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OXYGEN UPTAKE BY THE BENTHAL SLUDGE
OF A WASTE STABILIZATION POND

BY

EDWARD LANDON NIEDRINGHAUS, 1936-

A

THESIS

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(advisor)

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ABSTRACT

This thesis describes the laboratory evaluation of the benthal sludge oxygen uptake of a 6.7 acre waste stabilization pond which has served a city of 2,400 population for a period of seven years. Special emphasis is directed toward the explanation of laboratory techniques developed for this study to measure the oxygen uptake rate. The effects on oxygen consumption of temperature, nature of sludge, initial oxygen tension, and sludge consolidation are discussed.

Benthal sludge samples were taken from three locations in the pond. Oxygen consumption studies were conducted in a specially designed plastic cylinder which included a novel magnetic mixing system. BOD dilution water was employed as the supernatant over the sludge. Tests were run at 10, 22, and 35 degrees centigrade.

Oxygen uptake was measured using an automatic oxygen analyzer and recorded on a continuous recorder. The data were converted to mg O_2 uptake per minute per square meter of sludge surface area.

At the conclusion of each test, the supernatant was withdrawn and analyzed for COD, pH, alkalanity, and suspended solids. Additional oxygen consumption tests were performed on the unsettled and settled supernatants in order to evaluate the oxygen uptakes exerted by the dissolved and suspended organic materials apart from the sludge phase. Results obtained from this study indicated that the oxygen uptake bore a definite relationship with volatile solids suspended from the sludge phase. The supernatant which was siphoned off during the mixing showed an oxygen consumption rate approaching that of the supernatant-sludge system.

Temperature was also observed to have a significant effect on the oxygen uptake rate. At 35 degrees centigrade the dissolved oxygen in the test chamber was exhausted within a few minutes, while at 10 degrees centigrade the same sample took several days to deplete completely the oxygen content.

The effects of the oxygen tension and the sludge compaction on the oxygen uptake were also evaluated. Neither oxygen tension or sludge compaction could be shown to have a significant effect on the rate of oxygen consumption.

ACKNOWLEDGMENTS

The author is deeply indebted to his advisor, Dr. Ju-Chang Huang, whose capability and direction were major factors in the accomplishment of this investigation. Appreciation is also extended to Professor J. Kent Roberts and Dr. Nord L. Gale for their help during the revision of the manuscript.

Thanks are also expressed to the Civil Engineering Department of the University of Missouri-Rolla for providing equipment and facilities which made this thesis possible. Gratitude is also extended to the faculty and fellow students of the Civil Engineering Department for their suggestions and assistance in this investigation.

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Special acknowledgment is also due the author's wife for her patience and support during the undertaking of this study.

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I. INTRODUCTION

The waste stabilization pond has been recognized as an economical and efficient method of treating domestic and industrial wastewaters. This type of treatment facility is now widely used throughout the world especially in developing countries and in isolated rural areas where land costs are not expensive.

In general the waste stabilization pond operates upon the mutual cooperation between bacteria and algae. Bacteria have the capability of breaking down complex organic matter, thereby producing carbon dioxide and water as the major end products. Algae, on the other hand, obtain energy from sunlight and convert carbon dioxide and water into cell protoplasm during the process of algal photosynthesis. In this biochemical reaction free oxygen is evolved as a by-product, which then becomes available to aerobic bacteria for decomposing additional organic materials. Although the general principle of operation is simple and understood, relatively little is known about the complex microbiology and biochemistry within the pond ecosystem. This is especially true of our understanding about the nature of the pond benthic sludge and its effect on the pond operation.

In the waste stabilization process within the pond, bacteria oxidize only part of the waste substrate to provide energy for metabolic reactions, the remainder of the substrate is converted into the bacterial cell protoplasm. Algae obtain energy from sunlight and convert carbon dioxide, water and inorganic minerals into cell material. As a result there is a continuous production of cell material within the pond. Although some of the cell material is released in the pond effluent, much of the cell material is retained in the pond and eventually settles to the pond bottom. In addition, many ponds are used to receive raw wastewater which contains a high concentration of settleable solids. Therefore, within a relatively short period of operation a significant amount of sludge may be accumulated on the pond bottom. For example, it was cited by Eckenfelder and O'Connor (1) that within the pond approximately 80 to 90 percent of the influent soluble organics are converted to cell materials which eventually settle as benthal sludge deposits; this is equivalent to a buildup of 1.25 pounds of volatile solids on the pond bottom for each pound of BOD removed.

The accumulation of cell material and other organic and inorganic solids in the pond benthal deposits may affect the operation of the waste stabilization pond in the following ways: 1) In an aerobic waste stabilization pond bottom sludge accumulation may exert a significant amount of biochemical oxygen demand (BOD) on the overlying water and cause the pond to be overloaded, thus changing the pond to an anaerobic condition. In this case, not only will the treatment efficiency be reduced, but serious odor problems will also occur. 2) In a facultative or an anaerobic waste stabilization pond, the anaerobic degradation of bottom organic deposits can manifest itself by both evolution of gases and release of fermentation products. The evolved gas may result in the formation of floating sludge mats and the fermentation products will in most cases exert a considerable BOD on the overlying water. In this instance the total organic substrate present in the supernatant may exceed the assimilative capacity of the pond, thus treatment efficiency may be greatly reduced. 3) The gradual accumulation of benthal sludge will decrease the effective volume of the pond. If the extent of this sludge accumulation becomes very significant, the hydraulic and organic loadings of the pond will exceed its designed capacity due to the decrease of the pond volume.

Unfortunately, to date the effect of bottom sludges on the operation of waste stabilization ponds have received relatively little attention. Generally, the design criteria for the pond, whether empirically derived from research data or laid down by state regulation agencies, have attempted to incorporate the effect of benthal deposits into the design considerations. However, due to the lack of information on the nature of benthal deposits, this is normally done by merely an increase of the minimum pond depth on the basis of the belief that serious odor problems will not develop if an adequate depth of supernatant is provided and an upper aerobic environment is maintained. There is a definite need of further research in this area so that a better understanding regarding the sludge effect on the pond performance can be obtained.

A. Objectives

The objectives of this study were to evaluate the order of of magnitude and the rate of oxygen utilization by the waste stabilization pond benthal sludge under various environmental conditions. The physical, chemical, and biological characteristics of the pond sludge were also examined. Particular attention was given to determine the parameters which control the sludge oxygen consumption and correlate these parameters with the oxygen uptake data. Considerable effort was also directed toward the development of laboratory techniques for measuring oxygen consumption.

B. Scope

Sludge samples employed in this study were collected from three different locations, that is, from near the inlet, the center, and the outlet, of a sewage lagoon. The sludge collected was analyzed to determine: 1) the physical, chemical and biological characteristics of the sludge, 2) the oxygen utilization of the sludge at three different temperature levels, 10, 22, and 35 degrees centigrade and, 3) the effects of certain other test environmental conditions or parameters, including the BOD, COD, solids concentration and initial oxygen tension of the test supernatant and the sludge compaction on the rate of oxygen utilization.

A careful evaluation was also made to determine the suitability of the test assembly developed in this study for the measurement of oxygen consumption by the sewage lagoon benthal sludge.

II. REVIEW OF LITERATURE

A review of literature was conducted to obtain available information regarding oxygen consumption rates of the waste stabilization pond benthal sludge. No direct reference was found on this particular subject. Some references, however, are available on the nature of the waste stabilization pond benthal sludge and oxygen consumption of other benthal sludges. Therefore, the emphasis of the literature review was on the following two areas which are of special value to this study: the nature of waste stabilization pond benthal sludges, and the oxygen consumption of other benthal sludges which are related to this study.

A. Nature of Stabilization Pond Benthal Sludges

Middlebrooks, Panagiotou, and Williford (3) conducted an extensive study into the sludge accumulation in 15 waste stabilization ponds. The authors pointed out that considering only settleable organic solids present in raw wastewaters, it could be calculated mathematically that the sludge accumulation in a 10-acre waste stabilization pond serving a population of 1,000 would be only one foot per 135 years. However, they also indicated that this was not the case in actual practice, much of the sludge accumulation consisted of silt and other inorganic substances that may be contributed from the incoming waste streams or be washed in from outside the pond.

The average composition of all the pond sludges studied showed 9.25 percent total solids, of which 25.7 percent was volatile. The actual average rate of sludge accumulation was found to be one foot per 27.6 years.

In the study the authors collected the sludge core samples using a clear plastic sampling tube two inches in diameter. To collect the sample, the tube was lowered from a boat into the water, then driven through the sludge into the soil bottom deep enough to retain a soil core to prevent the sludge from escaping. Sampling directions were selected parallel and perpendicular to the prevailing winds to determine the effect of wind direction on sludge depth and distribution; however, the prevailing wind was found to have no significant effect. The authors also found a greater accumulation of sludge in the corners of the ponds. They felt that this was probably due to the fact that wind could blow the floating sludges, which were buoyed up by the gaseous products of anaerobic decomposition, into the corners of the ponds where they then settled.

Eckenfelder and O'Connor (1) in their discussion of treating domestic sewage by waste stabilization ponds have stated that the influent BOD is primarily removed by sedimentation and bioflocculation. This clarification process requires a rich and diverse population of microorganisms and is aided by the presence of invertebrates such as rotifers. The authors also cited the work of Oswald (2) which showed that up to 85 percent of the suspended and dissolved organics could be deposited on the pond bottom within four hours. The presence of high algal populations in the pond can lead to a high pH, thereby causing the precipitation of some inorganic salts. Some algal and bacterial cells may be enmeshed with the precipitating salts and add to the benthal sludge buildup.

B. Oxygen Consumption by Benthal Sludges

Compared to other phases of sanitary engineering investigations relatively little attention has been given to the study of aquatic benthic sludges until recently. Oneof the earliest studies of the benthic sludge was that performed by Rudolfs (4) in 1938 in which he investigated the BOD reduction in a sludge sample during a 400 day test period. That same year Mohlman (5) wrote an editorial expressing his satisfaction about seeing the start on the study of benthic sludges. He also commented, "Our efforts to abate stream pollution will be on a stronger foundation when we have more information on this important subject."

The next major studies on benthic sludges were those presented in a series of articles by Fair, Moore, and Thomas (6, 7, 8). The authors found that in heavily polluted streams the sludge activity was raised to the extent that the dissolved oxygen content of the flowing water became depleted by the high and rapid oxygen demand of putrescent sludge banks. These sludge banks were found to contain 10 to 40 percent solids, of which 10 to 30 percent were volatile. The authors also pointed out that in evaluating the oxygen uptake by a benthal sludge two factors must be considered when the sludge was taken from the natural anaerobic conditions and then placed in a water containing oxygen during the laboratory experiment. The first factor was the rapid chemical or immediate dissolved oxygen demand (IDOD) exerted by reduced organic or inorganic substances present in the sludge as a result of the anaerobic decompositions. The second factor was that a certain time lag in the oxygen uptake could exist before an active aerobic decomposition was established. To a certain extent these two effects might compensate each other.

The authors also found the oxygen utilization in the field pond was greatly dependent upon temperature; they reported that as the sludge deposits warmed up in the spring, chemical and biological activities were stimulated, diffusion was increased, and viscosity, density, and the solubility of gases were reduced.

Although the importance of benthic sludges in oxygen consumption was recognized, in practice this effect had long been ignored. For example, the Streeter-Phelps equation (1) for estimating the oxygen sag in a stream is developed by considering only two major processes taking place. First, BOD and dissolved oxygen are being removed along the stream by the bacterial oxidation of the organic matter. Secondly, oxygen is replenished by surface reaeration. Dobbins (9) pointed out that the following factors were important in considering the overall oxygen balance in a river system: 1) The removal of BCD from liquid phase by sedimentation or adsorption. 2) The addition of BOD to the liquid phase by the scour of bottom deposits or by diffusion of partly decomposed soluble organic products from the benthal layer to the overlying water. 3) The addition of BOD to a river system by local runoff. 4) The removal of the dissolved oxygen from the water by diffusion into the aerobic upper benthal layer to satisfy its oxygen demand. 5) The stripping-off of the dissolved oxygen from water by the purging action of gases produced from anaerobic benthal decomposition. 6) The addition of oxygen by the photosynthetic actions of phytoplanktons and fixed plants. 7) The removal of the dissolved oxygen by the respiration of phytoplankton and fixed plants. 8) The continuous redistribution of both BOD and oxygen through the longitudinal physical dispersion.

McKeown, Brown, and Grove (10) conducted studies to evaluate the accuracy of the dissolved oxygen probe for the measurement of the dissolved oxygen content in solutions. These studies showed the oxygen probe to be an accurate and very useful tool for determining the oxygen content in solutions. In addition, these studies showed that the membrane electrode used in the oxygen probe can accurately measure dissolved molecular oxygen in a variety of solutions where the Winkler method may not be able to determine the oxygen level without interference. The use of the oxygen probe not only allows an instantaneous reading and recording, but also allows the solution to be in a closed system which is extremely important in oxygen consumption studies.

O'Connell and Thomas (11) conducted studies to evaluate the effect of benthic algae on the dissolved oxygen in streams. This study showed that the oxygen produced by benthic algae and other attached plants was generally of little beneficial value to the stream reaeration; on the contrary, the respiratory requirements of algae at night can cause an extremely low minimum dissolved oxygen concentration. This study also demonstrated the sensitivity of the algal photosynthetic process to the change of available light, which is influenced by the degree of sky cloudiness and the turbidity of water. These factors explain the reason that the quantities of photosynthetic oxygen production are extremely variable, depending on light conditions. The authors also found that the excessive oxygen production during daylight hours may cause localized supersaturation and venting of oxygen directly to the atmosphere. Oxygen lost in this manner becomes unavailable for respiratory need of aquatic life during hours of darkness. As a consequence this study reflects the importance of the presence of algae in oxygen consumption studies, as algae can both produce and use oxygen.

Hanes and White (12) employed a de-inking process sludge cake, which had been settled, thickened and vacuum filtered, to investigate the effect of seawater on the benthal system. They discovered that within a relatively short period of time (six to 10 hours) the test biota can adapt to the saline conditions. They also found the rate of oxygen consumption was increased with an increasing seawater concentration or an increasing BOD in the test solution. In this investigation the authors used a reaction chamber constructed from a crystallization dish. This reaction chamber was supported by rubber stoppers on a magnetic stirrer. A magnetic stirring bar was placed in a petri dish which rested on the bottom of the crystallization dish. The sludge was placed around the petri dish and covered with an aluminum screen. The crystallization dish was filled with a mixture of BOD dilution water and seawater and sealed with a plexiglas lid. The oxygen probe and a thermister were then placed in holes in the lid. This type of reaction chamber proved very satisfactory for this study.

McKeown, Benedict, and Locke (13) investigated the oxygen utilization of benthal deposits of wood origin. Two types of sludge were used in this study. The first was a diluted vacuum filter cake from a paper mill treatment plant. The second was the clarifier underflow from a paperboard mill waste treatment plant. Two types of reaction chambers were used in this study, one being similar to the aforementioned used by Hanes and White (12) and the other employing a top stirring system in which an inverted magnetic mixer was supported on small wood blocks above the plexiglas lid. A magnetic stirring bar was supported inside the chamber against the lid by the magnetic force.

Important findings of this investigation included: 1) The uptake of oxygen by benthal deposits was directly proportional to surface area of the deposit. 2) The rate of BOD diffused from the sludge to the overlying water decreased with time, and in the case of shallow deposits up to a depth of four feet, the BOD diffusion was essentially zero after 100 days of contact. 3) Sludge depths of one, two, three and four feet showed a constant rate of oxygen demand. 4) Mixing or turbulence in overlying water tended to increase the oxygen demand of the cellulosic benthal deposits. Stagnant conditions produced an oxygen demand ranging from 0.2 to 0.8 g O_2/day/sq m. When agitation approached a scouring condition the sludge oxygen demand was increased to 2.7 g O_2/day/sq m. So in the oxygen uptake study consideration must be given to turbulence derived from the mixing operation, especially when scour occurs. 5) When the cellulosic deposits were covered with an inert sand layer the oxygen uptake was significantly lowered after compaction was complete. 6) Removal of the old sludge surface, thus exposing the underlying sludge, resulted in an increased oxygen demand identical to that exhibited by the original fresh sludge surface.

McDonnell and Hall (14) conducted studies on the oxygen uptake by the benthal sludge from a mildly polluted stream. Experiments were conducted in reaction chambers consisting of cylinders, six inches in diameter and 15 inches long, equipped with removable tops and bottoms. These studies were conducted in the dark thus eliminating algal photosynthetic activity. In these studies special attention was given to the evaluation of the effect on oxygen uptake of oxygen concentration, oxygen diffusion, temperature, and active invertebrate population. The authors disclosed that oxygen uptake by the benthal sludge was primarily due to the combined effect of benthal scours, diffusion of benthal organics into the overlying water, and diffusion of oxygen into the aerobic zone of the benthal layer.

Hanes and Irvine (15) pointed out the importance of benthal systems to the overall oxygen demand in a river. They indicate the effect of oxygen uptake by benthal deposits might be as high as 50 percent of the total dissolved oxygen removed in a river. The authors used a sludge obtained from a vacuum filter, and used a reaction chamber similar to the one described by Hanes and White (12). The supernatant used in the experiments consisted of the seeded BOD dilution water. These studies resulted in the following general conclusions: 1) the reaction chamber is a useful tool for the measurement of the oxygen demand of benthal deposits; 2) the results obtained with the reaction chamber were reproducible; 3) the rate of oxygen uptake decreases with decreasing temperature for old benthal deposits; 4) the rate of oxygen uptake for new deposits decreases when the temperature decreases from 25 to 20 degrees centigrade, but not from 20 to 15 degrees centigrade.

Davidson and Hanes (16) conducted a study primarily to determine the effect of sludge depth on the oxygen uptake by a benthal system. Several reaction chambers using sludge depths ranging from 5/8 to 12 inches with four inches of supernatant in each case were used. The construction of these chambers was generally similar to the one described by Hanes and White (12). The sludge mixture was prepared from a de-inking process sludge which had been settled, thickened, and vacuum filtered. The supernatant was the seeded BOD dilution water. This study resulted in the following conclusions: 1) Deeper deposits of a freshly laid down cellulosic material exert a significantly greater oxygen uptake rate than shallower ones. 2) Once consolidation of a bottom deposit is essentially complete, the oxygen uptake rate of a benthal sludge is independent of its depth. 3) The process of consolidation of the bottom deposit contributes appreciably to the resulting removal of oxygen from the overlying water. 4) Physical disturbances of the sludge due to anaerobic gas production from the deeper layers have a significant effect on the rate of oxygen uptake. This is probably attributed to the resuspension of sludge material by the gas passing through the sludge into the overlying water.

III. BACKGROUND OF THE POND STUDIED

The benthic sludge utilized in this study was obtained from a 6.7 acre sewage lagoon located in St. James, Missouri. The general backgrounds of the city and the lagoon are described in the following paragraphs.

St. James is located in south-central Missouri. The city is described physiographically by Mineral and Water Resources of Missouri (17) as being located in remnants of the maturily dissected, rolling upland surface, known as the Salem Plateau. St. James is situated on the Jefferson City formation of the Orodovician System. The overlying soil as described in Soils of Missouri (18) is the Clarksville-Fullerton-Talbott soil association. This soil association is characterized by surface soils which vary from grey through greyish brown to yellowish brown. The subsoil texture varies greatly from clay to stony silty clay loam. This soil association has a moderate to rapid permeability. The topography is generally rolling to hilly. The inherent fertility is low and the land is generally forest covered. This soil association is formed from limestone and is in an area where the loessial deposit ranges from two and a half to five feet.

St. James is a rural community having a population of about 2,500. The city has no major industry; the only major water user in the city is the State-Federal Soldiers Home. The city is served by three wells, two of which are described by Robertson (19), one being 700 feet deep into the Eminence formation of the Cambrian System, and the other being 1,100 feet deep into the Derby-Doerun formation of the Cambrian System. The water supply system was started in 1924 as described by Census of Public Water Supplies in Missouri (20), and currently serves about 2,350 persons through 610 services. The average water consumption is from 150,000 to 200,000 gallons per day, which amounts to a consumption of 64 to 85 gallons per capita per day. The water receives no treatment and has a reported alkalinity of 228 mg/L, a hardness of 308 mg/L, and a pH of 7.5.

The plans for treating the municipal sewage by the single celled, 6.7 acre waste stabilization pond were drawn in June of 1960 by the consulting engineering firm of Russel and Axon, located in St. Louis, Missouri. The operating permit was issued in December of 1961 by the Missouri Division of Health. The pond initially served a population of about 2,200, but this was reduced to 1,500 shortly after the operation began; the remaining population was served by an old trickling filter plant. In December of 1968, the trickling filter plant was abandoned and the loading on the pond was increased to its present value of about 2,400 persons. The city has one other small sewage lagoon which serves only a few houses in the city.

Based on the generally accepted value of 0.17 pounds of BOD per capita per day, the average loading amounted to 38.8 pounds of BOD per acre per day from the beginning of operation to December 1968. From that time to the present, the loading has amounted to about 61.5 pounds per acre per day. In A Guide for the Design of Municipal Waste Stabilization Lagoons in Missouri (21) the recommended loading is 45 pounds of BOD per acre per day. This waste stabilization pond has been well maintained and operated. It appears to be operating satisfactorily at its present loading level.

In order to establish certain background characteristics of the pond, performance data were obtained from the City of St. James on the effluent temperature, pH, and dissolved oxygen content for most of 1968. These data are shown in Figures 3-1, 3-2, and 3-3. As shown in these figures, the effluent temperature varied from approximately 10 degrees below zero during the winter season to 25 degrees centigrade during the summer. It is felt that the 10 degrees below zero reading is too low, probably resulting from instrument error. Although considerable ice cover occurred the lagoon did not freeze solid. The effluent pH remained rather stable within the range between 7 and 9 throughout most of the year of 1968. During the months of March, April, and May, data were not available due to the malfunction of the monitoring equipment. The dissolved oxygen of the effluent fluctuated from a high of 8 mg/l in the winter to a low of approximately 1 mg/l in the summer. Noteworthy is the fact that a zero reading of the effluent dissolved oxygen was recorded for only several days in late August. This seems to be contrary to the fact that some high values of effluent dissolved oxygen should be expected in the summer months because of an increase in the algal photosynthetic activity. The low values of dissolved oxygen are shown in Figure 3-3, and may probably result from a delay in fixing the sample during the monitoring program; this could allow the supersaturated oxygen to be consumed by bacteria. However, in general the data of effluent dissolved oxygen shown in Figure 3-3 reflects that the pond has been operated within its assimilation capacity.

In addition to the data obtained from the City of St. James as described above, the temperature and dissolved oxygen profiles were taken near the inlet, the center, and the outlet of the pond at the

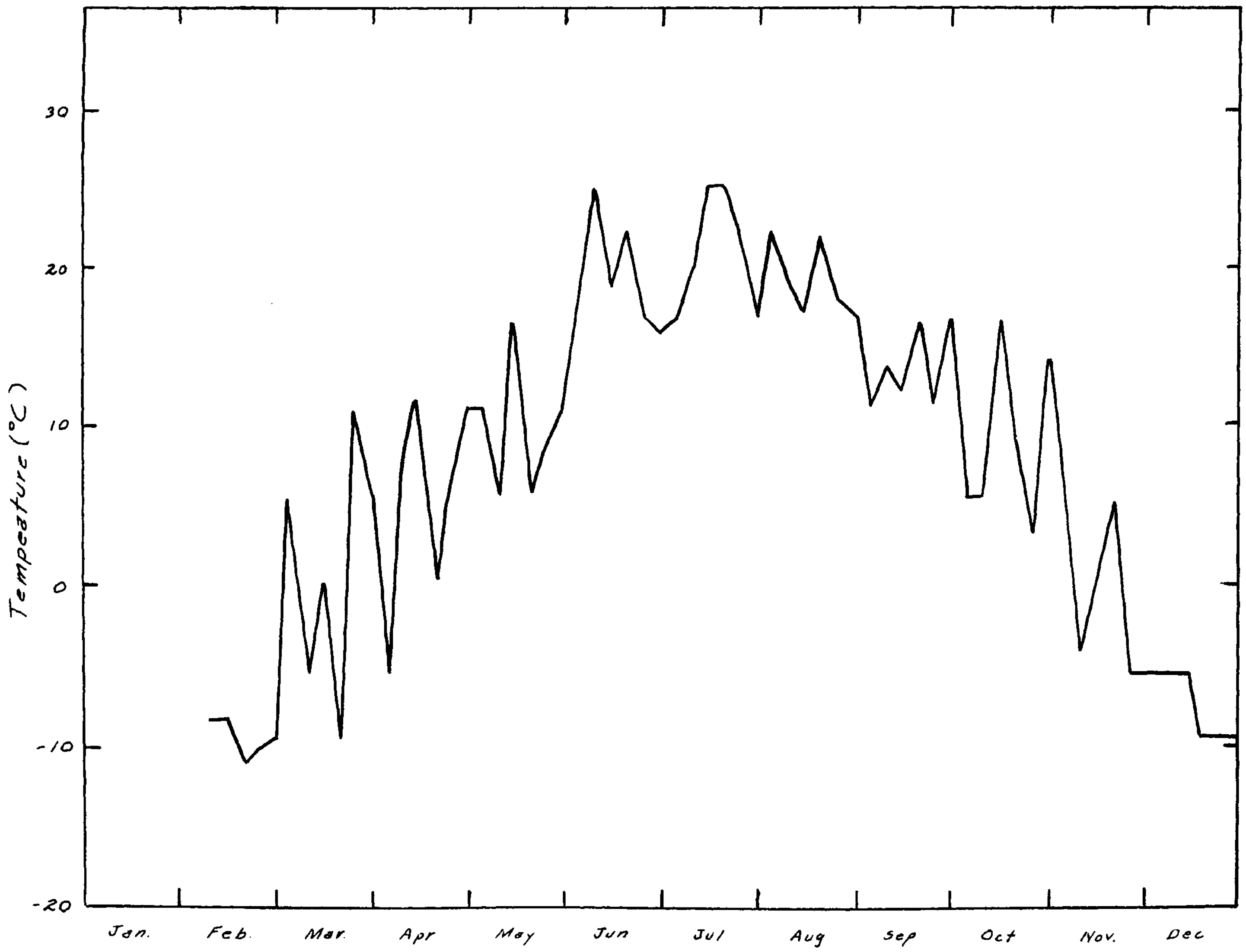

Figure 3-1

Effluent Temperature of the Sewage Lagoon throughout the Year of 1968

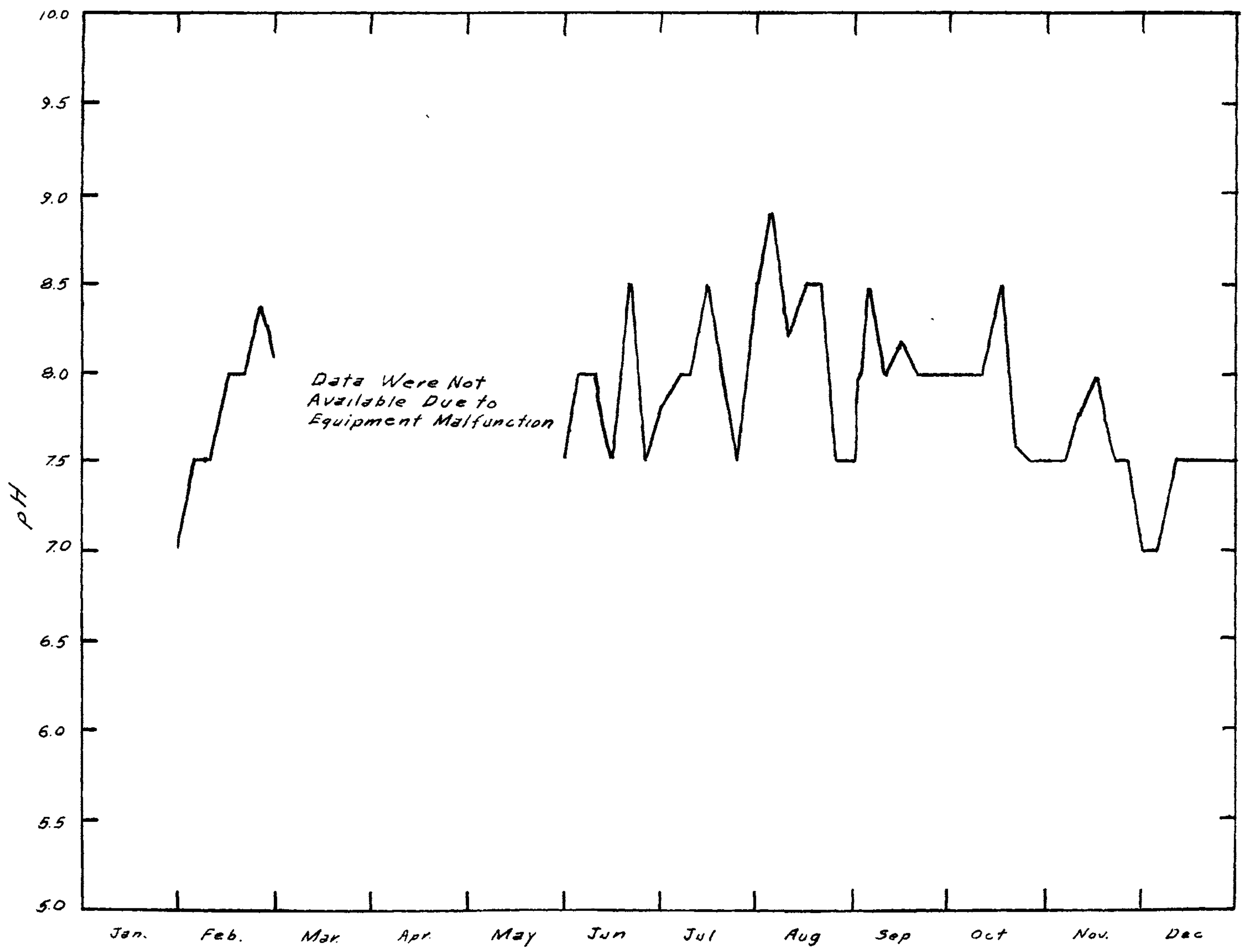

Figure 3-2

Effluent pH of the Sewage Lagoon throughout the Year of 1968

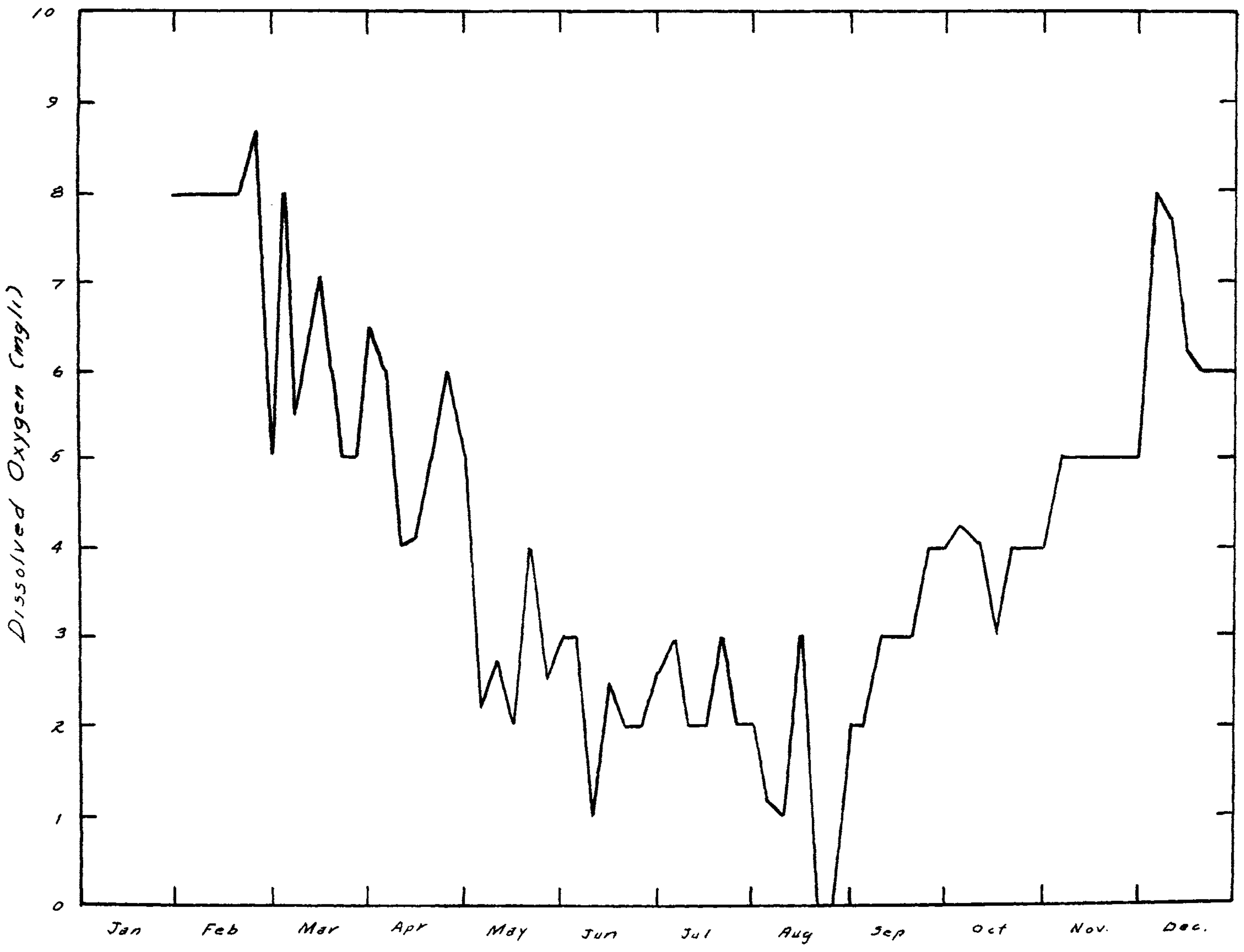

Figure 3-3

Effluent Dissolved Oxygen of the Sewage Lagoon throughout the Year of 1968 locations shown in Figure 3-4. These measurements were made at about eight in the morning, at noon, and about six in the evening, on June 4, 1969. The profiles are shown in Figures 3-5, 3-6, and 3-7, all of which show that generally both the temperature and the dissolved oxygen level decreased with depth, yet increased from morning to evening. It is interesting to note that a high degree of oxygen supersaturation was observed in the pond during the evening just before sunset, the level varying from 25 to 30 mg/l.

The characteristics of the pond supernatant including BOD, COD, and the predominant type of algae were also studied. Supernatant samples were collected with a BOD sampler at the aforementioned three sampling points from the surface, the mid-depth, and near the bottom of the lagoon. The BOD of the samples was determined by checking the oxygen depletion for seven days; the results are shown in Figures 3-8, 3-9, and 3-10. The COD of these samples were also determined. The correlation between the 5-day BOD and the COD of the samples is shown in Table 3-1. From this table it appears there was a consistent relationship between the BOD and the COD for these samples, with the BOD_5/COD ratio being about 0.75.

The pond supernatant was collected periodically for the microscopic examination for the predominant types of algae. During the early spring (late March and early April) the predominant forms of algae were Chlorella, Gomphosphaeria, and Euglena. By late spring (May and early June) the predominant types had changed to Euglena, Phormidium, and Spirulina. In late June and most of July a bloom of Spirulina occurred, which resulted in large floating mats and at times covered about one-third of the lagoon; during this bloom there was also a few Euglena and Phormidium observed. During August and

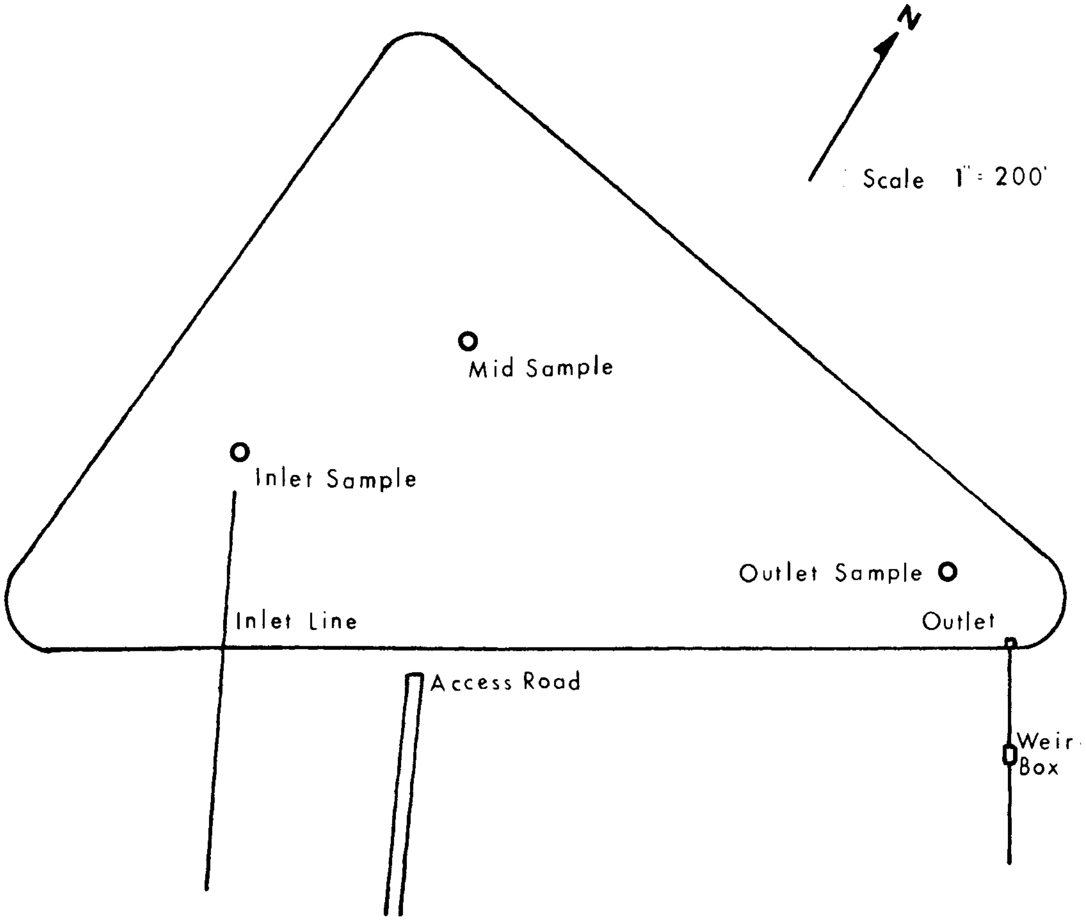

Figure 3-4

The Shape of the Sewage Lagoon and the Sampling Locations

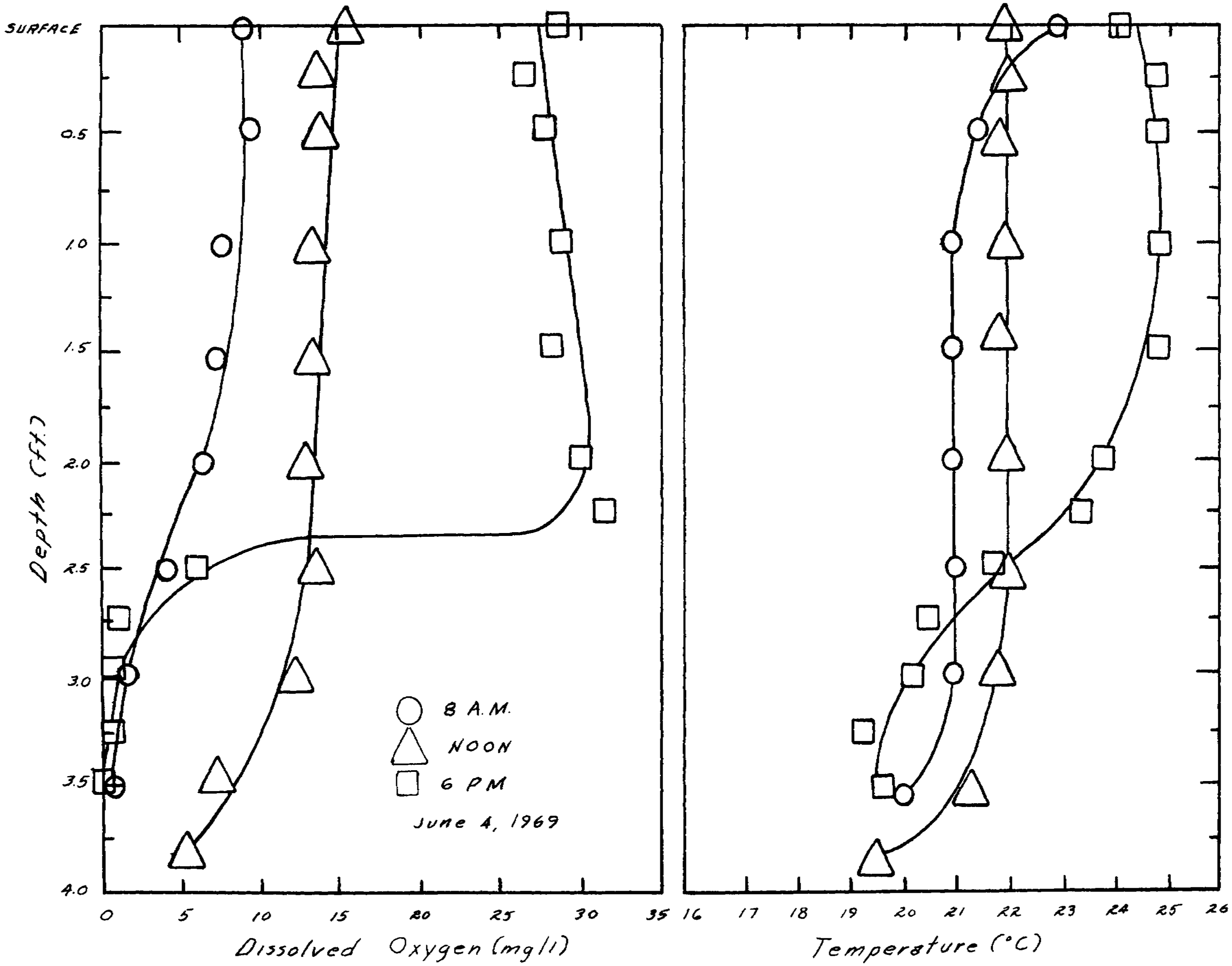

Figure 3-5

Dissolved Oxygen and Temperature Profiles

(Lagoon Inlet)

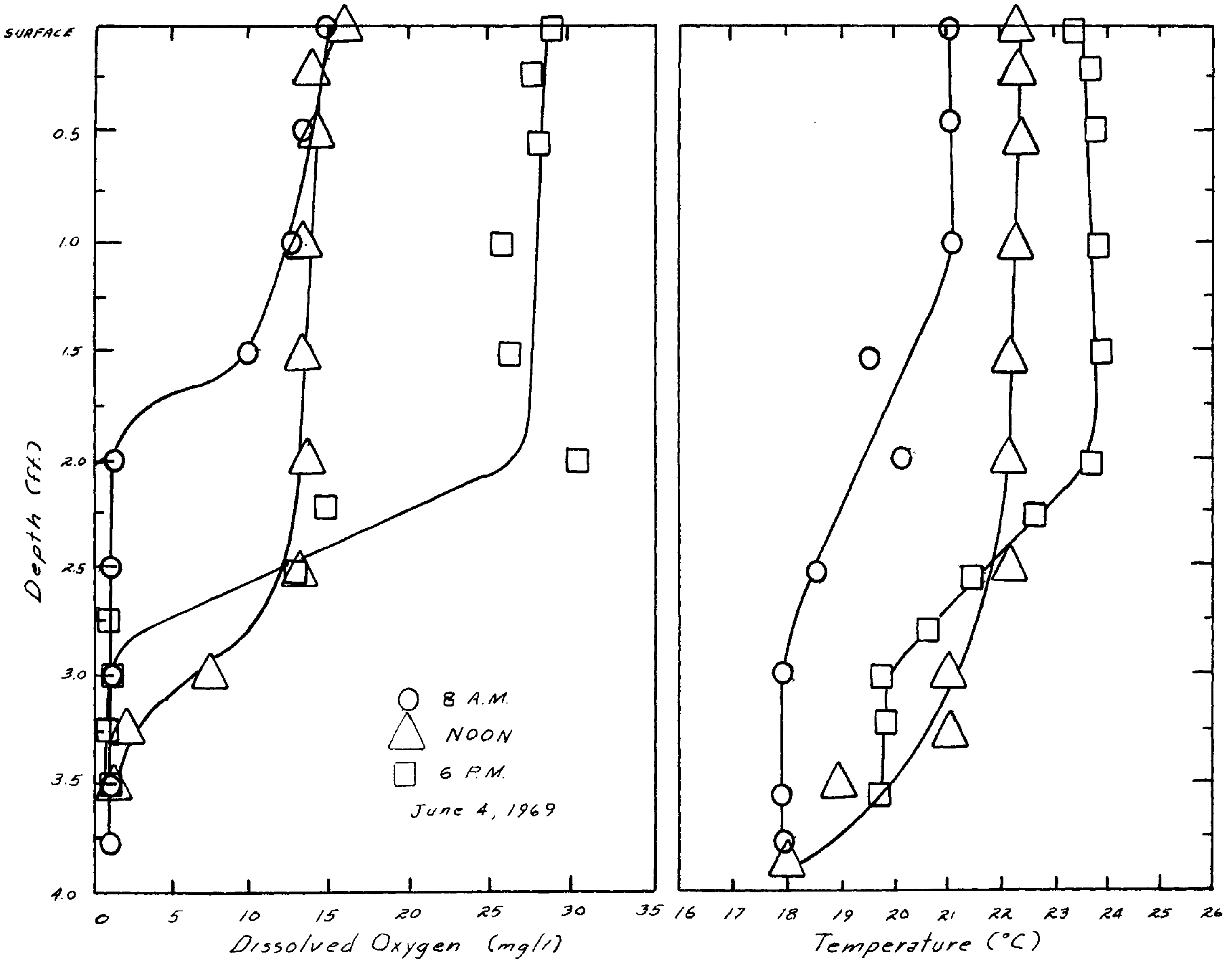

Figure 3-6

Dissolved Oxygen and Temperature Profiles

(Lagoon Center)

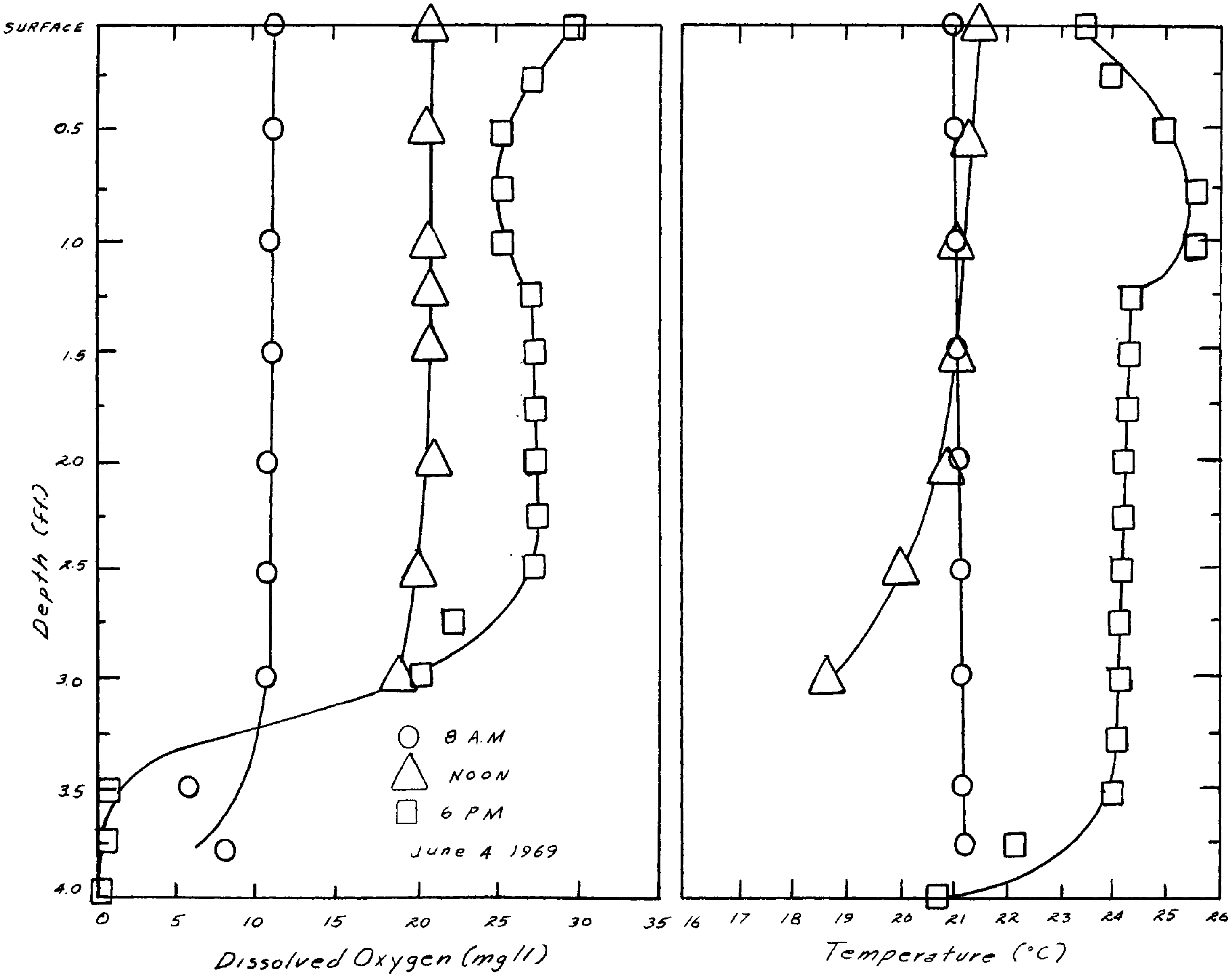

Figure 3-7

Dissolved Oxygen and Temperature Profiles

(Lagoon Outlet)

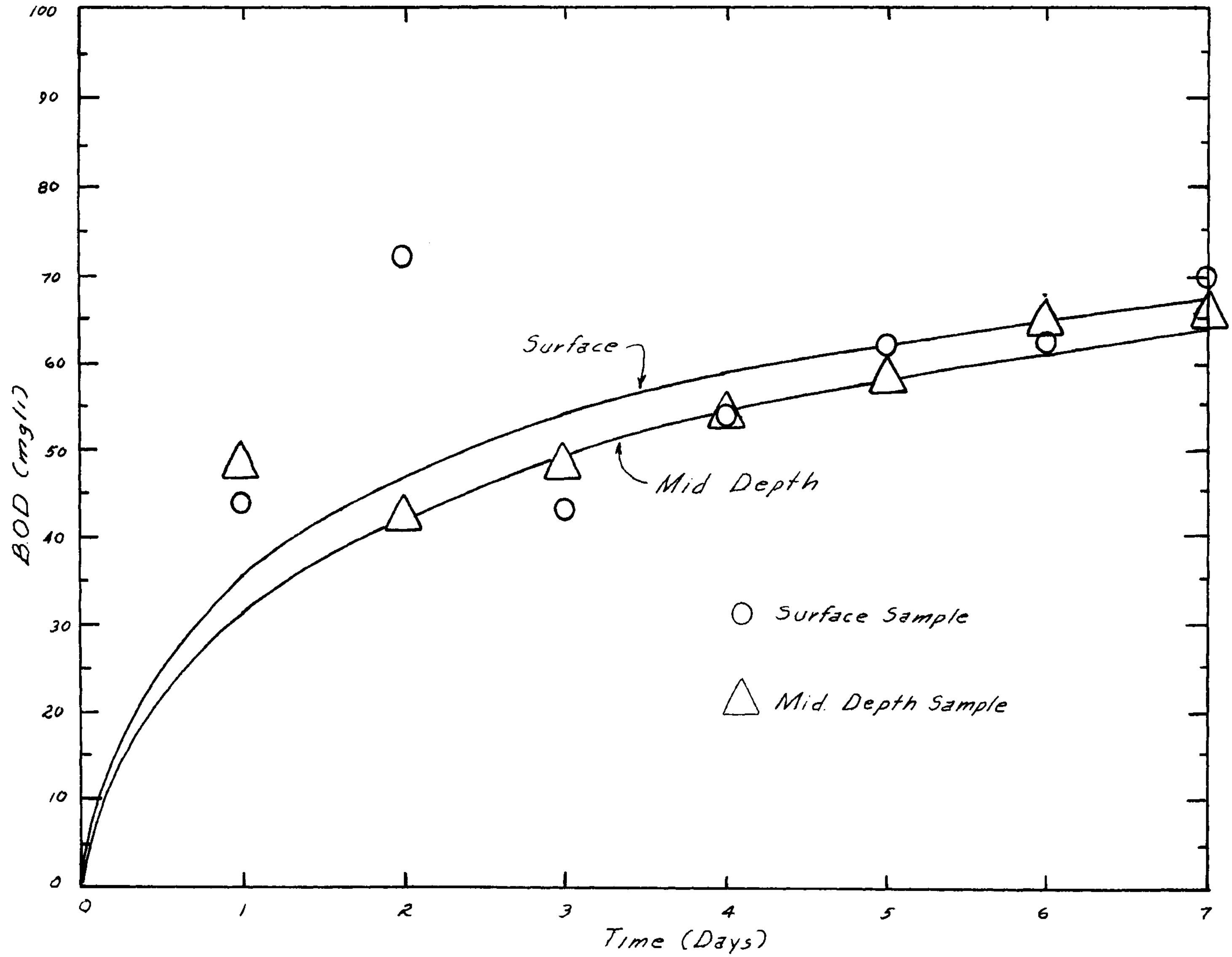

Figure 3-8

BOD of the Lagoon Supernatant (Inlet)

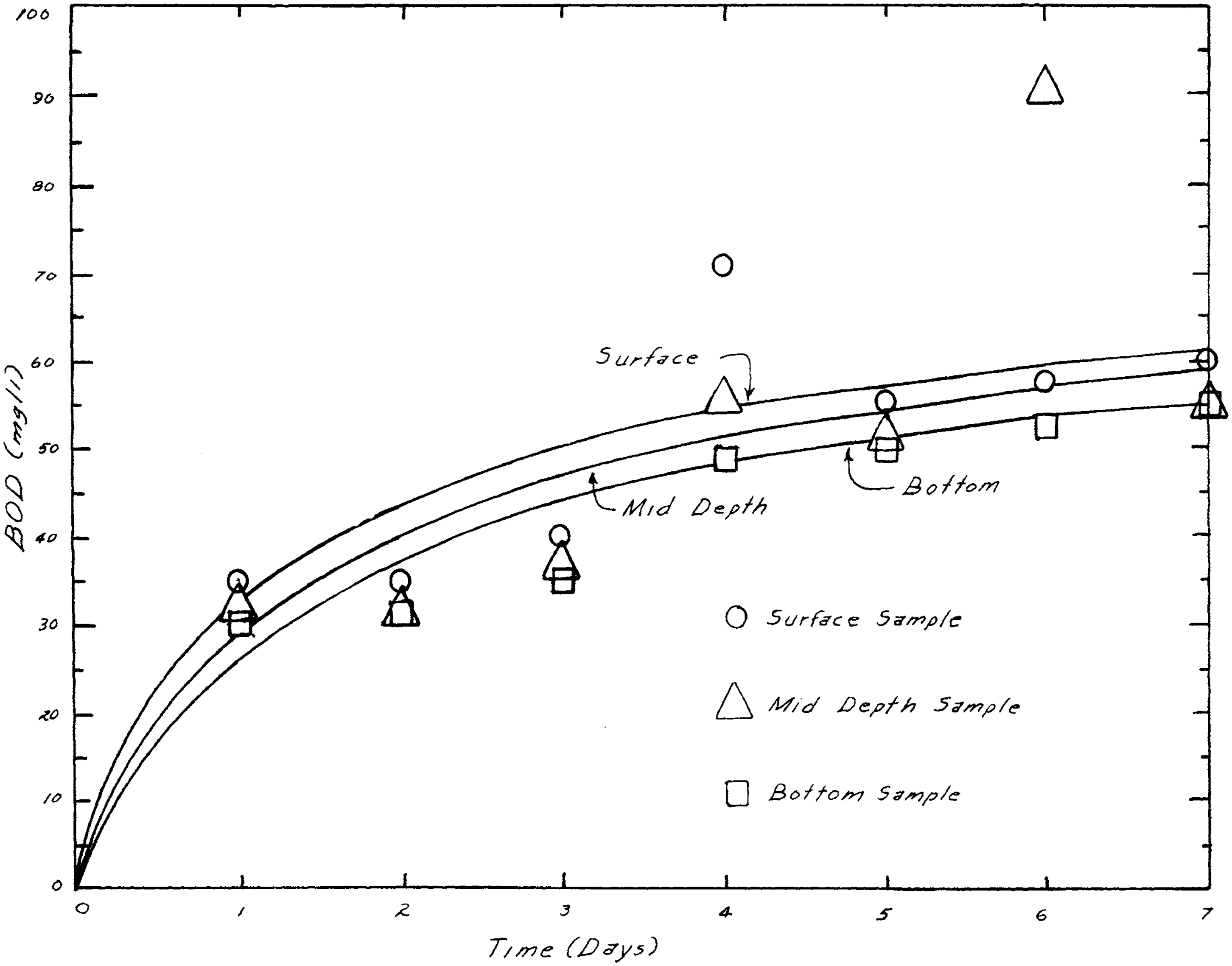

Figure 3-9

BOD of the Lagoon Supernatant (Center)

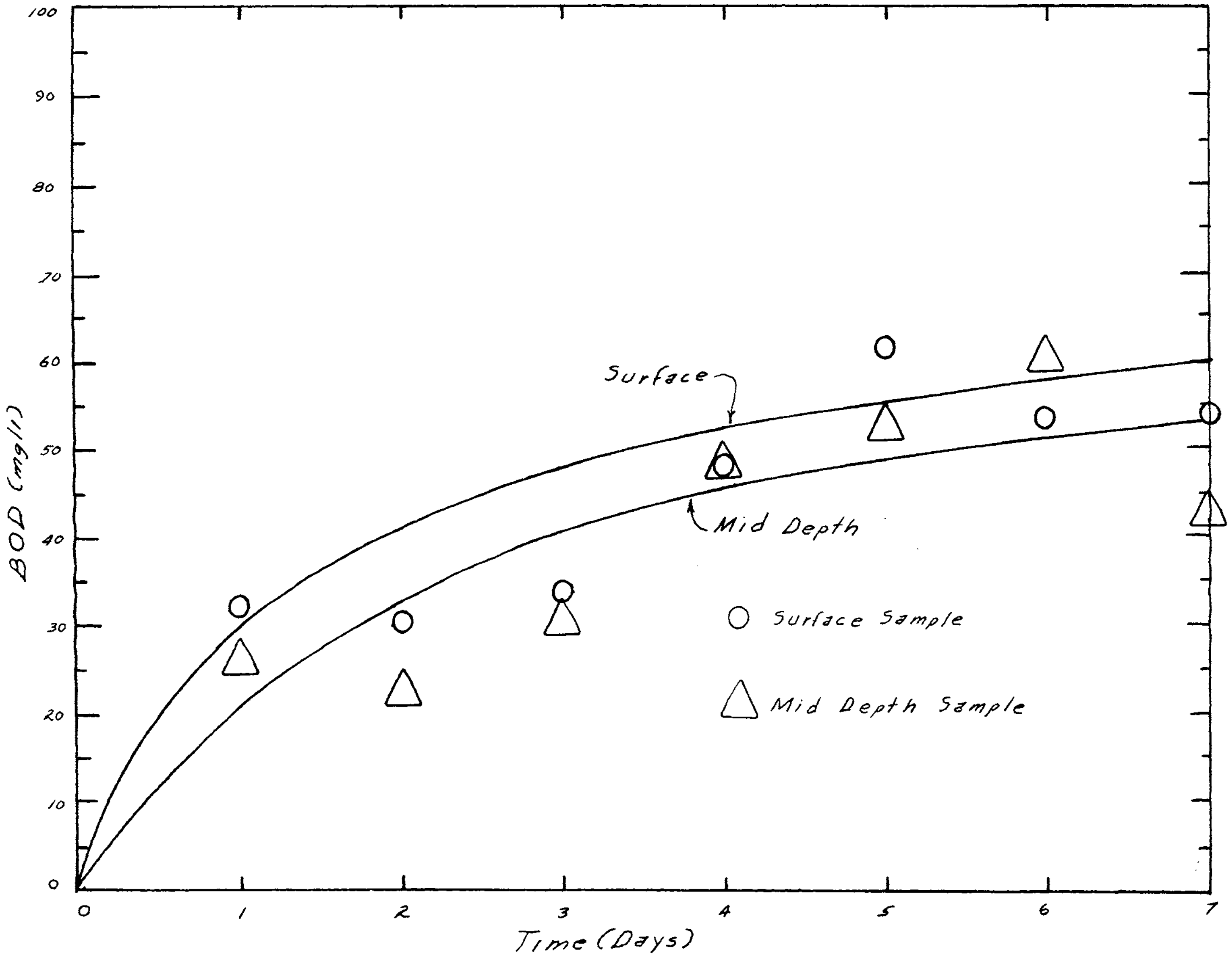

Figure 3-10

BOD of the Lagoon Supernatant (Outlet)

Sample	5-Day BOD (mg/l)	COD (mg/l)	BOD_5/COD
Inlet Surface	62	80	0.81
Inlet Mid	58	67	0.87
Inlet Bottom	*	*	*
Center Surface	56	72	0.78
Center Mid	52	72	0.69
Center Bottom	50	76	0.66
Outlet Surface	62	84	0.74
Outlet Mid	52	72	0.72
Outlet Bottom	*	*	*
Average	56.2	74.7	0.75

*Interference from the presence of sludge in the supernatant samples.

