, 4-feet high, and had a working capacity of 80 liters. The bottom of each was fitted with a conical sludge hopper. Several sampling ports on the sides allowed for withdrawal of supernatant.

Fresh barminuted raw sewage was pumped into the columns and mixed with the coagulants. A flocculation period followed during which the contents were stirred for several minutes.

Following settling, sludge was withdrawn from the bottom of the sludge hoppers.

Sludge for the control digester was obtained simultaneously by settling sewage in a large polyethylene tank.

It became apparent that it was not possible to obtain sufficient sludge in a reasonable length of time if the settling columns were drained completely each time coagulants were added. Therefore, after the first addition of coagulants and flocculation of the sewage, the flocs were allowed to settle past the mid-point of the columns and 40 liters of supernatant were withdrawn. The columns were then re-filled, additional coagulants were added and the contents were remixed and stirred while flocculation took place. This process was repeated several times before the columns were drained. The untreated raw sewage was handled in a similar manner for consistency. This procedure approximates the results which would be obtained by returning chemical sludge to the head of the primary sedimentation basin in a full scale plant.

Volatile solids concentrations of sludges were adjusted by the addition of supernatant to bring all sludges to approximately equal values before feeding to the digesters.

2.7 Filterability of Digested Sludges

Based on observations of uneven settling rates for the digested sludges, it appeared that the coagulants had retained some value as sludge dewatering aids. Therefore, Buchner funnel

vacuum filtration tests at vacuums of 375, 500 and 625 mm of mercury were conducted to determine the relative filterability of the three sludges as indicated by specific resistance. The procedure has been described by Rich [7].

CHAPTER III

RESULTS - POLYMER EVALUATIONS AND FILTERABILITY OF DIGESTED SLUDGES

3.1 Evaluation of Polyelectrolytes

Initial jar test results were discouraging. As sewage colloids are mainly anionic, first efforts were directed towards finding a single cationic polymer which would effectively act as a coagulant. Visual results were poor as either no flocculation occurred or very small flocs formed which settled slowly under static conditions and not at all under dynamic conditions at dosages up to 10 mg/l. Similar results were observed for several anionic polymers used alone at the same dosages.

Early in the investigation some polymer samples were not available and attention was directed towards finding effective combinations of polymers. A number of combinations of anionic polymer in dosages of about 1.0 mg/l followed by about 5 mg/l of cationic polymer produced tough, rapid settling flocs. Typical results of supernatant BOD tests after the addition of an anionic, followed by a cationic polymer are shown on Figure 2.

Results of some visual observations during jar testing are tabulated in Appendix A.

Among the last polymers to arrive were products of Hercules Incorporated and of Cyanamid of Canada Limited. Two cationic products of these companies, Hercofloc 812 and Magnifloc 560C, respectively, were found to produce good flocculation of raw sewage solids when used alone. When more

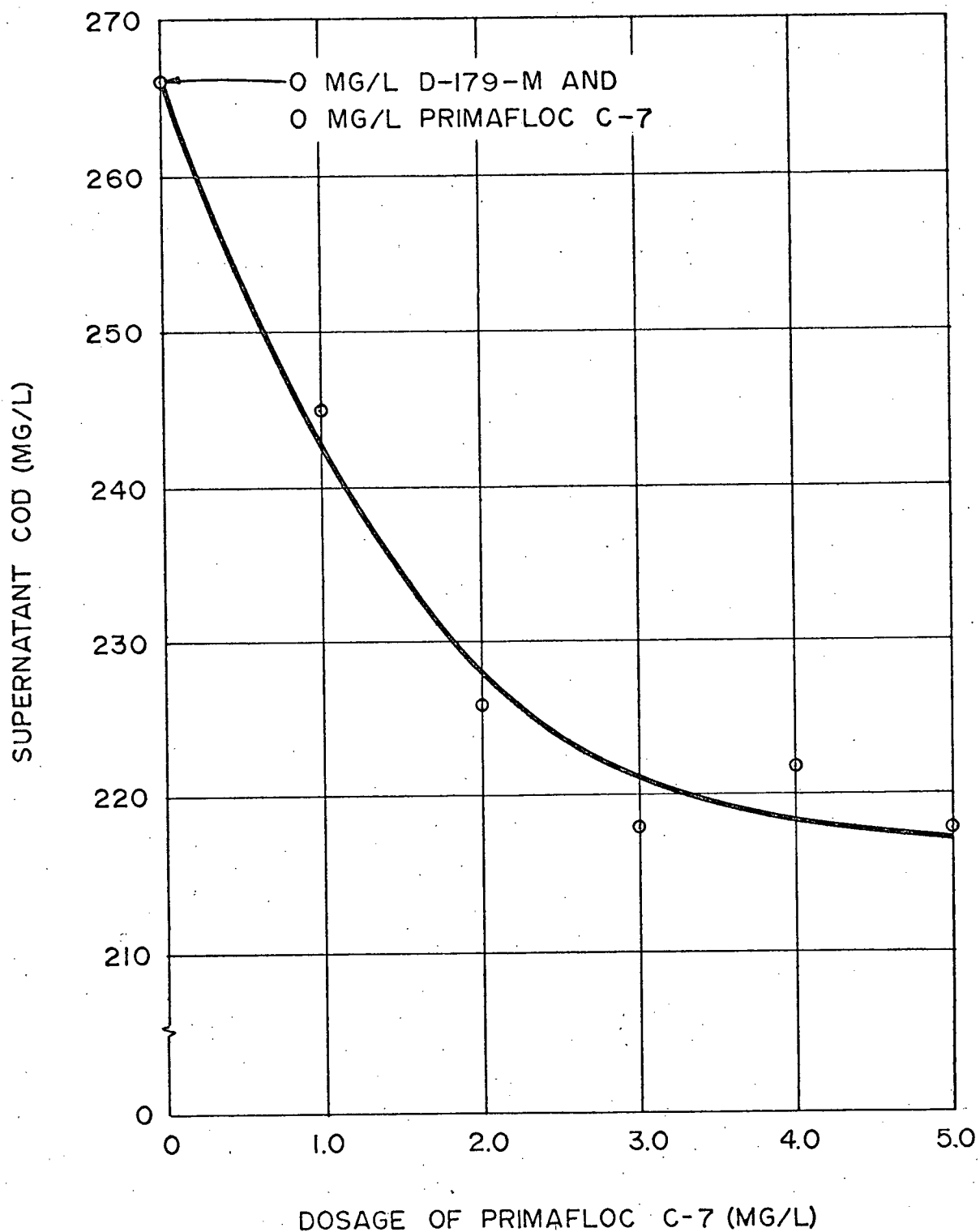


FIGURE 2 - JAR TEST SUPERNATANT COD AS A FUNCTION OF DOSAGE OF CATIONIC ROHM AND HAAS "PRIMAFLOC C-7" PRECEDED BY 1.0 MG/L OF ANIONIC ALCHEM "D-179-M"

samples were received from Hercules, cationic Hercofloc 814.2 was also found to produce good results. Typical results of BOD and COD analyses of jar test supernatants for these products are shown on Figures 3 and 4.

Two manufacturers suggested the addition of inorganic salts, such as ferric chloride, followed by anionic polyelectrolyte for the efficient removal of suspended solids and BOD in a primary plant. Subsequently jar tests were run using combinations of ferric chloride and anionic polymers. The results of one such test in which twelve jars were dosed with combinations of 5, 15, and 30 mg/l ferric chloride and 0, 0.5, 1.0, and 2.0 mg/l Hercofloc 836.2 are presented as supernatant BOD "contours" on Figure 5.

Results of BOD and COD removal efficiencies in tests using settling columns are presented in Table I.

In summary, the limited number of jar test and settling column results presented herein are inconclusive regarding removal of BOD and COD for various dosages of polymers and ferric chloride. They indicate, however, for a weak to medium strength sewage, that BOD and COD removal efficiencies of 50 to 70 percent can be obtained using 30 mg/l of FeCl_3 in combination with 0.5-1.0 mg/l of anionic Hercofloc 836.2. Similar efficiencies were achieved using 6-14 mg/l of either of the cationic Hercofloc polymers, 812 or 814.2, as the sole coagulant.

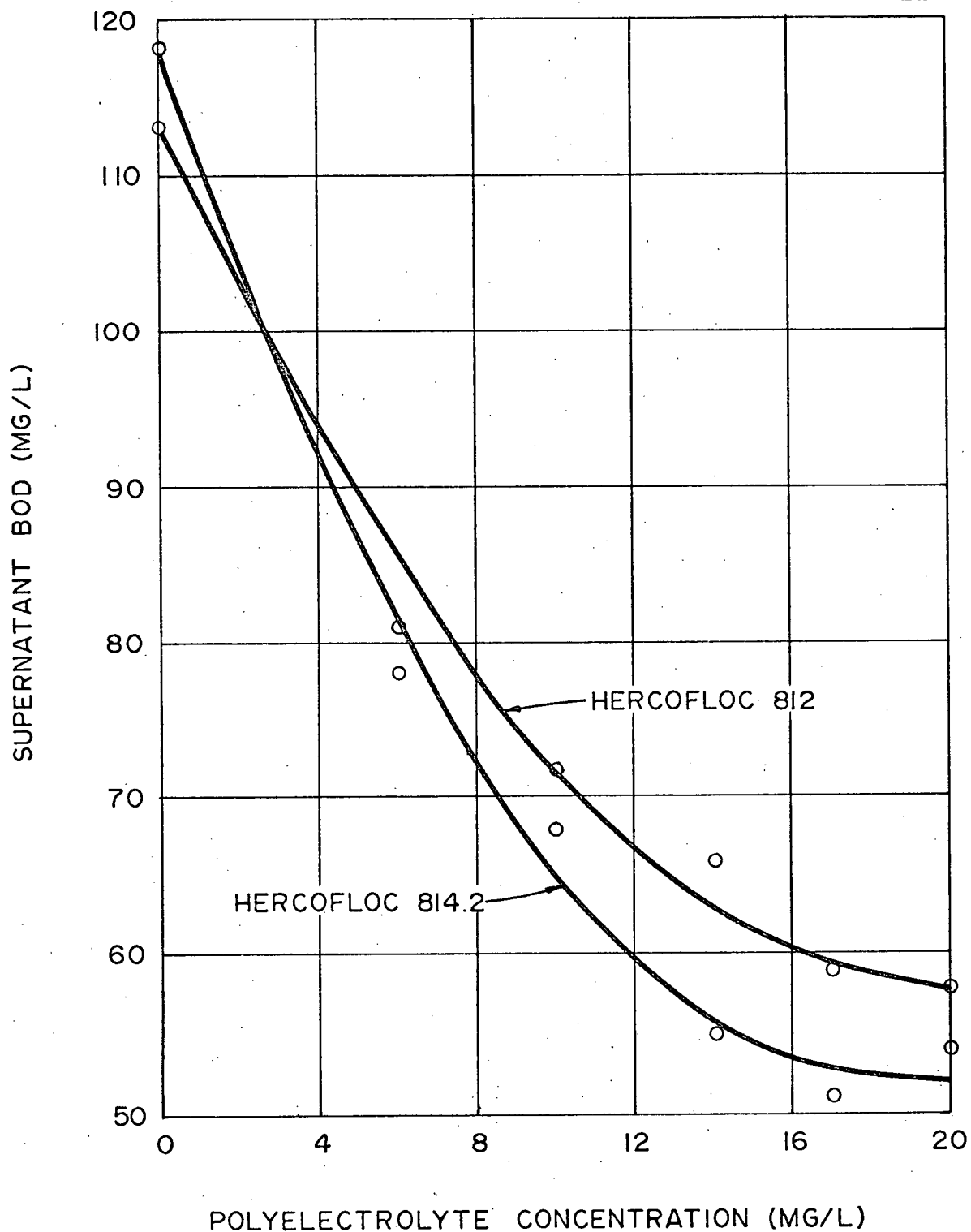


FIGURE 3-JAR TEST SUPERNATANT BOD AS A FUNCTION OF DOSAGE OF HERCULES INCORPORATED'S CATIONIC POLYELECTROLYTES "HERCOFLOC 812" AND "HERCOFLOC 814.2".

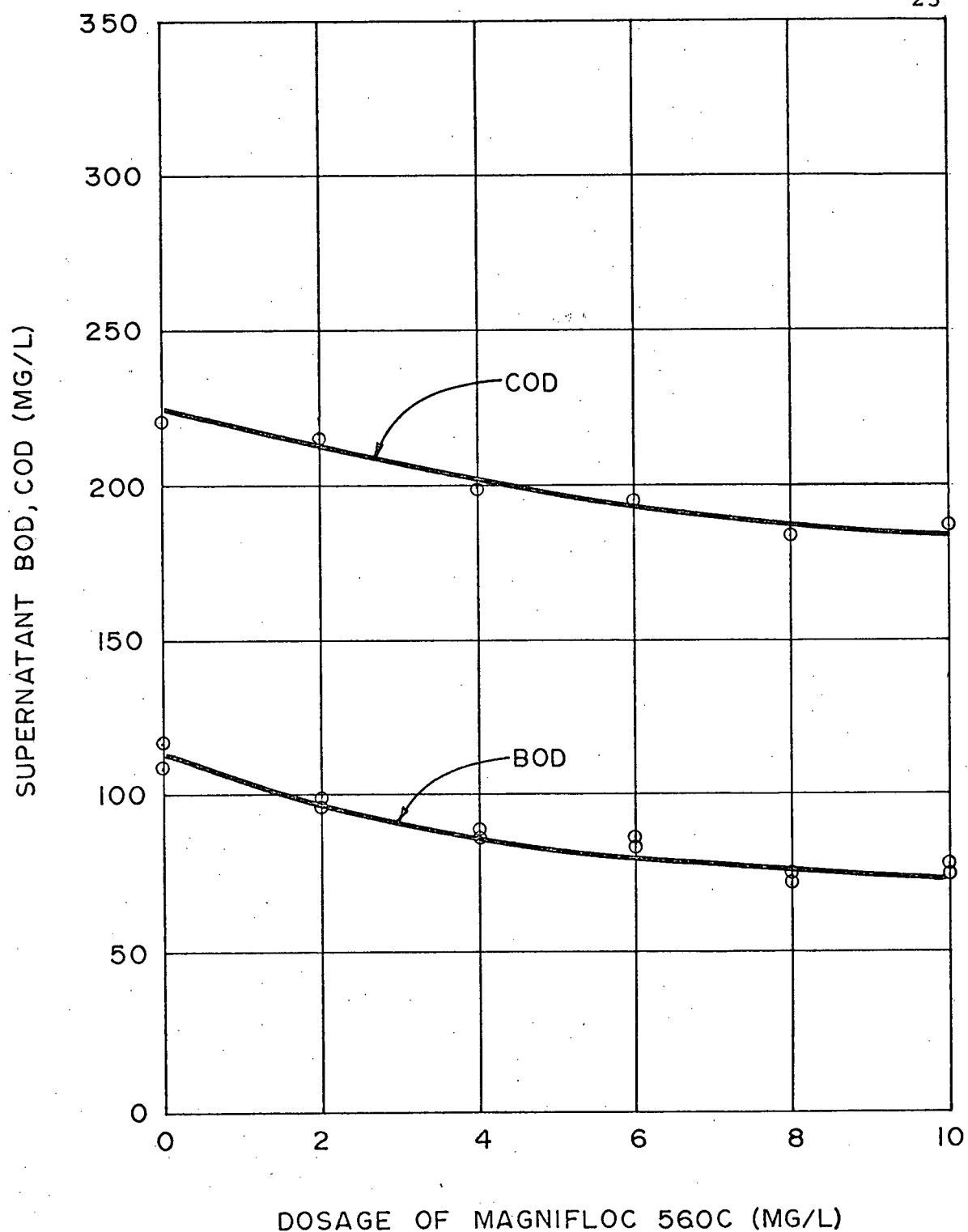


FIGURE 4-JAR TEST SUPERNATANT COD AND BOD AS FUNCTIONS OF DOSAGE OF CYANIMID'S CATIONIC POLYELECTROLYTE "MAGNIFLOC 560C".

