

October 1969 ✓
Report No. EVE 19-69-7

THE EFFECT AND REGULATION OF WASTEWATER RESIDENCE TIME IN SEWERS

David R. O'Toole and
Donald Dean Adrian, Project Investigator

Partially Funded by Office of Water Resources Research
Grant WR-BO11-MASS and Federal Water Pollution Control
Administration Training Grant 5T1-WP-77-04



ENVIRONMENTAL ENGINEERING
DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY OF MASSACHUSETTS
AMHERST, MASSACHUSETTS



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OF
WASTEWATER RESIDENCE TIME IN SEWERS

by

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ACKNOWLEDGMENT

This report with minor modifications embodies a thesis by Mr. O'Toole entitled "The Effect and Regulation of Wastewater Residence Time in Sewers," and submitted by Mr. O'Toole in partial fulfillment of the requirements for the degree of Master of Science in Environmental Engineering, Department of Civil Engineering, University of Massachusetts, September 1969.

Recognized is the cooperation received from both the Northampton and Amherst Departments of Public Works, with a special thanks to Mr. Francis (Pat) Ryan and Joseph Gessing, respectively City Engineer and Sewer Foreman of Northampton, and Mr. Stanley Ziomek, Superintendent of the Department of Public Works in Amherst.

Union Carbide Corporation is recognized for furnishing the friction-reducing polymer, POLYOX, used in these experiments. Helpful comments were received from Dr. John McCullough, Research Chemist, and Mr. A. K. Ingberman, Product Marketing Manager, both associated with Union Carbide Corporation.

Financial support for this study was provided by the Office of Water Resources Research Grant WR-B011-MASS, and by Federal Water Pollution Control Administration Training Grant Number 5T1-WP-77-04.

ABSTRACT

As population densities increase, there will be a gradual trend to larger and more centralized sewage treatment facilities which in turn will necessitate longer and larger collection systems. Since a collection system generally accounts for 40 to 70 percent of the entire sewerage system costs, proper collection system design will be most important. Therefore, it is imperative that investigations be made to establish proper design criteria. This study was designed to determine what sewage quality changes take place in transit since certain changes in quality could lead to sewer corrosion, and to determine what effect the addition of friction-reducing polymers have on the flow velocity.

It was found that a noticeable lag in oxygen uptake rate exists in fresh sewage; whereas sewage which had been retained in a pumping station for 8 - 12 hours exhibits an initially higher oxygen uptake rate during the first few hours.

The addition of a friction-reducing polymer produced a marked increase in the sewage flow velocity. The polymer was more effective when added to a high velocity flow than when added to a low velocity flow. The polymer showed no toxic effect on biological reactions in the sewage; in fact, the results indicated that it was used as a food source as other organics in the sewage were depleted.

From initial calculations it appears that when a sewer is overloaded by infrequent short period peak flows, it may be more economical to manage these peak flows by the addition of a friction-reducing polymer rather than by the construction of an additional sewer line.

It is recommended that polymer usage be considered when sewer lines are subject to infrequent surcharges. It is also recommended that polymer usage be encouraged in long lines which are subject to surcharge, as the cost of polymer dosage is a function of the flow rate and not a function of the length of the line. The cost of polymers is high enough that their routine continual use is not recommended for regulating quality changes in sewage by decreasing its transit time.

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PART 1. INTRODUCTION

1.1 Statement of the Problem

As the Environmental Engineer projects requirements for future waste collection and treatment systems, he must seek answers to several questions including:

- What economies of scale may be achieved by a single centralized waste treatment plant as contrasted with several smaller waste treatment plants?
- How large should the main interceptors of a waste collection system be to serve adequately in the future?
- What economic tradeoffs are available between the economies of scale of a large centralized waste treatment plant and a larger, more costly waste collection system to serve this plant?

A noted authority in Environmental Engineering has predicted the trend will be toward large centralized waste treatment plants saying, "When one weighs the arguments for and against the installation of larger and larger treatment plants, the apparent trend toward centralization at large treatment plants would seem to be justified." (1)

However, a larger treatment plant requires that the area to be served be proportionately larger. The larger service area necessitates longer transport distances for the sewage, thus providing a greater

opportunity for natural degradation in transit. The decline in the sewage's dissolved oxygen content prior to arrival at the waste treatment plant may necessitate aeration prior to treatment. In addition, there is the opportunity, in extreme cases, for structural damage through corrosion of the waste transport system.

Generally, as the residence or transit time of a sewage increases, the dissolved oxygen content (D.O.) of the sewage decreases to a point where there is no dissolved oxygen present; under this latter condition, the sewage becomes anaerobic (septic).

Under anaerobic conditions, one of the main products resulting from sewage degradation is the generation of hydrogen sulfide (H_2S) gas. This hydrogen sulfide is utilized in a series of reactions by microorganisms which may result in structural damage to concrete sewers through corrosion.

Gaudy (1) has investigated the problem of sewer corrosion. From his work, he has concluded that sewer pipe corrosion may occur in long runs of pipe with low velocities. To prevent anaerobic conditions from occurring the dissolved oxygen content (D.O.) of the sewage must be greater than 0.0 mg/l (2).

As one can see from the above statements, increasing the velocity decreases the residence time of the sewage in the sewer and reduces the opportunity for anaerobic conditions to develop. Thus, by avoiding the generation of hydrogen sulfide gas, sewer corrosion is precluded.

The rate at which the dissolved oxygen is removed from the sewage depends on such factors as the age, composition and strength of the waste. The standard for measuring the strength of the waste is the Biochemical Oxygen Demand (BOD) after five days at 20°C.

When one considers that the transport time of sewage is generally less than one day, the applicability of the five day BOD test to predicting quality changes occurring during transit is questioned. It would seem that a test measuring the oxygen uptake at certain intervals for a period of less than one day would be more suitable. This belief is strengthened by the fact that some researchers (3) have reported a high oxygen uptake rate during the first few hours while others (4) have stated that there may be an initial lag period during which little oxygen uptake occurs.

The injection of high molecular weight (4,000,000), straight chain polymers into the sewer line has recently been considered as a method of increasing the velocity of flow. This increase in velocity is brought about by the friction-reducing effect of the polymer. To date there is only one case where polymers have been applied to a sewer (5). In this case under certain conditions, polymers were found to increase the flow by more than twice the flow of the non-polymered solution.

Most of the work with polymers has been carried out by the U. S. Navy, with specific application to naval vehicles being able to provide sudden bursts of speed (6).

A. G. Fablua (6), of the Naval Ordnance Test Station at Pasadena, California, has experimented with several different types of polymers. He concluded that polyethylene oxide, a water-soluble, high molecular weight material of completely linear construction, was the most effective friction-reducing agent known. This polyethylene oxide is sold by Union Carbide Corporation under the commercial name, POLYOX.

In a regional wastewater collection system, the residence time may be sufficient to permit sewer corrosion caused by sewage quality changes. However, it may be possible to reduce this residence time with the addition of a friction-reducing polymer. Therefore, in order for the Environmental Engineer to properly design regional wastewater collection and treatment facilities, he must be aware of the sewage quality changes taking place in the collection system; he must know if there is a critical residence time after which sewer corrosion will occur; he must avoid designs which enhance corrosion; he should know the measures which can be taken to regulate these quality changes; and he should know if it would be beneficial to introduce a polymer solution into the sewer line.

1.2 Justification for the Study

Since a collection system generally accounts for 40 to 70 percent of the entire sewerage system costs, it will be extremely important to design the most economic collection system. When

considering a regional collection system, the length of the lines and consequently the residence time of the sewage will increase significantly; consequently, it will be important to determine if there is a critical residence time after which the collection system becomes damaged by sewage quality changes. Also, it would be important to know if a friction-reducing polymer could:

- regulate this quality change by increasing the velocity of the sewage,
- be used as a more economical method of increasing the present collection system capacity rather than constructing parallel sewer lines.

To date, there has been little research conducted which would provide answers to these questions.

1.3 Statement of Objectives

This thesis will be directed toward answering such questions as:

- How rapid are the quality changes which take place in the waste collection system?
- Will polymers exhibit similar friction reducing abilities in open channel flow that have been observed in closed conduit flow?
- *Can the time in transit of the wastewater be reduced by the introduction of friction reducing polymers into the flow?*

- When will it be economically feasible to increase the capacity of a sewer through the use of polymers instead of constructing a parallel larger capacity sewer?

PART 2. LITERATURE REVIEW

2.1 Sewage Quality

The literature provides little information on the quality changes of sewage while in transit. Considerable work has been done and published with reference to the standard 5-day Biochemical Oxygen Demand (BOD) Test. However, this test is not exactly applicable to this research because it does not give the rate of oxygen consumption for a period of less than one day.

The 5-day BOD test is widely used to determine the strength of wastes in water and sewage (7); in effect, it measures the amount of biodegradable organic material present in a wastewater by the quantity of oxygen consumed by microorganisms in decomposing the waste (8).

By taking dissolved oxygen measurements at one day intervals or less, the rate at which the organic material is stabilized can be determined. However, this method of determining the rate of stabilization becomes tedious when the DO determinations are more frequent than one day; the reasons being: several dilutions are required necessitating a large number of bottles, a large constant temperature storage space is required for the bottles, and great care must be taken in preparing the reagents to maintain the precision of the test.

Much has been written about the classical BOD curve. This curve is obtained by plotting the BOD exerted at one day intervals or less versus time. When the points are plotted, they approximate a first order reaction. Streeter and Phelps (9) stated that the rate of

biochemical oxidation is proportional to the concentration of unoxidized substrate measured in terms of oxidizability. This results in a first order reaction which can be expressed in equation form as:

$$y = L(1 - 10^{-kt}) \quad \text{Eq. (1)}$$

where y is the BOD exerted at time t , L is the ultimate BOD and k is the rate constant for the reaction.

Several methods have been proposed to calculate the parameters, L and k , for the BOD curve. Among the most widely used methods are Thereiault's tabular method (10), the Thomas slope technique (11), the Moore moment method (12), Navone's method using simultaneous equations (13), and several graphical methods by Fair (14), Wiegand (15) and Fujimoto (16).

From these methods a k value can be determined; however, some authors (3, 4) believe that the k value varies during the first several hours depending on the characteristics of the sewage. This variation is not important when one is concerned only with the strength of the waste, but for this proposed research, the amount of oxygen consumed during the first several hours is important. Fair has stated (4):

In unseeded samples (i.e., samples that harbor initially an inadequate flora and fauna to activate the BOD reactions), lag periods are experienced before the reaction proceeds normally. By contrast, wastewaters that have undergone partial anaerobic decomposition or contain reducing chemical substances may exert an immediate demand (sometimes called a chemical demand) at the beginning of the BOD run.

In contrast, Schroepfer (3) has conducted research on raw sewage from the Minneapolis - Saint Paul Sanitary District; he reported, "a very high rate of deoxygenation occurs in the first day and then decreases to usual values thereafter." Thus, k is time dependent with values in the first 4 to 12 hours being as high as 1.0 to 2.0 per day, gradually lowering to 0.2 to 0.3 per day after 1 to 3 days.

The lag phase in the first part of the BOD curve can be expressed in equation form as (12):

$$y = L[1 - 10^{-k(t-t_0)}] \quad \text{Eq. (2a)}$$

or

$$y = L(1 - c10^{-kt}) \quad \text{Eq. (2b)}$$

in which t_0 is the lag period and $c = 10^{kt_0}$. Both the slope method and moment methods can be extended to account for this lag period (17).

Researchers do not believe the calculation of lag factors are worthwhile. Ruchhoft (18) has summarized this feeling as follows:

The calculation of the lag factor, as embodied in either the modified slope method or the present moment method, has never seemed to be worthwhile in this work. This positive lag is a real thing especially when low temperature BOD observations are made. Under such circumstances, it is preferred simply to examine the data and apply it to the data after recovery from the lag is indicated.

For this proposed research it will be important to know the amount and rate of oxygen consumption during a period of less than one day. In other words, how long would it take for all the dissolved oxygen to be removed from the sewage? Once all the dissolved oxygen has

been removed, the sewage becomes anaerobic, a condition which could lead to serious problems such as sewer corrosion. Anaerobic conditions are one of the factors which cause the generation of hydrogen sulfide. Hydrogen sulfide does not cause corrosion itself, but is indirectly responsible for crown corrosion in concrete sewers.

Sewer corrosion is a problem in many areas of the United States; it occurs in regions where domestic wastewater temperatures are high and detention times are long (19). The transport system can be considered part of the overall treatment process for the sewage inasmuch as the sewage is continuously undergoing biological changes while in transit. If there is sufficient reaeration in the sewer to maintain aerobic conditions, the opportunities for sewer corrosion are remote, provided sewer velocities are high enough to preclude the build up of sludge deposits which may become anaerobic (sluggish velocities will be discussed in detail later).

The fact that sewage does undergo biological changes while in transport has caused researchers (20) at the University of Delaware to investigate the possibility of so-called "in-line treatment." They claim that a section of the sewer line can be adapted into a two-phase biological reactor. This reactor would consist of an aeration section followed by another aerated section to which is added activated sludge. This sludge is obtained at the head end of the plant. To show the advantages of this in-line treatment, the researchers completed a case study comparing the performance of a

typical, conventional, activated sludge plant that treats the effluent from a community of 100,000 having a 5-day BOD of 200 mg/l. From this, the researchers predict that the in-line treatment scheme would have a BOD removal of 96 percent as compared with 90 percent removal from the conventional plant. Also, the former method eliminates the secondary treatment aeration tank. Probably the most significant results of the study are the cost comparisons -- the in-line treatment method would cost 30 percent or \$700,000 less than the conventional plant. The major conclusion from this research was: "Pipeline sewage treatment is not only feasible, but promises to offer greater BOD reduction at lower initial capital costs than conventional activated sludge plants" (20).

The whole idea of in-line treatment has been summed up by Gaudy (1) as follows:

Indeed, the trend toward larger and larger collection systems has fostered a new concern in the pollution control field, i.e., a so-called *in-line treatment*. Concerning biological interactions in the collection system, we may on the one hand attempt to create conditions which would be ideal for the desired type of biological activity, thereby providing some type of pre-treatment before the waste enters the treatment plant, with the very important provision that the biological activity does not tend to deteriorate the materials of which the reactor is made. On the other hand, we can take the tact that the conducting material performs so vital a function that we can not afford to take the risk of deteriorating it in any way and we should provide an in-line treatment which arrests biological activity which may be deleterious to the materials. In either case it is obvious that we must give prime consideration to the interactions which take place between the microbes and materials of construction.

To measure the oxygen uptake of the sewage while in transit, it would be important to simulate as closely as possible the actual

conditions in the sewer. Such factors as the amount of mixing, the temperature of the waste, and actual strength of the sewage should be considered. With the standard BOD bottle method, these factors are not considered. In the standard BOD test, a very small sample is diluted down decreasing the probability of a representative sample (21), temperature is controlled at 20°C, there is no mixing, and nutrient salts and sometimes a seed is added to aid in the biological activity.

In this research the sewage should be at the same temperature as it is in the sewers. It should experience the same type of mixing as it does in the sewers, and no nutrient salts should be added which would enhance the biological activity which would otherwise exist in the sewer.

A respirometric method of measuring the biochemical oxygen demand appears to be ideal for this research because it can control to some extent all the parameters which are considered important for this work. A respirometer is an instrument designed to measure small quantities of gas, either adsorbed or evolved in biochemical reactions. The apparatus consists of a constant temperature water bath equipped with a shaking mechanism to which several small flasks are connected, each with a monometer for indicating changes in gas volume.

This respirometric method is based on the theory that only oxygen and carbon dioxide are involved in the gas exchange; and also the

effect of the latter is completely eliminated by using an alkali absorbent placed in a separate compartment within the reaction flask. This belief has been substantiated by Wooldridge and Standfast (22). They aerated sewage for considerable periods of time under conditions which enabled them to analyze the air by standard gas analysis methods. Their findings showed negative tests for hydrogen sulfide, hydrogen, nitrogen, and methane and they concluded that under ordinary conditions for the BOD test, there is no reason to suspect any other gases besides carbon dioxide and oxygen to be involved.

When the results obtained from the bottle method are compared to the manometric method, it is found that the manometric results are much higher. Also, dilution of the sample to be used in the respirometer has an effect on the results. Dilution lowers the calculated demand and this becomes more noticeable with high dilutions (23).

As can be seen, manometric techniques provide a method of observing changes in the system without destroying the sample which allows for a continuous BOD curve to be obtained.

2.2 Friction-Reducing Agents

As early as 1906, Blatch (24) demonstrated that water flowing with very low concentrations of solid particles had lower head losses than with water flowing alone. In 1927, Gregory (25) found that at low clay concentrations, head losses were somewhat suppressed. More recent investigations (26, 27) have proven conclusively that clay-water suspension head losses are definitely lower than plain water head losses.

Vanoni (28) used a laboratory flume to measure the friction factors for various channel slopes, and different concentrations of suspended loads. He found that sediment-laden water had less resistance than water without sediment; therefore, sediment-laden water flowed faster than clear water. The reduction in resistance varied with the grain size and total sediment load. With certain suspended loads the friction factor was decreased by 20 percent. Later, Vanoni and Nomicos (29) showed that suspended solutions could reduce the friction factor up to 28 percent.

Wood pulp and synthetic fiber solutions have also been used to reduce resistance. Daily and Bugliarello (30) found solutions of this type to decrease the friction factor with increasing solids concentration, fiber length and pipe diameter.

More recently, interest has centered on the addition of small amounts of soluble high-molecular weight polymers in causing drag reduction. Very small concentrations of these polymers (10 - 100 ppm) have caused significant drag reduction.