Table 3-1

Correlation Between the 5-Day BOD and COD

of the Lagoon Supernatant

September the predominant algal forms remained the same as earlier but decreased in number. By October and November the algal population was very low with Chlorella being the predominant type and a few Euglena were also found. Figure 3-11 illustrates the photomicrograph of some of the algal types observed in the pond.

Euglena *Spirulina*

Figure 3-11

Photomicrograph of Euglena and Spirulina Observed in the Lagoon

IV. EQUIPMENT AND METHODS

The laboratory equipment and the experimental methods employed in this study are described below.

A. Equipment

The major experimental apparatus used in this study consisted of a specially designed reaction chamber for measuring the oxygen uptake of benthal sludges. In addition to the test chamber, the sludge sampling facilities including an aluminum Jon boat and sampling tubes, and the laboratory equipment used in this study are described as follows.

1. Sampling Boat

Samples were collected using an eleven foot nine inch aluminum Jon boat purchased from the Sears and Roebuck Company, Kansas City, Missouri. During the sampling process the boat was anchored in place with a concrete block attached to a chain of six foot long which was attached to the boat.

2. Sampling Tubes

The sampling tubes used in this study were essentially designed after those described by Middlebrooks, Panagiotou, and Williford (9) with some minor modifications in the coupling device. One of the sampling tubes used is shown in Figure 4-1. Each of the sampling tubes consists of a two inch outside diameter plastic cylinder approximately 15 inches long. A PVC male pipe coupling having an inside diameter of one and one half inches was fitted to one end of the plastic cylinder. For this purpose the inside of the coupling had to be machined out slightly to allow the plastic cylinder to fit inside. A press fit was sufficient for most of the connections;

Figure 4-1

Sampling Tube

however, PVC solvent weld cement was used on some of the joints. The opposite end of the plastic tube was bevelled slightly to allow easier penetration into the pond bottom during the field sampling. In use, the sampling tube was attached to a five foot section of one and one half inch PVC pipe fitted with a female connection. The sampling tubes could be attached to and removed from the PVC pipe very easily as desired.

3. Reaction Chamber

The reaction chamber employed in this study for the measurement of the oxygen demand by lagoon benthal sludges is shown in Figures 4-2 and 4-3. This chamber was essentially patterned after those described in various articles by Hanes and others (12, 15, 16). However the design was modified to allow mixing from the top of the chamber. The chamber was constructed of a six-inch outside diameter plastic cylinder, approximately 15 inches long and having a one-fourth inch wall thickness. A nine inch square of one-fourth inch thick plastic sheet was attached to the bottom of the cylinder using a chloroform solvent weld. Six one-fourth inch rods were attached to the bottom plate using nuts and washers on both sides of the bottom plate. To provide a proper seal for the chamber, a solid disk of red rubber gasket material having a thickness of one-eighth inch was used on top of the cylinder, above which another one-fourth inch thick, nine inch square plate was placed. The top and bottom plates were then secured with wing nuts on the one-fourth inch rods. A hole was drilled through the top plastic plate and rubber gasket to allow insertion of the oxygen probe.

A mixing system was designed to allow continuous liquid movement past the oxygen probe. A heavy duty horseshoe magnet was attached

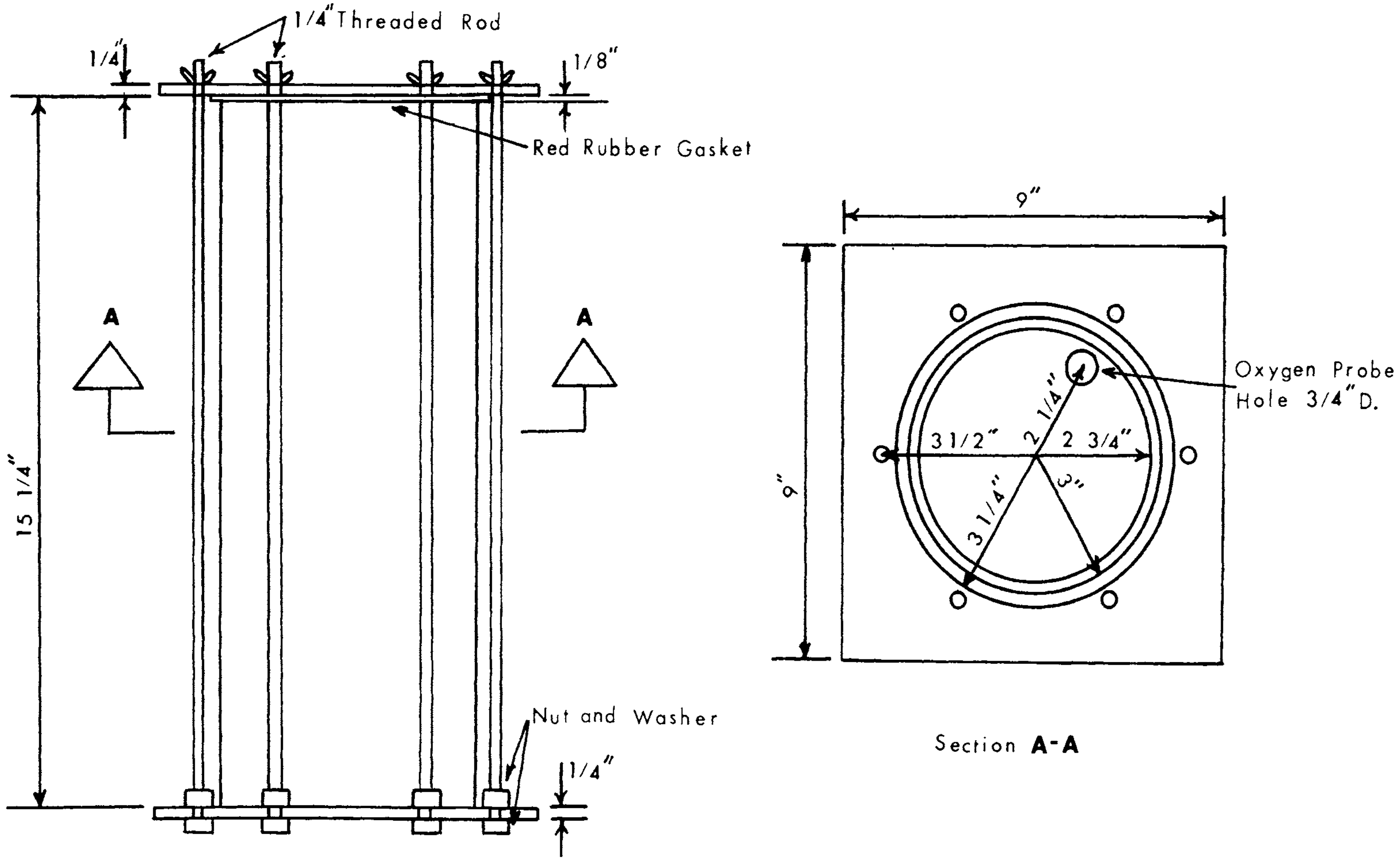

Figure 4-2

Detail Sketches of the Reaction Chamber

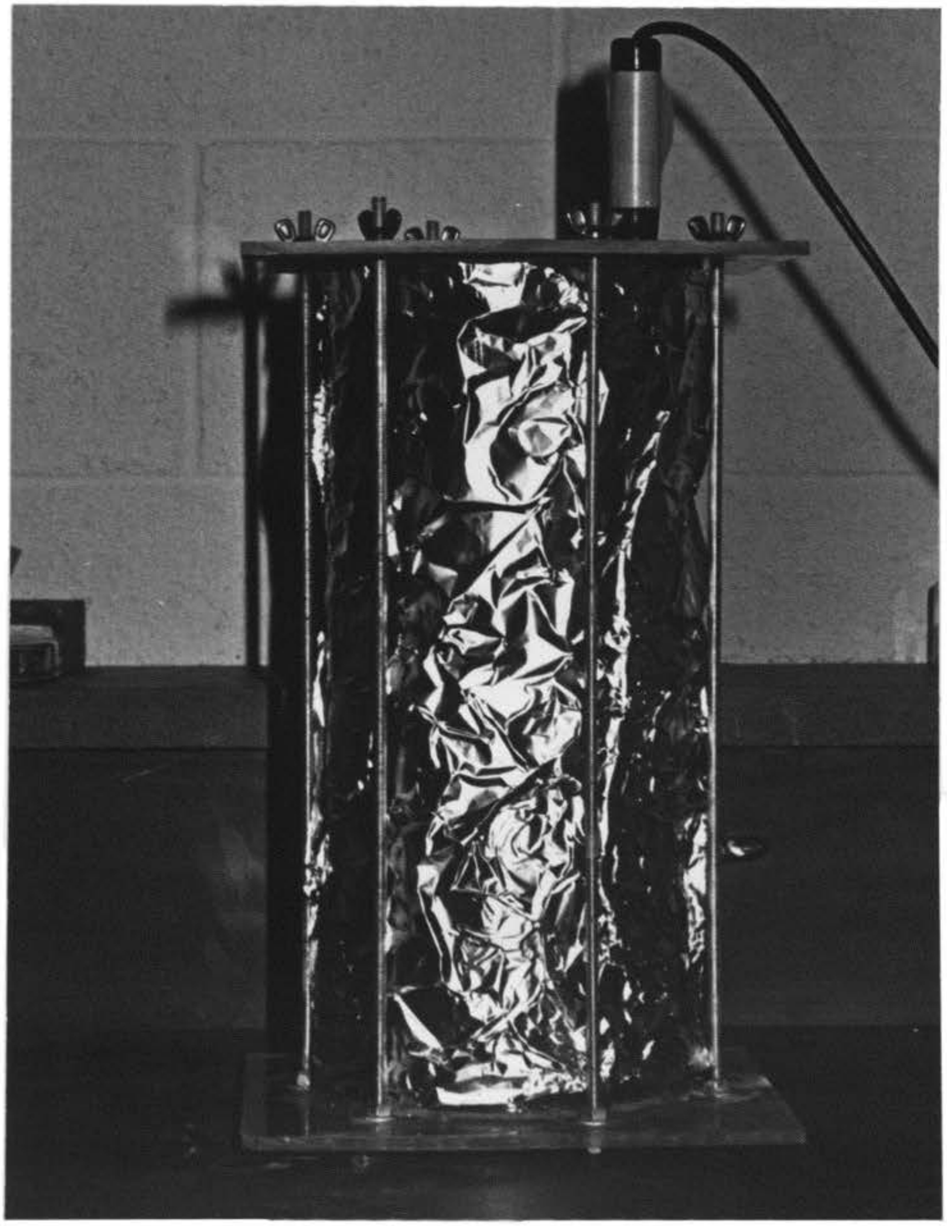

Figure 4-3

Reaction Chamber with Oxygen Probe in Place to an aluminum rod with epoxy cement. The rod was placed in a Jacobs chuck assembly in a Fisher Dyna-Mix stirrer. The magnet was used to turn a magnetic stirring bar which accomplished the mixing of the supernatant.

4. Oxygen Meter

Oxygen measurement was determined by the use of a Precision Galvanic Cell Oxygen Analyser, Catalog Number 68850, a product of Percision Scientific Company, 3737 West Cortland Street, Chicago, Illinois 60647. This instrument allows a direct reading of dissolved oxygen at levels from 0 to 15 mg/l, and is equipped with a scale tripler which allows the determination of dissolved oxygen at levels from 0 to 45 mg/l. Before each run the oxygen analyser was calibrated against a sample in which the oxygen level was determined by the Azide Modification of the Iodometric Method as described by Standard Methods (22). This oxygen analyser is shown in Figure 4-4.

5. Recorder

The output of the oxygen level measurement by the oxygen analyser was continuously recorded on a Rustrak single channel recorder, Model 288, a product of Rustrak Instrument Division, Municipal Airport, Manchester, New Hampshire 03103. This recorder has a motor and gear train assembly which gives a chart operating speed of two inches per hour. The full scale reading on this recorder is 10 millivolts. The recorder is shown in Figure 4-5.

6. Stirrer

Mixing of the test supernatant was accomplished by use of a Fisher Dyna-Mix stirrer, Model 43, a product of the Fisher Scientific Company, 1241 Ambassador Boulevard, St. Louis, Missouri 63132. This mixer can be adjusted to any speed varying from 0 to 6,000 rpm.

Figure 4-4

Oxygen Analyser

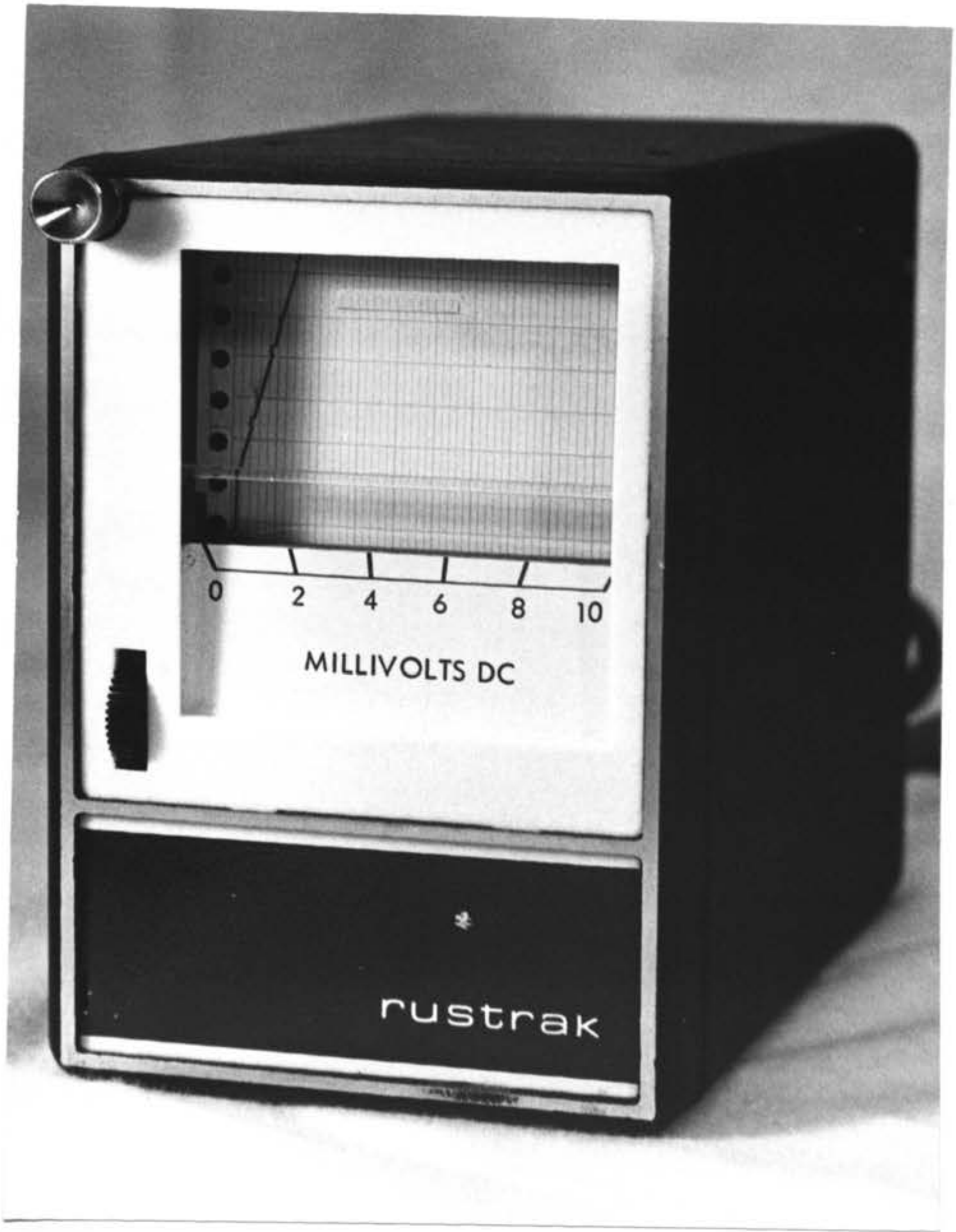

Figure 4-5

Recorder

In this study the speed was adjusted to approximately 100-120 rpm; although this might be more than the minimum speed required for mixing during the oxygen uptake test, a constant speed could not be maintained below that value.

7. Microscope

Microscopic examinations of the sludge and the pond supernatant were made using a Bausch and Lomb Dynazoom Microscope, Model PB-252, with a 35 mm camera attachment, a product of Bausch and Lomb, Inc., 635 St. Paul Street, Rochester, New York 14602.

8. Walk-in Incubator and Refrigerator

Two Labline incubators, models 704 and 704A, a product of Lab-Line Instruments Inc., 15th and Bloomingdale Avenues, Melrose Park, Illinois 60160, were utilized for the rigid control of experimental temperatures. One of these units was maintained at 35 degrees centigrade and was used in the high temperature studies. The other unit was maintained at 10 degrees centigrade and was used in the low temperature studies as well as for storage of samples. These units are shown in Figure 4-6.

9. Analytical Balance

A Sartorius analytical balance, Model 1503, as distributed by Brinkman Instrument Company, 115 Cutter Mill Road, Great Neck, New York 11020, was used for the gravimetric analysis of the various solids concentrations. This balance is shown in Figure 4-7.

10. pH Meter

The pH of the supernatant was determined by the use of a Beckman Zeromatic pH meter, Model 96, as manufactured by Beckman Instruments Inc., 2500 Habor Boulevard, Fullerton, California 92631. Prior to each use the pH meter was checked against a buffer solution

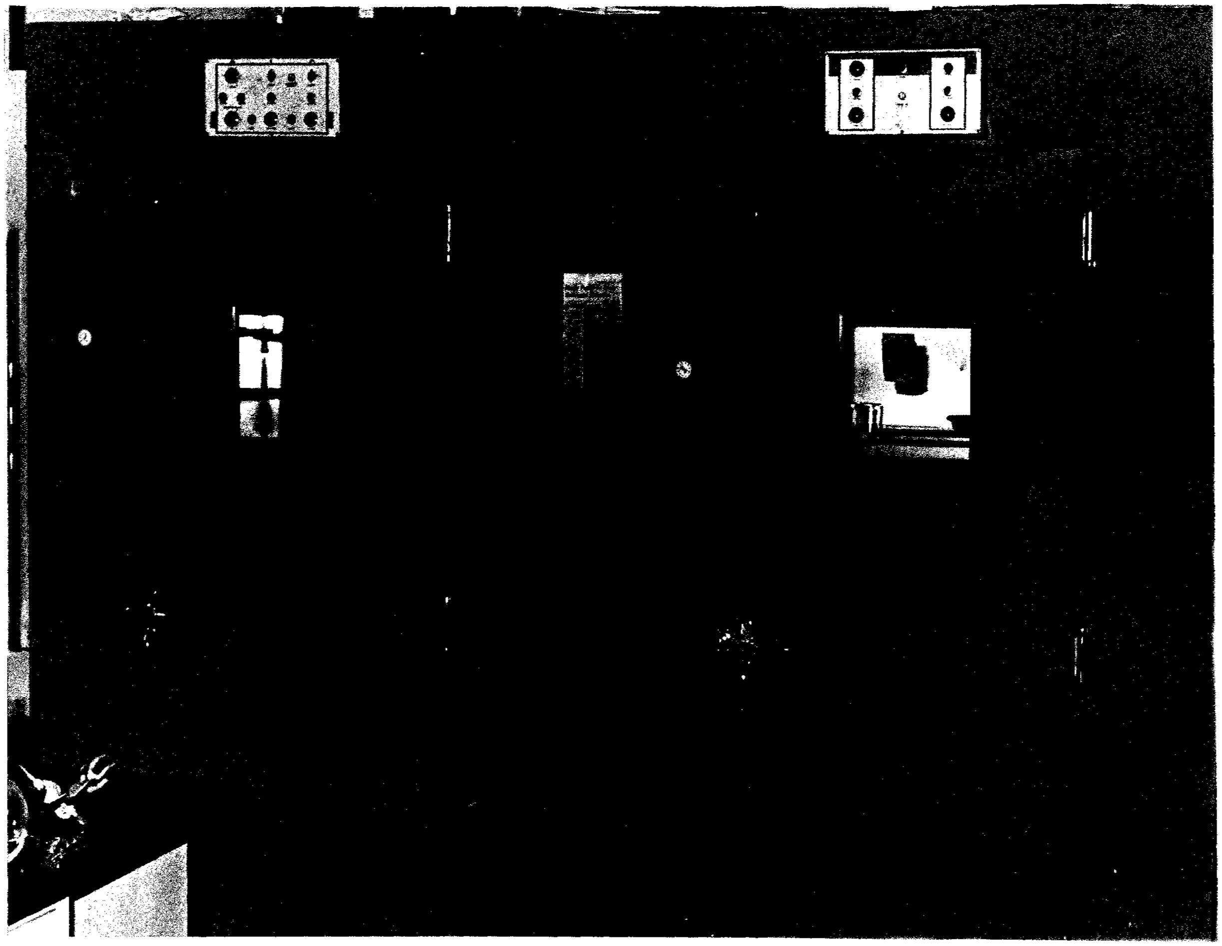

Figure 4-6

Walk-in Refrigerator and Incubator

Figure 4-7

Analytical Balance

having a pH of 7.04.

11. Drying Oven

During the determination of the suspended solids, samples were dried in a Precision Scientific Company Thelco drying oven, Model 17.

12. Muffle Furnace

When determining the fixed solids, the samples were fired in a Type 054-PT muffle furnace as manufactured by the Hevi-Duty Electric Company, Milwaukee, Wisconsin.

B. Methods

The sewage lagoon sludge employed in this study was of much finer consistency than other benthal sludges present in river or lake systems; therefore special attention must be given during the handling and the use of this sludge.

1. Collection of Sludge

Sludge samples were collected from three locations in the sewage oxidation pond. The first location was near the pond inlet, the second near the center of the pond, and the third near the pond outlet. Samples were collected from an aluminum Jon boat using the plastic sampling tubes attached to the PVC extension by a screw coupling. The boat was rowed to the proper position in the pond and anchored in place. The sampling tube was thrust into the pond and forced through the sludge into the clay bottom. The sampling apparatus was rocked slightly to shear the clay bottom and then was brought to the surface. By this sampling manner there was about a 50 percent chance that the clay plug would retain the sludge sample and pond supernatant in the tube. The sampling tube was unscrewed and the sludge directly placed in the reaction chamber, or held inside the tube by sealing both ends with plastic film and rubber bands, and returned to the laboratory. Some of the sludge returned to the laboratory was used for the physical, chemical, and biological analyses to determine the sludge characteristics.

2. Studies of Oxygen Consumption

Sludge was added to the reaction chamber in the field to a depth of slightly over four inches. The chamber was allowed to stand over night in the laboratory at a temperature at which the study would be conducted. The next day, any supernatant present was siphoned off and the sludge depth was adjusted to four inches. The unseeded BOD dilution water, which was prepared according to Standard Methods (22) and brought to the test temperature, was used as the sludge supernatant.

The oxygen consumption for each sludge sample was conducted at three different temperature levels, 35, 22, and 10 degrees centigrade. These three temperatures signify respectively the average temperature in hot, moderate, and cool seasons. The rigid temperature controls at 10 and 35 degrees centigrade were achieved by conducting the tests in the walk-in incubators, while the control at 22 degrees centigrade was accomplished by performing the tests in an air conditioned laboratory where the temperature was maintained at 22 degrees centigrade with a fluctuation of less than two degrees.

The evaluation of oxygen consumption for each sludge sample at each temperature level was conducted in three separate steps designated as Stages A, B, and C. Stage A was performed to determine the overall oxygen uptake exerted by both the sludge phase and the supernatant which had suspended solids churned up by the mixing process. Stage B was performed to measure the oxygen utilization by only the supernatant which still contained the churned-up materials. Comparing the data obtained from Stages A and B, the extent of the oxygen uptake by the sludge phase alone could be estimated. Stage C was to determine the oxygen consumption by the settled supernatant, so that the oxygen uptake by the dissolved organic material could be distinguished from the suspended organic material. The detailed procedures for tests of the above three stages are described below.

2.1. Stage A - Oxygen Consumption by Sludge Plus Supernatant

Stage A was conducted in the reaction chamber which was filled with four inches of sludge. To prepare for the test, the lid of the chamber was first removed from the chamber and a rubber gasket was placed under the lid. A magnetic stirring bar was held against the bottom side of the gasket by placing a horseshoe magnet on the lid. The lid was then carefully placed on the chamber and tightened with wing nuts. The magnet was then attached to the chuck of the mixer through a metal rod, which had been previously fixed to the magnet. Care was taken not to allow the mixing bar to fall into the sludge. The mixer was carefully positioned so that the magnet was suspended about one-fourth inch above the lid. Aerated BOD dilution water was siphoned into the chamber through the oxygen probe hole and allowed to run down the side of the chamber in order to minimize the disturbance of the sludge. When the chamber was filled, it was rocked slightly to allow any entrapped air to escape through the oxygen probe hole. The chamber was then refilled until a slight overflow occurred. The oxygen probe was inserted tightly into the hole in the lid of the chamber. During the tests the chamber was wrapped with aluminum foil to exclude light, and the magnetic stirrer was adjusted to a speed between 100 and 120 revolutions per minute, which was the lowest speed the stirrer could maintain a constant speed without any erratic rotation. However, at this speed considerable solids were suspended. If the size of the mixing bar was reduced from 2-3/4 inches long and 1/2 inch diameter to 1-1/2 inches long and 1/2 inch diameter the amount of solids suspended could be reduced. The readout of the oxygen level in the chamber was continuously recorded by the recorder. The test was allowed to continue until all the dissolved oxygen was utilized. After that, the oxygen probe was removed while the mixing was allowed to continue, and then about 400 ml of the supernatant was siphoned off for the test of Stage B.

2.2. Stage B - Oxygen Consumption by Supernatant Only

The purpose of Stage B was to distinguish the oxygen utilization of the organic material in the supernatant apart from the benthal sludge. After the supernatant was siphoned off at the conclusion of the Stage A test it was aerated to re-saturate with oxygen and then placed in a 300 ml BOD bottle which had a small magnetic mixing bar on the bottom. The oxygen probe was inserted into the bottle, which was then wrapped with aluminum foil and placed on a ring stand and the mixing apparatus used in the Stage A test was inverted and placed about one-half inch below the bottle as shown in Figure 4-8. During each test the mixing speed was adjusted to 100 to 120 revolutions per minute, which was the same as that used in Stage A. The oxygen meter and recorder were turned on and the study was allowed to continue until all the dissolved oxygen had been utilized.

2.3. Stage C - Oxygen Consumption by Settled Supernatant Only

After the Stage B test had been concluded, the supernatant was allowed to settle for at least an hour, usually over night. This supernatant was then carefully siphoned off, aerated, and then used in the Stage C test. The purpose of Stage C was to distinguish the oxygen utilization of the dissolved organic matter apart from the suspended organic matter. The aerated supernatant was placed in a 300 ml BOD bottle and the procedure described for Stage B was followed.

Chemical characteristics including COD, solids concentration, alkalinity and pH of the supernatant were evaluated; supernatants from tests of Stages A, B, and C were collected, acidified to pH 2 to inhibit the bacterial activity and stored in a refrigerator until COD determinations were performed. Stages A and B were assumed to have the same suspended solids content in the supernatant, therefore, only samples from Stages A and C were collected for the suspended solids analysis. Samples from Stage C were also used for pH and alkalinity determinations. All determinations were performed according to Standard Methods (22) and Sawyer and

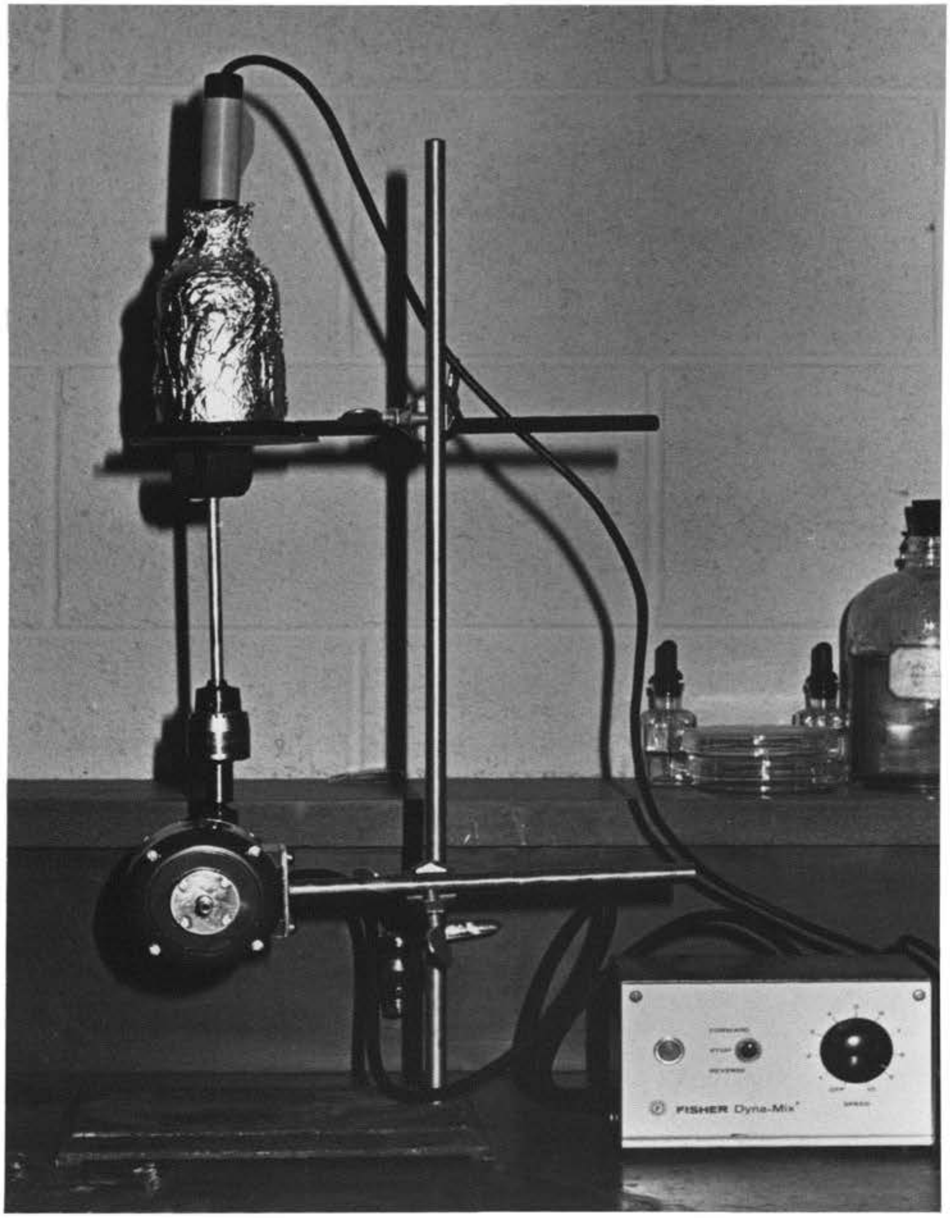

Figure 4-8

Experimental Arrangement Used in the Stage B Test of the Oxygen Consumption Studies

McCarty (23). For the evaluation of oxygen consumption and chemical characteristics of each sample, two tests were performed for each experimental condition.

3. Evaluation of the Initial Oxygen Tension on Oxygen Consumption

In order to determine if the initial oxygen tension had any effect on the rate of oxygen uptake, a series of tests were performed. The reaction chamber with four inches of sludge was filled with BOD dilution water and all the dissolved oxygen was allowed to be utilized. About one-half of the supernatant was siphoned off and aerated. This supernatant was returned to the reaction chamber and the test was continued following the procedure as described in the aforementioned Stage A test of the oxygen consumption study. When all the dissolved oxygen was utilized, about one-third of the supernatant was siphoned off and the test repeated. Finally, about one-sixth of the supernatant was siphoned off and the test was again repeated. This study was conducted at two temperature levels, 22 and 35 degrees centigrade.

4. Evaluation of the Sludge Compaction on Oxygen Consumption

A study was also conducted to determine if the compaction of the sludge had any effect on the rate of oxygen utilization. For each test, the reaction chamber containing four inches of freshly stirred sludge was filled with BOD dilution water and allowed to settle for one, three, and nine days respectively in order to give different degrees of sludge compaction. During each test, in order to minimize the sludge disturbance, only about one-half of the supernatant was siphoned off and aerated. This supernatant was carefully returned to the reaction chamber and the test was conducted following the same procedure as described in the Stage A test of the oxygen utilization study. This study was only conducted at one temperature level, 22 degrees centigrade.

5. Physical, Chemical, and Biological Examination of the Benthal Sludge

Some of the sludge samples brought back to the laboratory were examined for the physical, chemical and biological characteristics. Physical examination of the sludge disclosed that the lagoon sludge was a gelatinous black slurry having a musty odor, some particles were distinctly visible particularly in the sludge obtained near the inlet. Sludge obtained near the outlet was more gelatinous in nature and had fewer visible particles. The solids content of the sludge ranged from 45,000 to 50,000 mg/l total solids, of which about 35 to 45 percent were volatile. The COD of the sludge averaged about 500 mg per gram of solids. The sludge was also examined under the microscope to determine if there was any presence of protozoa or other higher macroorganisms such as rotifers, crustacean and worms; yet none were found which might probably indicate a very thin or no aerobic layer existing in the sludge.

6. Microscopic Examination of the Lagoon Supernatant

Samples of the lagoon supernatant were often brought back to the laboratory throughout the project for microscopic examination to determine the predominant types of algae. In most cases direct microscopic examination was suitable; however, when the algal population was very low the sample had to be centrifuged to concentrate the algal population. During the microscopic examination photographs were taken and notes were made to record the predominant algal forms.

V. RESULTS

A. Oxygen Consumption Curves

The oxygen consumption curves recorded on the chart paper were converted to a series of graphs showing the actual oxygen uptake rates. For this purpose, a sufficient number of points on the original chart paper were selected and the recorded data were adjusted to the actual oxygen values by properly applying the correction constants which were obtained from the calibration against the Azide Modification of the Iodometric Method for the oxygen determination (22). The time scale on the graphs were properly adjusted so that each oxygen consumption curve could be fitted into a standard size graph of five by seven inches.

To facilitate a meaningful evaluation of the many sets of oxygen consumption curves obtained in this research program, the results will be presented according to the scheme shown in Figure 5-1, although the actual testing was performed according to the sequence shown in Figure 5-2. Two experimental runs were conducted for each test with the same sludge, yet, attempts were made to induce different concentrations of suspended solids in the test supernatants of the two runs so that the effect of suspended solids may be determined. In addition to the presentation of the oxygen consumption curve for each test, a summary graph was also prepared for each sludge sample tested at each temperature level to show the relative oxygen consumption rates among the following three test systems: sludge with supernatant (Stage A test), unsettled supernatant only (Stage B test), and settled supernatant only (Stage C test).

Inlet Sludge Systems Tested at	$10^\circ C$	Sludge with Supernatant
		Unsettled Supernatant only
		Settled Supernatant only
	$22^\circ C$	Sludge with Supernatant
		Unsettled Supernatant only
		Settled Supernatant only
	$35^\circ C$	Sludge with Supernatant
		Unsettled Supernatant only
		Settled Supernatant only
Center Sludge Systems Tested at	$10^\circ C$	Sludge with Supernatant
		Unsettled Supernatant only
		Settled Supernatant only
	$22^\circ C$	Sludge with Supernatant
		Unsettled Supernatant only
		Settled Supernatant only
	$35^\circ C$	Sludge with Supernatant
		Unsettled Supernatant only
		Settled Supernatant only
Outlet Sludge Systems Tested at	$10^\circ C$	Sludge with Supernatant
		Unsettled Supernatant only
		Settled Supernatant only
	$22^\circ C$	Sludge with Supernatant
		Unsettled Supernatant only
		Settled Supernatant only
	$35^\circ C$	Sludge with Supernatant
		Unsettled Supernatant only
		Settled Supernatant only

Figure 5-1

Schematic Diagram Showing

Sequence of Presentation of Oxygen Consumption Curves

Center Sludge Systems Tested at	10°C	Sludge with Supernatant Unsettled Supernatant only Settled Supernatant only
	22°C	Sludge with Supernatant Unsettled Supernatant only Settled Supernatant only
	35°C	Sludge with Supernatant Unsettled Supernatant only Settled Supernatant only
Inlet Sludge Systems Tested at	35°C	Sludge with Supernatant Unsettled Supernatant only Settled Supernatant only
	22°C	Sludge with Supernatant Unsettled Supernatant only Settled Supernatant only
	10°C	Sludge with Supernatant Unsettled Supernatant only Settled Supernatant
Outlet Sludge Systems Tested at	10°C	Sludge with Supernatant Unsettled Supernatant only Settled Supernatant only
	35°C	Sludge with Supernatant Unsettled Supernatant only Settled Supernatant only
	22°C	Sludge with Supernatant Unsettled Supernatant only Settled Supernatant only

Figure 5-2

Schematic Diagram Showing

Sequence of Testing of the Oxygen Consumption Studies

As will be seen in the following oxygen consumption curves, some of them showed an unusually great initial oxygen uptake which was probably caused by an immediate chemical demand present in the test system, others showed an initial lag in the oxygen utilization, probably because of the period of bacterial acclimation. Some of the curves also showed a gradual decrease in the oxygen demand when the dissolved oxygen in the test chamber was gradually depleted. In calculating the average oxygen uptake rate for each system a most representative straight line portion on the curve was selected so that all of the above erratic effects could be eliminated.

The average oxygen uptake rate can be expressed, depending on the type of test, as milligrams of O_2 uptake per liter of supernatant per minute (mg/l/min) or as milligrams of O_2 uptake per minute per square meter of sludge (mg/min/m^2) for those tests which involved a sludge phase. The uptake data for all tests can be expressed as mg/l/min regardless if sludge was involved in the system or not. If sludge is used in the test, then the results can also be expressed as mg/min/m^2 by multiplying the oxygen uptake in mg/l/min by the supernatant volume in liters, and then the product being divided by the area of the sludge in square meters to give mg/min/m^2.

1. Oxygen Consumption by the Inlet Sludge Systems Tested at 10°C

The data of the first experimental run of oxygen consumption by the inlet sludge systems at a test temperature of 10 degrees centigrade are presented in Figures 5-3, 5-4, and 5-5 and those of the second experimental run are in Figures 5-6, 5-7, and 5-8. The average or representative oxygen uptake rate for each curve

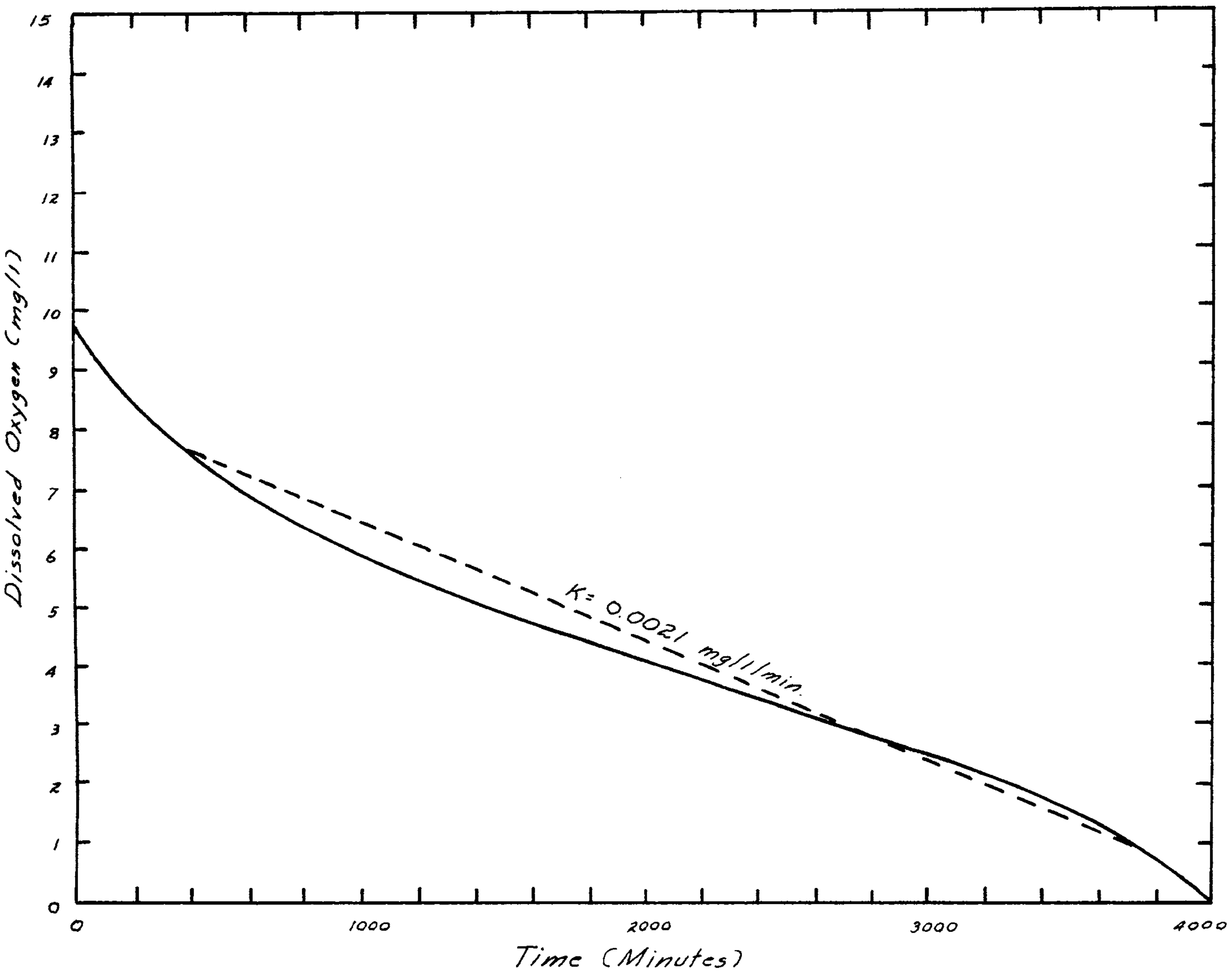

Figure 5-3

Oxygen Consumption by Inlet Sludge at 10°C - Sludge with Supernatant (Run #1)

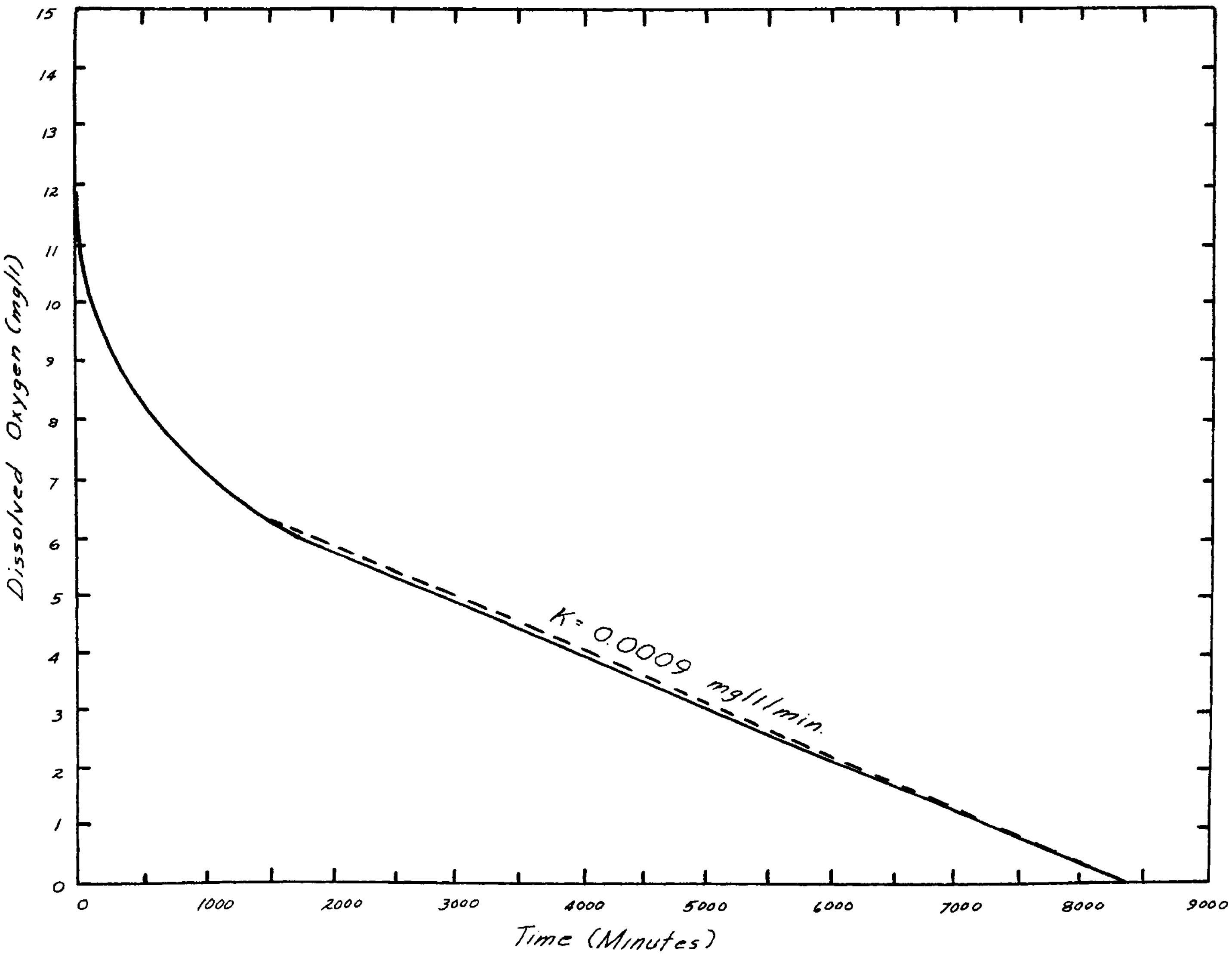

Figure 5-4

Oxygen Consumption by Inlet Sludge at 10°C - Unsettled Supernatant Only (Run #1)

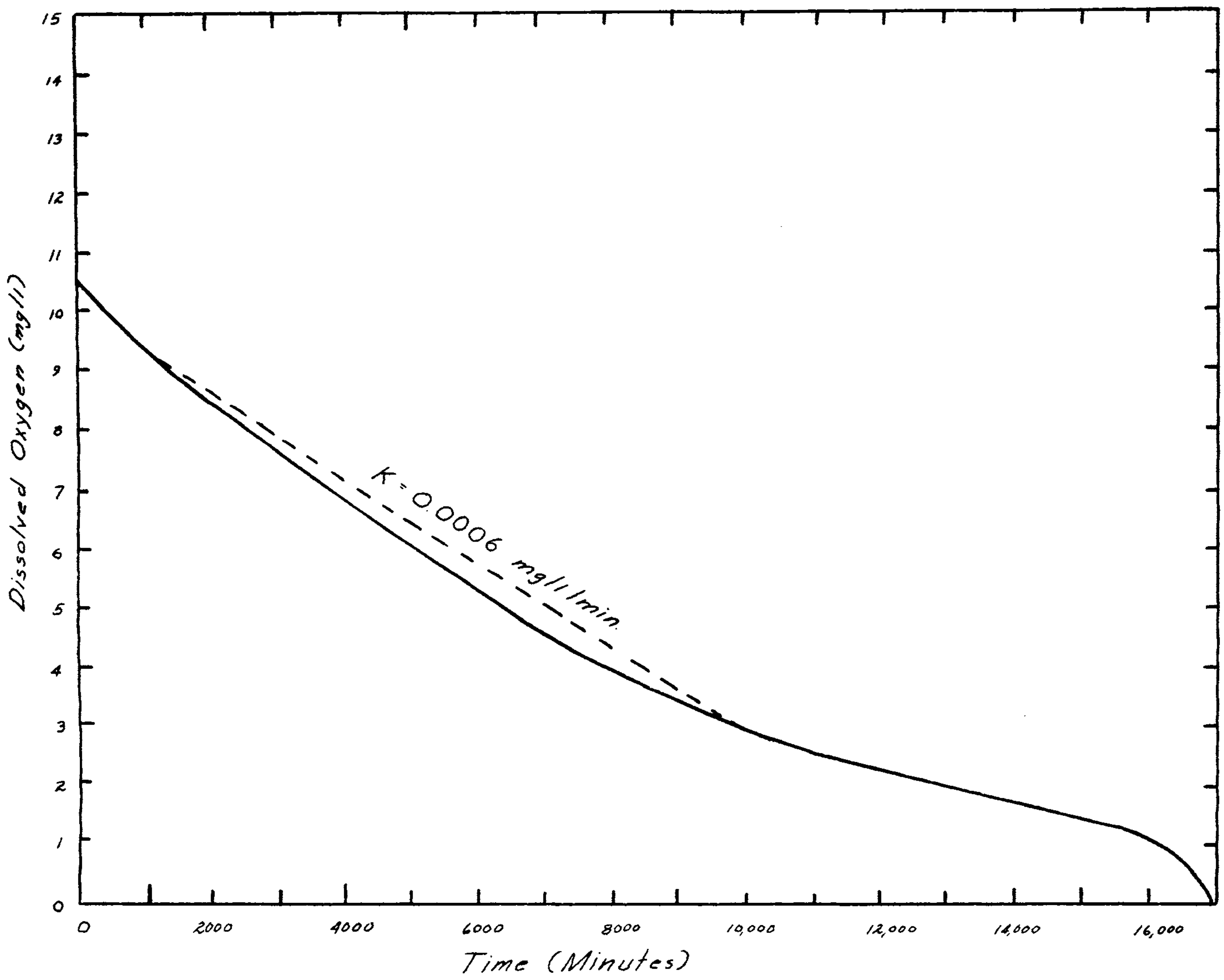

Figure 5-5

Oxygen Consumption by Inlet Sludge at 10°C - Settled Supernatant Only (Run #1)