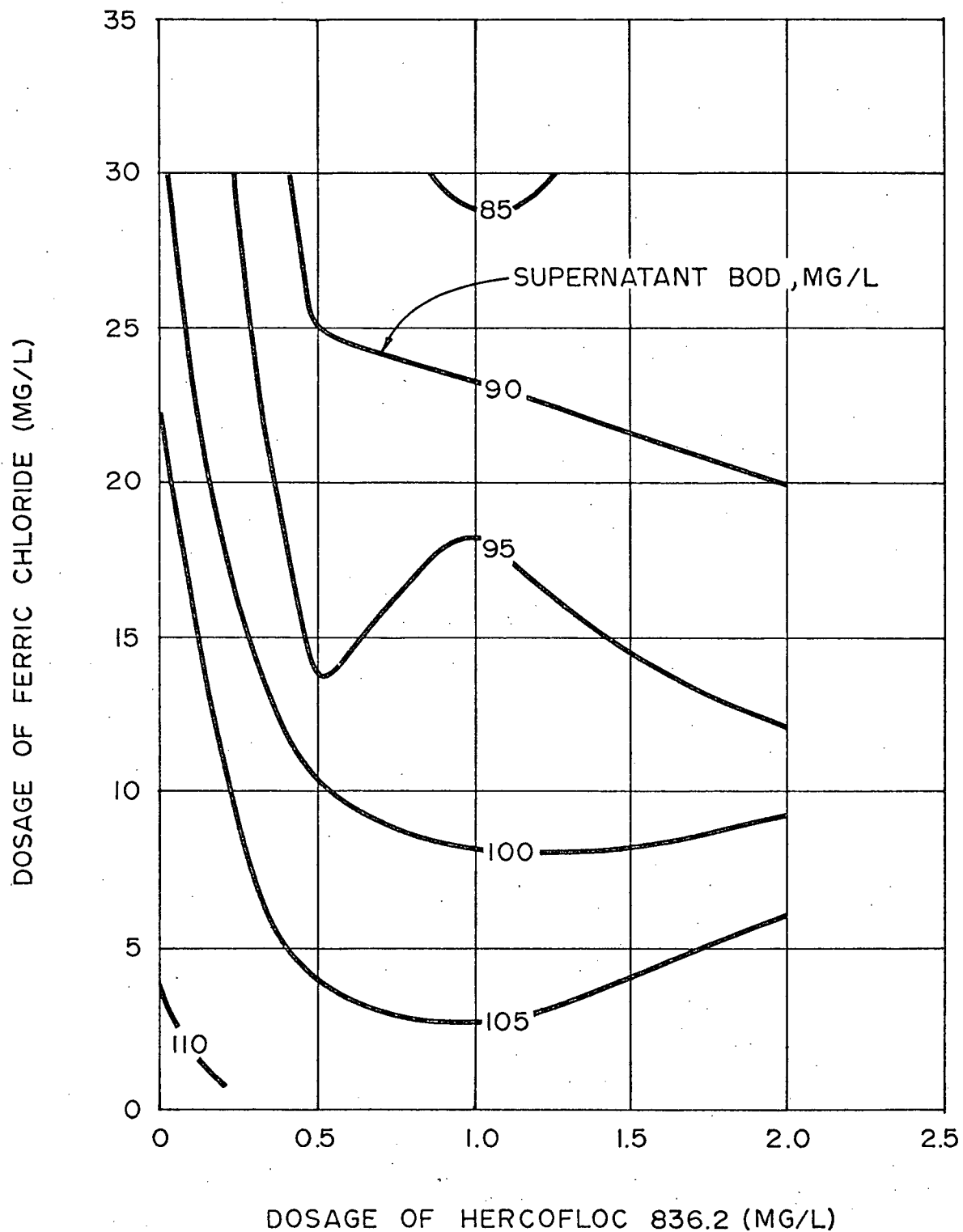


FIGURE 5- JAR TEST SUPERNATANT BOD AS A FUNCTION OF DOSAGE OF FERRIC CHLORIDE AND HERCULES INCORPORATED'S ANIONIC POLYELECTROLYTE "HERCOFLOC 836.2".

TABLE I

BOD₅ AND COD REMOVAL EFFICIENCIES
ACHIEVED IN SETTLING COLUMN TESTS*February 11, 1971

	No Coagulants		6 mg/l Hercofloc 812	
	BOD ₅	COD	BOD ₅	COD
Raw Sewage, mg/l	178	390	152	330
Supernatant, mg/l	125	260	70	160
% Removal	30	33	54	52

April 27, 1971

	30 mg/l FeCl ₃ and 1 mg/l Hercofloc 836.2		14 mg/l Hercofloc 814.2	
	BOD ₅	COD	BOD ₅	COD
Raw Sewage, mg/l	126	358	138	374
Supernatant, mg/l	50	159	63	175
% Removal	60	56	54	53

June 16, 1971

	No Coagulants		30 mg/l FeCl ₃ and 1 mg/l Hercofloc 836.2		14 mg/l Hercofloc 814.2	
	BOD ₅	COD	BOD ₅	COD	BOD ₅	COD
Raw Sewage, mg/l	180	551	180	551	180	551
Supernatant, mg/l	128	322	49	170	89	224
% Removal	29	42	73	69	51	59

* 15-minutes sedimentation

3.2 Problems with Air Mixing of Polymers and Sewage in Settling Columns

Large tenacious flocs formed almost immediately when compressed air was used to provide mixing of raw sewage and 14 mg/l of Hercofloc 814.2 in the settling columns. Air bubbles trapped in the flocs caused them to rise, whereas inorganic "grit" settled. Only by stirring the surface in a manner which created considerable turbulence could the flocs be broken up sufficiently to allow the trapped air to escape and the flocs to settle.

This observation suggested a possible means of separating organics from grit in a physical-chemical plant using polymers. Elimination of the conventional sedimentation basin may be possible by using a single aerated basin to achieve flotation of organics and sedimentation of grit. However further sludge dewatering may be required to obtain solids concentrations comparable to those achieved using conventional sedimentation basins, and the trapped air may preclude anaerobic digestion, unless removed.

3.3 Filterability of Digested Sludges

Effluent from the digester containing large amounts of the cationic polymer, Hercofloc 814.2, precipitated more rapidly than effluent from the other two digesters. It was hypothesized, therefore, that the polymer still retained some properties as a coagulant after digestion. These observations led to an

investigation of the filterability of the digested sludges using the Buchner funnel vacuum filtration test.

Results of the Buchner funnel filtration tests are presented in Table II.

TABLE II
VALUES OF SPECIFIC RESISTANCE IN SEC^2/G
OBTAINED FROM BUCHNER FUNNEL VACUUM
FILTRATION TESTS ON DIGESTED SLUDGES

Digester Number	Coagulant(s) Contained in Sludge	Vacuum in mm Hg		
		375	500	625
1	None	3000×10^7	2700×10^7	3200×10^7
2	Hercofloc 814.2 (cationic polymer)	165×10^7	180×10^7	205×10^7
3	FeCl_3 and Hercofloc 836.2 (anionic polymer)	2600×10^7	2750×10^7	2950×10^7

These results clearly indicated that cationic Hercofloc 814.2 in digester No. 2 retained some value as an aid to sludge dewatering throughout digestion, whereas the FeCl_3 and anionic polymer in digester No. 3 had not.

Various authors have published values of specific resistance for domestic sludge. Some of these values are:

BOLTON AND KELIN [8]

- Digested	$1420 \times 10^7 \text{ sec}^2/\text{g}$
- Digested and coagulated	$24 \times 10^7 \text{ sec}^2/\text{g}$
- Maximum for satisfactory vacuum filtration	$40 \times 10^7 \text{ sec}^2/\text{g}$

ECKENFELDER [4]

- Digested conditioned $10.5 \times 10^7 \text{ sec}^2/\text{g}$

METCALF AND EDDY [9]

- Digested $100-600 \times 10^7 \text{ sec}^2/\text{g}$
- Digested and coagulated $3-40 \times 10^7 \text{ sec}^2/\text{g}$

RICH [7]

- Digested (?) $900 \times 10^{10} \text{ sec}^2/\text{lb. mass}$
($2000 \times 10^7 \text{ sec}^2/\text{g}$)

As expected, the test values of specific resistance from the control digester were higher than published values because the digested "sludges" tested were the mixed contents of the digesters rather than the settled or elutriated sludges which would normally be dewatered by vacuum filtration, and thus contained excess colloidal matter which hinders filtration. Although the results are inconclusive, they indicate that a settled sludge from digester No. 2 could be successfully dewatered by vacuum filtration with little or no additional conditioning.

CHAPTER IV

RESULTS - ANAEROBIC DIGESTION

4.1 General

In the ensuing discussions of the effects on anaerobic digestion, the digesters have been numbered for convenience. Digester number one was the control digester and received sludge obtained by sedimentation without the use of coagulants; digester number two received sludge obtained using 14 mg/l of Hercofloc 814.2 as the coagulant; and digester number three received sludge obtained using 30 mg/l of ferric chloride as the primary coagulant and 1 mg/l of Hercofloc 836.2 as the coagulant aid. The influent or raw sludges and the effluent or digested sludges are given corresponding numbers.

The digestion parameters measured were discussed previously. Tabulated results of the tests performed are in Appendix B.

4.2 Problems During Digester Start-up

The laboratory digesters were put into operation on September 8, 1970 and filled to their working capacity of 7.5 l with digested sludge obtained from the Lions Gate sewage treatment plant in West Vancouver, British Columbia. On September 9, 1970, the first "feeding" of 250 ml of raw sludge from the same plant was added to each digester. Addition of sludge continued at the rate of 250 ml per day.

By September 14, the pH of the digesters had dropped to 6.6 from 7.1 initially. One day later, digester pH values dropped to a range of 6.3 to 6.4 and further addition of sludge was halted.

By September 28, with no further additions of sludge, the pH values had dropped further to less than 6.2. At this point an additional 3 liters of digested sludge was added to each digester, and 3 liters of the contents were removed. This raised the pH of each digester to the 6.4 to 6.5 range.

By October 5 there was no improvement in the digester pH values, even though no additional raw sludge had been added. It was decided, therefore, to add lime to the digesters to bring the pH up to a favorable level for the methane bacteria. Lime was added to digested sludge from the Lions Gate sewage treatment plant. This mixture, when added to the laboratory digesters at the rate of 50 ml per day, added lime at the rate of one pound of calcium hydroxide per day per thousand cubic feet of digester capacity. This sludge-lime mixture was added to each digester at a rate of 50 ml per day for four days, raising the pH of the digesters to the 6.6 to 6.7 range by October 8.

On October 17 the volatile acid content of the digesters was in the range of 500 to 900 mg/l as acetic. Because of these high values, the feeding was reduced initially to 50 ml of raw sludge per day, then gradually increased. The desired rate of 250 ml per day was reached on November 12. The pH of all three digesters was 6.9 on this date.

The digesters operated well at the desired rate of sludge addition for one week. During the night of November 18-19, however, the temperature controls on one digester malfunctioned. On the morning of November 19, the temperature of the digester was 35°C. A negative pressure in the digester indicated that gas production had fallen off and that the temperature was continuing to fall. When gas production failed to return to normal, sludge was exchanged between the healthy digesters and the upset one.

Raw sludge addition to the upset digester was reduced for the next few days. In spite of this, the volatile acids content of this digester was 440 mg/l as acetic on November 24 compared to 40 and 130 mg/l in the other two. The pH was 6.8 on this date, compared to 6.9 for the other two digesters.

The raw sludge addition rate of 250 ml per day was resumed on November 25, 1970 for all three digesters and no further problems occurred until March 29, 1971 when the pH of all three digesters began to fall. On March 31 the pH had dropped 0.2-0.3 units to values of 6.6-6.7. Therefore, raw sludge addition was discontinued for four days.

By April 5 the pH of all digesters was back to 6.8 and sludge addition was resumed. No more problems were encountered and addition of the experimental sludge began on April 29.

4.3 Results of Long-Term BOD Tests of Raw and Digested Sludges

Long-term BOD tests were performed on raw and digested sludges to determine the ratio of BOD_5 to BOD_L in order that the removal of BOD_L by digestion could be evaluated.

The classic formulation of the BOD curve is a continuous first order reaction of the form

$$y = L_0 (1 - e^{-Kt}) \quad \dots \quad (1)$$

where y is the amount of oxygen consumed or BOD after any time t ,

L_0 is the ultimate carbonaceous BOD or the total amount of oxygen consumed in the reaction,

K is the average reaction-rate constant,

e is the base of natural logarithms, and

t is time of incubation in days.

The BOD exerted by many complex wastes, including domestic sewage, conforms closely to this equation.

The three common methods of determining the values of L_0 and K , the method of moments, the log-difference method, and the graphical method, have been described by Eckenfelder [4]. All three methods were used and produced consistent results for the raw sludges tested.

Attempts to use these methods for the digested sludges were unsuccessful, and it is believed that the BOD exerted by digested sludge cannot be formulated by a first-order reaction

curve. The BOD curves for the digested sludges were "eyeballed", therefore, and the values for L_0 (BOD_L) are based on judgment.

The plotted long-term BOD curves are presented in Appendix C. The values of K and L_0 are shown in Table III.

TABLE III
RESULTS OF LONG-TERM, 20°C, BOD TESTS
ON RAW AND DIGESTED SLUDGES

	K (day ⁻¹)	L_0 (BOD_L) (g/l)	BOD_5 (g/l)	BOD_L/BOD_5
<u>Raw Sludges</u>				
1	0.31	10.5	8.3	1.27
2	0.44	13.2	11.7	1.12
3	0.36	12.2	10.2	1.20
<u>Digested Sludges</u>				
1	NA	3.4	1.45	2.34
2	NA	3.7	2.30	1.61
3	NA	3.6	1.95	1.85

NA - not applicable, first order reaction curve did not fit data.