The application of polymers for friction reduction has gone unnoticed for so many years because of the methods used in measuring friction reduction. Hoyt (6) stated:

The reason the drag-reducing effect of polymers escaped notice for so long probably lies in the characteristics of the instrument used traditionally to measure the friction created by the flow of fluids, the viscometer. Since all viscometers operate in laminar flow, measurement of polymer-solution viscosity as shown in Figure 1 indicates only that these solutions

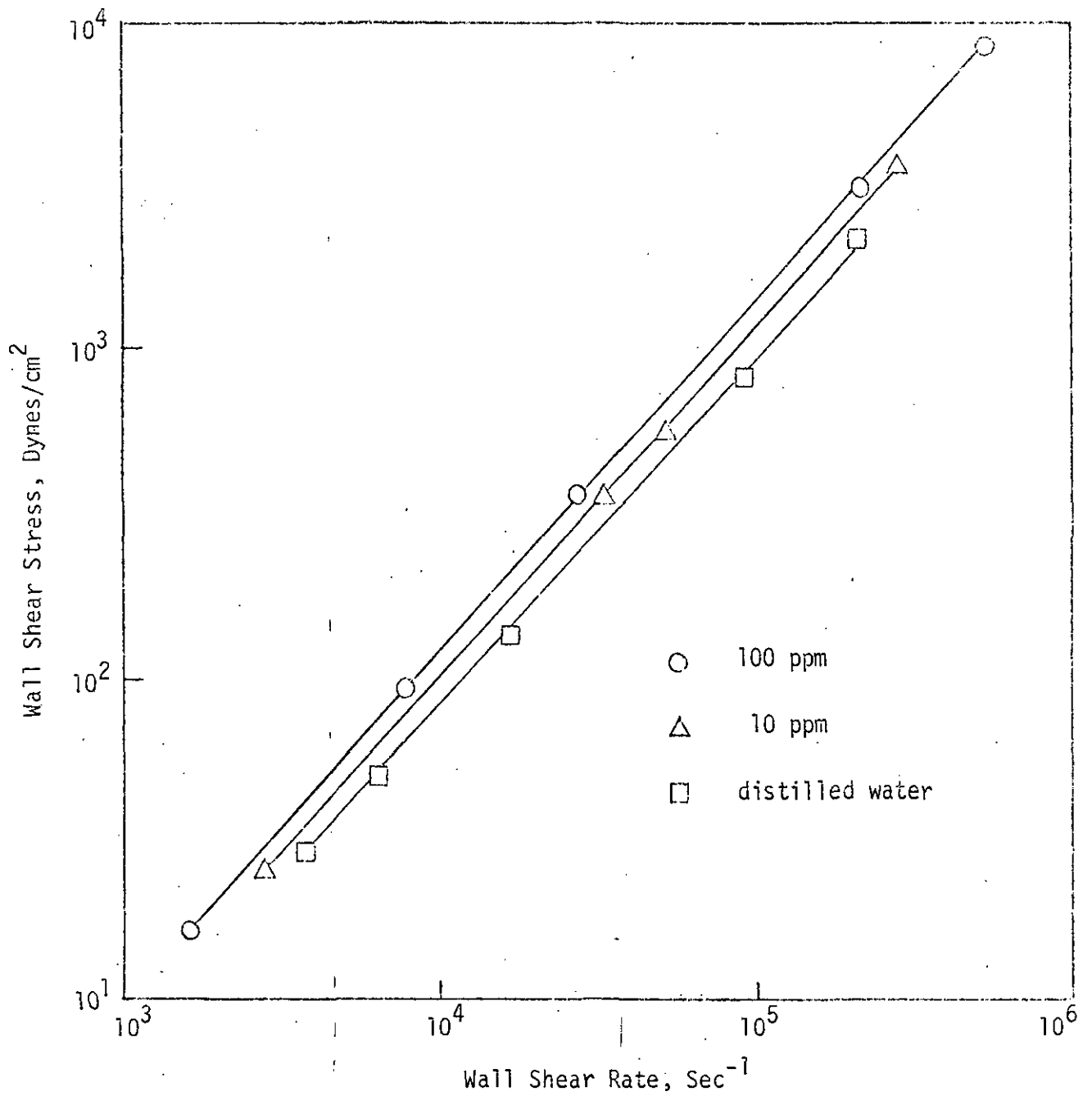


Figure 1. Rheogram for 10 and 100 parts per million of Polyethylene Oxide of 4-million Molecular Weight (6)

have a somewhat higher viscosity than the solvent. On the basis of this data only, one would logically predict that a slight friction increase, not a remarkable decrease, would occur during the turbulent flow of fluids containing polymers.

However, Hoyt (6) stated that when a solution of one of three polymers (polyethylene oxide) was pumped in turbulent flow through a pipe (i.e., at a Reynolds number greater than 3,000) friction reductions such as those shown in Figure 2 were obtained.

The U. S. Navy has done much work with polymers as friction-reducing agents. They first became interested in this subject in 1961 when Westco Research made known their findings. This firm is an oilfield equipment concern. Their workers found that less power was required to pump high-pressure water through pipelines when they added Guar gum to suspended sand particles in the water (6).

Based on these initial findings, the U. S. Navy set up an extensive screening program to determine useful high-molecular weight polymer additives. A. G. Fabula (6) of the Naval Ordnance Test Station has identified polyethylene oxide as the most effective known friction reducing agent. It is sold under the commercial name POLYOX. POLYOX is a high-molecular-weight material, having a straight chain structure consisting of oxygen, hydrogen and carbon. The U. S. Navy has identified several other promising chemical additives, such as the polyacrylamides, polysulfonates, and hydroxyethyl cellulose. See Table 1.

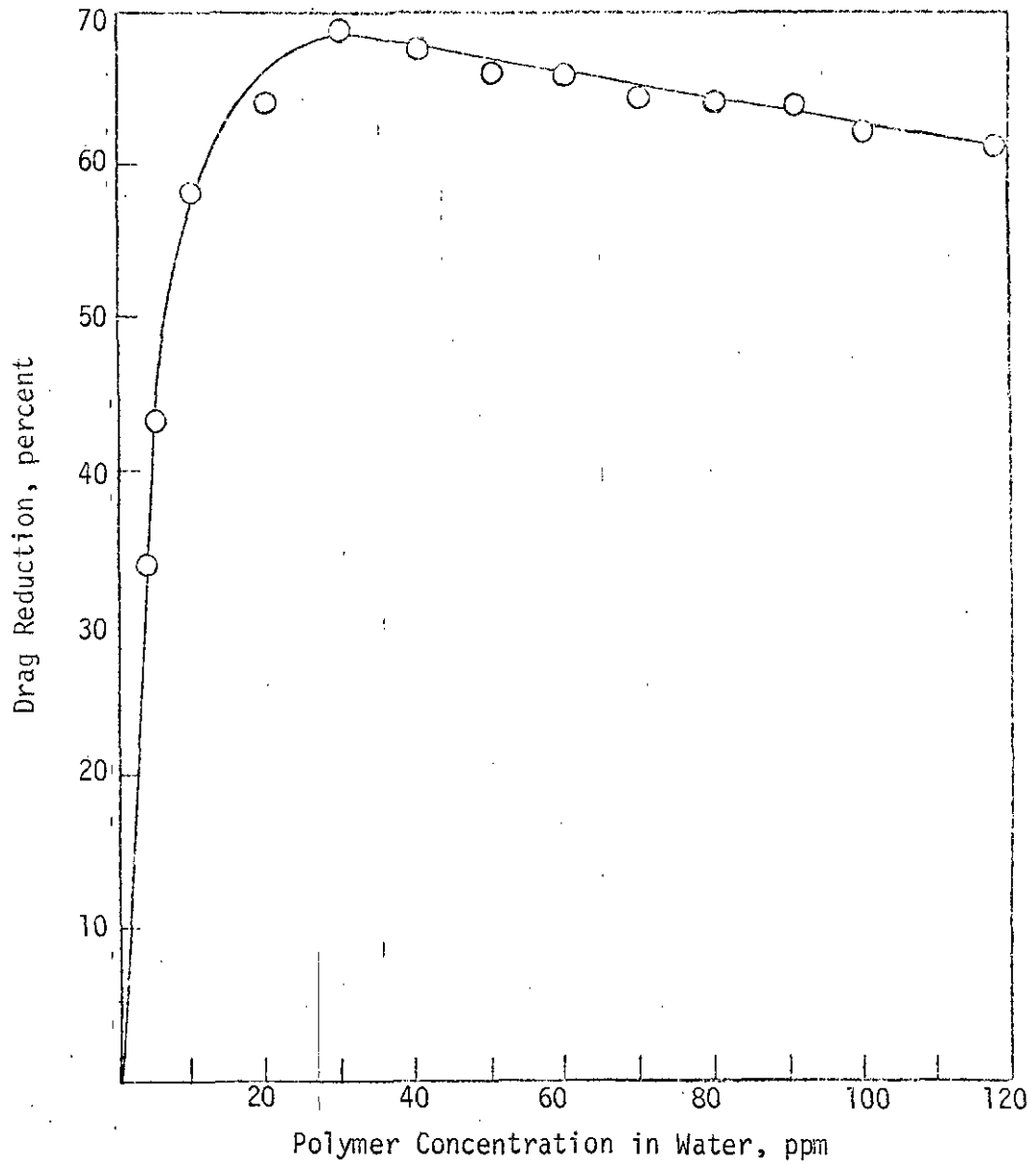


Figure 2. Friction Reduction versus Concentration
for POLYOX WSR-301 (6).

(0.19-CM. ID Pipe; Temperature 21.1°C; Re = 14,000)

TABLE 1. Various High Molecular Weight Polymer Additives (34)

<u>Trade Name</u>	<u>Chemical Identification</u>	<u>Manufacturer</u>	<u>Molecular Weight</u>
ADM-7097		Archur Daniels Midland Co. Minneapolis, Minn.	24×10^6
B-1459	Polysaccharide gum (fermentation)	Commercial Solvents Corp. New York, New York	-
B-1459		Elanco Products Co. Indianapolis, Ind.	-
Carbopol - 934	Carboxyl vinyl polymer	B. F. Goodrich Chemical Co. Cleveland, Ohio	-
DMC - 74SCP	Sodium carboxymethyl cellulose	Hercules Powder Co. Wilmington, Del.	$(5 \text{ to } 50) \times 10^4$
Dextran	Alpha glucosyl polysaccharide	Pharmacia, Uppsala, Sweden	$(5 \text{ to } 40) \times 10^6$
ET-597	Sulfonated polyvinyl toluene	Dow Chemical Co.	8×10^6
ET-720	Sodium polystyrene sulfonate	Midland, Mich.	$(8 \text{ to } 9) \times 10^6$
Jaguar - 124	Modified guar gum	Stein, Hall, and Co. New York, New York	-
Kelco Gel HV			-
Kelgin HV	Sodium alginate	Kelco Co., San Diego, Calif.	-

Table 1 (continued)

<u>Trade Name</u>	<u>Chemical Identification</u>	<u>Manufacturer</u>	<u>Molecular Weight</u>
Kelzan	Xanthon gum	Kelco Co., San Diego, Calif	-
Kelzan H			
Methocel - 90HG	Methyl cellulose	Dow Chemical Co., Midland, Mich.	-
Polyhall - 27	Non-ionic polyacrylamide	Stein, Hall, and Co. New York, New York	-
Polyox - 301	Ethylene oxide polymer	Union Carbide Chemicals Co. New York, New York	to 5×10^6
Reten - 205 MX	Cationic polymer	Hercules Powder Co. Wilmington, Del.	-
Separan - NP20	Non-ionic polyacrylamide	Dow Chemical Co. Midland, Mich.	2×10^6
Westco - J2	-	The Western Co. Dallas, Texas	2.2×10^5

With reference to polymer addition, Hoyt (31) concludes that this friction-reduction effect will manifest itself when the following conditions prevail:

- The flow is turbulent.
- The polymer used has a molecular weight of 50,000 or more.
- The polymer is straight-chained.
- The polymer is soluble.

Wilkinson, et al (32) tested two different polymers on a 6-inch test line. The polymer solutions were capable of increasing the flow by more than twice the flow of the non-polymered sewage. Under certain conditions the flow was increased by about 2.4 times. Table 2 shows these test results. It should be noted that the settleable solids content for the sewage used was 9 mg/l -- much less than the 120 mg/l (33) expected in a typical sewage. The names of the additives used were not given. They also added polymers to a 24-inch sewer line which was being surcharged. The line consisted of a 24-inch concrete sewer pipe having a grade of 0.32 percent. It was 4,100 feet long and discharged into a 30-inch outfall line. The line received flow from a 36-inch interceptor. During the testing the line was experiencing surcharges of six feet or more. Two different additives were used (their names were not given). In each of the tests, polymer addition stopped when the desired results were obtained -- the necessary reduction in head in the line to eliminate the surcharged condition. Table 3 shows these results. In this particular case,

TABLE 2. Polymer Concentration and Capacity Increase
for a 6-Inch Sewer Line (32)

Additive	Additive Concentration ppm	Sewage Concentration ml/l of S.S.	Sewage Temperature °F	Flow Rate GPM	Flow Increase %	FCIXOF*
No. 1	100	9	38	300	125	2.25
No. 1	100	9	70	300	114	2.15
No. 1	100	9	90	300	117	2.17
No. 2	200	9	38	300	125	2.25
No. 2	200	9	70	300	135	2.35
No. 2	200	9	90	300	110	2.10

* Flow Capacity Increase Times Original Flow

TABLE 3. Polymer Concentration and Capacity Increase
for a 24-Inch Sewer Line (32)

Additive	Additive Conc. ppm	Sewage Temperature F°	Sewage Conc. ml/l of S.S.	Flow Increase %	Flow Capacity Increase Times Original Flow
No. 1	35	80	10	40	1.40
No. 1	45	79	20	65	1.65
No. 1	50	80	10	70	1.70
No. 1	80	80	9	90	1.90
No. 2	40	84	15	50	1.50
No. 2	75	86	18	45	1.45
No. 2	80	86	15	55	1.55
No. 2	100	84	30	75	1.75

larger flow increases would have been realized if the concentrations were increased.

The cost of adding the two additives used on the 24-inch surcharged sewer has been figured at concentrations of 100 and 150 ppm (parts per million). The cost is given as materials cost in dollars per hour per injection. See Table 4 for costs at various wastewater flow rates.

Union Carbide, the manufacturer of POLYOX, has quoted prices ranging from \$1.50 to \$0.60 per pound, depending on the grade of POLYOX used, when purchased in 20,000 pound carloads.

In conclusion, the literature has provided information on a variety of chemical additives used as friction-reducing agents; however, the majority of this work was carried out in the laboratory under ideal conditions, that is, the major parameters such as flow rate, solids content, pipe roughness and mean velocity were controlled. Even in the reported field study (32), the settleable solids content was much less than the expected value in a typical wastewater.

What appears to be missing is chemical additive data on gravity sewers carrying a normal wastewater. Part of this research is directed to providing this data.

TABLE 4. Cost of Additive (32)

<u>Flow</u>		<u>Additive No. 2</u>		<u>Additive No. 1</u>	
CFS	MGD	100 ppm	150 ppm	100 ppm	150 ppm
1.12	0.72	5.29	7.94	7.17	10.76
2.23	1.44	10.59	15.89	14.34	21.52
5.57	3.60	26.48	39.72	35.86	53.80
11.14	7.20	52.96	79.45	71.73	107.60
16.71	10.80	79.45	119.17	107.60	161.40
22.28	14.40	105.93	158.90	143.46	215.20
27.85	18.00	132.41	198.62	179.33	267.00
33.42	21.60	148.90	238.35	215.20	322.80

This chart indicates the material cost in dollars per hour for injecting the slurry at 100 and 150 ppm polymer concentration at various wastewater flow rates.

PART 3. THEORETICAL CONSIDERATIONS

3.1 Sewage Quality Changes

Of concern in this research is the removal of dissolved oxygen from the sewage. If the rate of reaeration exceeds the rate of deoxygenation, the chance that sewage quantity changes will have an adverse effect on the transport system is remote. In theory an equation can be written to determine the dissolved oxygen content at any time (t) knowing the characteristics of the waste; however, in practice, predicting the dissolved oxygen concentration in a sewer line at time (t) is difficult. This difficulty can be seen by the fact that no researcher has developed any type of relationship which would predict the dissolved oxygen content in a typical sewer system. Much of the difficulty is due to the several factors involved. Among these factors are the velocity of flow, the strength of the waste, the sulfide content of the waste, temperature of the waste, depth of flow in the sewer line, toxicity of the waste, temperature of the waste, the number of force mains in the system, the amount of turbulence existing in the sewer line, the age and pH of the waste, and the amount of ventilation in the sewer.

Most of the work conducted on oxygen balance for wastewater has been done on rivers and streams, mainly to consider how much sewage can be discharged into a stream before the assimilative capacity is exceeded.

In their study of the pollution and natural purification of the Ohio River, Streeter and Phelps (9) developed the following equation:

$$C = C^m - \frac{K_1 L_0}{K_2 - K_1} (e^{-K_1 t} - e^{-K_2 t}) - (C^m - C_0) \cdot e^{-K_2 t} \quad \text{Eq. (3)}$$

where

t = flow time in days,

C = oxygen content of water at time t , (mg/l),

C_0 = Oxygen content of water at time 0, (mg/l),

C^m = Oxygen solubility of water in contact with air, (mg/l),

K_1 = constant of oxygen consumption, (d^{-1}),

K_2 = constant of oxygen reaeration, (d^{-1});

Utilizing the above equation, the dissolved oxygen content of the stream could be predicted at time t .