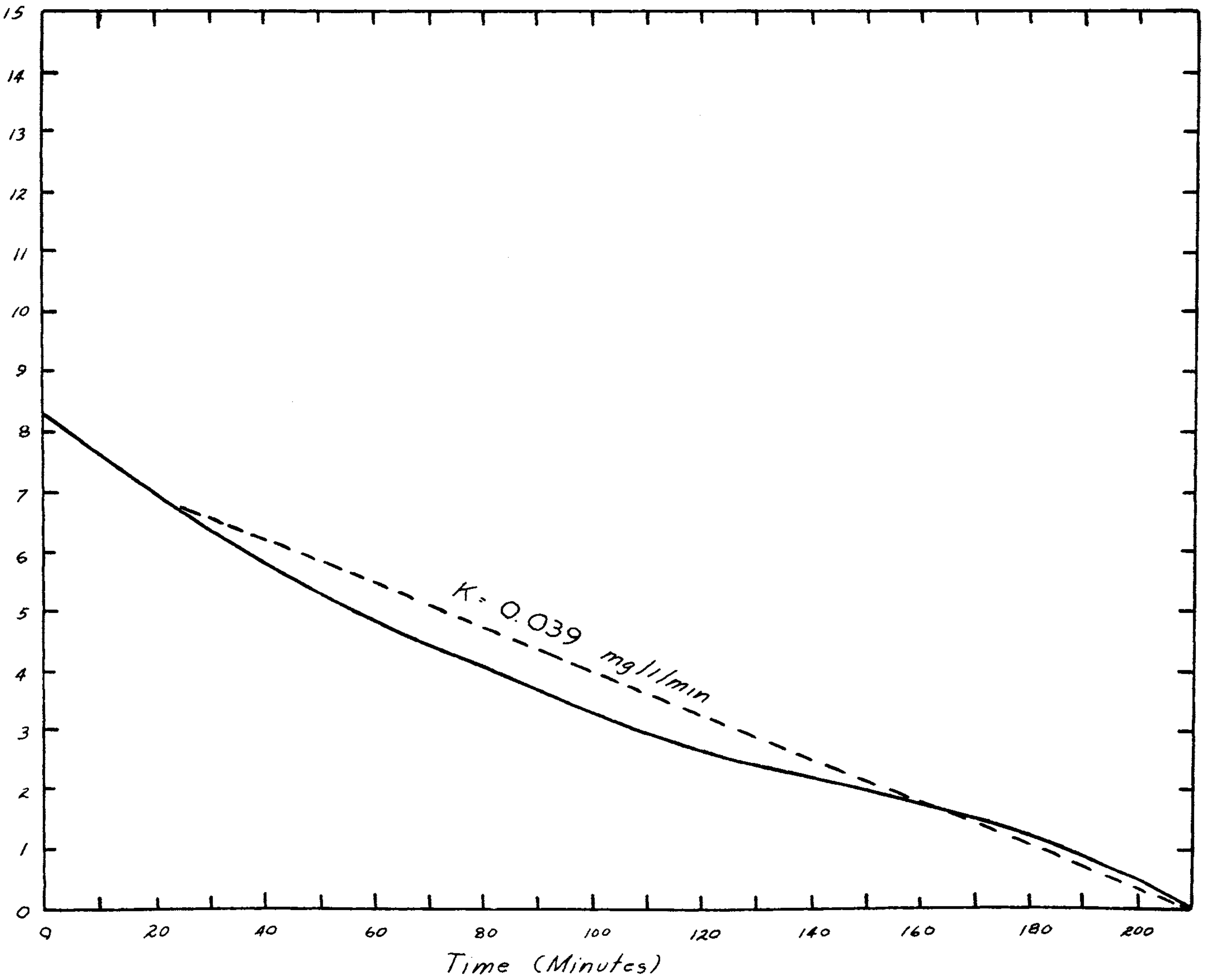

Figure 5-6

Oxygen Consumption by Inlet Sludge at 10°C - Sludge with Supernatant (Run #2)

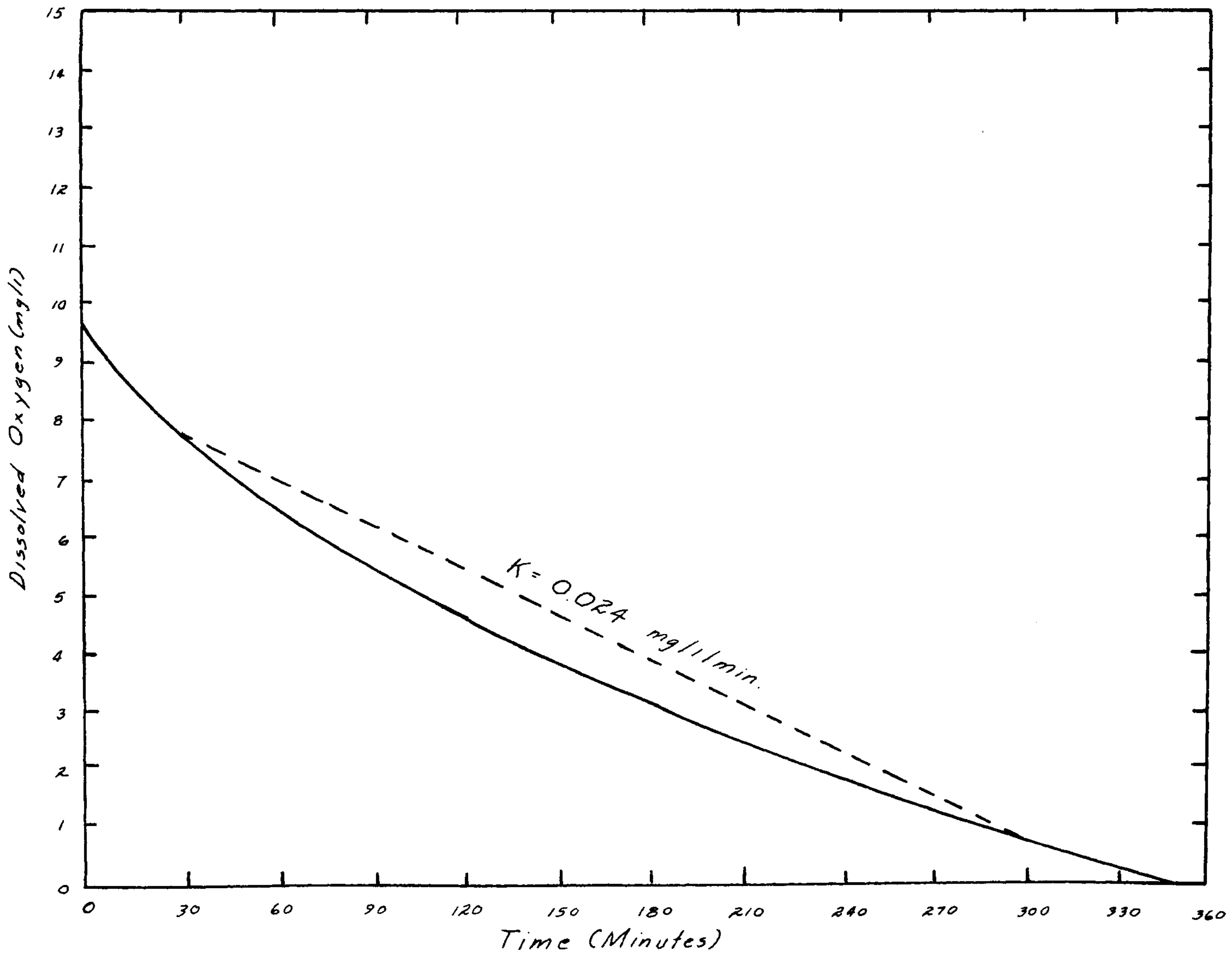

Figure 5-7

Oxygen Consumption by Inlet Sludge at 10°C - Unsettled Supernatant Only (Run #2)

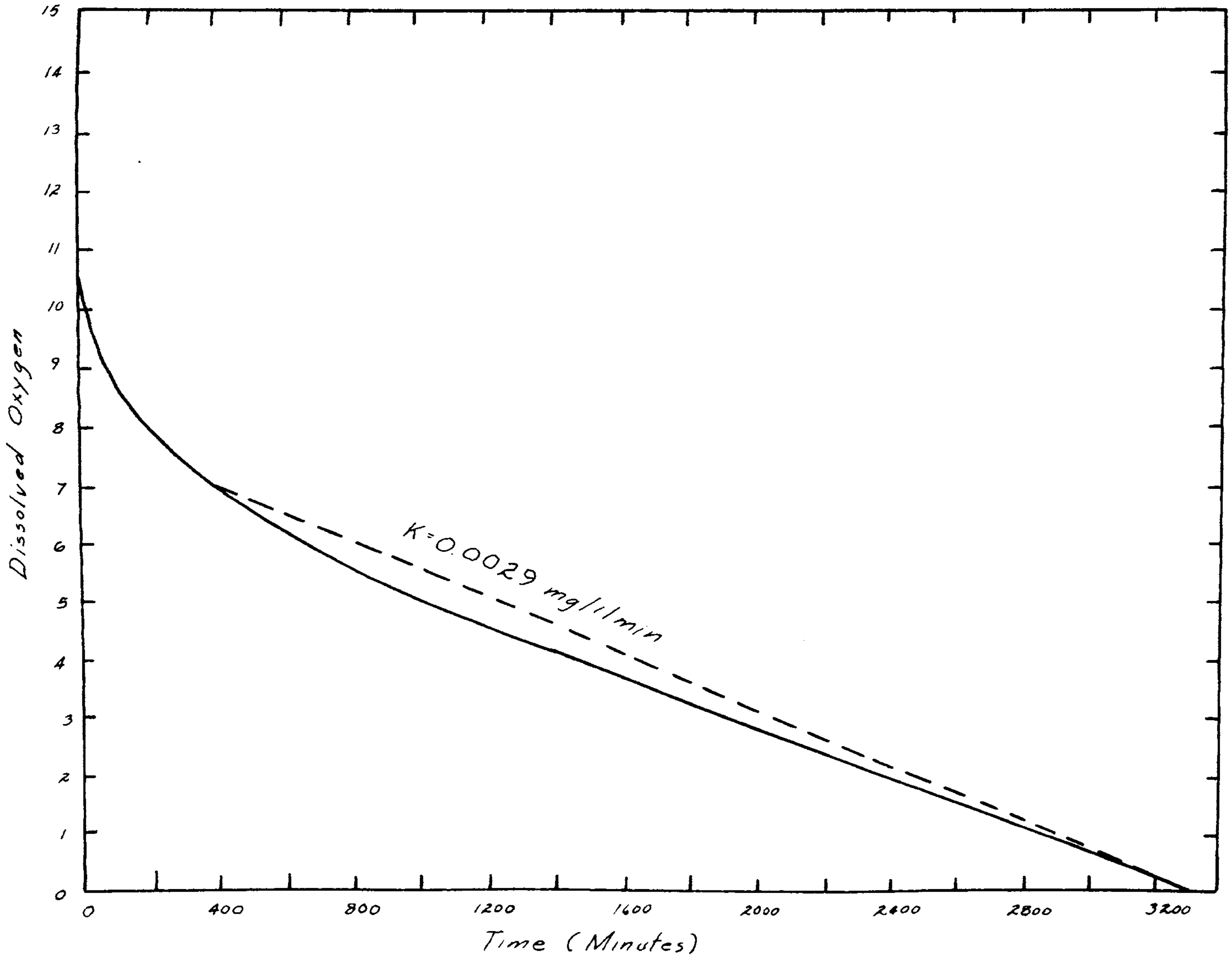

Figure 5-8

Oxygen Consumption by Inlet Sludge at 10°C - Settled Supernatant Only (Run #2)

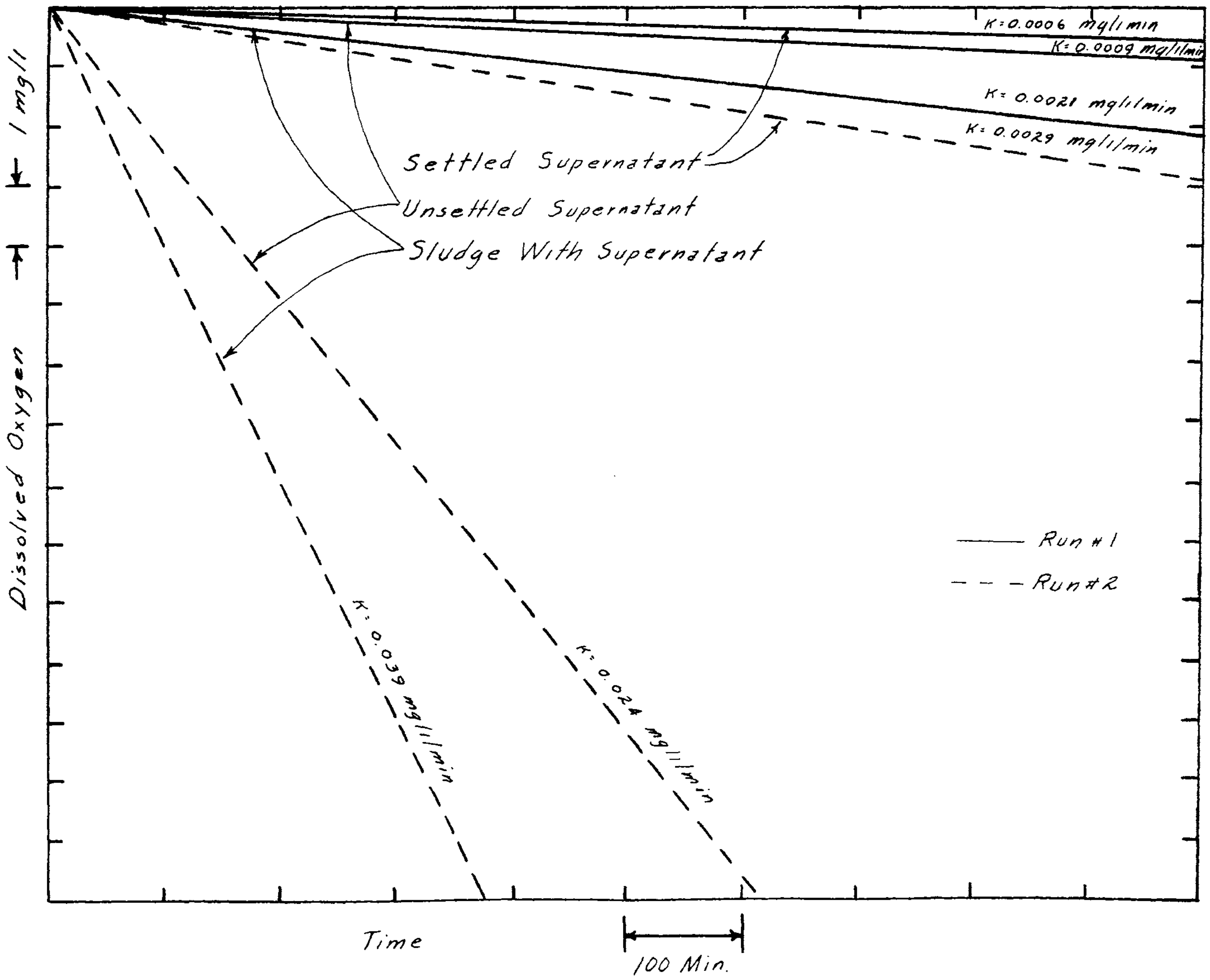

Figure 5-9

Relative Oxygen Consumption Rates of Inlet Sludge Systems at 10°C

is shown by a straight broken line. The slope of the broken line is the rate value designated by K, which has a unit of mg/l/min.

Figure 5-9 summarizes the relative oxygen consumption rates of the inlet sludge systems at 10 degrees centigrade obtained from the two experimental runs. As shown in this figure, the oxygen uptake rates observed in the first experimental run of the three test systems, that is, sludge with supernatant, unsettled sludge only, and settled sludge only, are 0.0021, 0.0009, and 0.0006 mg/l/min, respectively; the uptake rates for the corresponding systems in the second experimental run are 0.039, 0.024, and 0.0029 mg/l/min. It becomes apparent that the uptake rates obtained in the first experimental run are smaller than those obtained in the corresponding systems of the second experimental run. This type of inconsistency of the oxygen uptake rates between the two different experimental runs with the same sludge sample at the same test temperature will also be found in many of the following oxygen consumption data obtained from other test systems. The non-reproducibility of the data between the two experimental runs has been anticipated since during the experimental study it was intended to vary the mixing condition to a certain extent in order to induce different concentrations of suspended solids in the supernatant, so that the effect of suspended solids on the oxygen uptake may be evaluated. A summary account on the relationship among the supernatant chemical oxygen demand (COD), suspended solids and the oxygen uptake rate will be discussed in Section B of this chapter and the next chapter of Discussions.

2. Oxygen Consumption by the Inlet Sludge Systems Tested at 22°C

The oxygen consumption curves of the two experimental runs conducted for the inlet sludge systems at 22 degrees centigrade are presented in Figures 5-10 through 5-15. It must be pointed out here that the inlet sludge sample employed in these tests were the same as the one used in the 10 degrees centigrade test systems.

The relative oxygen uptake rates of each test system obtained from the two experimental runs are also compared in Figure 5-16. Again, there is little consistency in the uptake rates observed in the two independent experimental runs. Both the settled supernatant and the sludge with supernatant systems had an uptake rate value in the first experimental run about three times as much as that observed in the second experimental run. However, in the unsettled supernatant system, the first run had a consumption rate of about 1.34 times as much as the second experimental run.

3. Oxygen Consumption by the Inlet Sludge Systems Tested at 35°C

Figures 5-17 through 5-22 present the oxygen consumption data obtained in the inlet sludge systems tested at 35 degrees centigrade. It is interesting to note that in the first and second experimental runs of the sludge with supernatant system (Figures 5-17 and 5-19) the dissolved oxygen in the test chamber was completely depleted from an original 4 mg/l within a test period of 3.5 and 1.0 minutes, respectively. At the temperature of 35 degrees centigrade the sludge was observed to be rather uncohesive. The uncohesive nature of the sludge allowed the mixing action to suspend from the sludge phase a significant amount of solids, which coupled with a high bacterial activity at this elevated temperature may

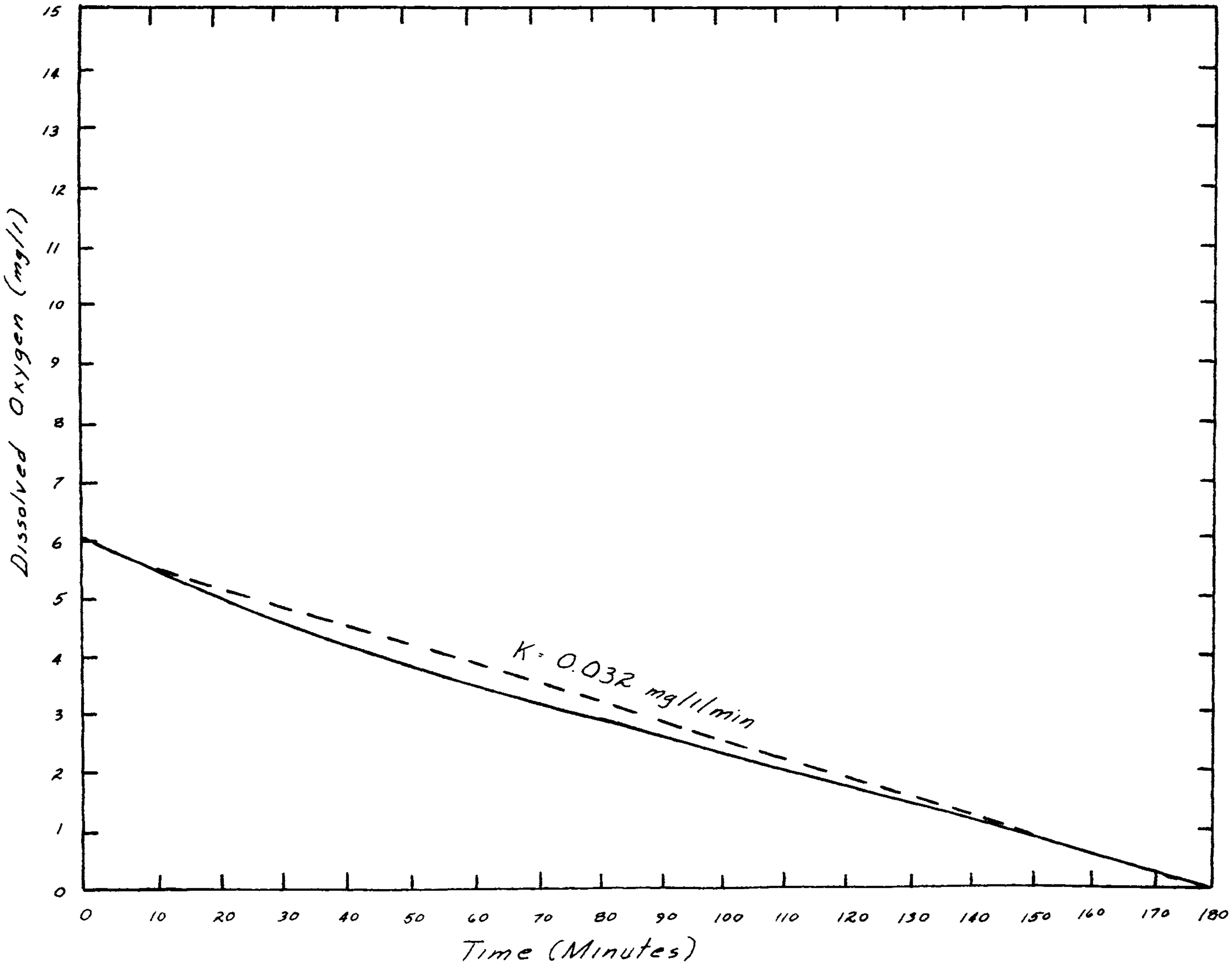

Figure 5-10

Oxygen Consumption by Inlet Sludge at 22°C - Sludge with Supernatant (Run #1)

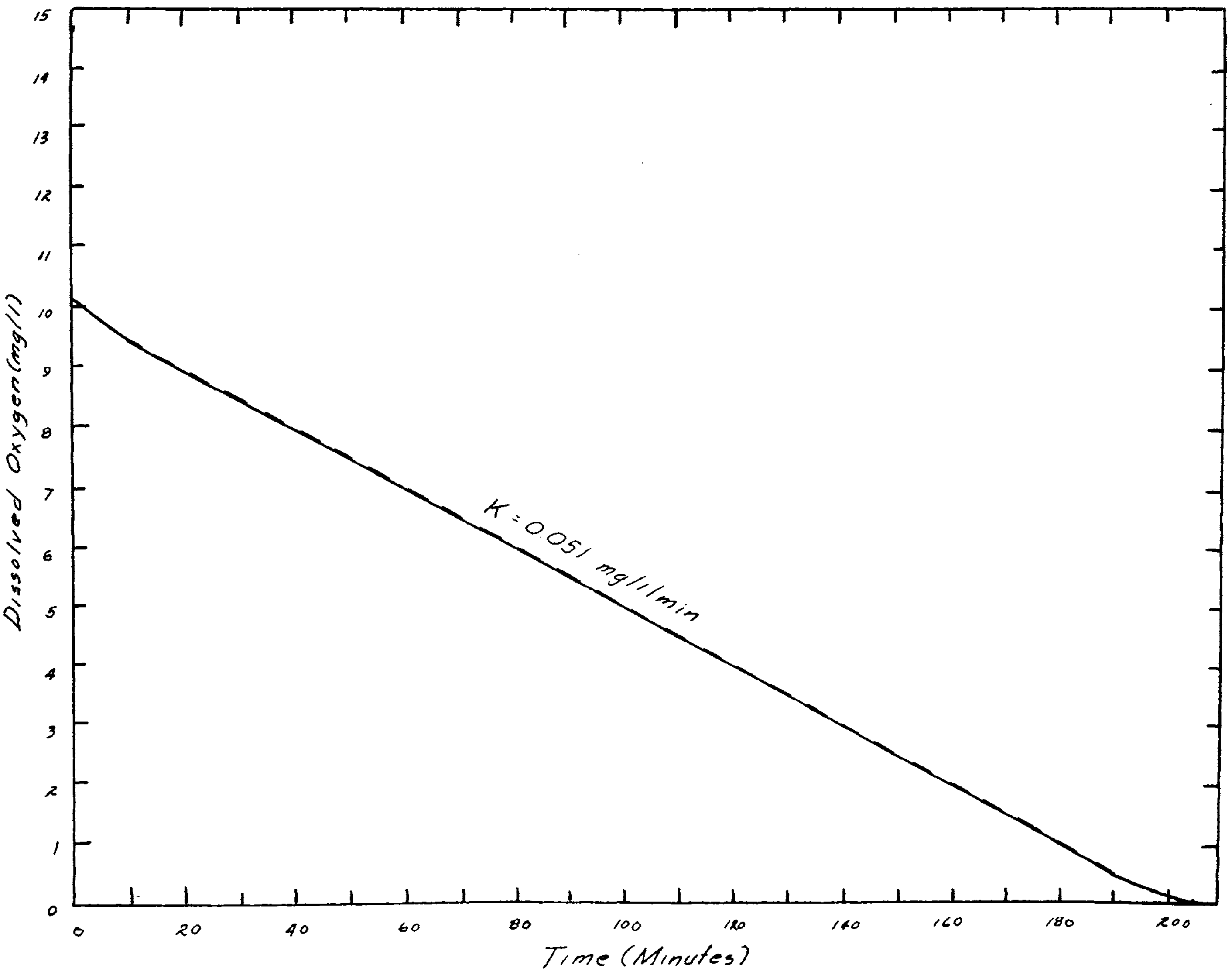

Figure 5-11

Oxygen Consumption by Inlet Sludge at 22°C - Unsettled Supernatant Only (Run #1)

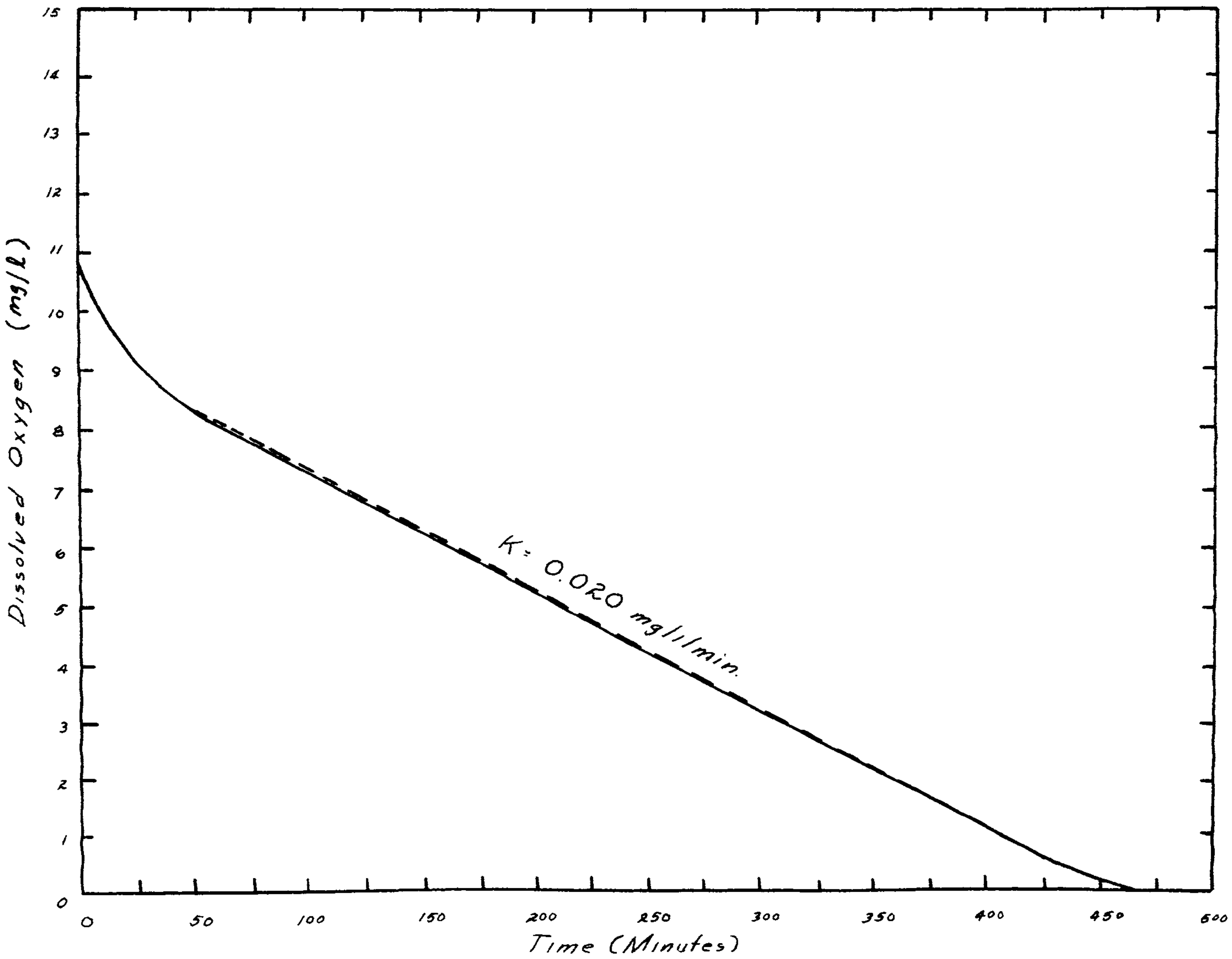

Figure 5-12

Oxygen Consumption by Inlet Sludge at 22°C - Settled Supernatant Only (Run #1)

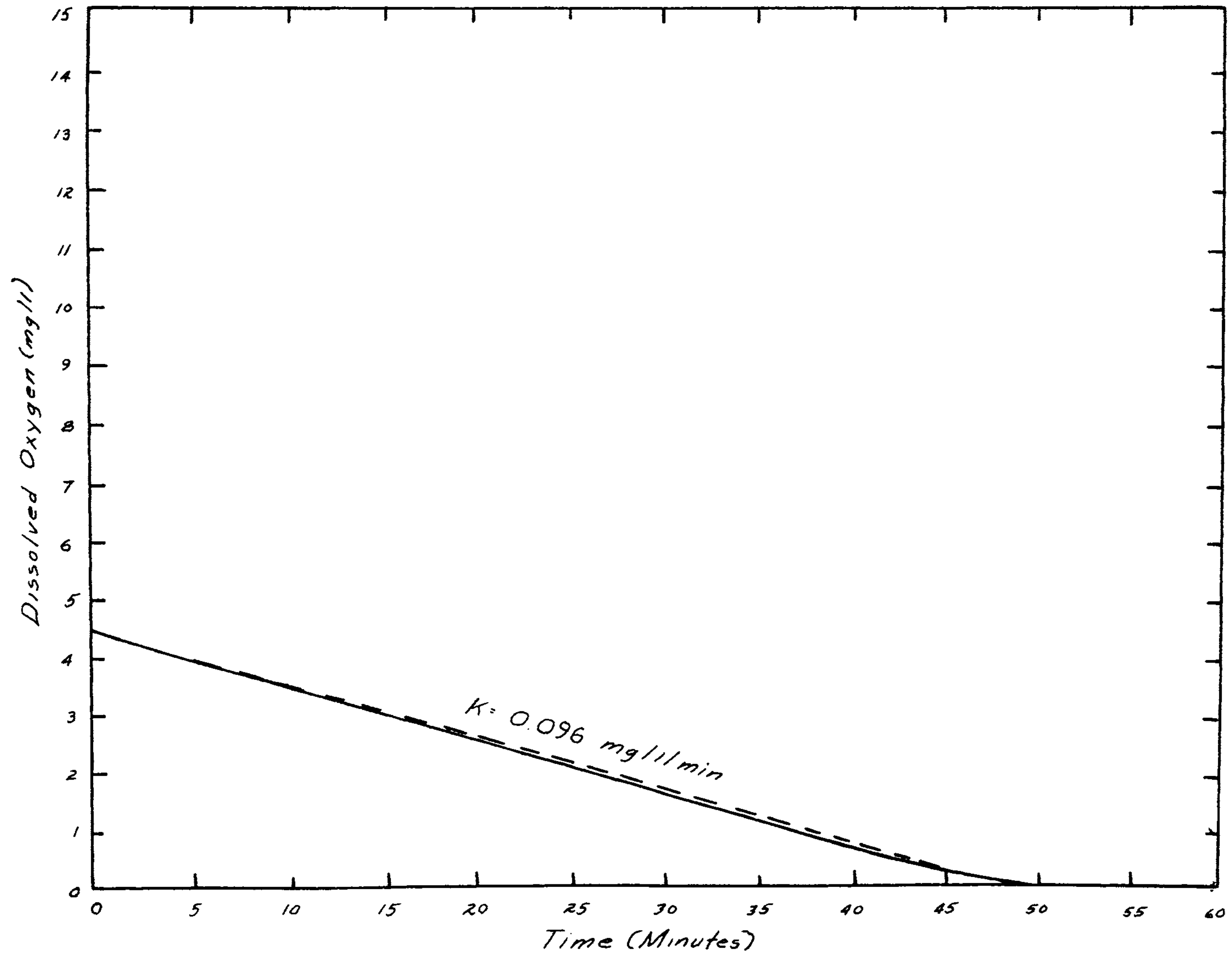

Figure 5-13

Oxygen Consumption by Inlet Sludge at 22°C - Sludge with Supernatant (Run #2)

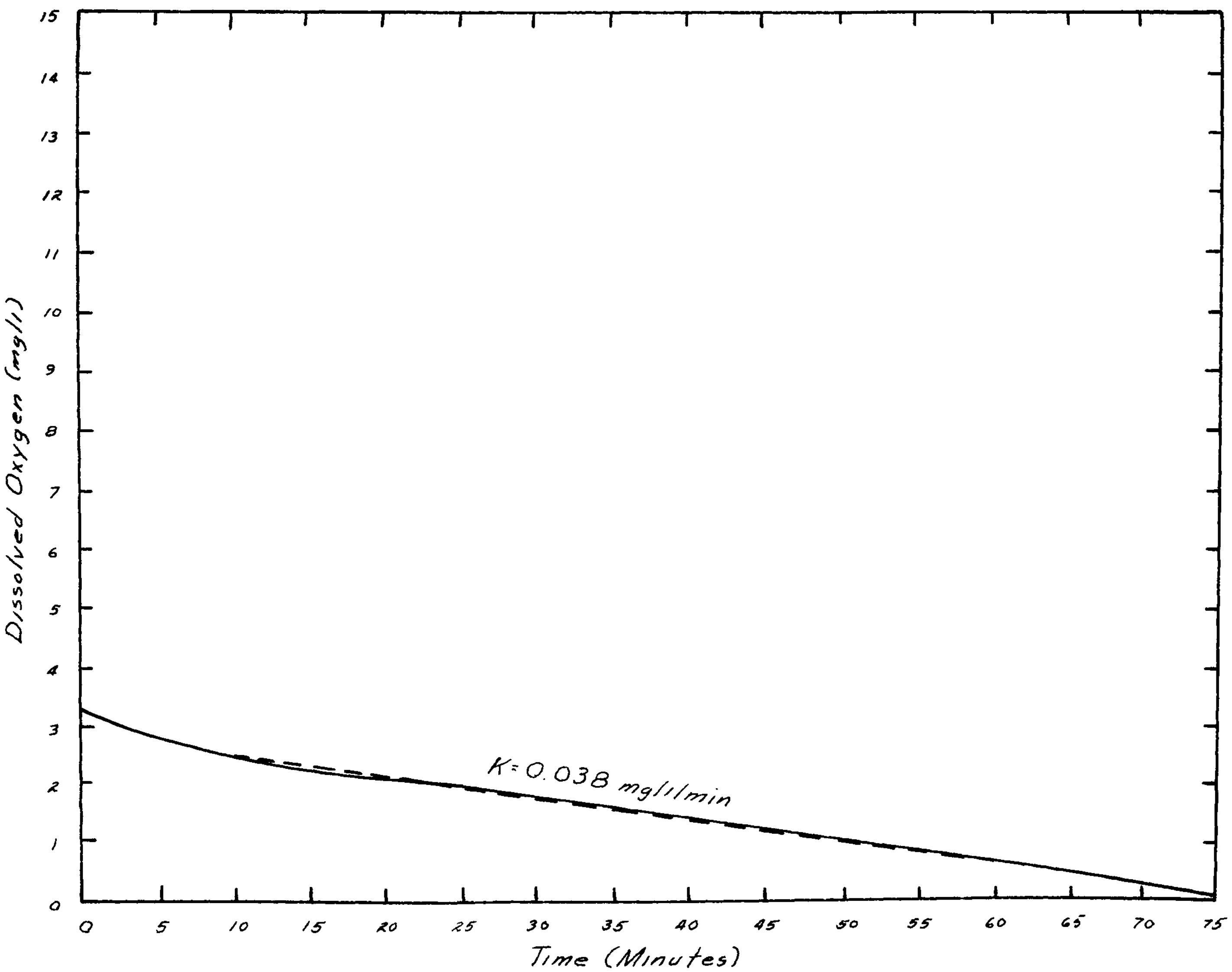

Figure 5-14

Oxygen Consumption by Inlet Sludge at 22°C - Unsettled Supernatant Only (Run #2)

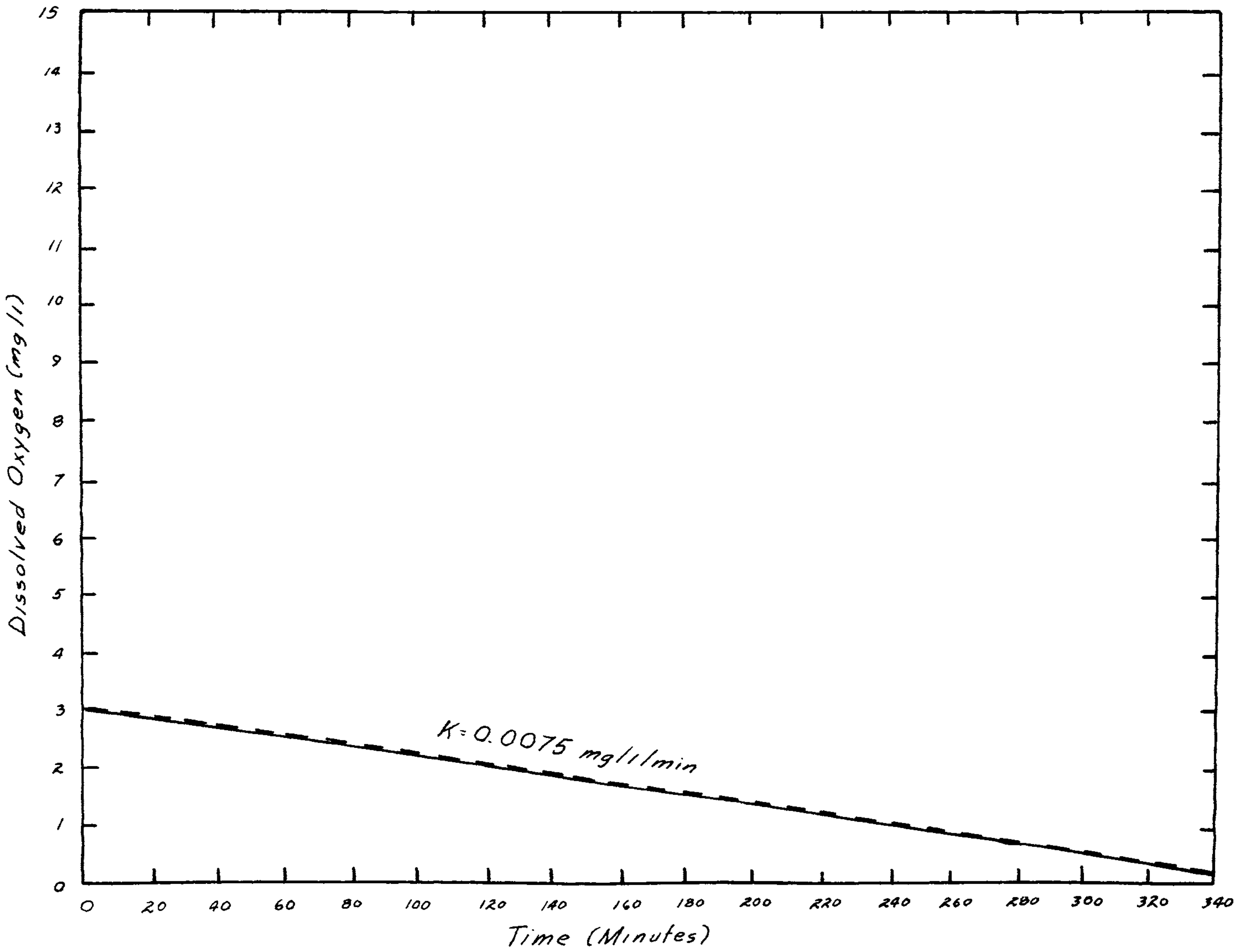

Figure 5-15

Oxygen Consumption by Inlet Sludge at 22°C - Settled Supernatant Only (Run #2)

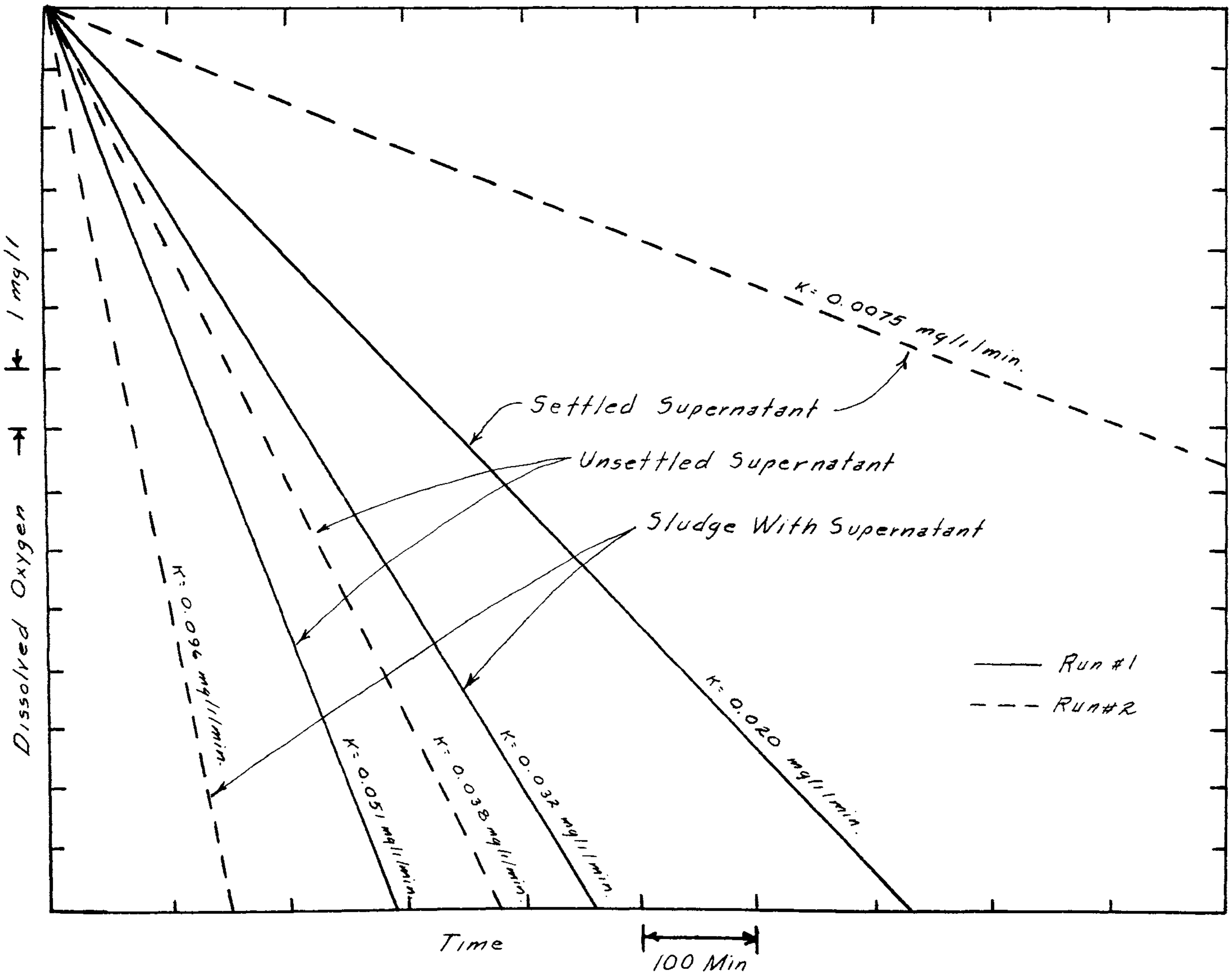

Figure 5-16

Relative Oxygen Consumption Rates of Inlet Sludge Systems at 22°C

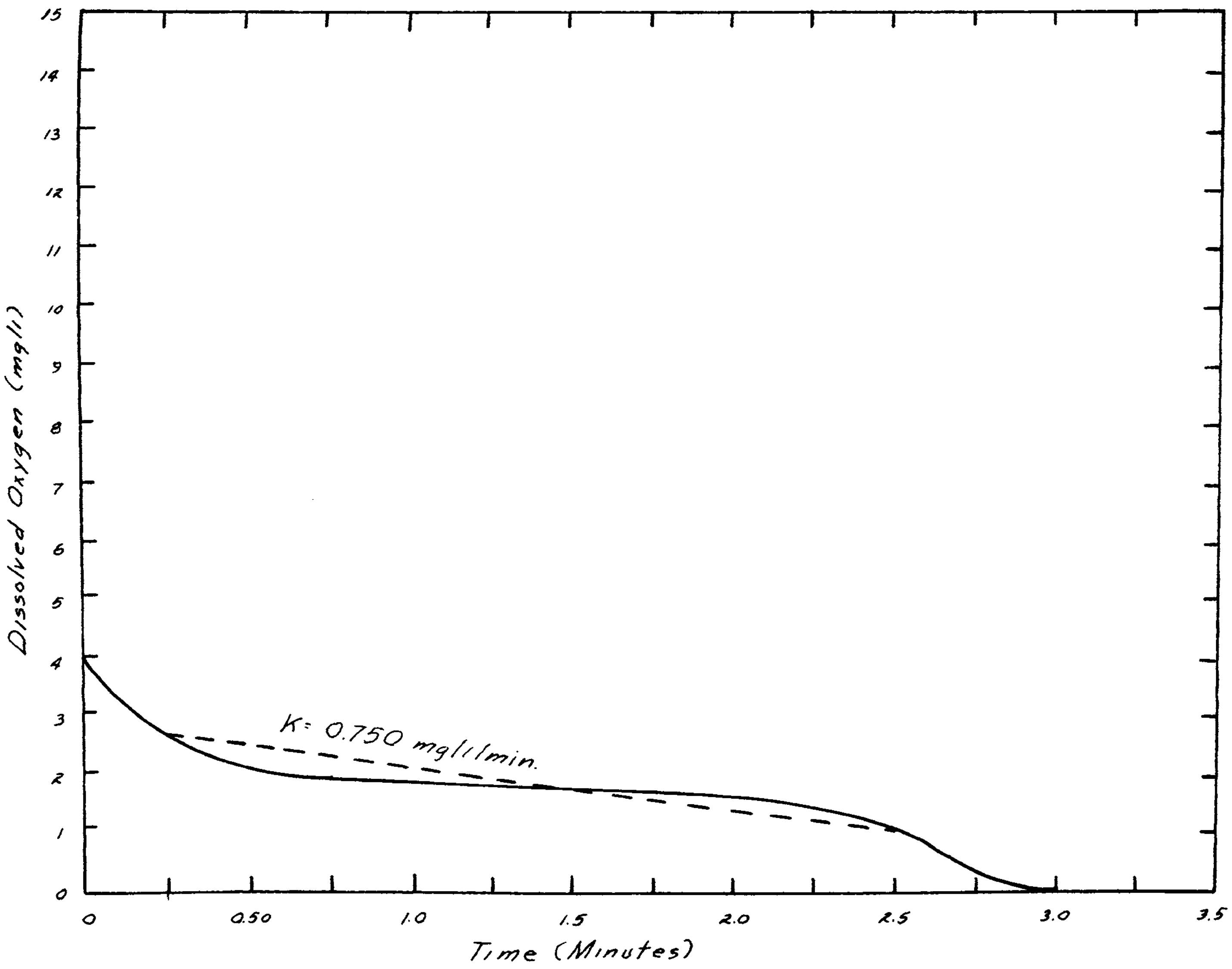

Figure 5-17

Oxygen Consumption by Inlet Sludge at 35°C - Sludge with Supernatant (Run #1)

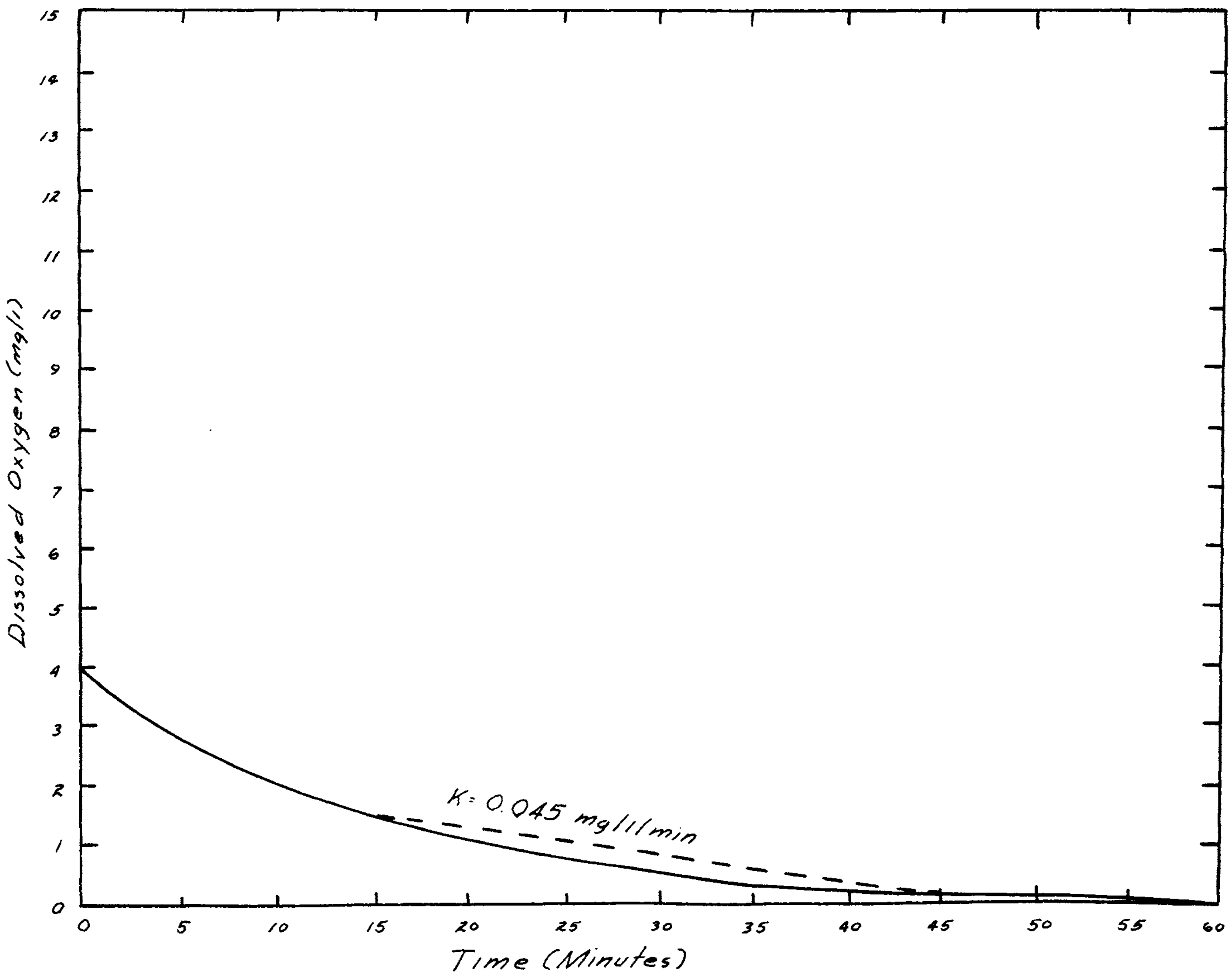

Figure 5-18

Oxygen Consumption by Inlet Sludge at 35°C - Unsettled Supernatant Only (Run #1)

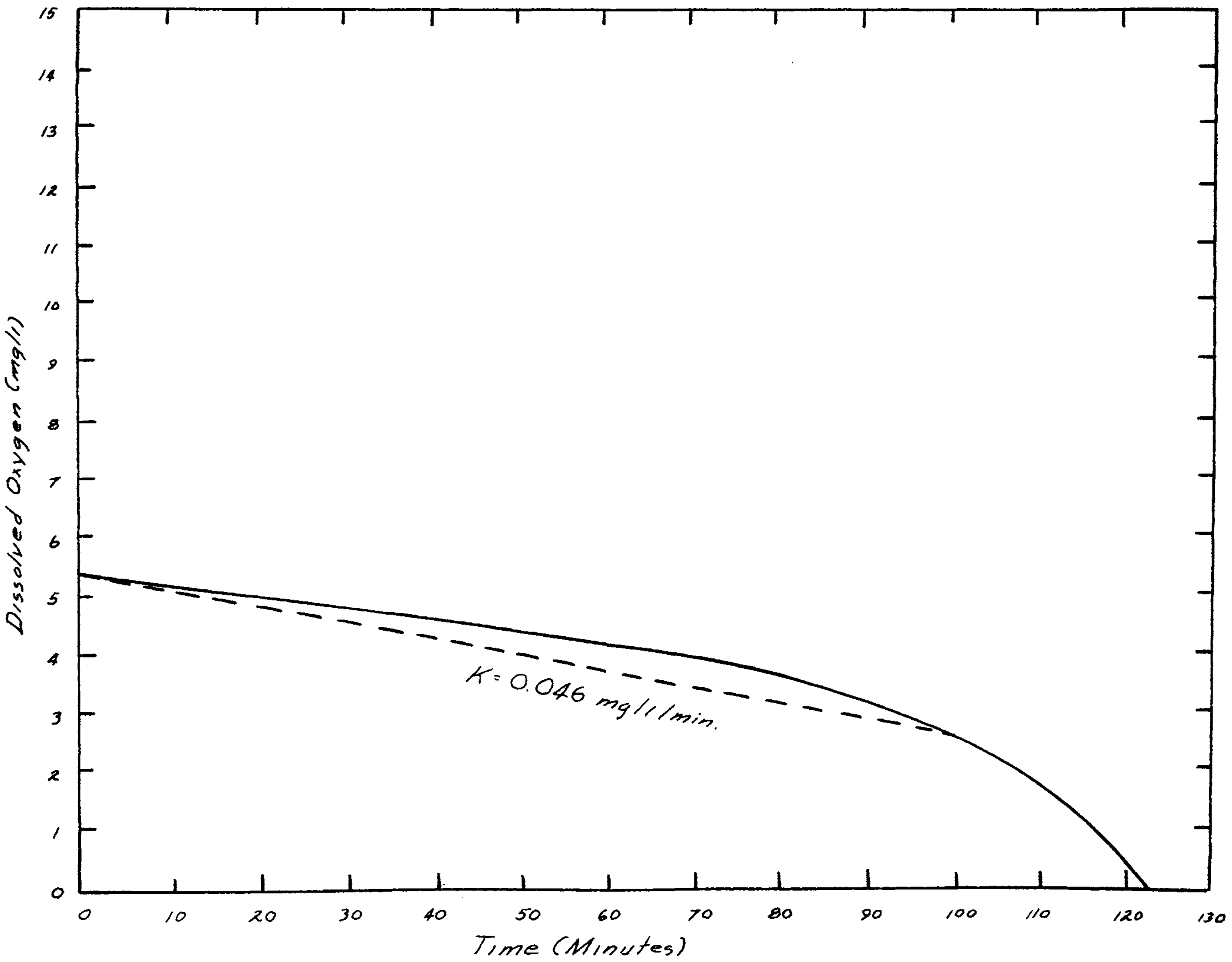

Figure 5-19

Oxygen Consumption by Inlet Sludge at 35°C - Settled Supernatant Only (Run #1)