4.4 Stabilization of Organics Calculated from BOD, COD and Volatile Solids Results

The removal of organics from the digesters is achieved biologically by conversion to more stable substances and gases, and physically during withdrawal of sludge. The purpose of this study was to determine the effects of chemicals on biological removal, thereby requiring the calculation of physical removal to account for it in the removal efficiency calculations.

In a system which is completely mixed, when sludge addition and withdrawal are continuous, and when influent sludge strength is constant, the concentration of volatile solids, BOD or COD at any time assuming physical removal only, can be determined from the following equation (see Appendix D):

$$C = C_o e^{-K_2 t} + \frac{K_1}{K_2} C_r (1 - e^{-K_2 t}) \dots (2)$$

where C is the volatile solids, BOD or COD concentration in the system at any time,

C_o is the initial concentration in the system at time zero,

C_r is the concentration in the raw sludge being added,

e is the base of natural logarithms,

K_1 is a rate constant equal to the volume of raw sludge added per unit of time divided by the volume in the system,

K_2 is a rate constant equal to the volume of digested sludge removed per unit of time divided by the volume in the system, and
 t is time.

The concentration of the raw sludge added to the digesters was not constant throughout the life of the project but it was nearly constant for several days at a time. In addition, sludge was not added and withdrawn continuously but occurred during a few minutes of each day.

The first problem was overcome by using a sequential calculation. A calculation was made for each different sludge using the "C" value obtained from the preceding calculation as the " C_0 " value in the new calculation.

The problem of addition and withdrawal during a few minutes of each day does not invalidate equation 2, as addition and withdrawal of sludge occurred simultaneously while the system was thoroughly mixed. A time unit of one day was used.

The calculated "C" value at any time therefore represents the theoretical concentration (volatile solids, BOD, COD) in the digester at that time assuming only physical removal.

The values of the constants K_1 and K_2 depend on the rate of sludge addition and removal. Raw sludge was added at the rate of 250 ml per day to a digester volume of 7.5 liters. The value of K_1 , therefore, was 0.0333 per day.

In order to maintain a constant volume of 7.5 l in the digesters, it was necessary to remove less than 250 ml per day from each digester to account for losses, mainly evaporation. The average rate of sludge removal was 243 ml per day from each digester. The value of K_2 therefore was 0.0324 per day.

Influent and effluent volatile solids, BOD and COD results have been used in conjunction with equation 2 to calculate the efficiency of removal of organics by the anaerobic process. The results are presented in Table IV. A sample calculation is included as Appendix D.

TABLE IV

EFFICIENCY OF STABILIZATION OF SLUDGE ORGANICS
CALCULATED FROM INFLUENT AND EFFLUENT BOD, COD AND VS RESULTS

	Volatile Solids (g/l)			BOD ₅ (g/l)			BOD _L (g/l)			COD (g/l)		
	Digester No.			Digester No.			Digester No.			Digester No.		
	1	2	3	1	2	3	1	2	3	1	2	3
<u>June 11, 1971</u>												
Organic Loading by Calculation	27.0	26.6	27.0	8.35	10.7	9.97	10.7	12.0	11.9	45.6	49.7	48.8
Organics in Digester Effluent	10.8	11.2	10.3	1.55	1.77	1.55	3.6	2.8	2.9	17.6	19.7	17.5
Efficiency of Removal by Bacteria, %	60	58	62	81	83	84	66	77	76	61	60	64
<u>June 28, 1971</u>												
Organic Loading by Calculation	26.5	26.1	26.6	8.03	11.2	9.85	10.3	12.6	11.7	45.7	50.4	48.9
Organics in Digester Effluent	10.7	11.1	11.2	1.85	2.08	2.16	4.3	3.3	4.0	17.3	18.8	18.5
Efficiency of Removal by Bacteria, %	60	57	58	77	81	78	58	74	66	62	63	62
<u>July 4, 1971</u>												
Organic Loading by Calculation	26.3	26.2	26.6	8.04	11.4	9.98	10.3	12.8	11.9	45.7	50.6	49.2
Organics in Digester Effluent	10.3	11.3	10.8	1.45	2.30	1.95	3.4	3.7	3.6	17.1	19.9	18.4
Efficiency of Removal by Bacteria, %	61	57	59	82	80	80	67	71	70	63	61	63
Average Efficiency, %	60	57	60	80	81	81	64	74	71	62	61	63

These results do not show any significant difference in the waste stabilization achieved by microbial action in the three digesters. Although a greater removal of ultimate carbonaceous BOD in the digesters receiving chemical sludges is indicated, this parameter is the least reliable of the four because of the difficulties experienced in determining BOD_L for the digested sludges.

It is significant also that the long-term BOD tests were run on effluent sludges obtained on July 4 and on the raw sludges used during the period of June 18 to July 4. The results for July 4, therefore, are considered to be the most representative of the true stabilization of BOD_L . These results are in close agreement within the accuracy of the experimental methods and add further credence to the conclusion that there was no significant difference in the waste stabilization achieved by microbial action in the three digesters as evidenced by the results for BOD_5 , volatile solids, and COD.

These results also indicate that the coagulants used were not toxic and did not physically interfere with the ability of the micro-organisms to penetrate the flocs formed during sedimentation.

4.5 Stabilization of Organics Calculated from Methane Production

McCarty [10] has shown stoichiometrically that 5.62 cubic feet of methane at standard temperature and pressure (STP) are produced per pound of BOD_L (ultimate carbonaceous BOD) or COD

stabilized (0.351 l/g). Thus, methane production serves as a measure of the efficiency of the stabilization of organics. Efficiency is calculated according to the equation:

$$S = \frac{100 C}{0.351 F} \quad \dots (3)$$

where S is the percentage of added BOD_L or COD

which is stabilized,

C is liters of methane produced per day,
(STP), and

F is grams of BOD_L or COD added per day.

Total gas production was also considered for use as an indicator of digester efficiency but was rejected. Various authors [2,4,9] report that gas production for a well-operating digestion tank is 12 to 22 cubic feet per pound of VS destroyed (0.75 to 1.37 l/g). This wide range of reported values renders total gas production impractical as a measure of VS stabilization.

When the strength and amount of the waste added to a digester varies, as it did in this study, a problem arises in attempting to determine the percentage of organics stabilized from the methane produced. Gas production and composition on a particular day is influenced to a considerable extent by the waste added within a few days prior to gas measurement but both composition and amount of gas produced also reflect to some extent the strength and amount of raw sludge added weeks prior to measurement and analysis. Only a very detailed, complicated

and time-consuming experiment could sort out the relative contributions from the sludges added at various times.

For the purpose of estimating efficiency of stabilization of organics, the organic strength of the sludge added on the day the gas production was monitored and composition analyzed was assumed to account for total methane production for the day.

Estimates of waste stabilization based on methane production are presented in Table V. The following observations are based on these results.

1. The values of ultimate carbonaceous BOD removed far exceed 100% suggesting that the aerobic BOD test provides a poor measure of the biodegradability anaerobically of domestic wastewater sludge. Although the validity of the stoichiometrically determined ratio of methane produced to COD or BOD_L destroyed can be questioned, its validity has reportedly been shown to be correct for "a wide variety of wastes varying from pure laboratory substrates to complex waste sludge" [10]. It can be concluded, therefore, that domestic sludge contains large quantities of organic substances which are biodegradable anaerobically during conventional digester detention times, but which require longer periods of time or are not stabilized at all aerobically. Cellulose is such a substance.

TABLE V

ESTIMATES OF EFFICIENCY OF STABILIZATION
OF SLUDGE ORGANICS FROM METHANE PRODUCTION

<u>Period of Operation</u>	<u>Digester Number</u>	<u>Gas Pro- duction @ STP*, Liters/ day</u>	<u>Percent Methane by Volume</u>	<u>Methane Produc- tion @ STP*, Liters/ day</u>	<u>Reduction in Oxygen Demand from Methane Produced, Grams/day</u>	<u>COD Added, Grams/ day</u>	<u>BOD_L Added, Grams/ day</u>	<u>Percent COD Reduced</u>	<u>Percent BOD_L Reduced</u>
June 4	1	3.94	58.2	2.29	6.54	11.4	1.99	57	330
to	2	4.04	63.6	2.57	7.33	12.5	3.00	59	240
June 17	3	3.81	62.2	2.37	6.75	11.2	2.30	60	290
June 18	1	3.38	59.2	2.00	5.70	11.0	2.49	52	230
to	2	3.62	63.4	2.30	6.55	12.5	3.36	52	195
July 4	3	3.21	62.9	2.02	5.76	12.2	3.07	47	190

*Standard temperature and pressure

2. No particular significance is attached to the lower efficiencies obtained for the period of June 18-July 4 than for the period of June 4-17. One possible explanation for this is that the sludges used during the latter period contained a greater ratio of organic compounds which were slow to degrade anaerobically, resulting from differences in the domestic sewage on the days the sludges were obtained.
3. The differences in relative values of waste stabilization parameters for the three digesters based on methane production are not significant. Therefore, neither toxicity of coagulants nor physical inability of micro-organisms to penetrate the flocculated particles added to the digesters is indicated.

4.6 Comparison of Results Obtained for Waste Stabilization by the Two Methods

A comparison of organic stabilization efficiencies calculated directly from influent and effluent results and indirectly from methane production is presented in Table VI. The following additional comments are based on these results.

1. The results obtained by direct calculation using influent and effluent waste strength parameters are more reliable. The problem with calculating stabilization efficiency from gas measurements,

TABLE VI

COMPARISON OF THE EFFICIENCY OF STABILIZATION OF ORGANICS
 CALCULATED DIRECTLY FROM BOD, COD AND VS RESULTS
 AND INDIRECTLY FROM METHANE PRODUCTION

<u>Date</u>	<u>Digester No.</u>	<u>From Methane Production</u>		<u>From Calculations</u>			
		<u>BOD_L</u>	<u>COD</u>	<u>VS</u>	<u>BOD₅</u>	<u>BOD_L</u>	<u>COD</u>
June 4	1	330	57	60	81	66	61
to	2	240	59	58	83	77	60
June 17	3	290	60	62	84	76	64
June 18	1	230	52	60	80	62	62
to	2	195	52	57	80	72	62
July 4	3	190	47	58	79	68	62

under the test conditions of varying influent strength, was the previously mentioned difficulty of assigning representative BOD and COD values to the raw sludge contributing to gas production on any particular day.

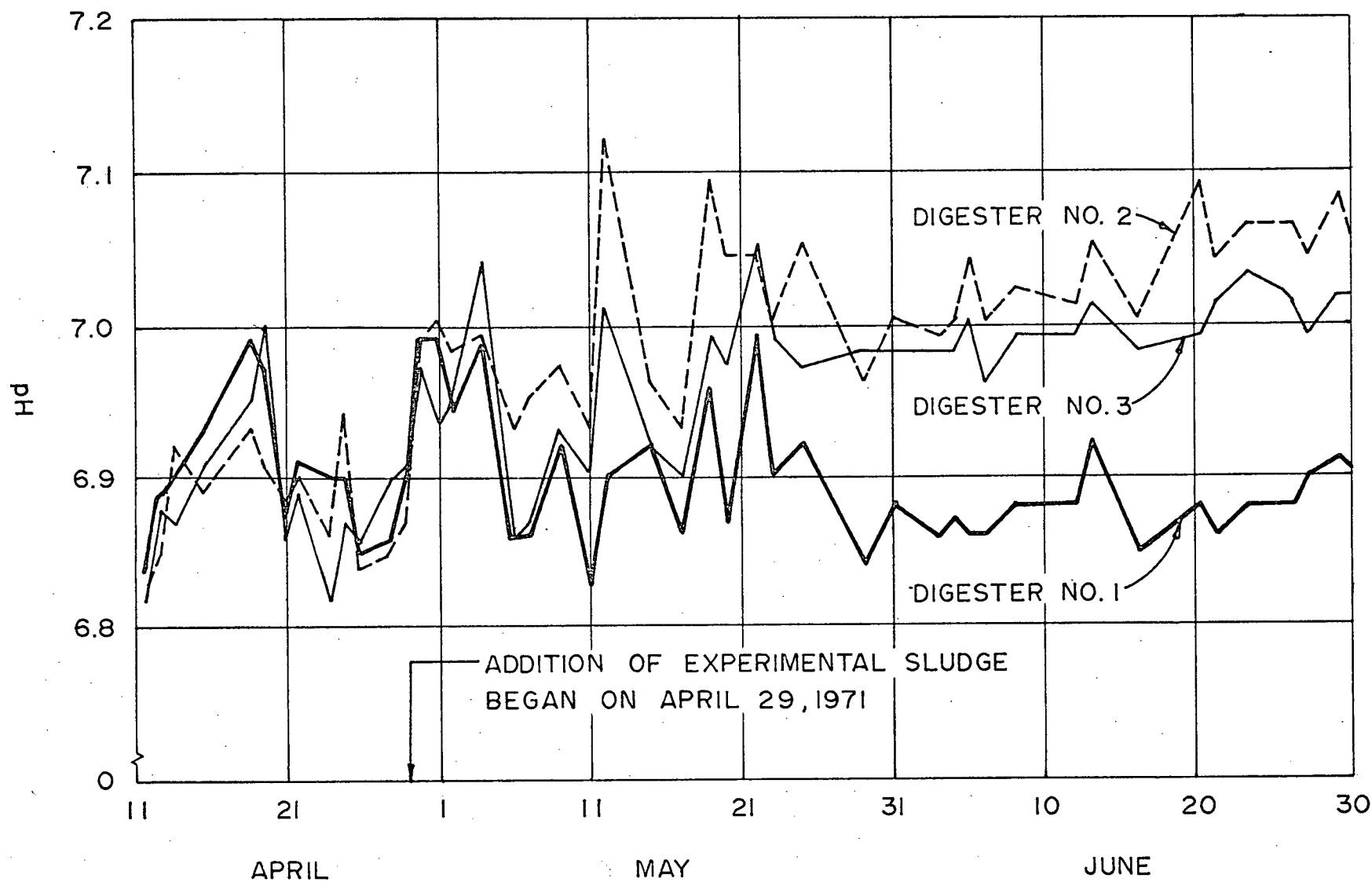
2. Comparisons of BOD_L and COD results indicate that COD is a reasonably accurate parameter for the determination of oxygen demand satisfied by anaerobic digestion. The aerobic BOD test clearly underestimated the oxygen demand of the raw domestic sludges used in the experimental program.

4.7 Significance of Other Digestion Parameters Monitored

The results of determinations of pH, alkalinity, volatile acids, and CO_2 content of digester gas (Appendix B) during the addition of the tests sludges all fall within the limits for normal anaerobic treatment as indicated by McCarty [10]. None of these parameters indicated unbalanced treatment.