This equation assumes as constant K_1 . This assumption is valid because the BOD of a stream is generally low; also the time period is usually several days, a period long enough for K_1 to stabilize itself at a constant value. K_2 , the reaeration constant, is calculated on the basis that the percent oxygen in the air above the stream remains the same. This, too, has been shown to be a valid assumption (9).

When this equation is applied to a sewer line, problems result. The K_1 value of raw sewage has been shown to vary considerably during

the first day (3, 4). The strength of a raw sewage is much greater than that of a stream; this fact coupled with a variable K_1 introduces considerable error in predicting a dissolved oxygen content. K_2 will vary depending on the depth of flow, and the amount of mixing. Also, there is a decrease in the oxygen content of the air in a sewer as the dissolved oxygen in the sewage is consumed and reaeration depletes the supply of oxygen in the air space above the sewage.

For the reasons pointed out above, the Streeter-Phelps equation does not lend itself to sewer line application.

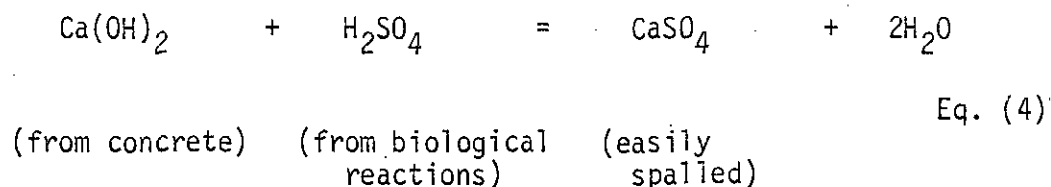
A practical method of evaluating oxygen uptake can be obtained by using a respirometer. This, too, does not fully simulate the condition in a sewer line, but it does have certain mechanisms (i.e., shaking apparatus, constant temperature bath) which can be employed to resemble sewer conditions. By using this instrument, the time required for a waste to utilize the initial dissolved oxygen could be determined. Knowledge of this time would not permit the solution to all sewer line problems, but it would be a piece of information that would bring engineers to better understand what is going on in the sewer and how important is the concept of maintaining a certain dissolved oxygen level in the sewer line.

3.2 Sewer Corrosion

This section concerns itself with corrosion brought about by the generation of hydrogen sulfide. Corrosion of a concrete sewer is

brought about by a complex series of biological and chemical reactions.

The final chemical reaction in the series is:



As seen in the reaction, the sulfuric acid (H_2SO_4) reacts with the lime (Ca(OH)_2) in the concrete to form calcium sulfate. Gaudy (1) stated: "The formation of CaSO_4 adds to the injurious effect since it may be considerably hydrated, and internal stresses caused by the increase in volume enhance spalling, thus exposing fresh surfaces to attack."

3.2.1 Biological Reactions

This reaction described above has several intermediate steps which are brought about by a series of bacterial populations.

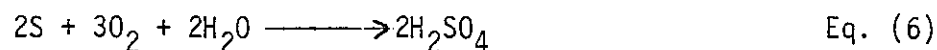
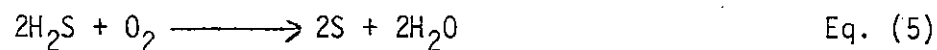
The organic matter and other substances contained in the sewage satisfy the nutritional requirement for a group of bacteria classified as heterotrophs; i.e., these organisms need organic material as a food source. When the sewage becomes anaerobic or when velocities are such that sludge deposits collect along the bottom of the sewer line, these organisms reduce sulfates to sulfides, one of which is hydrogen sulfide. Under certain conditions (i.e., vertical drops,

turbulence) some of the hydrogen sulfide is stripped from the flowing sewage and vented to the atmosphere, while some is adsorbed in a layer of condensed water on the walls of the pipe (1). The hydrogen sulfide dissolved in this water layer forms a weak acid which can attack some free lime in the concrete. This reaction proceeds slowly and the corrosion it may cause is not considered significant. The major concern is the presence of a source of reduced sulfur in the layer, coupled with dissolved oxygen transferred from the air above the water line. This combination provides an enriched environment for the growth of autotrophic bacteria which can utilize carbon dioxide (CO_2) as their sole carbon source. These autotrophs obtain the energy needed to make use of this carbon by the oxidation of hydrogen sulfide (1).

Gaudy has summarized these biological reactions as follows:

The type of autotrophic bacteria involved in concrete corrosion are of the genus Thiobacillus. Two types of thiobacilli contribute to corrosion. The non-aciduric species, Thiobacillus novellus and Thiobacillus thioparus, can oxidize reduced sulfur compounds to sulfur and sulfate, and can increase the hydrogen ion concentration to 10^{-5}M . Below a pH of 5, these organisms die off. (1).

However, the lowering of the pH to 5 provides for the growth of a second type of thiobacilli; the aciduric species, Thiobacillus thiooxidans and Thiobacillus concretivorus; since they can reduce the pH to 1.00 or below, these species can create severely corrosive conditions. The reactions which take place in the condensed water layer on the pipe wall are as follows: (1)



The sulfuric acid then reacts with the lime in Equation (4), producing calcium sulphate which is easily spalled from the concrete pipe. The corrosion pathway is now complete.

3.2.2 Factors in Sulfide Generation

Several factors influence the amount of hydrogen sulfide which is actually generated in the sewer line. These factors are temperature, strength, age, and pH of the wastewater and the velocity of flow.

3.2.2.1 Temperature of the Wastewater

The amount of sulfide produced depends on the biological activity of certain organisms and temperature has a direct bearing on their activity.

Baumgartner (35) measured the sulfide generation in bottles at four different temperatures. The rate of sulfide generation was found to increase 7 percent per degree rise in temperature up to 30°C. Between 30° and 37°C the rates were similar.

Pomeroy and Bowlus (36) have found that the rate of sulfide generation increases progressively up to 38°C. There is an appreciable lag at 42°C before the maximum rate of generation is reached, and this

is not as great as at 38°C. The lag is even more pronounced at 46°C and 52°C but eventually maximum rates are attained which exceed those of lower temperatures. Table 5 lists the maximum rates of sulfide generation at various temperatures. The figures in this table are intended only to show the effects of temperature in a general way.

Field tests (35) have shown that sewage with a temperature of 15°C or less is devoid of sulfides except for small amounts of inert metallic sulfides.

With reference to gravity sewers, Pomeroy and Bowlus (36) conclude that "for any specified flow conditions and sewage strength in a free-flowing sewer, there is a minimum temperature below which sulfide build-up will not occur."

In force mains where the sewage is not in contact with the atmosphere, a different situation exists. Under these conditions the relationship between sulfides and temperatures follows more closely the results of bottle experiments (36).

3.2.2.2 Strength of Wastewater

Other factors remaining constant, more sulfides will be generated as the strength of the waste increases. This is because of the high concentration of bacterial nutrients in a stronger wastewater. The exact nutrients utilized by the sulfide-producing microbes are not known; however, generalizations can be made and field tests have shown that

TABLE 5. Estimated Maximum Rates of Sulfide Generation (36)

Temperature (°C)	Maximum Rate of Sulfide Increases (ppm per hr)
4 - 6	0.015
15	0.18
20	0.34
25	0.50
30.5	0.68
38	0.89
42	0.49
46	0.87
52	1.15

sulfide generation in sewers is related to the BOD of the waste. These field tests were conducted in a sewer line over a period of several hours; Figure 3 shows the results of this work. As can be seen from the figure, sulfide generation practically stops when the BOD is below 80 mg/l. This is due to aeration at the surface which destroyed the sulfides as fast as they were formed, provided the strength of the waste is below this limiting value. This value of 80 mg/l as being the critical value before sulfides would be present was also reported by Shreve (37) in Florida. As shown by this field testing, sulfide problems may occur only during certain periods of the day. Bowlus and Banta (38) also found that sulfides may be present only at certain times.

In situations where sewage may enter a filled pipe with no oxygen or in longer force mains, sulfides may be present in sewage having a very low BOD value, below 80 mg/l.

This work on the strength of wastewater causing sulfide problems can be summed up in the following statement: There is a limiting wastewater strength below which no sulfide build-up will occur for any specified flow condition and temperature (36).

3.2.2.3 Velocity of Flow

The sewage flow velocity is an important factor in the control of hydrogen sulfide because accumulation of slimes and debris below the water surface are a direct result of low velocities. These slimes and debris provide a most suitable habitat for sulfide-producing bacteria (37).

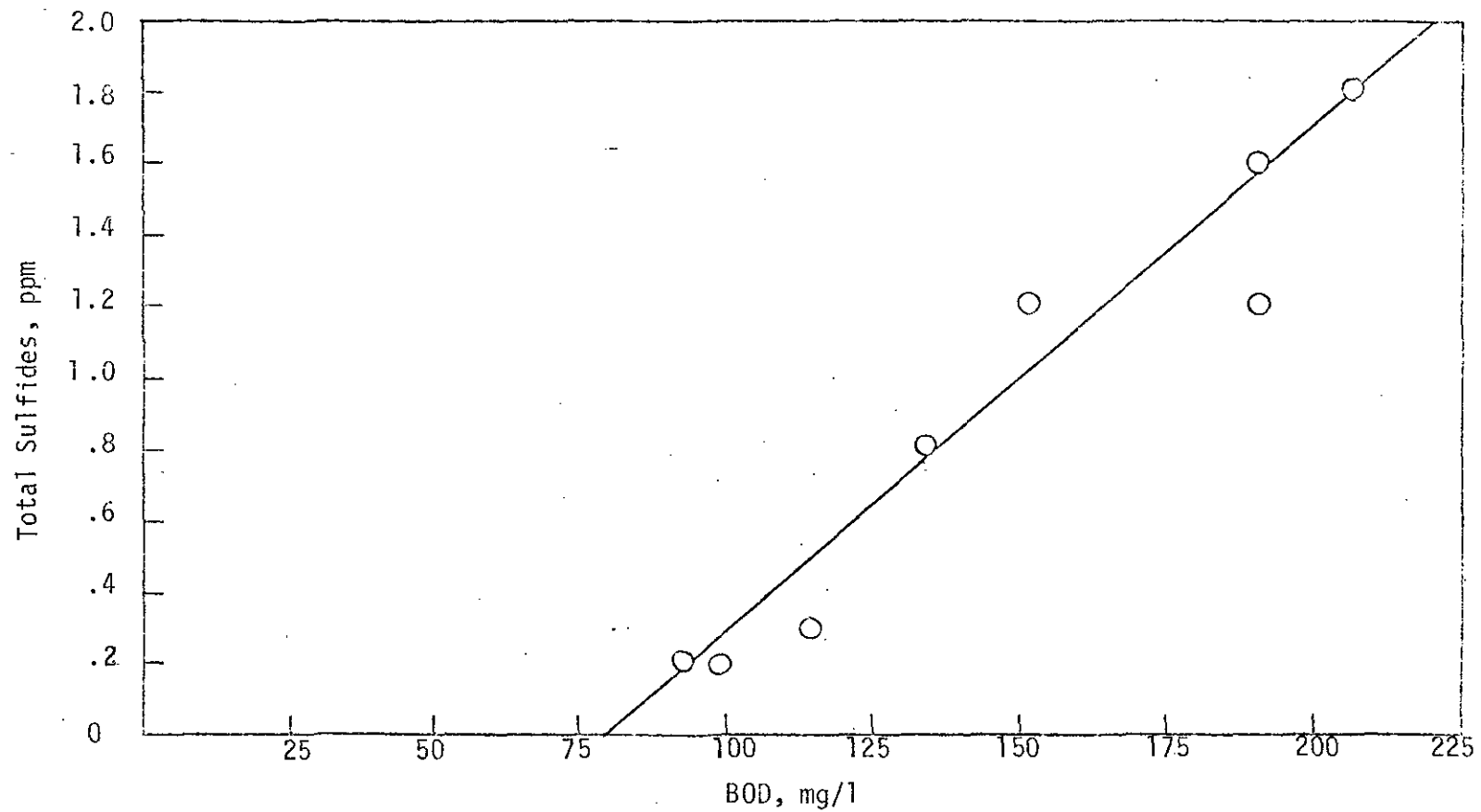


Figure 3. Correlation of BOD and Sulfide Concentrations (36)
(reaching treatment plant).

Debris and other types of bottom deposits can be prevented by having flow velocities of three ft. per sec. or more (36). The rate at which sulfides are destroyed at the surface has also been shown to depend on velocity. Streeter, et al (39) have found that absorption of oxygen by a stream varies as the 1.75 power of the velocity. Of less importance is the evolution of hydrogen sulfide but this may also vary in a similar way. From this, it can be concluded that velocity is a major factor in determining whether the rate of sulfide subtractions from the stream by evolution and oxidation will keep up with the rate of sulfide generation by the slimes (36). This principle may be stated as follows: For any sewage strength and temperature combination, there is a limiting velocity above which sulfide build-up will not occur. This principle applies only to free-flowing (gravity) sewers (36).

Since the limiting velocity is dependent on both temperature and sewage strength, it has been found convenient to combine these two conditions into a single factor called "effective BOD." Based on the standard BOD at 20°C, the BOD for any other temperature is calculated on the assumption that biological activity will increase 7 percent per degree (geometrically). This is expressed in a formula (36) as:

$$\text{Effective BOD} = \text{Standard BOD} \times (1.07)^{t-20}$$

where

t = temperature in degrees centigrade

Table 6 shows the minimum velocity needed to prevent sulfide build-up (36).

TABLE 6. Required Velocity to Prevent Sulfide Build-up (36)

Effective BOD (mg/l)	Velocity (ft. per sec.)
55	1
125	1.5
225	2
350	2.5
500	3
690	3.5
900	4

3.2.2.4 Age of Wastewater

The effect wastewater age has on the sulfide problem depends on how much reaeration is taking place to destroy these sulfides. If there is sufficient reaeration, wastewater age has no effect; however, when reaeration is not adequate there will be a continual build-up of sulfides (36).

3.2.2.5 pH of Wastewater

The pH of wastewater has been shown to have an effect on the total sulfides generated. Figure 4 shows the relative rates of sulfide production at various pH values. The portion of the sulfides in the form of hydrogen sulfide is also greatly influenced by the pH. At a pH of 6.0, 83 percent of the dissolved sulfide content is hydrogen sulfide. When the pH is 7.0 only 33 percent, and when the pH is 8.0 the portion of hydrogen sulfide is only five percent (36).

Shreve (37) has reported that it is not economically feasible to control the pH because sulfide-producing organisms thrive over a wide range of pH values.

3.2.2.6 Effect of Sulfate Concentration

Sulfides in sewage arise chiefly through the reduction of sulfates. However, from work on sulfate concentrations versus sulfide generation no direct relationship has been found between the amount of sulfides

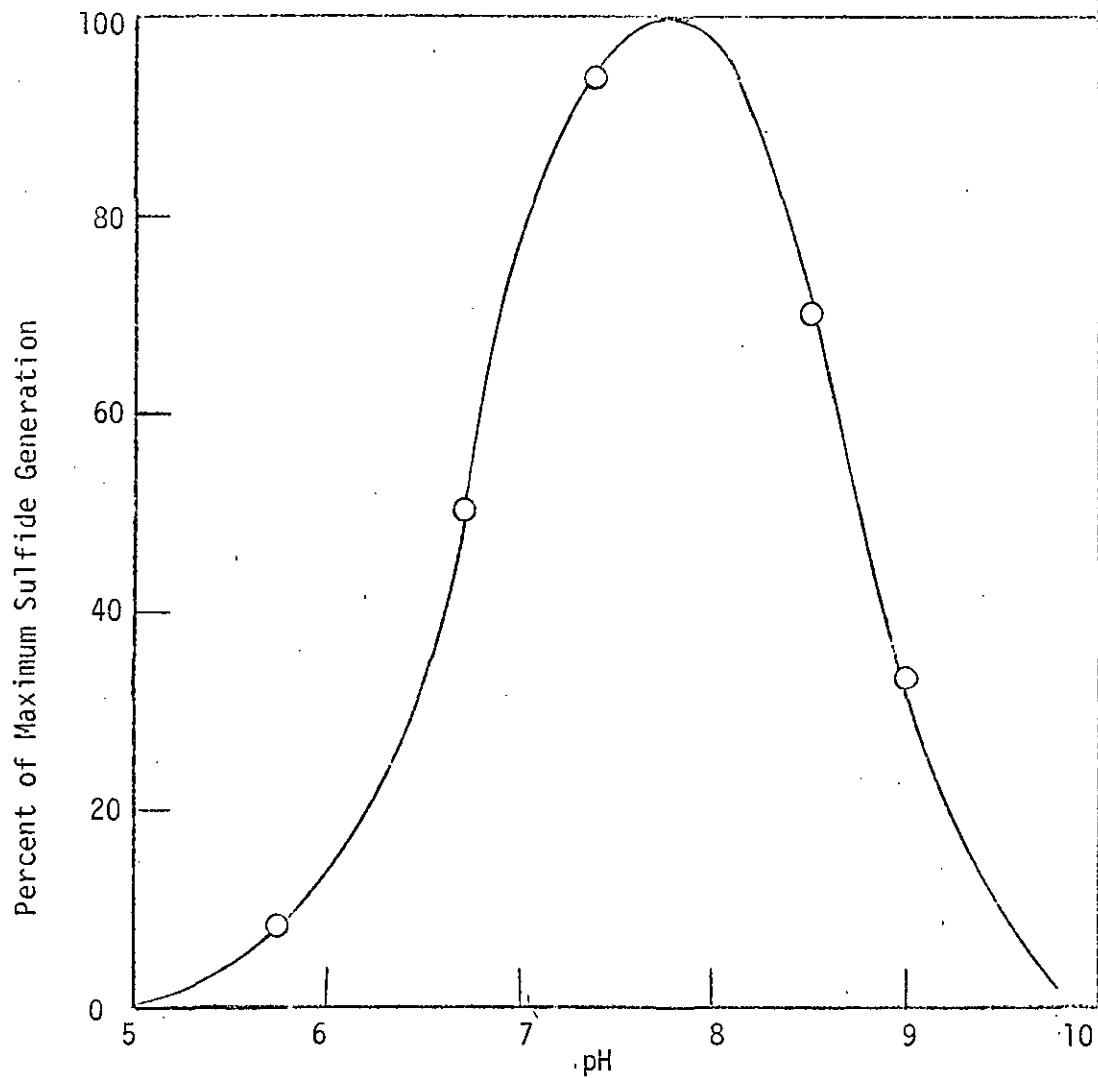


Figure 4. Relative Rates of Sulfide Production at Various pH Values (36)

generated at certain sulfate concentrations (36); this was shown by an experiment in which bottles of sewage containing 220 ppm of sulfate were incubated along with bottles of the same sewage enriched with sodium and magnesium sulfates to 390 ppm and 560 ppm of sulfate. At the end of three days all bottles had 8 to 9 ppm of sulfide (36).