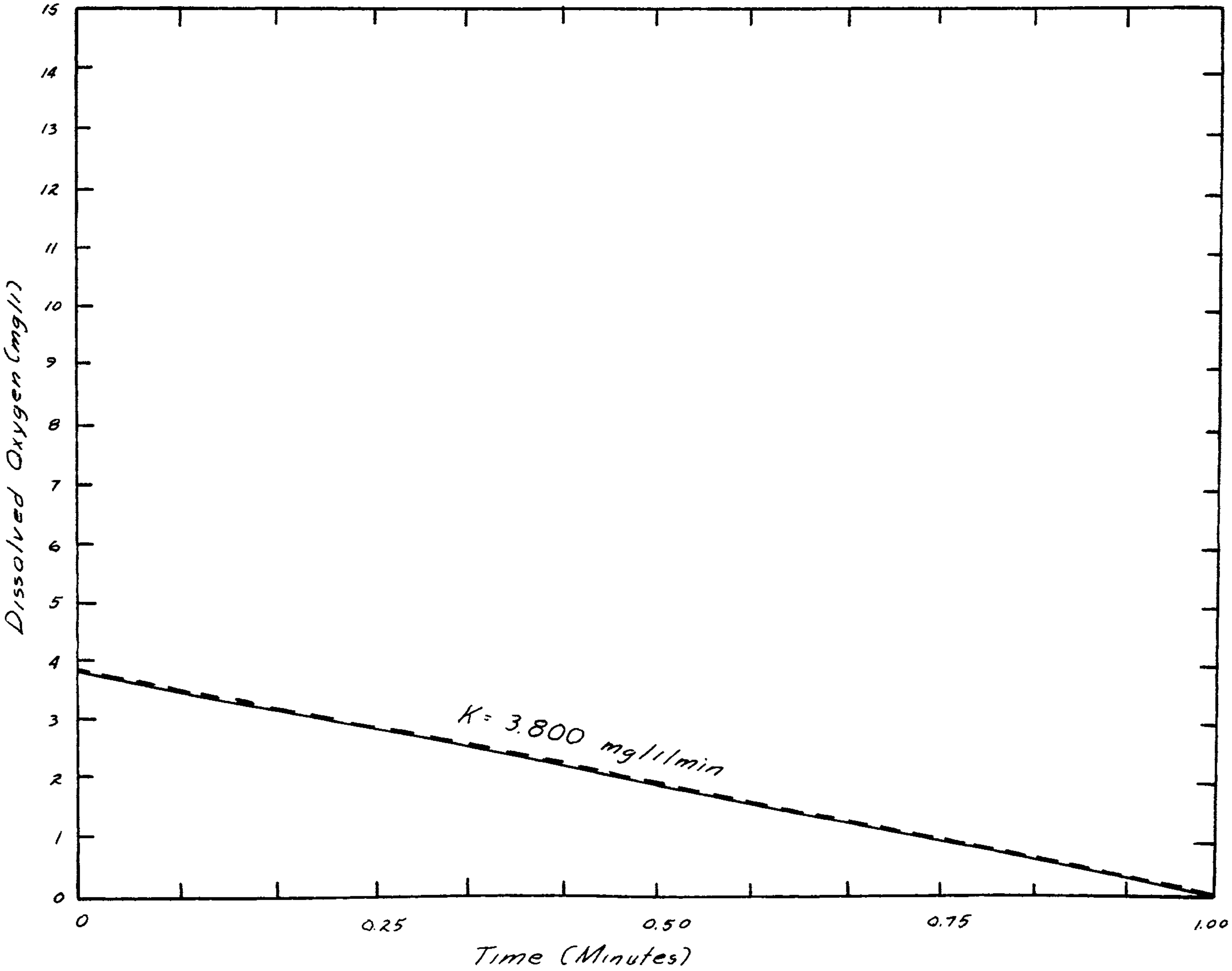

Figure 5-20

Oxygen Consumption by Inlet Sludge at 35°C - Sludge with Supernatant (Run #2)

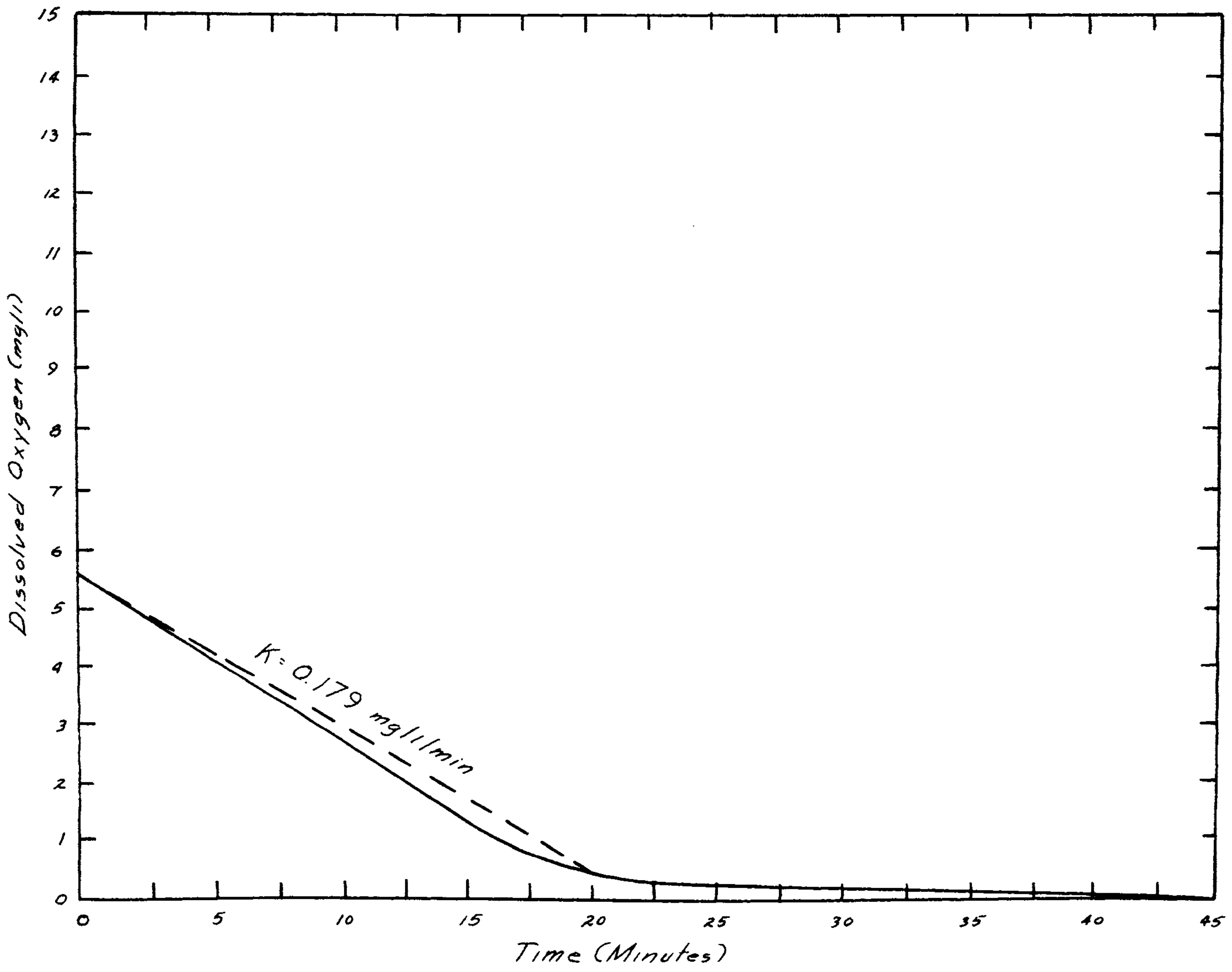

Figure 5-21

Oxygen Consumption by Inlet Sludge at 35°C - Unsettled Supernatant Only (Run #2)

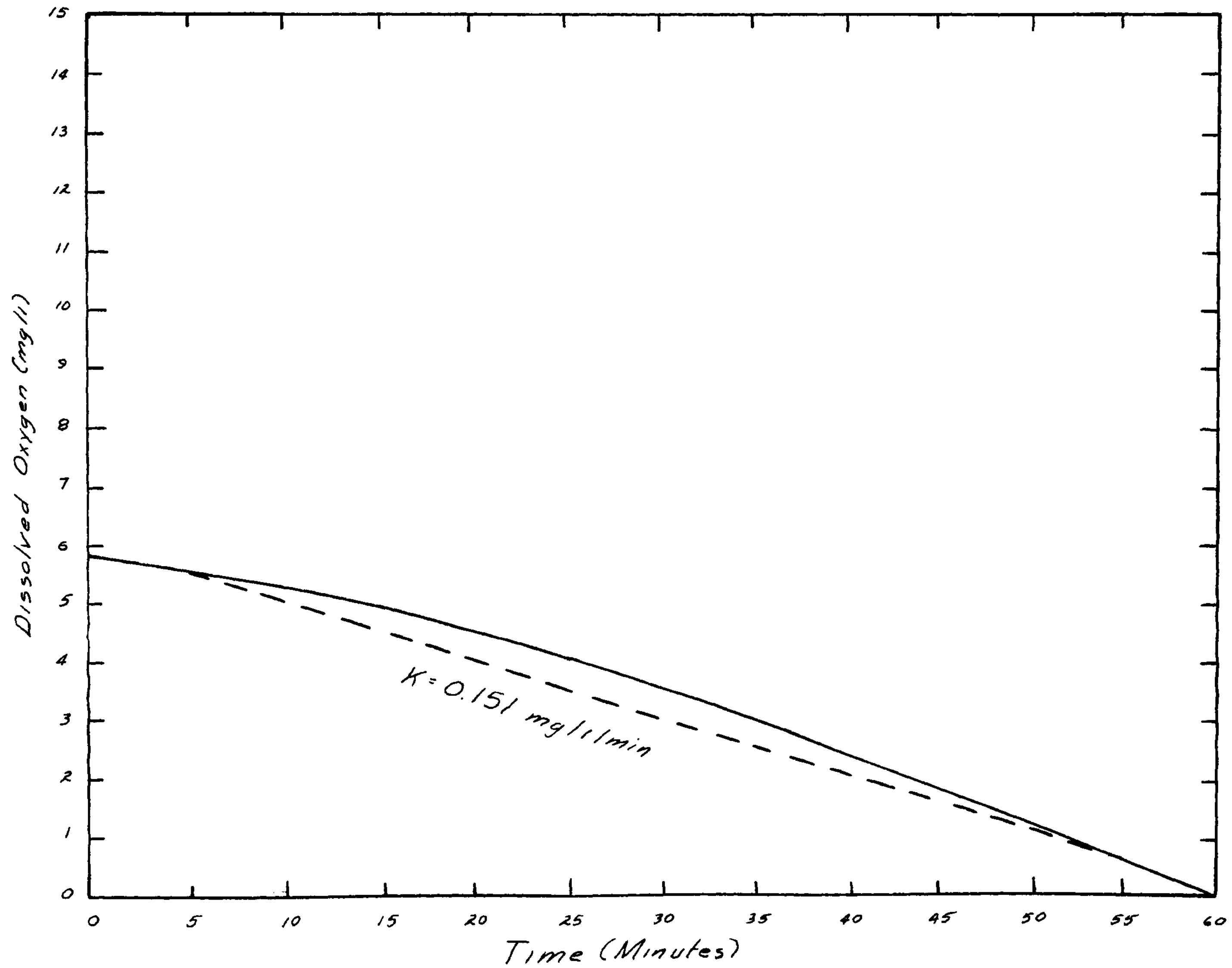

Figure 5-22

Oxygen Consumption by Inlet Sludge at 35°C - Settled Supernatant Only (Run #2)

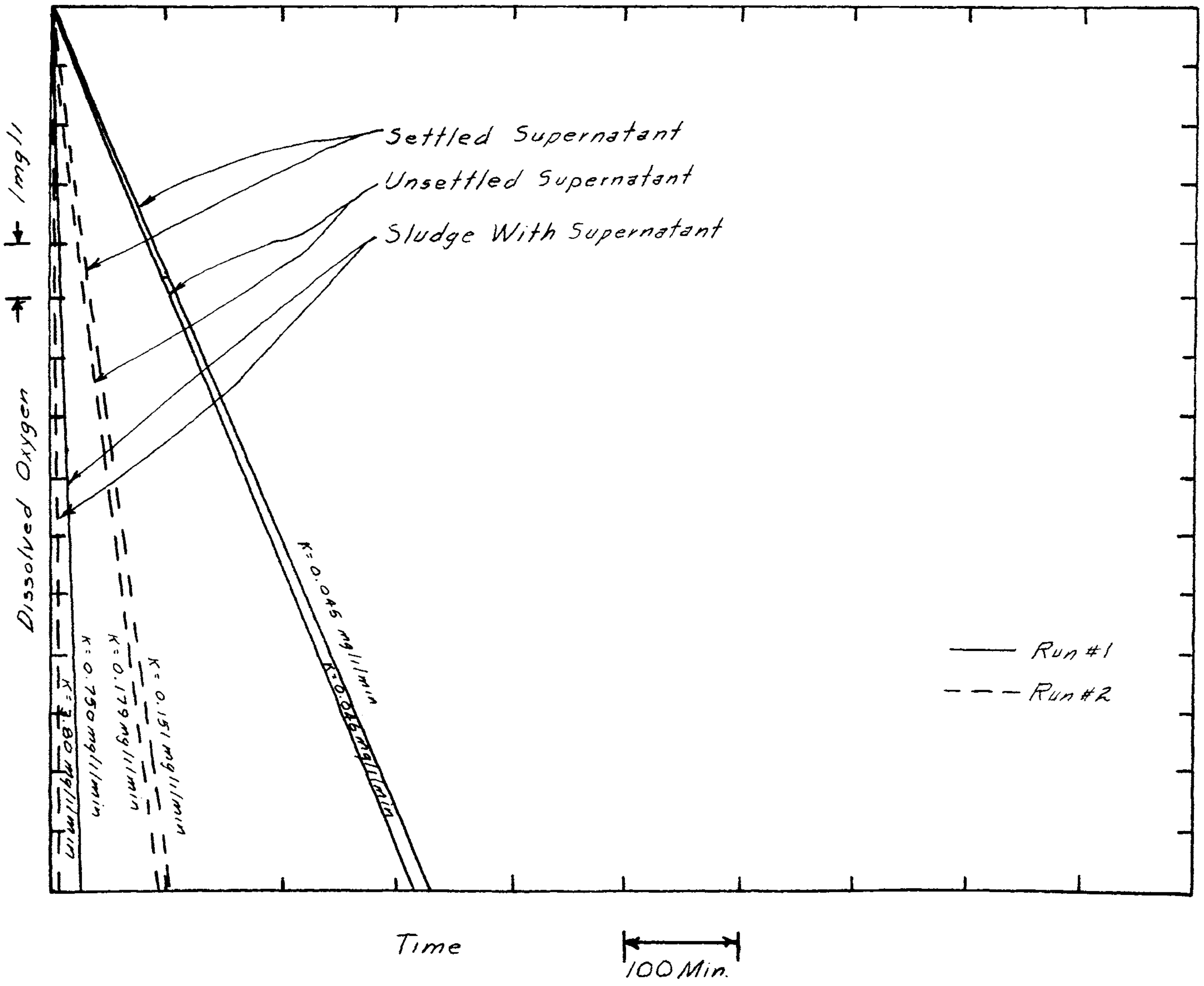

Figure 5-23

Relative Oxygen Consumption Rates of Inlet Sludge Systems at 35°C

cause a very high rate of oxygen uptake.

The relative oxygen consumption rates of the different systems conducted at 35 degrees centigrade are shown in Figure 5-23. Each of the three test systems conducted in the second experimental run had an uptake rate almost three fold greater than that observed in the corresponding system of the first run.

4. Oxygen Consumption by the Center Sludge Systems Tested at 10°C

The oxygen consumptions by the center sludge system tested at 10 degrees centigrade are presented in Figures 5-25 through 5-29, the first three of which are obtained from the first experimental run and the next three from the second experimental run. The same sludge sample was employed in both of the separate experimental runs.

The relative oxygen consumption rates of the above center sludge systems are compared in Figure 5-30. As shown in this figure, the oxygen uptake rates in the first experimental run are approximately twice as much as those in the second experimental run. Comparing the oxygen uptake rates by the sludge with supernatant and the unsettled supernatant only, i.e., 0.144 vs 0.133 and 0.084 vs 0.062 mg/l/min in the first and second experimental runs respectively, it becomes evident that the sludge itself did not increase the oxygen consumption rate significantly. Most of the oxygen uptake is primarily due to the organic matter suspended in the test supernatant system.

It must be pointed out here that in this research study the first test was performed on this center sludge at 10 degrees centigrade, as shown in Figure 5-2. Figure 5-26 shows that during the

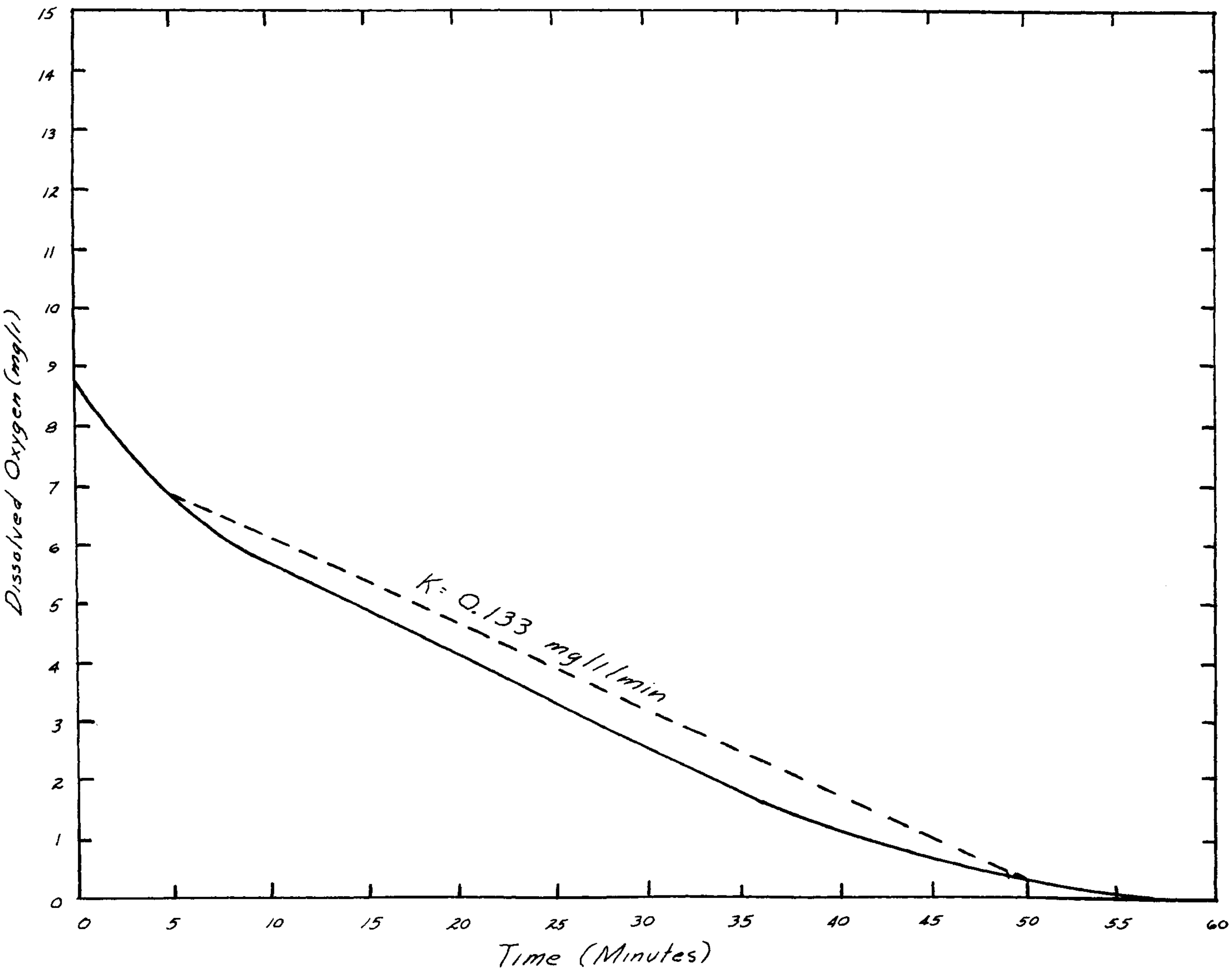

Figure 5-24

Oxygen Consumption by Center Sludge at 10°C - Sludge with Supernatant (Run #1)

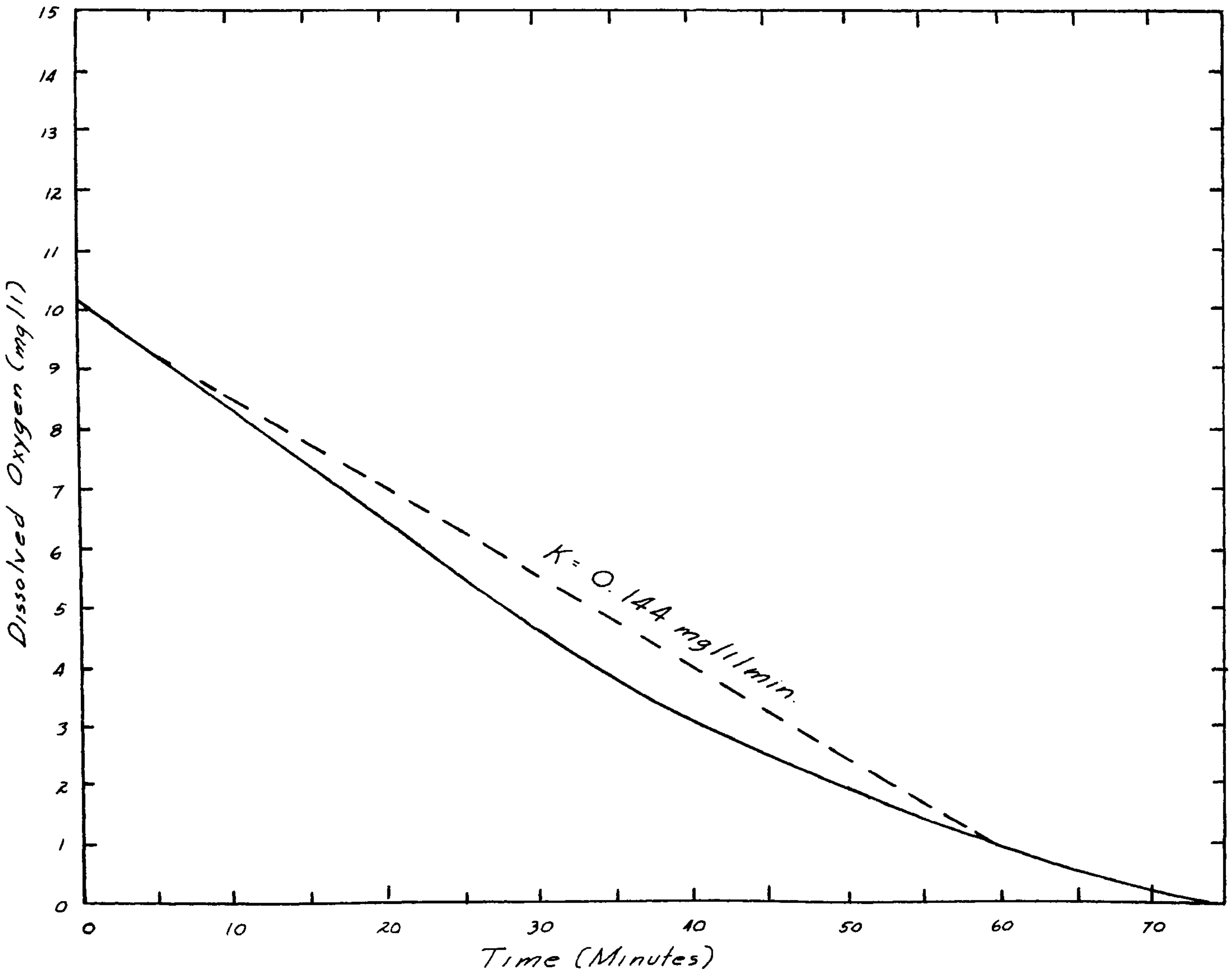

Figure 5-25

Oxygen Consumption by Center Sludge at 10°C - Unsettled Supernatant Only (Run #1)

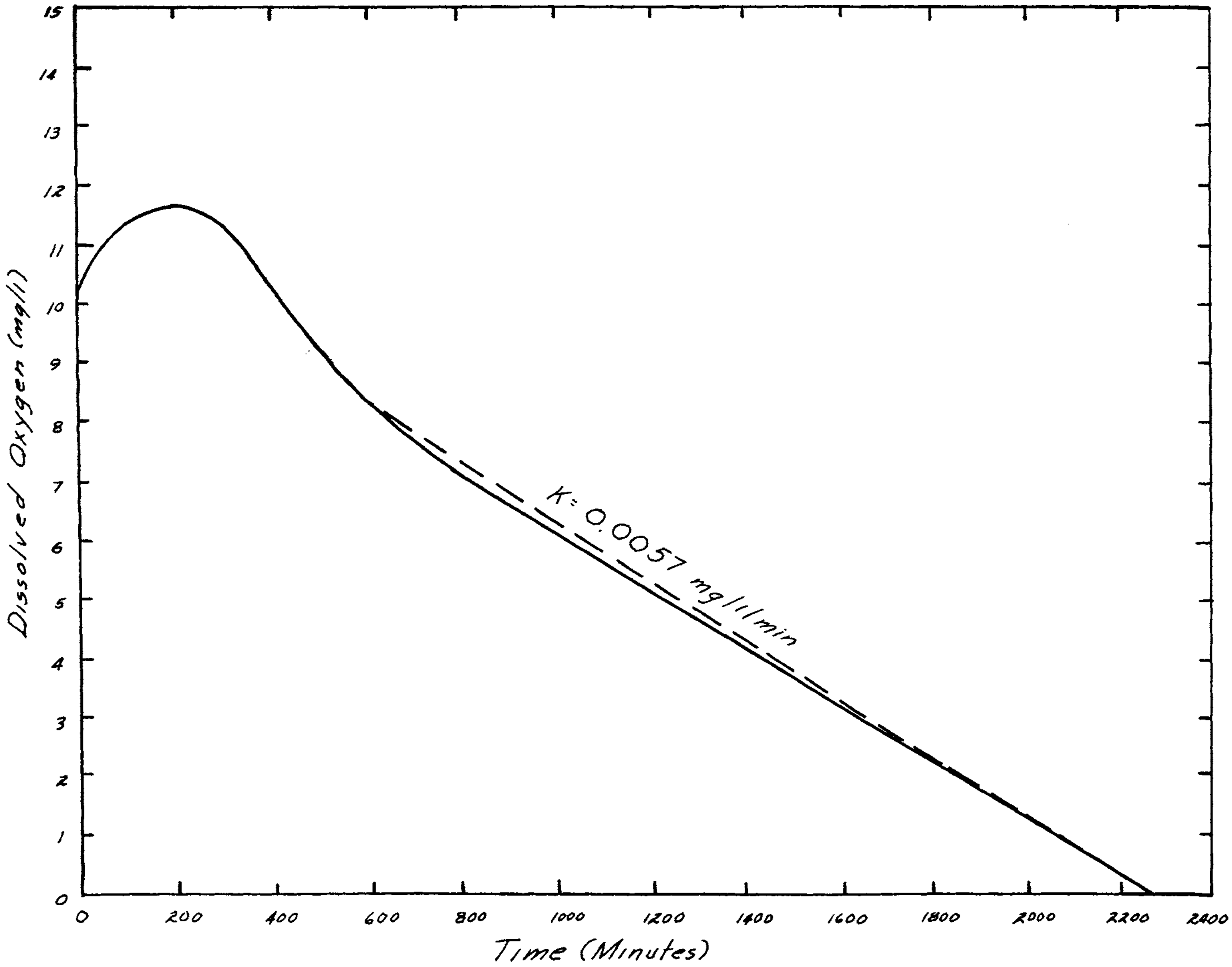

Figure 5-26

Oxygen Consumption by Center Sludge at 10°C - Settled Supernatant Only (Run #1)

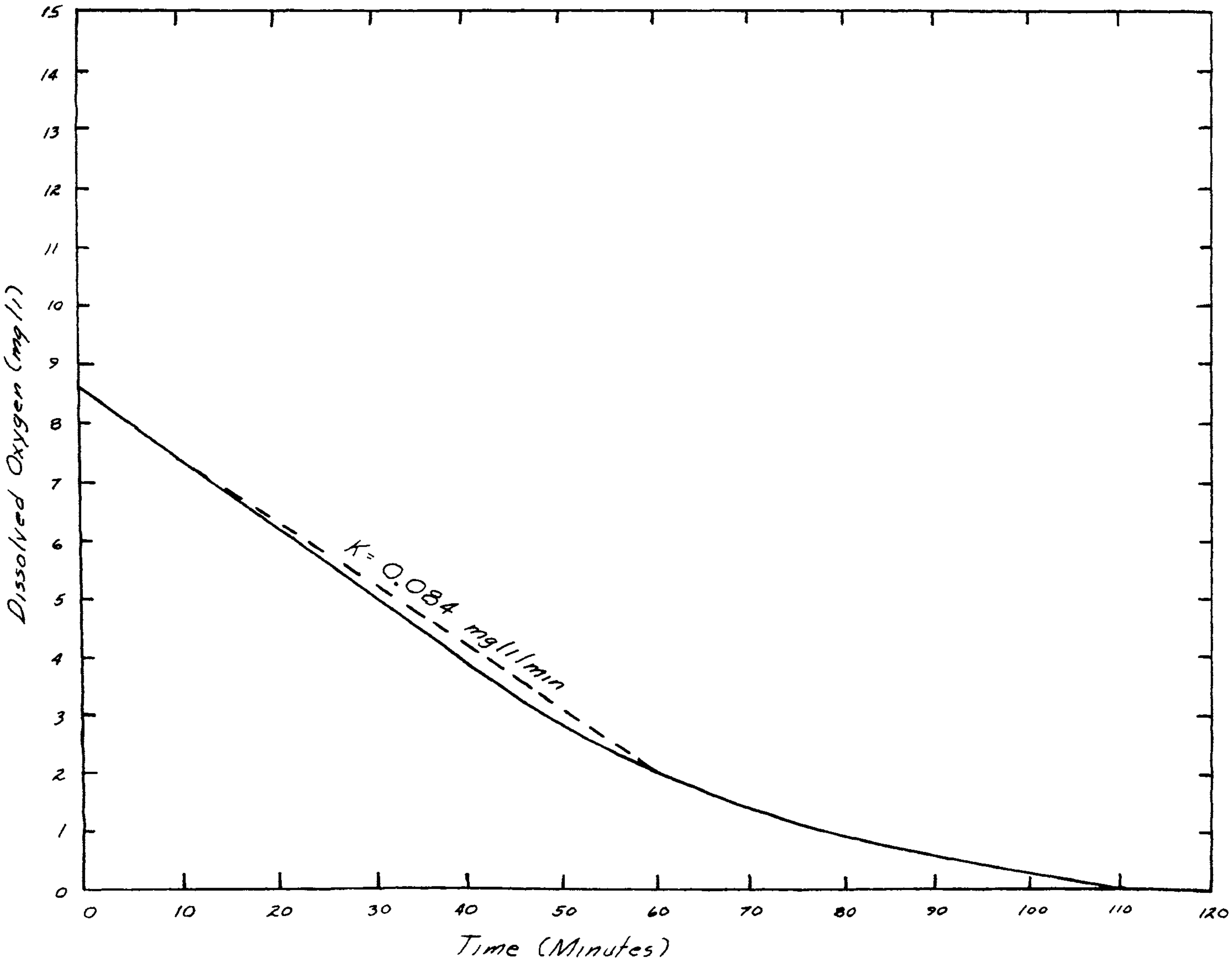

Figure 5-27

Oxygen Consumption by Center Sludge at 10°C - Sludge with Supernatant (Run #2)

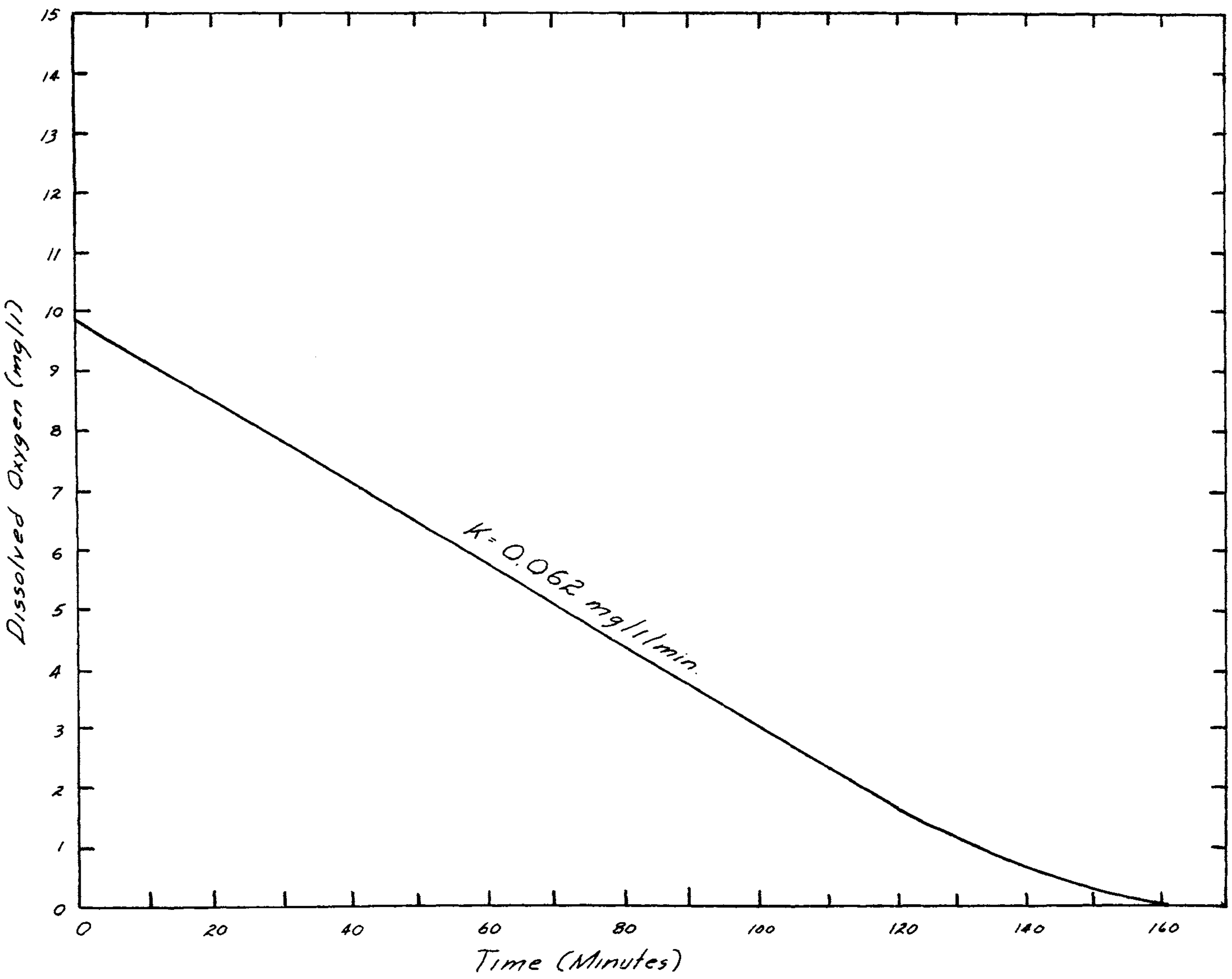

Figure 5-28

Oxygen Consumption by Center Sludge at 10°C - Unsettled Supernatant Only (Run #2)

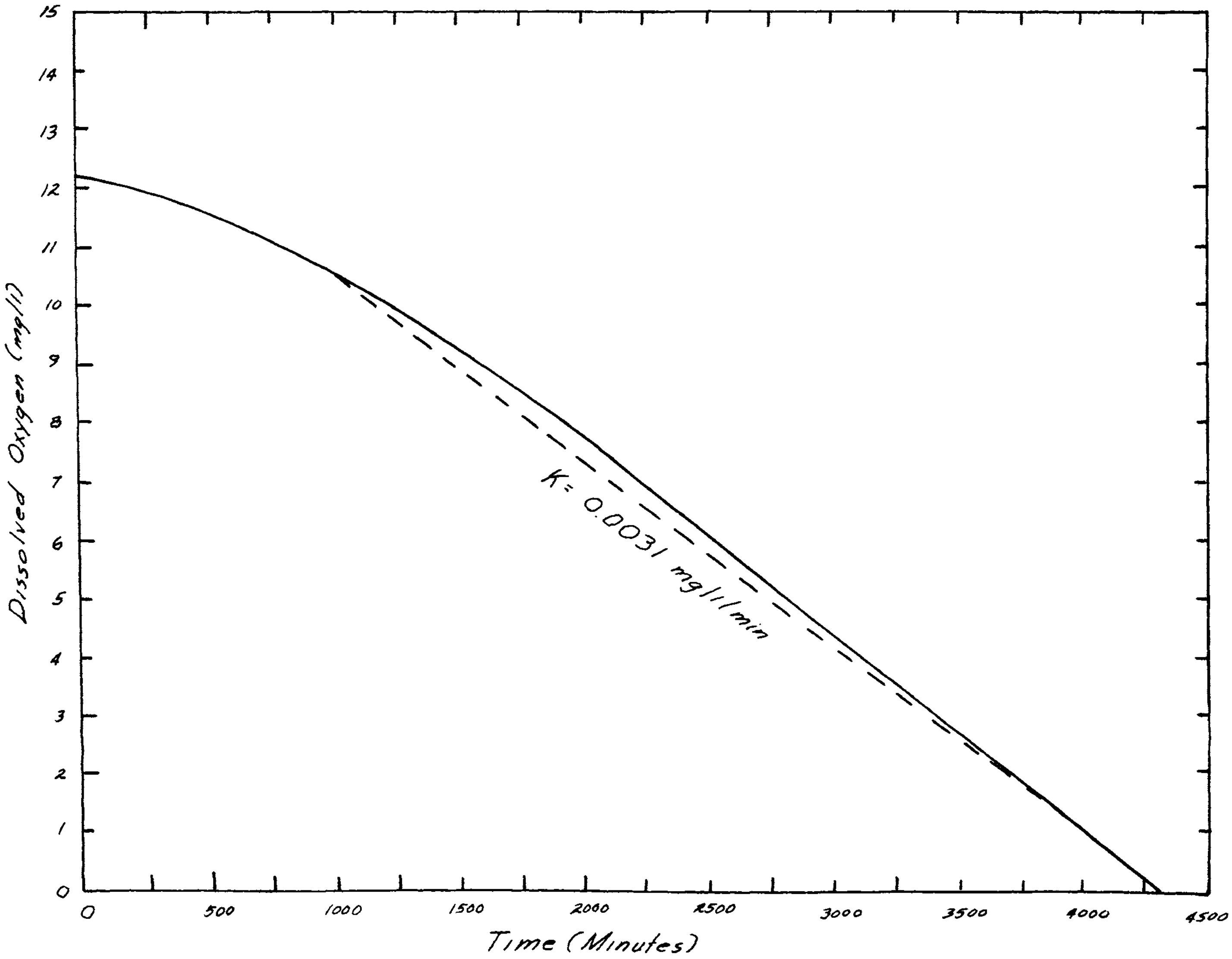

Figure 5-29

Oxygen Consumption by Center Sludge at 10°C - Settled Supernatant Only (Run #2)

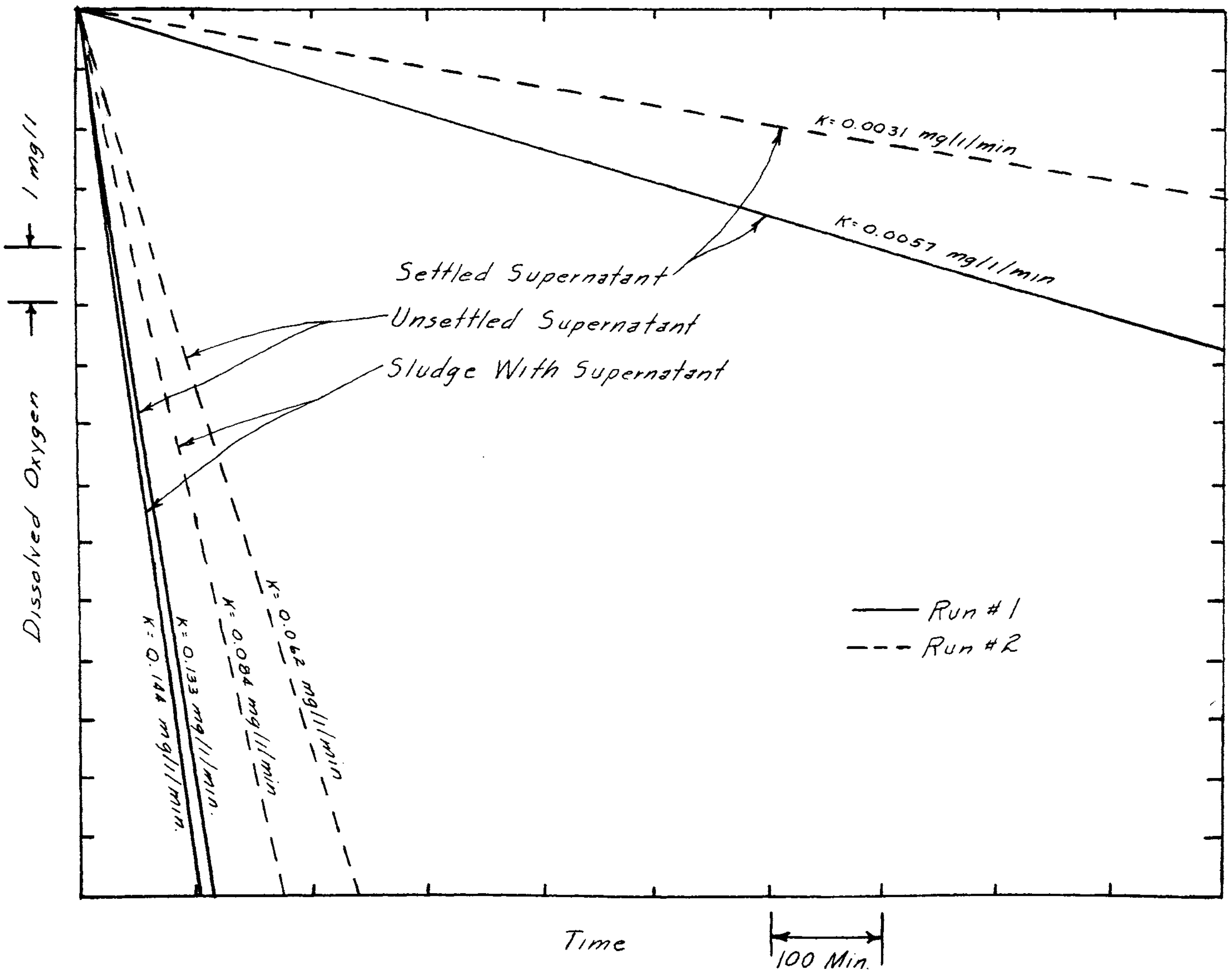

Figure 5-30

Relative Oxygen Consumption Rates of Center Sludge Systems at 10°C

initial 200 minutes of the test there was an apparent rise in the oxygen level. The reason for this erratic phenomenon will be discussed in the chapter of Discussion.

5. Oxygen Consumption by the Center Sludge Systems Tested at 22°C

The oxygen consumption curves by the center sludge systems conducted at 22 degrees centigrade are presented in Figures 5-31 through 5-36. Figure 5-37 summarizes the average oxygen uptake rate for each of the above test systems. As indicated in the previous sections of the oxygen consumption study, the two experimental runs for each test system has different concentrations of suspended solids and thus different rates of oxygen uptake.

6. Oxygen Consumption by the Center Sludge Systems Tested at 35°C

Figures 5-38 through 5-43 are presented to show the oxygen consumption by the center sludge systems tested at 35 degrees centigrade. As shown in these curves, the initial dissolved oxygen content in the test systems are relatively low, being between two to four mg/l. This mainly resulted from the rapid oxygen uptake in that short period when the oxygen-saturated supernatant was siphoned into the test chamber. This phenomenon will be discussed further in the following chapter of Discussion.

The relative oxygen uptake rate in each of the above test systems are compared in Figure 5-44.

7. Oxygen Consumption by the Outlet Sludge Systems Tested at 10°C

The oxygen utilization by the outlet sludge systems at 10 degrees centigrade are shown in Figures 5-45 through 5-50. In one of the tests with the unsettled supernatant system, the recorder ran out of chart paper after 17,200 minutes of test, as shown in

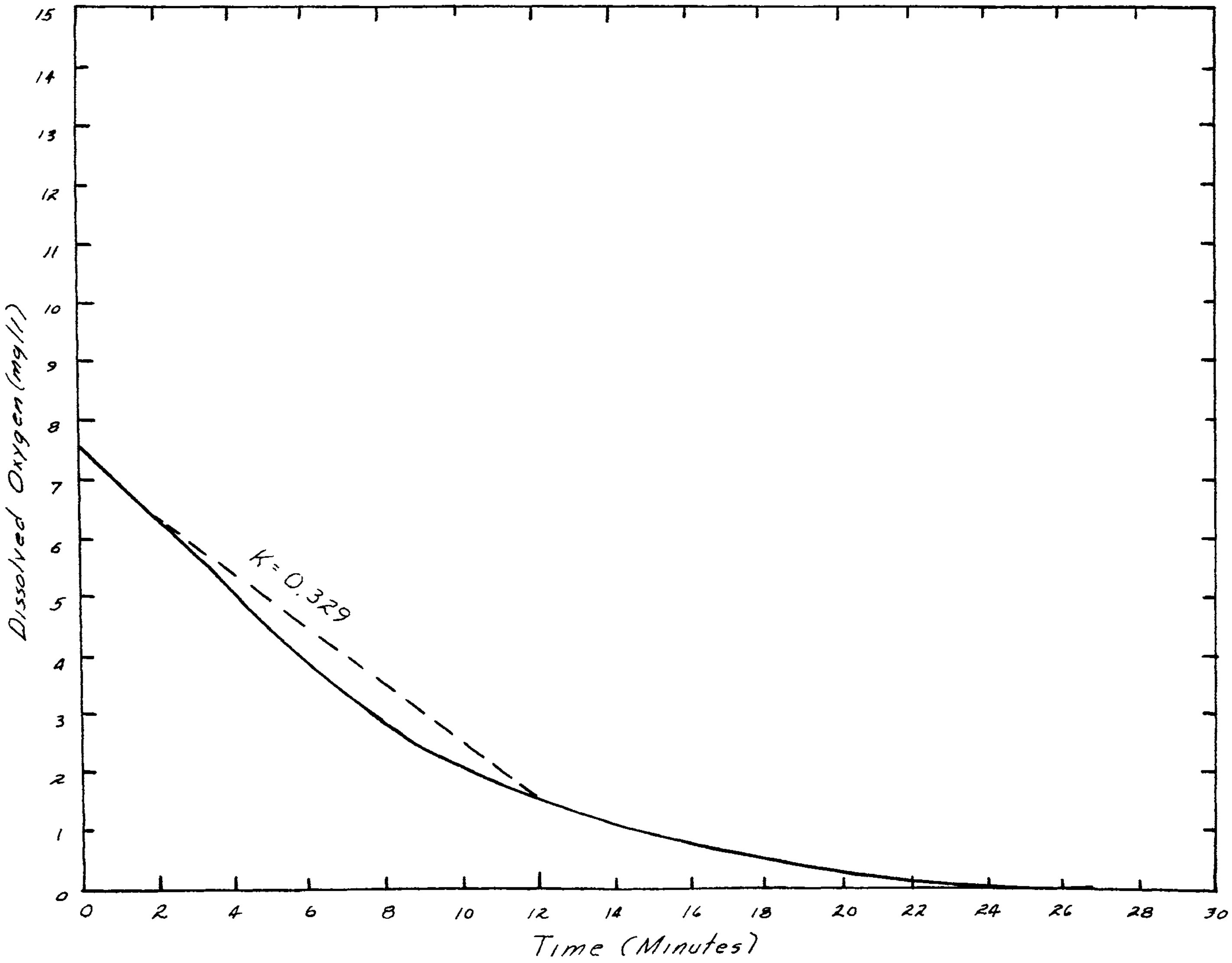

Figure 5-31

Oxygen Consumption by Center Sludge at 22°C - Sludge with Supernatant (Run #1)

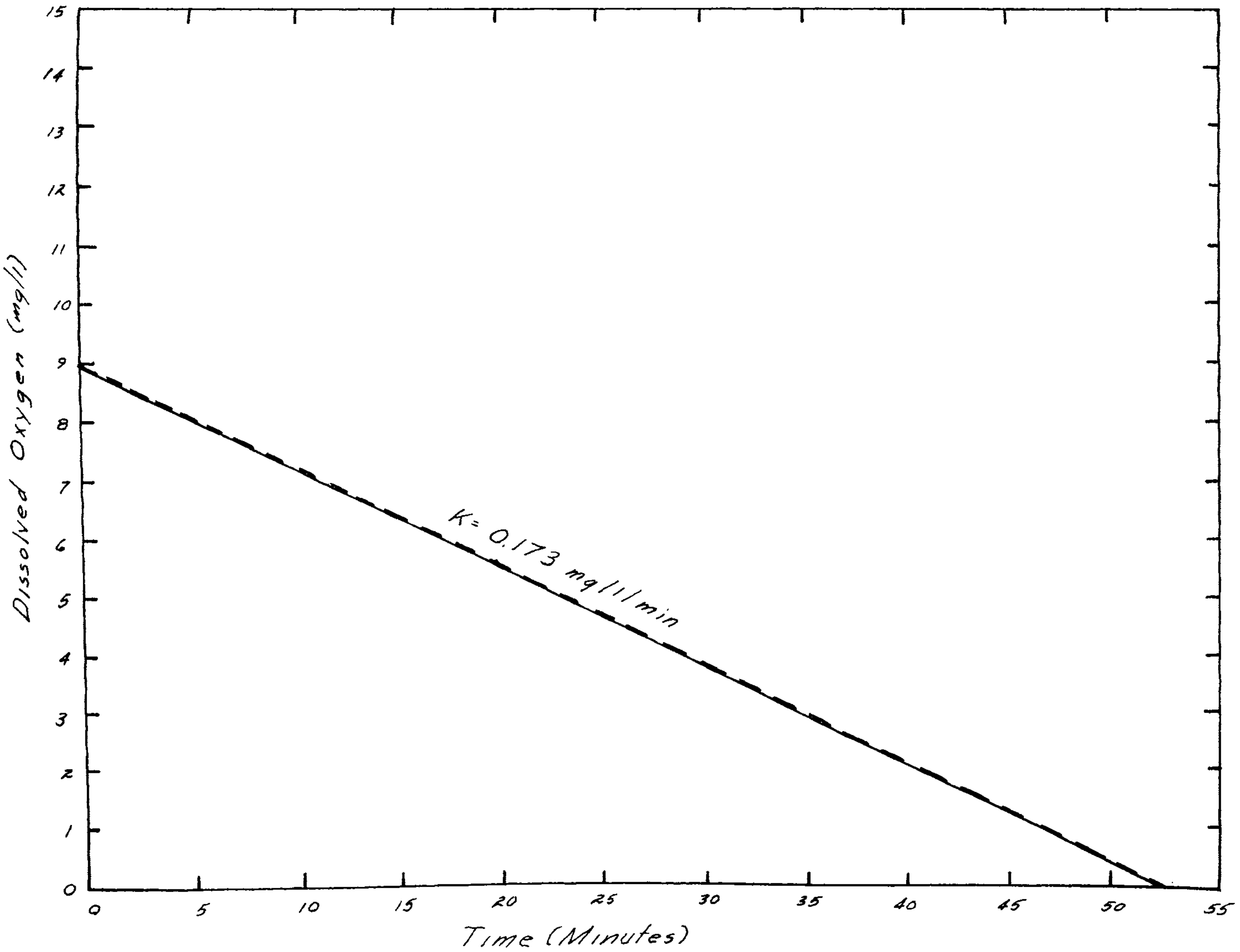

Figure 5-32

Oxygen Consumption by Center Sludge at 22°C - Unsettled Supernatant Only (Run #1)