Results of digester pH and CH_4 content of digester gas are plotted on Figure 6 and 7. Throughout the test period digester No. 2 consistently registered the highest values of pH, alkalinity, and methane content of gas. No. 2 was followed closely by No. 3, and No. 1, the control digester, consistently registered the lowest values for these parameters.

FIGURE 6 - pH OF DIGESTERS



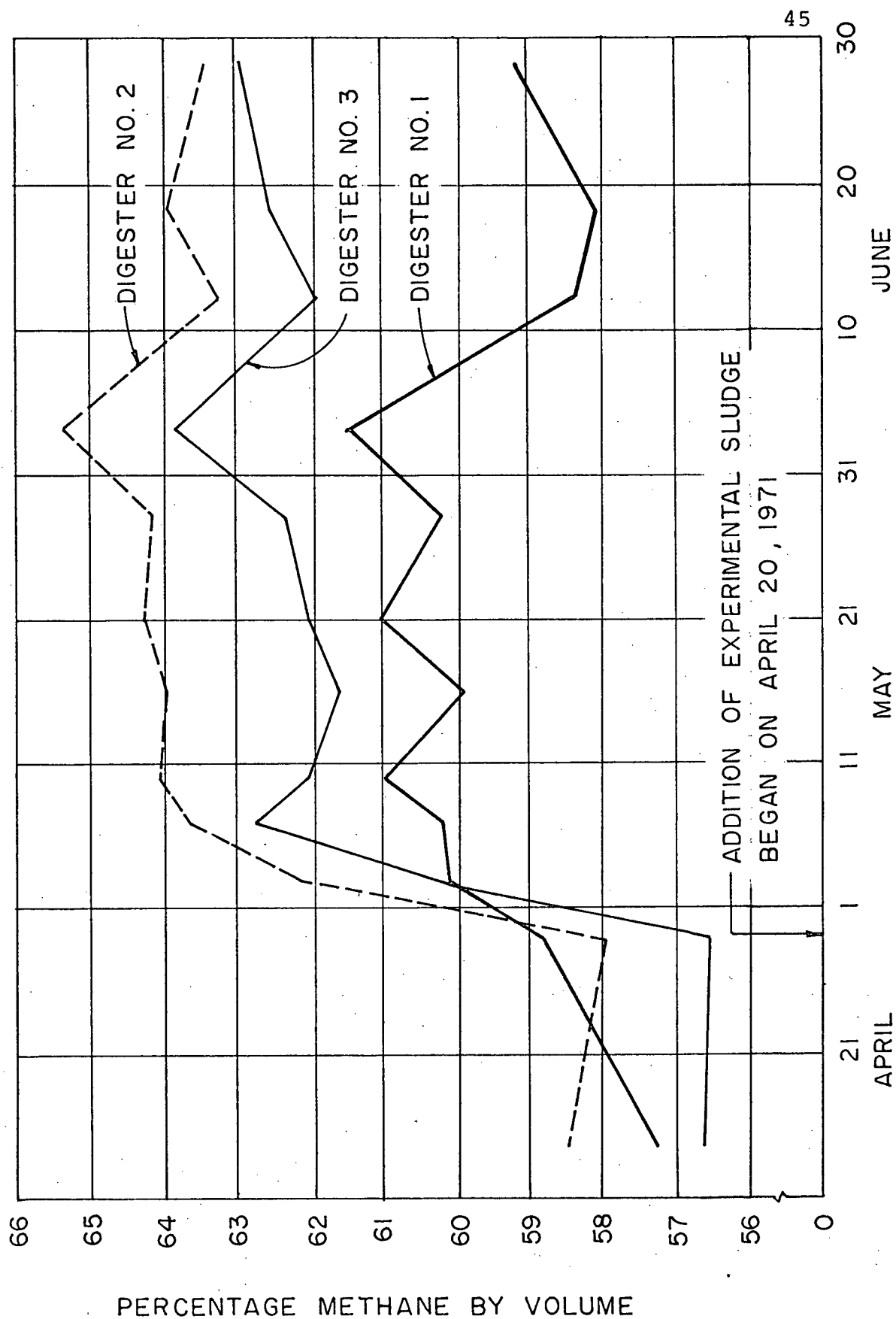


FIGURE 7- METHANE CONTENT OF DIGESTER GASES

These results indicate better operating conditions for the digesters receiving chemically coagulated sludge. The higher values of alkalinity signify a greater buffering capacity against a temporary digester imbalance due to changes in the nature of the waste or organic loading.

The higher methane content of the gas from No. 2 and No. 3 digesters is important in sewage treatment because of the calorific value of methane.

The total iron content of the raw sludges averaged 130 mg/l for sludge No. 1, 110 mg/l for sludge No. 2 and 630 mg/l for sludge No. 3. The maximum value of total iron in the effluent from No. 3 digester was 500 mg/l. There was no apparent impairment of digestion efficiency as a result of this iron concentration nor, apparently, did ferric chloride act synergistically with the anionic polymer to create toxicity.

CHAPTER V

ECONOMICS OF CHEMICAL TREATMENT

As discussed in Chapter I, there are a number of instances in which chemical treatment of sewage may be beneficial. Usually the choice of treatment processes is governed by economic considerations, but in two cases, specifically the use of coagulants to assist an existing overloaded plant or when a waste contains components which are inhibitory to biological processes, some form of chemical treatment may be mandatory to meet effluent requirements. In addition, when there are seasonal variations in the volume and strength of sewage, when plain sedimentation is normally adequate but receiving water limitations at times necessitate better treatment, or when land is expensive, chemical coagulation in combination with physical treatment may be a particularly attractive alternative to biological processes.

While it is recognized that plain sedimentation assisted by chemical coagulation cannot be expected to achieve the BOD and solids removal efficiencies of biological treatment, the basis of cost comparisons used herein is the difference between the amortized capital plus annual operation and maintenance costs for conventional activated sludge versus primary treatment. This difference is used to calculate the quantities of coagulants and coagulant aids which could economically be added before it becomes more economical to provide biological treatment of the supernatant. Capital and operation and maintenance costs are extracted from a paper by Smith [11] and are reported to

include preliminary expenses such as engineering and legal fees, land acquisition, and interest during construction, whereas ancillary works such as interceptors, outfalls, or pumping stations are excluded.

Cost figures presented by Smith represent June, 1967 prices. Capital costs have been adjusted to August, 1975 prices using the U.S. Environmental Protection Agency Sewage Treatment Plant Construction Cost Index. This index stood at 119.11 in June, 1967 and has been projected to 244 for August, 1975 (Figure 8). Operation and maintenance costs reflect the wages paid to employees, hence the U.S. Department of Labour Average Earnings for Nonsupervisory Workers in Water, Steam and Sanitary Systems was used to adjust all operating and maintenance costs to the August, 1975 level (Figure 9) [12]. The June, 1967 value was \$2.80 and the projected August, 1975 value is \$4.94.

The updated cost estimates for primary and for conventional activated sludge treatment are shown on Figure 10. To bring all costs to a common base, capital costs were amortized over a twenty-five year period at ten percent interest and shown as debt service. Operating and maintenance costs are added to debt service costs to obtain total treatment costs.

Figure 11 shows the economic dosages of cationic Hercofloc 814.2 and of ferric chloride used in combination with 0.5 mg/l of anionic Hercofloc 836.2 versus design capacity. Costs used in the analysis were \$0.40 per pound for anhydrous ferric chloride, \$1.40 per pound for the cationic polymer and \$1.20 per pound for the anionic polymer. Polymer costs were supplied by

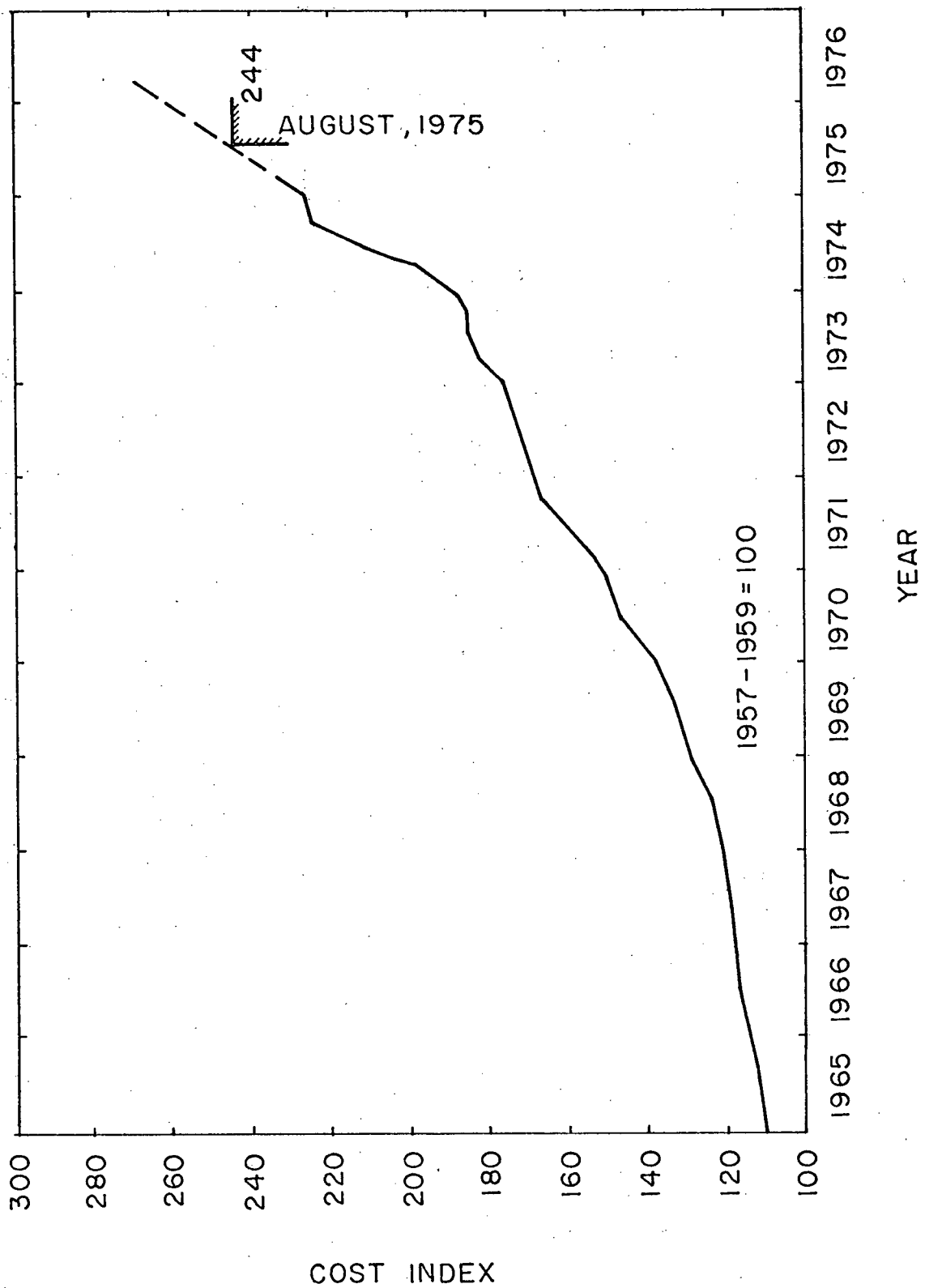


FIGURE 8 - U.S. ENVIRONMENTAL PROTECTION AGENCY
SEWAGE TREATMENT PLANT CONSTRUCTION COST INDEX.