Shreve (37) also reports that sulfate concentrations above 50 mg/l have little effect on the rate of sulfide production over a period of several days.

3.2.3 Sulfide Control

3.2.3.1 Proper Design

The concept of sulfide generation should be considered in the design of any sewerage system. It should be taken into account in the design of such features as velocity, force mains, vertical drops, and construction materials and coatings (36).

For a wastewater of constant strength and temperature, the controlling factor as to whether sulfide build-up will occur or not depends on the velocity. Based on the estimated peak BOD and temperatures, the minimum safe velocity can be found in Table 6. An allowance of 25 percent should be made to the value found in Table 6 as a factor of safety. When dealing with industrial wastes, this allowance should be increased to 50 percent. Sulfides may be a problem in the early part of a design period but will disappear as the flow reaches the design flow.

Sulfide generation can be expected in sewers flowing completely full except where the sewage is quite weak or it is fairly well aerated. Because of this, force mains should be kept at a minimum. In some cases it may be beneficial to lift the sewage vertically from one gravity sewer to another, at the expense of deeper excavations, in order that possible sulfide problems may be eliminated (36).

Often sewage has a high velocity just before entering the treatment plant. In cases where it has a high sulfide concentration, these large velocities should be avoided. Vertical drops in manholes should also be avoided when possible because this type of design leads to excessive release of hydrogen sulfide.

As discussed earlier, unprotected concrete has been attacked severely to the extent of causing damage to structures. Vitrified clay liners have been used for protection. More recently Ocrated concrete has been found to resist sewer corrosion. One of the major constituents in this Ocrated concrete is fluoride which has an inhibiting effect on the formation of elemental sulfur which is used by certain organisms to bring about acid conditions (1).

3.2.3.2 Control of BOD

Since the BOD of the waste is proportional to the rate of sulfide generation, a reduction in the BOD would reduce the rate at which sulfide is produced. This reduction can be brought about by pretreatment and (or) dilution.

3.2.3.3 Control of Temperature

The rate of sulfide generation can be reduced by lowering the temperature. This is not considered a practical solution and is not practiced except incidentally when an unpolluted water is combined with a polluted wastewater reducing the effective BOD.

3.2.3.4 Control of pH

Since sulfide-producing organisms can operate over a wide pH range, it is not feasible to control pH.

The control of pH may be considered when dealing with industrial wastes. An industrial waste which would lower the pH of the sewage would cause a high portion of the sulfide to exist as hydrogen sulfide (36):

3.2.3.5 Chlorination

Chlorination is one of the principal methods used to control sulfide production. It has been used successfully over the past twenty years and should continue to be an important method in the future.

Chlorination acts in three ways (36):

- it destroys sulfides by chemical reaction;
- it causes mild oxidizing compounds to be produced in the sewage which temporarily retards biological activity, thus permitting sewage to accumulate a little dissolved oxygen; and
- it destroys the sulfide-producing organisms, thus preventing sulfide generation.

3.2.3.6 Aeration

The surface aeration which occurs in large, well-ventilated, partly filled sewers is quite important in the control of sulfides. Pomeroy and Bowlus (36) considered placing compressed air stations in the sewer line at suitable intervals, such as one mile; however, they found it was not economically feasible.

3.2.3.7 Sodium Nitrate

Next to air, sodium nitrate is the cheapest industrial oxidizing agent (36). The nitrate competes with the sulfate as an oxygen supplier for the oxidation of organic matter. Shreve (37) reports that sodium nitrate is added to sewage in Fort Lauderdale, Florida, to prevent odors which were caused by high concentrations of sulfate. In these experiments, it was found that the energy requirement to extract chemical oxygen from nitrates was much lower than that required to extract chemical oxygen from sulfate. Consequently, bacteria will reduce nitrates before reducing sulfates. The reduction of nitrate produces odorless nitrate compounds.

3.3 Friction Reducing Additives

3.3.1 Type of Additive Used

The additive used in this research was polyethylene oxide, a water soluble, high-molecular weight material, of completely linear

construction, sold under the commercial name, POLYOX. See Figure 5. This POLYOX is manufactured by Union Carbide Corporation.

POLYOX comes in many grades. The grade is based on its molecular weight. POLYOX WRS-301 was the grade used in this research. POLYOX WRS-301 has an approximate weight of 4,000,000. The following information was furnished by Union Carbide Corporation (40) and pertains to this grade of polymer which will simply be referred to as POLYOX.

POLYOX is an instantly wettable and completely water-soluble high polymer. This polymer was included in the diet of rats and found to have a low degree of oral toxicity at a concentration of 2 percent for two years. No harm was detected by gross observations. POLYOX does not cause skin irritation. The possibility of eye injury is also remote; only moderate inflammation of the eyes resulted when rabbits' eyes were flooded with a 5 percent aqueous solution of POLYOX.

The stability of POLYOX is affected by mechanical agitation. The degree to which these long chains are ruptured depends on the total energy input. Because of this shear sensitivity, solutions of this polymer are carefully prepared.

The viscosity of POLYOX decreases as the temperature increases.

Normally, the pH has little effect on the solution viscosity of POLYOX. In fact, the viscosity of POLYOX varied less than three percent over a pH range from 2 to 12. For a pH below two, hydrolysis and chain scission may cause a rapid decline in viscosity. At a pH above 12, the viscosity is reduced due to the high hydroxyl ion concentration

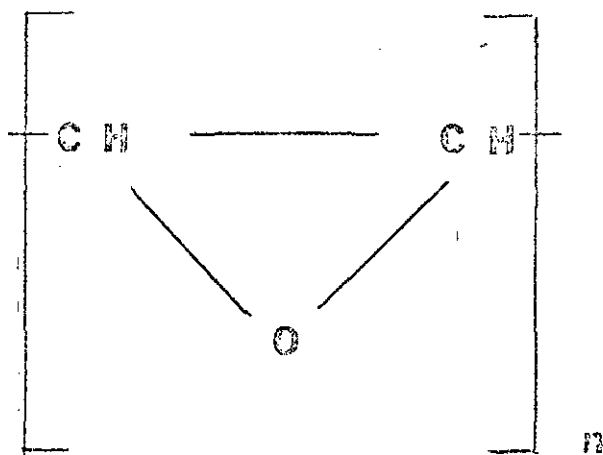


Figure 5. Molecular Structure of Polyethylene Oxide

precipitating the POLYOX from solution.

3.3.2 Scour Effect

This concept of scour is extremely important in the design of a sewer line for without sufficient scour solid particles will settle out reducing the capacity. Also, these bottom deposits provide a good environment for sulfide-producing organisms. A minimum velocity of 2 ft/sec is considered necessary to avoid deposition of solids in a sewer.

Shields and Camp (41) have done much work on minimum velocities necessary to prevent settlement of solids. Based on their work, they have developed the following equation:

$$v = \sqrt{\frac{8\beta}{f} g (s - 1)d} = \frac{1.486}{n} r^{1/6} \sqrt{\beta(s - 1)d} \quad \text{Eq. (7)}$$

where

v = mean velocity of stream, in feet per second

f = is the Weisbach-Darcy friction factor of the conduit;

g = is the acceleration of gravity, in feet per second;

s = is the specific gravity of the particle;

d = is the diameter of the particle, in millimeters;

β = is the dimensionless constant with a value of about

0.04 to start the motion of granular particles and

it is about 0.8 to insure adequate self-cleaning of

sewers and drains;

n = is the roughness coefficient;

and

r = is the hydraulic radius.

Under uniform flow open channel conditions, when the polymer solution is added to the sewer, the hydraulic radius (r) will decrease. In addition, with the addition of a polymer solution, the roughness coefficient (n) decreases. If the ratio $r^{1/6}/n$ increases, the above equation would be needed to prevent scour. Experiments with closed conduits have shown that the Manning's n value may be cut in half by the addition of a polymer. While the reduced boundary shear brought about by the presence of a polymer will reduce the depth of flow in an open channel, and consequently the hydraulic radius (r), the effect of the change on the sediment carrying capacity will be minor due to the exponent (1/6) in the above equation. For example, if the original hydraulic radius were 20 and it decreased to 10 with the addition of polymer, the respective changes on $r^{1/6}$ would be 1.65 and 1.46, i.e., halving r decreases $r^{1/6}$ by about 12 percent. Thus, it may be concluded that the minimum scouring velocity change will be about inversely proportional to the change in the roughness coefficient.

PART 4. EXPERIMENTAL PROCEDURES

The sewage used in this study was collected from the influent line at the Amherst, Massachusetts, Sewage Treatment Plant. There are three separated lines merging at the intake structure of the plant. One line is from North Amherst, the second from the University of Massachusetts, and the third from South Amherst. Individual samples were taken from the University of Massachusetts line and from the South Amherst line. The residence time in the University line is approximately 15 minutes, whereas the residence time in the South Amherst line varies from 12 to 18 hours because of detention time in pumping stations.

4.1 Sample Collection, Preservation and Storage

The samples of raw sewage were collected in a 6 1/2 gallon polyethylene bottle. To limit aeration, the sample was transferred to the bottle through a funnel attached to a long hose and allowed to gently fill the bottle.

No preservatives were added to the sewage because they might adversely effect the characteristics of the sewage which were to be investigated. After the polyethylene bottle was filled with the sample, it was placed in a large cylindrical container. There was 1-inch of air space between the outside wall of the bottle and the inside wall

of the cylindrical container. This space was completely filled with crushed ice.

When the raw sewage reached the laboratory, it was placed in a Waring Blender Model BC-5. The purpose of this mixing was to yield a more homogenous sewage. Prior to mixing, the raw sewage contained large solid particles.

4.2 Temperature of Sewage

Temperature measurements were made on raw sewage in transit from both the Town of Amherst and the City of Northampton and at the Amherst sewage treatment plant. The temperature of the sewage at all locations was found to be approximately 21°C. These temperature measurements were taken for several days in the months of June and July. In all determinations there was never a fluctuation of more than one degree above or below this value of 21°C.

4.3 Analysis Performed to Determine Quality Changes

The biochemical oxygen demand (BOD) was determined as described by Standard Methods (42) and a respirometer method (43). The BOD was determined each day for a period of five days. The BOD test was performed in triplicate on each sample. Dissolved oxygen levels were determined by the azide modification of the Winkler method.

A Gilson Model GRP-20 Differential Respirometer, similar to the Barcroft type, was used in this study. Fifty milliliter sample aliquots of raw sewage were used throughout. Studies were performed on a 14-hour basis and on a five-day basis. The temperature was maintained at 21°C and the changes in barometric pressure were accounted for by the application of appropriate multiplication factors which reflected standard atmospheric conditions at the time measurements were taken. The Gilson Medical Electronics Company furnished the following equation to calculate the multiplying factor. This factor is applied to each measurement:

$$\frac{(273)(P_b - 3 - P_w)}{(t + 273)(760)} = \text{multiplying factor} \quad \text{Eq. (8)}$$

where

273 = correction to absolute temperature.

3 = compensation for the specific gravity of mercury at room temperature.

760 = standard barometric pressure in millimeters of mercury.

P_b = barometric pressure at start of respirometer run in millimeters of mercury.

t = water bath temperature in degrees centigrade.

The measurements obtained from the respirometer are in microliters of dry oxygen consumed. Conversion of three measurements into mg/l BOD

is accomplished by application of a multiplication factor equal to 0.028572. This factor reflects the use of a 50 ml sample of sewage (See Appendix for factor derivation).

During respiration, CO_2 is liberated. To maintain the pressure of CO_2 at zero, 1 ml of 20 percent KOH is placed in the center well of the flask. This alkali (KOH) adsorbs the CO_2 .

Throughout the testing program, all the flasks were shaken at 100 oscillations per minute. This rate of shaking insured that the sample of sewage was saturated with the gas phase. This point is important for it allows respiration to proceed at the actual reaction rate rather than at a rate dependent on the rate of oxygen uptake (44). Umbriet, Burris, and Stauffer (43) have found in two separate studies between 600-700 microliters of oxygen per hour can be safely measured with diffusion at a shaking rate of 100 oscillations per minute with a Barcroft respirometer.

The raw BOD data obtained from the respirometer was plotted versus time and compared to the BOD obtained from bottles.

To measure the effect POLYOX has on sewage degradation, raw sewage having 0, 50, and 100 mg/l of the polymer were run on the respirometer. Also, bottle BOD's having the same concentration of polymer were attempted. The bottle method of measuring the BOD proved to be meaningless since the sulfuric acid, used in the BOD test, reacted with the polymer, causing erroneous dissolved oxygen readings.

Samples of raw sewage were taken from both the University of Massachusetts line and the South Amherst line. Duplicate 75 ml samples of each sewage having polymer concentrations of 0, 50, and 100 mg/l were run on the respirometer. At various times over a period of five days the pH of each sample was taken. The instrument used to measure the pH was a Copenhagen Model 25 glass electrode Radiometer. Again, in order to simulate stream conditions, the temperature of the water bath was maintained at 21°C and the flasks were shaken at 100 oscillations per minutes.

4.4 Addition of Friction Reducing Additives.

As stated earlier, the preparation of a POLYOX solution is a delicate operation in the sense that timing and coordination are required to make a successful batch. Union Carbide Corporation (40) has suggested Zimmerman's method of preparing a solution of the polymer.

The following instructions are for a 50 gallon solution of one percent POLYOX:

1. To a 55 gallon drum, add approximately 42 gallons of distilled or deionized water.
2. Aim a propeller stirrer toward the center of the bottom of the drum, to obtain as fast and as deep a vortex as possible.
3. Slurry four pounds of POLYOX in two gallons of anhydrous isopropanol (industrial grade is sufficient). Disperse the POLYOX completely, making certain that there are no lumps

unwetted or stuck to the bottom of the container.

4. Quickly pour the well-suspended slurry into the horizontal ring on the surface of the water, midway between the edge of the drum and the vortex. This step should take approximately ten seconds.
5. Quickly add enough water to bring the volume up to fifty gallons. Slow down or stop the stirrer to measure the height.
6. Stir rapidly until the additional water is mixed, then slowly for ten minutes. Remove stirrer.

If the POLYOX solution is to be stored for a period of more than one day, the following chemical should be added prior to Step 2 to inhibit chemical degradation of the polymer:

Dissolve in the 42 gallons of water:

a. 1 lb. Borax decahydrate ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$).

b. 1 lb. Dibasic sodium phosphate, anhydrous (Na_2HPO_4)

or

2 lbs. Dibasic sodium phosphate heptahydrate

($\text{Na}_2\text{HPO}_4 \cdot 7\text{H}_2\text{O}$)

In this study, five gallons of a one percent solution of POLYOX was made at a time. Thus, one-tenth of the chemicals and water were used per batch. The mixing device used was a Fisher Scientific Jumbo Stirrer Model No. 47. No preservatives were added to the POLYOX

solution since it was used on the one day.

The POLYOX was applied in a one percent solution from 10 gallon circular, polyethylene containers. Each container was calibrated in liters and had a stopcock valve arrangement at the bottom edge which allowed for the flow rate to be controlled.

The container was situated at the edge of the open sewer manhole to allow the polymer solution discharge to fall directly into the stream of sewage in the sewer. A stop watch was employed to record the time period during which the polymer was added. The volume of polymer in the container was also recorded to determine the amount of polymer added during the time period. Knowing the time of application, amount of polymer added and the flow rate of the sewage, the concentration of polymer in the sewage could be determined.

In all sewer testing a mixing length was used. This mixing length was the distance between the first two manholes and the measurements were made between the second and third manholes.

All sewers tested were in the City of Northampton, Massachusetts. Three different sewers were tested. They will be designated as Sewer Number 1, Sewer Number 2 and Sewer Number 3. Profile views of each sewer are shown in Figures 6, 7, and 8 respectively.