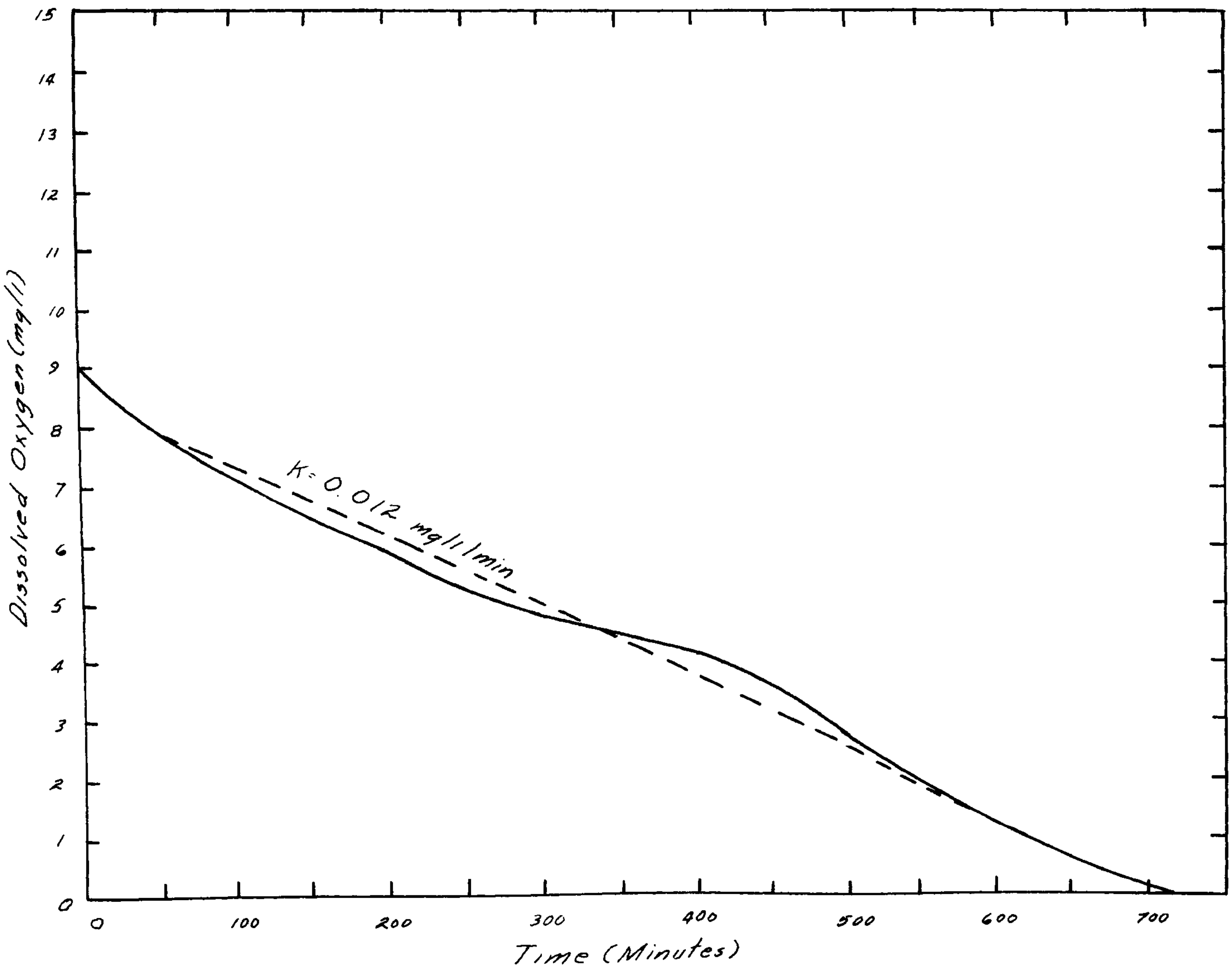

Figure 5-33

Oxygen Consumption by Center Sludge at 22°C - Settled Supernatant Only (Run #1)

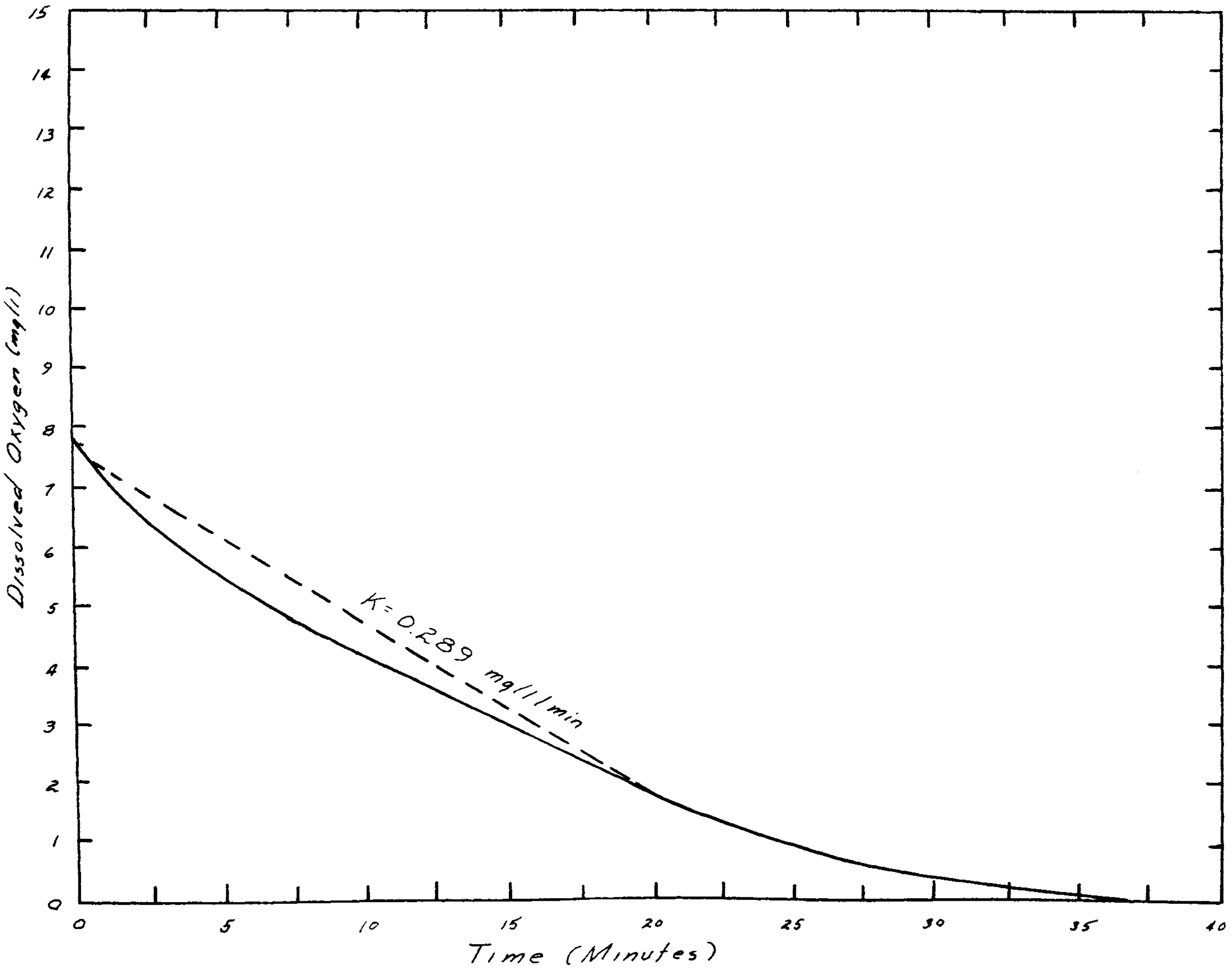

Figure 5-34

Oxygen Consumption by Center Sludge at 22°C - Sludge with Supernatant (Run #2)

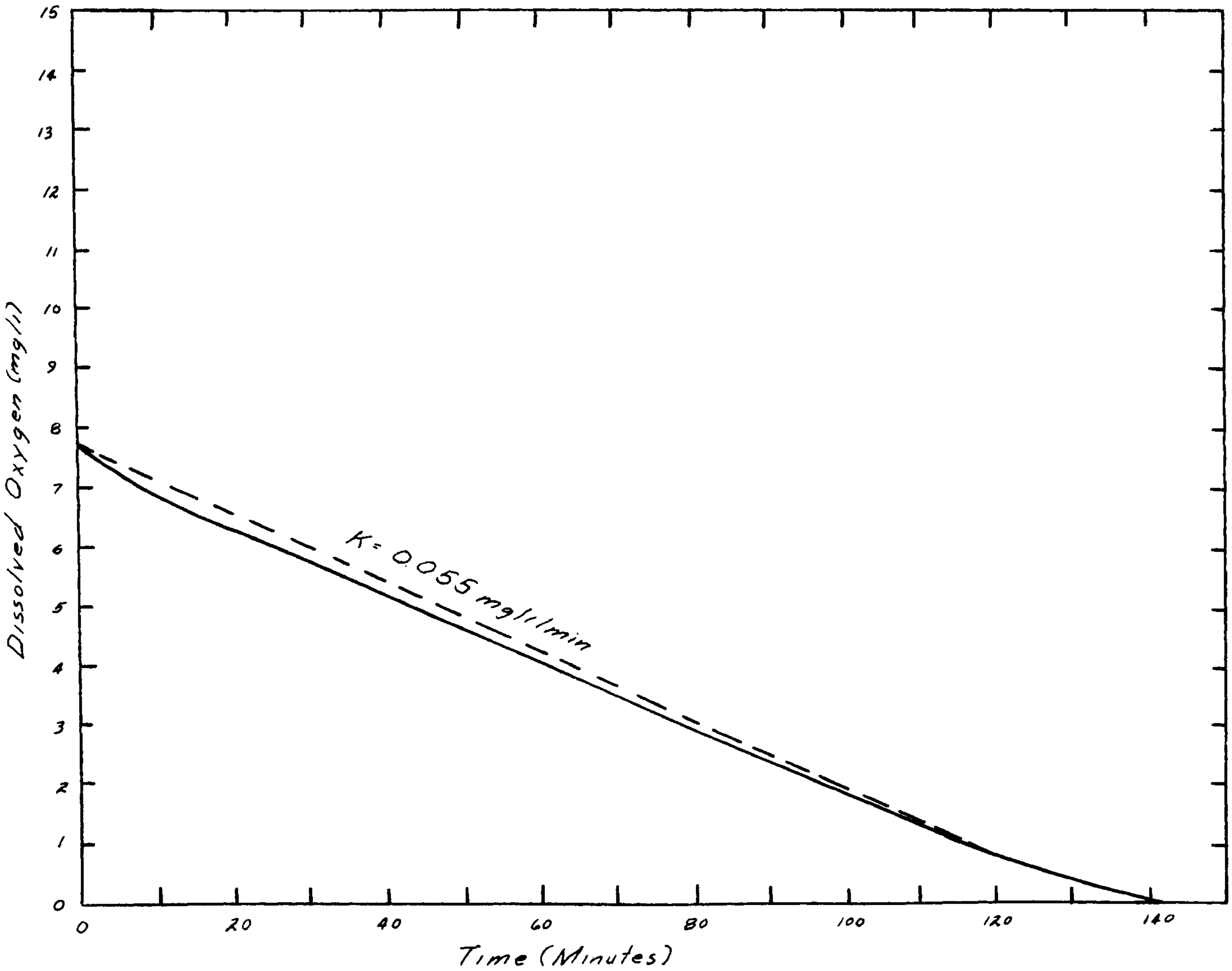

Figure 5-35

Oxygen Consumption by Center Sludge at 22°C - Unsettled Supernatant Only (Run #2)

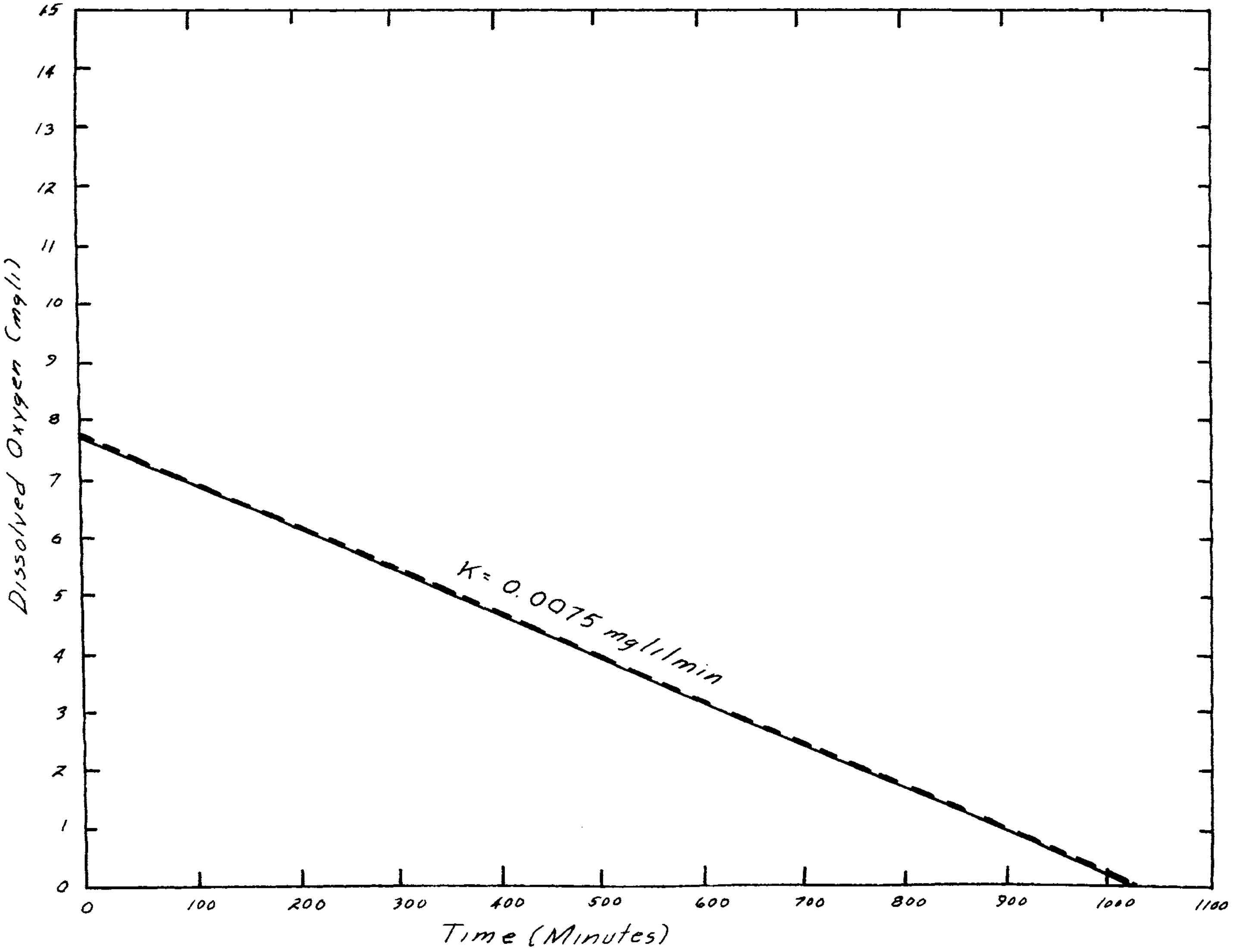

Figure 5-36

Oxygen Consumption by Center Sludge at 22°C - Settled Supernatant Only (Run #2)

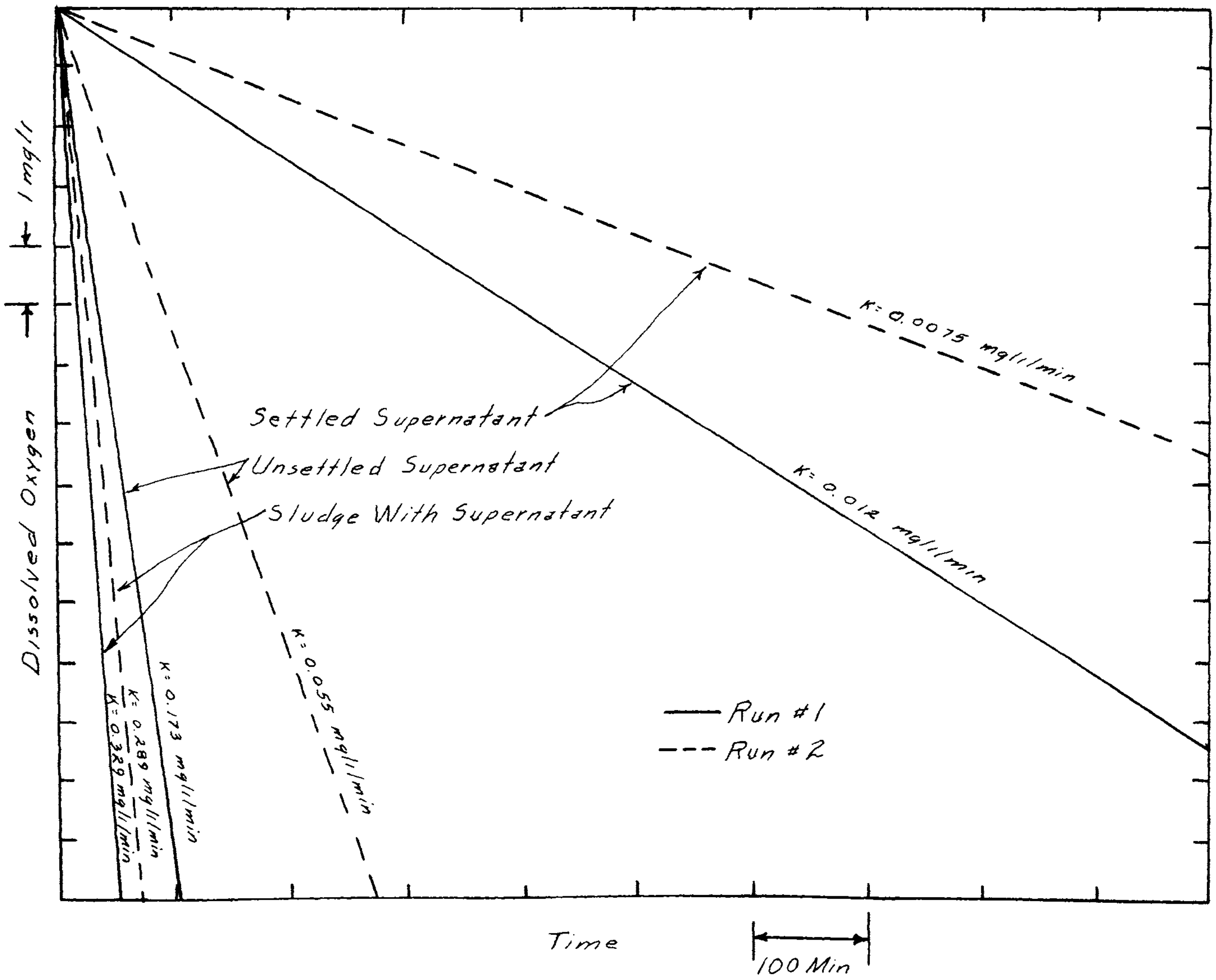

Figure 5-37

Relative Oxygen Consumption Rates of Center Sludge Systems at 22°C

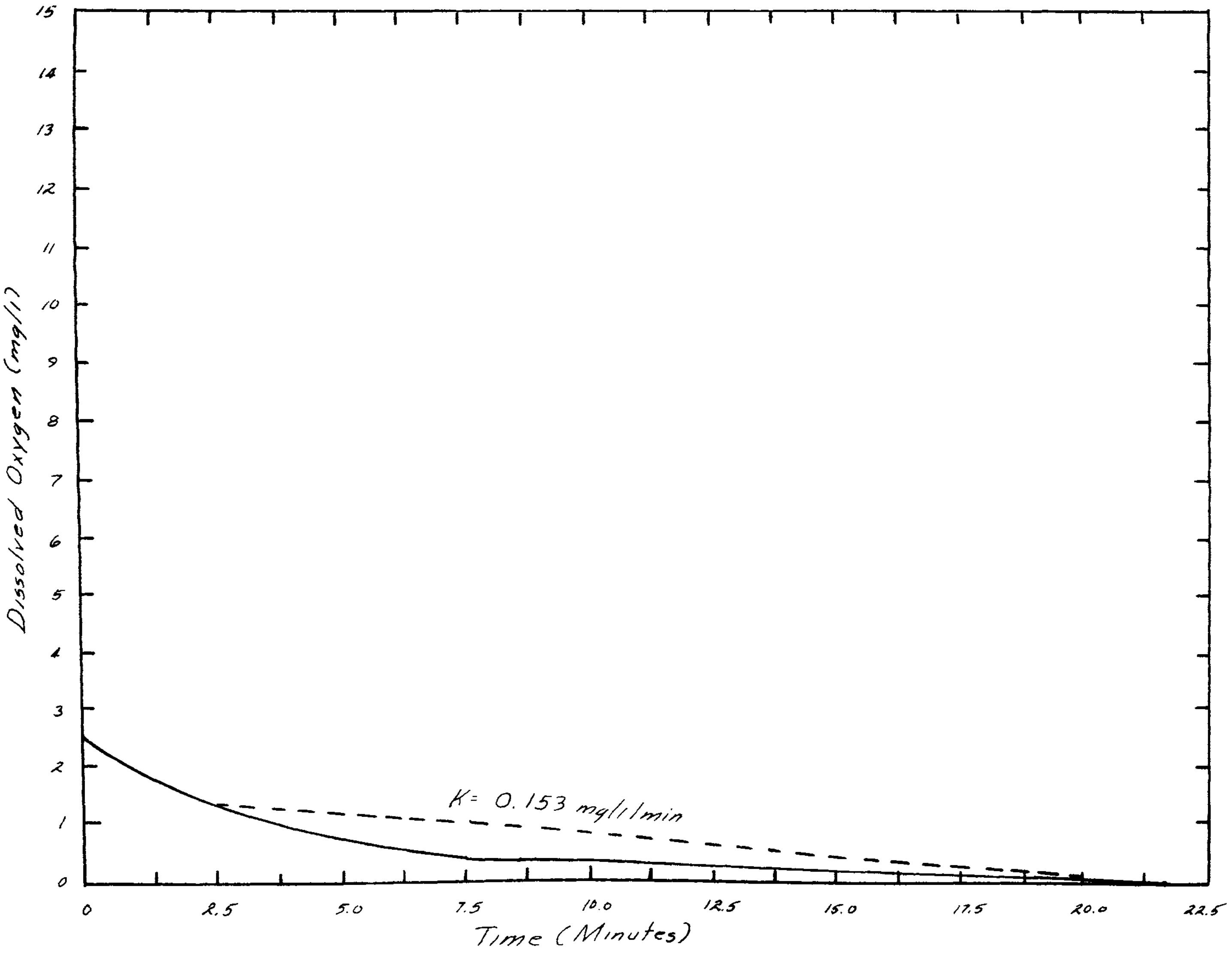

Figure 5-38

Oxygen Consumption by Center Sludge at 35°C - Sludge with Supernatant (Run #1)

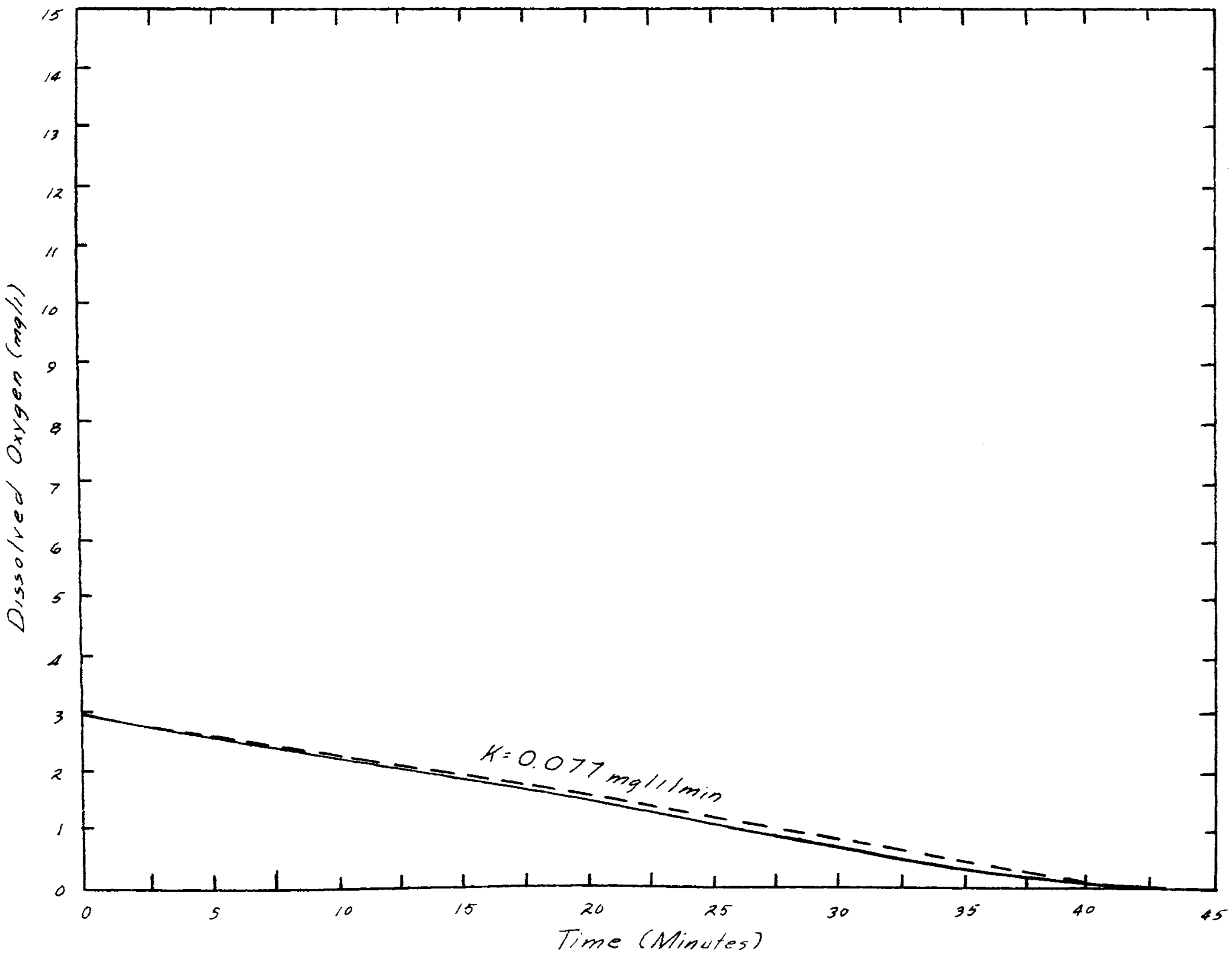

Figure 5-39

Oxygen Consumption by Center Sludge at 35°C - Unsettled Supernatant Only (Run #1)

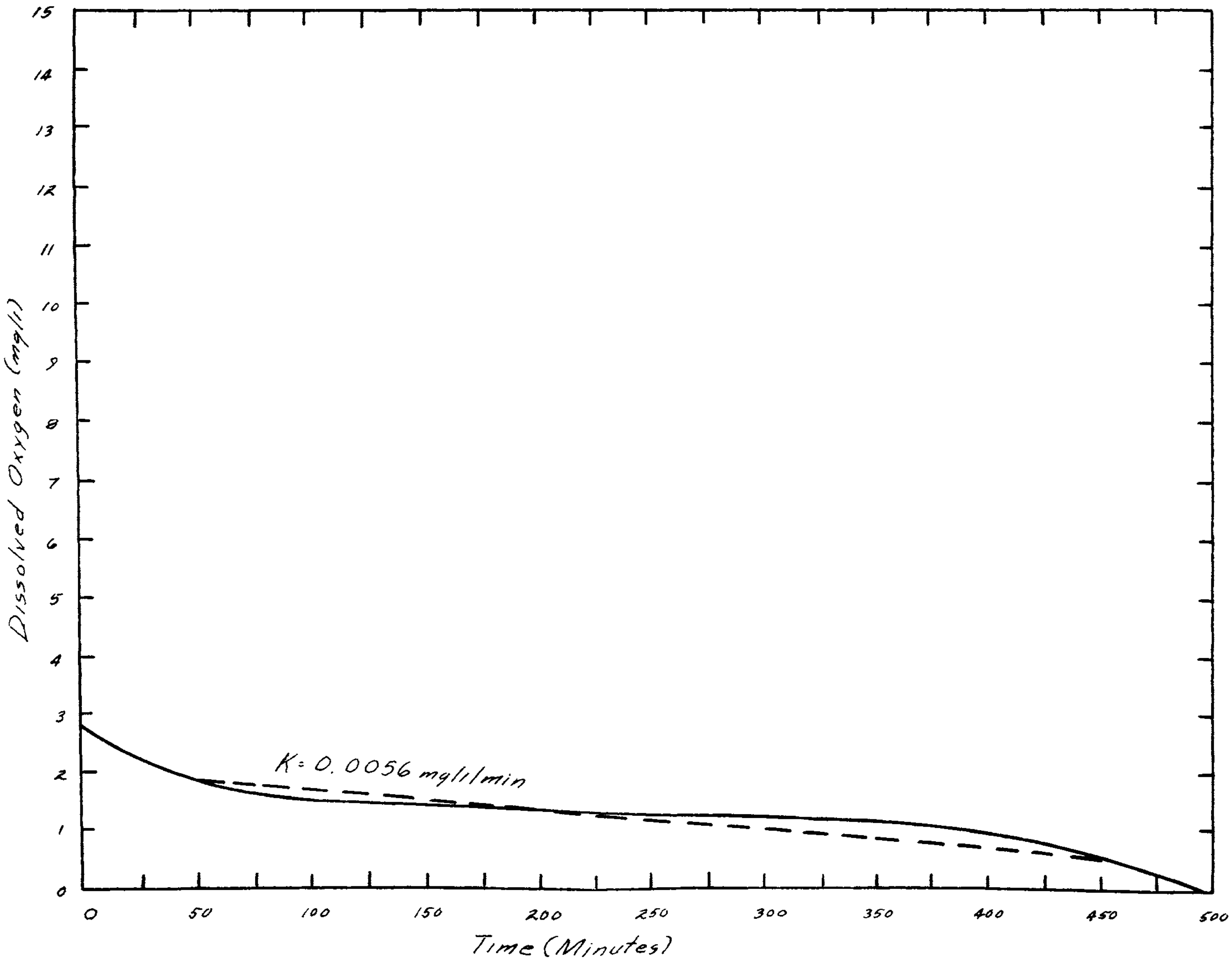

Figure 5-40

Oxygen Consumption by Center Sludge at 35°C - Settled Supernatant Only (Run #1)

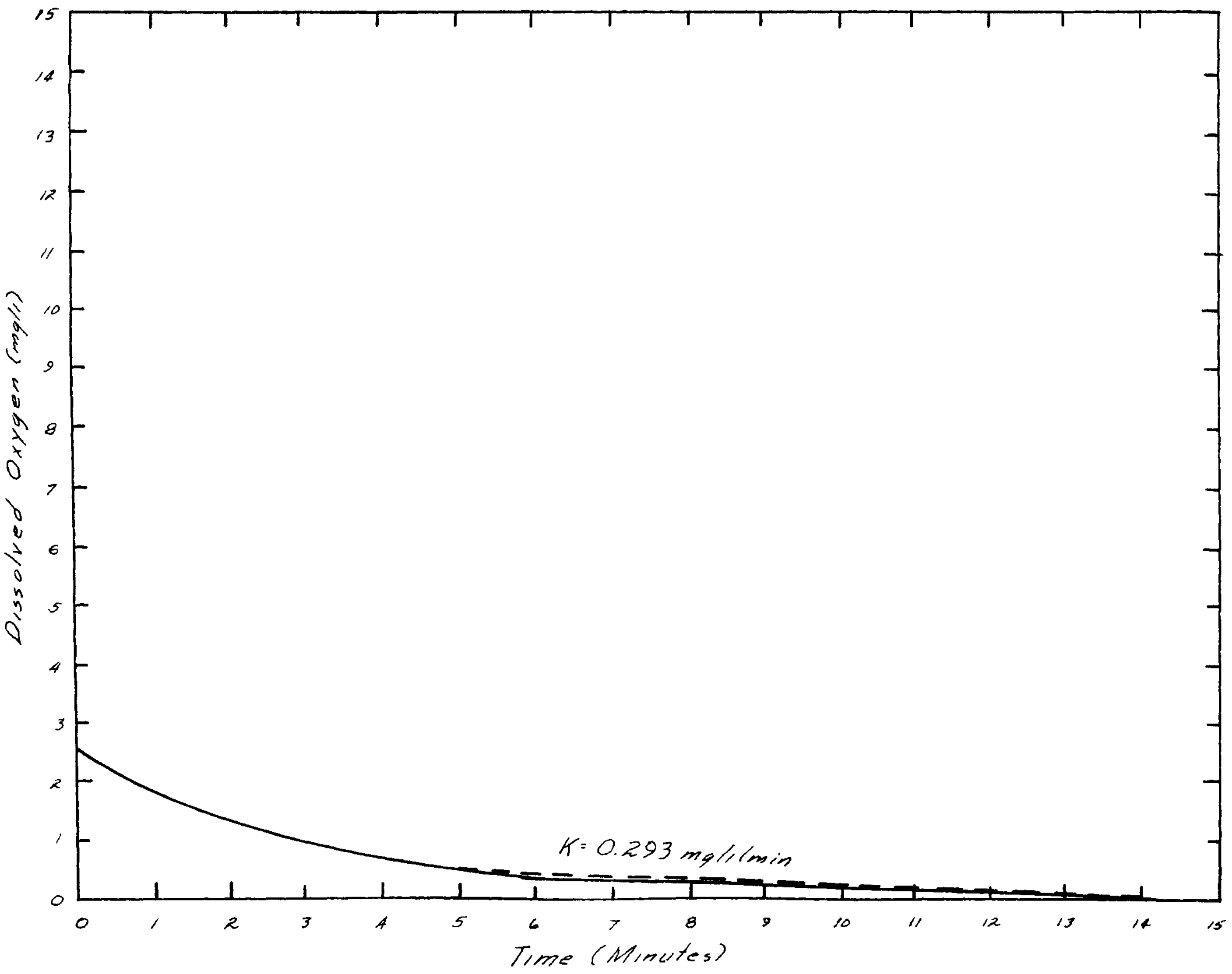

Figure 5-41

Oxygen Consumption by Center Sludge at 35°C - Sludge with Supernatant (Run #2)

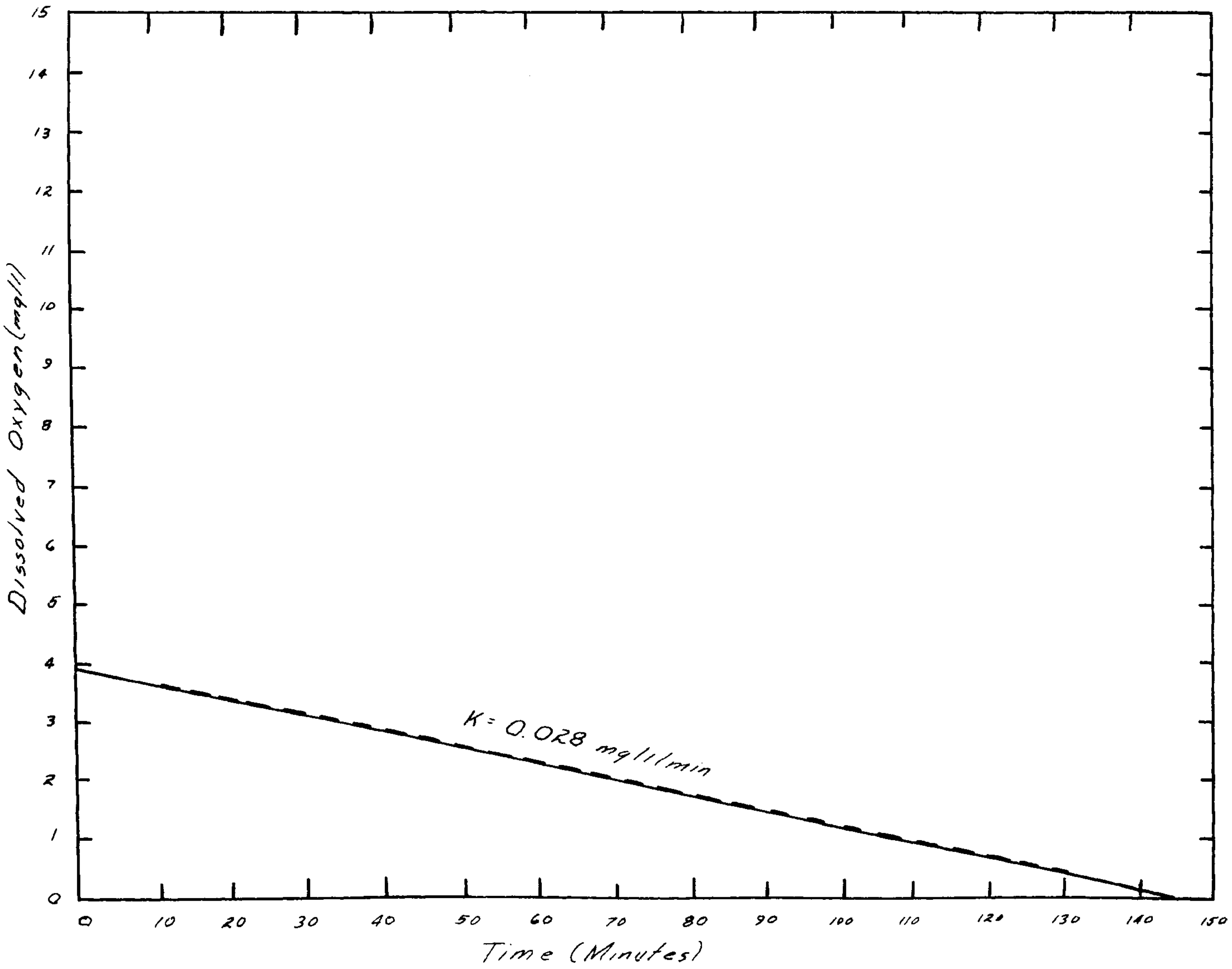

Figure 5-42

Oxygen Consumption by Center Sludge at 35°C - Unsettled Supernatant Only (Run #2)

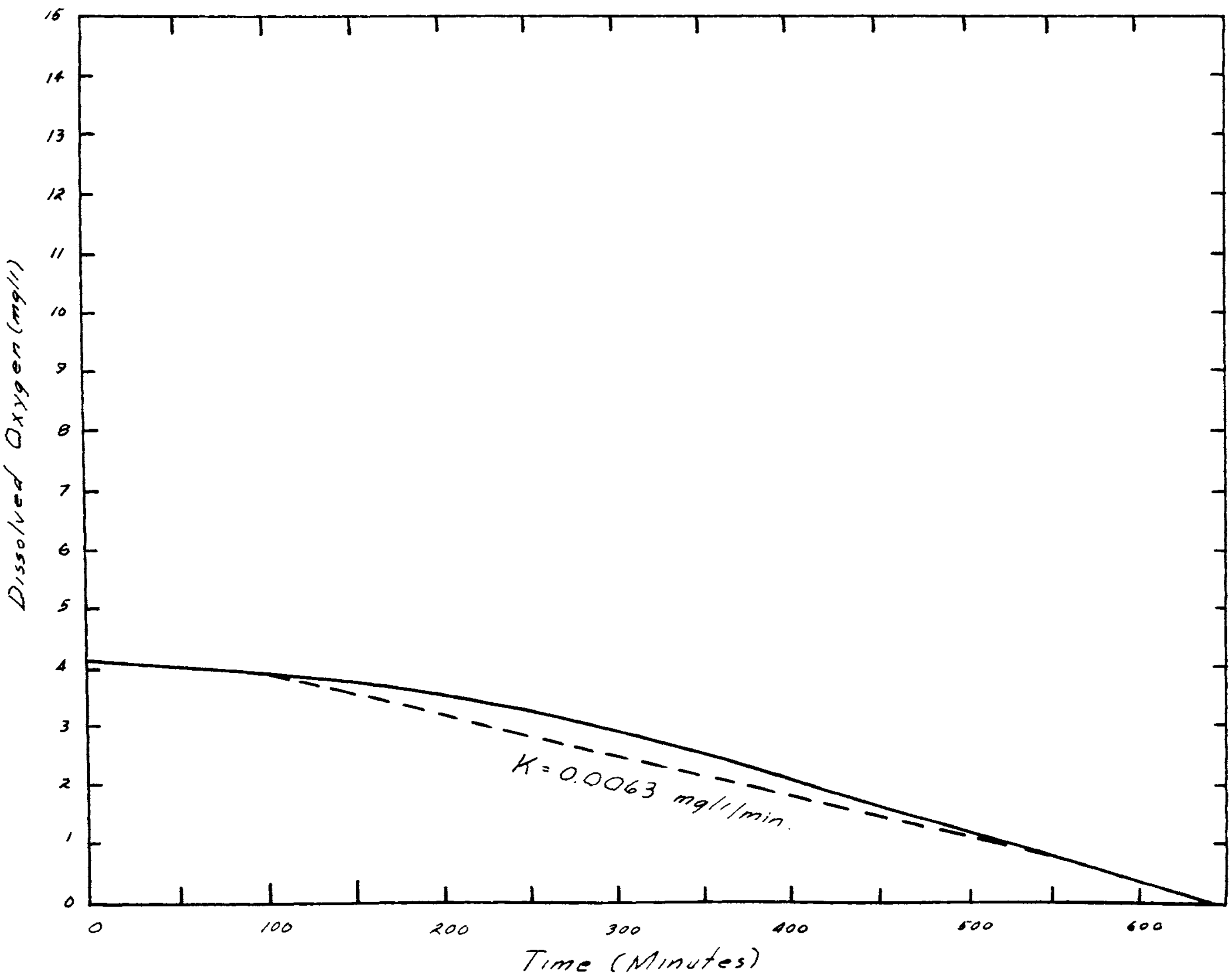

Figure 5-43

Oxygen Consumption by Center Sludge at 35 C - Settled Supernatant Only (Run #2)

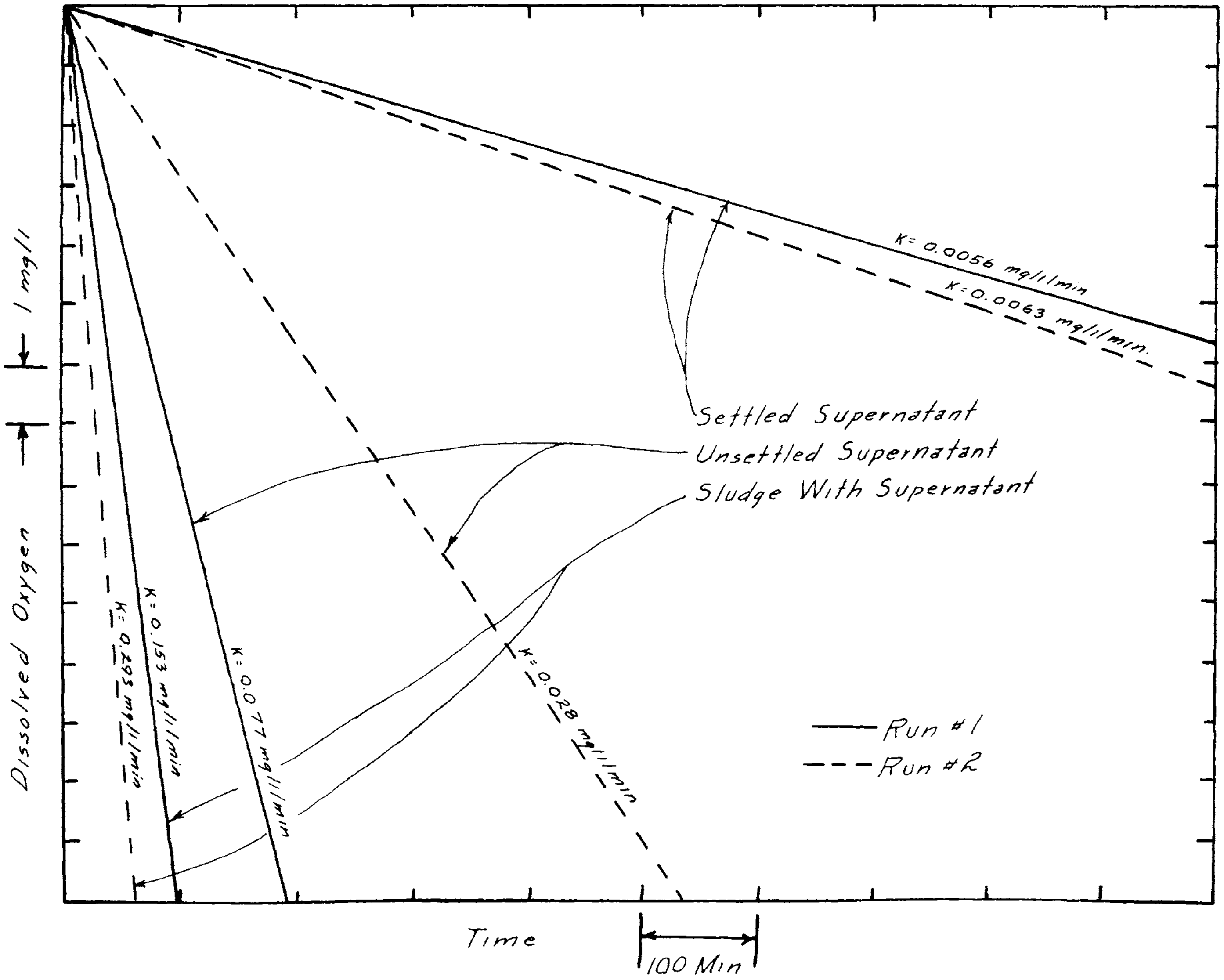

Figure 5-44

Relative Oxygen Consumption Rates of Center Sludge Systems at 35°C

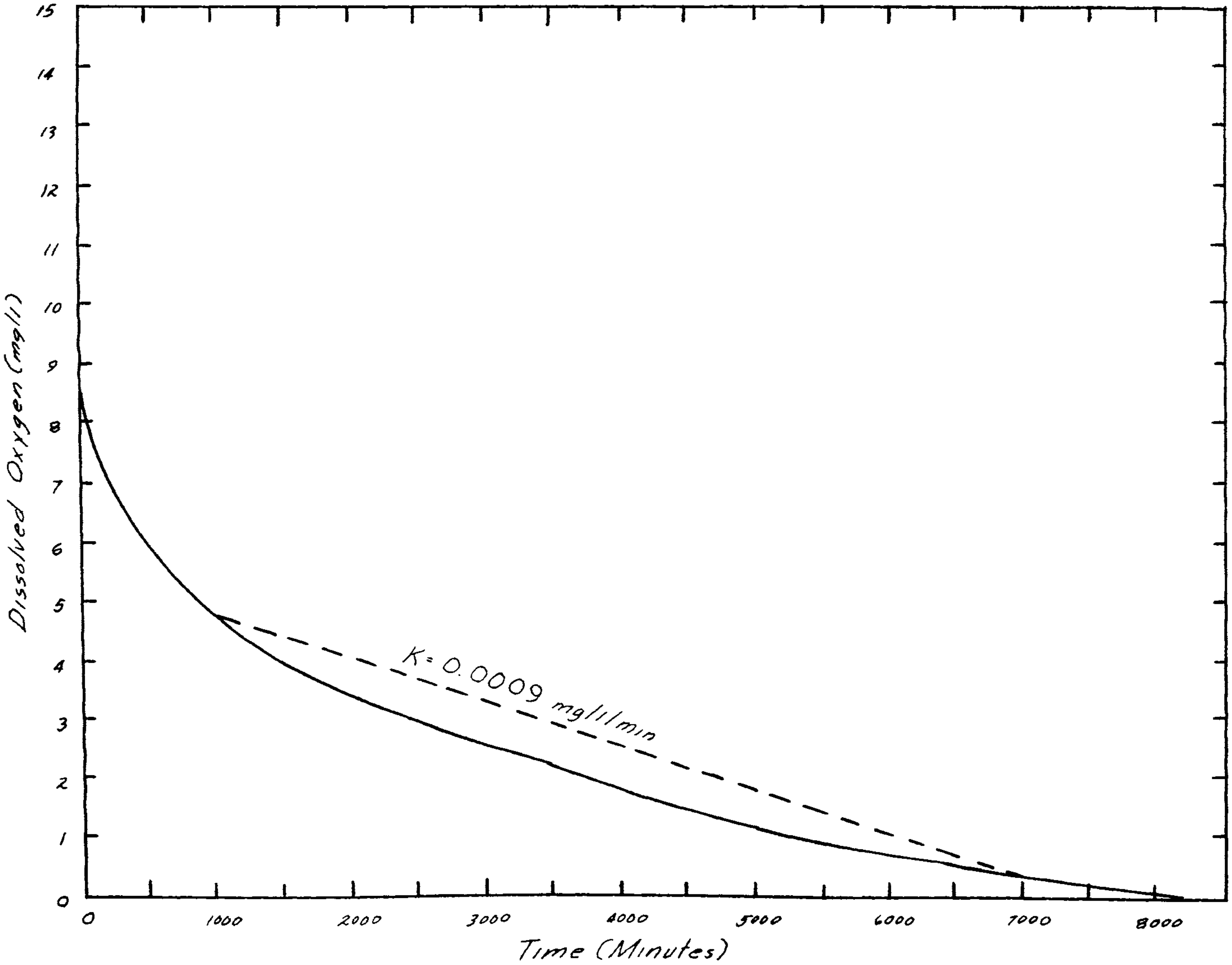

Figure 5-45

Oxygen Consumption by Outlet Sludge at 10°C - Sludge with Supernatant (Run #1)

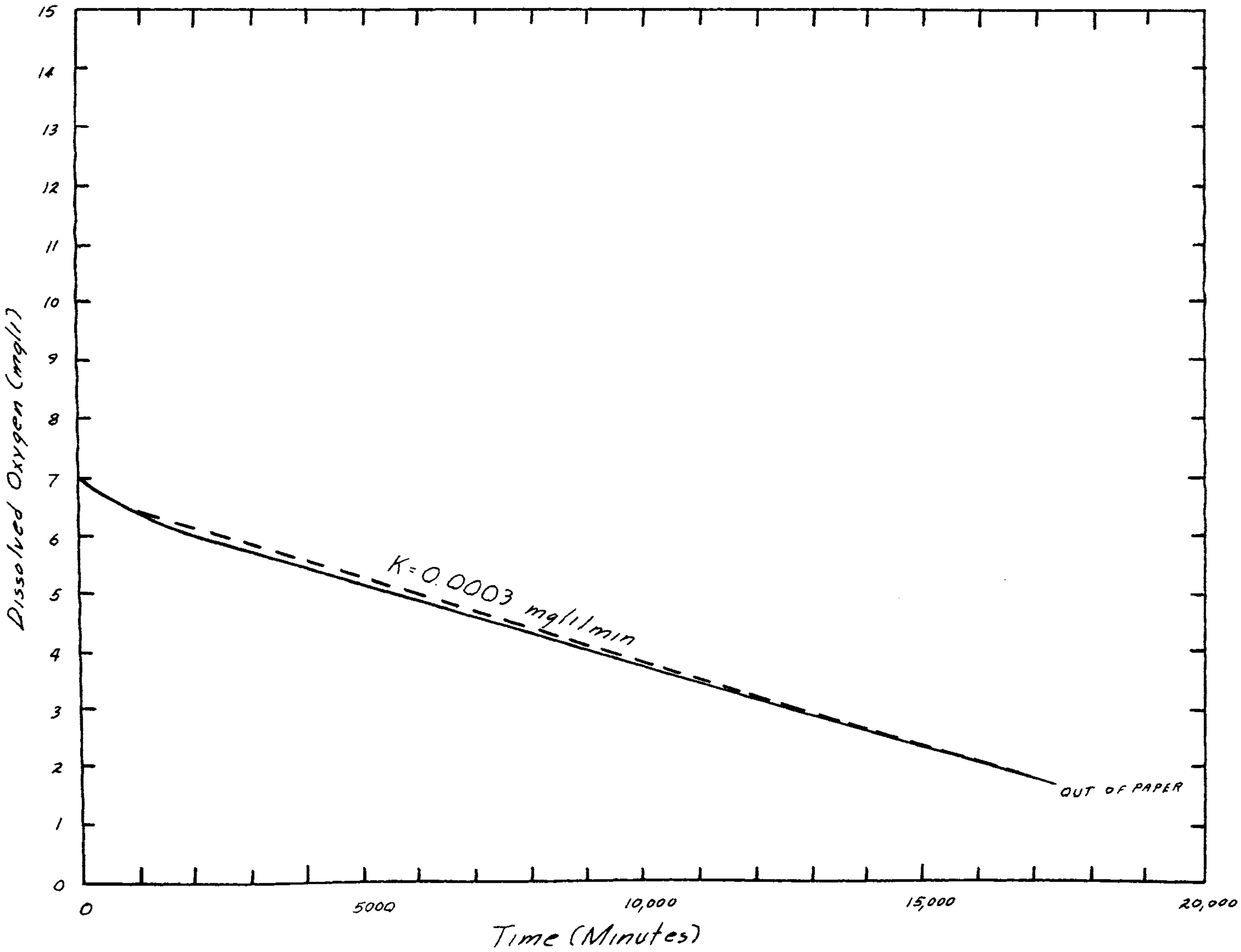

Figure 5-46

Oxygen Consumption by Outlet Sludge at 10°C - Unsettled Supernatant Only (Run #1)

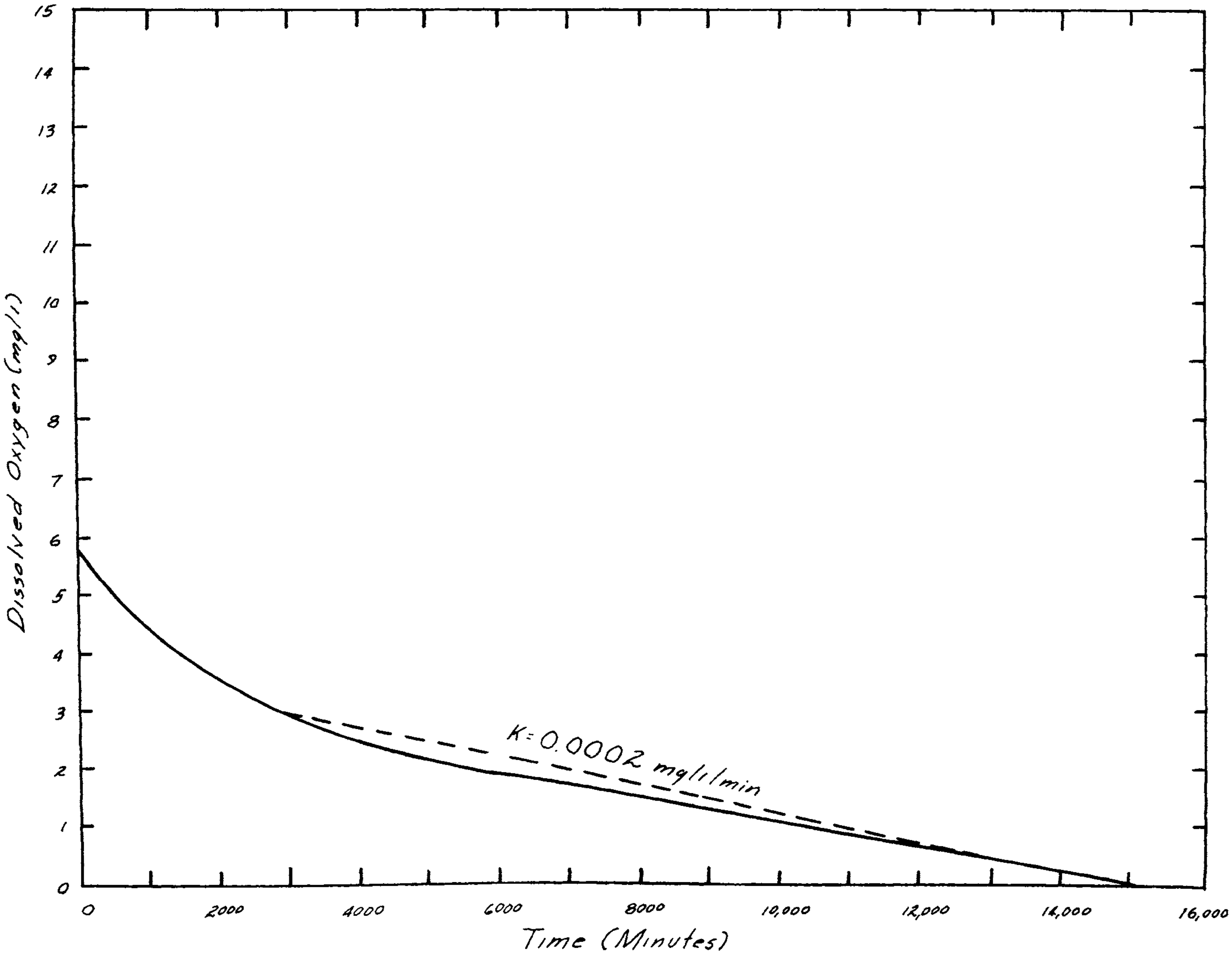

Figure 5-47

Oxygen Consumption by Outlet Sludge at 10°C - Settled Supernatant Only (Run #1)

