Acknowledgement

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CHAPTER ONE

INTRODUCTION

A portion of the suspended matter discharged into streams and other drainage channels from sewer outfalls and land runoff settles to the bottom of sluggish river reaches, lakes, reservoirs and other water bodies to form a bottom sediment or benthal deposit. These benthal deposits of organic character will undergo biological decomposition by benthal organisms such as the saprophytic bacteria. The process may be aerobic, anaerobic, or both. If the water overlying the sediments contains dissolved oxygen, aerobic conditions will prevail at the surfaces of the deposits. This will result in a significant amount of dissolved oxygen demand upon the water. Although the oxygen will penetrate into the deposits to some extent, in most cases the diffusion of oxygen is not sufficient to maintain aerobic conditions below the superficial layers. In deposits of some thickness, where the diffused oxygen is exhausted in the upper layers, anaerobic decomposition becomes established. Gases of the decomposition, principally CO_2, CH_4 and H_2S are produced within the sludge. If they bubble up in sufficient volume, they may lift some of the sludge into the supernatant water and even to the water surface.

There is, in general, an upward diffusion of products and residues of anaerobic decomposition and, accompanying the consolidation of deposits with time, an upward displacement of the liquid contained in the interstices of the sediments. In the region where bottom-dwelling organisms are active, the vertical transportation of substances is further complicated. Some of the organisms, the sludge worms and insect larvae, for instance, ingest subsurface debris and cast their fecal pellets on the mud surface or burrow into the deposits and expose previously - covered material to the flowing water. Such vertical transportation is an important element in benthal decomposition since many of the substances reaching the sludge - water interface may exert a biochemical oxygen demand on the overlying water, as well as affecting the quality of the supernatant water. In heavily polluted parts of the stream, sludge activity may be raised to the point where the dissolved oxygen content of the flowing water becomes depleted by the high and rapid oxygen demand of putrescent sludge banks. Anaerobic conditions may then exist in the flowing water and result in a hazard to the aquatic life.

Depending on the hydrography of the stream, the vertically - transported substances may be dispersed and carried along by the flow, or, when flow becomes turbulent to the point of creating scouring velocities, masses of sludge may be lifted into the supernatant waters and exert a considerably increased oxygen demand in the downstream water.

Temperature changes, running their seasonal course in streams lakes, and other bodies of water, exert profound effects upon the rate of decomposition of river muds and pollutional sediments. Chemical and biological activities, rates of diffusion, and the solubility of gases are all functions of temperature. As the deposits warm up in the spring, chemical and biological activities are stimulated, diffusion is increased, and the solubility of gases is reduced. These conditions combine to increase benthal decomposition but, at the same time, the enhancement of its orderly progress exhausts the available dissolved oxygen, liberates gas bubbles, and raises and leaches the bottom materials. These combined effects of rising temperature may cause the oxygen demand of the benthal deposits to become a critical factor in the amount of oxygen present during the late summer and early fall months when both the oxygen in the water and the total rate of flow tend to reach seasonal lows. Falling temperatures result in the opposite effects, but an ice cover may bring about objectionable conditions in the water overlying sludge deposits because of the lack of atmospheric reaeration of the overlying water.

In recent years, the benthal deposits of waste products from the pulp and paper manufacturing industries have become of increasing concern in many stream pollution problems, especially downstream of the sites of wood-processing plants. In the production of paper the primary objective of the pulping process is to separate cellulose from other constituents of the wood. The cellulose is used to make paper while the other constituents, along with the spend pulping chemicals, are discharged as waste. The main constituent of the waste, lignin, is resistant to biological attack and possesses a high coloring effect. It decomposes at an overall slow rate of $k = 0.027 \text{ day}^{-1}$ according to Raabe (1968), and over a period of 100 days, less than 50 percent of the compounds present are oxided.

Several paper mill companies existing on the Ottawa River take advantage of the natural water course to transport logs and to dispose of their intermediate processing and final wastes. The effects of these paper mill operations on this river of high recreational potential have become a cause for concern from both aesthetic and economic considerations. The water near the outfall of the mills is highly colored and turbid with suspended solids. In some areas floating masses of sludge are visible at the surface, and gases of benthal decomposition can be seen bubbling up. Due to the combined facts of unsightly conditions and unpleasant odors, the utility of water for recreational purpose has become lessened or completely lost.

Because of the recent construction of a dam at Hawkesbury, the flow characteristics within the reach immediately downstream of Ottawa have been changed. The reduced hydraulic gradient and velocity of flow are conducive to more sedimentation of the continuously discharged wastes which contain high amounts of suspended solids. The expected result will be increased sludge banks which will undergo benthal decomposition and a further degradation of the quality of the river water.

Paper waste sludge deposits usually possess an acidic nature. When decomposing under benthal conditions, the pH values are not found to rise, according to Lardieri (1954). These low pH values seem largely responsible for the low and constant rate of oxygen utilization and the small amounts of gas produced. Also, according to Zobell and Stadler (1940), the species of microorganisms that utilize lignin are relatively limited, and their rate of assimilation is very slow and incomplete.

In general, most studies up to date have been concerned with the oxidation characteristics of various types of paper mill waste deposits and the self-purification rates of the many streams into which these wastes are discharged. However, little information is available on the overall effects of woody benthal decomposition. This study is concerned with the effects of the decomposition on the over flowing river water, taking into consideration of a number of characteristics of the water. These may be divided into three groups: those associated directly with the dissolved oxygen; those which indicate the physical characteristics of the water; and, finally, the pH value.

Depending on the nature of the polluting substances and the body of water, the degree of pollution and the natural purification can be measured physically, chemically, and biologically. When the oxygen content of the flowing water is the criterion, the DO and

BOD, taken together, are relied upon to trace the profile of pollution and natural purification on which engineering calculations of permissible pollutional loadings can be based. The BOD identifies in a comprehensive manner the degradable load added to the overflowing water; the DO identifies the capacity of the body of water to assimilate the pollutional loadings of degradable material.

The substances which are vertically transported from the sludge deposits into the water may affect the solids content, the turbidity, and the color of the water. These parameters, although not necessarily critical, may show objectionable characteristics from the standpoint of appearance for domestic use or for industrial use of the water. From them, the acceptability of the water for different uses may be determined and they indicate the kind of treatment and chemical dosages required in treatment plants employing chemical processes. The turbidity identifies the presence of suspended matters, such as clay, silt, finely divided organic matters, plankton, and other microscopic organisms. The total solids content, or residue on evaporation, is an indication of amount of foreign matter in the water while the total volatile solids content is a measurement of the amount of organic matter present. The total solids may be further divided into those in dissolved form or not dissolved. The "apparent" color intensity is due to the present of suspended matter and organic extracts that are in colloidal form. The measurement of color can be used as a rough guide in estimating the concentration of suspended matter.

The pH, which expresses the intensity of the acid or alkaline condition of a solution, is an important factor in biochemical reactions. It may serve as an indicator in the progress of the decomposition process under anaerobic conditions. Previous studies of the decomposition of woody deposits have shown the importance of pH. It has been determined that the pH of these deposits is low enough to inhibit the methane formers.

In this study the first consideration was given to the oxygen demand of the sludge deposit. It was not felt necessary to duplicate previous studies on such effects as the area and the depth of the deposit, the pH adjustment, and the degree of mixing. Of greater concern was the desire to perform the tests under condition which would approximate the conditions in the river within the limitations of the laboratory. To this end the tests were performed in a horizontal reaction tube which contained the sludge and in which the overlying water was mixed by an oscillating screen. It was felt that this set up would better represent the mixing conditions which exist within the turbulent boundary layer at the river bottom than the experimental apparatuses which have been used in previous studies.

In order to investigate the effect of the deposit on the overlying water as the deposit slowly decomposed or aged, the horizontal tube was used as a batch reactor for short-term tests of durations up to 24 hours as well as a continuous flow reactor wherein flow over the deposit was maintained for periods of several days. The flow rate in the reactor was taken so that a contact time was obtained which would approximate that which might exist over an extensive deposit in the river.

It was not the intent of this study to investigate the importance of temperature change on the effects of the deposit on the overlying water. Biochemical reactions are well-known to be temperature dependent to an important degree. However, it is felt that this effect can be approximated satisfactorily for this case from previous studies.

The study was restricted to nonscouring conditions over the deposit. This is the case in the river during critical low flow conditions.

Finally, the tests were conducted using water from the Ottawa River itself. While much can be said for using a water whose characteristics can be closely controlled, it was felt that there could be several factors which might affect the process which would be difficult to duplicate with laboratory prepared water. For example, the presence of bacterial seed, the natural buffering capacity of the water, and the presence of nutrients in the water are factors which would required considerable study to determine whether or not they were of importance. Rather, it was decided to use the natural river water in the tests, hoping to make them of greater value for the local conditions even though their general application might be limited.

To summarize, the purpose of this study was to investigate the effects of a woody benthal deposit on some of the quality characteristics of the overlying water by a laboratory study. The water used in the study was the natural river water. The mixing conditions and time of contact were made to approximate the river conditions. The specific quality characteristics studied were the dissolved oxygen uptake of the deposit, the release of BOD to the overlying water, and pH, color, turbidity and solids content of the overlying water.

CHAPTER TWO

PREVIOUS INVESTIGATION

Numerous previous investigations have been made of benthal decomposition which have a bearing on this study. Also related studies have been made on the relationships among the water characteristics studied here. In this chapter these investigations are briefly discussed and summarized.

The complex relationships which are involved in benthal decomposition as well as the varied nature of these deposits have led to studies of a number of factors under various conditions. Close comparison of the different studies is difficult as a result.

Baity (1938), working with settled domestic and industrial wastewater sludges, found the oxygen uptake of benthal deposits to be independent of the oxygen concentration of the supernatant water above 1.5 mg/l, but dependent on depth of deposit. He examined several shallow depths of sewage sludge ranging from 0.5 to 4.0 cm, and postulated a depth function as a near parabola having the following relationship:

$$y = 2{,}700\ x^{0.485}$$

where x = sludge depth (cm)

y = rate of oxygen demand (mgO_2/day/sq.m.)

Experiments showed that complete stabilisation of thin sludge films which are less than 0.1 cm was accomplished in about 36 days.

Fair, et al (1941) in an investigation with a sewage sludge deposit which contained lower concentrations of volatile solids, proposed the following empirical relationship:

$$y_{so}' = 2.45\ m^{0.485}$$

$$y_{s2}' = 0.91\ m^{0.516}$$

where

y_{so}' = initial rate of oxygen demand in grams of oxygen per sq. m. daily

m = areal concentration of volatile matter in Kg. per sq. m.

y_{s2}' = half-life rate of oxygen demand in grams of O_2 per sq. m. daily.

He concluded that the oxygen uptake in the overlying water related primarily to the rate of transport of oxidizable substances from the interior of the deposits to the overlying water, and not by the rate of diffusion of oxygen into the deposit from the water.

Rudolfs (1938) carried out studies on the BOD of comminuted and screened sewage sludge as well as activated sludge. The decanted liquor and the sludge showed a marked BOD reduction with time. A rapid rise in sludge pH accompanied by a high rate of BOD reduction in the sludge was observed. The pH values continued to decrease while the BOD of the material fluctuated greatly during the first few weeks. When a gradual decrease in BOD took place, the pH values remained constant. After the BOD began to decrease rapidly, the pH values of the sludge increased greatly.

Lardieri (1954), using acidic sludge collected from a stream below a paper mill, showed that the decomposition of paper sludge deposits progressed at a constant rate rather than at a rate which decreased with time, such as occurs with most sewage sludges. Also, the rate of dissolved oxygen uptake remained low and constant. He believed that this was due primarily to the low pH in the deposits. Adjustment of the sludge pH to a value of 7.0 approximately doubled the oxygen demand.

A study made by Pipes (1962) is of interest here because it considers the influence of pH on Oxygen Uptake. He observed that the control of influent pH does not have a pronounced effect on BOD removal in the conventional type stabilization ponds, but it is an important factor in achieving high BOD removals in high-rate stabilization ponds. He pointed out that when the influent pH is greater than 7.2, increasing detention period increases BOD removal; when the pH is 7.2 or less, increasing detention period decreases BOD removal.

Edwards and Rolley (1965), using samples of benthal material collected from several English rivers, found that the oxygen consumption of this material was dependent on oxygen concentration of the overlying water up to about 8 - 10 ppm and suggested that at oxygen concentrations of about 2 ppm, the relation may be described by

$$y = a_3c^b$$

where c is the oxygen concentration in the overlying water (mg per litre), a_3 and b are constants, and y is oxygen consumption (g per hr. per sq.m.)

They also concluded that the oxygen consumption was independent of sediment depth at depths greater than about 2 cm.

Mukherjee, et al (1968), in their studies with wastewater collected from a city outfall, showed that the k value varied with the change in pH of the diluted sample. In the pH range of 6.0 to 8.0, at various temperature from 20° to 37°C, the magnitude of k is maximum in the acidic region, tends to decrease with increase in pH, and is minimum in the neutral zone, and again increases in the alkaline region.

McDonnell and Hall (1969), in their studies on samples of benthal material collected at 1.5 miles below the outfall of a secondary treatment wastewater plant, reached the conclusion that the oxygen consumption of the benthos was dependent on oxygen concentration up to levels of about 8 mg/l, and that this dependence was primarily because of the respiration of the macroinvertebrate populations which may be present.

McKeown, et al (1968), in a study of cellulosic benthal deposits using both continuous-flow and batch systems, concluded that the biochemical oxygen demand that was transferred to the supernatant water decreased with time and reached zero after 100 days for the case of shallow deposits, and that the oxygen demand exerted directly by the deposits decreased with increasing time. In their studies of sludge depth of 1, 2, 3 and 4 ft, they noted that the dissolved oxygen demands of the overlying water remained constant through all cases showing, in other words, that the demand was independent of the depth of deposit for deep deposits.

Hanes and Irvine (1968), in studies on a paper-waste sludge, demonstrated the existence of the processes of substrate transport and oxygen diffusion. Their data indicate an independence of oxygen uptake with dissolved oxygen concentration from the overlying water.

Raabe (1968) showed that the BOD of a stream polluted with Kraft paper mill wastes was related to the concentration of carbohydrates, the fraction of lignin compounds oxidizable in 100 days, and possibly to other slowly decomposable organics. The rate constant for the BOD curve which indicated the oxidation of wood sugars and other readily decomposable materials was observed to be 0.455 day^{-1}, and that for the decomposition of the lignin was 0.072 day^{-1}.

Black and Christman (1963) found that the color intensity of naturally colored water varied reversibly with pH. The slope of the curve relating color intensity to pH in an acid solution was considerably less than that in a basic solution. The greatest increase in color value for the pH range 2 to 10 employed was obtained with samples with the lowest original color, and the smallest increase was obtained in waters with the highest original color.

These previous studies reveal much valuable information and general trends about the decomposition of benthal deposits, some of which were of a woody nature. This may be summarized as follows:

1. The oxygen uptake of a deposit is proportional to the surface area of the deposit.
2. The oxygen uptake appears to be independent of the depth of the deposit for deposits greater than about 2 centimeters in depth.
3. The degree of mixing affects the uptake rate greatly. Mixing which approaches scouring may increase the uptake rate from 3 to 10 times over that experienced under laminar flow conditions.
4. The naturally low pH of woody deposits may reduce the oxygen uptake by half of that experienced with pH control by a buffered water.
5. Oxygen uptake rates differ significantly in different laboratory tests. This is demonstrated in information presented later in this thesis. Some of this variation is due to the characteristics of the sludge. Domestic sewage sludge shows a higher initial uptake rate than sludge of a woody nature.
6. Decomposition of woody benthal deposits is a slow process which may require times up to or exceeding 100 days.

Because of the variations in previous studies, it was felt that the best approach to this problem of determining the effect of the deposits upon the water of a particular river, the Ottawa, would be to approximate the conditions as closely as feasible within the limitations of the laboratory. Furthermore, it is noted that the previous works which treated the effects on woody benthal deposits were conducted with distilled or seeded dilution water as the overlying water which is not, of course, the actual case in nature. Thus the plan of this study as detailed in the introduction was formulated.