Sewer Number 1 was beneath College Lane. The mixing section started at the intersection of College Lane and Elm Street. This sewer consisted of a 15 1/2-inch tile pipe. It had a mixing length of

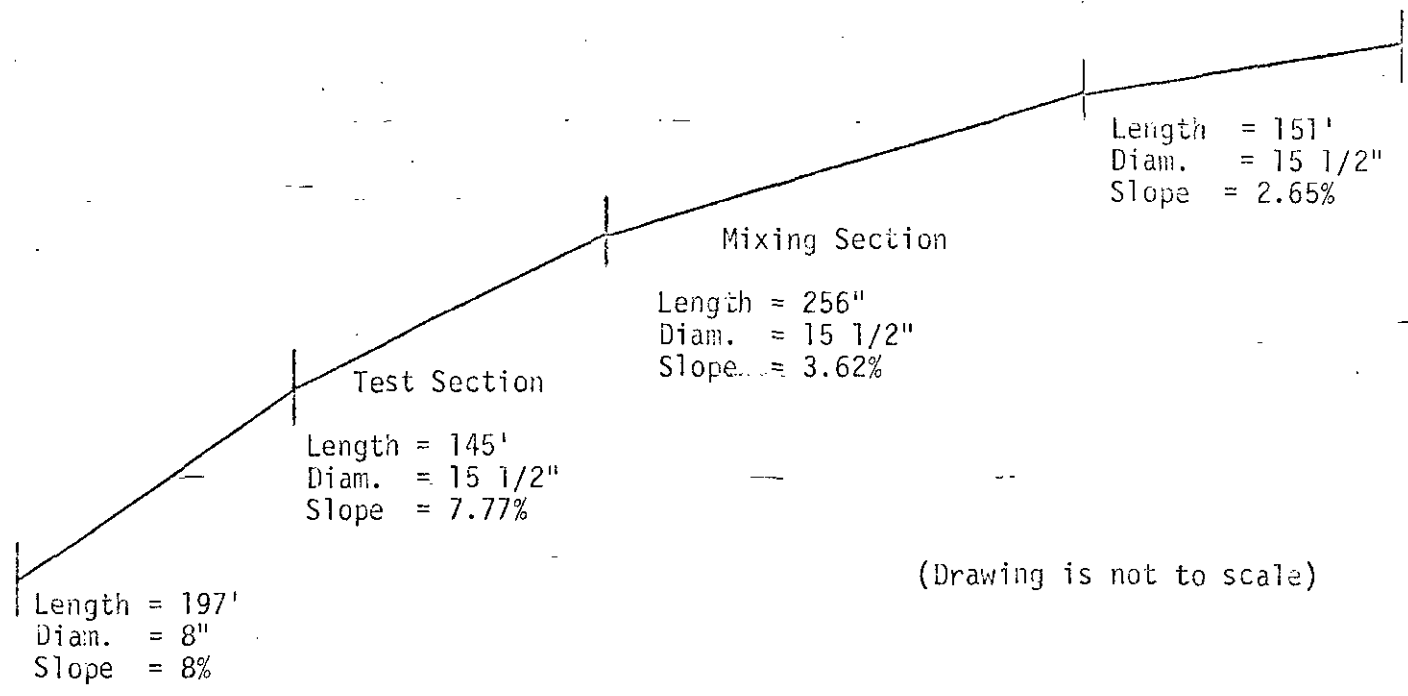
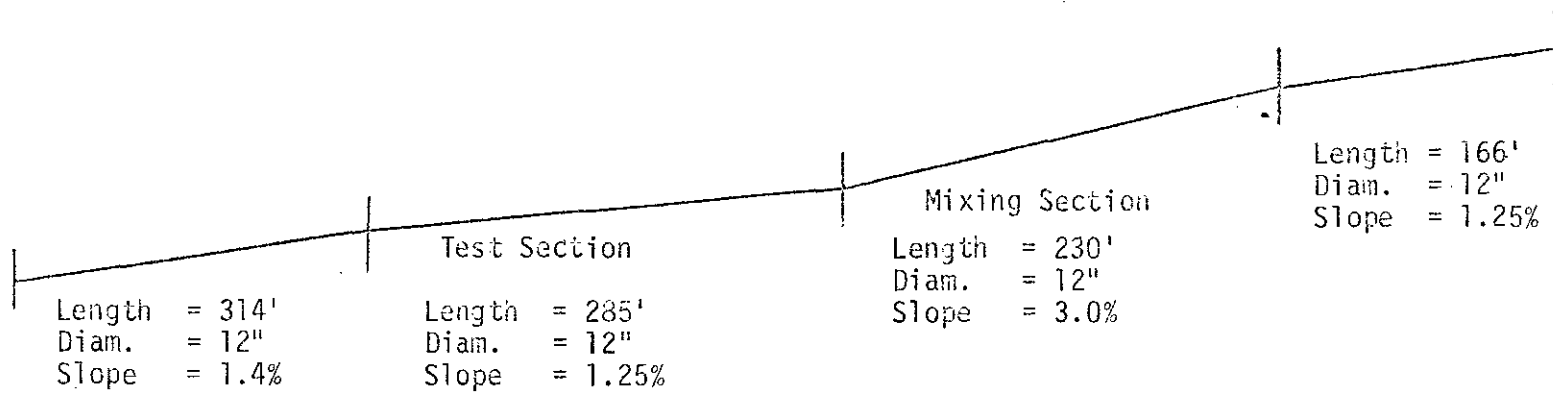
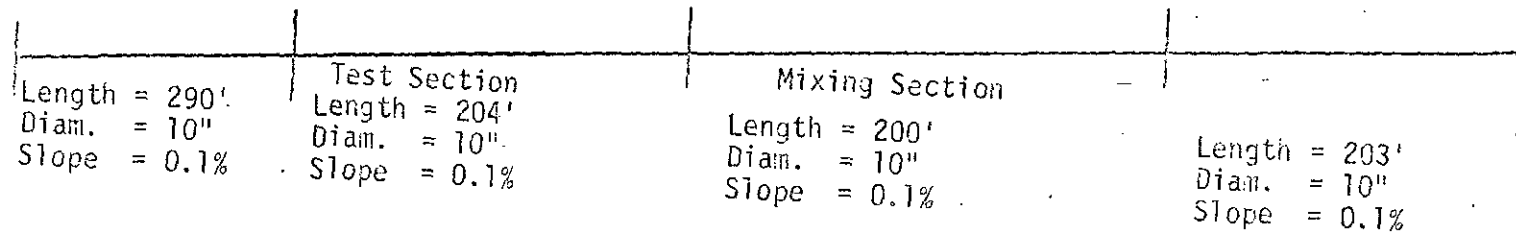


Figure 6. Profile of Sewer Number 1



(Drawing is not to scale)

Figure 7. Profile of Sewer Number 2



(Drawing is not to scale)

Figure 8. Profile of Sewer Number 3

256 feet at a slope of 3.62 percent and a test section length of 145 feet at a slope of 7.77 percent. During the testing period, the depth of flow was 1-inch.

Sewer Number 2 was located under Federal Street. The section of interest was between the intersection of Federal Street with Winslow Avenue and Warren Street. This sewer consisted of a 12-inch tile pipe. It had a mixing length of 230 feet at a slope of 3.0 percent and a test section length of 285 feet at a slope of 1.25 percent. The depth of flow was 5-inches without polymer during the test period.

Sewer Number 3 was located beneath Mains Field which is adjacent to Riverside Drive. The sewer consisted of a 10-inch tile pipe. The mixing length was 200 feet and the test length was 204 feet with both sections having a slope of 0.1 percent. This section of sewer was selected because of its extremely low velocity.

As stated before, there were two sections in each sewer -- the mixing section and the test section. The three manhole covers were removed from the manholes included in this sewer length.

Several trial runs were made to determine the best procedures. Based on the trials, it was decided that a fluorescent dye be used to measure the velocity. Two men were at the beginning of the mixing section, a man was stationed at the middle manhole, and two men were at the end of the test sections. With no polymer added, a premeasured amount of dye, which remained the same throughout the tests, was added at the beginning of the mixing section. When this green-colored

dye appeared at the middle manhole, the man stationed there started his stopwatch and at the same time signalled to one of the men stationed at the end of the test section to start his stopwatch. When the dye appeared at the end of the test section, both stopwatches were stopped according to the signals just described. The two stopwatches acted as a check. Hence, knowing the time and distance, the velocity could be determined.

While the velocity was being timed, the other man at the end of the test section was measuring the distance between the inside diameter at the top of the pipe and the water surface from which the depth could be determined.

This same procedure was carried out when the polymer solution was added to the line. It should be noted here that the dye was not added until the transient flow condition created by the polymer had passed. This condition resulted when only a portion of the first part of the line was exposed to the polymer effect. This transient condition was caused by the polymer reducing the boundary shear stress (32). This caused a surge which moved along the line until the polymer solution was in the entire line.

In all test manholes, the invert of the trough matched the invert of the incoming pipe and had the same slope as this pipe. The trough was constructed in the form of a half-circle, having the same diameter as the incoming pipe. Therefore, depth measurements were taken at the point where the sewer pipe met the trough. To obtain the depth of

flow, the distance from the top inside diameter of the pipe to the water surface was measured. This distance was then subtracted from the diameter of the pipe to obtain the depth of flow.

PART 5. EXPERIMENTAL RESULTS AND DISCUSSION

5.1 Sewage Quality Changes

5.1.1 Oxygen Uptake

Evaluation of the data during this phase of the study shows a remarkable difference in the oxygen uptake rate between the sewage samples taken from the University of Massachusetts outfall and the sewage sample taken from the South Amherst outfall during the initial hours of testing on the Gilson Respirometer.

Tables 7, 8, and 9 contain the data for short runs (less than one day) on the respirometer. The arithmetic averages of test samples for each run are plotted in Figures 9, 10 and 11 respectively. As can be seen from these figures, there is an initial lag in the oxygen uptake rate ranging from 8 to 10 hours. This initial lag is plausible since the University of Massachusetts sewage is relatively fresh, having a residence time of not more than thirty minutes. It is possible that this short residence time is not sufficient for the microorganisms in the sewage to acclimate themselves to their new environment.

In contrast to the University of Massachusetts sewage, the South Amherst sewage has a higher initial oxygen uptake rate during the first three hours than it does after this period. Table 10 shows the oxygen uptake for this sewage which was run on the Gilson Respirometer. The arithmetic average of this sample is plotted in Figure 12.

TABLE 7. Exerted BOD as a Function of Time as Measured
by a Gilson Differential Respirometer
Test Series Number 1 on University
of Massachusetts Sewage

<u>Time from Start</u>	<u>Sample 1</u>	<u>Sample 2</u>	<u>Sample 3</u>	<u>Arithmetic Average of Samples</u>
hours	mg/l	mg/l	mg/l	mg/l
1	3.88	3.31	4.83	4.01
2	6.23	5.26	6.91	6.13
3	8.43	6.74	10.40	8.50
4	12.31	9.88	14.31	12.15
5	17.51	14.83	19.26	17.20
6	22.43	19.28	24.63	22.10
7	28.91	25.54	31.23	28.90
8	37.09	33.34	39.80	36.80
9	49.40	40.57	47.60	45.80
10	59.26	50.06	57.54	55.50
11	68.00	58.57	66.23	64.10
12	77.30	67.74	75.63	73.60
13	88.74	78.63	86.77	85.00
14	100.71	89.49	98.26	96.10

TABLE 8. Exerted BOD as a Function of Time as Measured
by a Gilson Differential Respirometer
Test Series Number 2 on University
of Massachusetts Sewage

<u>Time from Start</u>	<u>Sample 1</u>	<u>Sample 2</u>	<u>Arithmetic Average of Samples</u>
hours	mg/l	mg/l	mg/l
1	6.46	7.40	6.93
2	8.51	10.06	9.29
3	13.60	15.43	14.52
4	22.46	21.20	21.83
5	28.32	26.68	27.59
6	36.48	35.07	35.77
7	43.43	41.17	42.30
8	52.20	49.71	50.95
9	63.69	61.20	62.44
10	71.37	68.94	70.15
11	81.20	77.65	79.43
12	96.00	89.97	92.98
13	106.60	98.77	102.68
14	114.14	105.71	109.92

TABLE 9. Exerted BOD as a Function of Time as Measured
by a Gilson Differential Respirometer
Test Series Number 3 on University
of Massachusetts Sewage

<u>Time from Start</u>	<u>Bottle 1</u>	<u>Bottle 2</u>	<u>Bottle 3</u>	<u>Bottle 4</u>	<u>Arithmetic Average of Samples</u>
hours	mg/l	mg/l	mg/l	mg/l	mg/l
1/2	1.46	1.20	1.45	1.40	1.38
1	2.68	2.20	2.68	2.54	2.52
1 1/2	3.63	2.91	3.63	3.34	3.37
2 1/2	7.23	6.20	7.74	7.17	7.08
3 1/2	11.03	9.68	11.80	10.91	10.85
4 1/2	15.23	13.68	16.31	15.11	15.08
5 1/2	19.26	17.17	20/60	18.91	18.98
6 1/2	24.34	21.97	25.85	23.97	24.03
7 1/2	29.74	27.14	31.97	29.57	29.60
8 1/2	35.46	32.37	37.85	35.17	35.21
9 1/2	41.31	37.88	43.91	40.80	40.97
10 1/2	45.80	41.94	48.63	45.57	45.48
11 1/2	53.66	49.48	56.28	53.05	53.62
12 1/2	62.51	58.22	65.28	62.03	62.01
13 1/2	71.57	67.40	74.05	70.80	70.95
14 1/2	79.43	75.88	82.34	79.08	79.18

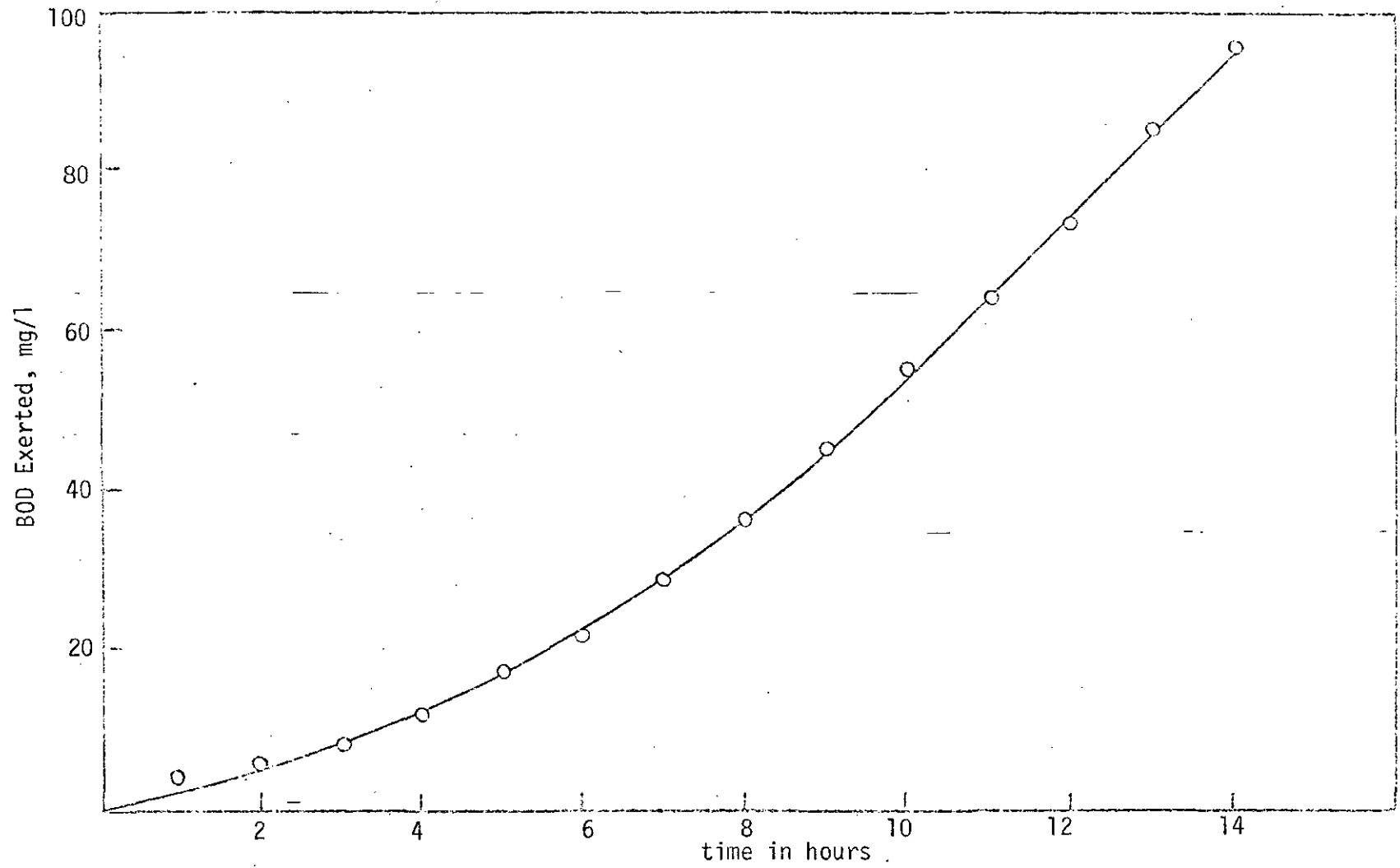


Figure 9. BOD Curve for Test Series Number 1 on University of Massachusetts Sewage