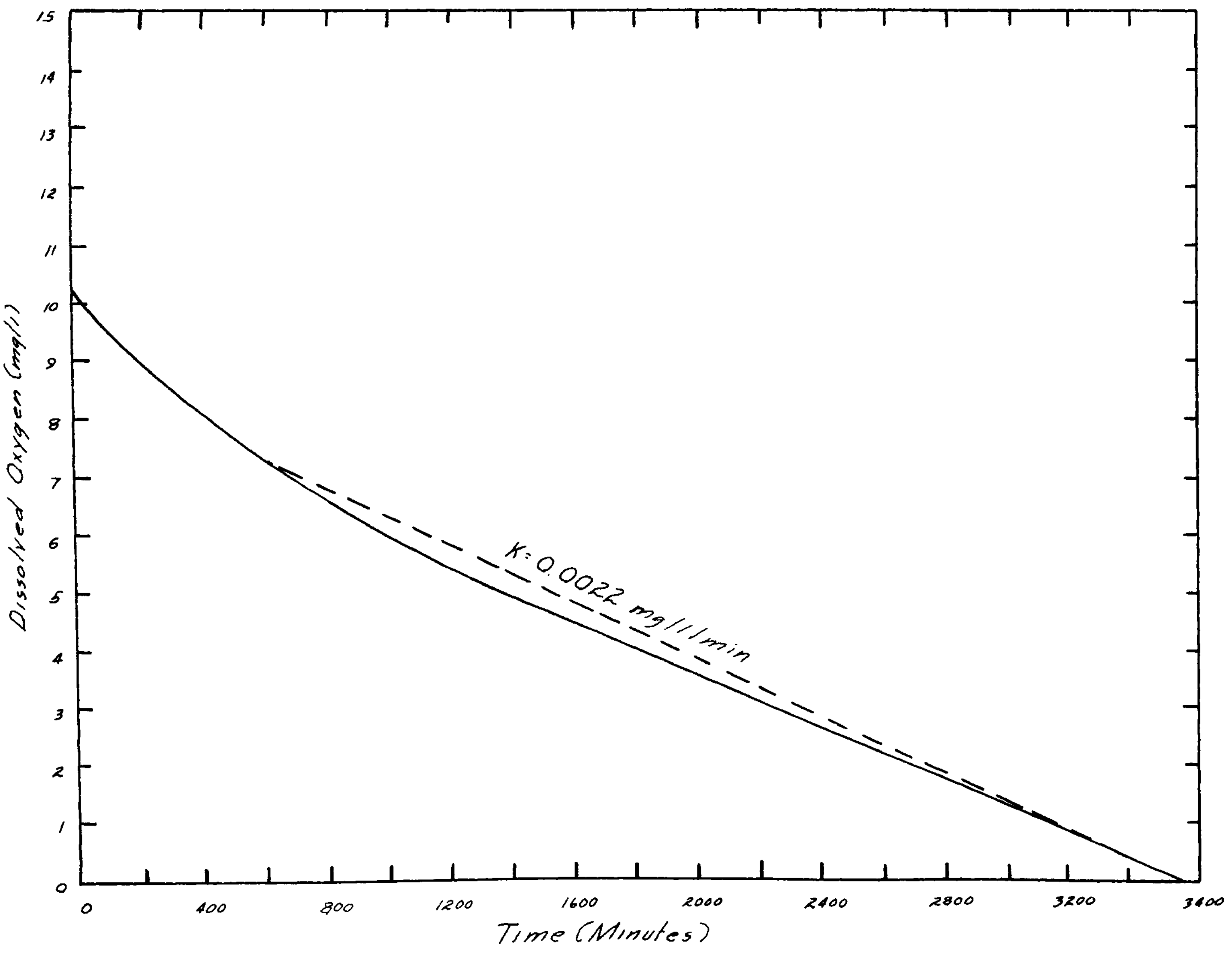

Figure 5-48

Oxygen Consumption by Outlet Sludge at 10°C - Sludge with Supernatant (Run #2)

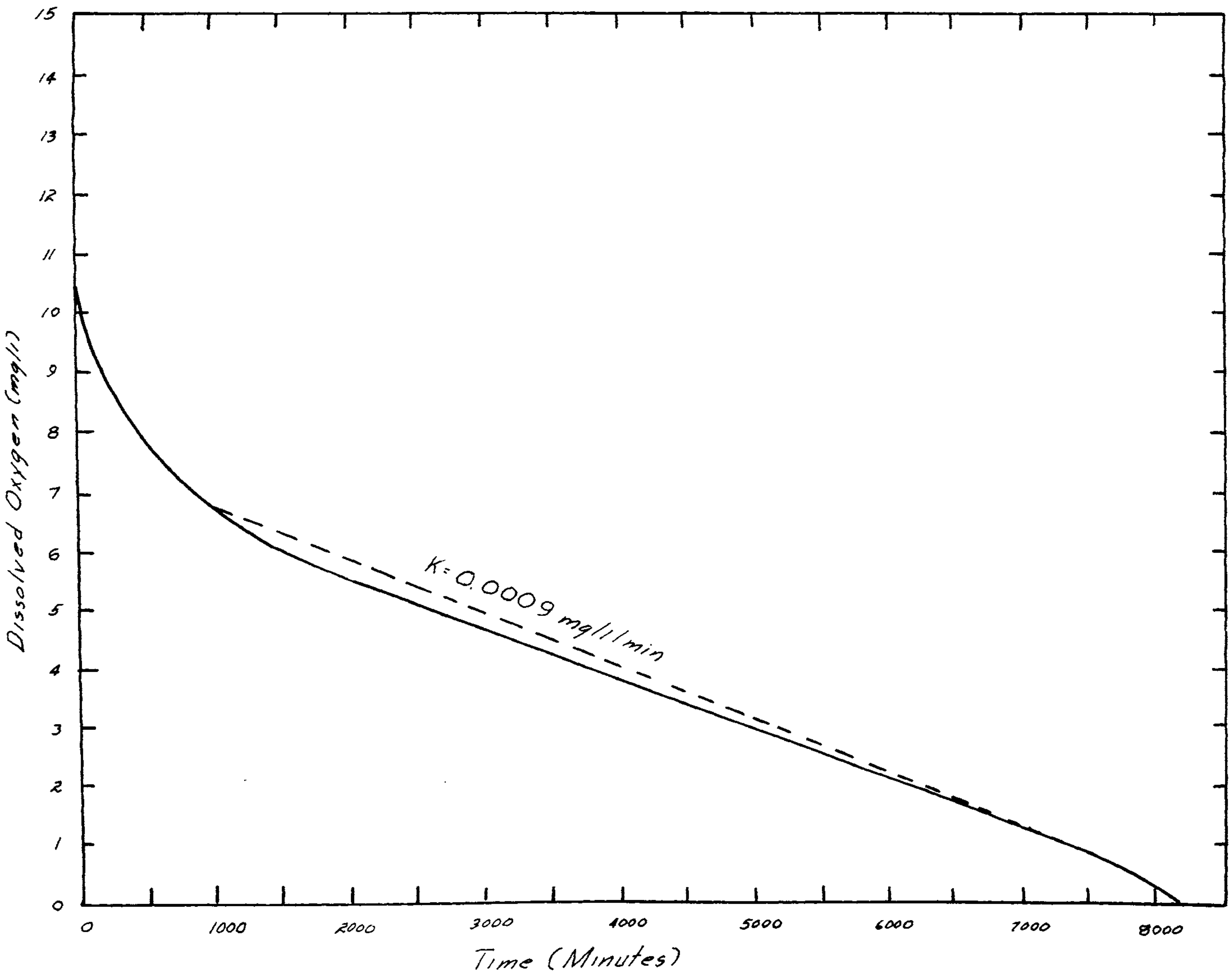

Figure 5-49

Oxygen Consumption by Cutlet Sludge at 10°C - Unsettled Supernatant Only (Run #2)

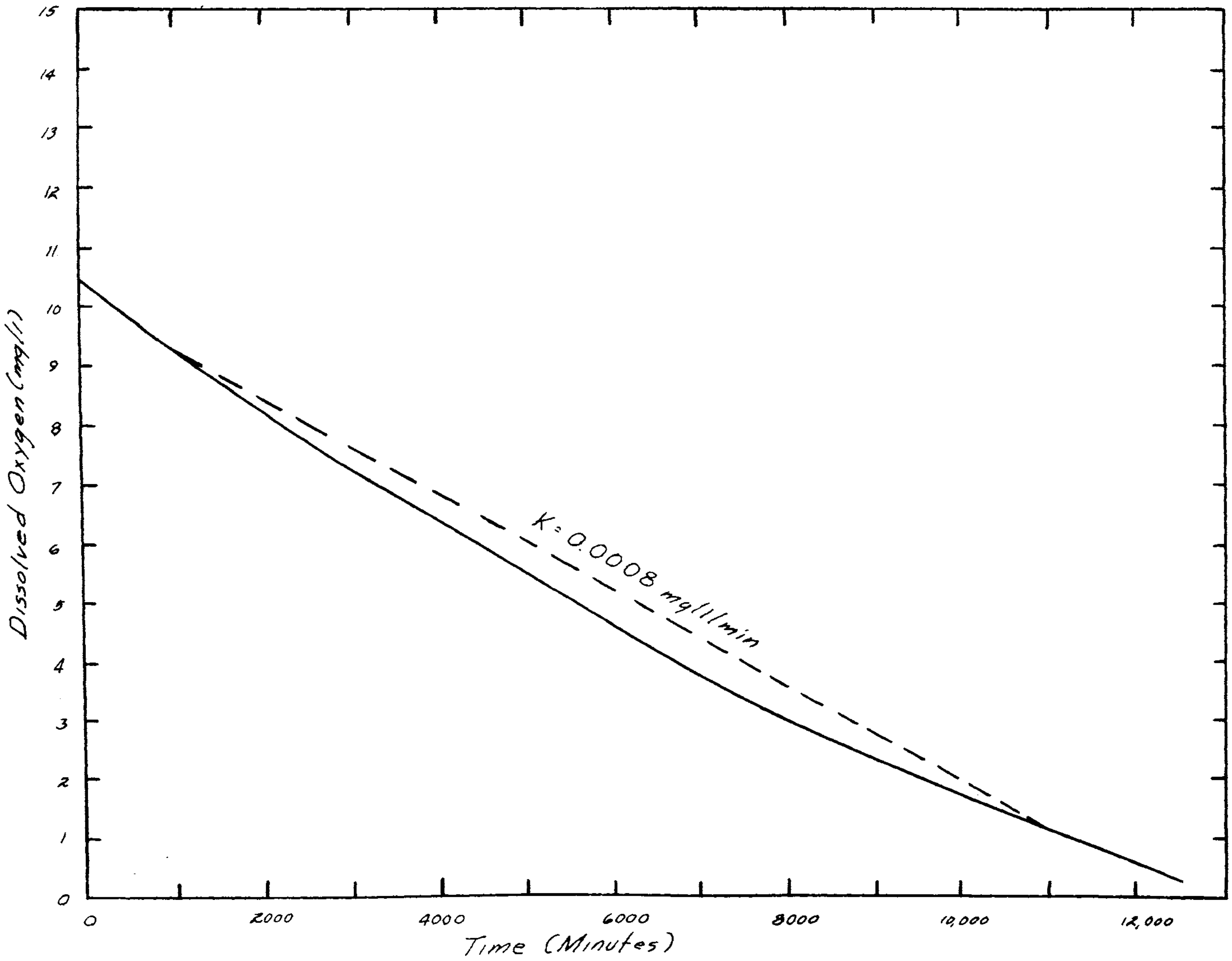

Figure 5-50

Oxygen Consumption by Outlet Sludge at $10^{o}C$ - Settled Supernatant Only (Run #2)

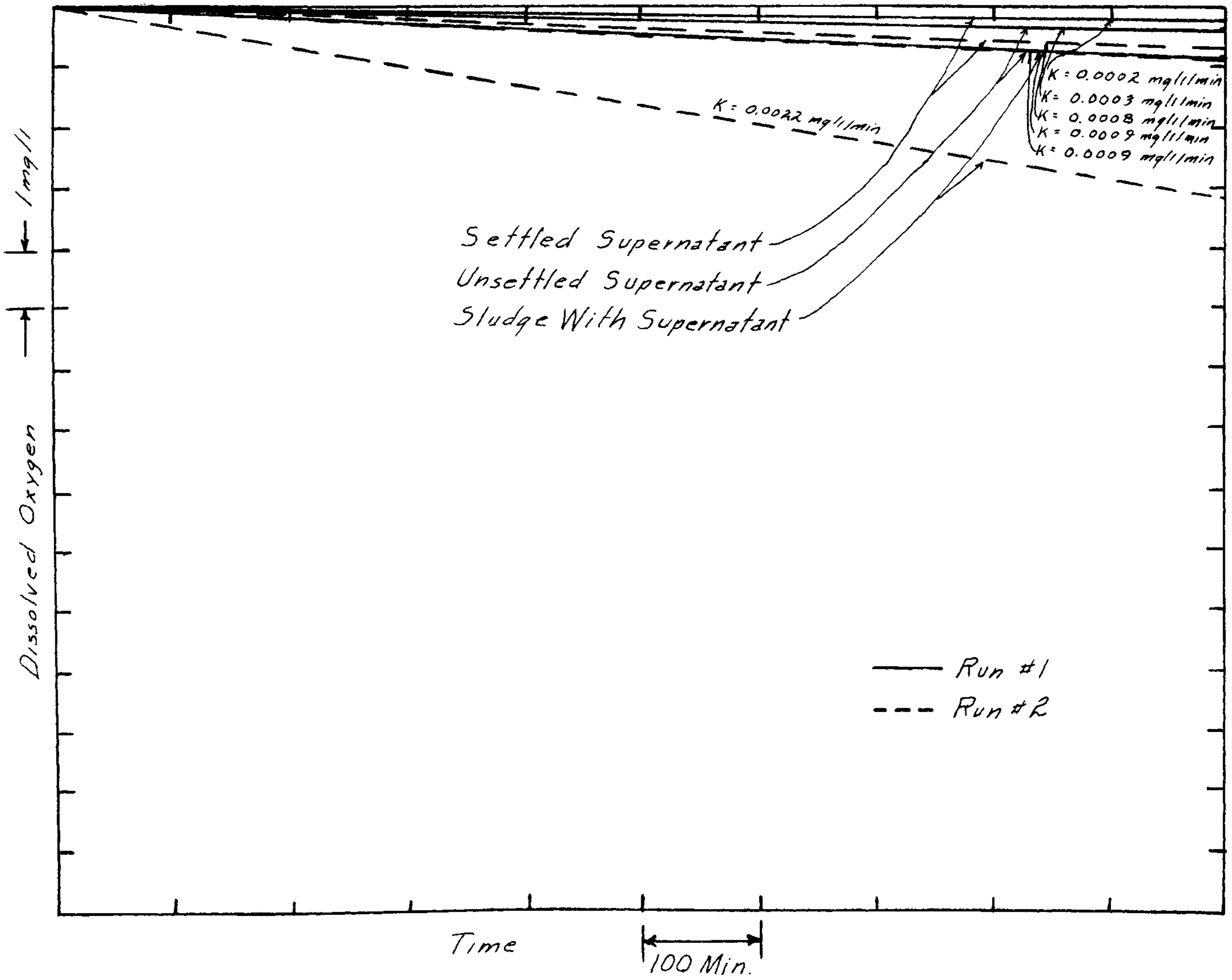

Figure 5-51

Relative Oxygen Consumption Rates of Outlet Sludge Systems at 10°C

Figure 5-46. However, the already recorded portion of the oxygen consumption curve of that test was sufficient to permit the calculation of the average oxygen uptake rate. In some of the tests, as shown in Figures 5-45, 5-47, and 5-49, the data showed a rather high initial oxygen uptake rate followed by a relatively constant uptake of the dissolved oxygen; it is possible that in these test systems there might exist some reduced organic or inorganic matter which consumed a significant amount of dissolved oxygen in order to satisfy their chemical reactions.

The average oxygen uptake rate of each of the outlet sludge systems tested at 10 degrees centigrade are shown in Figure 5-51. Of particular interest is that the uptake rates of these outlet sludge systems were relatively lower than those of the inlet and center sludge systems.

8. Oxygen Consumption by the Outlet Sludge Systems Tested at 22°C

Figures 5-52 through 5-57 illustrate the oxygen utilization by the outlet sludge systems studied at 22 degrees centigrade. The average uptake rate for each test system is shown in Figure 5-57.

9. Oxygen Consumption by the Outlet Sludge Systems Tested at 35°C

The consumption of dissolved oxygen by the outlet sludge systems tested at 35 degrees centigrade are shown in Figures 5-59 through 5-64. As shown in these figures, the initial oxygen levels in the test systems were rather low due to the initial high oxygen demand before the tests were started.

The relative oxygen consumption rates of these systems are compared in Figure 5-65.

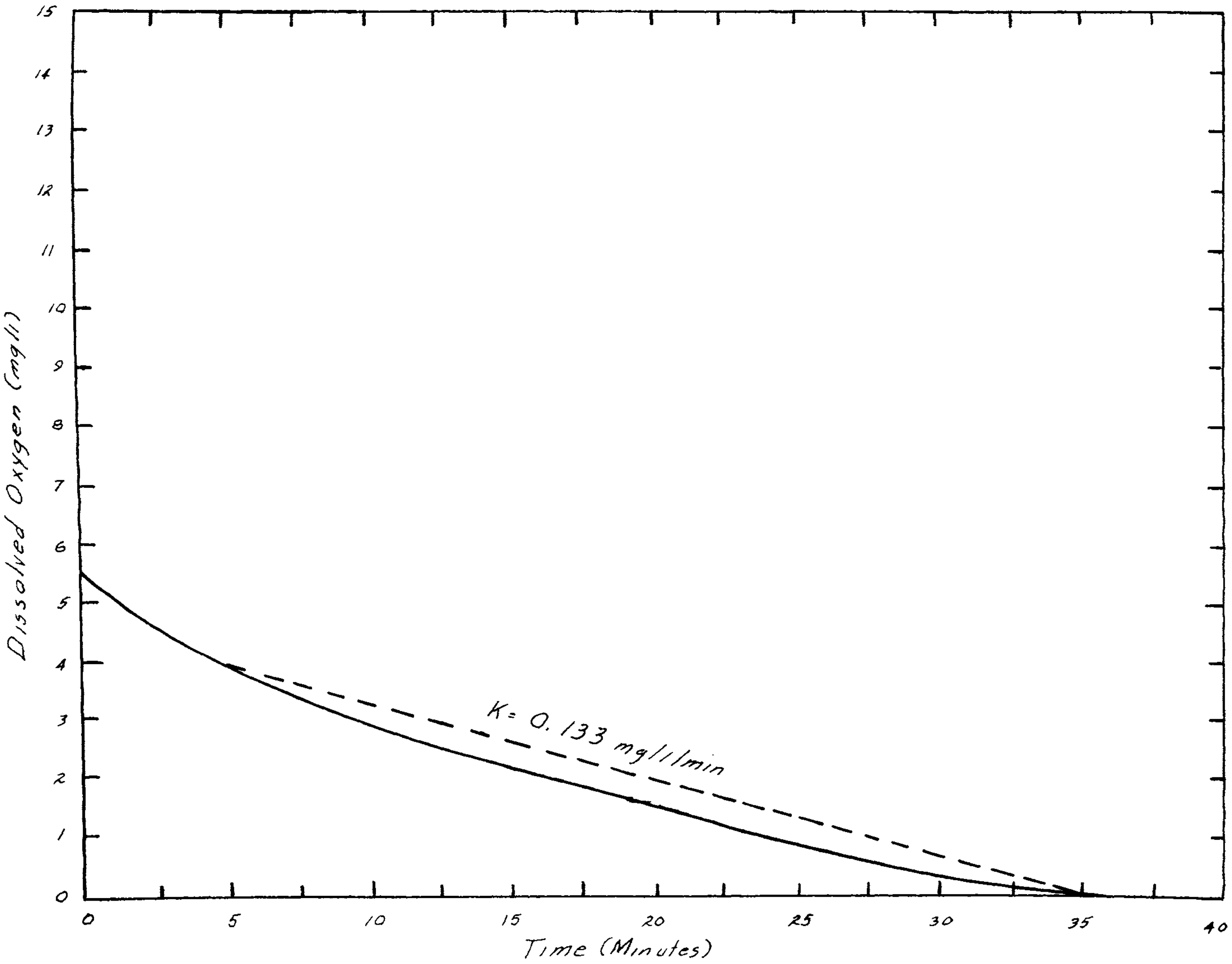

Figure 5-52

Oxygen Consumption by Outlet Sludge at 22°C - Sludge with Supernatant (Run #1)

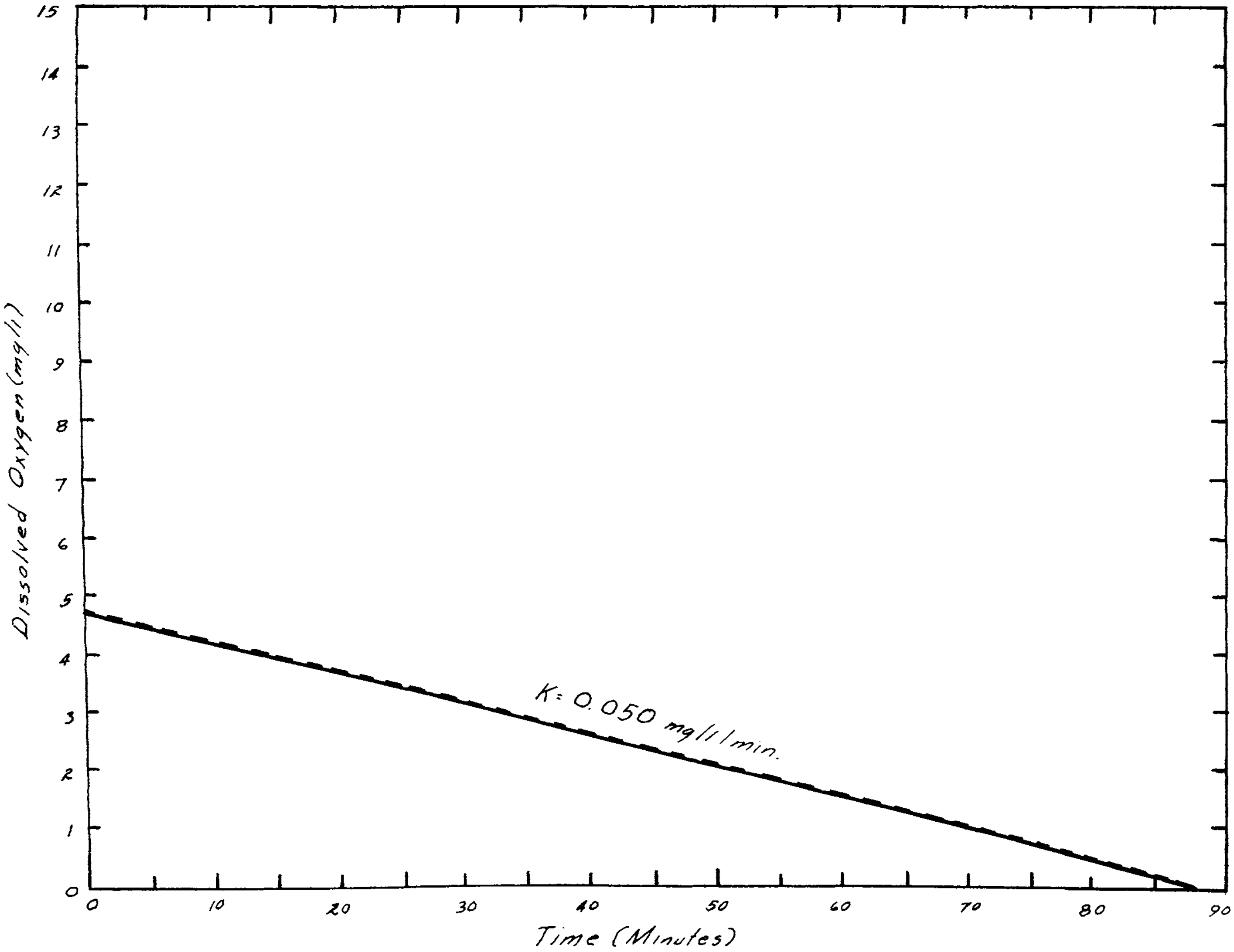

Figure 5-53

Oxygen Consumption by Outlet Sludge at 22°C - Unsettled Supernatant Only (Run #1)

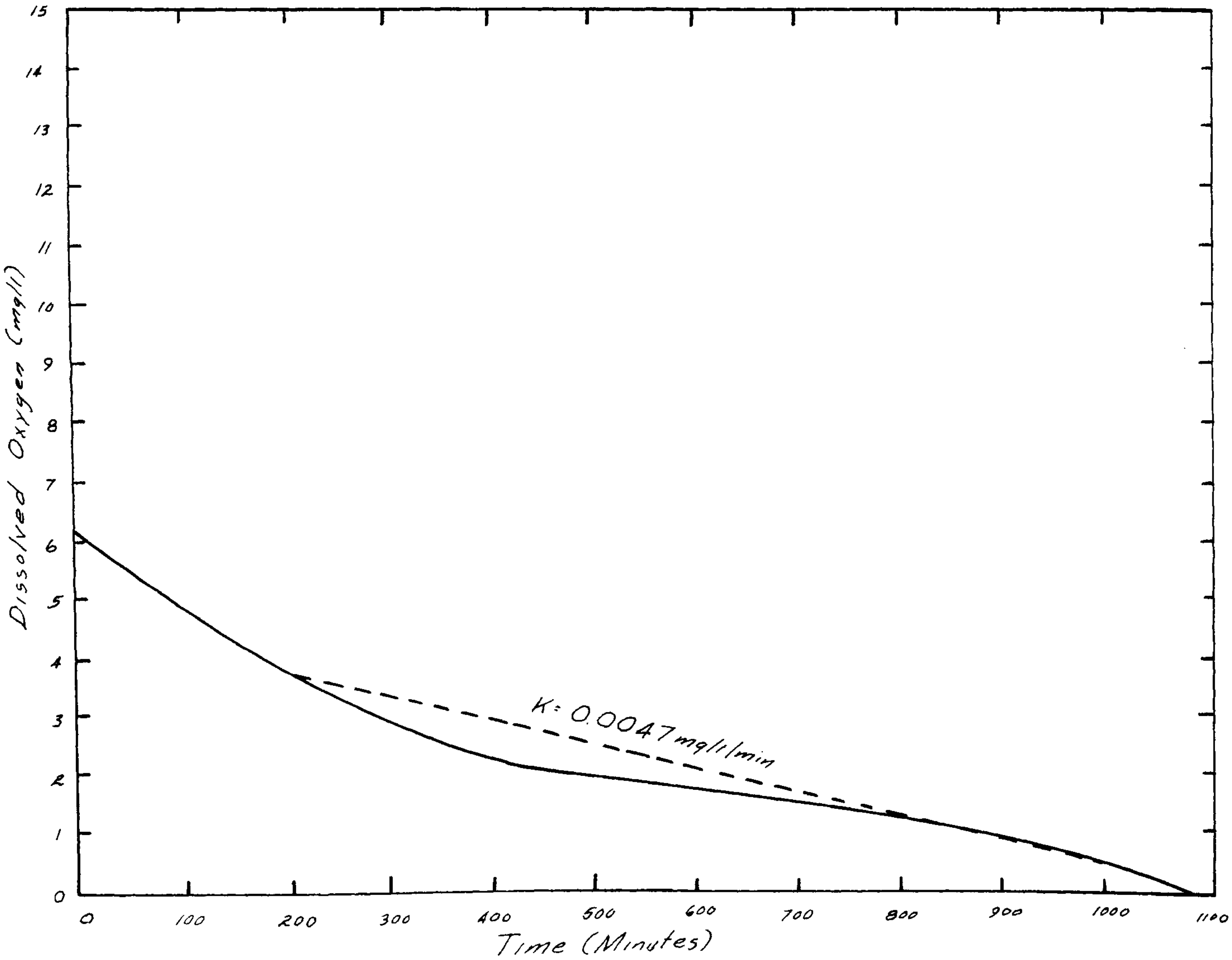

Figure 5-54

Oxygen Consumption by Outlet Sludge at 22°C - Settled Supernatant Only (Run #1)

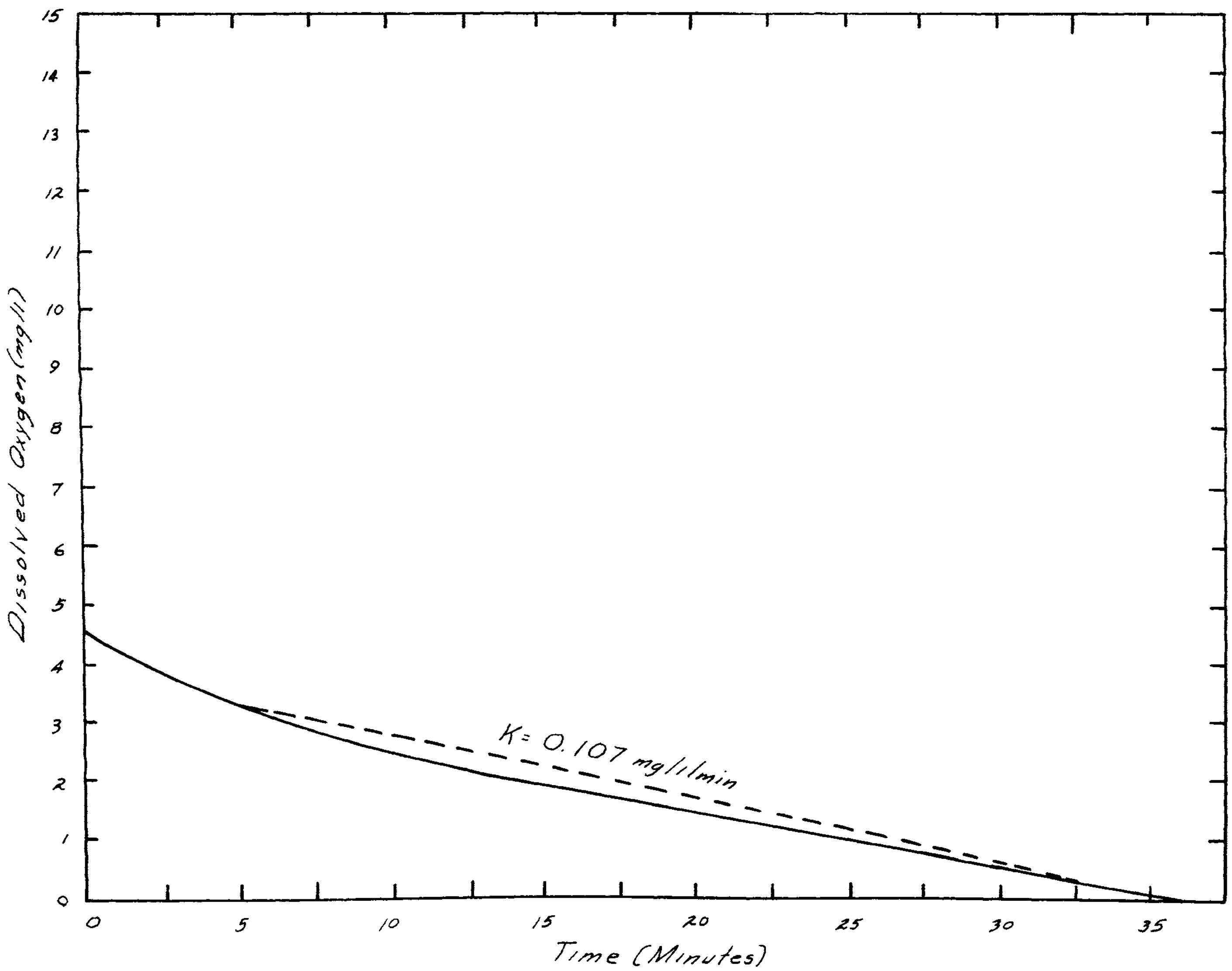

Figure 5-55

Oxygen Consumption by Outlet Sludge at 22°C - Sludge with Supernatant (Run #2)

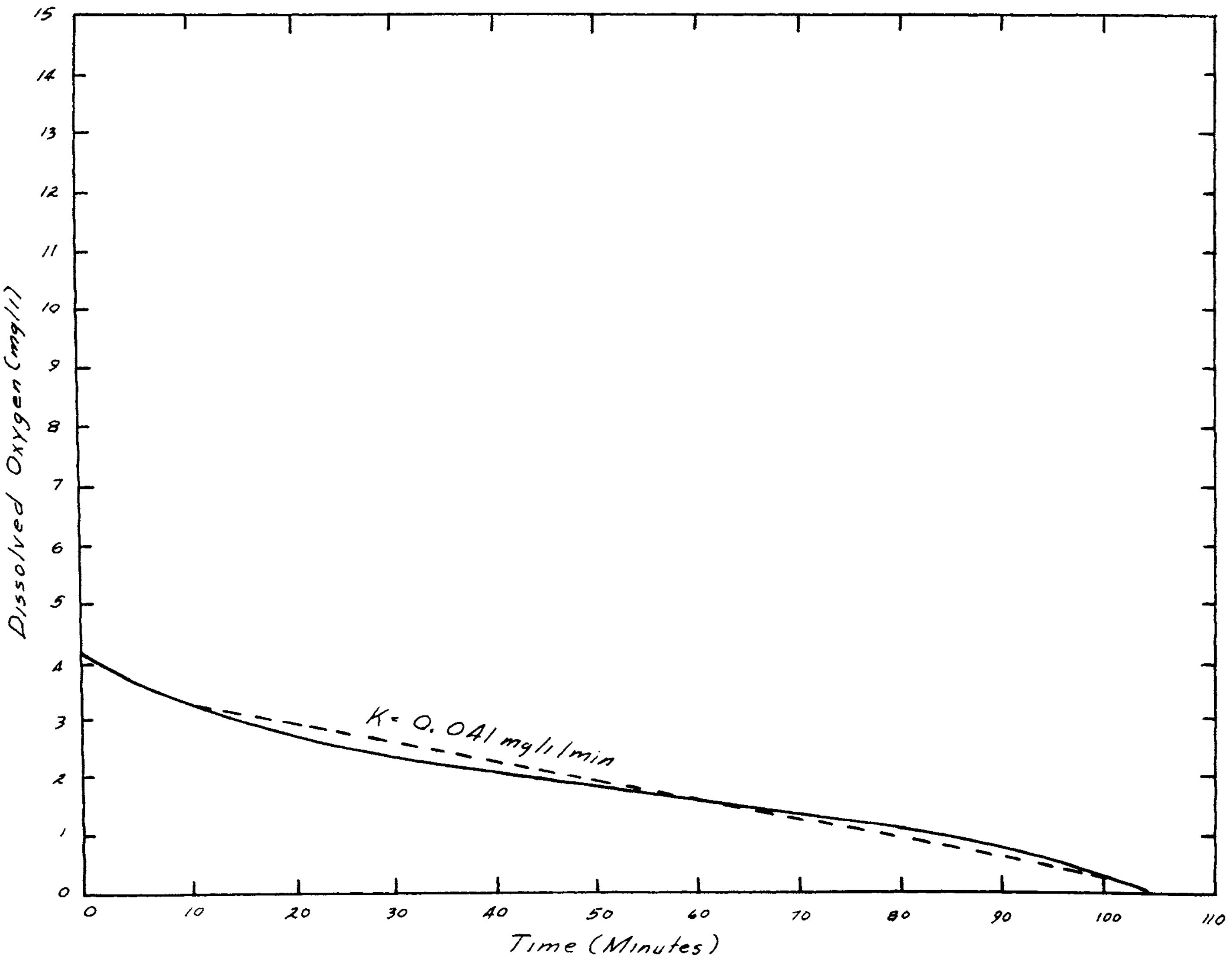

Figure 5-56

Oxygen Consumption by Outlet Sludge at 22°C - Unsettled Supernatant Only (Run #2)

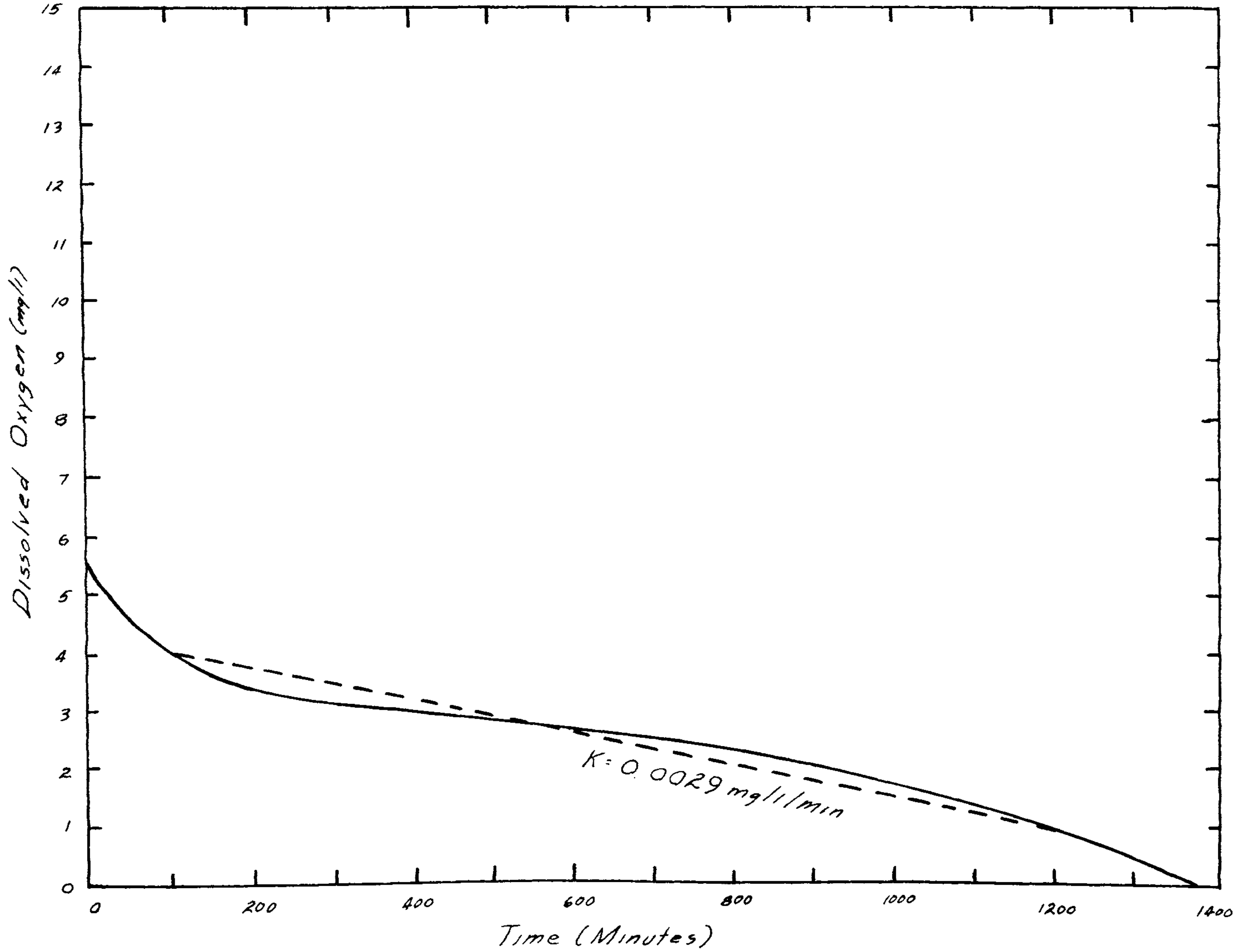

Figure 5-57

Oxygen Consumption by Outlet Sludge at 22°C - Settled Supernatant Only (Run #2)

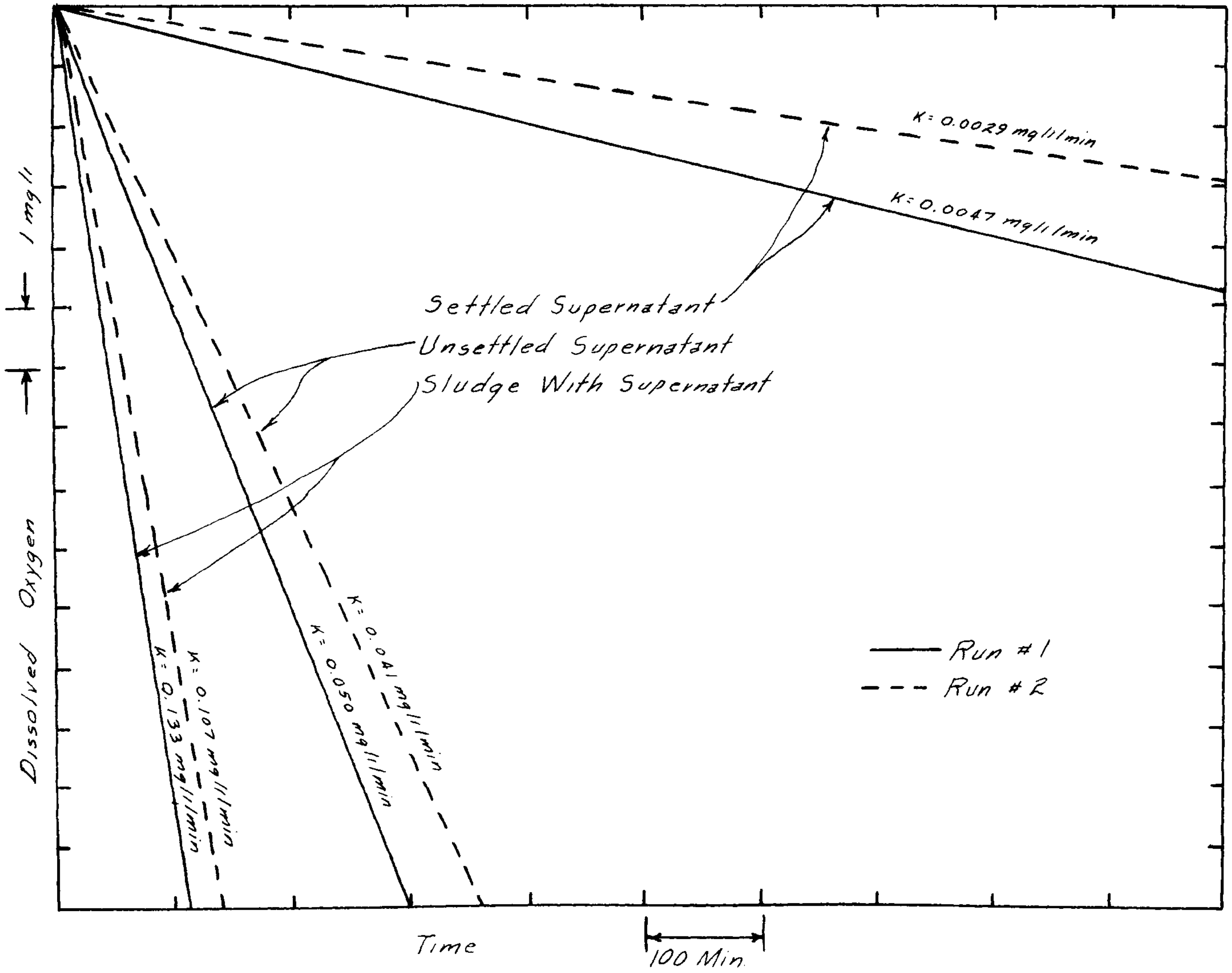

Figure 5-58

Relative Oxygen Consumption Rates of Outlet Sludge Systems at 22°C

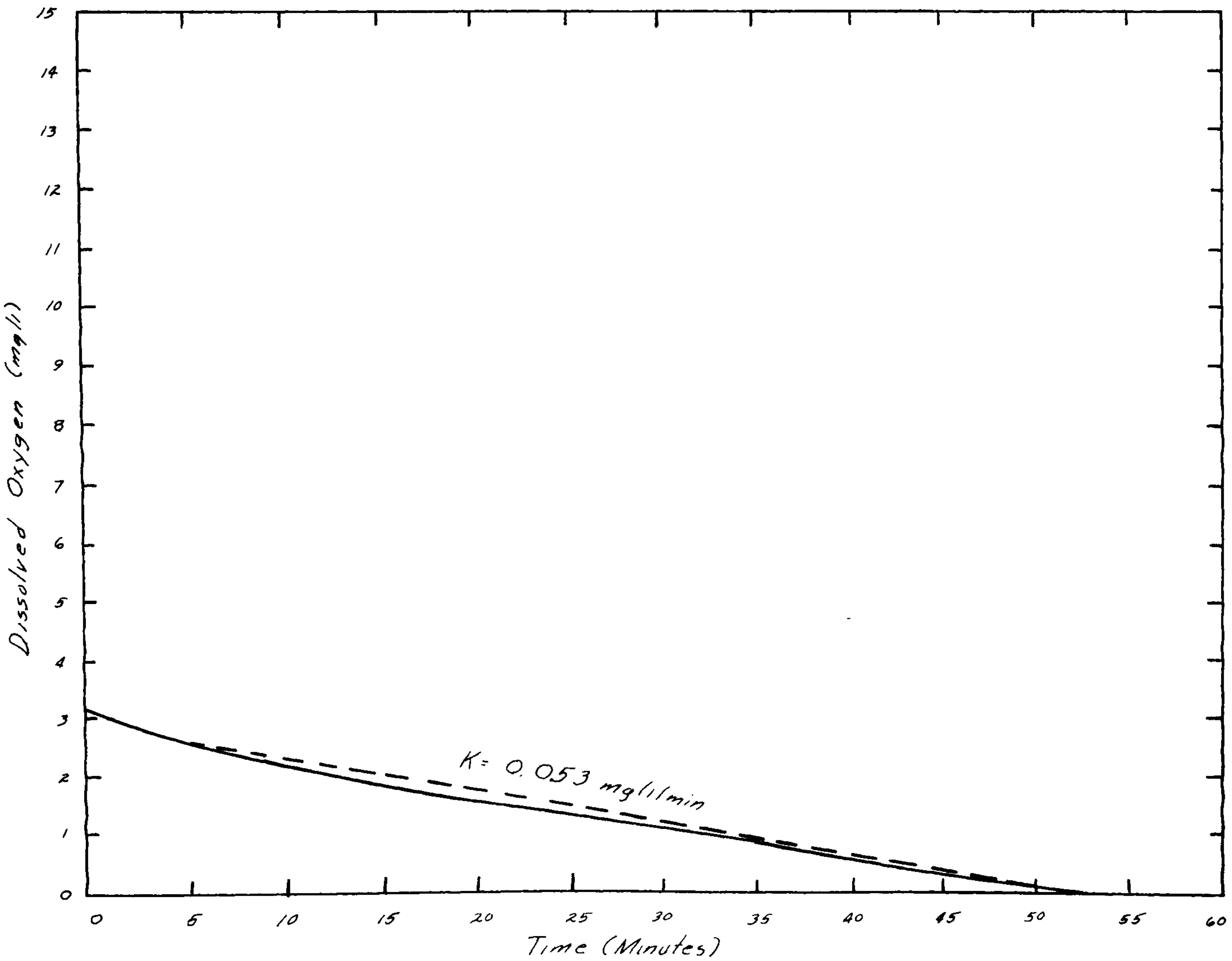

Figure 5-59

Oxygen Consumption by Outlet Sludge at 35°C - Sludge with Supernatant (Run #1)

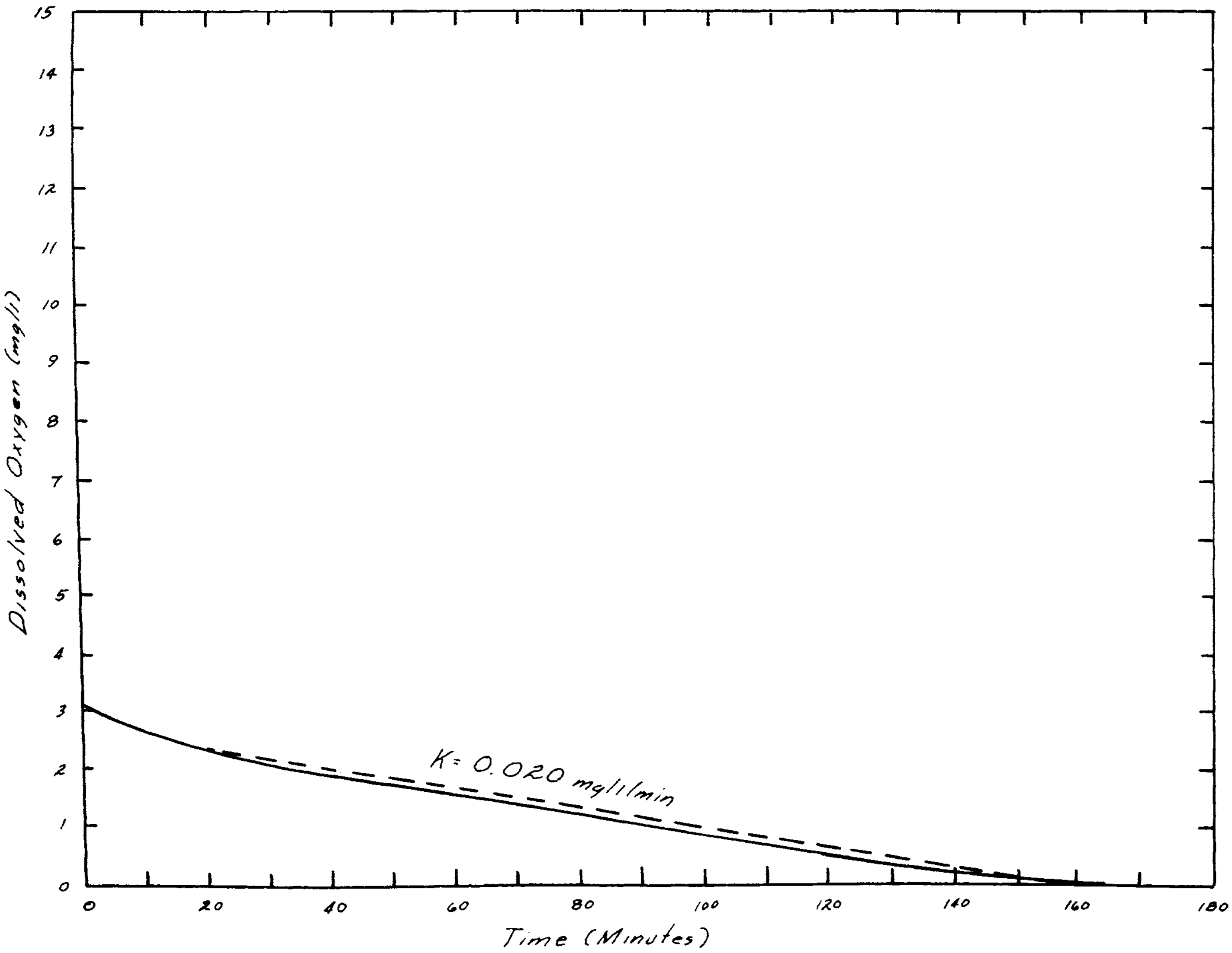

Figure 5-60

Oxygen Consumption by Outlet Sludge at 35°C - Unsettled Supernatant Only (Run #1)

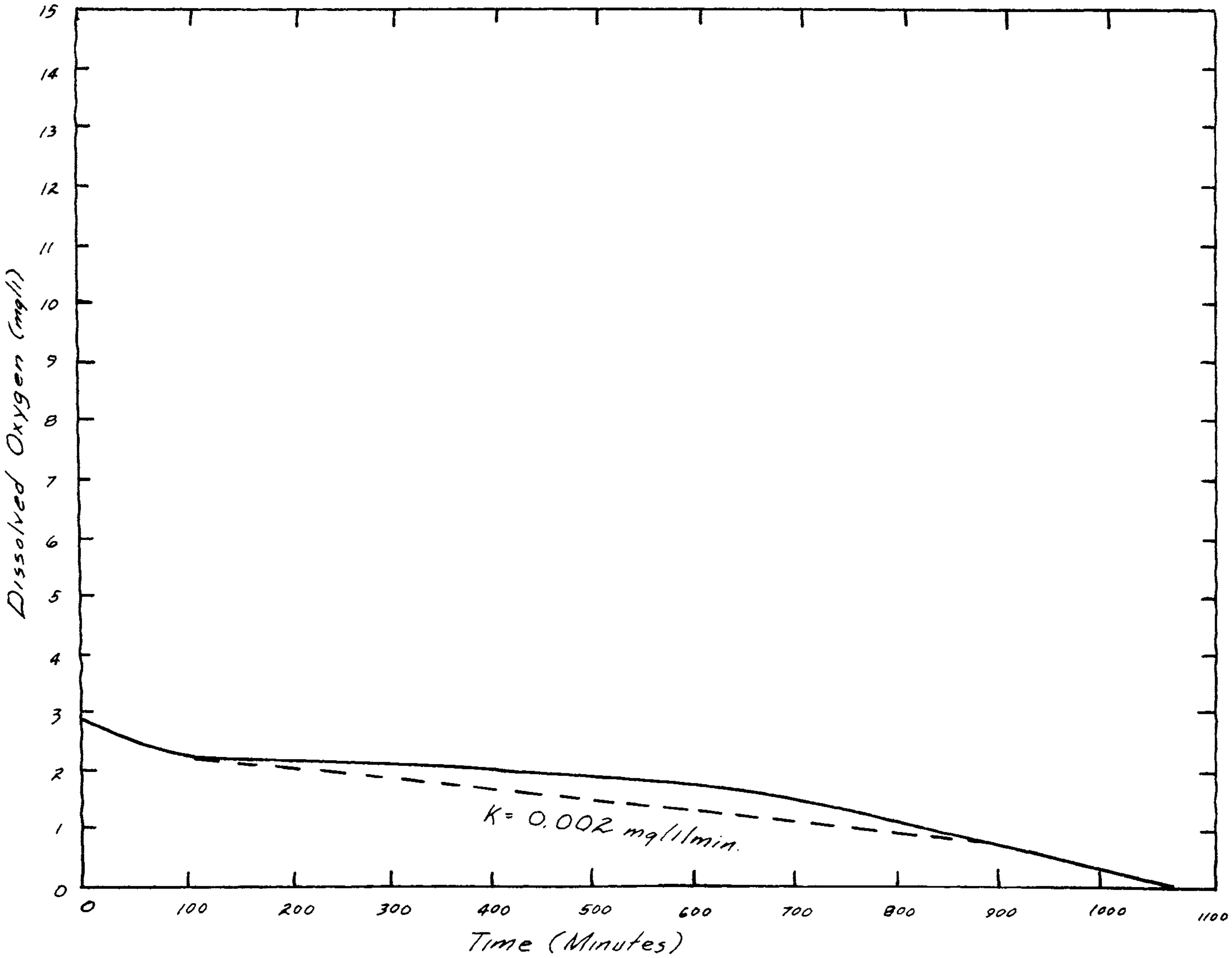

Figure 5-61

Oxygen Consumption by Outlet Sludge at 35°C - Settled Supernatant Only (Run #1)