CHAPTER THREE

EXPERIMENTAL WORK

3-1. Experimental Apparatus

The progress of benthal decomposition can be traced in many different ways. Interpretation of benthal decomposition in engineering terms requires, however, that the yardsticks employed shall either measure the effect of river muds and pollutional sediments upon the supernatant water in terms of changes in water quality or that they shall evaluate in over-all terms the amount of stabilization that is accomplished on the sludge itself. The first of these measures was the primary type used in this study.

Among the methods reported in the literature, the system employed by Hanes and Irvine (1968) has yielded quantitative and reproducible results, and they do define the phenomenon associated with a benthal system which does not receive additional settled solids. The material in the reaction chamber was agitated by a magnetic stirrer. Both the oxygen level and temperature in the chamber were measured by a precision oxygen analyzer and a thermistor. The oxygen level was recorded continuously by a recorder. The temperature was controlled by placing the whole assembly in a walk-in incubator. The conditions of the system, however, appear to be quite unlike those encountered in many receiving waters, particularly streams, in which the flow is overflowing the sludge continuously and washes away some of the products leaching from the bottom sludge simultaneously.

In the continuous-flow, horizontal-tube assembly employed by McKeown, et al (1968), samples of sludge were placed at the bottom of the reactor through which a continuous flow of water was supplied by making use of a constant-head tank. The flow was controlled by vertical adjustment of the outlet capillary.

The apparatus employed in this study followed along the lines of that used by McKeown, with one major change, the nature of mixing in the reactor tube. As noted above, previous studies have been made using continuous flow reactors and batch reactors with or without stirring. It was felt that the natural conditions could be best approximated by a horizontal flow-through system such as that used by McKeown, et al, with a device to promote mixing within the tube. Otherwise, at the flow rates in the laboratory, laminar flow would result which would not simulate very well the turbulent conditions existing in the river. Altogether the departures from McKeown's design were: (1) alternations in the flow mixing device, (2) provision for collecting and measuring a sample of inflow, and (3) modifications of the piping system to eliminate, in so far as possible, the interruption of flow in the reactor by inflow.

The apparatus consisted of a horizontal reactor-tube, a constant-head tank, a horizontal agitator driven by an electric motor, a pump, an inflow sampling device, an outflow sampling part, a fine-mesh plastic screen, outlet capillary, gas bleeder and incu-

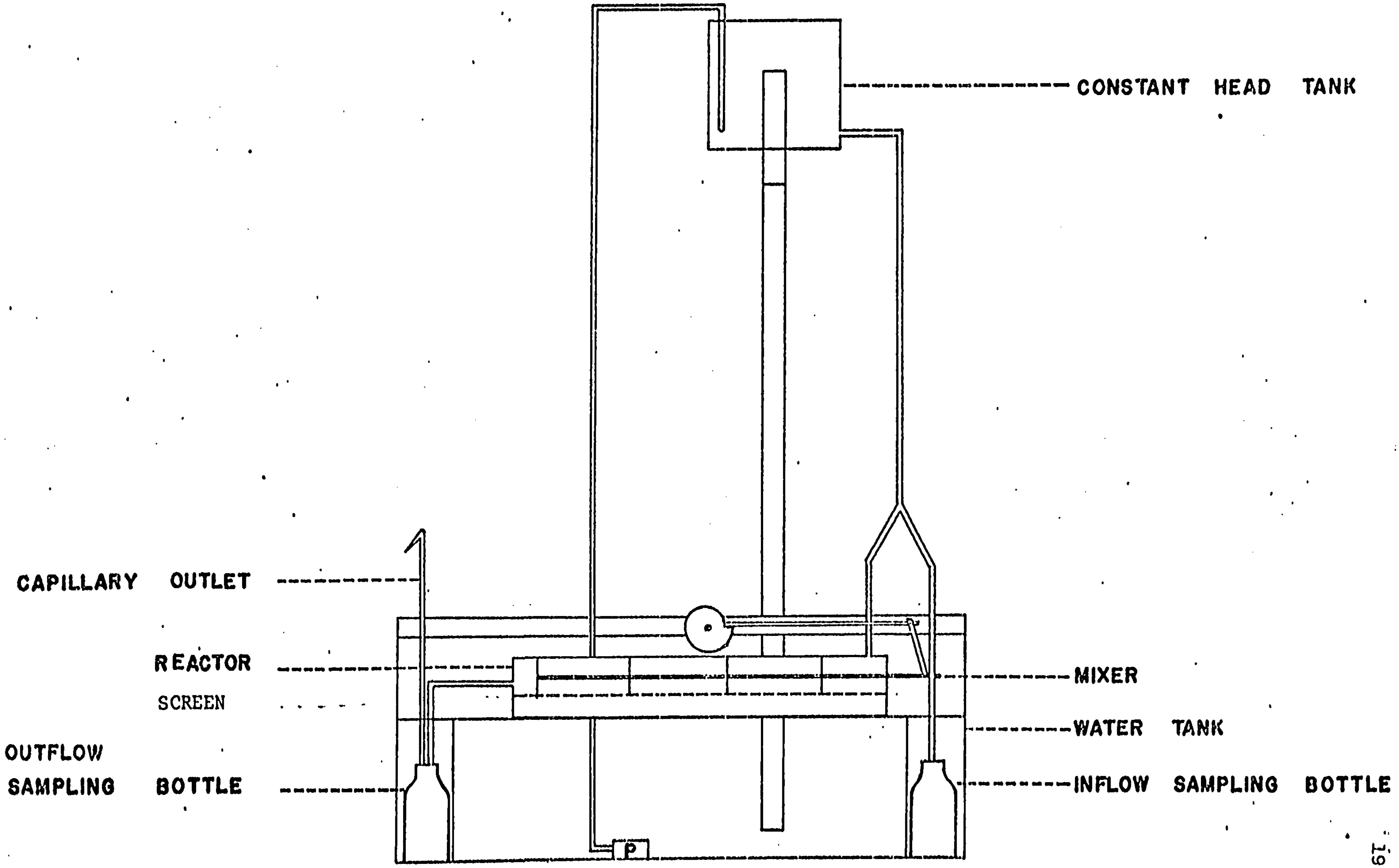


FIGURE 1 - ASSEMBLY FOR BENTHAL DEPOSIT STUDIES

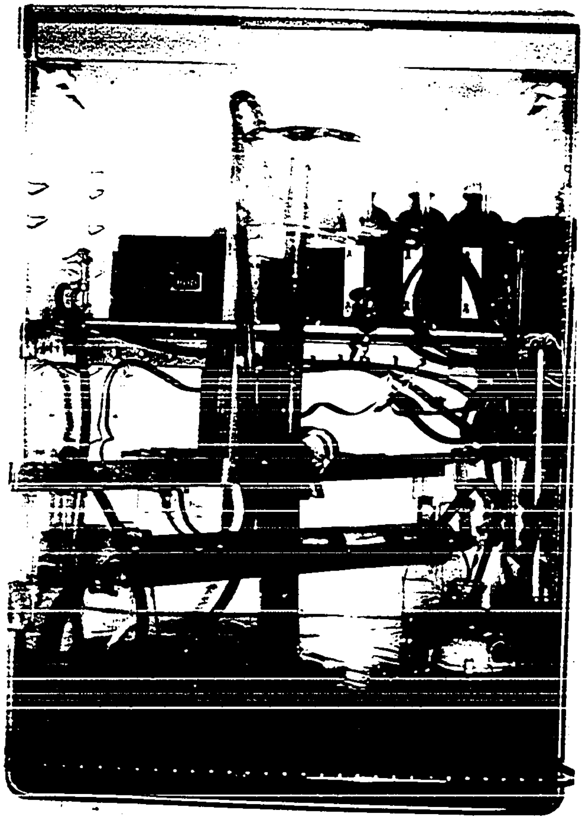
bator. All connections were fitted tightly to insure an air-tight seal. A sketch of the apparatus is shown in Figure 1.

A 2-inch diameter, lucite tube, 18 inches in length, was used as the benthal reactor. In it a fine-mesh plastic screen was placed horizontally and parallel to the axis of the tube, 0.25 in from the axis, to prevent large masses of sludge from being raised into the overlying water during operation. Mixing was achieved in the reactor by a horizontal agitator. This agitator consisted of a rod with several perforated lucite plates rigidly attached to it. The perforated plates were the same size as the channel cross-section above the fine screen.

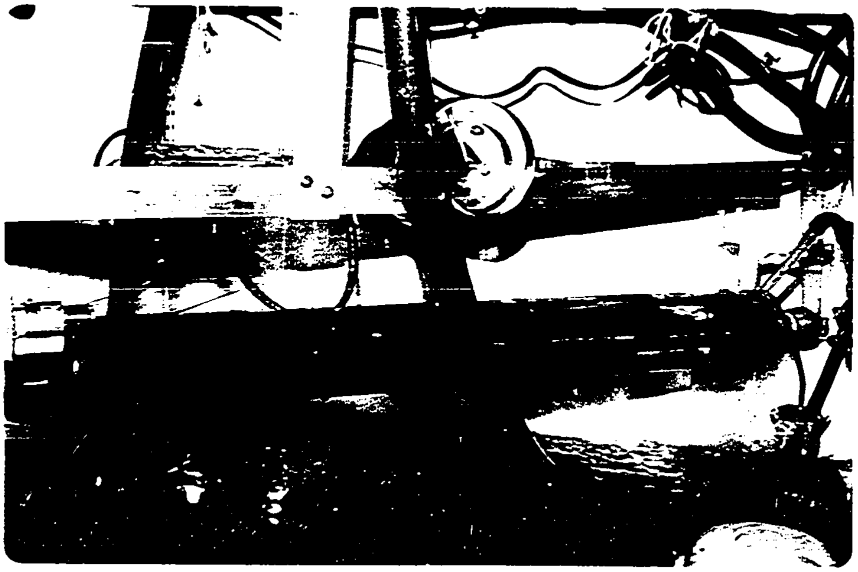
The agitator rod was driven by the motor through a cam which moved the rod slowly in one direction. At the end of the stroke, a spring returned the agitator to its original position with a sudden movement, thereby mixing the water. The frequency of the mixing movement was about one stroke per minute. The length of the stroke was 0.79 in. A brief study, using dye as a tracer, was carried out to check the completeness of mixing at mixer speeds sufficiently low to prevent scour of the deposits. The entire reactor was observed to become colored within a few seconds after the introduction of dye in the inlet of the reactor.

The system was designed to maintain constant and continuous flow by making uses of a constant-head reservoir and an electric pump. The water supplied to the reactor was first held in a large

PLATE 1

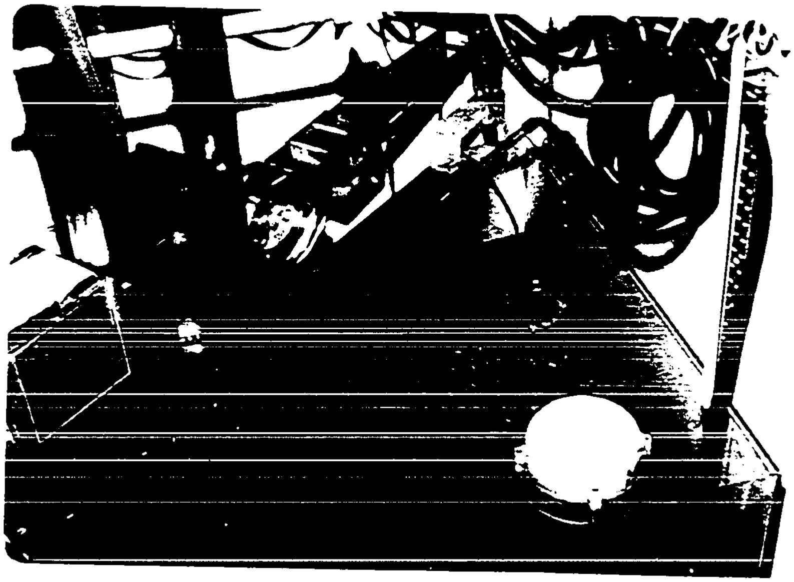


Apparatus in Operation



Reactor

PLATE II



Inflow Sampling Device

Outflow Sampling Part

water tank, and was then pumped continuously into a small constant-head tank which was installed 12 inches above the water level. Through a small outlet of this tank, the water was then delivered to the reactor. The rate was controlled most simply by vertical adjustment of the outlet capillary. The constant-head tank, reservoir and all of the necessary parts were products of either rubber or plastic to insure that no reaction with the water occurred.

The apparatus was assembled inside a dark incubator where the temperature was maintained at $20^{\circ} \pm 0.5$C. Photographs of the experimental set-up are shown in Plate I and II.

3-2. Sample Collection and Preparation

The benthal material used in this investigation was collected in August from the Ottawa River. The sample was taken from the surface layers as it was desired to study material which might be redeposited in the river. The sampling station was located approximately 100 yards below the outfall of the Canadian International Paper Company plant in Gatineau Point, Quebec (See map, Plate III). The woody sludge was washed with a few gallons of river water to simulate conditions occurring in an actual new benthal system formed by the redeposition of scoured material. After washing and removal of the supernatant, the sludge was tested for its characteristics (Table 1) before being placed into the bottom of the reactor. Approximately 400 ml of prepared sludge were used for this investigation. This gave a depth of approximately 2 cm which had been found by previous

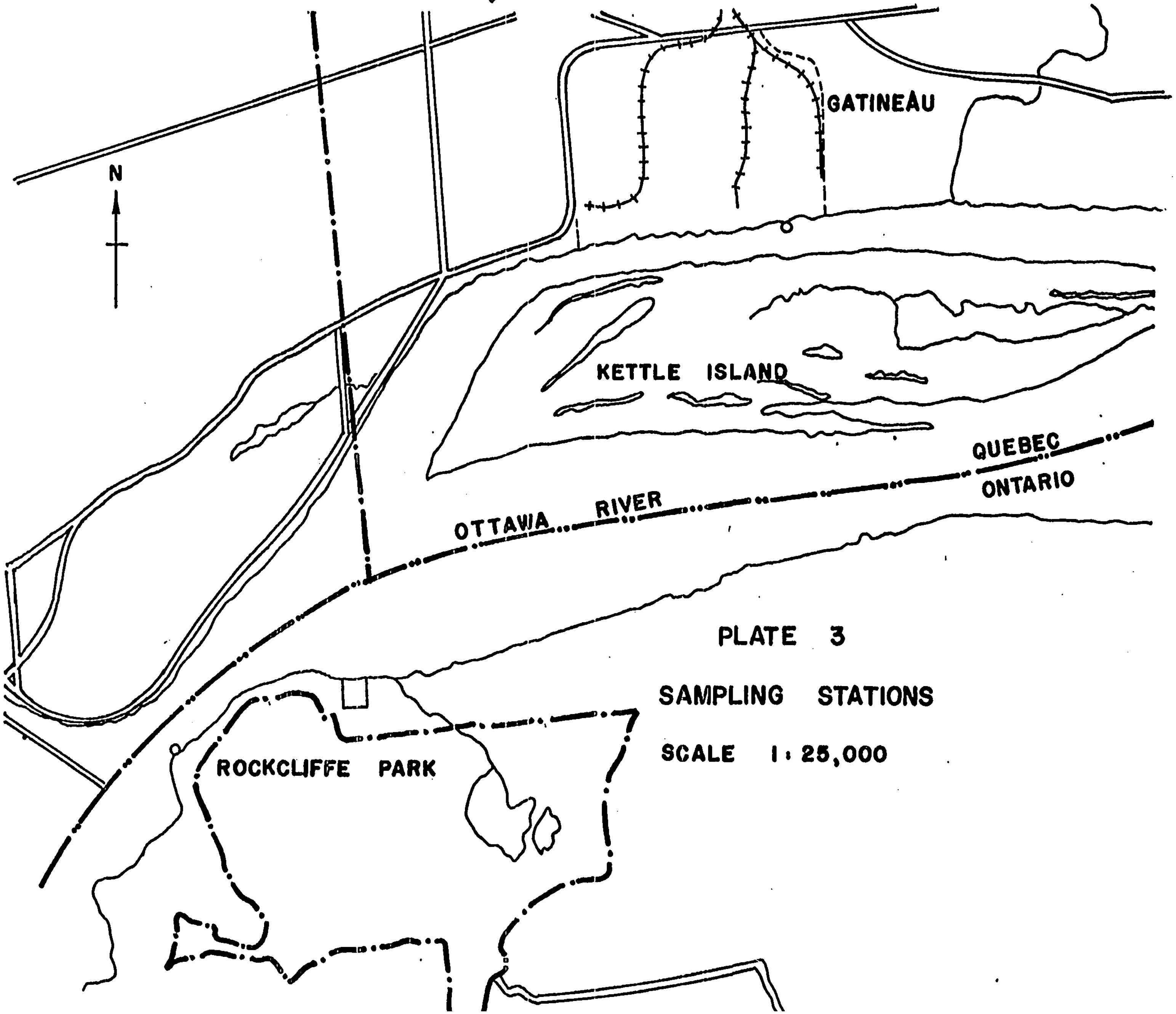


PLATE 3

SAMPLING STATIONS

SCALE 1 : 25,000

investigators to be the depth beyond which the oxygen demand was independent of the depth. The contact area between sludge and water was found to be 20.63 in^2. For the first two days, a constant and continuous flow of 1 ml. per min. was maintained over the sludge. The sludge was then considered to be sufficiently settled for beginning the tests.