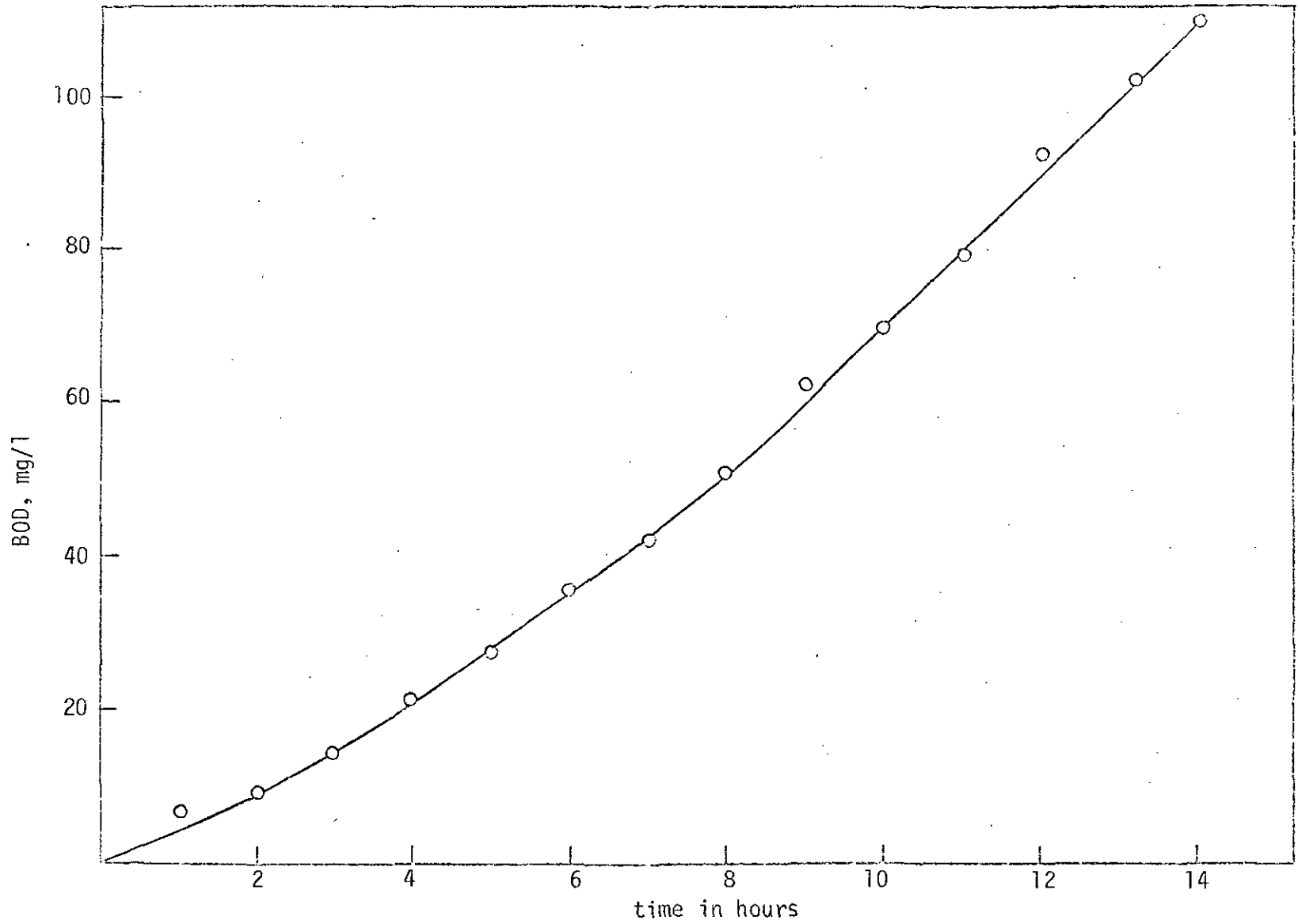


Figure 10. BOD Curve for Test Series Number 2 on University of Massachusetts Sewage

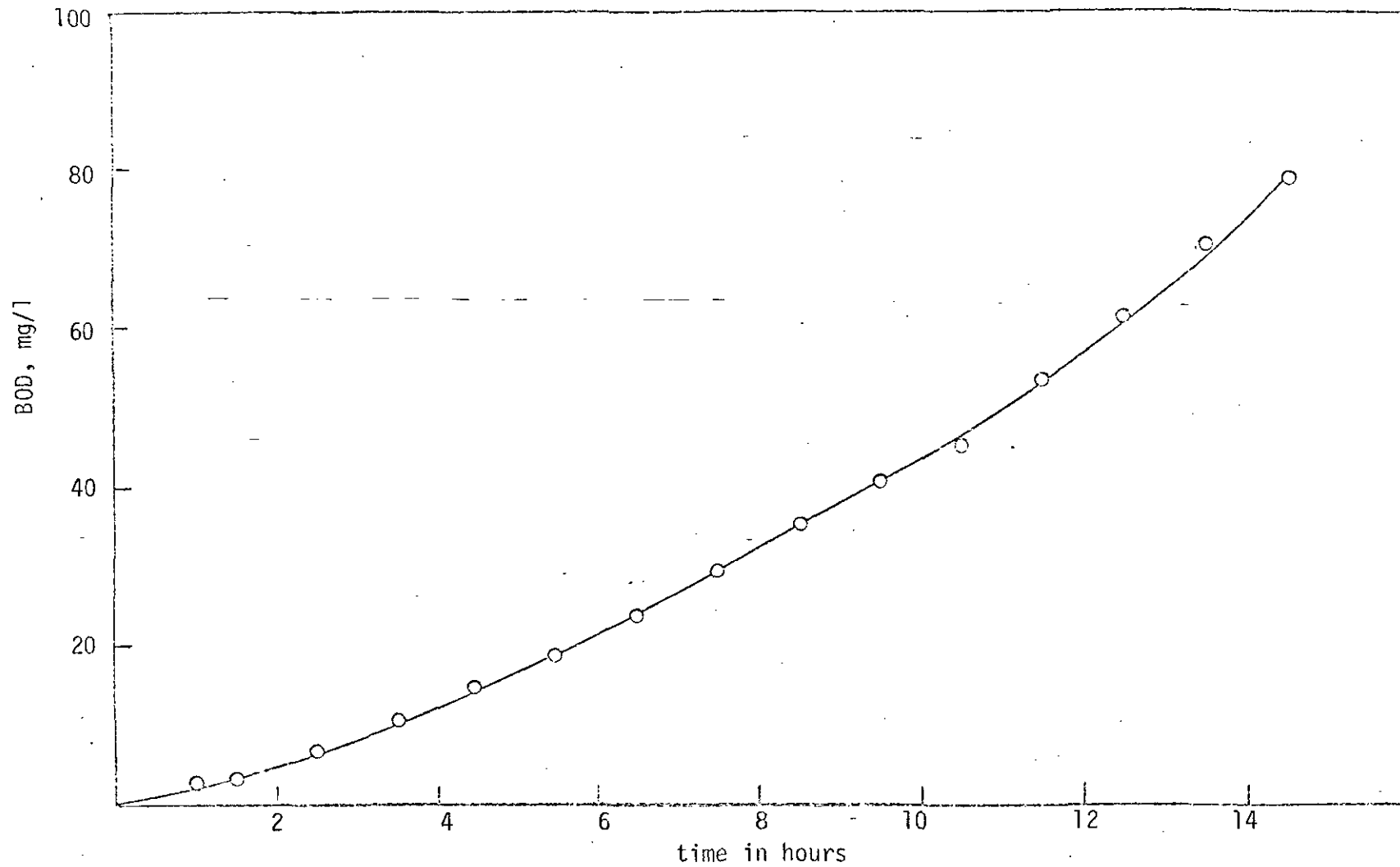


Figure 11. BOD Curve for Test Series Number 3 on University of Massachusetts Sewage

TABLE 10. Exerted BOD as a Function of Time as Measured by a
 Gilson Differential Respirometer
 Test Series Number 1 on South Amherst Sewage

<u>Time from Start</u>	<u>Sample 1</u>	<u>Sample 2</u>	<u>Sample 3</u>	<u>Sample 4</u>	<u>Sample 5</u>	<u>Arithmetic Average of Samples</u>
hours	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
1	10.37	10.26	10.23	9.91	10.34	10.22
2	17.57	17.23	17.09	16.65	16.88	17.08
3	23.88	23.31	23.37	22.82	22.88	23.25
4	29.82	28.82	28.94	28.19	28.36	28.83
5	35.42	34.19	34.60	33.59	33.87	34.34
6	40.88	39.42	40.00	38.81	39.44	39.72
7	46.14	44.36	45.23	43.96	44.70	44.88
8	51.34	49.13	50.14	48.59	49.61	49.76
10	62.37	59.64	60.88	58.56	60.15	60.32
11	67.71	64.81	66.08	63.70	65.26	65.51
12	74.04	70.55	71.85	69.50	71.03	71.39
13	80.15	76.29	77.85	75.27	77.03	77.32
14	86.44	81.83	83.48	80.78	82.72	83.05
15	92.84	87.85	89.39	86.52	88.58	91.04

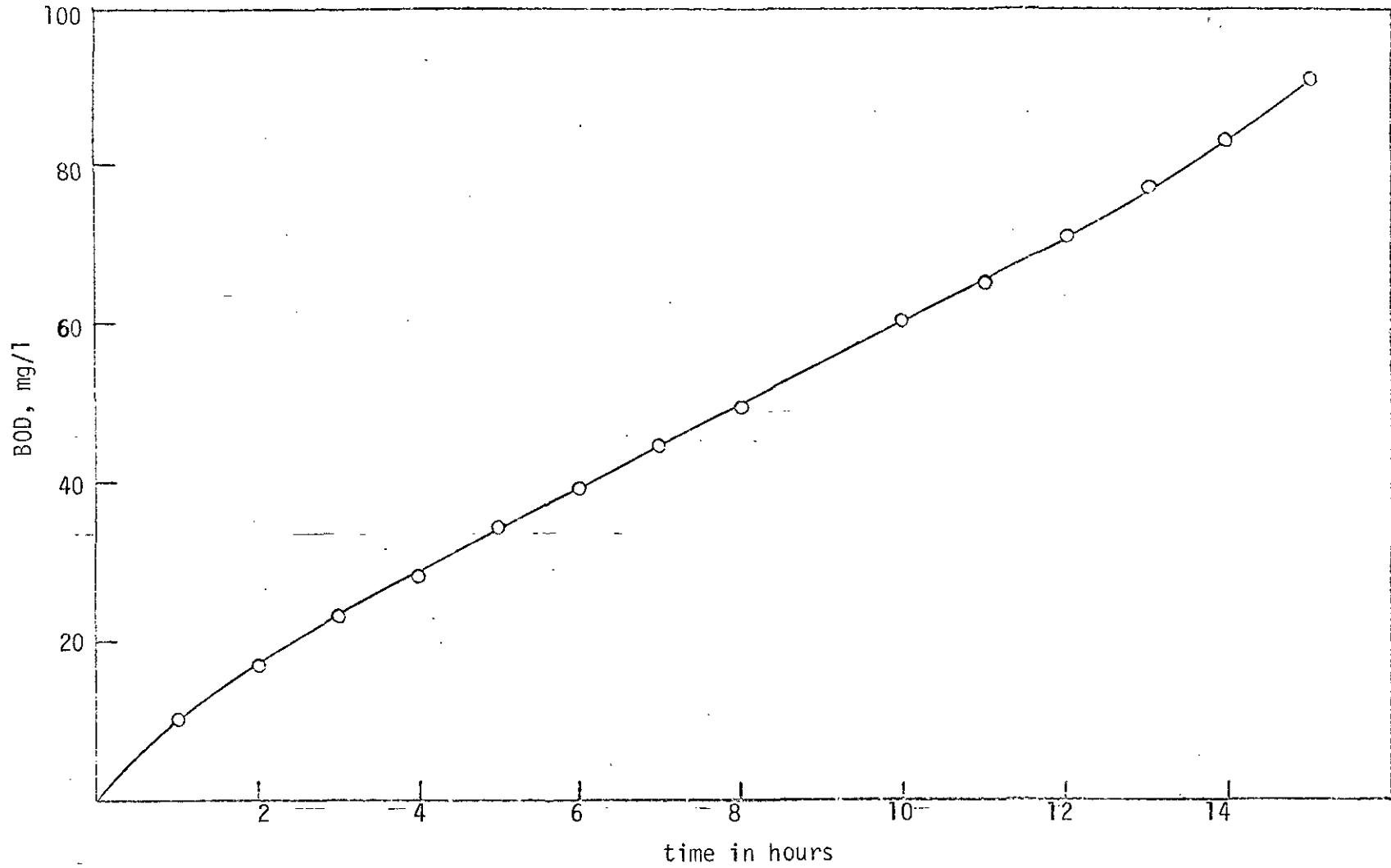


Figure 12. BOD Curve for Test Series Number 1 on South Amherst Sewage

This high initial uptake rate may be accounted for by the fact that the sewage from South Amherst goes through a pumping station; the residence time in this pumping station may be as high as fourteen hours depending on the flow. The samples run had an estimated residence time in the wet well of approximately eight hours. It was also possible that this sewage may have become anaerobic in the wet well. Fair (4) stated that sewage which has undergone partial anaerobic decomposition may exert a higher uptake at the beginning of the run. This initially high uptake rate agrees with Schroepfer (3) who reported high oxygen uptake during the first several hours of testing. Since his sewage was taken from a large metropolitan sewage treatment plant, it is reasonable to assume that Schroepfer's sewage was, like the South Amherst Sewage, exposed to one or more pumping stations.

A long term respirometer run was made to compare the respirometer results with BOD bottle results. The sewage used was from the University of Massachusetts outfall. Table 11 shows the respirometer data for this run. The arithmetic average of this data is shown in Figure 13 -- also shown is the daily bottle BOD for five days at 20°C. As can be seen, there is a considerable discrepancy between the two methods. The figure also points out the applicability of the respirometer method in indicating an initial lag period which would have gone unnoticed using the bottle method.

TABLE 11. Exerted BOD as a Function of Time as Measured by a
 Gilson Differential Respirometer
 Test Series Number 4 on University of Massachusetts Sewage

<u>Time from Start</u>	<u>Sample 1</u>	<u>Sample 2</u>	<u>Sample 3</u>	<u>Sample 4</u>	<u>Sample 5</u>	<u>Sample 6</u>	<u>Arithmetic Average of Samples</u>
hours	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
1	2.88	3.57	3.37	2.86	2.97	3.54	3.41
2	5.66	7.60	7.00	6.14	5.94	6.86	6.54
3	8.86	11.94	11.17	10.40	9.37	10.88	10.46
4	12.88	17.00	16.14	14.86	13.49	15.54	15.00
5	16.63	21.91	20.80	19.51	17.57	20.06	19.40
6	21.88	27.54	26.17	24.57	22.31	25.20	24.60
7	27.46	33.63	32.31	30.06	27.74	30.91	30.40
8	33.43	40.11	38.54	36.03	33.54	37.29	36.55
9	39.46	46.57	44.71	41.91	39.23	43.71	42.60
10	45.43	53.06	50.97	47.92	45.34	50.43	48.9
11	51.00	59.40	57.00	54.03	51.29	56.74	54.9
12	56.42	65.49	62.77	59.83	56.89	62.89	60.6
13	61.00	70.54	67.69	64.72	63.80	67.86	65.9
14	65.57	75.91	72.60	69.68	68.40	72.80	70.6
15	70.00	80.91	77.46	74.54	72.83	74.80	75.0

Table 11 (continued)

<u>Time from Start</u>	<u>Sample 1</u>	<u>Sample 2</u>	<u>Sample 3</u>	<u>Sample 4</u>	<u>Sample 5</u>	<u>Sample 6</u>	<u>Arithmetic Average of Samples</u>
hours	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
16	74.09	85.66	81.91	78.89	76.86	79.29	79.4
18	82.91	95.29	91.23	87.94	85.69	88.54	88.5
20	91.68	105.00	100.66	97.14	94.34	97.83	97.6
22	99.49	113.80	109.20	105.46	102.03	106.17	106.4
24	107.29	122.34	117.49	113.60	109.57	114.34	114.0
26	114.34	130.03	125.26	120.74	116.23	121.69	121.5
28	121.71	138.32	133.26	128.80	123.54	129.43	129.2
30	129.94	147.09	141.94	137.23	131.46	137.86	137.5
32	136.94	154.86	149.66	144.71	138.23	145.40	145.0
34	144.23	162.70	157.43	152.15	145.17	152.97	152.6
36	152.37	171.66	166.12	160.63	152.97	161.57	161.0
38	160.40	180.29	174.57	169.00	160.77	169.83	169.0
40	168.00	188.37	182.63	176.63	167.92	177.60	176.0
42	175.31	196.37	190.35	184.12	175.20	185.32	184.5
44	182.57	204.35	198.26	191.77	182.09	193.00	192.0
47	193.03	215.80	209.46	202.93	192.35	203.92	202.5
50	203.50	227.15	220.52	213.92	202.75	215.00	214.0

Table 11 (continued)

<u>Time from Start</u>	<u>Sample 1</u>	<u>Sample 2</u>	<u>Sample 3</u>	<u>Sample 4</u>	<u>Sample 5</u>	<u>Sample 6</u>	<u>Arithmetic Average of Samples</u>
hours	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
53	213.95	238.46	231.63	227.72	213.12	226.15	225.5
56	224.31	249.86	245.57	235.77	223.46	237.20	236.0
59	234.58	260.89	253.55	246.54	233.55	248.00	246.0
62	244.78	272.00	264.52	257.40	243.66	258.63	257.0
65	254.83	283.03	275.49	268.09	253.49	269.03	268.0
69.5	266.80	296.75	288.12	280.74	264.92	284.12	280.0
72	280.35	309.83	302.06	294.69	278.20	297.89	294.0
75	288.89	322.09	314.26	306.09	289.23	309.63	305.0
79	300.38	333.98	326.20	318.40	300.38	321.43	317.0
82	311.89	346.26	338.58	330.46	311.49	333.44	329.0
85	322.95	356.89	350.32	341.98	322.26	344.95	338.0
88	333.78	369.26	361.75	353.26	332.86	356.15	352.0
91	345.49	381.29	373.98	365.37	344.32	368.21	364.0
94	356.26	392.78	385.12	376.72	355.23	379.35	374.0
97	357.86	405.04	398.26	388.95	366.75	391.38	386.0
100	379.63	417.01	410.92	401.55	378.44	403.72	399.0
103	390.43	427.89	422.38	412.80	388.83	414.81	409.0

Table 11 (continued)