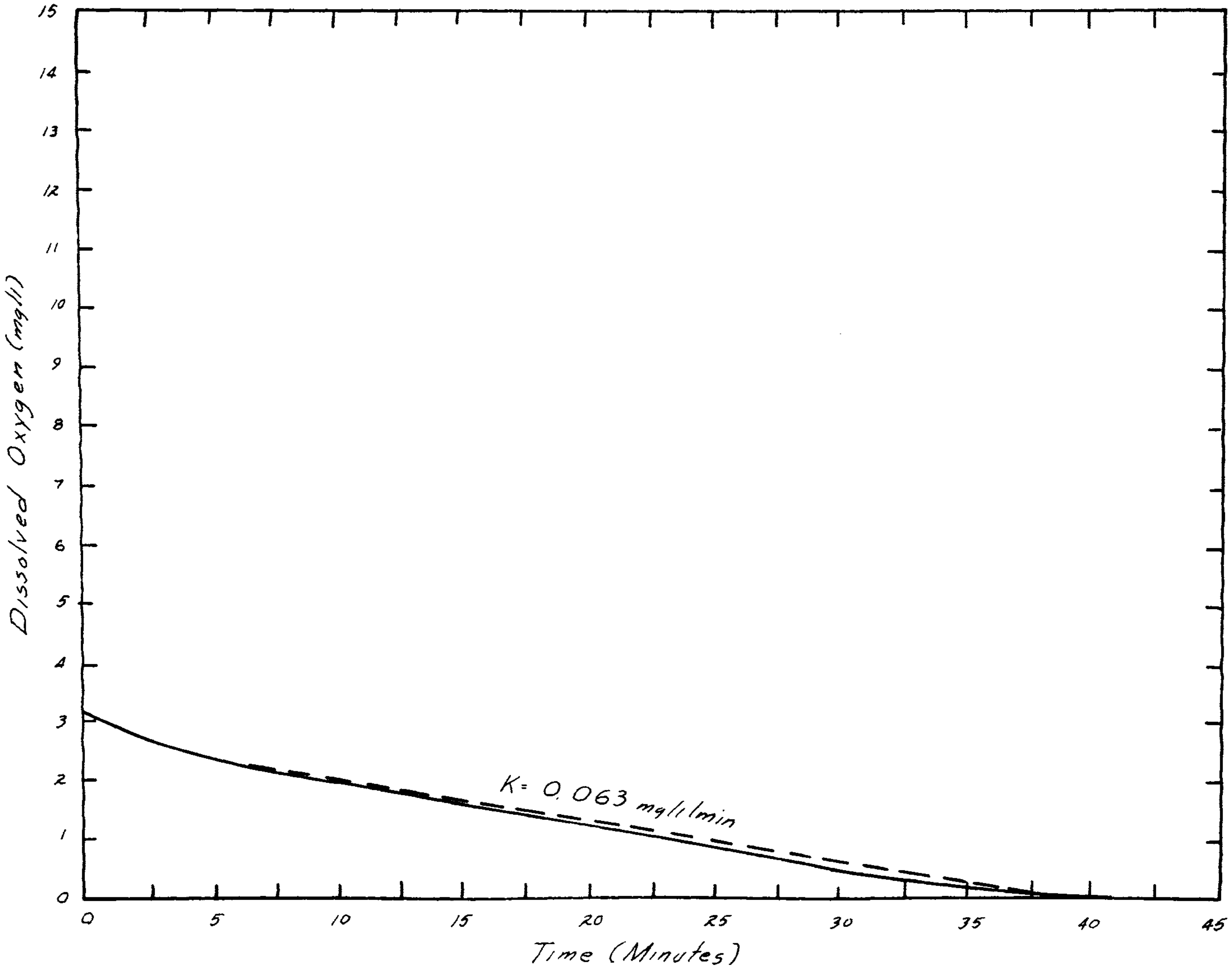

Figure 5-62

Oxygen Consumption by Outlet Sludge at 35°C - Sludge with Supernatant (Run #2)

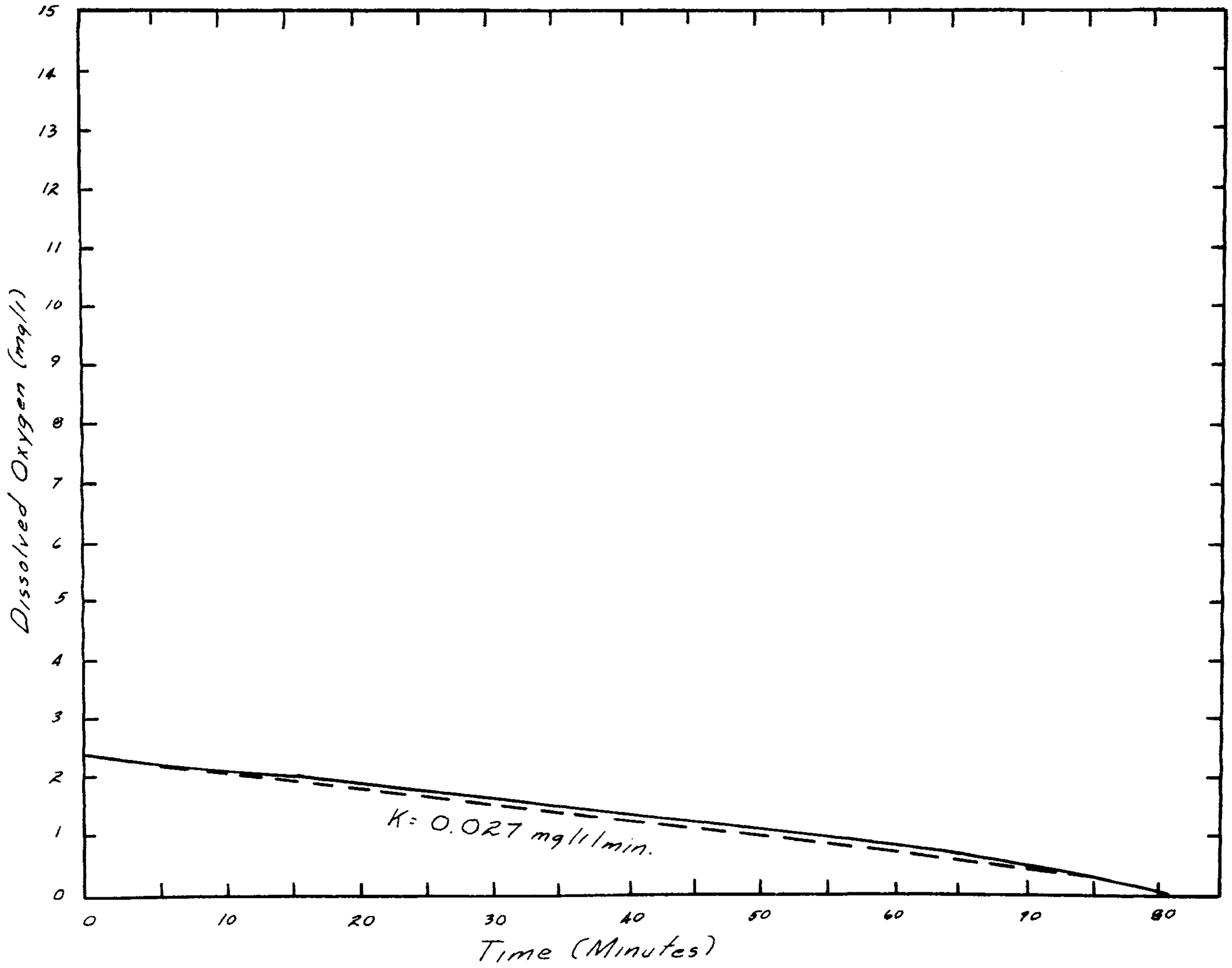

Figure 5-63

Oxygen Consumption by Outlet Sludge at 35°C - Unsettled Supernatant Only (Run #2)

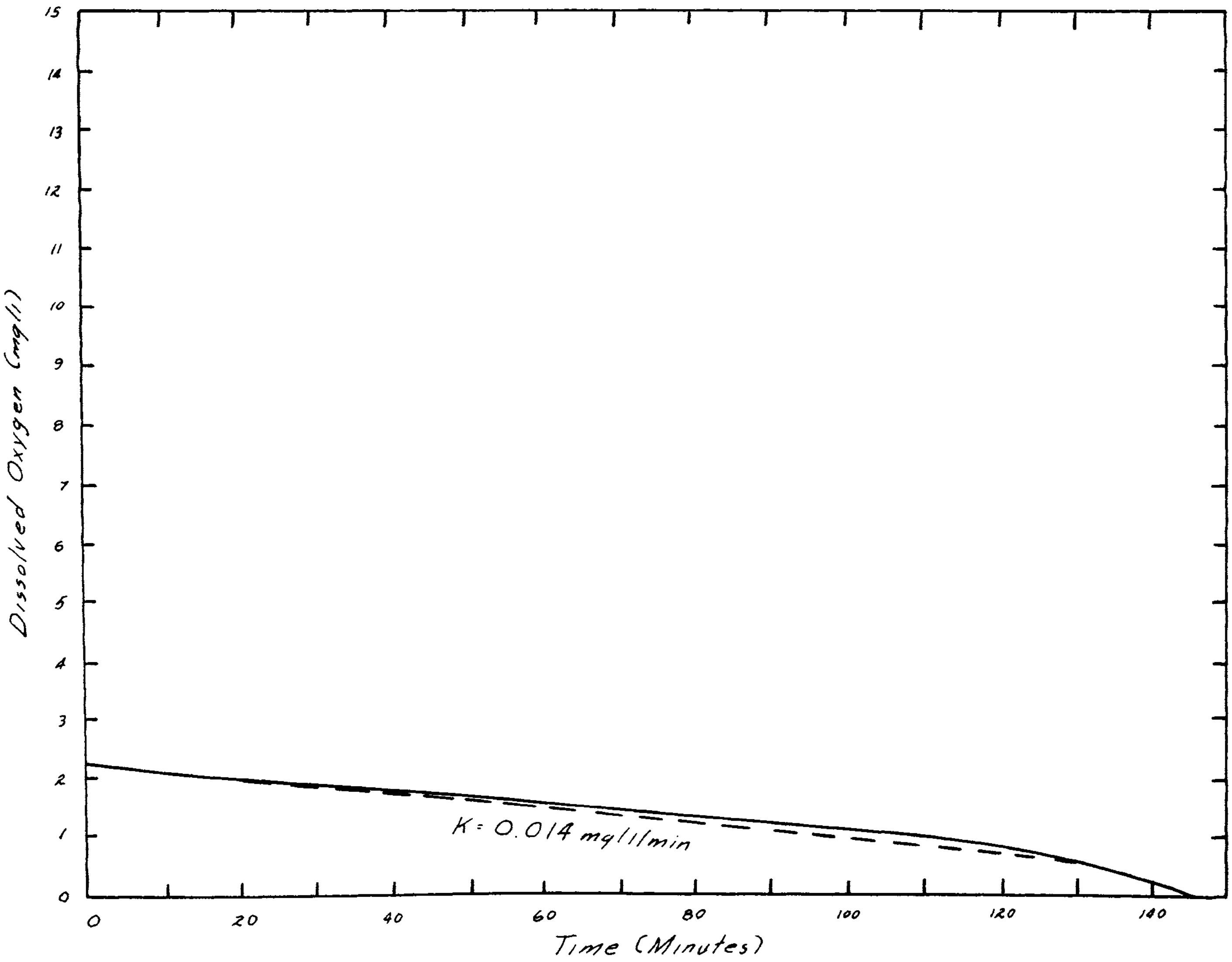

Figure 5-64

Oxygen Consumption by Outlet Sludge at 35°C - Settled Supernatant Only (Run #2)

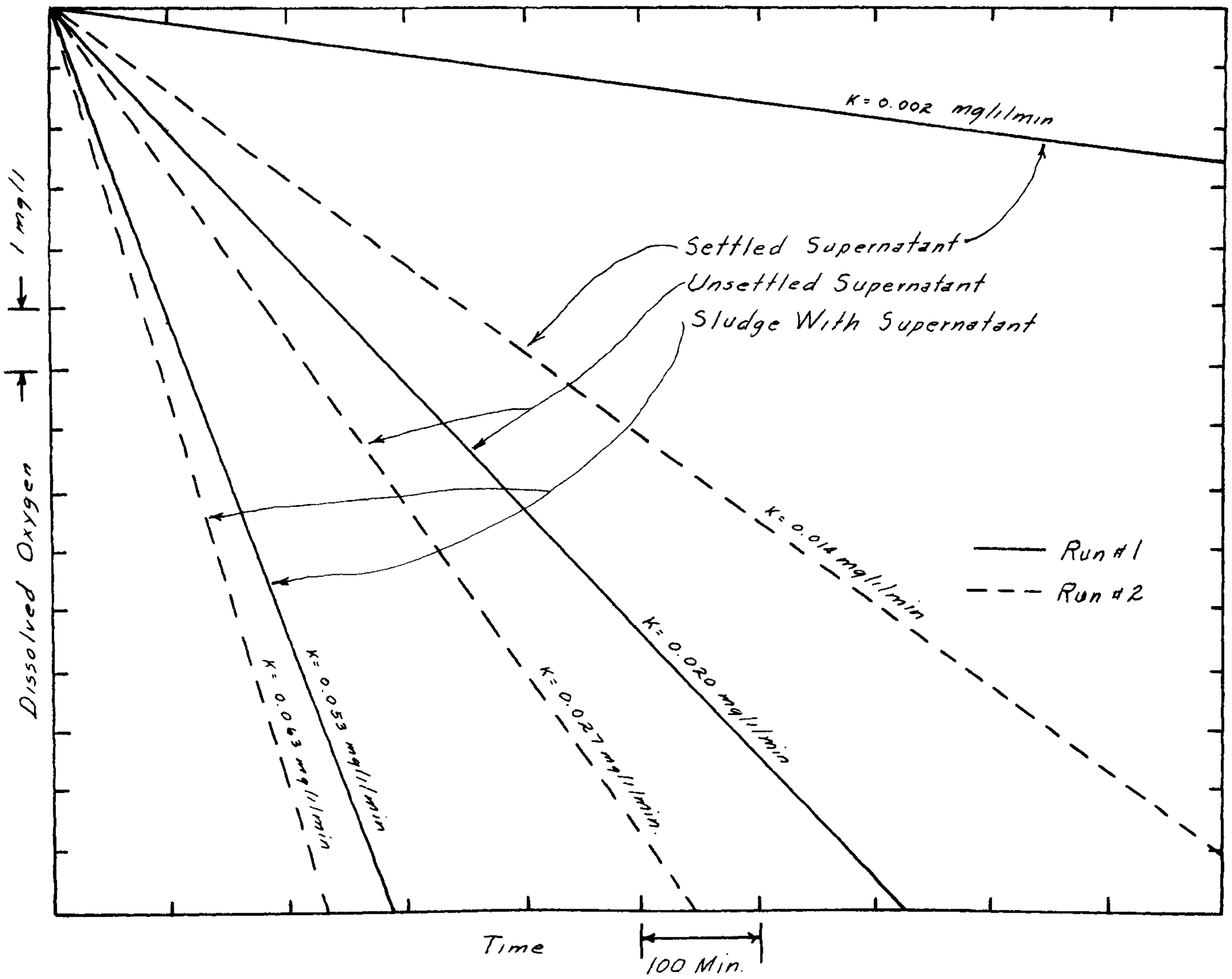

Figure 5-65

Relative Oxygen Consumption Rates of Outlet Sludge Systems at 35°C

B. Summary of Oxygen Consumption Rates and the Test Supernatant Characteristics

As described earlier in this chapter, the oxygen consumption rate for each test system can be calculated from the slope of a representative portion of the uptake curve. These rate values have been shown in the previously presented oxygen consumption curves, and are now summarized in Tables 5-1, 5-2, and 5-3. Presented in these three tables are also certain supernatant characteristics of each test system including suspended solids (SS), volatile suspended solids (VSS), chemical oxygen demand (COD), pH, and alkalinity of the supernatant.

As shown in these tables, there appears to be little consistency in the oxygen uptake rates between the two experimental runs for each test condition; this is primarily due to the inconsistency in the suspended solids content. Other possible reasons for this discrepancy will be given in the next chapter of Discussion.

The dissolved oxygen consumption by the unsettled supernatant system can be subtracted from the dissolved oxygen consumed by the sludge with supernatant system to give an indication of the oxygen consumption by the sludge phase alone. This resultant value in mg/l/min can be converted to $mg/min/m^2$ as described previously in this chapter. A summary of the oxygen utilization by the sludge phase alone is presented in Table 5-4. Similar to the data presented in the previous three tables, the oxygen uptake rate by the sludge alone were not the same, or even close, between the two experimental runs for each test condition. However, the data shown in Table 5-4 seems to reflect the trend that the oxygen utilization rate of the

Test Temp °C	Run No.	Test System	D.O. Consumption Rates		Supernatant Characteristics				
			mg/l/min	mg/min/m^2	S.S. mg/l	V.S.S. mg/l	COD mg/l	pH	AlK mg/l as $CaCO_3$
10	1	Sludge with Supernatant	0.0021	6.05	44	8	106	--	--
		Unsettled Supernatant only	0.0009	--	44	8	95	--	--
		Settled Supernatant only	0.0006	--	32	8	97	6.5	36
	2	Sludge with Supernatant	0.039	11.11	2,760	1,452	2,555	--	--
		Unsettled Supernatant only	0.024	--	2,760	1,452	2,070	--	--
		Settled Supernatant only	0.0029	--	136	132	331	7.0	86
22	1	Sludge with Supernatant	0.032	9.16	1,303	718	1,200	--	--
		Unsettled Supernatant only	0.051	--	1,303	718	1,120	--	--
		Settled Supernatant only	0.020	--	200	180	564	6.6	56
	2	Sludge with Supernatant	0.096	27.35	3,380	1,692	3,195	--	--
		Unsettled Supernatant only	0.038	--	3,380	1,692	3,080	--	--
		Settled Supernatant only	0.0075	--	364	204	648	6.6	64
35	1	Sludge with Supernatant	0.0021	6.05	44	4,860	9,990	--	--
		Unsettled Supernatant only	0.0009	--	44	4,860	6,615	--	--
		Settled Supernatant only	0.0006	--	32	344	946	6.5	36
	2	Sludge with Supernatant	0.039	11.11	2,760	4,755	9,400	--	--
		Unsettled Supernatant only	0.024	--	2,760	4,755	10,330	--	--
		Settled Supernatant only	0.0029	--	136	248	932	7.0	86

Table 5-1

Summary of Oxygen Consumption Rates

and Supernatant Characteristics for Inlet Sludge Systems

Test Temp °C	Run No.	Test System	D.O. Consumption Rates mg/l/min	D.O. Consumption Rates mg/min/m^2	Supernatant Characteristics S.S. mg/l	V.S.S. mg/l	COD mg/l	pH	AlK mg/l as $CaCO_3$
10	1	Sludge with Supernatant	0.133	35.9	12,280	5,880	--	--	--
		Unsettled Supernatant only	0.144	--	12,280	5,880	--	--	--
		Settled Supernatant only	0.0057	--	368	272	536	7.3	136
	2	Sludge with Supernatant	0.084	23.95	3,110	1,488	3,840	--	--
		Unsettled Supernatant only	0.062	--	3,110	1,488	--	--	--
		Settled Supernatant only	0.0031	--	204	200	550	7.1	50
22	1	Sludge with Supernatant	0.329	93.8	7,000	2,976	5,460	--	--
		Unsettled Supernatant only	0.173	--	7,000	2,976	--	--	--
		Settled Supernatant only	0.012	--	222	146	490	7.2	70
	2	Sludge with Supernatant	0.289	82.4	6,000	2,360	5,100	--	--
		Unsettled Supernatant only	0.055	--	6,000	2,360	--	--	--
		Settled Supernatant only	0.0075	--	228	100	525	6.0	42
35	1	Sludge with Supernatant	0.153	43.7	7,620	2,990	5,460	--	--
		Unsettled Supernatant only	0.077	--	7,620	2,990	--	--	--
		Settled Supernatant only	0.0056	--	148	76	278	7.5	78
	2	Sludge with Supernatant	0.293	83.5	4,024	1,294	1,882	--	--
		Unsettled Supernatant only	0.028	--	4,024	1,294	--	--	--
		Settled Supernatant only	0.0063	--	124	56	141	7.0	62

Table 5-2

Summary of Oxygen Consumption Rates

and Supernatant Characteristics for Center Sludge Systems

Test Temp °C	Run No.	Test System	D.O. Consumption Rates		Supernatant Characteristics				
			mg/l/min	mg/min/m^2	S.S. mg/l	V.S.S. mg/l	COD mg/l	pH	AlK mg/l as $CaCO_3$
10	1	Sludge with Supernatant	0.0009	0.251	8	6	35	--	--
		Unsettled Supernatant only	0.0003	--	8	6	38	--	--
		Settled Supernatant only	0.0002	--	8	6	41	6.3	48
	2	Sludge with Supernatant	0.0022	0.629	24	16	116	--	--
		Unsettled Supernatant only	0.0009	--	24	16	101	--	--
		Settled Supernatant only	0.0008	--	14	8	90	6.8	62
22	1	Sludge with Supernatant	0.133	38.10	3,240	1,310	2,715	--	--
		Unsettled Supernatant only	0.050	--	3,240	1,310	2,160	--	--
		Settled Supernatant only	0.0047	--	156	112	212	6.9	42
	2	Sludge with Supernatant	0.107	30.60	2,320	845	1,644	--	--
		Unsettled Supernatant only	0.041	--	2,320	845	1,069	--	--
		Settled Supernatant only	0.0029	--	124	72	150	6.7	30
35	1	Sludge with Supernatant	0.053	15.22	1,072	544	1,307	--	--
		Unsettled Supernatant only	0.020	--	1,072	544	420	--	--
		Settled Supernatant only	0.002	--	112	104	115	6.4	40
	2	Sludge with Supernatant	0.063	18.10	2,190	867	2,612	--	--
		Unsettled Supernatant only	0.027	--	2,190	867	1,107	--	--
		Settled Supernatant only	0.014	--	224	76	258	7.4	122

Table 5-3

Summary of Oxygen Consumption Rates

and Supernatant Characteristics for Outlet Sludge Systems

Test Temperature °C	Run Number	Oxygen Consumption Rates by the Sludges Alone mg/min/m^2		
		Inlet Sludge	Center Sludge	Outlet Sludge
10	1	-0.345	-2.69	0.143
	2	4.29	6.58	0.457
22	1	-5.42	44.4	23.65
	2	16.53	66.3	18.81
35	1	201	21.6	9.50
	2	106.0	73.0	10.50

Table 5-4

Summary of the Oxygen Consumption Rates by the Sludge Phases Alone sludge phase increased with temperature and also with proximity to the inlet. It was noted in this research program that the sludge collected near the inlet was less gelatinous and less cohesive than that collected in the pond center and outlet. The sludge from the outlet showed the highest degree of cohesiveness. Figures 5-66, 5-67, and 5-68 depict the relative cohesiveness of the sludges as observed under a microscope. The inlet sludge appears to have many clearly distinguishable individual solids while the outlet sludge seems to be rather homogeneous and cohesive. Therefore, the solids in the inlet sludge were suspended easier by the stirrer mixing action than the other sludges during the oxygen consumption test. As a consequence, the oxygen utilization rates were greater in the inlet sludge system due to the fact that more volatile solids and more supernatant COD were released from the sludge phase during the test.

It is interesting to note that some negative values in the uptake rate are tabulated. This could result from slight experimental error when the oxygen consumptions by the sludge alone were virtually negligible, or from inconsistent microbial activity present in the different test systems.

C. Effect of Initial Oxygen Tension on the Rate of Oxygen Consumption

The effect of initial oxygen tension on the rate of oxygen consumption by the benthal sludge was evaluated at two temperatures, 35 and 22 degrees centigrade. Three separate tests were conducted at each temperature level.

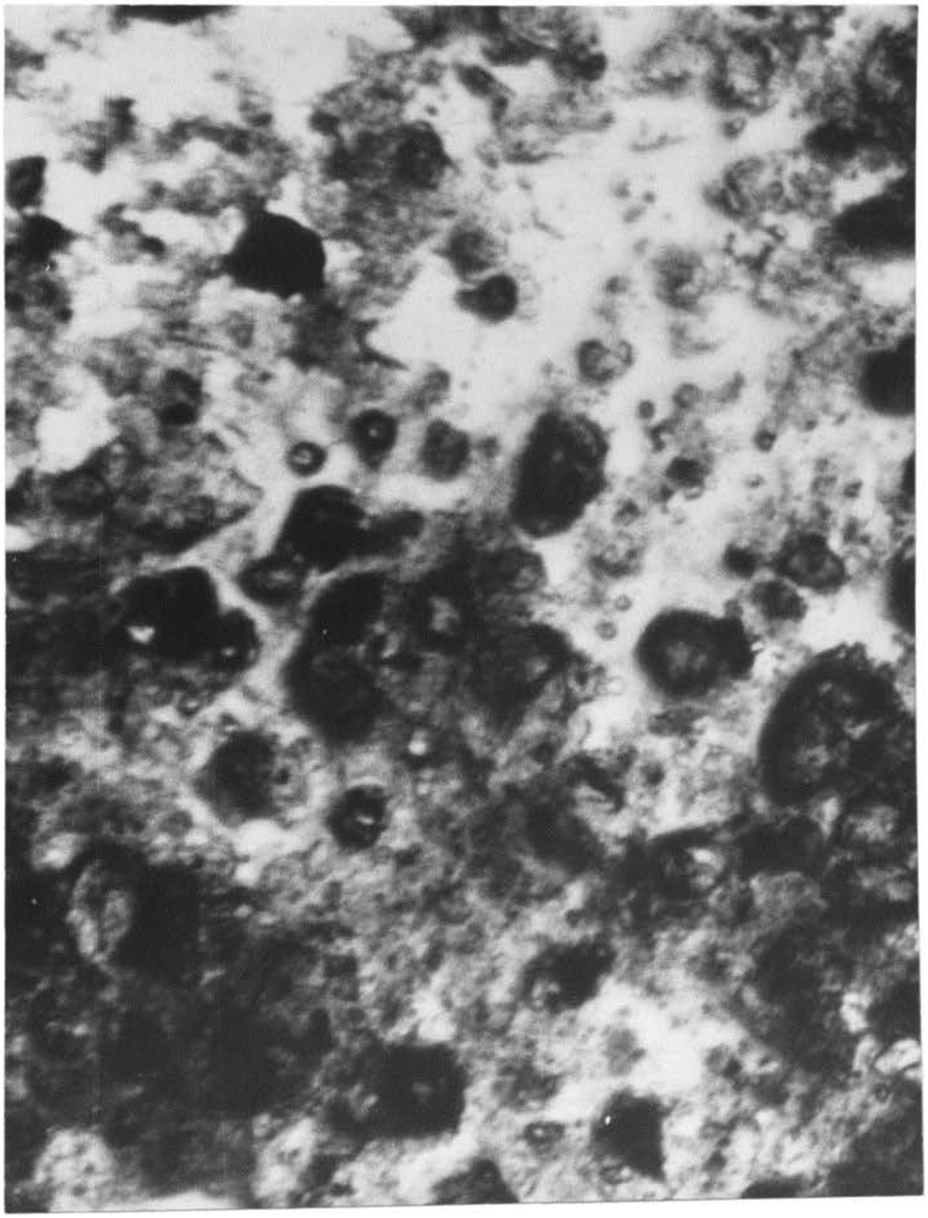

Figure 5-66

Photomicrograph of Inlet Sludge

Figure 5-67

Photomicrograph of Center Sludge

Figure 5-68

Photomicrograph of Outlet Sludge

At 35 degrees centigrade, the initial oxygen tensions were 1.4, 1.0, and 0.6 mg/l. During this study only about one-half to one-sixth of the supernatant was siphoned off for reaeration in order to minimize the amount of solids suspended when returning the aerated supernatant. In addition, during the short period of returning the aerated supernatant, considerable amount of oxygen was consumed by the high bacterial activity at 35 degrees centigrade. All of these facts explain why the range of initial oxygen tension was so narrow in this study. The oxygen consumption curves for these three tests are shown in Figures 5-69, 5-70, and 5-71. The relative oxygen uptake rates for these three tests are shown in Figure 5-72.

At 22 degrees centigrade, the initial oxygen tensions were 2.2, 0.5, and 0.4 mg/l. Figures 5-73, 5-74, and 5-75 illustrate the oxygen utilization curves and Figure 5-76 the relative uptake rates for the three tests.

Table 5-5 summarizes the oxygen consumption rates at different initial oxygen tensions conducted at 35 and 22 degrees centigrade. From this table it appears that the rate of oxygen utilization may increase as the initial dissolved oxygen concentration is reduced. However, two factors must be considered when analyzing these data. First, a low initial dissolved oxygen concentration used in this system resulted in a relatively short period of experimental run. Therefore it might be possible that the oxygen uptake was part of the initial immediate oxygen demand. Secondly, any reduced products formed by anaerobic fermentation in the sludge phase might contribute an additional oxygen demand, and the lower the initial

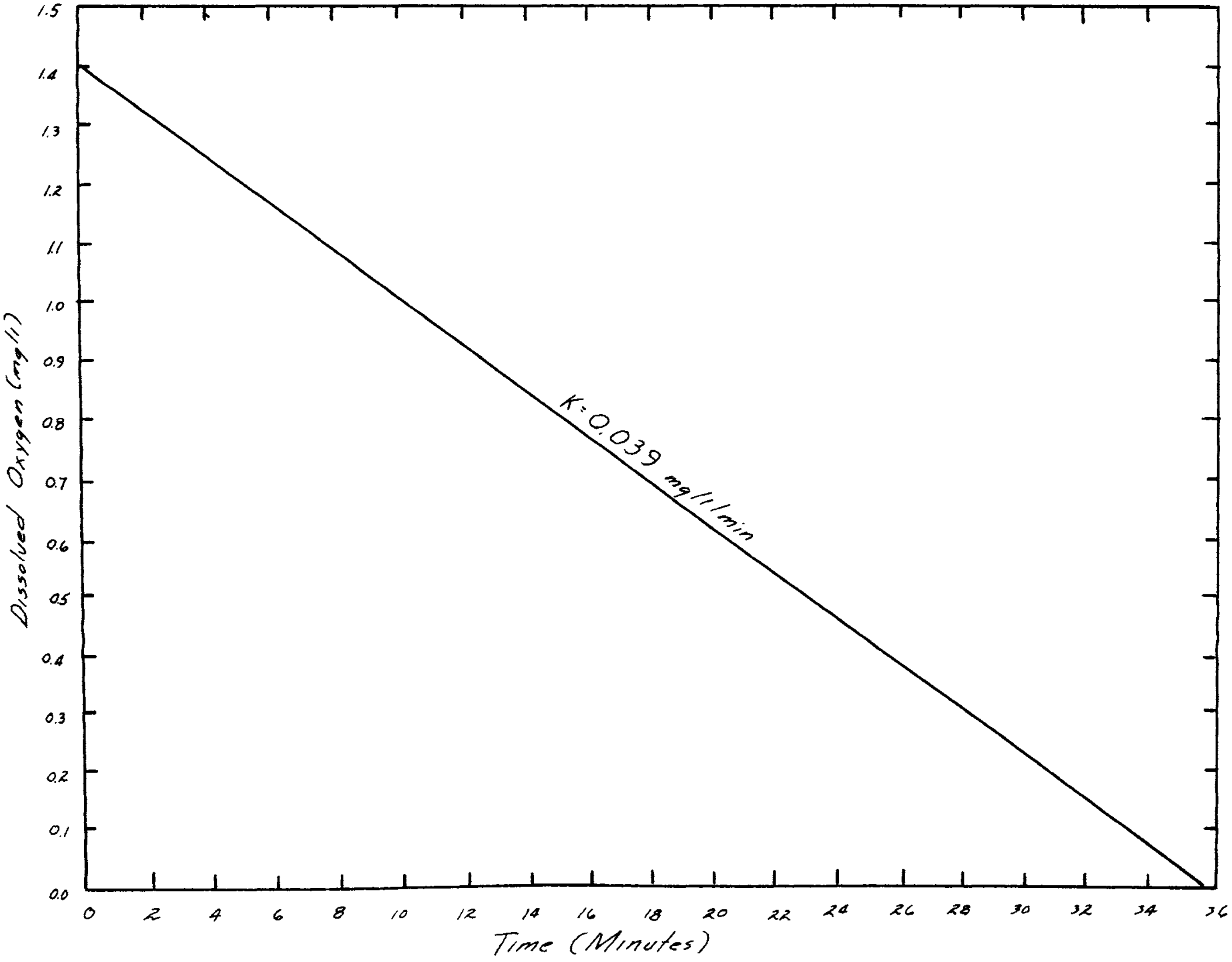

Figure 5-69

Oxygen Consumption Curve at an Initial Oxygen Tension of 1.4 mg/l at 35°C

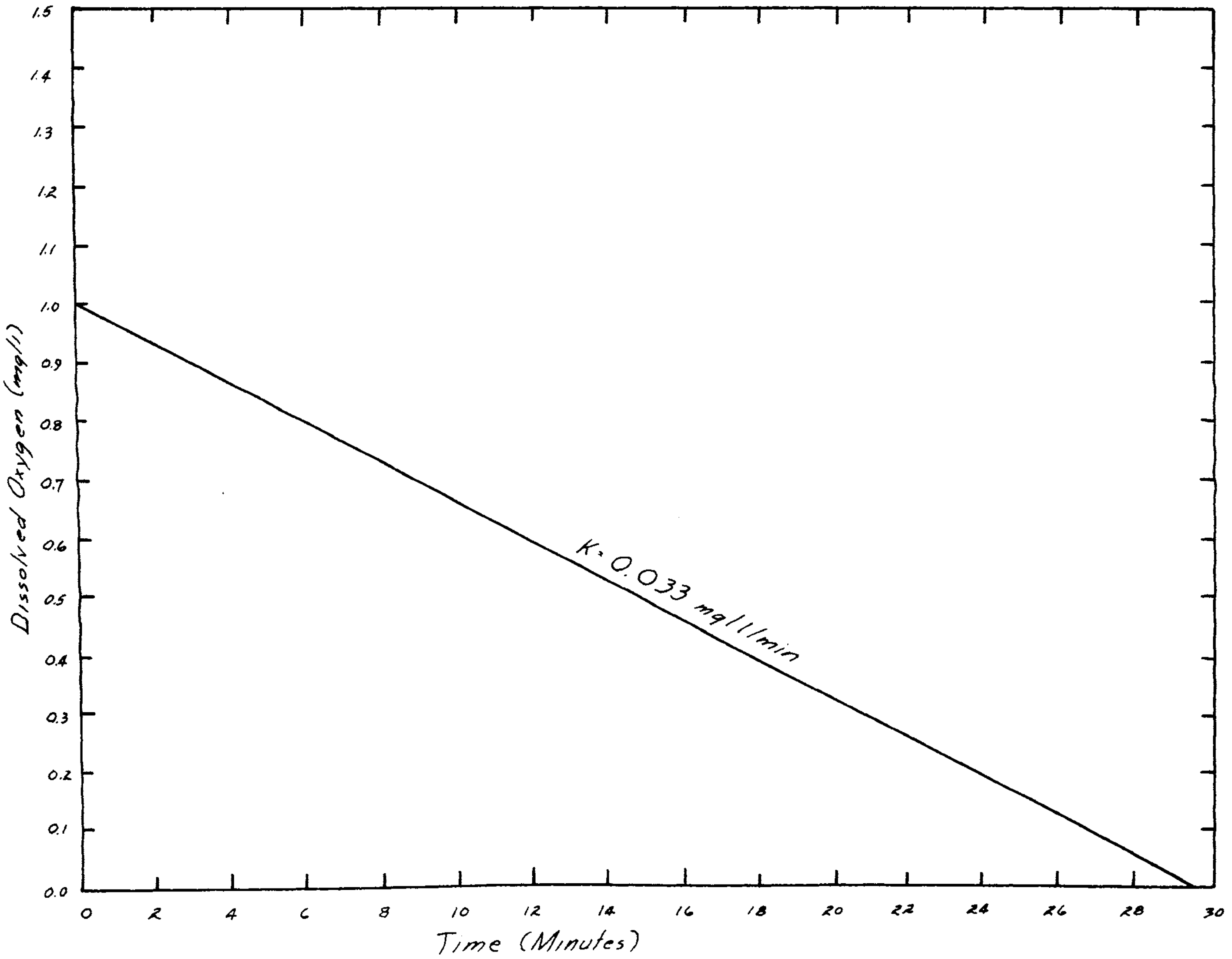

Figure 5-70

Oxygen Consumption Curve at an Initial Oxygen Tension of 1.0 mg/l at 35°C

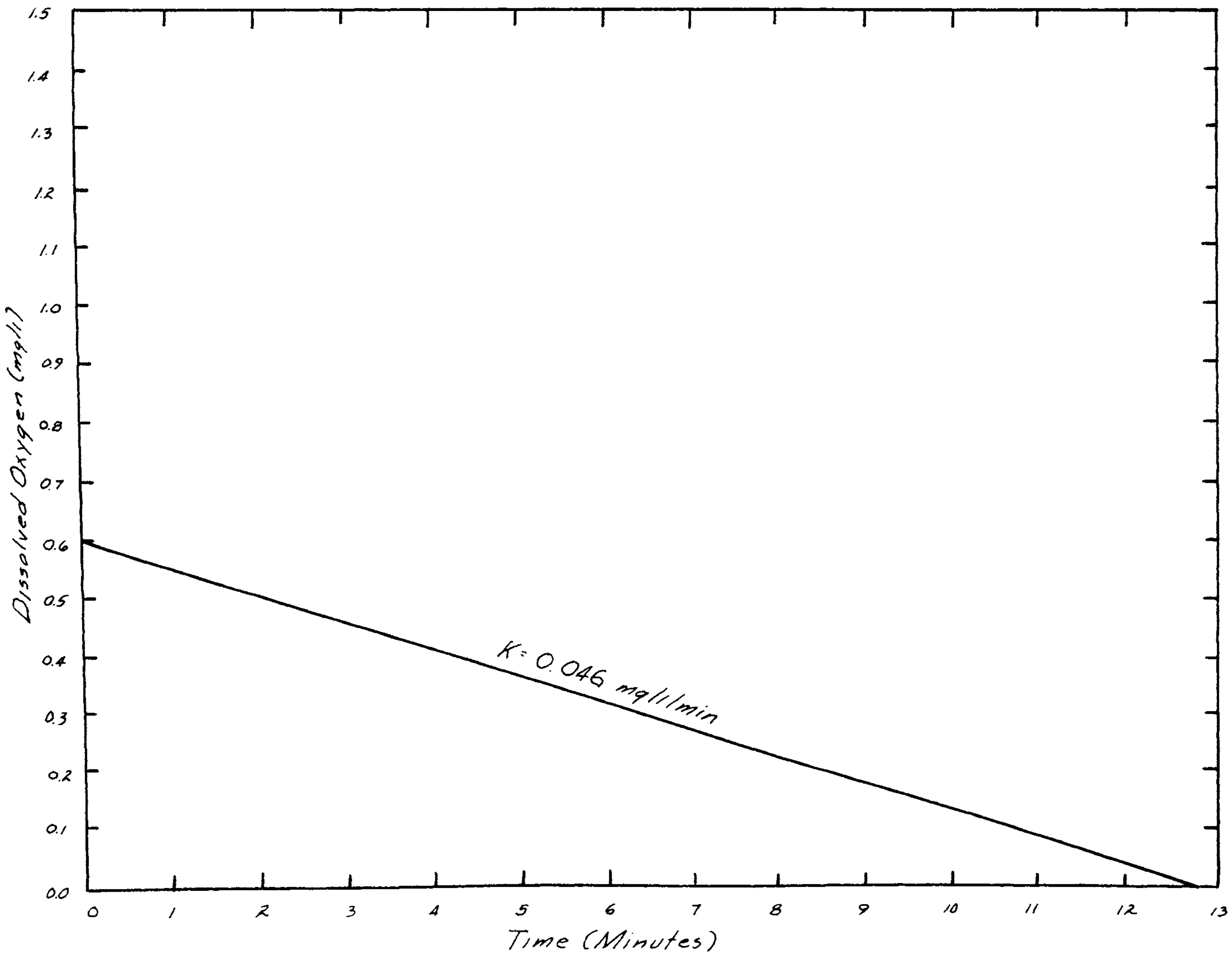

Figure 5-71

Oxygen Consumption Curve at an Initial Oxygen Tension of 0.6 mg/l at 35°C

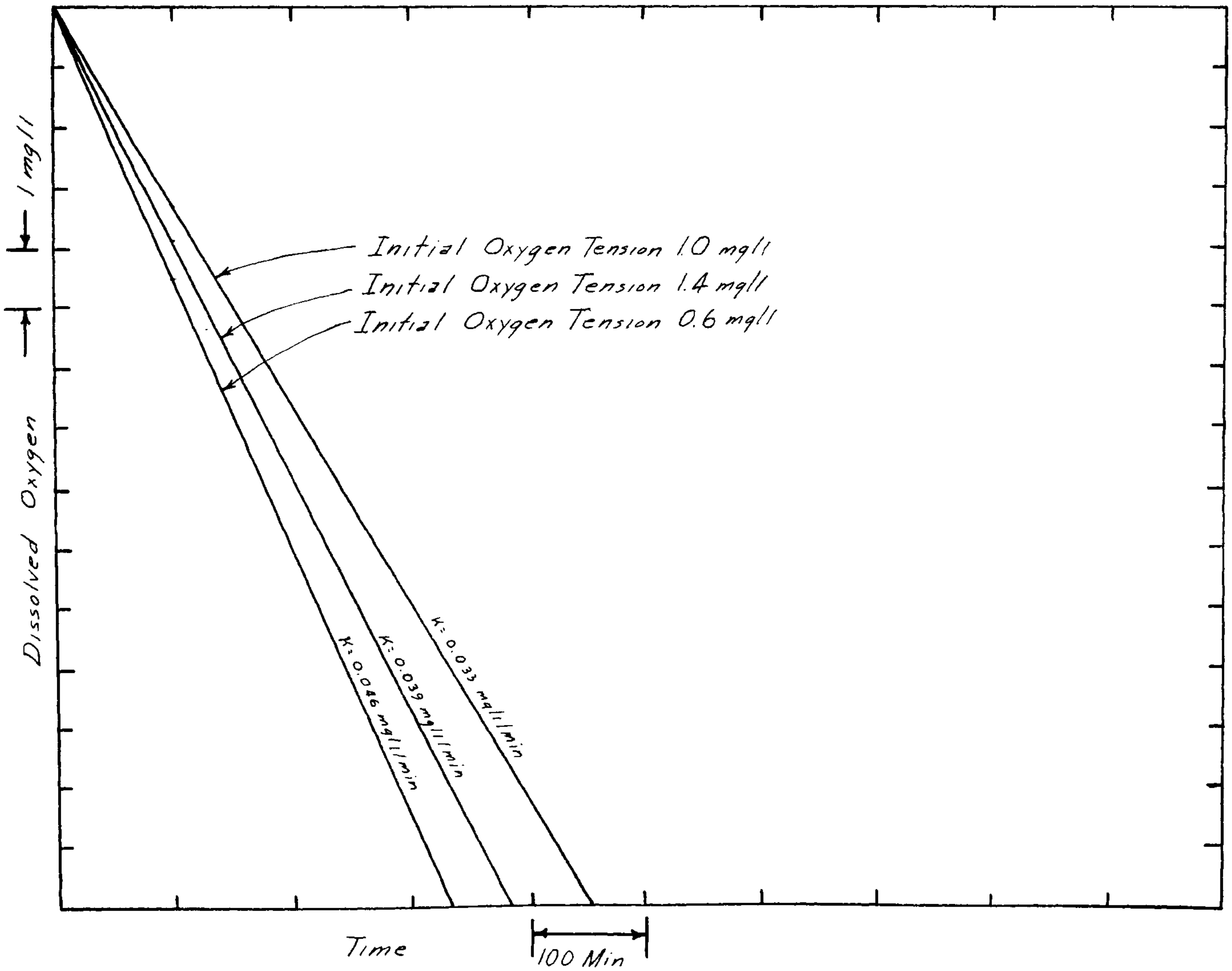

Figure 5-72

Relative Oxygen Consumption Rates for Different Initial Oxygen Tensions at 35°C

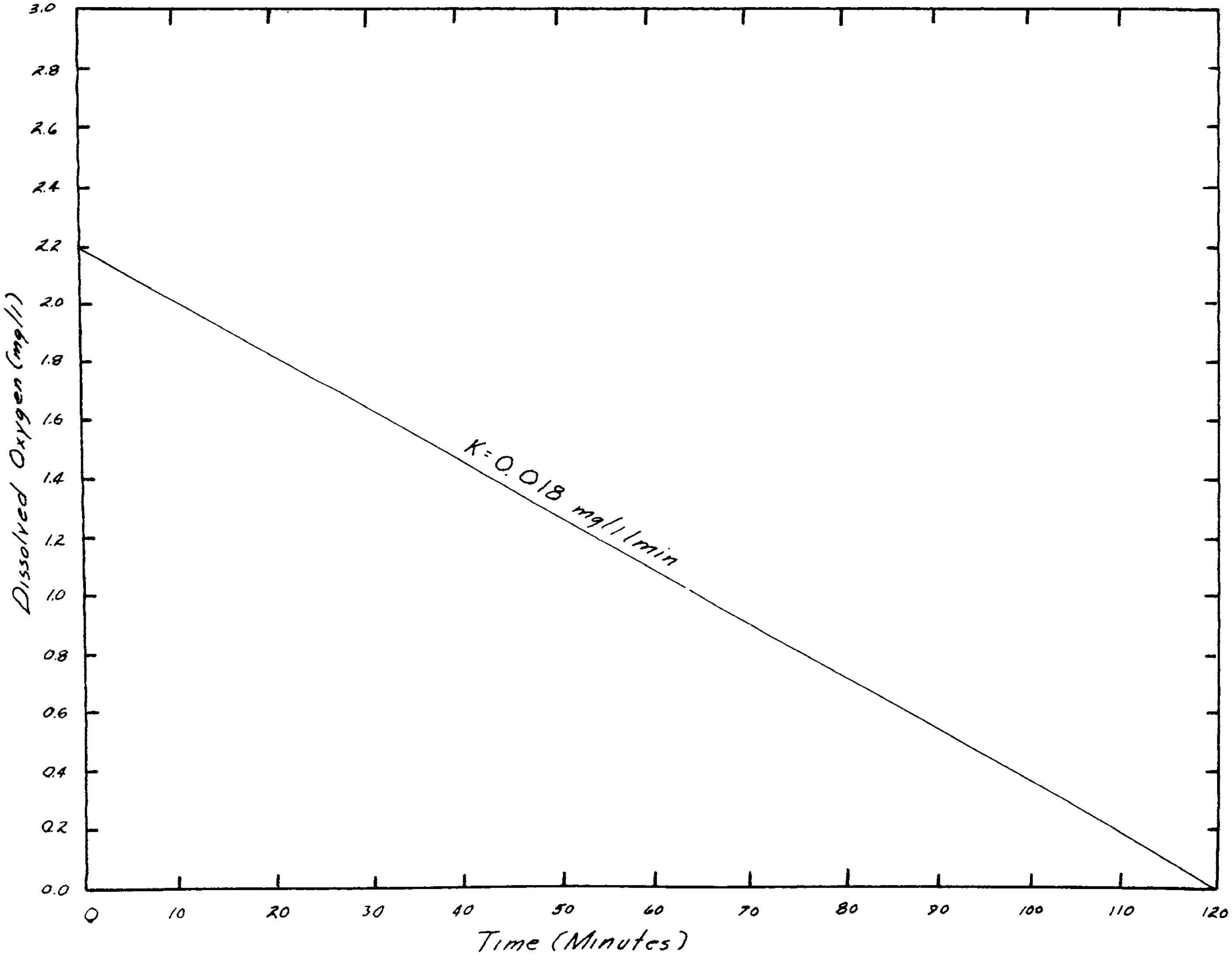

Figure 5-73

Oxygen Consumption Curve at an Initial Oxygen Tension of 2.2 mg/l at 22°C

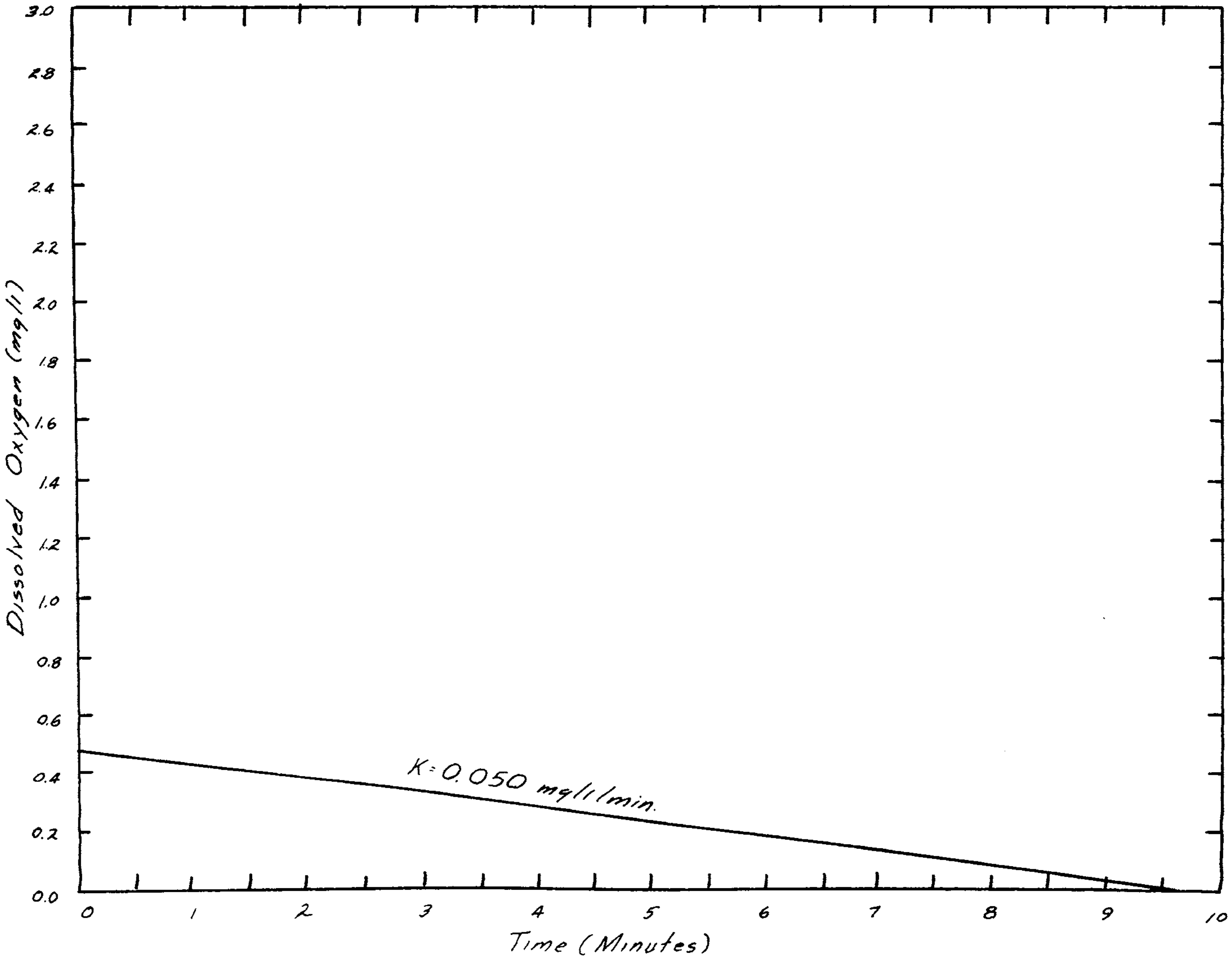

Figure 5-74

Oxygen Consumption Curve at an Initial Oxygen Tension of 0.5 mg/l at 22°C

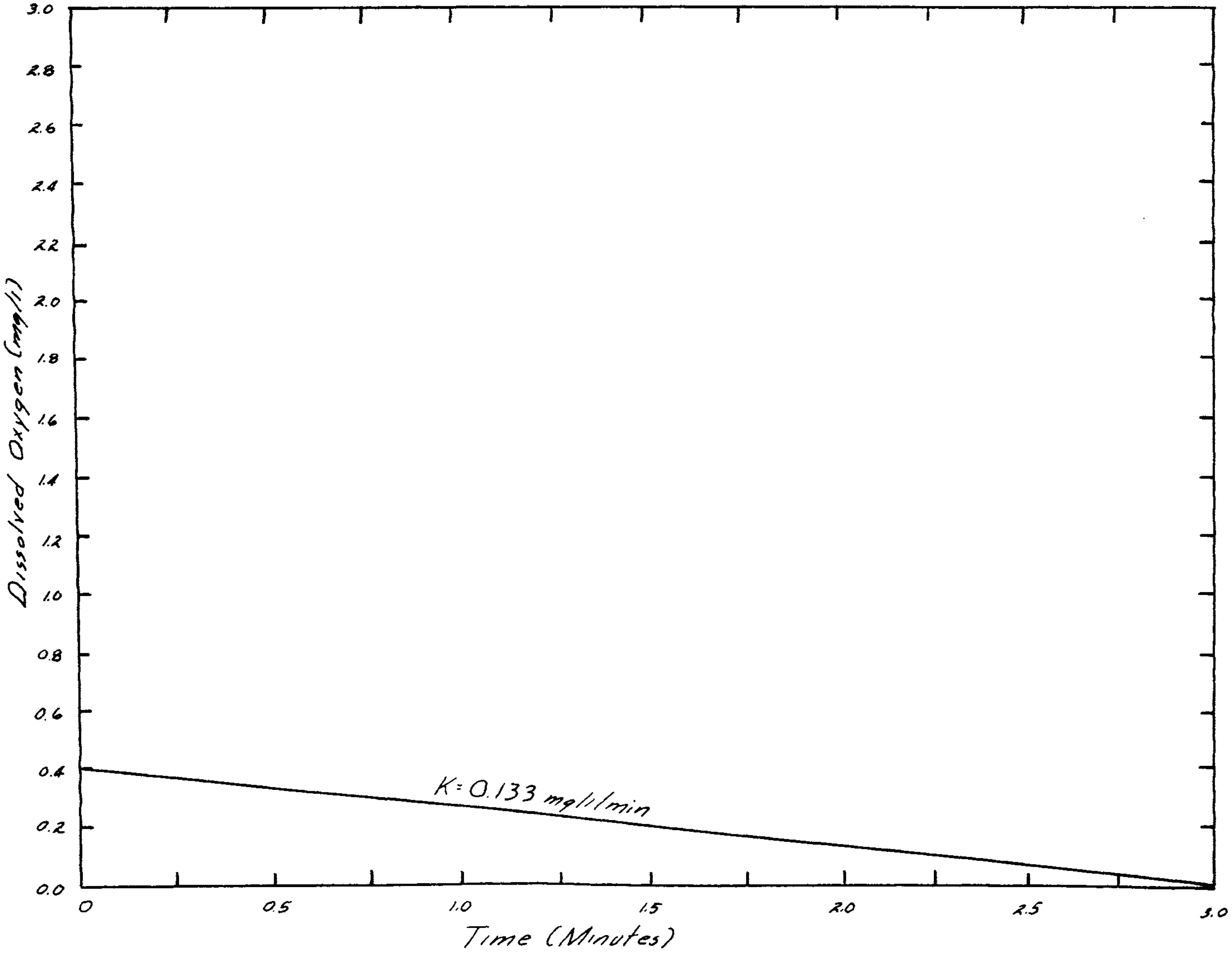

Figure 5-75

Oxygen Consumption Curve at an Initial Oxygen Tension of 0.4 mg/l at 22°C

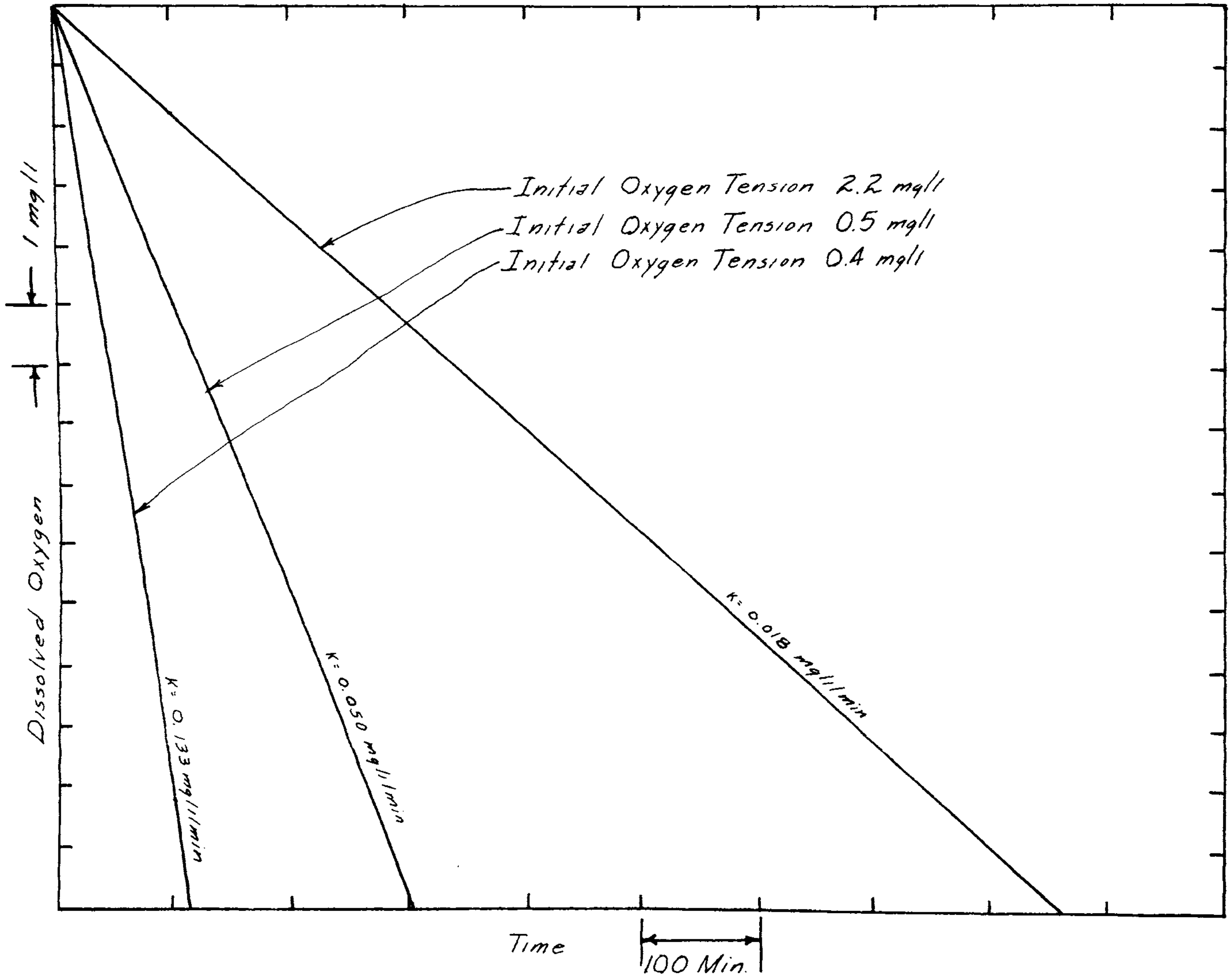

Figure 5-76

Relative Oxygen Consumption Rates for Different Initial Oxygen Tensions at 22°C

Test Temperature °C	Initial Oxygen Tension, mg/l	Oxygen Consumption mg/1/min	Oxygen Consumption mg/min/m^2
35	1.4	0.039	11.55
35	1.0	0.033	9.36
35	0.6	0.046	13.03
22	2.2	0.018	5.18
22	0.5	0.050	14.19
22	0.4	0.133	37.90

Table 5-5

Summary of Oxygen Consumption Rates

at Different Initial Oxygen Tensions

oxygen concentration the greater would be the possibility that more fermentation products were released, thereby increasing the rate of oxygen uptake.