Table 1. - Sludge Deposit Characteristics

BOD	1370 ppm
pH	5,72
Total solid	21.26% by wt. of wet sample
Total volatile solid	37.63% by wt. of total solid
Contact area	133.00 cm^2 (20.625 in^2)
Max. depth of sludge	1.91 cm (0.75 in.)

After placement of the sludge the reactor was used in a batch process to evaluate the effect of the sludge deposit on the overlying water for four different, independent detention periods. Fresh river water was put in the reactor and kept there for 6 hours. Mixing by the horizontal agitator was maintained throughout the period. From the same samples initial tests for the dissolved oxygen, BOD, pH, color, turbidity and solids were made. After 6 hours the water was removed from the reactor, the same tests were repeated on this sample which had been treated in the reactor. Also, a fresh sample of water was placed in the reactor and the same process was repeated for a detention period of 18 hours. This was followed by detention periods of 12 hours and of 24 hours with the same tests being repeated at the beginning of each detention period and upon the treated water at the end of the period. The order of the detention periods which was used was chosen so that the periods could be started during daylight hours, for convenience.

Prior to the tests with sludge, the tests were performed in the same manner on the river water alone to determine the oxygen uptake, the pH change, the change in turbidity in the water. Also this opportunity was used to test the apparatus in general. One series of tests with sludge was begun but abandoned because of leakage developing in the setup.

The overall time required for the series of experiments was 60 hours. After the 24-hour detention period of each series of tests, the sludge was aged with the overlying water flowing at a controlled rate of about 1 ml/min. The agitator was operated at all times to promote mixing.

The water used throughout the investigation was collected from a station located approximately ½-mile upstream and on the opposite bank of the river from the point at which the sludge sample was taken. It was felt that the characteristics of the water were adequately representative of those at any point in the river.

This water was taken and transferred to the laboratory within 15 min. before each experiment started. The dissolved oxygen content in the river water during the period of studies was observed to range from 7.4 to 8.7 parts per million while the pH value ranged between 6.7 to 7.8. No attempt was made to change the water quality for the studies. All of the analyses were carried out and completed within a short period after collection.

3-4. Analytical Methods

Measurements of dissolved oxygen were made following the standard method for the Azide Modification of the Winkler Method given in Standard Methods (1965) using fresh reagents. In some analyses of the outflow a calibrated Yellow Springs oxygen probe was used to determine the dissolved oxygen content.

Biochemical oxygen demand (BOD) was determined by employing the procedure given in Standard Methods (1965). Measurements of initial and final dissolved oxygen were made as described above. The BOD dilution water for each experiment was freshly prepared with distilled water which had been stored and aerated at 20°C for 24 hours prior to use.

All pH values were determined electrometrically on a Fisher pH meter with glass and saturated calomel electrodes.

Tests for color and turbidity through all the investigations were made by colorimetric methods using a Hach direct-reading colorimeter.

Determination of total, total volatile, dissolved and volatile suspended solids were based on the methods given in the Standard Methods. Amount of total solids was obtained by drying the residue on evaporation to constant weight at 103°C in an oven. Amount of total volatile solids was determined by igniting the residue on evaporation at 600°C in an electric muffle furnace to constant weight, the loss of which was reported as the volatile solid. Measurements of dissolved solid were made by evaporating a filtered sample and drying to a constant weight at 103°C. Volatile suspended solids were the weight lost on ignition of the crucible with the suspended matter.

CHAPTER FOUR

ANALYSIS AND DISCUSSION OF EXPERIMENTAL RESULTS

4-1. Introduction to Analysis

The raw data, which consists of the test results on the water before contact with the sludge and after contact for the prescribed detention period, are presented in the Appendix. In this chapter these raw data are analysed. In all cases the quantity of interest was the change in the characteristic over the detention period. Thus, the results used here are increments or decrements of these measures of quality.

As previously mentioned, an initial evaluation of the experimental system was made using river water alone. The reason for doing this is to determine the changes in certain of the parameters which would occur even if no sludge were present. This was done by filling the reactor with fresh river water and running the apparatus for 6- , 12- , 18- and 24- hour detention periods as described in test procedures from Step 1 through Step 4. The results, which show changes in the river water itself, are presented in Table III, Appendix, and shown in Figures 2 and 3. These figures show measurable changes in oxygen concentration, turbidity, and the pH value. The similarity of the curves shows that depletions of dissolved oxygen are accompanied by associated decreases in pH value and turbidity.

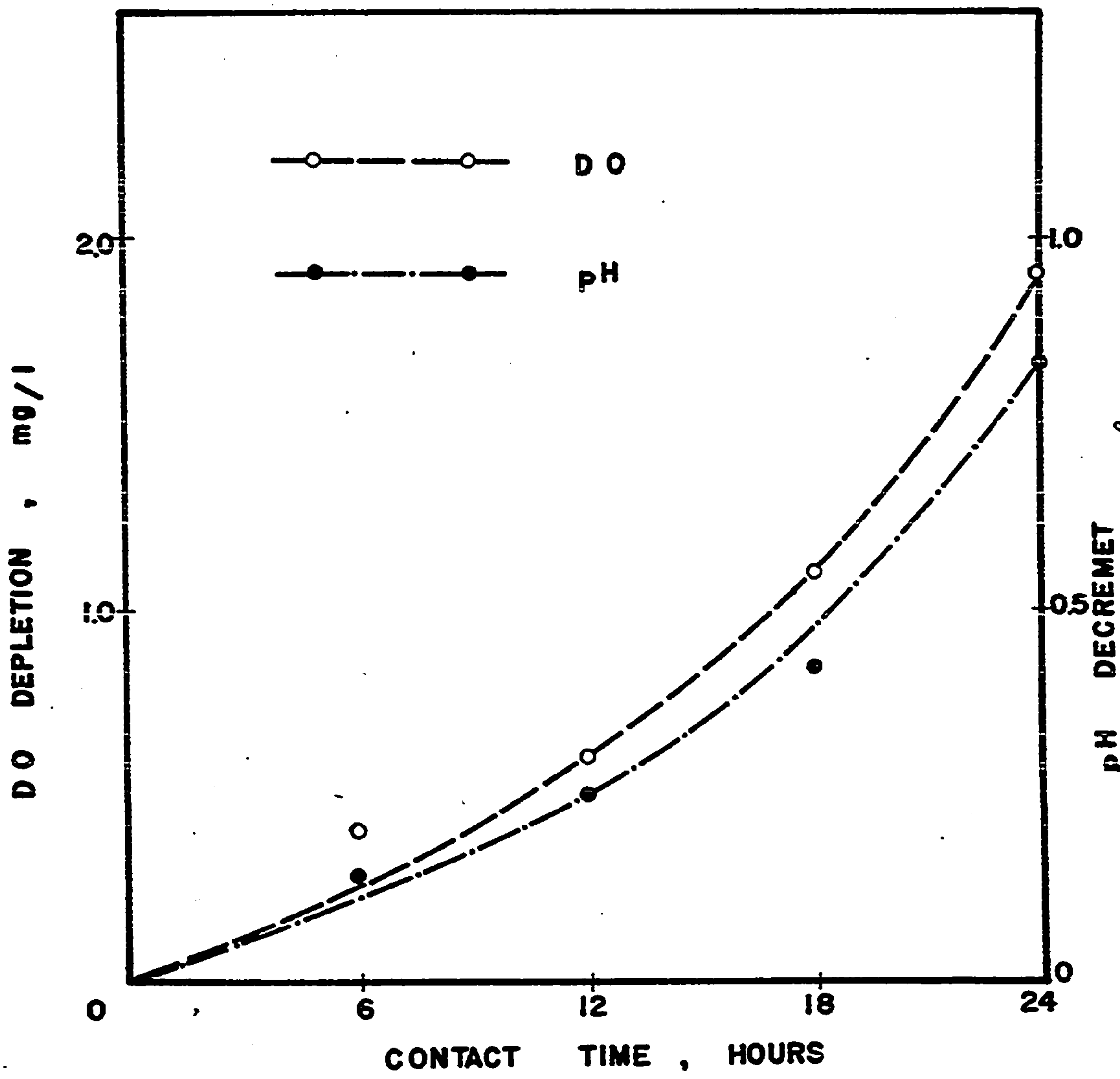


FIGURE 2 - D O DEPLETION AND pH DECREMENT , OTTAWA RIVER WATER

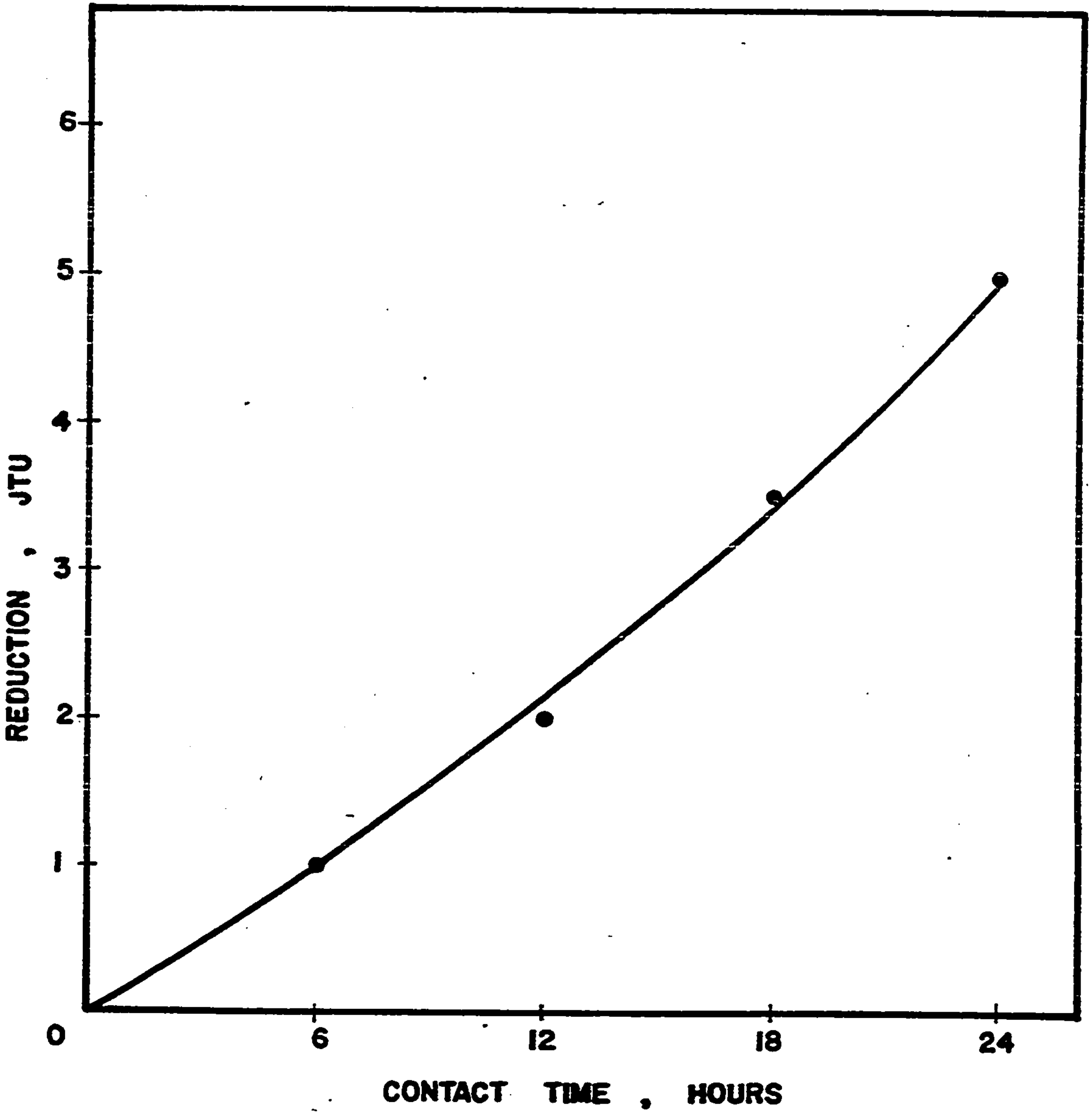


FIGURE 3 - TURBIDITY REDUCTION , OTTAWA RIVER WATER

4-2. Analysis of Individual Characteristics

The analysis of the data can be grouped into two parts: (a) the determination of the effects of the bottom deposits on the overlying water characteristics and (b) the study of the inter-relation of the characteristics. Of primary interest is the first analysis. This will show how the deposit affects the solids in the water, the pH, the color and turbidity, the BOD and the DO content. The second analysis may indicate relationships between the characteristics. Such relationships, if they exist, could be useful in predicting one characteristic from another.

4-2-1 Solids

To define quantitatively the total, total volatile, and dissolved residues imparted from benthal deposits to the overlying water as a result of the combined processes of upward diffusion and lifting by gas, tests for these solids were conducted as previously described. Table IV, Appendix, presents the analytical results for the four detention times. Increments are shown throughout as they indicate the increase in solids due to contact with the sludge. Graphs showing the increment of each are presented in Figures 4 through 6. Generally, these figures illustrate noticeable increments of solids imparted to the overlying water.