<u>Time from Start</u>	<u>Sample 1</u>	<u>Sample 2</u>	<u>Sample 3</u>	<u>Sample 4</u>	<u>Sample 5</u>	<u>Sample 6</u>	<u>Arithmetic Average of Samples</u>
hours	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
106	400.09	437.95	432.95	423.24	309.41	424.98	419.0
109	409.61	447.58	443.07	433.29	407.78	434.95	429.0
113	421.38	459.55	455.61	445.66	419.29	447.12	442.0
117	433.95	464.15	463.18	458.64	431.69	460.04	452.0

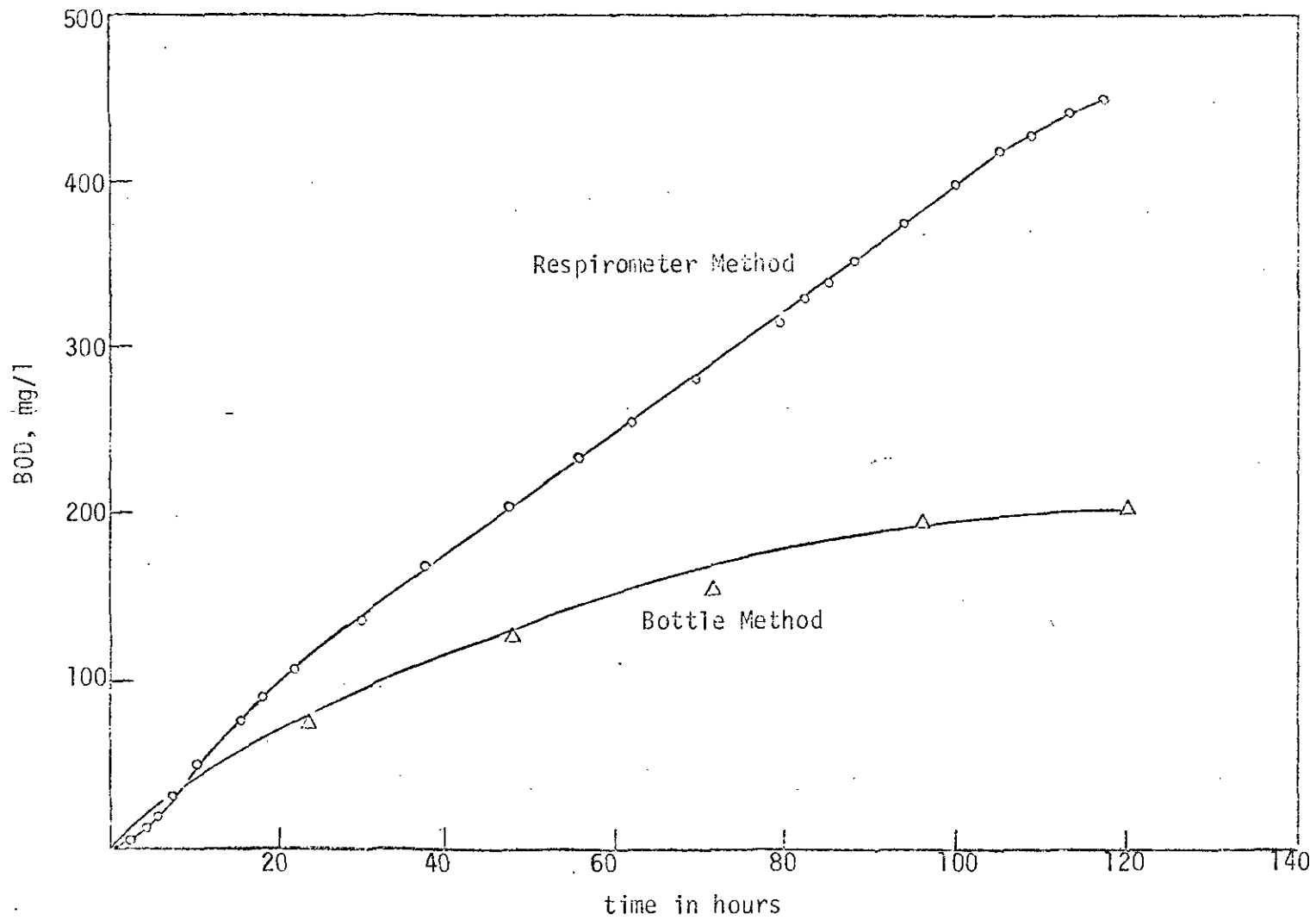


Figure 13. BOD Curve for Test Series Number 4 on University of Massachusetts Sewage

5.1.2 pH Variation With Time

Samples of both University of Massachusetts and South Amherst sewage were run on the respirometer with polymer concentrations of 0, 50, and 100 ppm. The University of Massachusetts sewage had an initial pH of 7.4 for all concentrations. As time increased, the pH for both the 0 and 50 ppm samples increased; however, the pH of the 100 ppm sample began to increase and then decreased and increased again.

Figure 14 graphically shows the variations in pH for each sample.

The South Amherst sewage had an initial pH of 7.5. As with the University of Massachusetts sewage, the 0 and 50 ppm samples had an increase in pH with time at approximately the same rate. The sample having a polymer concentration of 100 ppm initially experienced an increase in pH with time but reached a plateau while the other two samples continued to experience a pH increase. These pH variations are shown in Figure 15.

This study on pH was intended only to determine the variation in pH with the age of the wastewater and with the polymer concentration. This study of pH has indicated that for all practical purposes the concentration of polymer between 0 and 100 ppm, has very little effect on pH; it was true that for high concentration of polymer (100 ppm) the pH decreased, but this was after a detention time of approximately 100 hours; for a time up to 40 hours, which was a more meaningful residence time, the concentration of polymer had no effect. Also, the study has shown that pH increased with time. Recalling Figure 4, which

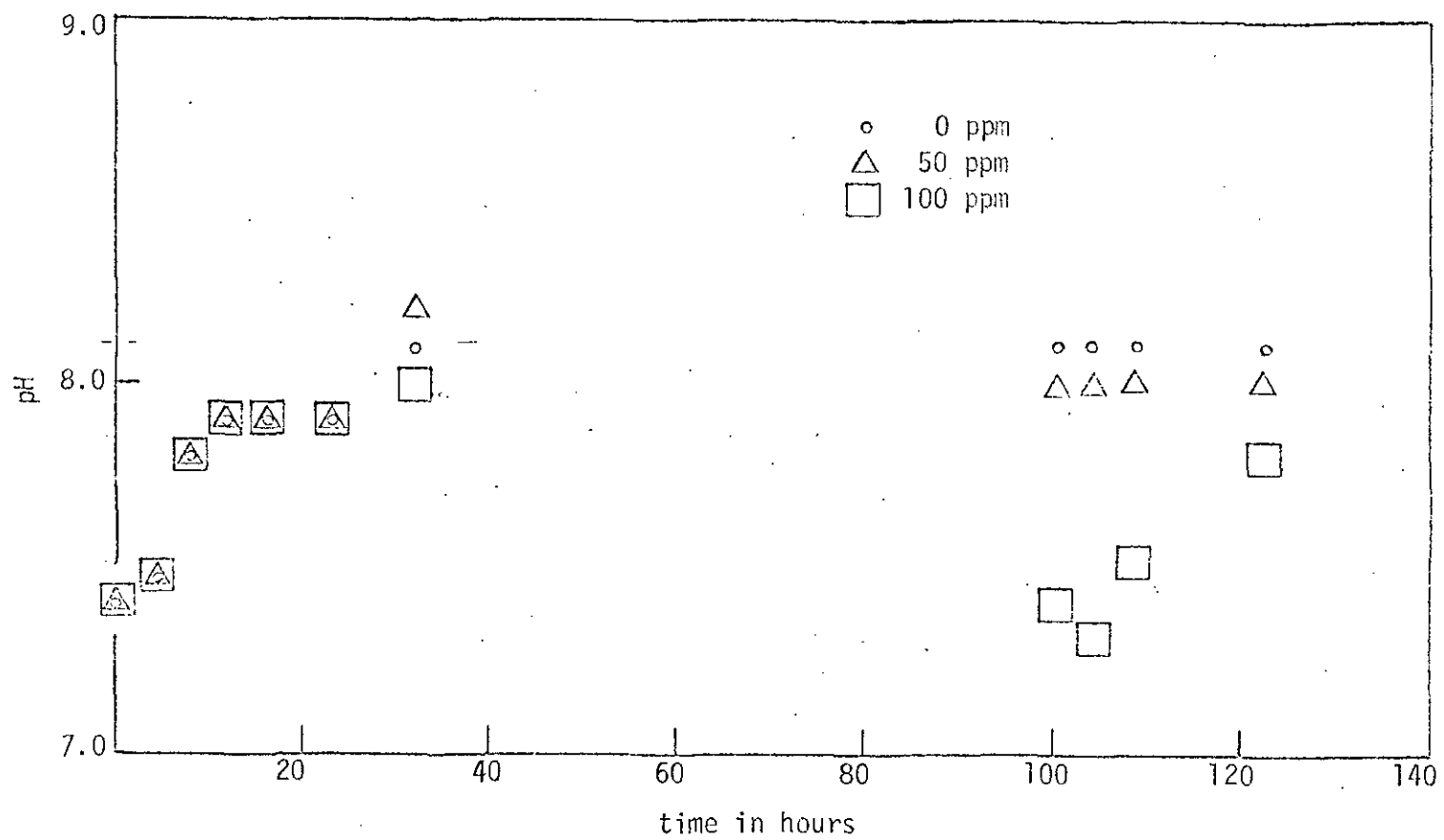


Figure 14. pH of University of Massachusetts Sewage at Various Polymer Concentrations Versus Time

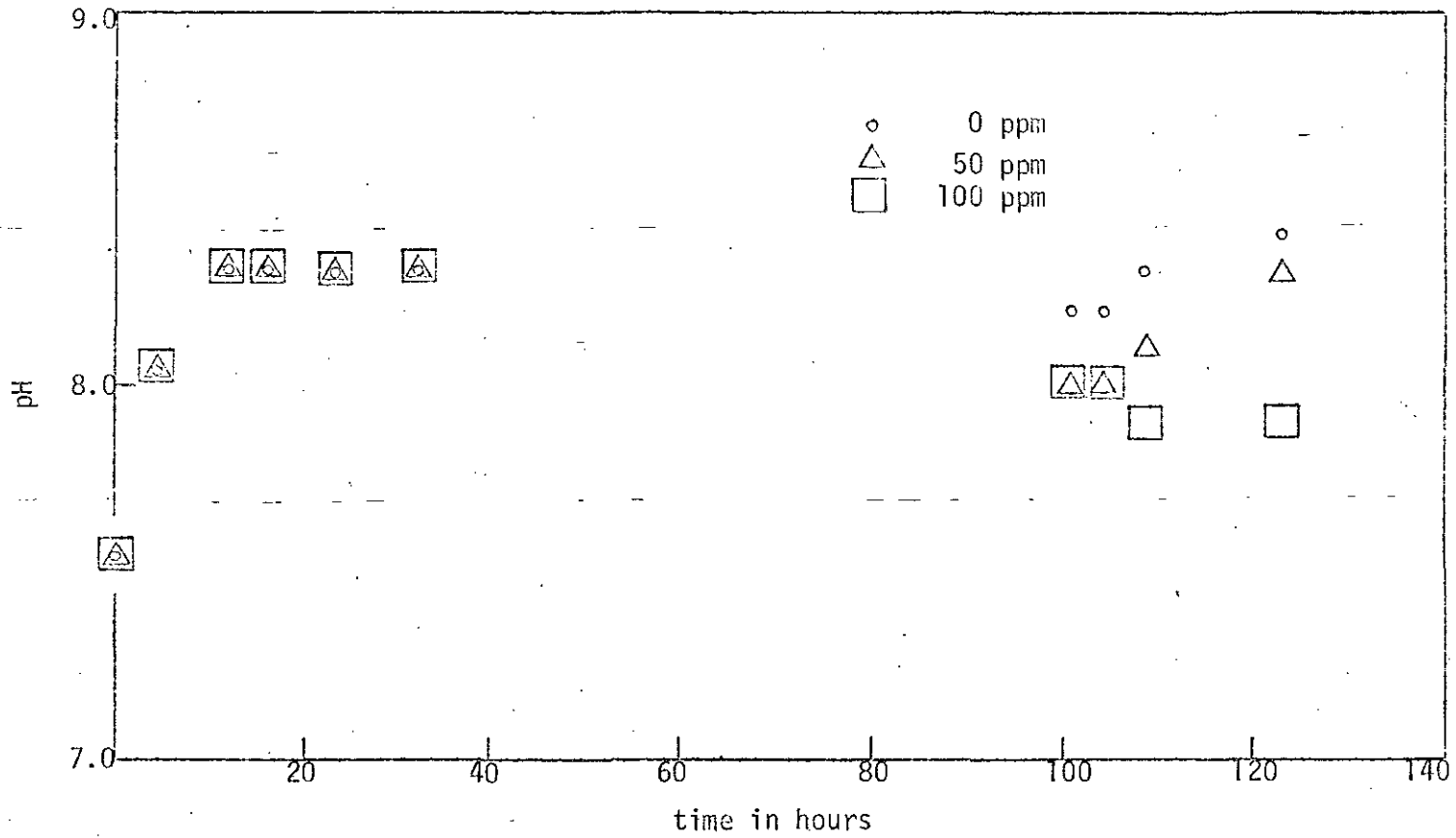


Figure 15. pH of South Anherst Sewage at Various Polymer Concentrations Versus Time

showed an increase in sulfide generation with time; it can be seen that there was a greater chance for sewer corrosion as the sewage becomes aged.

5.1.3 Effects of Polymer on Sewage Degradation

Duplicate University of Massachusetts sewage samples having polymer concentrations of 0, 50, and 100 ppm were run on the respirometer for a 57 hours period. Table 12 has the oxygen uptake rates for each sample and the arithmetic average for each concentration. This arithmetic average is plotted versus time in Figure 16. As shown by the figure, the uptake rates are practically the same for the first 35 hours. When readings were taken again at the 53rd hour, the sewage having a 0 ppm concentration of polymer was found to have a decreasing oxygen uptake rate while the sewages containing 50 and 100 ppm of polymer were found to have increasing oxygen uptake rates of about the same magnitude. These results show that the polymer in a concentration of up to 100 ppm, does not interfere with the biodegradation of the sewage. Also, it appears the polymer itself is biodegradable.

5.2 Effects of Polymer Addition on Sewer Velocity

Figure 17 shows the effect of polymer addition on velocity in Sewer Number 1. As can be seen, the velocity increased rapidly for

TABLE 12. Comparison of Oxygen Uptake Rates at Various Polymer Concentrations of University of Massachusetts Sewage

Time from Start	c o n c e n t r a t i o n								
	0 - ppm			50 - ppm			100 - ppm		
hours	Sample 1 mg/l-hr	Sample 2 mg/l-hr	Arith. Average mg/l-hr	Sample 1 mg/l-hr	Sample 2 mg/l-hr	Arith. Average mg/l-hr	Sample 1 mg/l-hr	Sample 2 mg/l-hr	Arith. Average mg/l-hr
1	5.80	5.48	5.64	5.51	4.91	5.22	5.28	5.43	5.35
2	5.05	4.97	5.02	5.08	4.60	4.84	4.87	4.85	4.83
3	5.45	5.57	5.51	5.77	5.34	5.55	5.74	5.83	5.79
4	6.74	6.28	6.51	6.14	5.74	5.94	5.80	5.88	5.84
5	5.77	5.48	5.62	5.77	5.51	5.64	5.71	5.80	5.76
6	5.74	5.62	6.80	5.88	5.42	5.65	5.43	5.71	5.58
8	12.71	12.40	6.27	12.57	12.68	6.32	12.43	12.54	6.24
10	12.17	11.71	5.96	12.00	12.23	6.06	11.77	11.94	5.91
12	12.08	11.82	5.97	12.20	12.00	6.05	11.97	12.05	6.00
14	11.94	11.54	5.86	11.71	11.31	5.75	11.42	11.42	5.71
31	8.91	8.91	4.46	9.51	9.46	4.74	9.48	9.60	4.76
33	9.17	9.05	4.56	9.71	9.54	4.81	9.74	9.83	4.89
35	9.37	9.08	4.64	9.77	9.60	4.84	9.71	9.71	4.86
53	9.45	9.17	4.65	12.25	12.54	6.19	12.26	12.54	6.20
55	8.05	7.85	4.00	11.80	12.28	6.02	11.94	12.37	6.07
57	8.51	8.22	4.18	13.22	14.05	6.81	12.83	14.02	6.70