D. Effect of Sludge Compaction on the Rate of Oxygen Consumption

Tests were conducted at 22 degrees centigrade to evaluate the effect of sludge compaction on the rate of oxygen consumption. The different degrees of sludge compaction were attempted by providing three different periods of standing for sludge before tests. The three different periods of sludge compaction employed were one-half day, three days, and nine days. The oxygen uptake curves for the three tests are shown in Figures 5-77, 5-78, and 5-79. The relative oxygen consumption rates for these three tests are compared in Figure 5-80 and summarized in Table 5-6.

As shown in Figure 5-80 and Table 5-6, the oxygen uptake rates for the sludge with one-half and three day compaction are nearly the same, being 0.027 and 0.026 mg/l/min respectively. However a higher rate of oxygen utilization was found for the nine day compaction. It must be pointed out here that during the experiment, the sludge level in the test chamber was marked after one day compaction; later it was observed that there was no further degree of compaction in the same sludge even after nine days of standing.

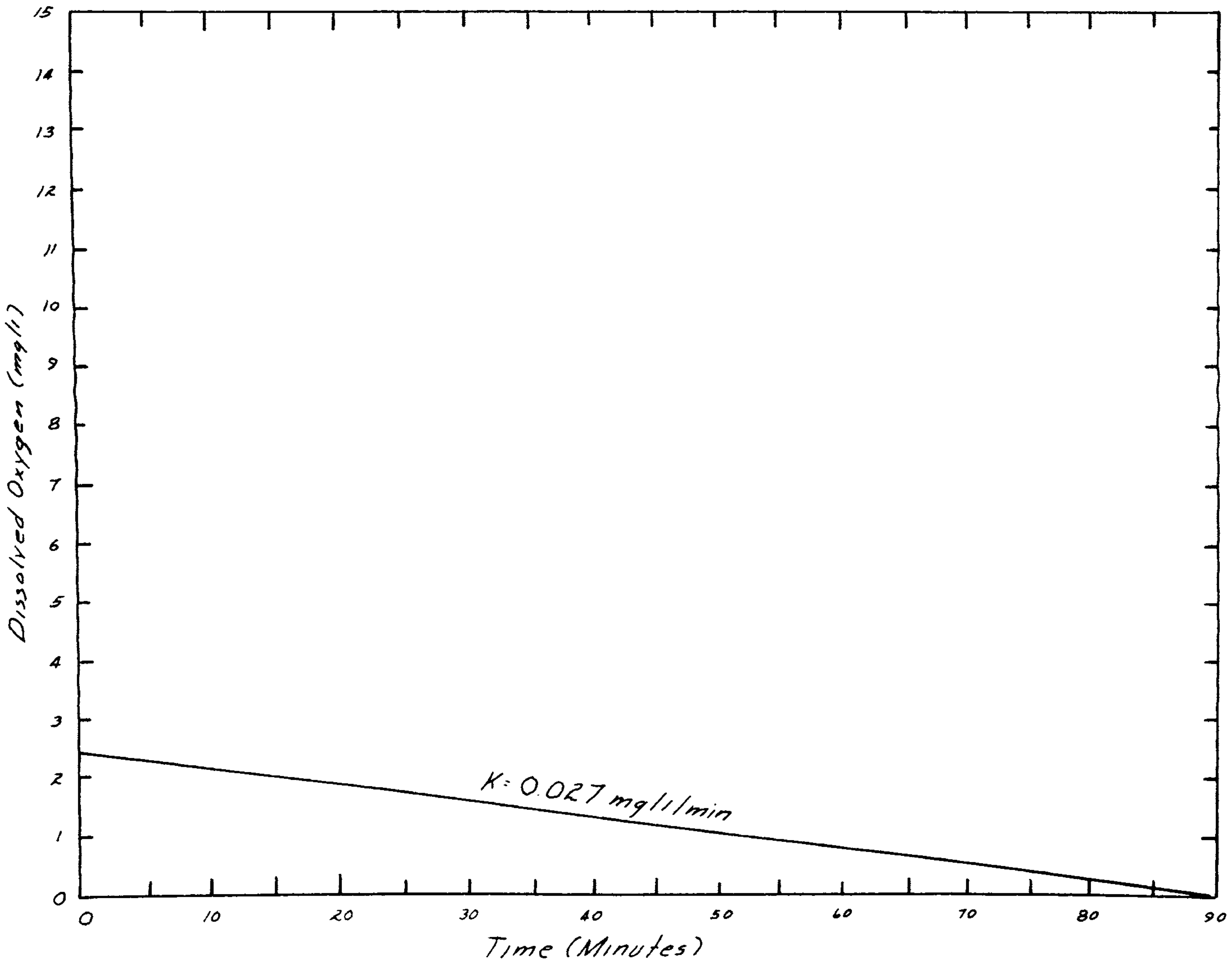

Figure 5-77

Oxygen Consumption Curve at 22°C by Sludge with One-Half Day Compaction

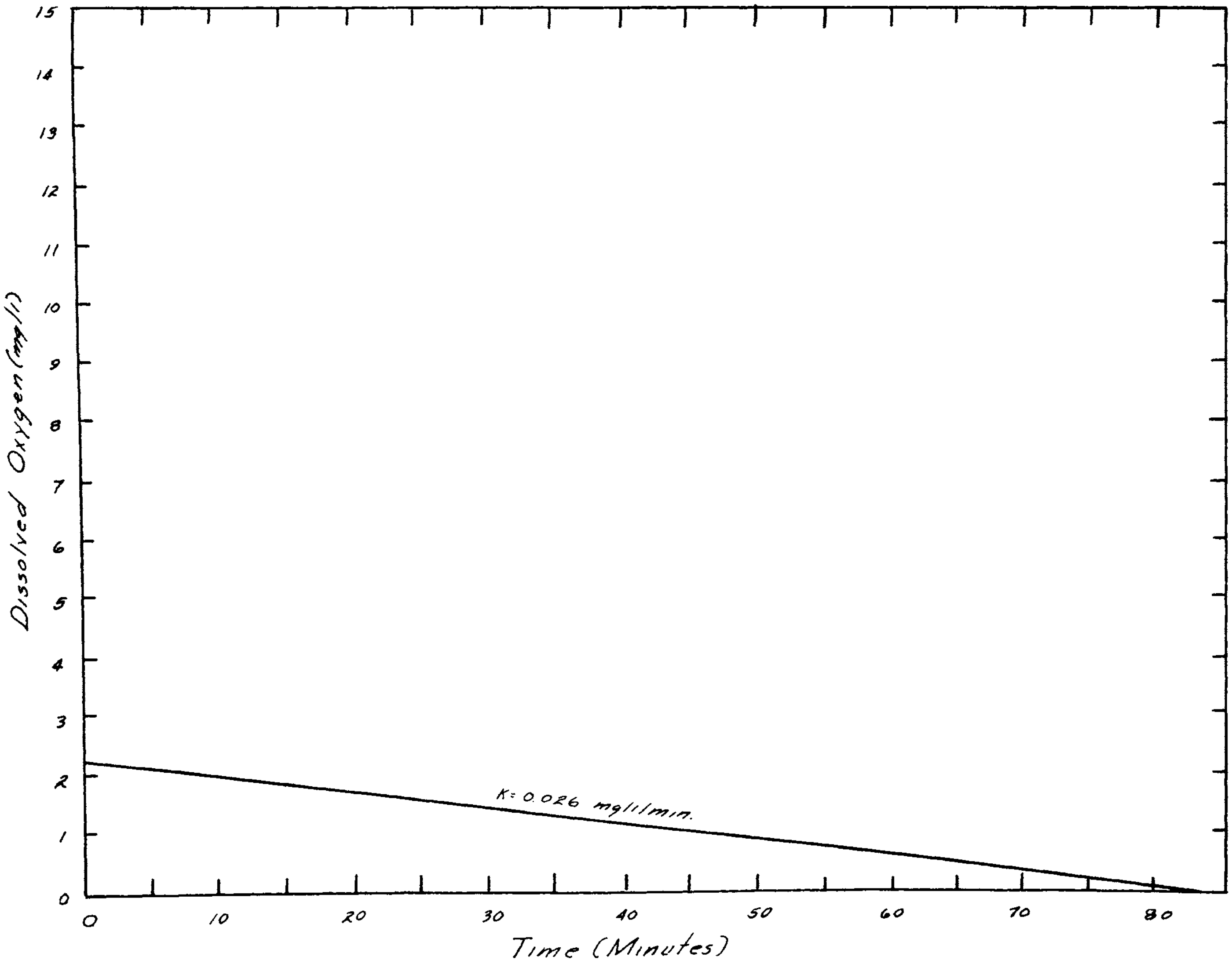

Figure 5-78

Oxygen Consumption Curve at 22°C by Sludge with Three Day Compaction

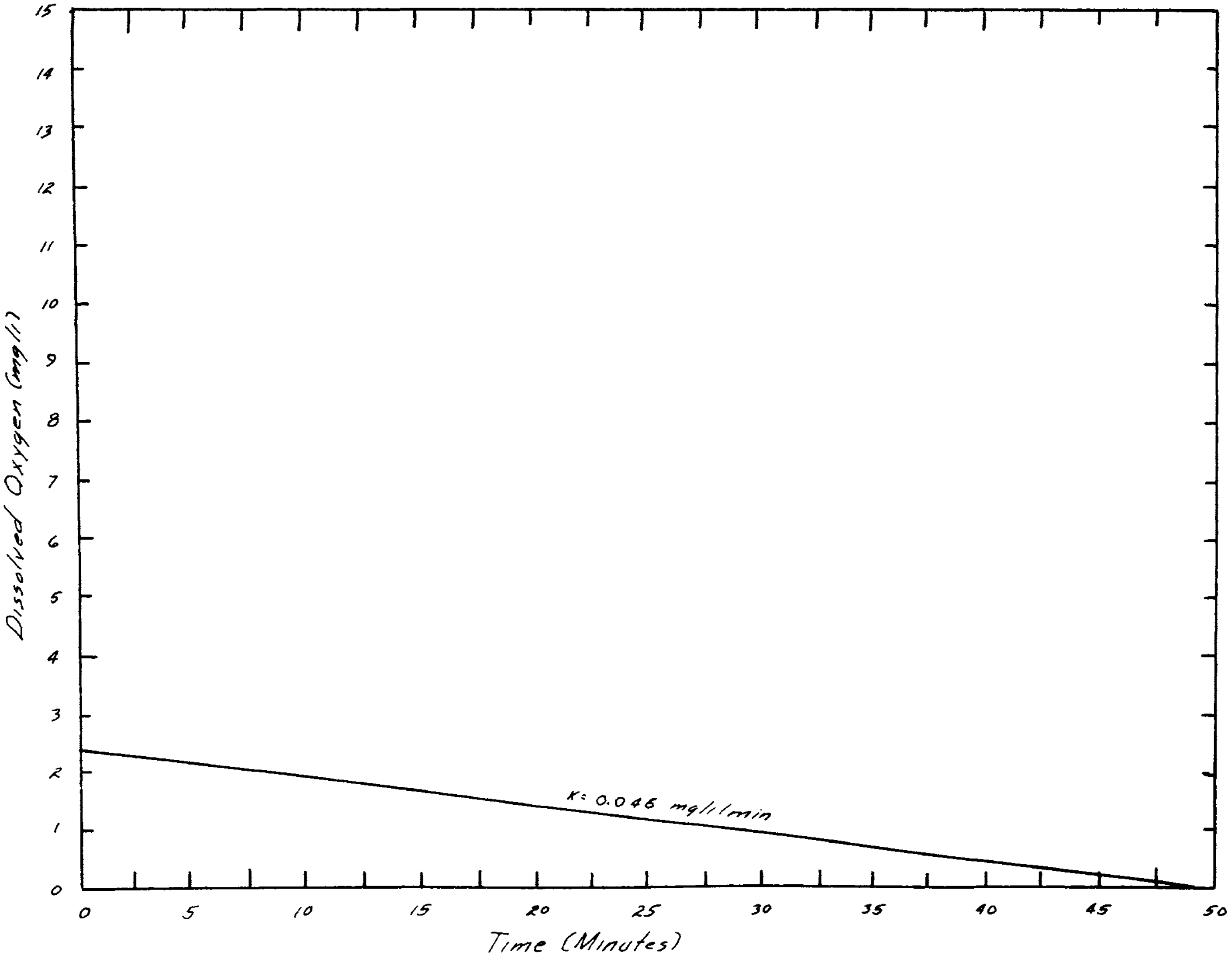

Figure 5-79

Oxygen Consumption Curve at 22°C by Sludge with Nine Day Compaction

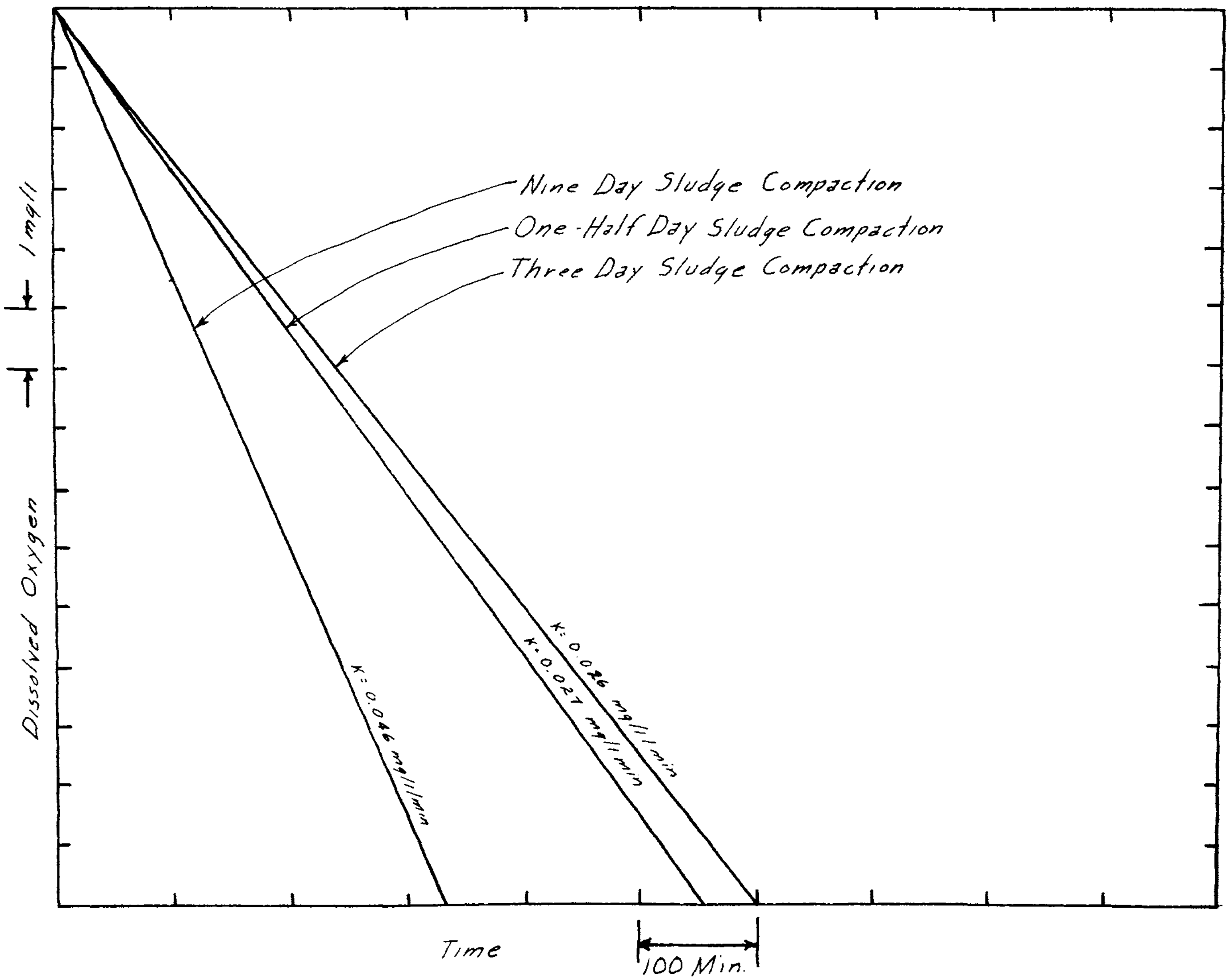

Figure 5-80

Relative Oxygen Consumption Rates at 22°C by a Sludge Sample with Different Periods of Compaction

Test Temperature °C	Compaction Time, Days	Oxygen Consumption Rates	
		mg/l/min	mg/min/m^2
22	0.5	0.027	7.54
22	3	0.026	7.34
23	9	0.046	13.03

Table 5-6

Summary of Oxygen Consumption Rates

by a Sludge Sample with Different Periods of Compaction

VI. DISCUSSION

This research study has been successful in the development of a laboratory test assembly. Considerable experience has also been gained with the problems encountered while working with the sewage lagoon's benthal sludge. In addition, some information regarding the chemical and biological nature of the benthal sludge was also uncovered. Because of the many variables and uncertainties involved in the oxygen consumption test program, such as degree of mixing and microbial activity, etc., a precise quantitative correlation between the oxygen uptake and several possible parameters controlling the reaction was not possible.

When performing the two runs for each experimental condition, it was intended to provide different concentrations of suspended solids so that there would be more data points available to allow correlation of the oxygen uptake with several important factors. Therefore, consistent uptake rates were not expected between the two runs. However, when the uptake rate by the unsettled supernatant only was subtracted from that by the sludge with supernatant system, a fairly consistent uptake rate for the sludge alone would be expected. Unfortunately, this was not the case as can be seen from Table 6-1. In spite of the fact that many experimental data were out of anticipation, the experience obtained from this research will be of great value in developing a successful laboratory technique for future investigations dealing with the sewage lagoon's benthal sludge, which in many aspects, such as the sludge texture, composition, and organic content, etc.,

Sludge Location	Test Temperature	Run Number	Oxygen Consumption Rate mg/l/min
Inlet	10°C	1	0.345
Inlet	10°C	2	4.29
Inlet	22°C	1	-5.42
Inlet	22°C	2	16.53
Inlet	35°C	1	201.0
Inlet	35°C	2	106.0
Center	10°C	1	-2.96
Center	10°C	2	6.58
Center	22°C	1	44.4
Center	22°C	2	66.3
Center	35°C	1	21.6
Center	35°C	2	73.0
Outlet	10°C	1	0.143
Outlet	10°C	2	0.457
Outlet	22°C	1	23.65
Outlet	22°C	2	18.81
Outlet	35°C	1	9.50
Outlet	35°C	2	10.50

Table 6-1

Summary of Oxygen Consumption

Rates by Sludge Phase Alone

are different from the other benthal sludges found in rivers and lakes which have been commonly studied by other investigators.

In this chapter a general discussion will be given to each of the following subjects: 1) the effect of the supernatant COD on the rate of oxygen consumption, 2) the effect of temperature on the rate of oxygen consumption, 3) the effect of the sludge sampling location on the rate of oxygen consumption, 4) the effect of the initial oxygen tension on the rate of oxygen consumption, 5) the effect of the sludge compaction on the rate of oxygen consumption, 6) the possible reasons which may account for the inconsistency of the oxygen uptake by the sludge phase alone between the two separate experimental runs for each test condition.

The discussion of the above subjects will not only shed some light on the nature of the sewage oxidation pond benthal sludge, but will also be useful in designing certain experimental controls for future related studies.

A. The Effect of the Supernatant COD on the Rate of Oxygen Consumption

Among all possible factors considered, the COD of the test supernatant appears to have the greatest effect on the rate of oxygen consumption. The data obtained in this investigation show a direct relationship between the COD of the test supernatant and the rate of oxygen consumption, as shown in Figures 6-1, 6-2, and 6-3, which were plotted according to data presented in Tables 5-1, 5-2, and 5-3 respectively. As shown in these three figures, the

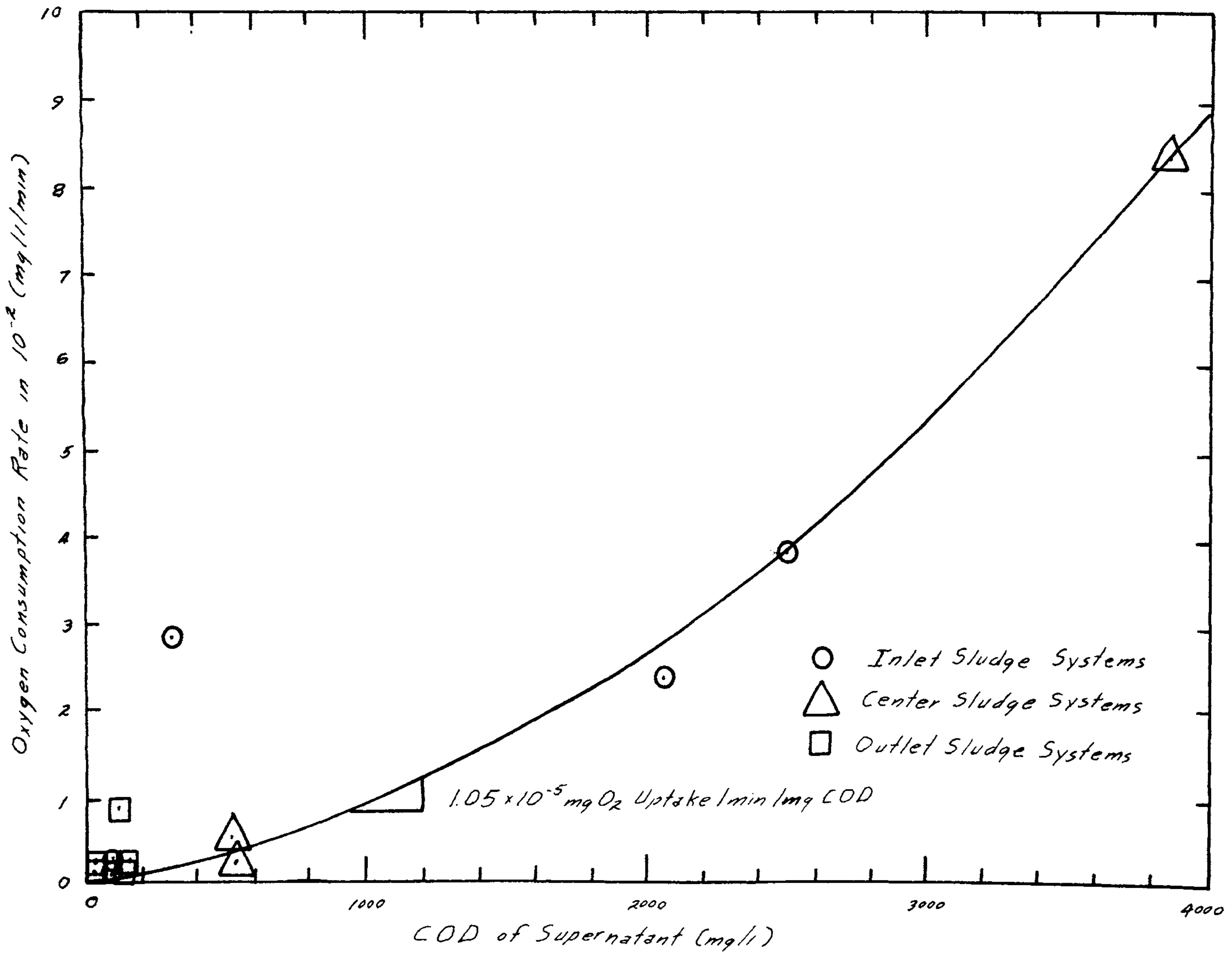

Figure 6-1

Relationship Between the Supernatant COD and the Oxygen Consumption Rates at 10°C Test Systems

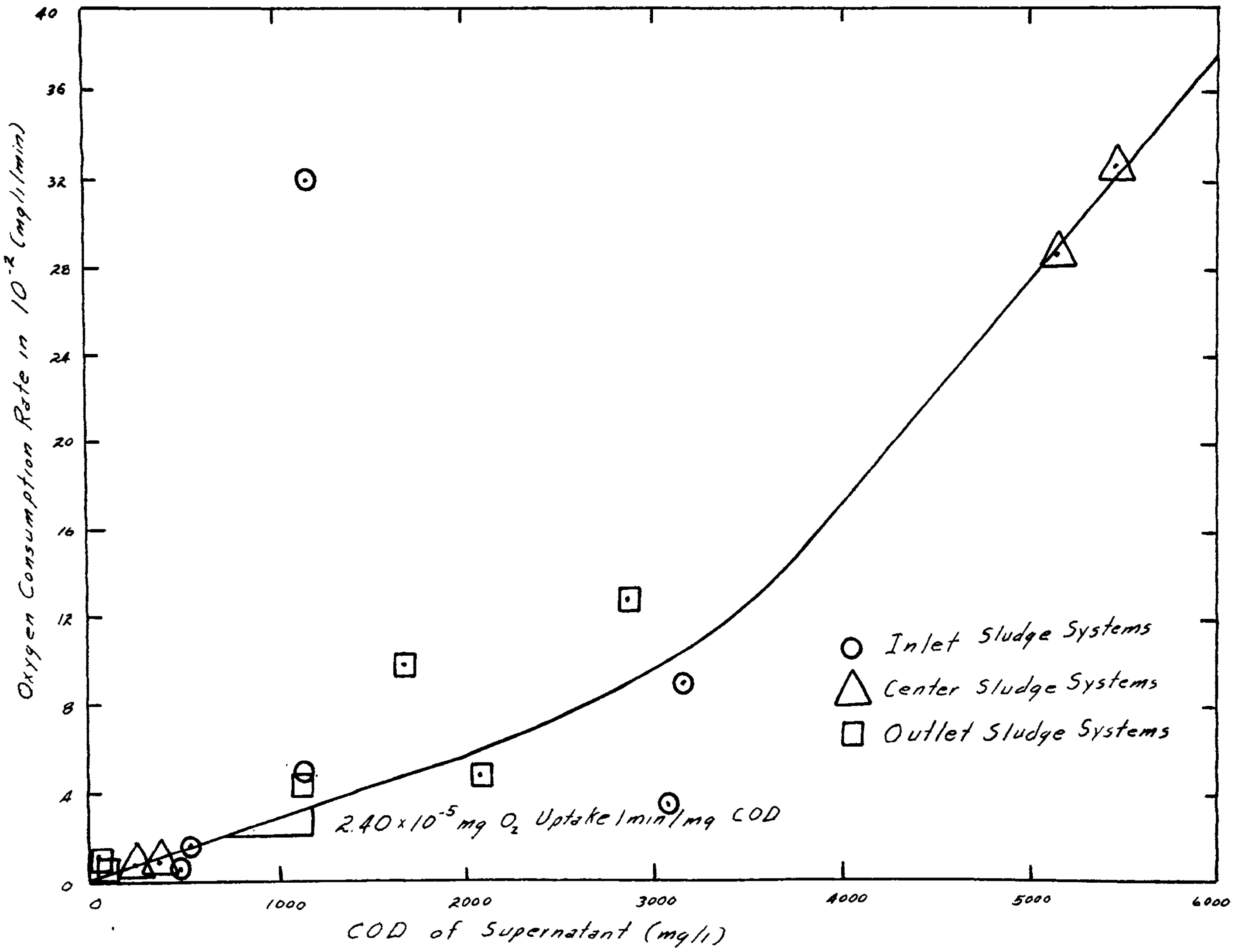

Figure 6-2

Relationship Between the Supernatant COD and the Oxygen Consumption Rates at 22°C Test Systems

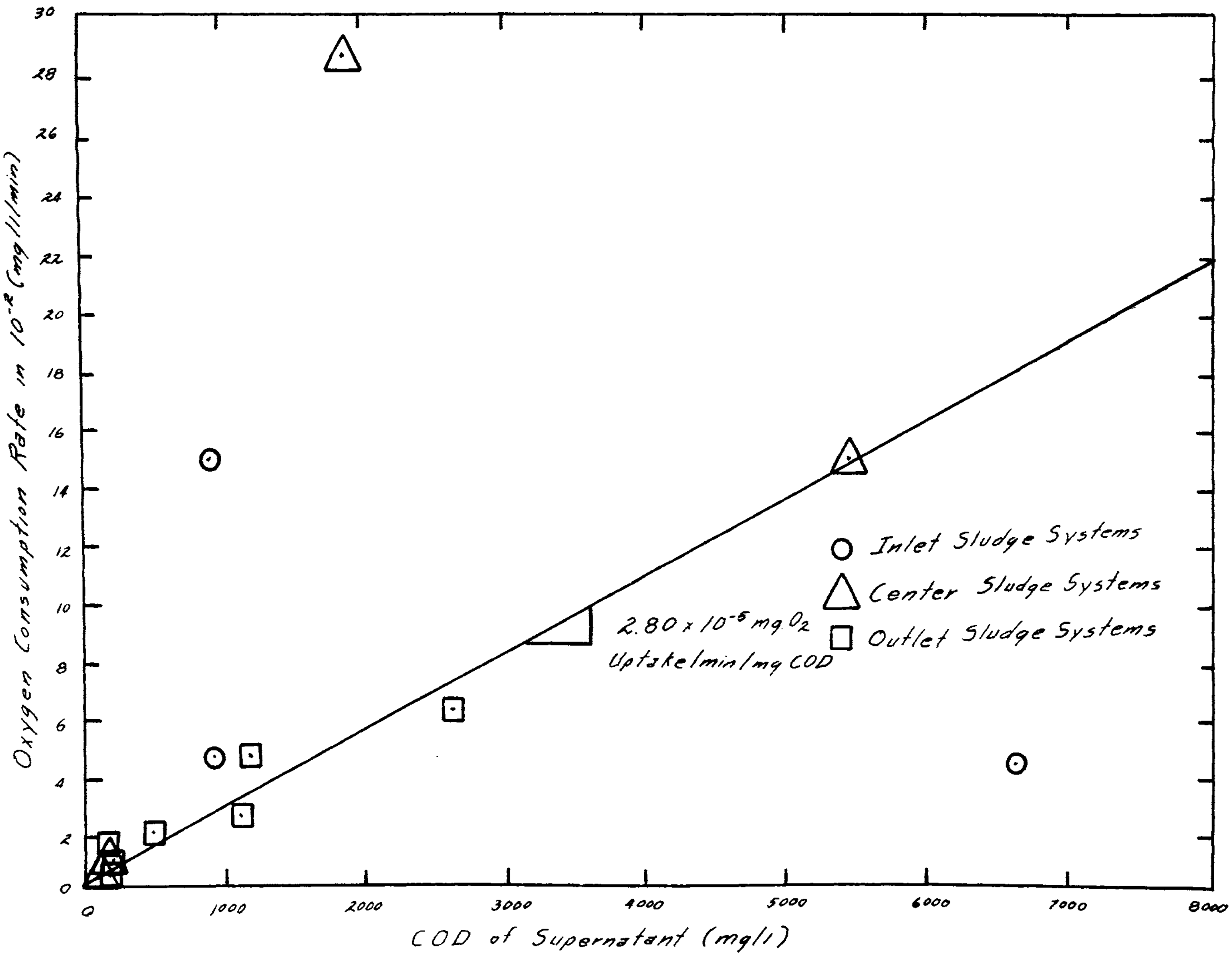

Figure 6-3

Relationship Between the Supernatant COD and the Oxygen Consumption Rates at 35°C Test Systems

rate of oxygen consumption generally increases with the COD of the test supernatant. However, there are still many data points which do not fit into the curve representing the correlation between the oxygen uptake rate with the supernatant COD. This indicates the presence of other influencing factors, some of which will be discussed later.

The unseeded BOD dilution water which was used as the test supernatant had no COD. Therefore, any COD present in the supernatant must originate from the sludge phase. The organic matter may be transferred to the supernatant in the form of suspended particles or in the soluble form. In general, the supernatant COD is closely related to the concentration of volatile suspended solids present in the system, as shown in Figure 6-4.

It is evident that the test involving the unsettled supernatant measures the oxygen utilization of both the suspended and dissolved organic matter, and the test using the settled supernatant, measures the oxygen utilization of the dissolved and colloidal organic matter only. Since the oxygen uptake is strongly influenced by the COD of the test supernatant, which in turn is related to the suspended solids content, careful controls on the mixing of supernatant should be taken in future studies.

B. The Effect of Temperature on the Rate of Oxygen Consumption

There is also a direct relationship between temperature and the rate of oxygen consumption. This investigation disclosed that temperature has at least two direct effects on the rate of oxygen consumption. First, as the temperature increases the biological

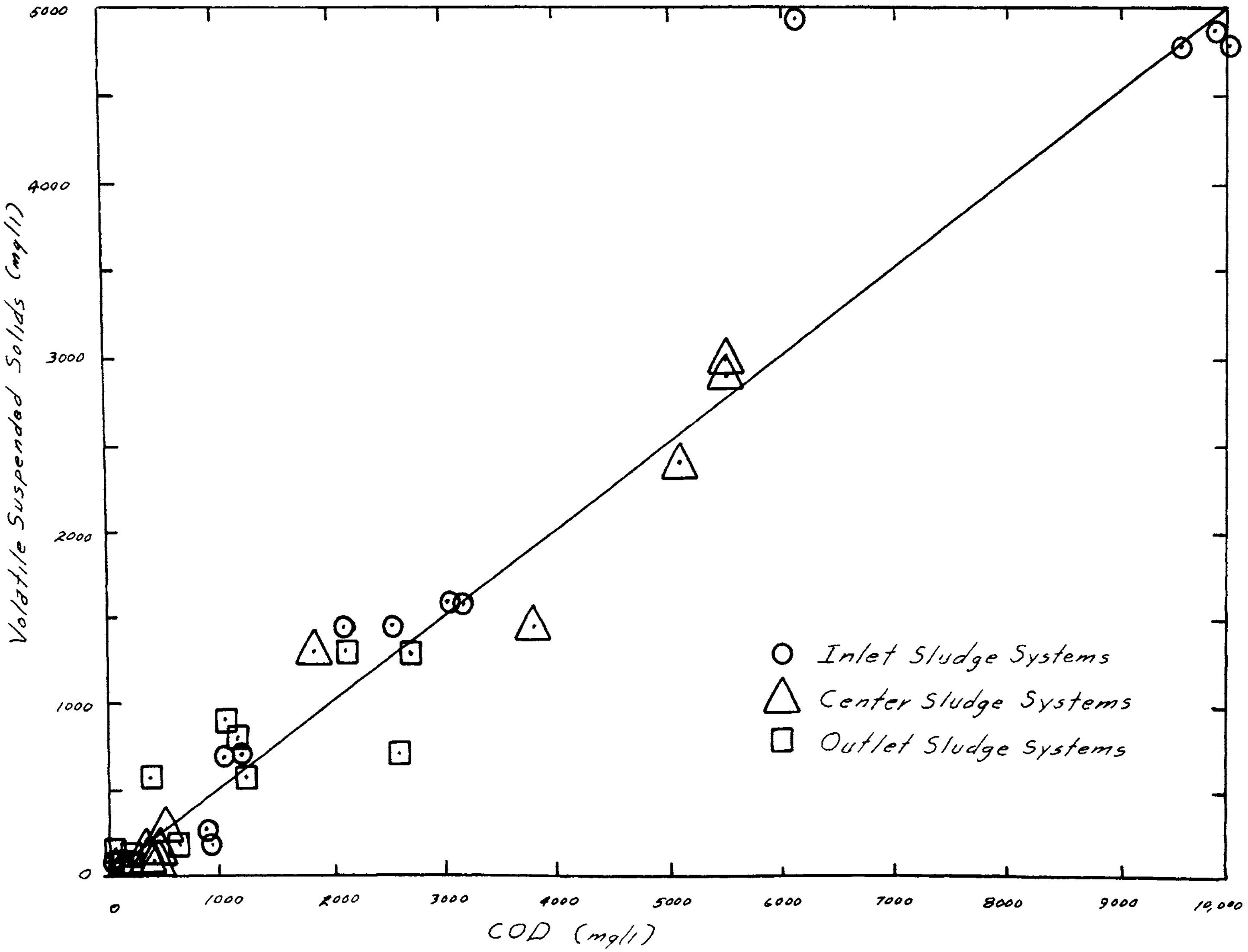

Figure 6-4

Correlation Between the Volatile Suspended Solids and COD in the Test Supernatant activity also increases. The predominant groups of microorganisms present in the 10, 22, and 35 degrees centigrade test systems, respectively, might be psychrophiles, mesophiles, and facultative thermophiles. Although some variations in biological activity might exist among the different groups of microorganisms, it is believed that the overall biological activity of the mixed groups of microorganisms present in the test system would increase with increasing temperature.

Secondly, the sludge becomes less gelationous and less cohesive as the temperature increases. Therefore, as the temperature rises, solids are suspended more easily by the mixing action. This in turn increases the COD of the supernatant and also the rate of oxygen consumption as described above. Between the aforementioned two factors, the second factor may have a much greater effect on the rate of oxygen consumption than the first. It is therefore very important to maintain a strict temperature control during the test program.

C. The Effect of the Sludge Sampling Location on the Rate of Oxygen Consumption

Sampling location is also believed to have at least two direct effects on the rate of oxygen consumption. First, it appears reasonable to assume that the sludge obtained near the outlet is of a more stabilized form with less biological availability, and thus would exert less oxygen demand than the sludge obtained near the inlet. Results of physical examination of the sludge and the oxygen profiles presented in Chapter III, Background of the Pond

Studied, seem to verify this assumption.

Secondly, the sludge is less cohesive and gelatinous near the inlet as described in the previous chapter. This factor will cause an increase in the oxygen consumption because of the easiness that the sludge solids can be suspended in the supernatant. Although it was not included in this investigation, it is possible that the reduction in the mean sludge particle size from the inlet to the outlet may offset the above effect to some extent.

D. The Effects of the Initial Oxygen Tension on Rate of Oxygen Consumption

As pointed out in the previous chapter, the results of the oxygen tension study seem to indicate that the rate of oxygen utilization increases as the initial dissolved oxygen concentration is reduced. However, it must be pointed out that the narrow range of initial oxygen tension used in this study will not allow a conclusive statement to be drawn. A wider range of initial oxygen tension levels will be needed for a satisfactory evaluation of this parameter. An understanding of the effect of initial oxygen tension on the oxygen uptake may be helpful in finding the precise mechanism controlling the oxygen utilization by a lagoon's benthal sludge.

E. The Effect of the Sludge Compaction on Rate of Oxygen Utilization

Although only a relatively superficial investigation was performed, the results show no relationship between the length of time for which the sludge is allowed to compact and the rate of oxygen utilization. Additional investigations are, however, required before the effect of sludge compaction can be concluded. As stated above, an understanding of the sludge compaction effect on the oxygen uptake will aid in determining the basic mechanism governing the sludge oxygen uptake.

F. The Possible Reasons for the Inconsistent Oxygen Uptakes Observed in This Study

Many factors may have an influence on the rate of oxygen consumption. Some of these factors may exert a significant effect on the rate of oxygen consumption, others may have only a negligible effect. The factors which are believed to have a significant influence on the inconsistent results will be discussed in this section. One of the most important factors leading to the inconsistent results may be the inconsistent time periods which elapsed between the two experimental runs. No attempt was made in this research program to establish a strict control on the test schedule regarding the time intervals between tests or the periods of aeration for the supernatant. A long time interval between the end of one test and the beginning of another may result in some significant changes in the nature of the benthal sludge. For example, the sludge may change from an aerobic to an anaerobic condition. Thus, some oxidized minerals in the sludge may transform to the reduced state and certain reduced organic products and gases may also be formed and retained in the sludge phase. As the next test starts, these reduced materials consume oxygen as they are released into the supernatant. In addition, the length of aeration given to the siphoned supernatant may also have a significant effect on the number and type of organisms present in the supernatant. A longer aeration period can result in the development of a larger number of aerobic bacteria, thereby raising the biological activity in the test system. The number of nitrifying bacteria present in the supernatant may also affect the rate of oxygen consumption. Unfortunately, the concentration of bacteria or the total bacterial activity present in the test supernatant was not evaluated in this research study. In view of the high concentrations of COD available in many test supernatants, it seems quite possible that in some test systems the biological activity may become a limiting factor. This fact may have also contributed to the inconsistency of the experimental results.

The sequence order of the tests with respect to temperature may also have an effect on the rate of oxygen consumption. If the 35 degrees centigrade temperature was used first for the investigation, the high suspended solids content would result in high concentrations of dissolved and colloidal material. After the series of tests at 35 degrees centigrade was over, this supernatant was discarded, thus resulting in a loss of certain dissolved and extremely fine organic matter from the sludge system. The change of the sludge composition caused by this manner may have affected the subsequent oxygen consumption tests. It is also possible that the sludge might not have the same cohesiveness when it was cooled from 35 to 22 degrees centigrade as when it was heated from 10 to 22 degrees centigrade.

Another factor which must be considered is that at high concentrations of suspended solids a significant amount of dissolved oxygen could possibly diffuse into the large floc of suspended solids in the same manner as that into the sludge phase. In this case the surface area of the suspended particles would act, in its oxygen consumption, in a manner similar to the surface of the benthal sludge.

Temperature can also have an indirect effect in addition to the two direct effects discussed earlier in this chapter, on the oxygen uptake data due to its influence on the oxygen measurement. For example, during the first experimental run using the settled supernatant of the center sludge system, the oxygen uptake curve as illustrated in Figure 5-26 shows an apparent rise in the oxygen level during the first 200 minutes of the test. It must be pointed out here that this was the first test performed in the oxygen uptake program and was not run using the equipment described in the chapter of Equipment and Methods. In this test, the BOD bottle containing the settled supernatant and a mixing bar were placed directly on the magnetic mixer, as shown in Figure 6-5. After the erratic results as noted above were found, an investigation was begun to determine if the heat transfer from the mixer could cause the error of the recorded oxygen rise encountered. For this purpose a BOD bottle was filled with distilled water, a thermometer was placed in a hole in a rubber stopper, and the stopper was inserted into the bottle. The bottle was on the mixer and this assembly was maintained at 10 degrees centigrade in the walk-in refrigerator. After the water temperature

Figure 6-5

Magnetic Mixing System

had been in equilibrium at 10 degrees centigrade, the mixer was turned on to mix the distilled water. Temperature readings were taken periodically for a period of four hours. The results of the experiment were plotted graphically in Figure 6-6. It can be seen that the heat transfer from the mixer raised the temperature of the distilled water three degrees centigrade after a three hour period. The sensitivity coefficient of the oxygen probe for this test at 10 degrees centigrade was 0.51 and at 13 degrees centigrade was 0.61. The dissolved oxygen of the sample is determined by dividing the oxygen meter reading by the sensitivity coefficient. Therefore, if the temperature of the supernatant was raised to 13 degrees centigrade the meter reading should have been divided by 0.61, but the temperature was assumed to be ten degrees throughout the test and the meter reading was divided by 0.51. This would result in an apparent error of about 19.5 percent higher than the true value. The oxygen utilization curve shown in Figure 5-25 indicates an apparent oxygen reading about 14.5 percent higher than the initial reading. This erratic result may have possibly been due to the rise of water temperature by the heating process. The temperature in the air conditioned laboratory had been noted at times to vary plus or minus two degrees from the mean of 22 degrees centigrade. Although the liquid in the test chamber or BOD bottle would not change as rapidly as the ambient air temperature in the laboratory, this indirect temperature effect could be a factor in causing the erratic results.

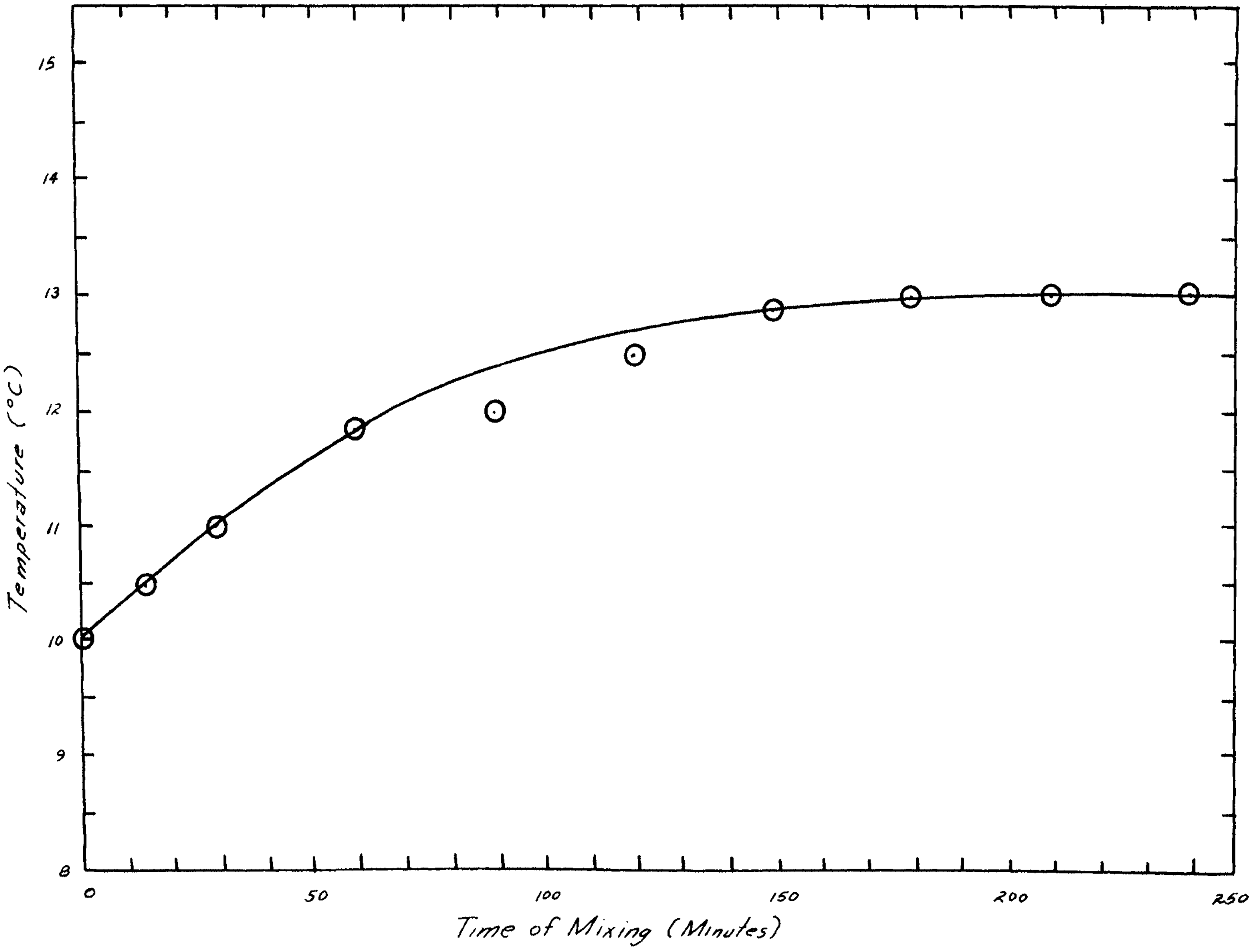

Figure 6-6

Temperature Rise From a Magnetic Mixer

VII. CONCLUSIONS

The following conclusions may be made from the evaluation of the data obtained from this investigation.

1. The oxygen consumption in the sludge system is primarily caused by the organic matter dissolved or suspended in the supernatant phase. The rate of oxygen uptake by the sludge phase alone is rather insignificant, as observed in this study, being in the magnitude of from 0 to 200 $mg/min/m^2$.
2. The organic content expressed in terms of Chemical Oxygen Demand (COD) of the supernatant phase is directly proportional to its concentration of volatile suspended solids. Since the rate of oxygen uptake is directly determined by the level of the supernatant COD, the rate is also related to the volatile suspended solids concentration.
3. The rate of oxygen utilization increases with temperature, which has a dual effect on the oxygen uptake, that is, increasing the biological activity and reducing the cohesiveness of the sludge. A decrease in the sludge cohesiveness will allow more solids to be suspended during the mixing of the supernatant.
4. The rate of oxygen utilization is higher for sludge obtained near the inlet and lower for that obtained near the outlet. The decrease in the oxygen uptake is believed to be due to a decrease in the sludge biological degradability and an increase in the sludge cohesiveness, which reduces the amount of solids suspended during the supernatant mixing.

5. The rate of oxygen utilization was observed to increase as the initial oxygen tension decreased. However, due to the narrow range of initial oxygen tension used and the limited amount of work performed in this research, the above observation is still considered rather preliminary.
6. The preliminary investigation showed no detectable sludge compaction after nine days of standing. Also, the rate of oxygen uptake was not substantially different for a sludge having one-half, three, and nine days of standing.
7. The sludge was found to be a gelatinous black slurry, having a musty odor. The solids content of the sludge ranged from 45,000 to 50,000 mg/l total solids of which 35 to 45 percent were volatile. The COD of the sludge averaged about 500 mg per gram of sludge.
8. Examination of the sludge under the microscope for the presence of protozoa or other higher macroorganisms such as rotifers, crustacean, and worms, disclosed that none of these organisms were present. This may probably indicate a very thin or no aerobic layer existing in the sludge.

VIII. RECOMMENDATIONS FOR FUTURE STUDIES

From the findings and experience obtained in this study, the following recommendations are made for future investigations:

1. In view of many variables involved in affecting the sludge oxygen uptake, it is recommended that future studies should first concentrate on the sludge from one location, and testing should also concentrate on one temperature until the parameters controlling the sludge oxygen uptake are fully understood.
2. Investigate a better mixing control which would provide a sufficient agitation for the oxygen probe, yet cause less disturbance to the sludge. This could be accomplished by using a smaller mixing bar, a slower mixing speed, or a combination of both.
3. Since in this study temperature was found to have a significant effect on the oxygen uptake, in future studies a dual channel recorder should be used so that both oxygen level and temperature can be recorded. If a dual channel recorder is not available the testing should be conducted in such a condition that temperature can be rigidly controlled.
4. In order to simulate more accurately the actual pond conditions, an investigation should be conducted to determine the advantage and disadvantage of using the actual pond supernatant for testing in the future.
5. In order to eliminate any possible effect resulting from the variations in the test schedule, in future studies a

strict time control should be established regarding the time interval between tests, and the length of time allowed for the supernatant reaeration.

6. Carefully determine in future studies if the biological activity of the test system is a limiting factor in the oxygen uptake, especially when the substrate concentration in the supernatant is high.

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VITA

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