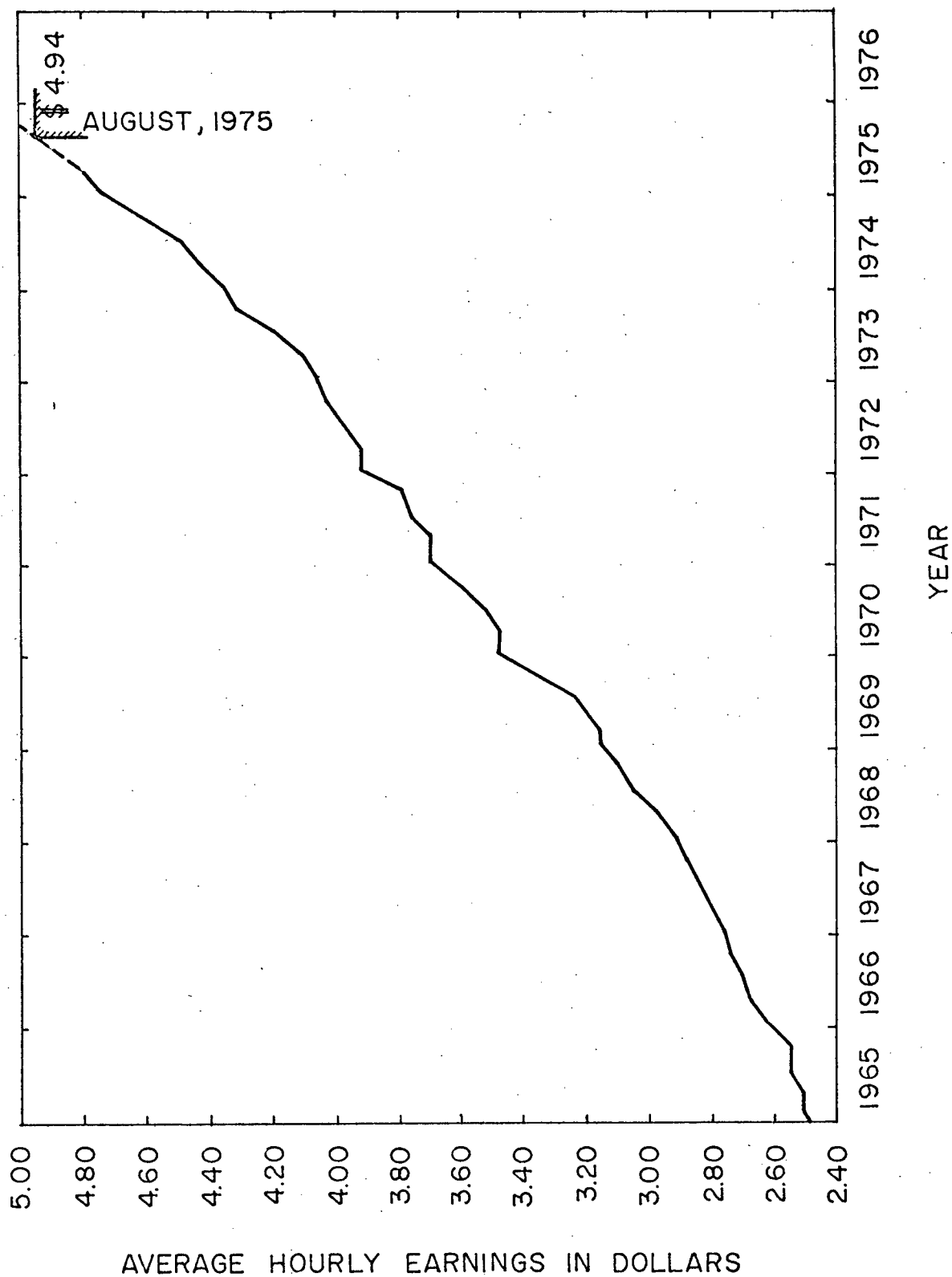
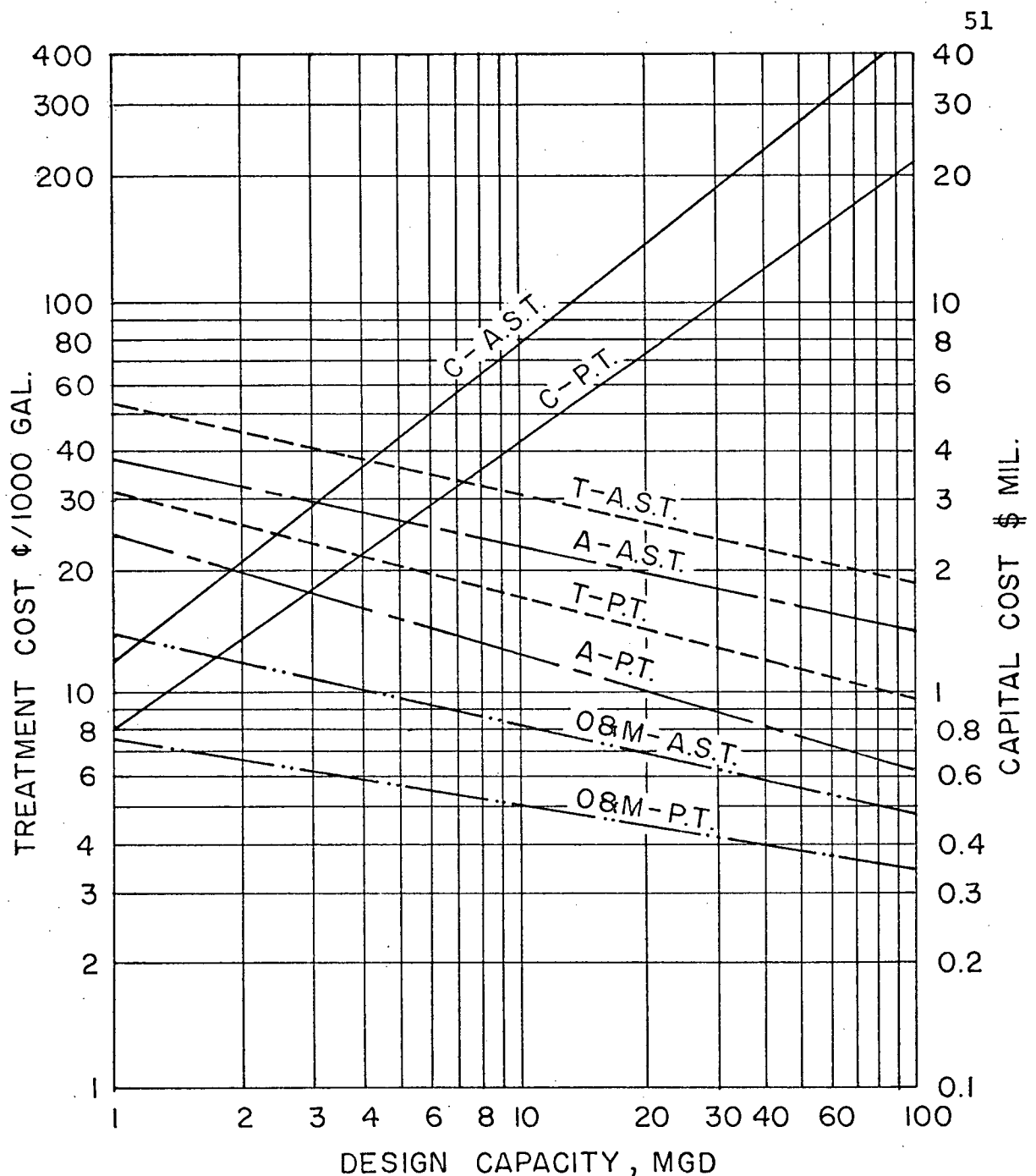


FIGURE 9 - U.S. DEPARTMENT OF LABOR - AVERAGE EARNINGS FOR NONSUPERVISORY WORKERS IN WATER, STEAM AND SANITARY SYSTEMS.



C=CAPITAL COST, \$ MIL.

A=DEBT SERVICE, ¢/1000 GAL. (10%-25 YEARS)

O&M=OPERATING AND MAINTENANCE COST, ¢/1000 GAL.

T=TOTAL TREATMENT COST, ¢/1000 GAL.

P.T.=PRIMARY TREATMENT

A.S.T.=ACTIVATED SLUDGE TREATMENT

FIGURE 10-CAPITAL COST, OPERATING AND MAINTENANCE COST AND DEBT SERVICE VS. DESIGN CAPACITY FOR PRIMARY AND ACTIVATED SLUDGE PLANTS ADJUSTED TO AUGUST, 1975.

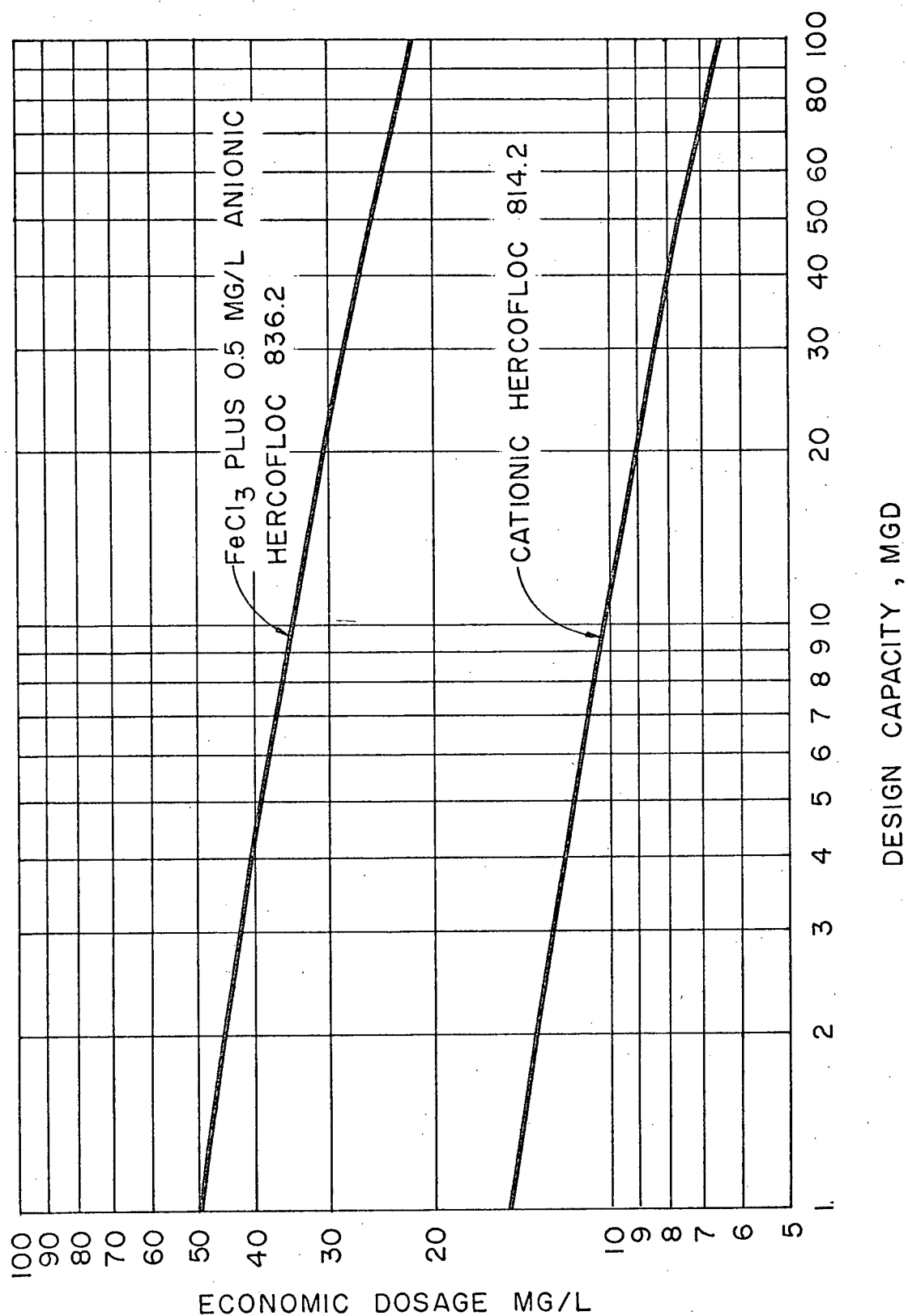


FIGURE II- ECONOMIC DOSAGES OF CATIONIC POLYELECTROLYTE AND OF FERRIC CHLORIDE AND 0.5 MG/L OF ANIONIC POLYELECTROLYTE FOR PLANTS OPERATING AT DESIGN CAPACITY

Hercules Incorporated in August, 1975. Economic dosages were obtained on the basis of the difference in total annual cost of conventional activated sludge and primary treatments.

The capital cost of a polymer mixing and feeding installation including dispersing mechanisms, automatic controls, mixers, tanks and transfer pumps is less than \$20,000 and was ignored as it did not significantly affect the analysis. This cost would be slightly higher if ferric chloride and a polymer were used. The additional cost of manpower in a plant utilizing chemical treatment was also ignored as it wasn't documented and does not appear to be significant.

Economic dosages were obtained on the basis of design capacity of the two types of plants considered. Therefore, Figure 11 presents economic dosages for plants operating at capacity. Normally treatment plants operate below capacity for a number of years, and even higher chemical dosages are economical under these circumstances.

The economic analysis considers the overall cost of treatment rather than the cost to a municipality or regional sewerage authority. Usually senior government financial assistance is available for capital expenditures in the form of grants or debt forgiveness whereas no assistance is normally available toward operating costs. Such assistance favours biological treatment over chemical treatment.

Results of the economic analysis show that maximum economic dosages of the cationic polymer Hercofloc 814.2 added continuously to primary plants operating at capacity are 14.9, 10.2,

and 6.6 mg/l for 1, 10, and 100 mgd plants, respectively. Similarly, for ferric chloride and 0.5 mg/l of the anionic polymer Hercofloc 836.2, the economic dosages of FeCl_3 are 51, 34 and 21.5 mg/l, respectively. For dosages greater than these amounts, the addition of secondary activated sludge treatment becomes more economical.

Economic dosages were determined on the basis of the assumption that the degree of treatment afforded by physical-chemical treatment is adequate to meet required receiving water quality objectives. The additional removal of organics obtainable using biological treatment is considered to be of no economic value in this analysis. A comparison based on cost per pound of BOD removed would further reduce these economic quantities.

When these results are combined with the jar and settling column test results of Chapter III, it becomes apparent that use of the cationic polymer, Hercofloc 814.2, as a primary coagulant, would not likely be an economically feasible alternative to secondary treatment for plants operating at capacity, unless pilot plant tests indicate that a dosage of somewhat less than 14 mg/l could achieve an acceptable degree of treatment. Use of ferric chloride as the primary coagulant in combination with anionic Hercofloc 836.2 as a coagulant aid, however, appears to be an economically attractive alternative to secondary treatment for plants in the 1 to 10 mgd size range.

An additional economic benefit, not considered here, would be the improved dewaterability of the digested sludge when using Hercofloc 814.2.

CHAPTER VI

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 Summary

1. The advent of high molecular weight, long-chain polyelectrolytes has stimulated research into their use in sewage treatment for removal of organic solids in primary and secondary treatment and as sludge dewatering aids in vacuum filtration and centrifugation.

2. The research reported on herein stems from a concern about possible polymer toxicity to microbial life in biological treatment processes.

3. The scope of this study was limited to a determination of the effects on the anaerobic digestion process of the chemical sludge obtained from the coagulation and sedimentation of a domestic sewage employing polyelectrolytes and ferric chloride as coagulants.

4. Jar tests were performed to evaluate several polymers as primary coagulants or as coagulant aids for clarification of domestic wastewater.

5. Effects on anaerobic digestion were evaluated using three laboratory scale model digesters. Digester contents were mixed continuously and operating temperatures were $32 \pm 1^\circ\text{C}$. Digesters were "fed" once per day on a fill and draw basis. Hydraulic and solids retention times were 30 days.

6. Digester No. 1 served as a control and received sludge obtained by sedimentation without the use of coagulants; No. 2 received sludge obtained using 14 mg/l of Hercofloc 814.2 as the coagulant; and No. 3 received sludge obtained using 30 mg/l of ferric chloride as the primary coagulant and 1 mg/l of Hercofloc 836.2 as a coagulant aid.

7. A limited number of jar tests and settling column tests were carried out to determine BOD and COD reductions with the aid of coagulants. The results indicate, for a weak to medium strength sewage, that BOD and COD removal efficiencies of 50 to 70% can be obtained using 30 mg/l of FeCl_3 in combination with 0.5-1.0 mg/l of anionic Hercofloc 836.2. Similar efficiencies were achieved using 6-14 mg/l of either of the cationic Hercofloc polymers, 812 or 814.2, as the sole coagulant.

8. Visual observations of jar tests indicate that certain combinations of anionic polymers followed by a cationic polymer were capable of producing tough, rapid-settling flocs. Dosages of about 1 mg/l and 5 mg/l, respectively, were required.

9. The value of specific resistance obtained from a Buchner funnel vacuum filtration test of the effluent sludge from Digester No. 1, the control digester, was 18 times as high as the value obtained for sludge from No. 2, the digester containing the cationic polymer Hercofloc 814.2, clearly indicating that the polymer retained some value as a sludge dewatering aid throughout digestion. However, the sludge from No. 3, the digester containing FeCl_3 and anionic polymer, did not dewater more readily than sludge from the control digester.

10. Calculations of waste stabilization from BOD_5 , BOD_L , COD and VS results indicate treatment efficiencies of approximately 81, 70, 62 and 59 percent, respectively, for all three digesters.

11. Waste stabilization calculations, based on influent and effluent BOD, COD, and VS results and on methane production, failed to indicate any toxicity or physical inability of anaerobic micro-organisms to penetrate the flocs formed as a result of the addition of coagulants and aids to sewage sedimentation.

12. Estimates of efficiency of waste stabilization based on methane production include removal efficiencies for BOD_L ranging from 190 to 330% of the BOD_L added to the digesters. It was concluded, therefore, that the conventional aerobic BOD test is a poor means of measuring the anaerobic biodegradability of domestic sludge.