The graph for the increment of dissolved solids show only a slight decline with sludge age. This suggests that the production of dissolved solids is closely related to the decomposition process

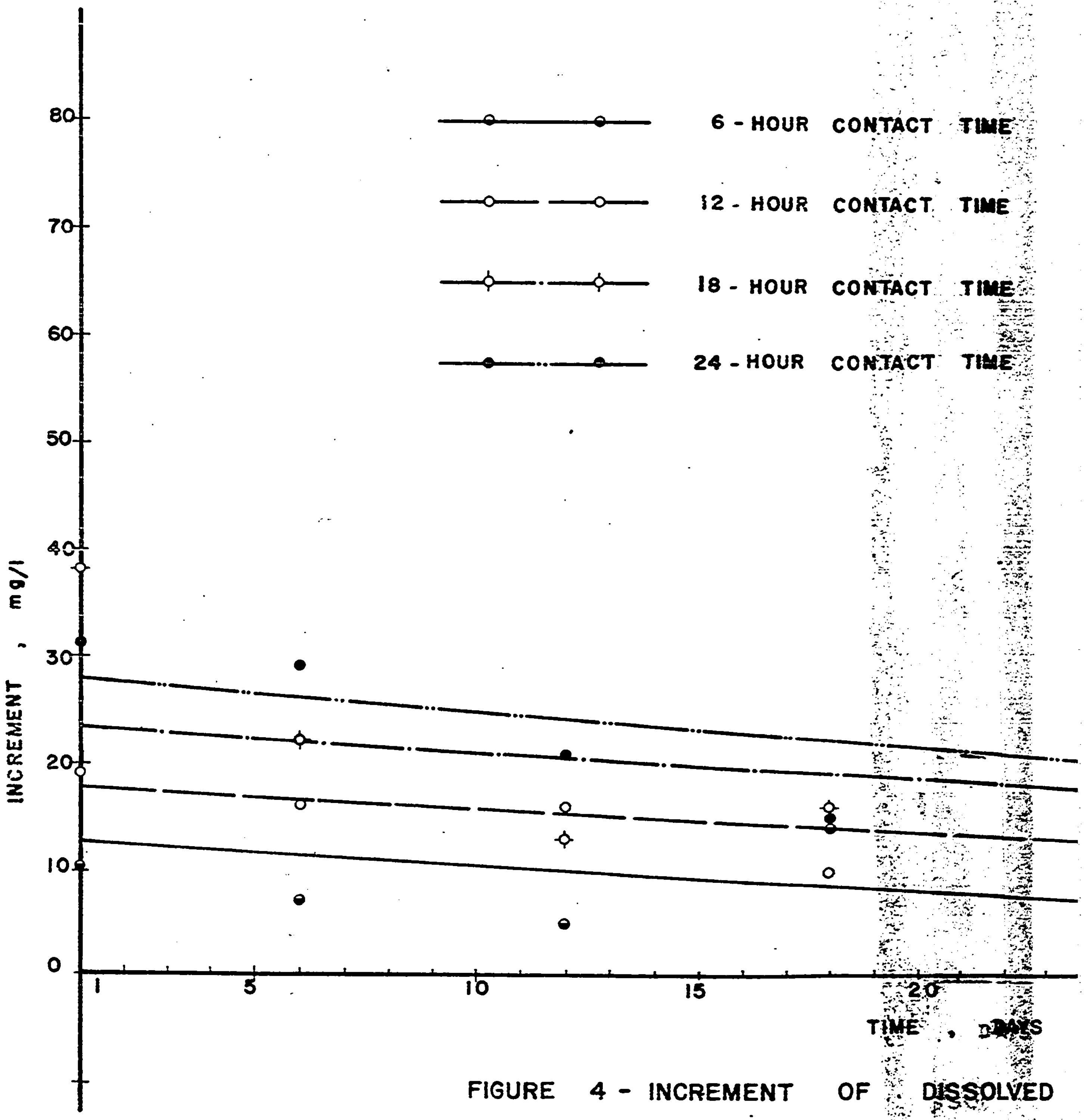


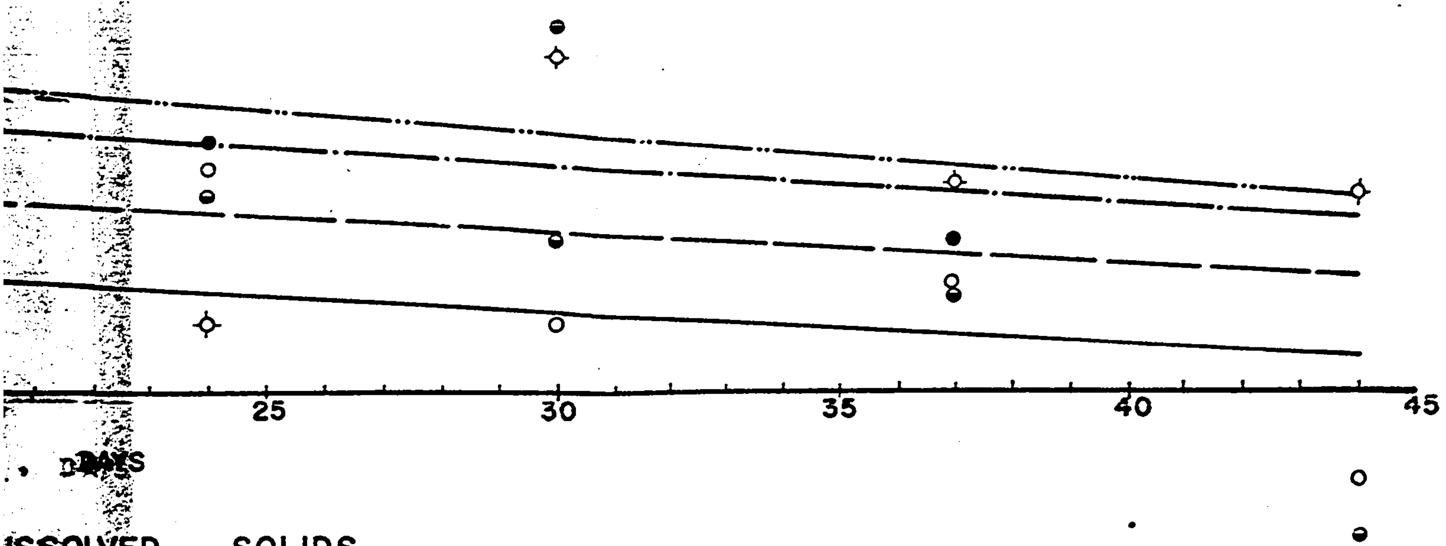
FIGURE 4 - INCREMENT OF DISSOLVED

TIME

TIME

TIME

TIME



ISSOLVED SOLIDS

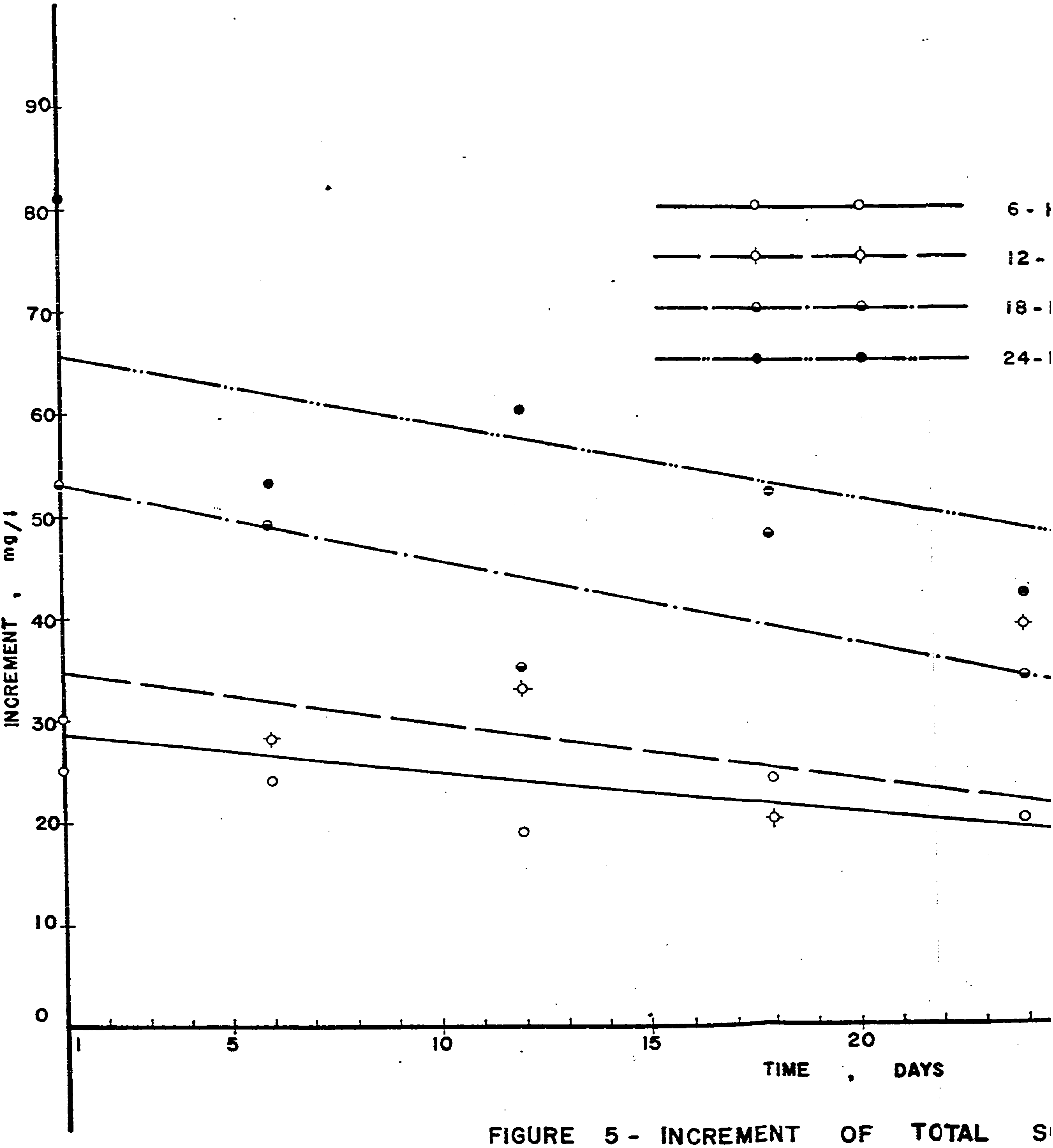
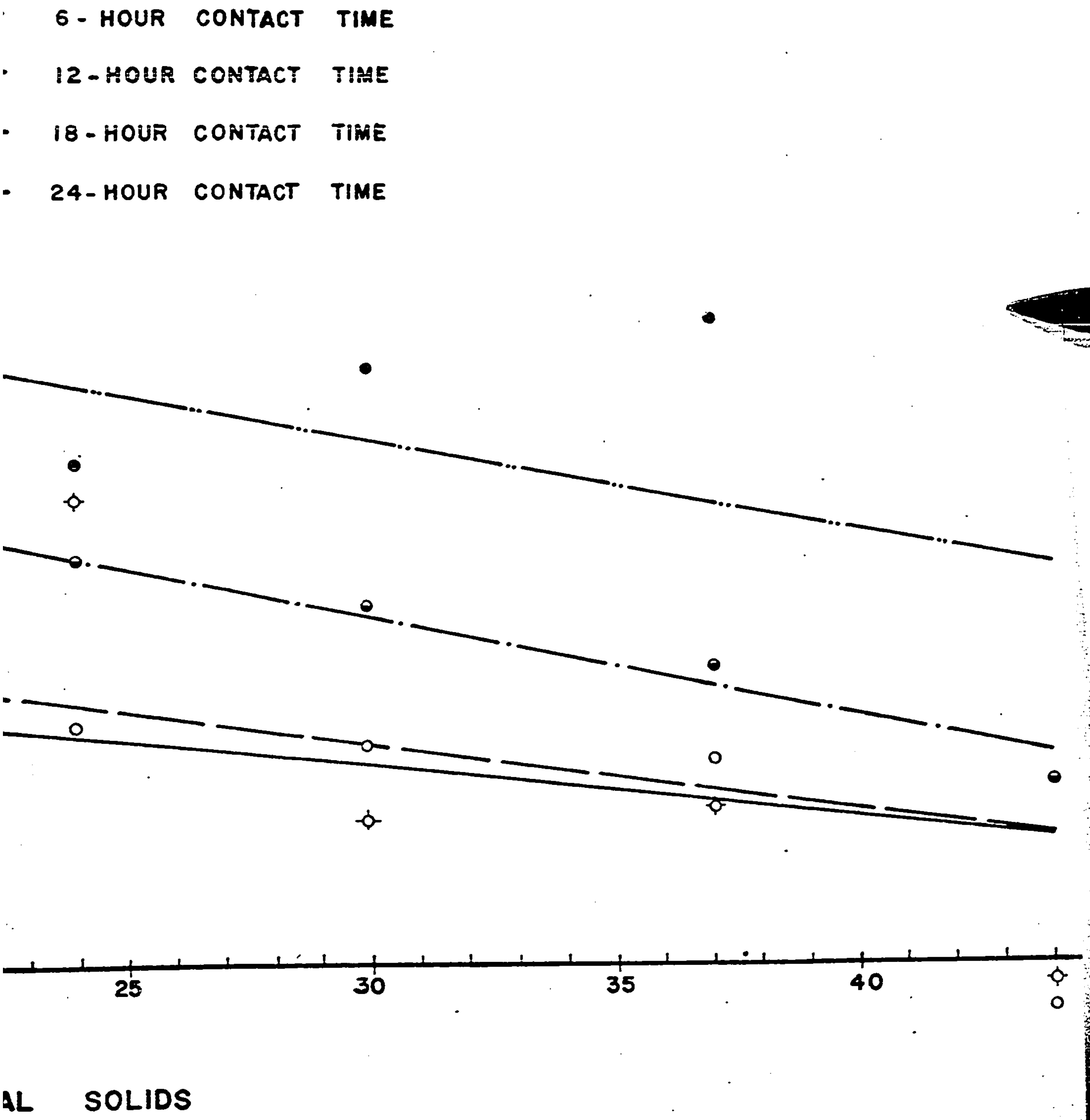