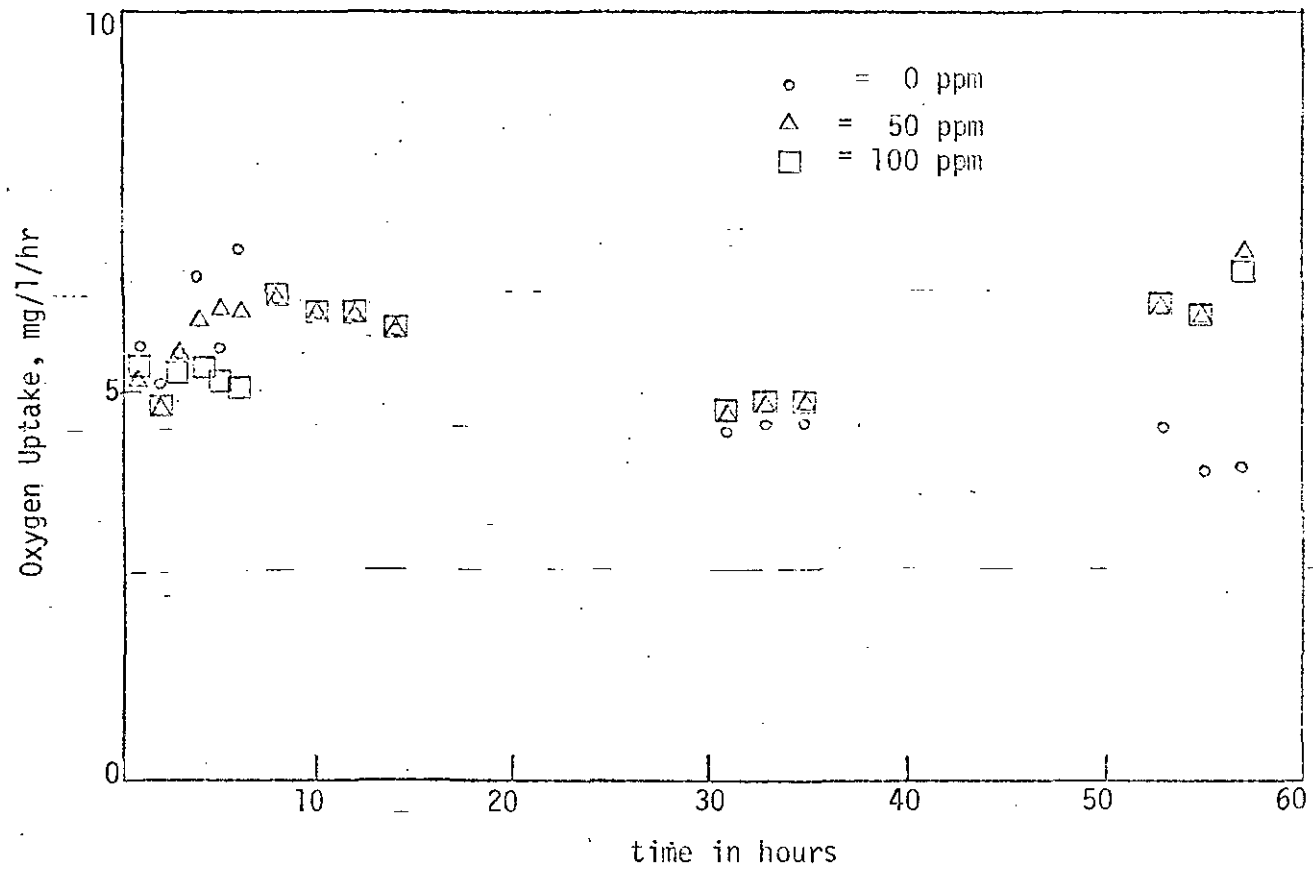


Figure 16. Comparison of Oxygen Uptake Rates at Various Polymer Concentrations of University of Massachusetts Sewage with Time

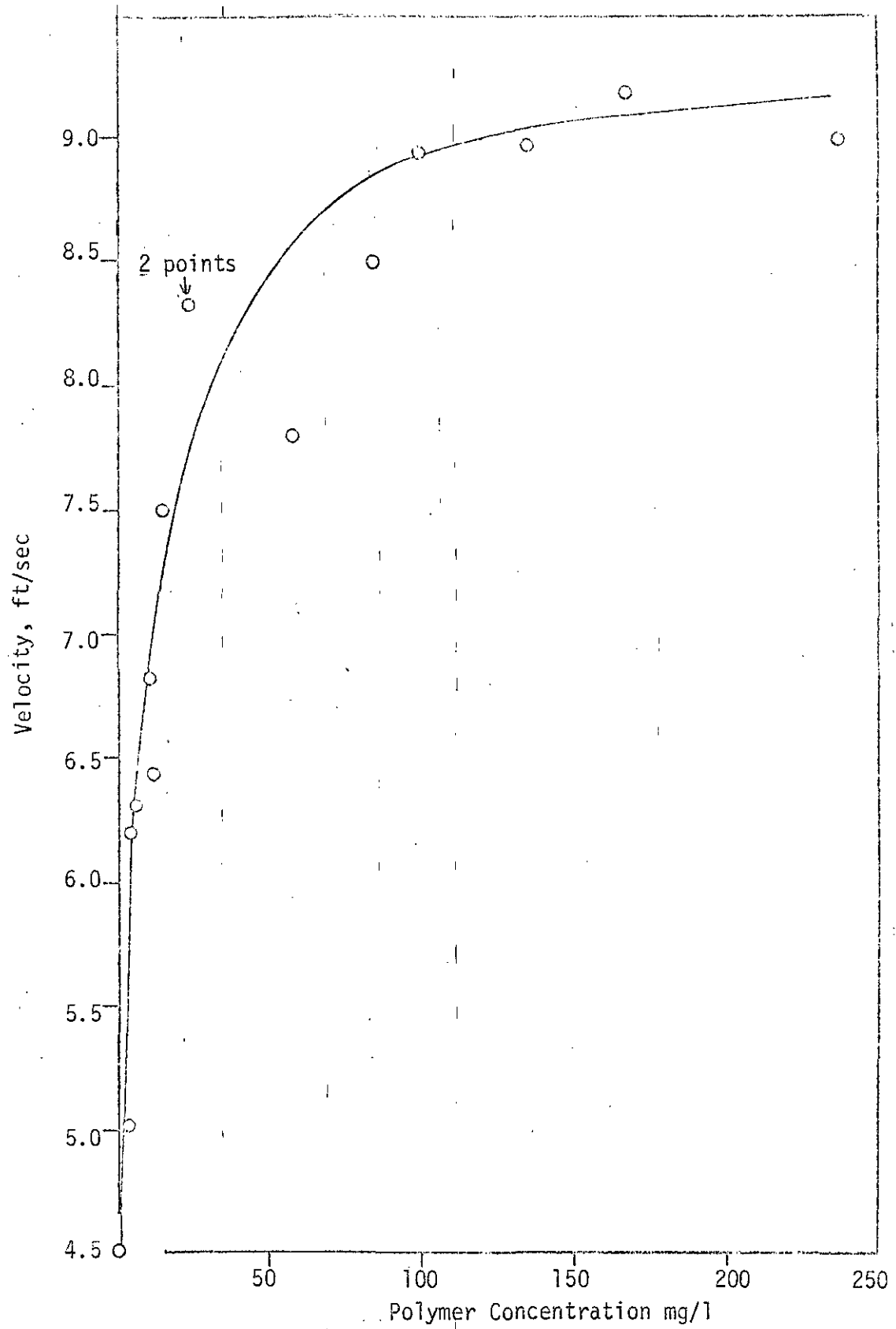


Figure 17. Comparison of Velocity Increase With Polymer Concentration for Sewer Number 1

a small increase in polymer concentration up to 75 ppm; after this point the velocity increase is less dramatic for a small increase in polymer concentration.

Figure 18 shows the same relationship for Sewer Number 2. Although in this sewer the large velocity change for a small change in polymer concentration stopped at about 50 ppm.

In Sewer Number 3 which had a velocity of 0.3 ft/sec., there was no velocity change when the polymer was added in a concentration of approximately 50 ppm. It is quite likely that the very low velocity did not promote adequately mixing between the polymer and the sewage. It should also be noted that this line was nearly half full of sludge and debris which may have had an effect on the results.

Without the polymer additive Sewer Number 1 had a velocity of 4.5 fps; with a polymer concentration of 168 ppm the velocity was increased 9.3 fps, the largest value recorded during the test period.

Sewer Number 2 had a velocity of 3.5 fps without polymer addition and had a maximum velocity of 6.8 fps at a concentration of 238 ppm during the test period.

Sewer Number 3 experienced no velocity increase with a polymer concentration of 50 ppm.

From these results, it can be said that the effect of polymer addition, in increasing the velocity of sewage in the sewer, depends on the initial velocity, that is, the velocity before the polymer is added. The effect becomes greater as the initial velocity becomes

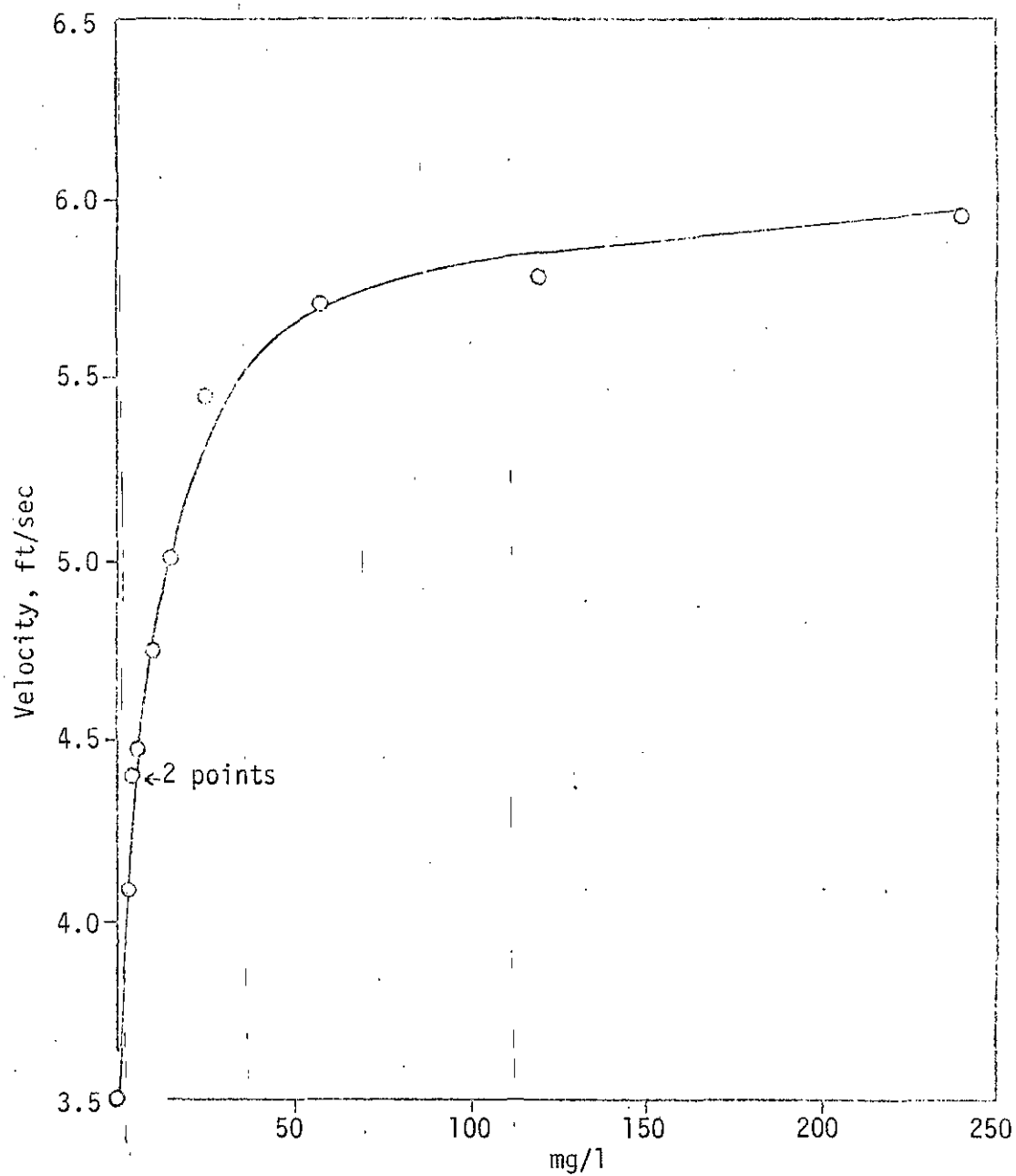


Figure 18. Comparison of Velocity Increase With Polymer Concentration for Sewer Number 2

greater. Perhaps this relates to the adequacy of mixing between the polymer and the sewage.

Attempts were made to measure the depth of flow change with various polymer concentrations; however, these attempts proved to be futile since there was much turbulence and surface waves, causing depth fluctuations in the shallow flow. Because of this inability to measure depth changes, no predictions can be made on the increased carrying capacity of the sewer.

5.3 Economic Considerations

Wilkinson, et al (32) found that a 24-inch reinforced concrete sewer with a 0.32 percent slope had its carrying capacity increased 1.9 times with the addition of 80 ppm of a certain polymer. Without polymer addition this sewer had a carrying capacity of 7.65 MGD; with the addition of 80 ppm of this polymer, its capacity would be increased to 14.55 MGD. Based on this information, an economic analysis will be performed to determine the feasibility of adding this friction-reducing polymer.

Case 1: A flow of 14.55 MGD must be carried. The 24-inch sewer described above is presently in existence. The sewer's length is 20,000 feet. There are two possible solutions:

Alternate 1: Add a polymer concentration of 80 ppm to the existing sewer.

Annual Cost

Polymer Cost (32) = \$5.75 per hr. per MGD at 80 ppm.

$$24 \text{ hr/day} \times 14.55 \text{ MGD} \times 360 \text{ day/yr} \times \$5.75/\text{hr-MGD} = \\ \$724,000/\text{yr.}$$

Alternate 2: Construct an additional 24-inch sewer.

Annual Cost

Cost of 24-inch reinforced concrete sewer (45) =

\$12.82 per ft.

$$20,000 \text{ ft} \times \$12.82/\text{ft} = \$256,400.$$

$$\$256,400 \times 0.07823 \text{ (crf-6\%-25)} = \$20,000/\text{yr.}$$

Cast 2: A peak flow of 14.55 MGD must be carried for a 2-hour period per day for 60 days per year. During non-peak time the flow rate is less than 7.65 MGD. The same 24-inch sewer is in existence. Sewer length is 20,000 feet.

Alternate 1: Add a polymer concentration of 80 ppm.

Annual Cost

$$14.55 \text{ MGD} \times \$5.75/\text{MGD-hr} \times 2 \text{ hr/day} \times 60 \text{ day/yr} = \\ \$10,100/\text{yr.}$$

Alternate 2: Construct an additional 24-inch sewer.

$$20,000 \text{ ft} \times \$12.82/\text{ft} = \$256,400.$$

$$\$256,000 \times 0.07823 \text{ (crf-6\%-25)} = \$20,000/\text{yr}.$$

This economic analysis clearly shows that polymer addition is feasible when peak flows are infrequent and of short duration; however, polymer addition does not appear feasible when used on a daily basis. Also, the polymer is a useful alternative to constructing additional lines, especially if the line to be augmented is long. In this case the cost of polymer addition is independent of the length of the line while the cost of constructing a new line is directly proportional to its length.

PART 6. CONCLUSIONS

On the basis of the studies conducted on University of Massachusetts and South Amherst sewage and the studies of polymer addition in sewer lines, the following conclusions may be drawn:

1. Sewage having a short residence time, less than one hour, has a noticeable lag in its oxygen uptake rate for a period of 8-12 hours.
2. Sewage which is exposed to long detention time (12-18 hours), in a pumping station wet well, does not have a lag period, but rather a higher oxygen uptake rate during the first few hours.
3. The pH of sewage increases with age, allowing for a higher percentage of sulfide generation.
4. Polymer concentration in the range of 0-100 ppm had no effect on the pH during the first 35 hours.
5. Polymer concentrations in the range of 0-100 ppm had no effect on the biodegradation of the sewage and it appeared that the polymer was used as a secondary food source.
6. The addition of polymer solutions to sewer lines subject to gravity, open channel flow produced results similar to those obtained by others for closed conduit flow. In certain cases the velocity more than doubled.
7. The effect of the polymer was shown to be dependent on the velocity of flow before addition of polymer -- the polymer

being more effective the higher the initial velocity.

8. Polymer concentrations in the range of 40-100 ppm appear to be the most useful in increasing the carrying capacity of a sewer.
9. Under certain conditions, such as an infrequent peak flow situation, the addition of a polymer solution is economically more feasible than building an additional sewer line to carry excess flow.

PART 7. RECOMMENDATIONS

On the basis of this study the following recommendations are made:

1. It is recommended that the polymer usage be considered when sewer lines are subject to infrequent surcharges.
2. It is recommended that polymer usage be encouraged in long lines which are subject to surcharge, as the cost of polymer dosage is a function of the flowrate and not a function of the length of the line.
3. It is recommended that more research be conducted using friction-reducing additives with specific application to measuring changes in Manning's roughness coefficient (n) for various polymer concentrations on gravity sewers.
4. It is recommended that investigations be made to determine what effect friction-reducing additives have on the scour velocity.
5. It is recommended that the BOD test be conducted on friction reducing additives to determine their oxygen consumption.

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APPENDIX

Derivation of Multiplication Factor to Change Microliters
of Dry Oxygen to mg/l BOD
(Gilson Differential Respirometer Study)

1. Gram molecular volume of any gas equals 22.425 liters.
2. Gram molecular weight of dry O₂ equals 32.000 grams.
3. Therefore:

$$32,000 \text{ mg} - 22,425,000 \text{ } \mu\text{l}$$

and dry O₂ weighs

$$\frac{32,000 \text{ mg}}{22,425,000 \text{ } \mu\text{l}} = 0.0014286 \text{ mg/} \mu\text{l} = 0.0014286 \frac{\text{mg BOD}}{\mu\text{l O}_2 \text{ measured}}$$

Thus, each μl of dry oxygen uptake recorded by the respirometer weighs 0.0014286 milligrams.

4. Since each reaction flask contained 50 ml of sewage, and because BOD is usually recorded in mg/l, a correction for sample volume is required as follows:

$$\frac{100 \text{ ml/l}}{50 \text{ ml}} = \frac{20}{1}$$

5. The combined effect of steps 4 and 5 yields the multiplication factor referred to on page 50.

$$0.0014286 \frac{\text{mg BOD}}{\mu\text{l O}_2 \text{ measured}} \left(\frac{20}{1}\right) = 0.028572 \text{ mg/l BOD per } \mu\text{l}$$

O₂ measured.