13. Measured values of COD removal corresponded closely to estimated values based on methane production. It was concluded, therefore, that the COD test is a reasonably good method of determining the oxygen demand stabilized by anaerobic digestion.

14. Results of pH, alkalinity, and volatile acids testing of digester effluents and total methane production from the digesters did not indicate unbalanced treatment due to the presence of coagulants at any time. These values all fell within the published limits for normal anaerobic treatment.

15. pH and alkalinity results were consistently higher in the digesters receiving chemically coagulated sludge than in the control digester, signifying a greater buffering capacity against digester upset due to changes in the nature of the waste or in organic loading.

16. The average total iron content of the sludge added to digester No. 3 was 630 mg/l. The maximum value of total iron in the digester was 500 mg/l. There was no impairment of digester efficiency as a result of this iron concentration nor did ferric chloride act synergistically with the anionic polymer to create toxicity.

17. Results of an economic analysis show that the maximum economic dosages of the cationic polymer Hercofloc 814.2 added continuously to primary plants operating at capacity are 14.9, 10.2, and 6.6 mg/l for 1, 10 and 100 mgd plants, respectively. Similarly, for ferric chloride and a 0.5 mg/l of the anionic polymer Hercofloc 836.2, the economic dosages of FeCl_3 are 51, 34, and 21.5 mg/l, respectively. For dosages greater than these amounts, the addition of secondary activated sludge treatment becomes more economical.

6.2 Conclusions

1. Hercules Incorporated's cationic polyelectrolyte, Hercofloc 814.2, produced BOD_5 and COD removal efficiencies of approximately 60% in jar tests and settling column tests using a weak to medium strength domestic sewage. The dosages required were 6 to 14 mg/l of polymer.

2. An economic analysis which compared the total annual cost of treatment for primary and secondary activated sludge plants showed that the difference in cost was equivalent to dosages of 14.9, 10.2 and 6.6 mg/l of Hercofloc 814.2, for 1, 10, and 100 mgd plants, respectively. Thus it was concluded that the use of Hercofloc 814.2 as an aid to the primary clarification of domestic sewage is not an economically attractive alternative to providing activated sludge treatment unless an adequate degree of treatment can be achieved at dosages of somewhat less than 14 mg/l.

3. The coagulated sludge produced, using 14 mg/l of Hercofloc 814.2 added to domestic sewage, neither improved nor impaired the efficiency of the anaerobic digestion process in a laboratory digester. On the other hand, following digestion, this sludge dewatered more readily than non-coagulated sludge from a control digester. Apparently, little or no additional conditioning would be required prior to vacuum filtration of such a digested sludge.

4. Jar tests and settling column tests using 30 mg/l of ferric chloride as a primary coagulant in combination with 0.5-1.0 mg/l of anionic Hercofloc 836.2 as a coagulant aid produced BOD₅ and COD removal efficiencies of approximately 60% for a weak to medium strength domestic sewage.

5. Comparison of the total annual cost of treatment for primary and secondary activated sludge plants showed that the difference in cost was equivalent to dosages of 51, 34 and 21.5 mg/l of ferric chloride for 1, 10, and 100 mgd plants, respec-

tively, assuming a dosage of 0.5 mg/l of Hercofloc 836.2 as the coagulant aid. Thus it was concluded that the use of ferric chloride and anionic polymer as aids to the sedimentation of domestic sewage presented an economically attractive alternative to secondary treatment for plants in the 1-10 mgd range, provided that an adequate degree of treatment could be obtained.

6. The coagulated sludge produced, using 30 mg/l of FeCl_3 and 1 mg/l of Hercofloc 836.2 added to domestic sewage, neither improved nor impaired the efficiency of the anaerobic digestion process in a laboratory digester. Also there was no significant difference in the dewaterability of the digested sludge when compared to the non-coagulated sludge from a control digester.

6.3 Recommendations for Future Research

1. This research has failed to indicate any adverse effects on anaerobic digestion as a result of using Hercofloc 814.2 as a primary coagulant or Hercofloc 836.2 as a coagulant aid in combination with ferric chloride for the clarification of domestic wastewater. However, the question of polymer toxicity to biological processes has not been answered.

Before any further research along these lines is begun, more information must be obtained about the polymers - specifically their base compounds and the functional groups which account for their electrolytic properties. Only then can the products of various manufacturers be grouped according to specific properties and duplication of effort be prevented.

2. Further research along the lines of that reported on herein could include an assessment of the effect of reducing digester detention times.

3. Favourable results of Buchner funnel vacuum filtration tests on digested, coagulated sludge suggest research to determine the feasibility of using cationic polymer for the dual purpose of increasing solids captured during sedimentation and as an aid to dewatering of the sludge obtained, with or without an intermediate biological digestion process. Of particular interest would be a comparison of amount of polymer required when added just prior to the dewatering process versus the amount required for optimum sludge dewatering when added to the incoming sewage or at some other stage of treatment. Any increase in treatment efficiency must be weighed against the increase in coagulant costs.

4. Problems with flotation of the large tenacious flocs formed when air mixing of cationic polymer and sewage was attempted suggested further investigation of this as a means of separation of grit and organic solids in sewage treatment. Whereas separate grit tanks and sedimentation basins are now used, it may be possible to eliminate the sedimentation basin and employ one dual-purpose aerated basin.

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APPENDICES

APPENDIX A
JAR TEST RESULTS
RAW SEWAGE FLOCCULATION

APPENDIX A
JAR TEST RESULTS
RAW SEWAGE FLOCCULATION

Test No.	Polyelectrolytes Used*	Dosage Range (mg/l)	Results
1	1	1-10	No apparent flocculation
2	2	1-5	No apparent flocculation
3	7	0.2-1.0	No apparent flocculation
4	7	1-5	No apparent flocculation
5	3	1-5	Small flocs formed. Poor settling
6	7, then 3	0.1-0.5 1-5	No apparent flocculation
7	3, then 7	1-5 0.1-0.5	Lacy flocs. Poor settling
8	3, then 1	1-5 1-5	Good flocs. Rapid settling. 2 mg/l of each worked best
9	3, then 1	2 1-5	Good flocs. Rapid settling. 5 mg/l of #1 worked best
10	3, then 1	1-5 2	All combinations appear equally good
11	3, then 1	0.5-2.5 5	All combinations appear equally good
12	3, then 1	1 5-9	There is no apparent improvement at concentrations of #1 above 5 mg/l
13	3, then 7	1 1-5	Medium flocs. Good settling. 2 mg/l of #7 appeared best
14	5, then 6	1-5 2	Very small flocs appeared to form. Poor settling

Test No.	Polyelectrolytes Used*	Dosage Range (mg/l)	Results
15	4, then 2	1-5 1-5	Large flocs. Good settling. 5 mg/l of each appeared best.
16	4, then 6	1-5 1-5	Medium flocs. Fair settling. A considerable number of fine particles remained in suspension
17	5, then 2	1-5 1-5	Poor flocculation
18	3, then 8	1 0.5-2.5	Large flocs. Good settling. Concentrations of 2.0 and 2.5 mg/l of #8 worked best
19	3, then 8	0.5-2.5 1.5	All combinations appear equally good
20	3, then 9	1 1-5	Small flocs. Poor settling
21	10, then 8	1 1-5	Large flocs. Rapid settling. 5 mg/l of #8 worked best
22	3, then 8	1 1-5	Large flocs. Fair settling. 4 and 5 mg/l of #8 appeared slightly better
23	3, then 8	1,1,1,2,2,2 3,4,5,3,4,5	Approximately equal results. 2 mg/l of #3 and 5 mg/l of #8 appeared to produce the strongest, least lacy, floc
24	4, then 8	2 1-5	Medium floc. Fair settling. Flocs appeared "flimsy"

<u>Assigned No.*</u>	<u>Polyelectrolyte</u>	<u>Type</u>
1	Alchem 603	Cationic
2	Alchem 607	Cationic
3	Alchem D-179-M	Anionic
4	Alchem D-176	Anionic
5	Alchem 633-HD	Anionic
6	Alchem 636-HD	Cationic
7	Rohm & Haas Primaflor C-7	Cationic
8	Hercules Corp. Hercoflor 812	Slightly Cationic
9	Dow Puriflor C-31	Cationic
10	Dow Puriflor A-23	Anionic

APPENDIX B
DIGESTION PARAMETER TEST RESULTS

RAW SLUDGE DATA

Dates Sludge Used (1971)	Number of Days Used	Total Iron (mg/l)			Total Solids (g/l)			Volatile Solids (g/l)			BOD ₅ (g/l)			COD (g/l)		
		Digester No.			Digester No.			Digester No.			Digester No.			Digester No.		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Prior to April 29		-	-	-	-	-	-	36.5	36.5	36.5	12.0*	12.0*	12.0*	65.0*	65.0*	65.0*
April 29 to May 4	6	-	-	-	22.0	19.4	23.1	19.4	16.9	19.0	5.81	6.77	7.72	33.0	31.0	36.6
May 5 to May 11	7	160	88	643	24.5	23.9	29.0	21.3	20.8	23.9	5.81	8.79	8.68	36.2	39.3	42.2
May 12 to May 24	13	125	150	500	28.2	29.8	29.7	24.0	23.5	25.1	9.00	10.3	10.2	37.3	44.4	49.5
May 25 to June 3	10	112	102	675	25.5	25.4	25.6	21.7	22.0	20.9	6.65	10.2	10.0	33.7	40.8	35.1
June 4 to June 17	14	105	110	640	30.0	28.9	30.1	26.0	24.8	24.7	6.26	10.7	7.65	45.5	49.9	45.0
June 18 to July 4	17	150	112	666	30.7	36.9	41.1	24.7	25.3	25.7	7.84	12.0	10.2	44.2	49.9	48.9

*Estimated from volatile solids

DIGESTER EFFLUENT DATA

Date (1971)	Total Iron (mg/l)			Total Solids (g/l)			Volatile Solids (g/l)			BOD ₅ (g/l)			COD (g/l)		
	Digester No.			Digester No.			Digester No.			Digester No.			Digester No.		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
April 12	-	-	-	29.6	23.6	26.5	15.8	15.2	15.5	2.18	2.05	1.85	-	-	-
May 30	96	110	386	17.3	21.4	18.0	11.4	12.6	11.4	2.41	2.63	2.36	19.2	21.8	20.4
June 7	144	188	394	17.0	20.3	16.6	10.9	11.7	10.6	1.47	2.07	1.64	18.8	20.4	17.9
June 11	138	140	332	17.8	18.6	15.8	10.8	11.2	10.3	1.55	1.77	1.55	17.6	19.7	17.5
June 28	140	156	396	16.0	17.2	19.0	10.7	11.1	11.2	1.85*	2.08*	2.16*	17.3	18.8	18.5
July 4	183	220	500	16.7	20.1	17.1	10.3	11.3	10.8	1.45	2.30	1.95	17.1	19.9	18.4

*These BOD values are not statistically sound as dilutions were used which gave dissolved oxygen depletions less than 2.0 mg/l

pH OF DIGESTER EFFLUENT

Day of Month	April Digester No.			May Digester No.			June Digester No.		
	1	2	3	1	2	3	1	2	3
1	6.93	6.66	6.88	6.99	7.00	6.93	-	-	-
2	6.92	6.67	6.92	6.94	6.98	6.95	-	-	-
3	-	-	-	-	-	-	6.86	6.99	6.98
4	-	-	-	6.99	6.99	7.04	6.87	7.00	6.98
5	6.83	6.79	6.83	-	-	-	6.86	7.04	7.00
6	6.97	6.90	6.96	6.86	6.93	6.86	6.86	7.00	6.96
7	6.89	6.83	6.88	6.86	6.95	6.87	-	-	-
8	-	-	-	-	-	-	6.88	7.02	6.99
9	-	-	-	6.92	6.97	6.93	-	-	-
10	-	-	-	-	-	-	-	-	-
11	-	-	-	6.83	6.93	6.90	-	-	-
12	6.84	6.82	6.82	6.90	7.12	7.01	6.88	7.01	6.99
13	6.89	6.85	6.88	-	-	-	6.92	7.05	7.01
14	6.90	6.92	6.87	-	-	-	-	-	-
15	-	-	-	6.92	6.96	6.92	-	-	-
16	6.93	6.89	6.91	-	-	-	6.85	7.00	6.98
17	-	-	-	6.86	6.93	6.90	-	-	-
18	-	-	-	-	-	-	-	-	-
19	6.99	6.93	6.95	6.96	7.09	6.99	-	-	-
20	6.97	6.90	7.00	6.87	7.04	6.97	6.88	7.09	6.99
21	6.87	6.88	6.86	-	-	-	6.86	7.04	7.01
22	6.91	6.90	6.89	6.99	7.04	7.05	-	-	-
23	-	-	-	6.90	7.00	6.99	6.88	7.06	7.03
24	6.90	6.86	6.82	-	-	-	-	-	-
25	6.90	6.94	6.87	6.92	7.05	6.97	6.88	7.06	7.02
26	6.85	6.84	6.86	-	-	-	6.88	7.06	7.01
27	-	-	-	-	-	-	6.90	7.04	6.99
28	6.86	6.85	6.90	-	-	-	-	-	-
29	6.90	6.87	6.91	6.84	6.96	6.98	6.91	7.08	7.02
30	6.99	6.99	6.97	-	-	-	6.90	7.04	7.02
31	-	-	-	6.88	7.00	6.98	-	-	-

DIGESTER EFFLUENT
VOLATILE ACIDS AND ALKALINITY

Date	Volatile Acids, mg/l as Acetic Digester No.			Alkalinity, mg/l as CaCO ₃ Digester No.		
	1	2	3	1	2	3
March 17	40	70	90			
May 19	50	50	50	1,675	1,790	1,770
May 30	70	100	70	1,650	1,940	1,890
June 5	60	40	50	1,620	1,960	1,890
June 9	130	120	140	1,510	1,830	1,770
June 22	160	170	170	1,780	2,480	2,150