FIGURE 5 - INCREMENT OF TOTAL S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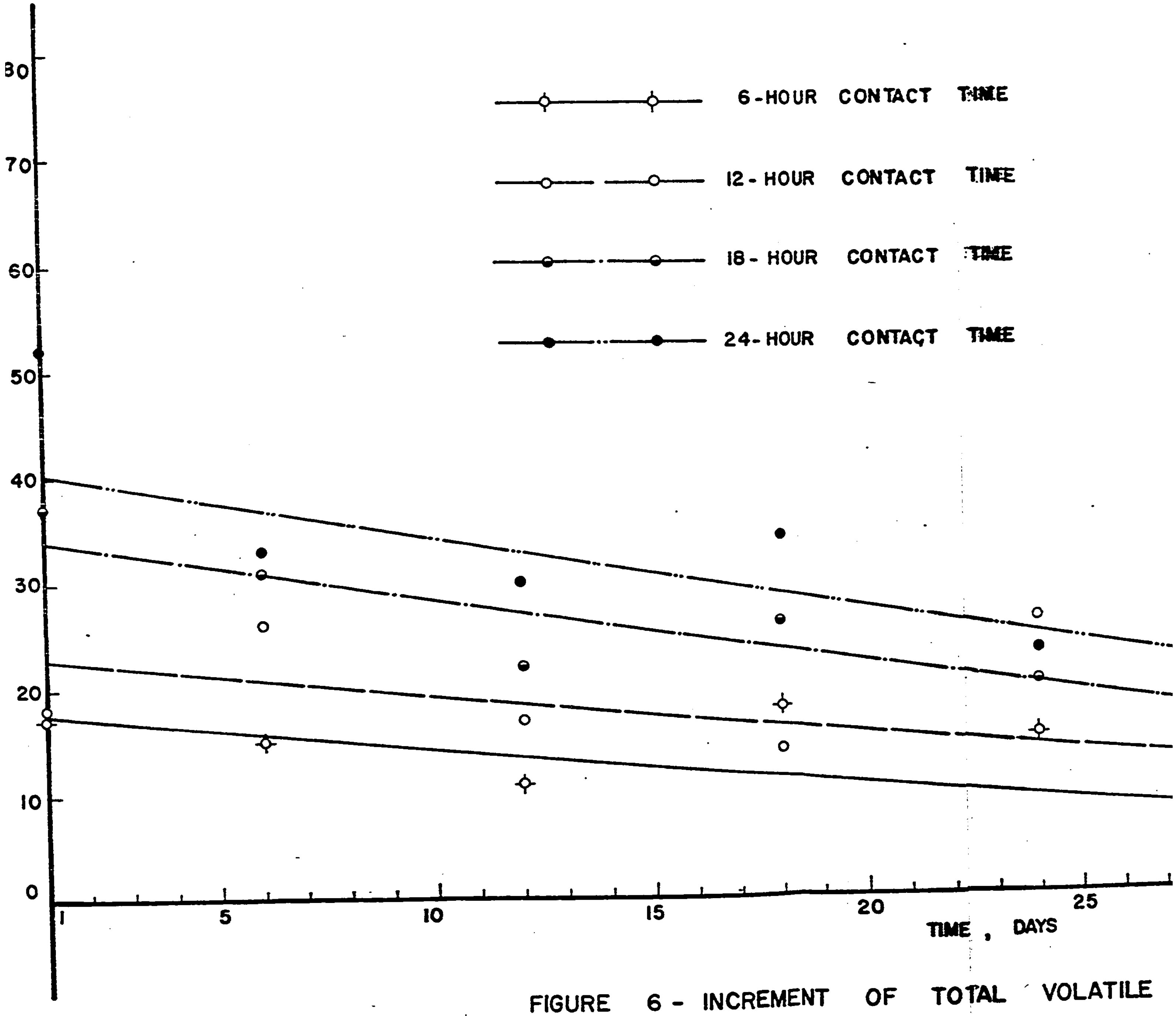
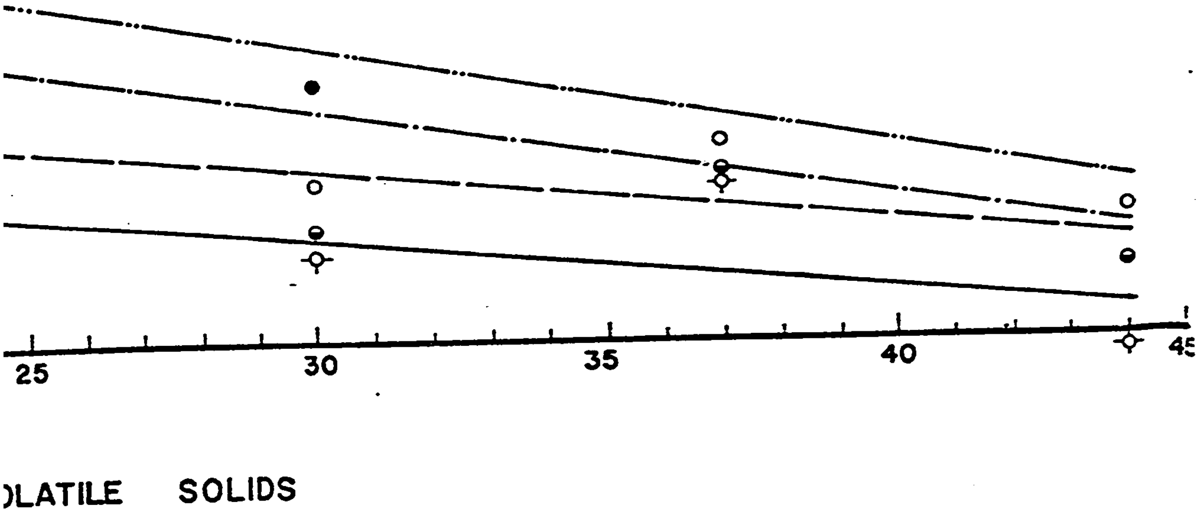


FIGURE 6 - INCREMENT OF TOTAL VOLATILE


25
30
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40
4
LATILE SOLIDS

under way which is a process that occurs at a relatively constant rate. The increase in increment appears to be about linear with increase in contact time. This also implies a relatively steady process.

The graph for the increment of total solids, however, shows a considerable decline with sludge age. This can be explained as being due to a decrease in the availability of solids which can be suspended. It would be expected that the increment of suspended solids would decrease as the availability of material which is suspendable is decreased. Also, one would not expect a sizable conversion of non-suspendable material to suspendable material by the decomposition process.

An interesting feature of the total solids increments is that those for 18- and 24- hour contact times are considerably larger than those for 6- and 12- hour times for a given sludge age. This feature may be explained by the effect of the lifting of solid material into the overlying water by gaseous byproducts. Since the reactor was emptied of water before each test was started, any gas present would be released. In the 6-hour and 12-hour periods it would appear that sufficient gas pressure had not been built up to contribute much suspension of material but in the longer periods the build-up of pressure by the gaseous byproducts could be sufficient to lift, effectively, suspended material into the overlying

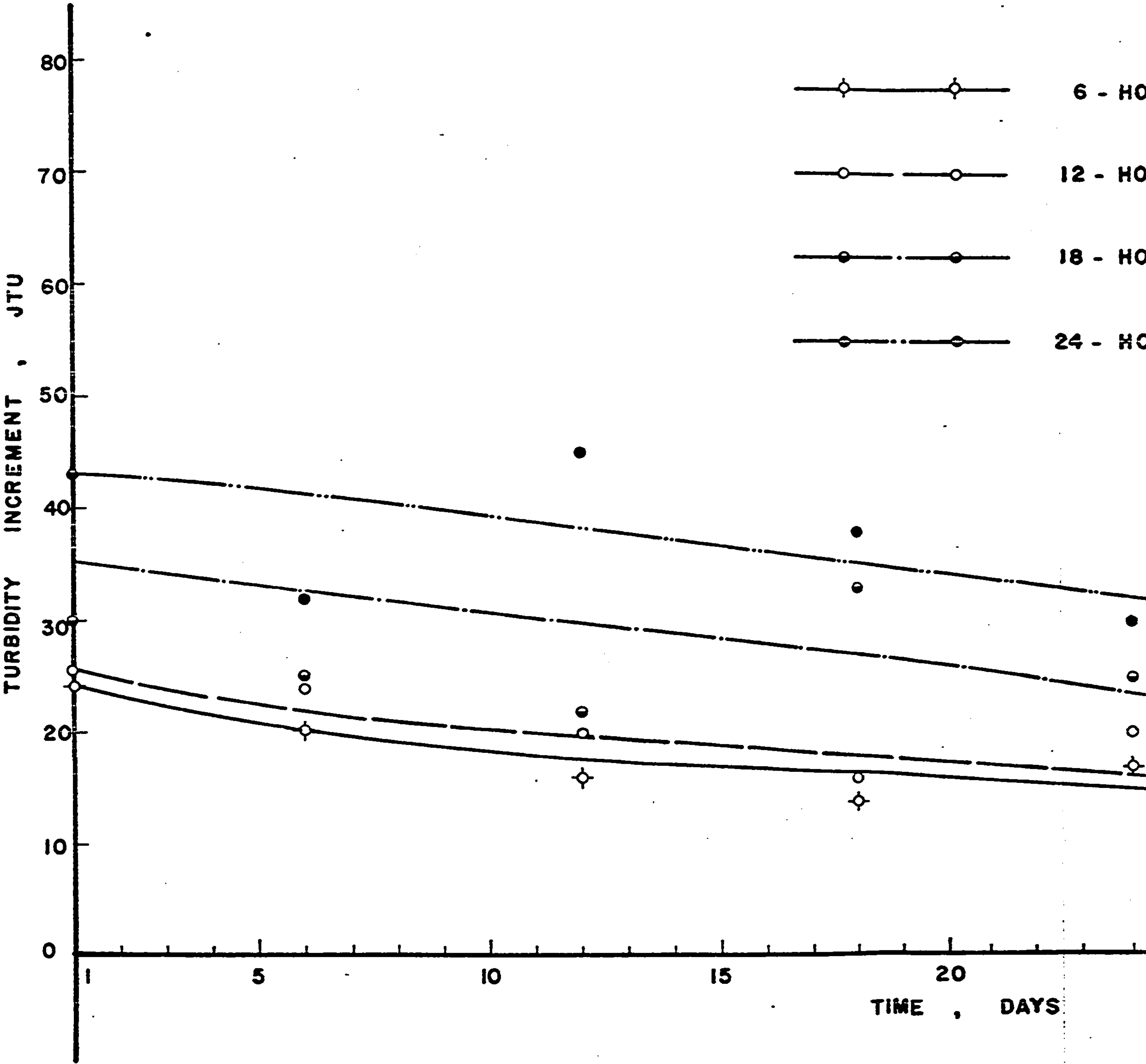
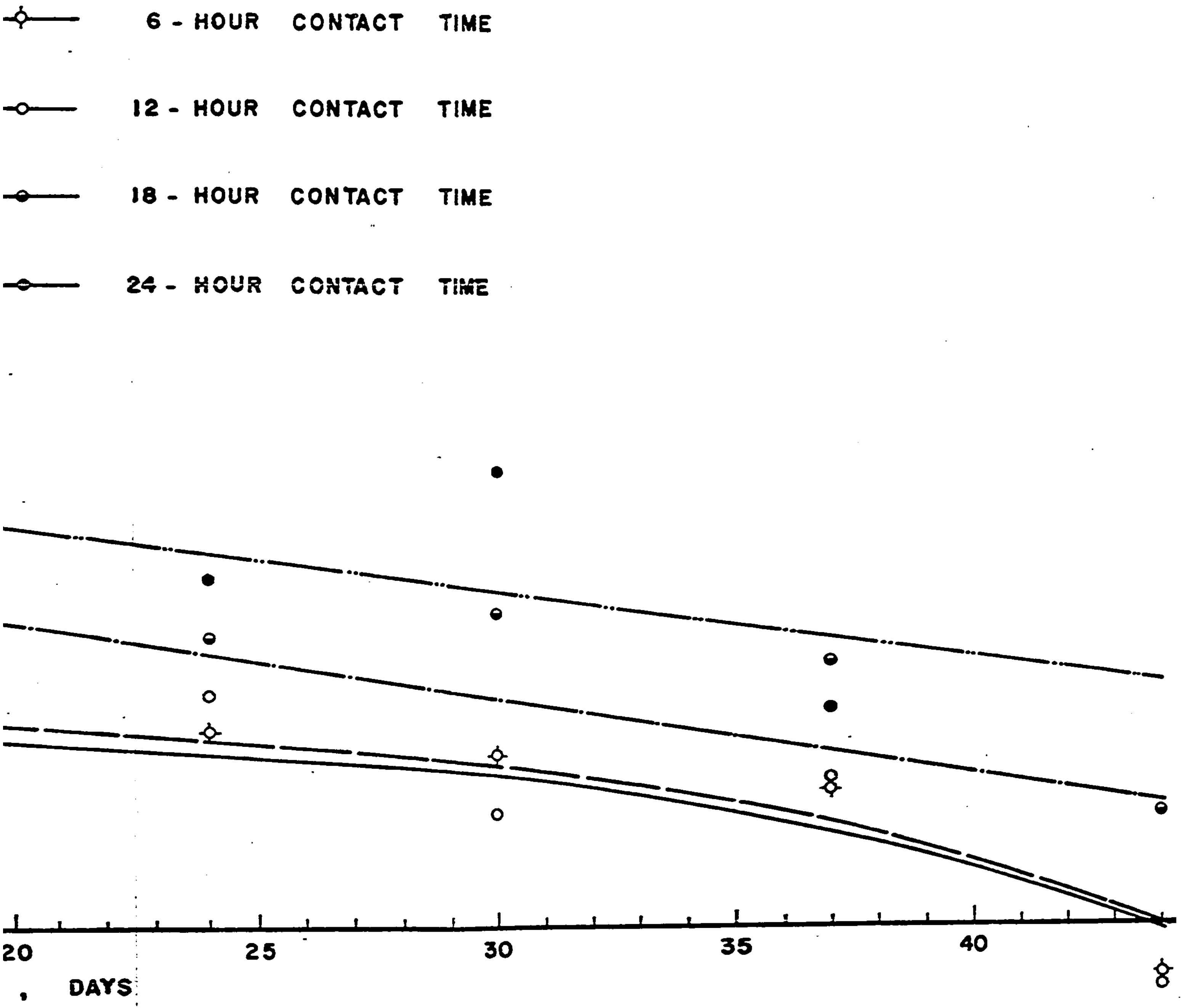


FIGURE 7 - TURBIDITY I



TURBIDITY INCREMENT

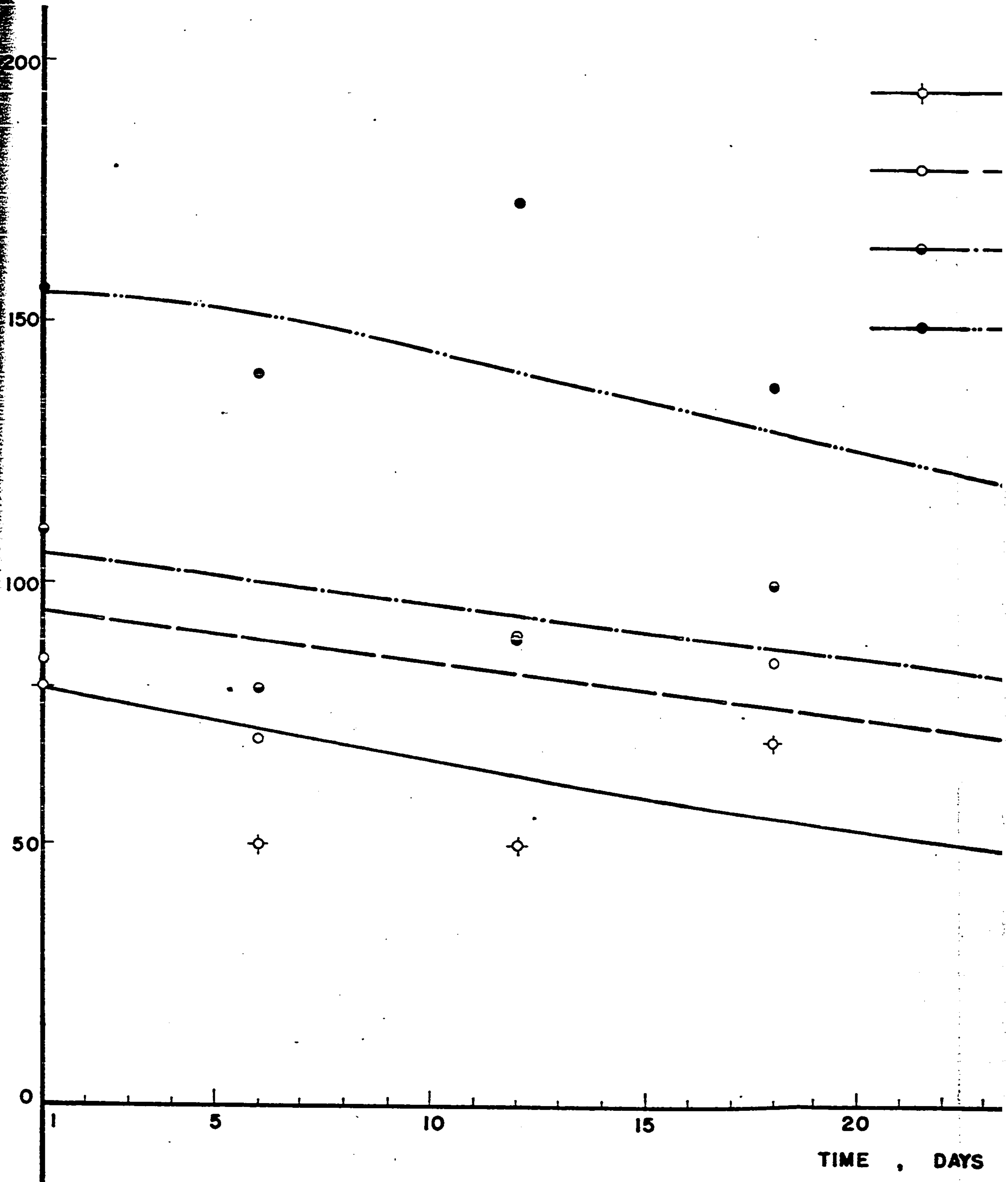
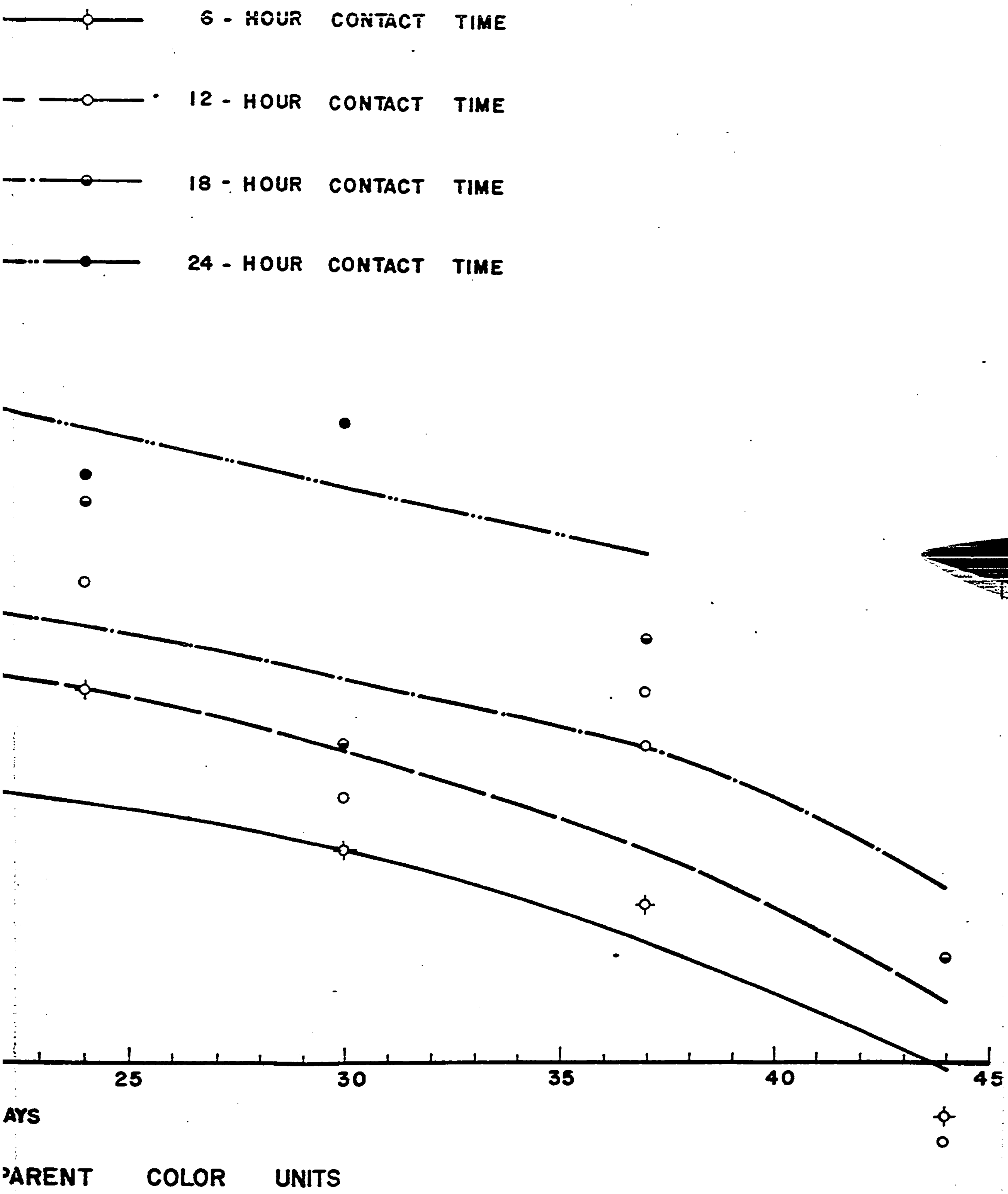


FIGURE 8 - INCREASE IN APPARE


6 - HOUR CONTACT TIME
12 - HOUR CONTACT TIME
18 - HOUR CONTACT TIME
24 - HOUR CONTACT TIME
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AYS
ARENT COLOR UNITS

water.

The graph for volatile solids shows a decreasing effect of contact time as the sludge age is increased. These results agree with the results of the BOD tests which will be discussed later.

4-2-2 Turbidity.

As discussed in a previous section, the benthal decomposition of the woody deposit causes a measurable amount of solids in the overlying water. It is, therefore, of importance to determine quantatively the turbidity that would be contributed by these increments of solid. The turbidity data obtained simultaneously with solids are presented in Table V of the Appendix and Figure 7. By inspection of Figure 7, it is found that the increment curve for each detention period agrees quite well with the total solids shown in Figure 5. The increment, however, shows less effect with sludge age, but increases with time of contact.

4-2-3 Apparent Color

In a similar way to the turbidity, the apparent color of the overlying water may be affected by the load transferred from the bottom deposit to some extent. In this investigation, the apparent color, which is differentiated from color due simply to organic extracts in colloidal form, was measured for varying contact time. The results are listed in Table VI in the Appendix and plotted in Figure 8. Curves fitted by eye to the observed data show a decrease

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in the units imparted with increased age of sludge.

Increased contact time between sludge and water shows an increasing effect on the imparted color value, particularly for the longest detention period as indicated in Figure 8. Because of the high concentration of not readily oxidizable lignin content, it is likely that a higher color increase could be expected when decomposition of the lignin takes place after sufficient time.

Table VI also shows that the observed color value for the overflowing water is generally on the order of two to four times higher than that of the initial value. Although a value ranging from 90 to 253 units is far beyond the 15 units which has been recommended by Canadian Public Health Engineering (1968) for water for human consumption, in the river the effect of the bottom deposit is diluted by the large quantities of water presented. However, the color in the Ottawa River is unacceptably high as can be seen by the initial values. Added color means an increased cost for its removal.

4-2-4 pH Value

The pH value which indicates the acidic or alkaline condition of the water is of interest both because of its utility in muncipal or industrial water supply treatment and as an indicator of the process of decomposition. It is of importance, therefore, to determine whether the acids produced by benthal decomposition remain in the deposits, or whether they diffuse sufficiently enough to

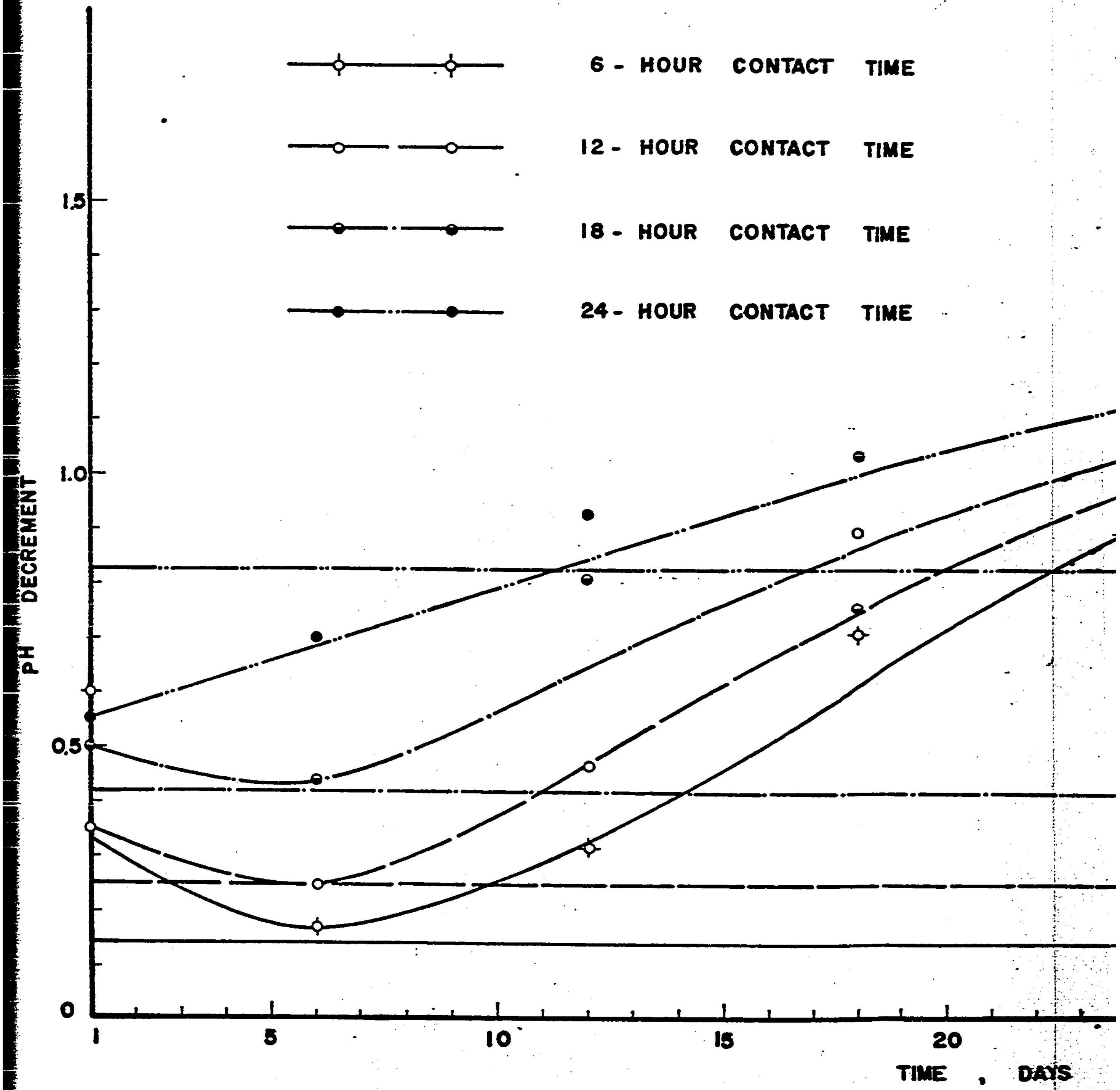
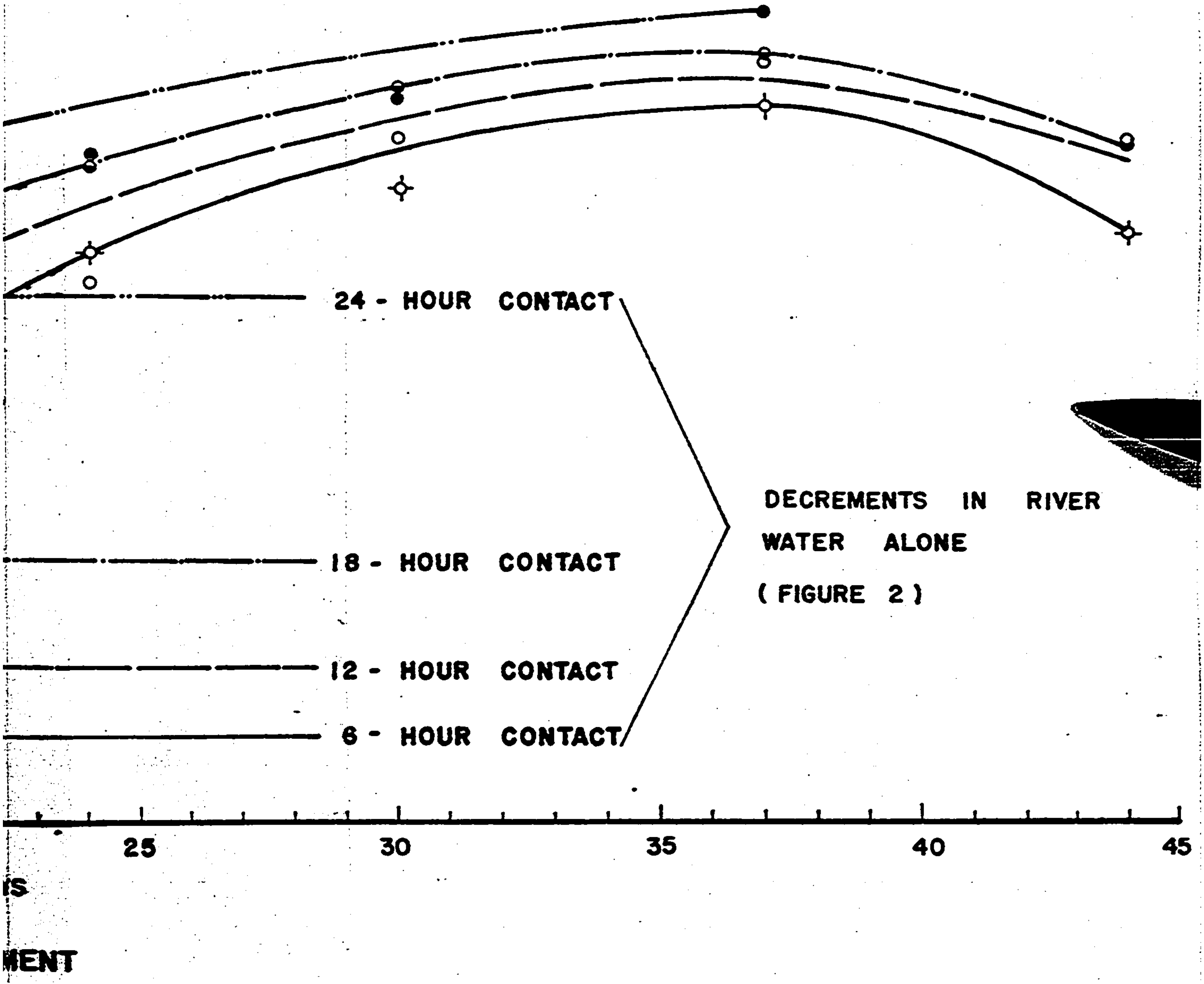


FIGURE 9 - pH DECREMENT


24 - HOUR CONTACT
18 - HOUR CONTACT
12 - HOUR CONTACT
6 - HOUR CONTACT
DECREMENTS IN RIVER WATER ALONE
(FIGURE 2)
25
30
35
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IS
MENT

augment the acidic condition of the flowing water.

The changes in the pH value in the overlying water are summarized in Table VII of the Appendix. Curves showing the decrement of pH are presented in Figure 9. These results demonstrate that the fresh water, after passing or being retained within the reactor for a certain time, showed a pronounced change in pH value, becoming more acidic. This shows that benthal decomposition involves an appreciable production of acids from a bottom deposit of a woody nature along with quantities being contributed to the overlying water. The shift in pH noted persisted for about thirty-seven days whereupon a decrease in the change was observed. The maximum decrements for the entire test occurred on the thirty-seventh day as shown in Figure 9 and are approximately 1.13, 1.20, 1.21, and 1.28 respectively, ranging in the order of two to three fold greater than the decrements in the initial phase.