GAS PRODUCTION FROM DIGESTERS
LITERS/DAY AT STANDARD TEMPERATURE AND PRESSURE

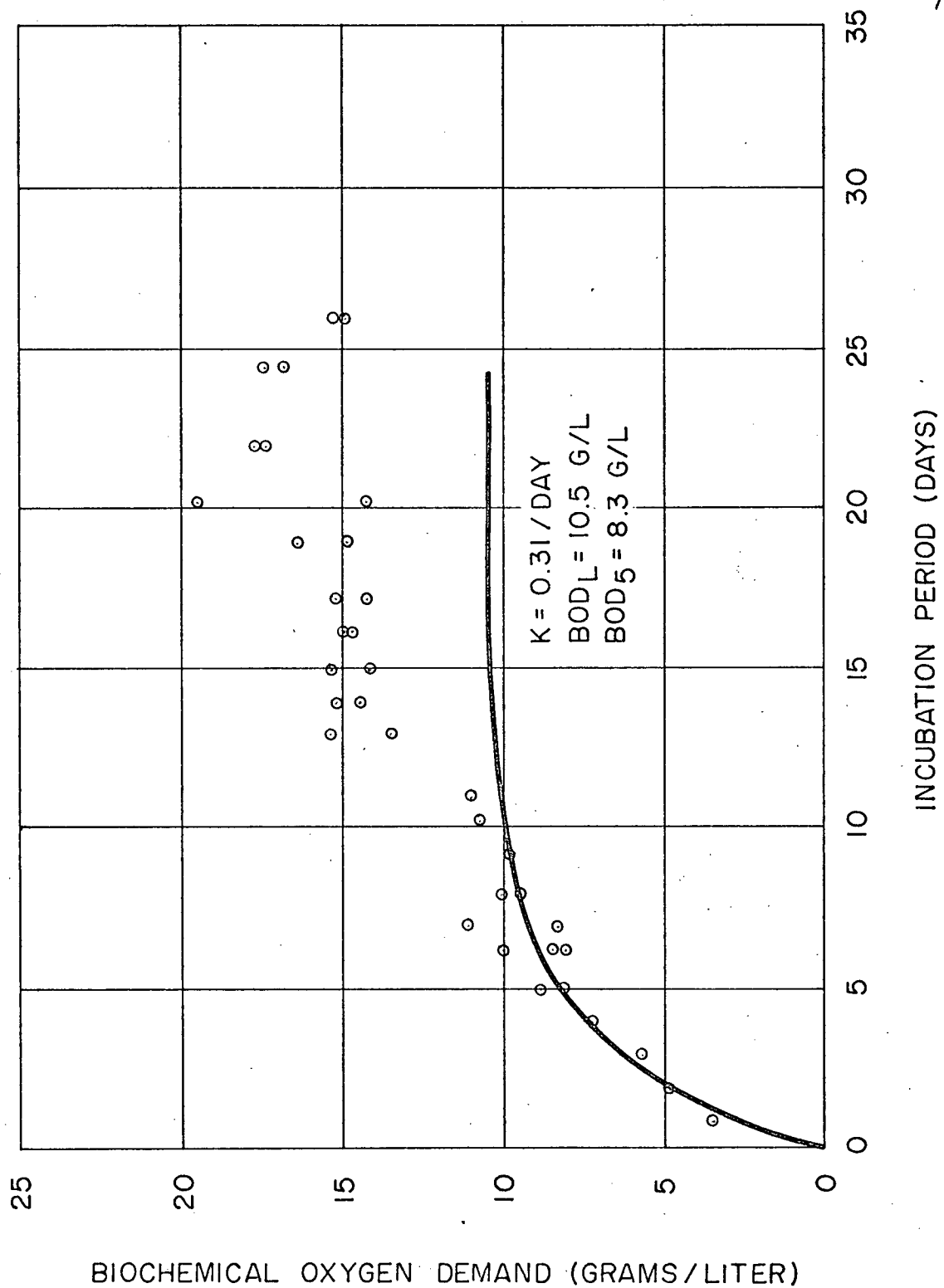
<u>Date</u>	Digester No.		
	<u>1</u>	<u>2</u>	<u>3</u>
April 28-29	5.52	5.98	6.51
June 5-6	3.86	3.96	3.85
June 7-8	4.11	4.10	3.73
June 9-10	3.85	4.06	3.85
June 19-20	3.17	3.40	3.10
June 20-21	-	3.78	-
June 22-23	3.78	-	-
June 24-25	-	-	3.31
June 25-26	-	3.62	-
June 28-29	3.46	-	-
June 29-30	-	-	3.22
June 30-July 1	-	3.71	-
July 1-2	3.12	-	-
July 2-3	-	-	3.21

COMPOSITION OF DIGESTER GAS

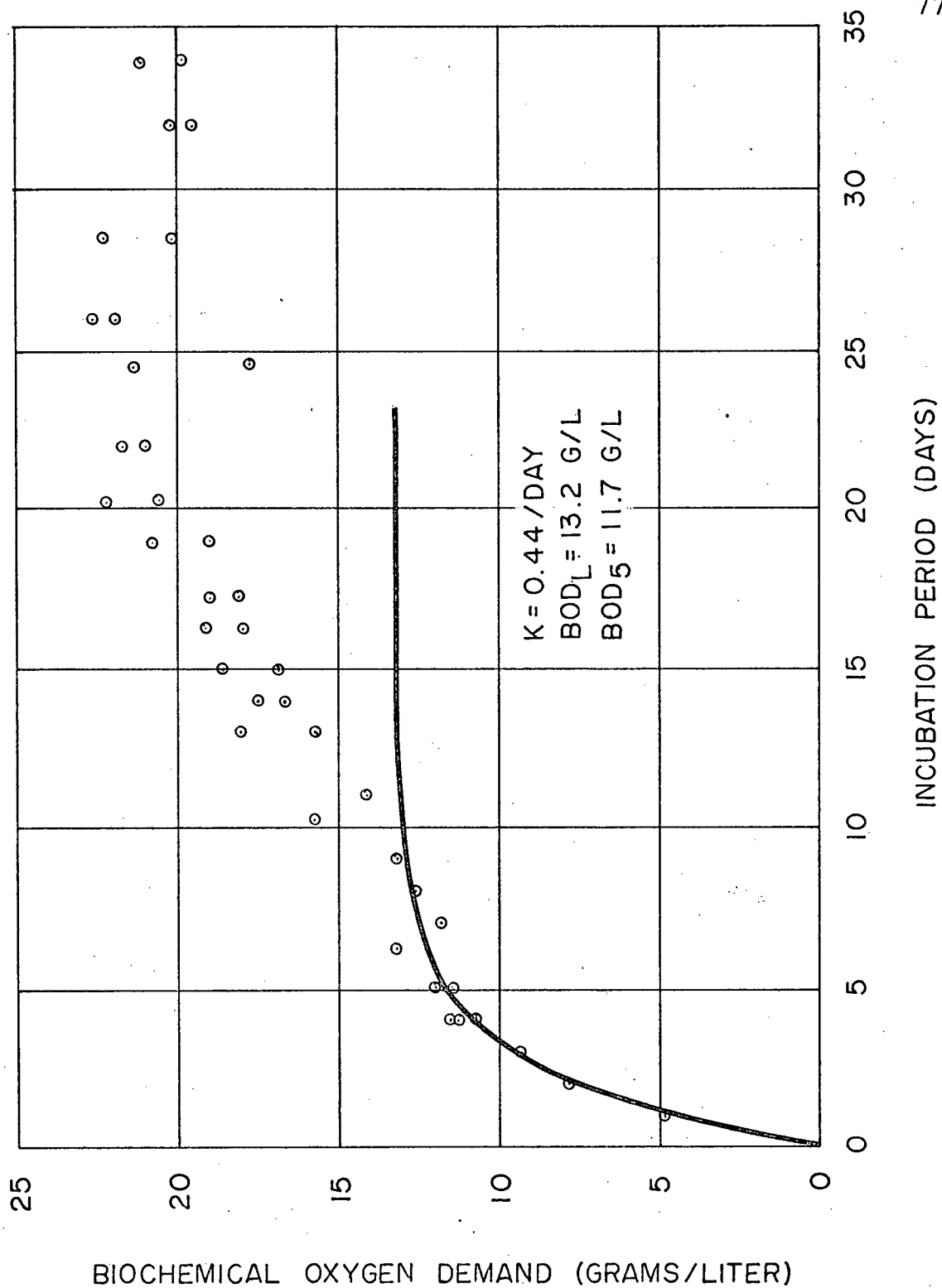
PERCENTAGE BY VOLUME

<u>Date</u>	<u>Digester Number</u>	<u>H₂S</u>	<u>N₂</u>	<u>CH₄</u>	<u>CO₂</u>	<u>H₂O</u>
April 15	1		0.4	57.3	41.8	0.5
	2		0.2	58.5	40.8	0.5
	3		0.1	56.7	42.7	0.5
April 29	1		0.6	58.8	40.1	0.5
	2		0.3	58.0	41.0	0.7
	3		0.3	56.6	42.0	1.1
May 3	1		0.8	60.1	38.6	0.5
	2		0.3	62.1	37.0	0.6
	3		0.3	60.2	38.7	0.8
May 7	1		0.4	60.2	38.7	0.7
	2		0.3	63.6	35.4	0.7
	3		0.2	62.7	36.4	0.7
May 10	1		0.2	61.0	38.2	0.6
	2		0.2	64.0	35.1	0.7
	3		0.2	62.0	36.7	1.1
May 16	1	NOT DETECTABLE	0.3	59.9	39.1	0.7
	2		0.2	63.9	35.2	0.7
	3		0.1	61.6	36.8	1.5
May 21	1		0.2	61.0	38.2	0.6
	2		0.4	64.2	34.8	0.6
	3		0.2	62.0	36.8	1.0
May 28	1		0.5	60.2	38.0	1.3
	2		0.3	64.1	34.1	1.5
	3		0.5	62.3	36.0	1.2
June 3	1		0.5	61.4	37.4	0.7
	2		0.2	65.3	33.6	0.9
	3		0.4	63.8	35.0	0.8
June 12	1		0.4	58.4	40.6	0.6
	2		0.3	63.2	35.8	0.7
	3		0.4	61.9	37.2	0.5
June 18	1		0.5	58.1	40.6	0.8
	2		0.3	63.9	34.9	0.9
	3		0.4	62.5	36.2	0.9
June 28	1		0.6	59.2	39.4	0.8
	2		0.5	63.4	35.1	1.0
	3		0.5	62.9	35.8	0.8