The pH decrement curves in Figure 9 also indicate a marked increase in decrement for increasing contact time as the sludge becomes acclimatized. This effect of acclimatization, however, becomes less with contact time as the sludge age increases. It is further noticed that during this very period, most of the acidic diffusion occurred within the first six hours with only 0.4 to 0.6 contributed to each increment of contact time. This fact suggests that for a single deposition of woody sludge the acids produce and

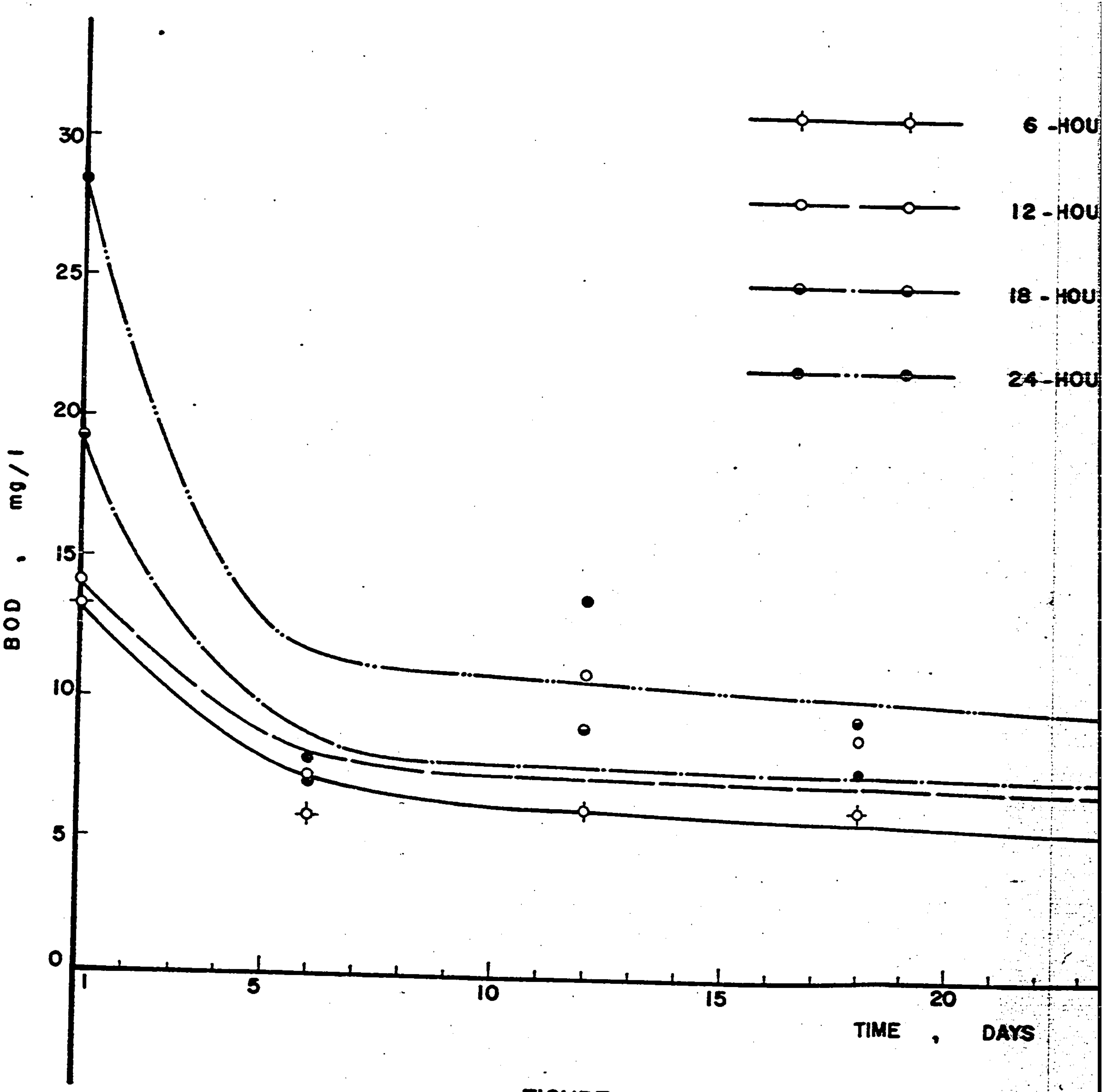
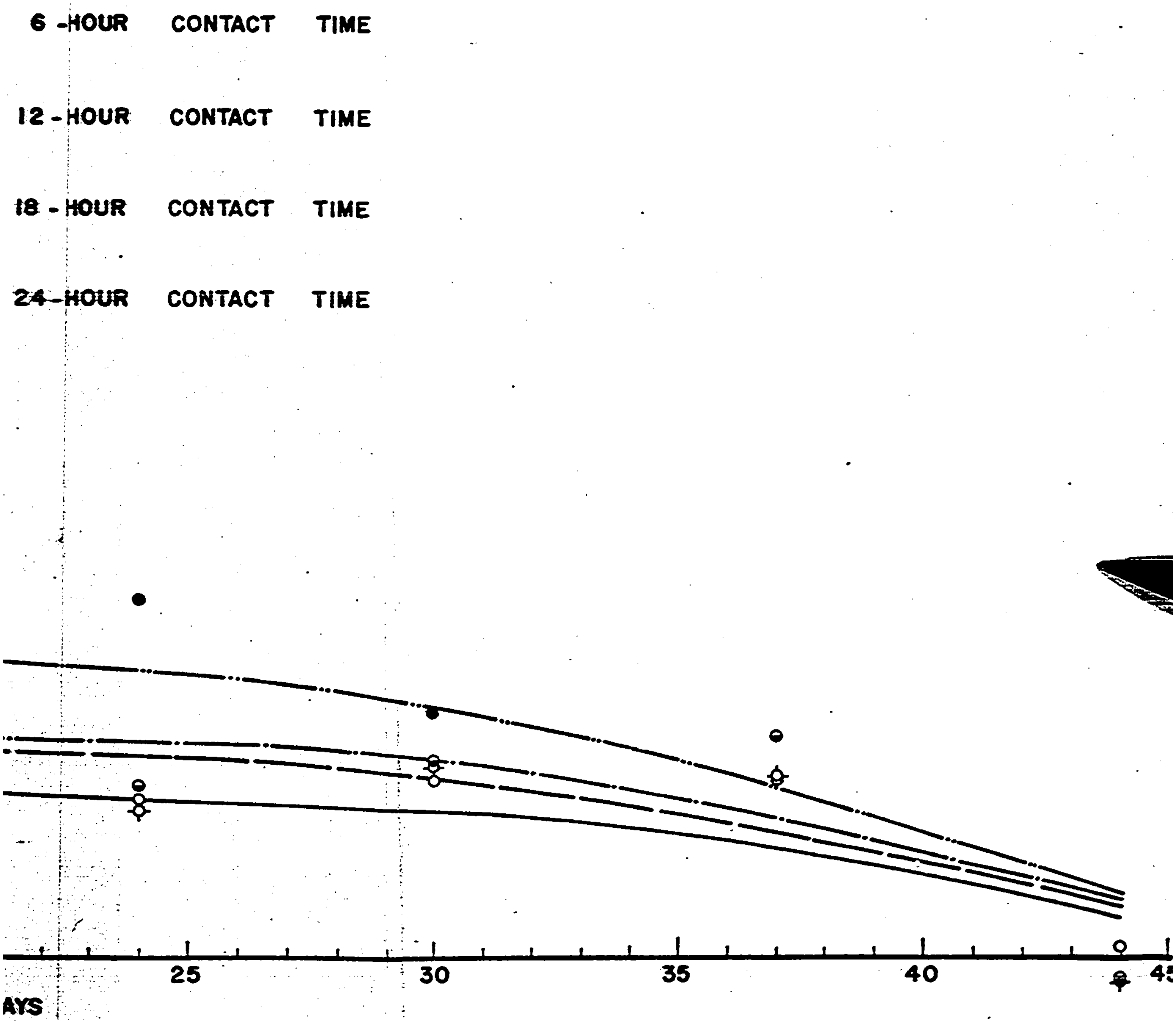


FIGURE 10 - 5-DAY BIOCHEMICAL

SHALLOW DEP



MICAL OXYGEN DEMAND RELEASED FROM
DEPOSITS

contribute progressively to the overlying water with contact time. As the importance of the effect of the acids produced in the sludge increases, the rates of diffusion or leaching - out of acidic by-products are retarded with time because of concentration - dependence. It may also be related to decreased activity due to decreased availability of oxygen. The tapering-off of the decrement curves at the final stage is probably due to the combined effect of gradual decrease of available food and reduced population of bacteria affected by the high acidic production. For the case in which the woody sludge is deposited continuously, the acidic products could influence the overlying water more and the pH remains constant over the entire warmer period of the year.

4-2-5 Biochemical Oxygen Demand (five-day)

During the course of stabilization of an organic deposit, both amount and availability of the food supply diminish progressively. The quantity of organic matter decreases as a consequence of its utilization by bacteria as a source of energy and growth. There is, however, a selective action of successive generations of microorganisms; the more available food is attacked first, leaving the less-readily available compounds for subsequent destruction. As a result, the load that is added to the overlying water from decomposing sludge is subjected to continual deceleration. The picture is more apparent when the physical barriers to transport of material are

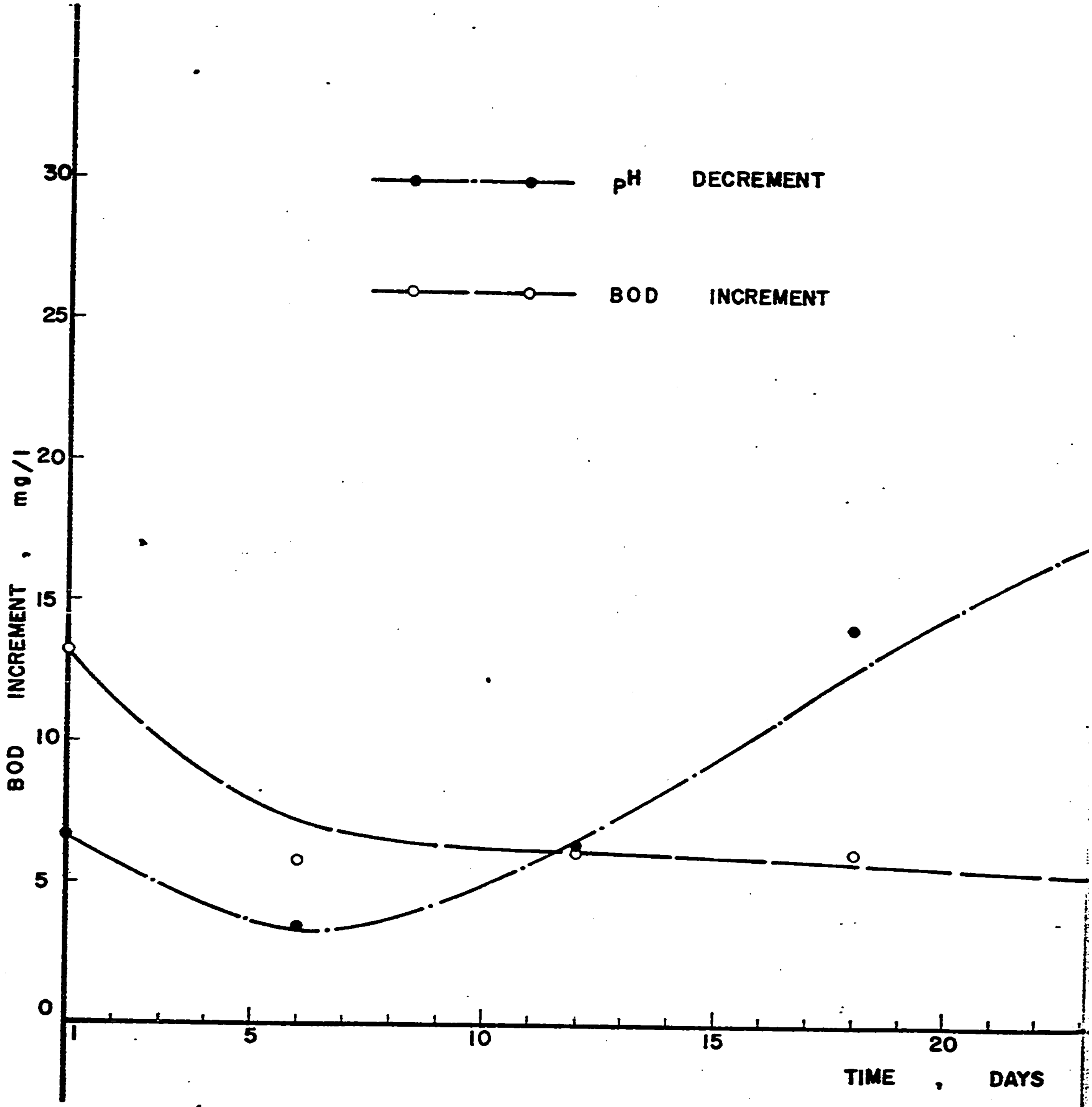
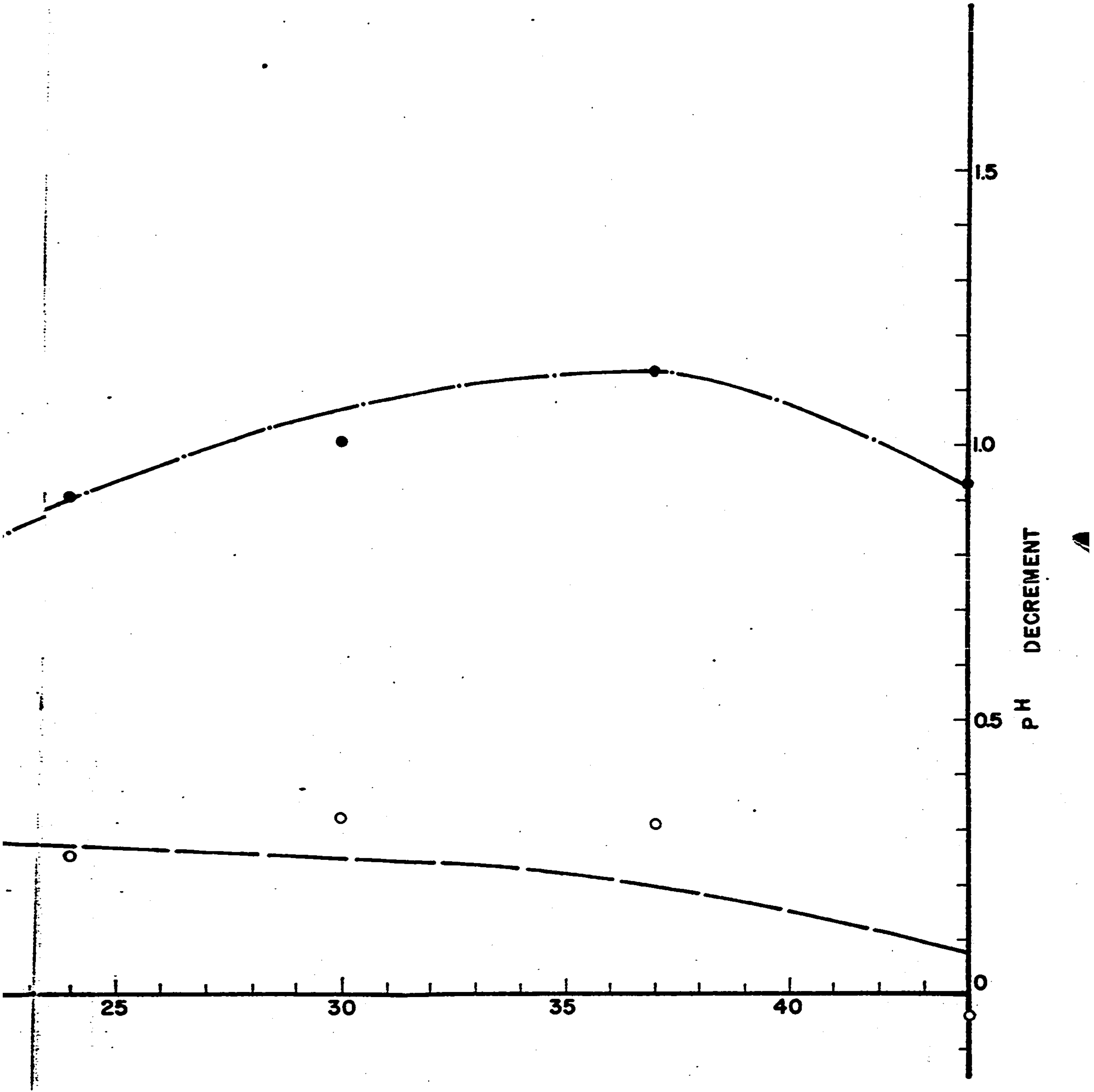