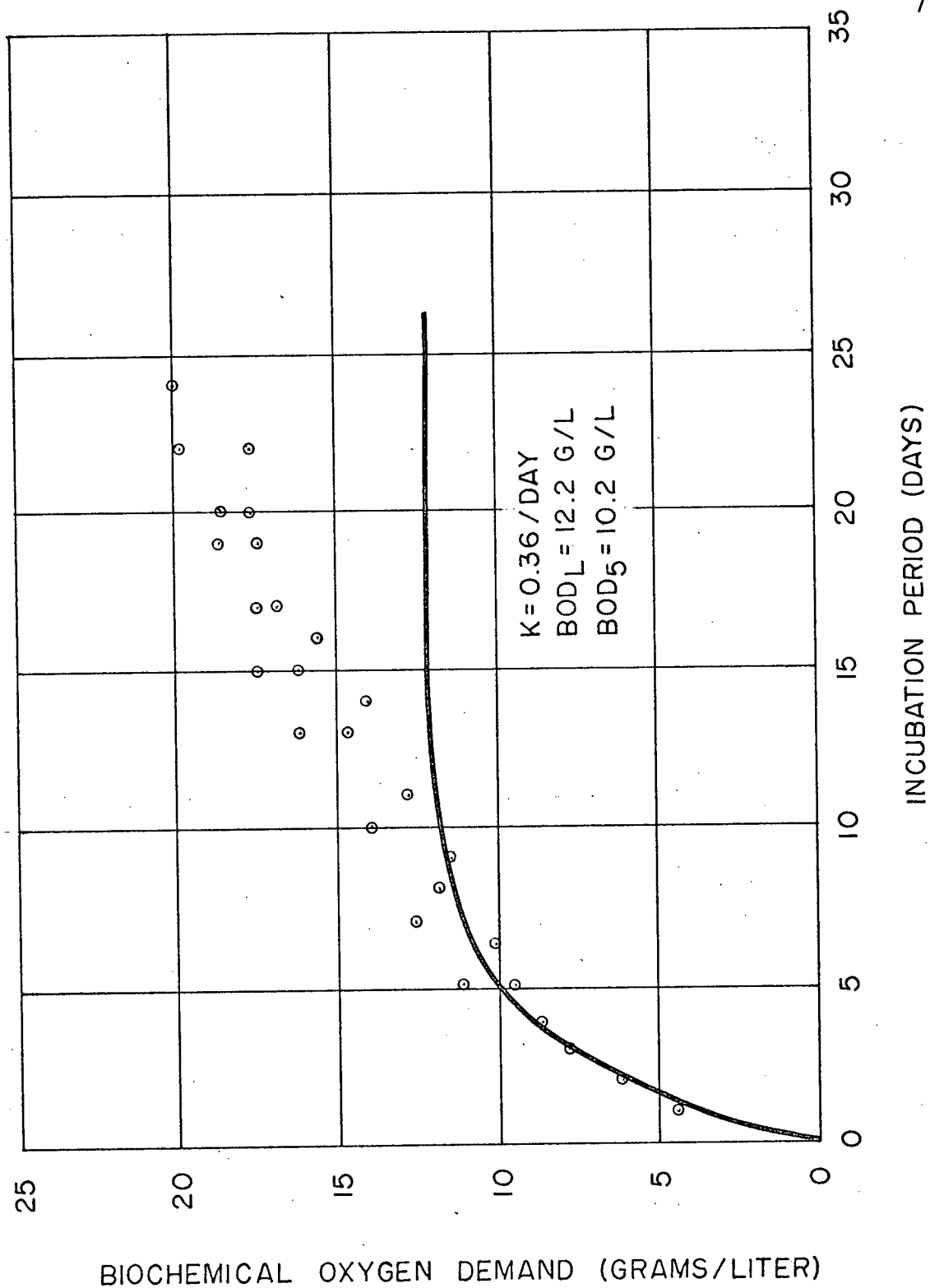
APPENDIX C
RESULTS OF LONG-TERM
BOD TESTS ON RAW AND DIGESTED SLUDGES



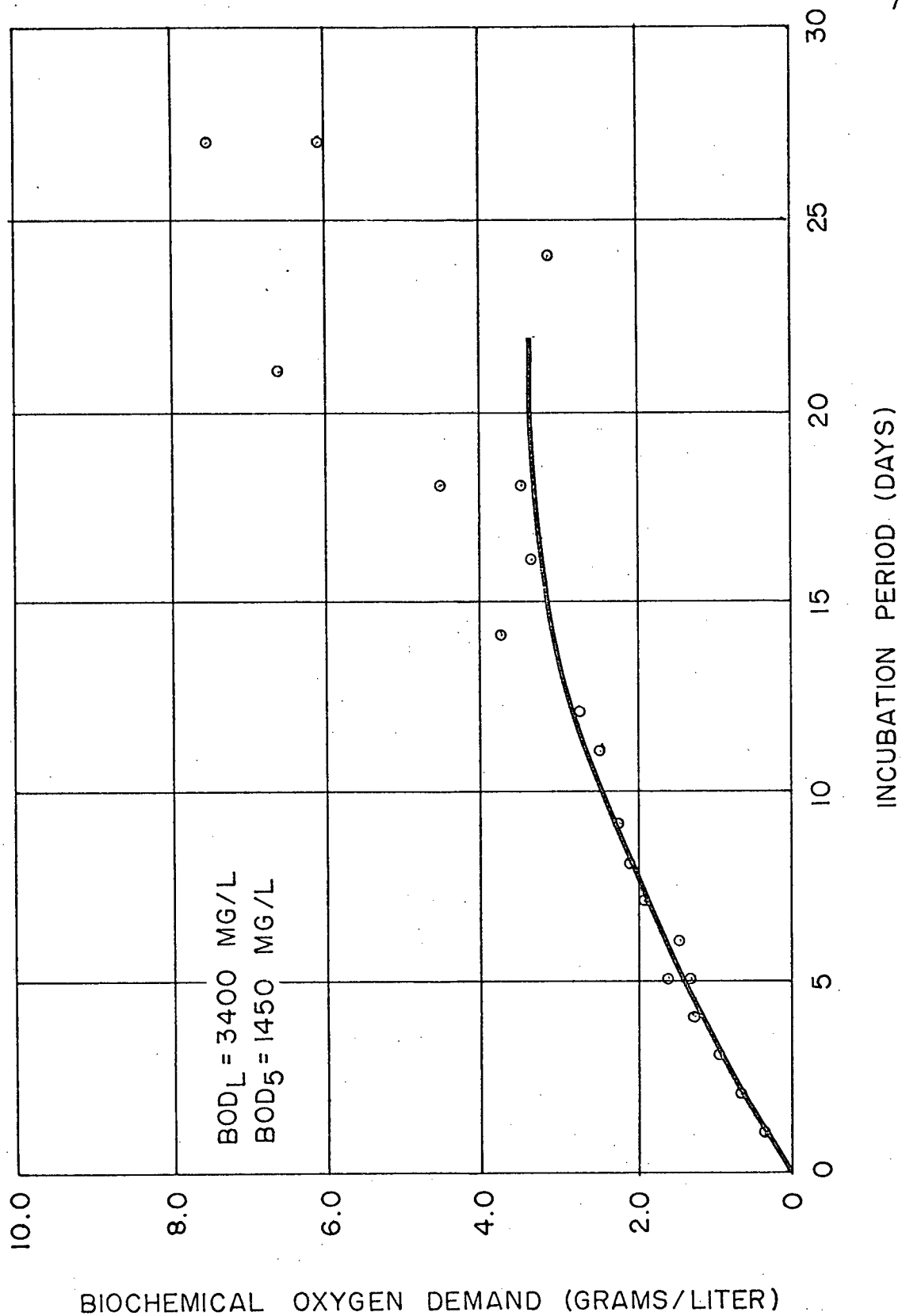
LONG-TERM BOD TEST
RAW SLUDGE NO.1



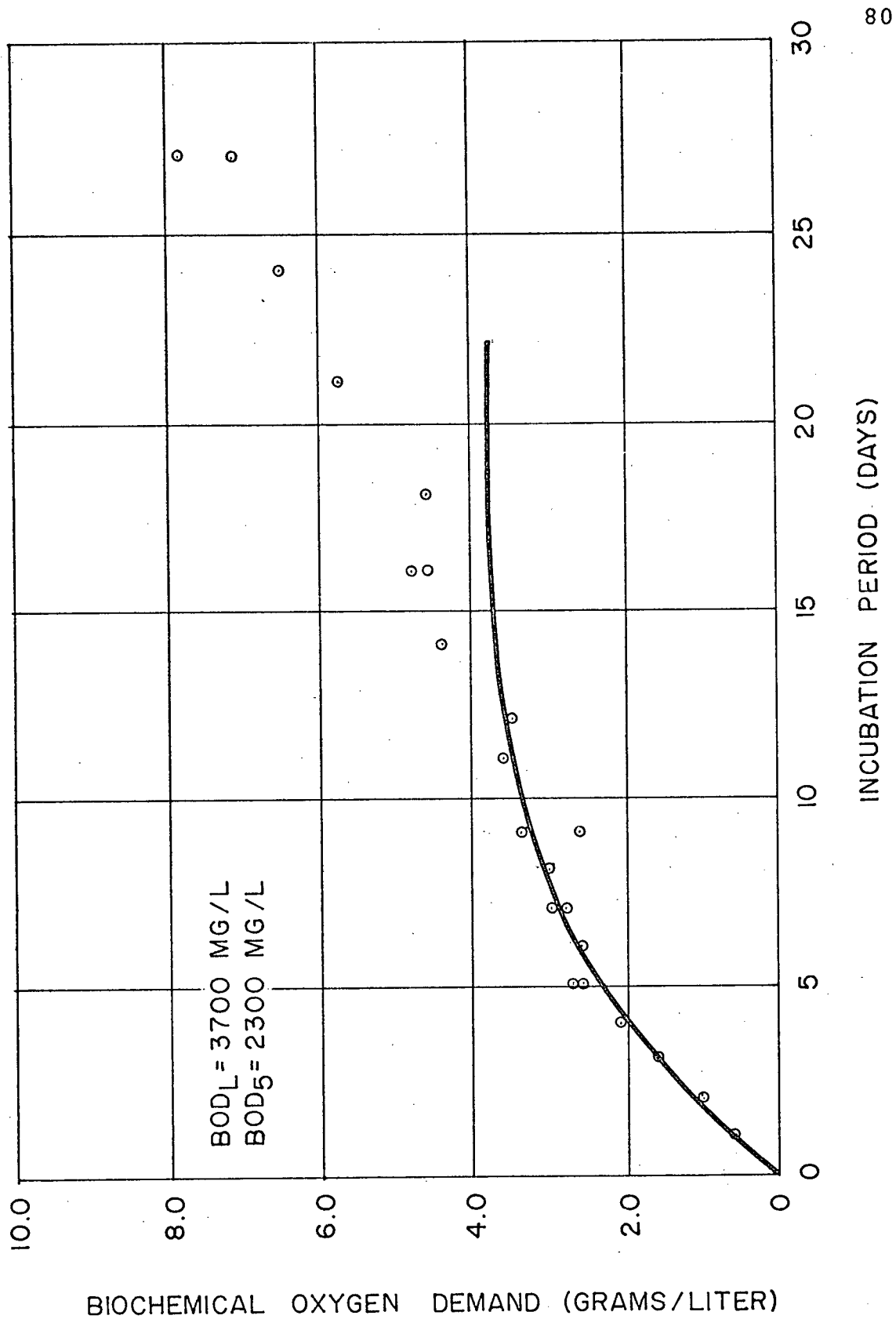
LONG-TERM BOD TEST
RAW SLUDGE NO. 2



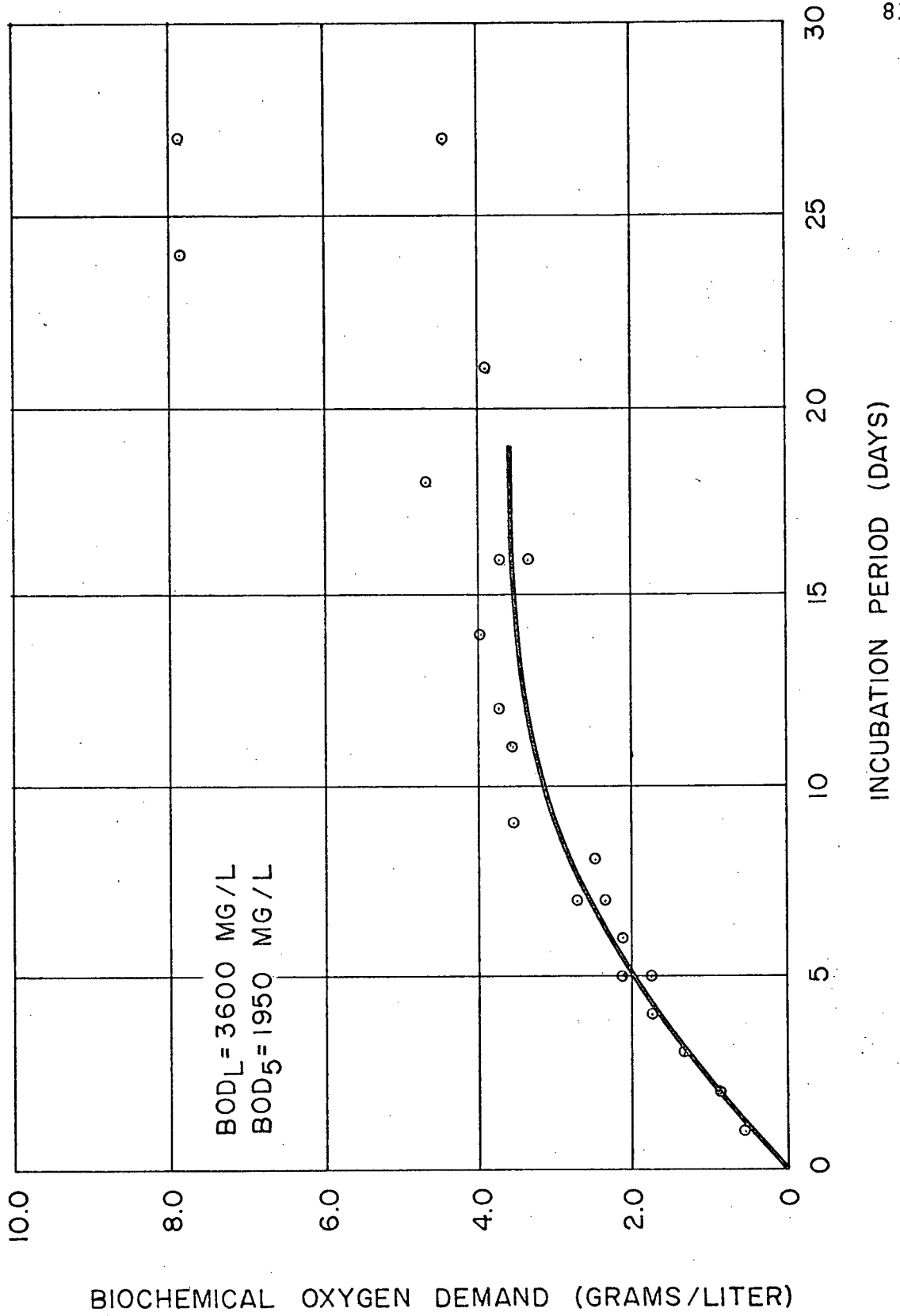
LONG-TERM BOD TEST
RAW SLUDGE NO. 3



LONG-TERM BOD TEST
EFFLUENT SLUDGE NO. 1



LONG-TERM BOD TEST
EFFLUENT SLUDGE NO.2



LONG-TERM BOD TEST
EFFLUENT SLUDGE NO. 3

APPENDIX D

SAMPLE CALCULATION OF THE MICROBIAL STABILIZATION OF VOLATILE SOLIDS, BOD, OR COD IN A DIGESTER

APPENDIX D

PROBLEM:

To determine the microbial stabilization of VS in Digester #1 on July 4, 1971

SOLUTION:

Calculate the theoretical concentration on July 4 assuming only physical removal and compare this result with the actual VS concentration as measured in the digester effluent

DERIVATION OF EQUATION 2:

Where sludge is added to a digester, the rate of change of the VS concentration in the digester is expressed by the equation

$$\frac{dC}{dt} = K_1 C_R \quad \dots (D1)$$

where: C is the VS concentration in the digester,

C_R is the VS concentration in the sludge added to the digester,

K_1 is a rate constant equal to the volume of sludge added per unit of time divided by the volume in the digester, and

t is time.

Similarly, when sludge is removed from the digester, the rate of change of the VS concentration in the digester is expressed by the equation

$$\frac{dC}{dt} = -K_2 C \quad \dots (D2)$$

where: K_2 is a rate constant equal to the volume of sludge removed per unit of time divided by the volume in the digester.

Combining the two equations

$$\frac{dC}{dt} = K_1 C_R - K_2 C \quad \dots (D3)$$

The steady state solution of this equation is obtained by setting

$$\frac{dC}{dt} = 0$$

Therefore, $C = \frac{K_1}{K_2} C_R$

Rearranging terms, equation D3 becomes

$$\frac{dC}{dt} + K_2 C = K_1 C_R$$

The general solution of this equation is obtained by setting

$$\frac{dC}{dt} + K_2 C = 0$$

Solving for C yields

$$C = ae^{-K_2 t}$$

where: a is a constant, and

e is the base of natural logarithms

Combining the steady state and general solutions, yields

$$C = \frac{K_1}{K_2} C_R + ae^{-K_2 t} \dots (D4)$$

At time $t = 0$, C equals the initial volatile solids concentration in the digester, C_0 . Substituting in equation D4 and solving for "a" yields

$$a = C_0 - \frac{K_1}{K_2} C_R$$

Substituting this result back into equation D4 yields equation 2

$$C = C_0 e^{-K_2 t} + \frac{K_1}{K_2} C_R (1 - e^{-K_2 t}) \dots (2)$$

The calculated values of K_1 and K_2 are:

$$K_1 = \frac{250 \text{ ml/day}}{7,500 \text{ ml}} = 0.0333 \text{ per day}$$

$$K_2 = \frac{243 \text{ ml/day}}{7,500 \text{ ml}} = 0.0324 \text{ per day}$$

SOLUTION:

Prior to April 29, 1971

Average VS content of sludge added = 36.5 mg/l

April 29 - May 4

$$C_O = 36.5 \text{ mg/l}$$

$$C_R = \text{VS concentration of sludge added} = 19.4 \text{ mg/l}$$

$$t = 6 \text{ days}$$

$$C_O e^{-K_2 t} = 30.05 \text{ mg/l}$$

$$\frac{K_1}{K_2} C_R (1 - e^{-K_2 t}) = 3.53 \text{ mg/l}$$

$$C = 30.05 + 3.53 = 33.58 \text{ mg/l}$$

May 4 - May 11

$$C_O = 33.58$$

$$C_R = 21.3$$

$$t = 7$$

$$C = 26.55 + 4.45 = 31.22 \text{ mg/l}$$

May 11 - May 24

$$C_O = 31.22$$

$$C_R = 24.0$$

$$t = 13$$

$$C = 20.49 + 8.49 = 28.98 \text{ mg/l}$$

May 24 - June 3

$$C_O = 28.98$$

$$C_R = 21.7$$

$$t = 10$$

$$C = 20.96 + 6.18 = 27.14 \text{ mg/l}$$

June 3 - June 17

$$C_O = 27.14$$

$$C_R = 26.0$$

$$t = 14$$

$$C = 17.24 + 9.76 = 27.00 \text{ mg/l}$$

June 17 - July 4

$$C_O = 27.00$$

$$C_R = 24.7$$

$$t = 17$$

$$C = 15.57 + 10.76 = 26.33 \text{ mg/l}$$

C = theoretical VS concentration in Digester #1 on
July 4 assuming no microbial stabilization

Measured VS concentration in Digester #1 on July 4 =
10.3 mg/l

$$\text{Microbial VS Stabilization} = \frac{26.3 - 10.3}{26.3} = \underline{61\%}$$

This method also applies to BOD and COD removal efficiency determinations.