FIGURE 11 - RELATION BETWEEN BOD INCR
OVERLYING WATER FOR 6-HOUR



ICREMENT & pH DECREMENT ON THE
UR CONTACT TIME

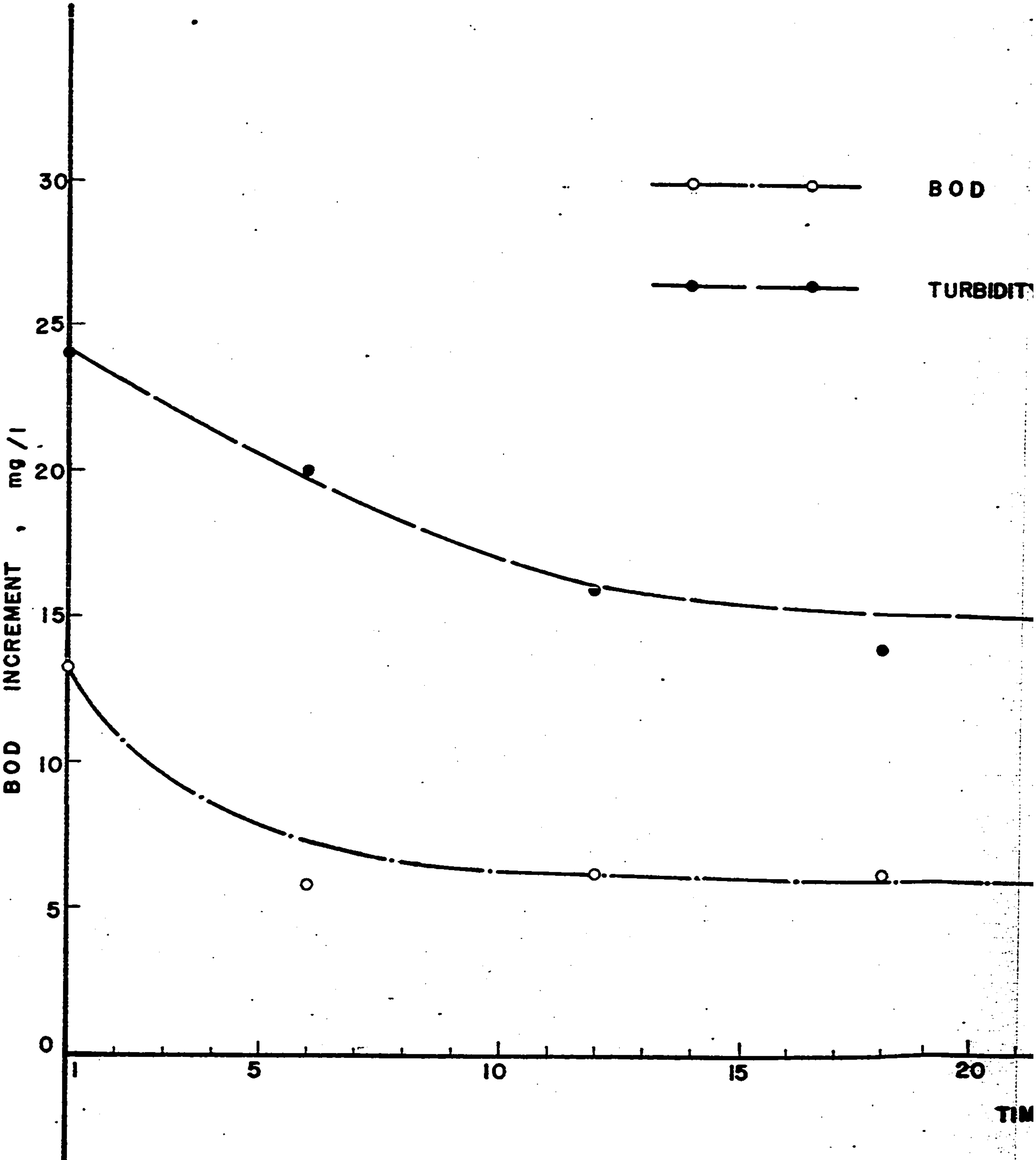
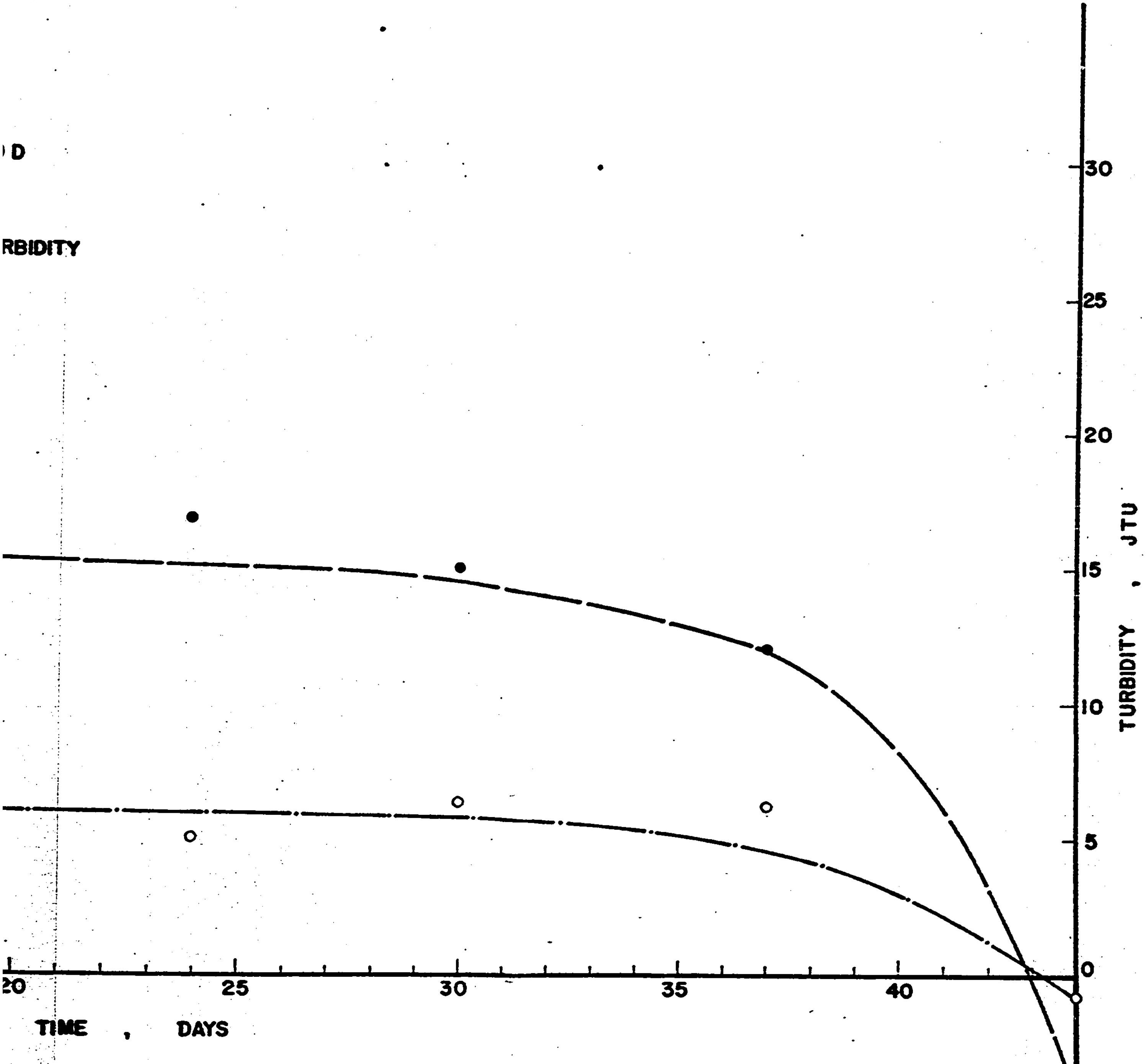


FIGURE 12 - RELATION BETWEEN BOD & T



TURBIDITY INCREMENT FOR 6-HOUR CONTACT TIME taken into account. By the process of consolidation, rates of diffusion and transport of oxidizable substances into the surface zone will be influenced and reduced. Thus, it would seem in accord with these combined effects that the BOD caused by the finely-divided and soluble volatile matter leached from the benthal deposits will decrease.

The extent to which the BOD was imparted from the bottom deposit to the overlying water was measured. Figure 13 shows the increment of BOD with varying sludge age. These results are also presented in Table VIII in the Appendix. The indication here is that the BOD load added to the overlying water decreased as the sludge age is increased. For the initial phase of about six days, the sharp drop in BOD was probably a result of the initially unsettled nature of the sludge and was caused by the constantly decreasing rate of removal of suspended solids. Before the bottom organisms have been acclimated to the redeposited sludge, the benthal decomposition is not active enough to produce a sufficient amount of gas to help buoy up any of the bottom solids to the water body. For the latter phase, the relatively constant rate at which BOD is imparted is believed to be due to the combined effect of reduced quantity and selective availability of food. A decreasing effect of contact time would be expected if consolidation of sludge by its weight reaches a condition that retards the rate of vertical diffusion.

The BOD increment and the pH decrement are shown together in

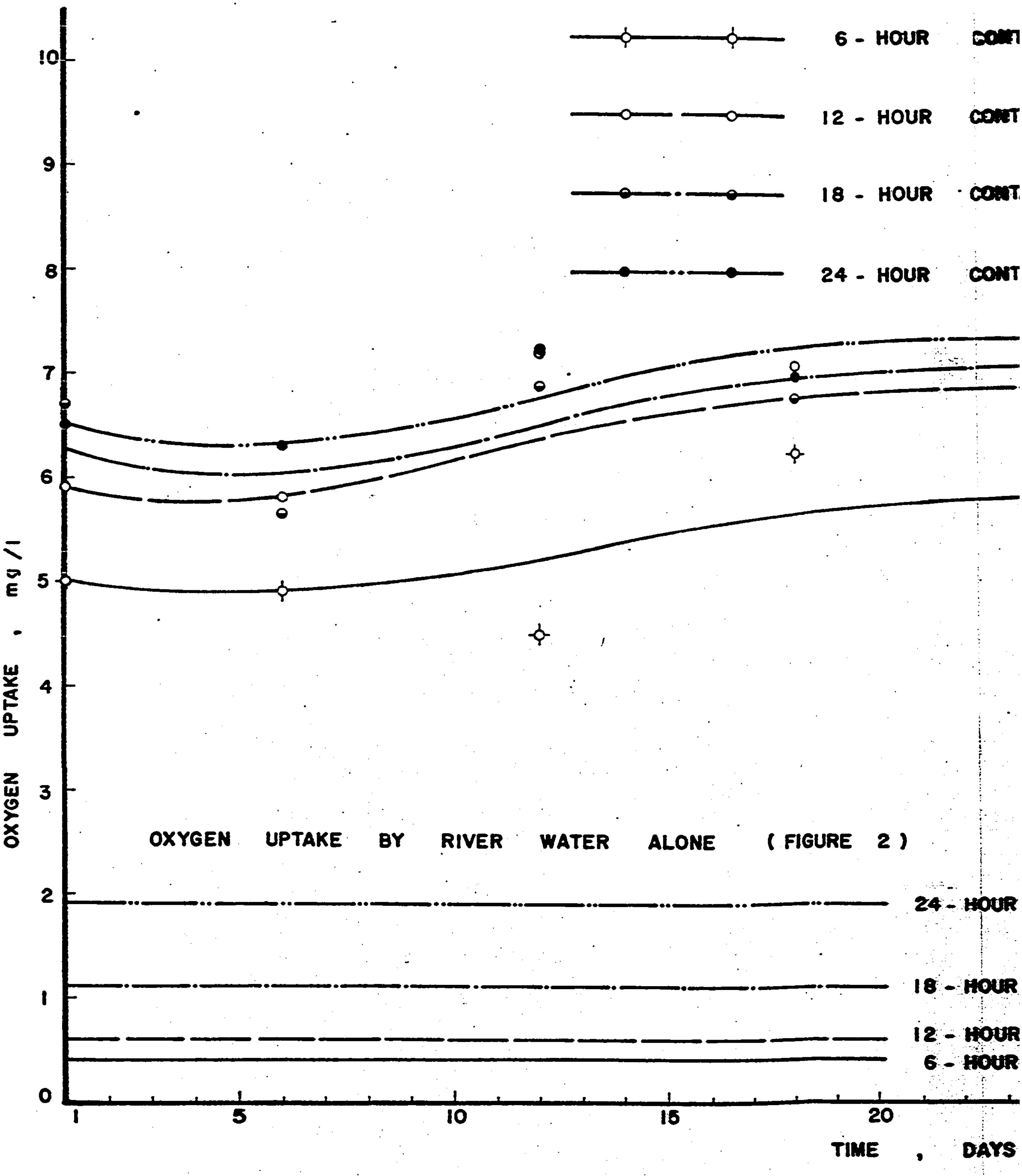
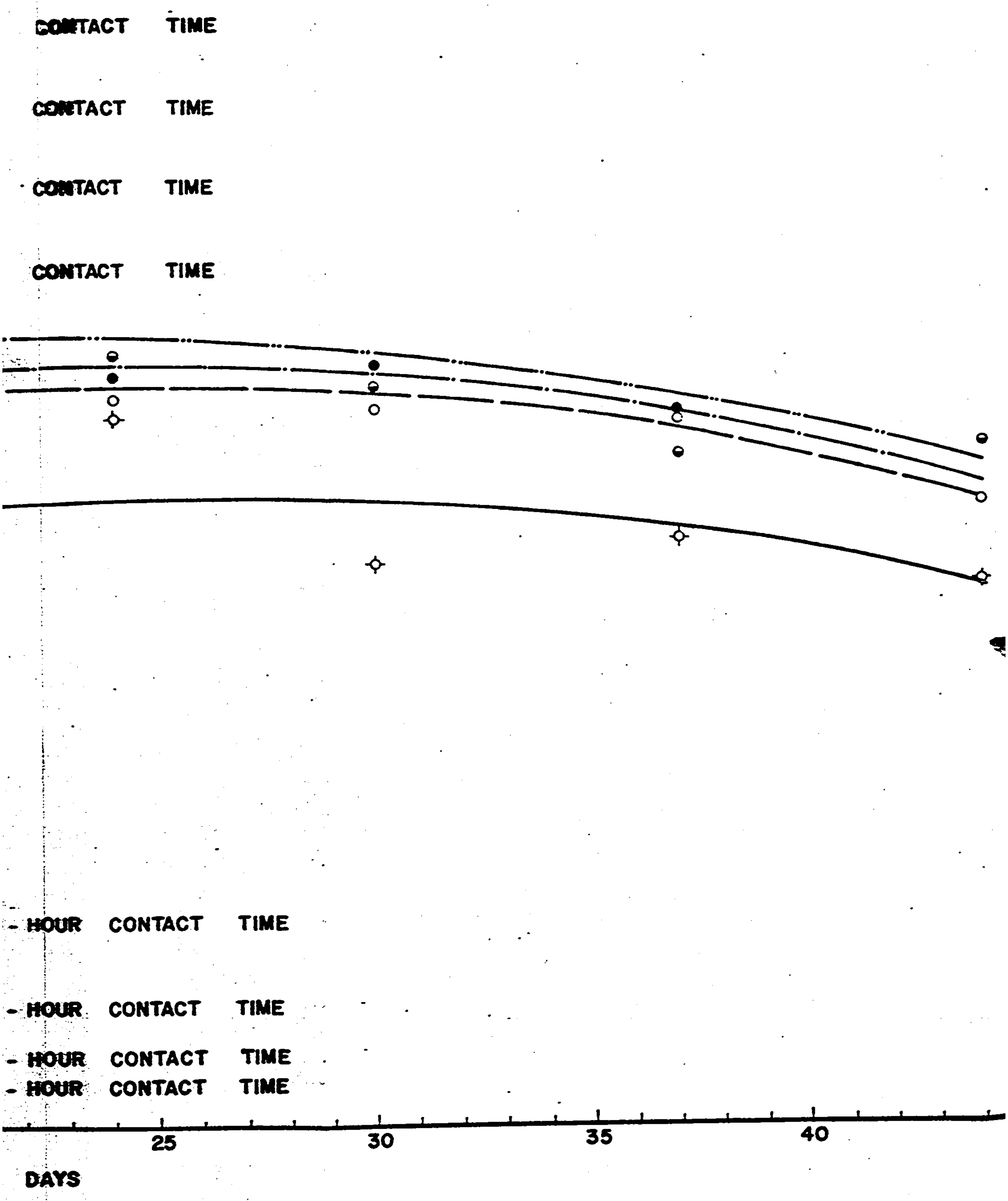


FIGURE 13 - BENTHAL OXYGEN DEMAND WITH



TH VARYING CONTACT TIME

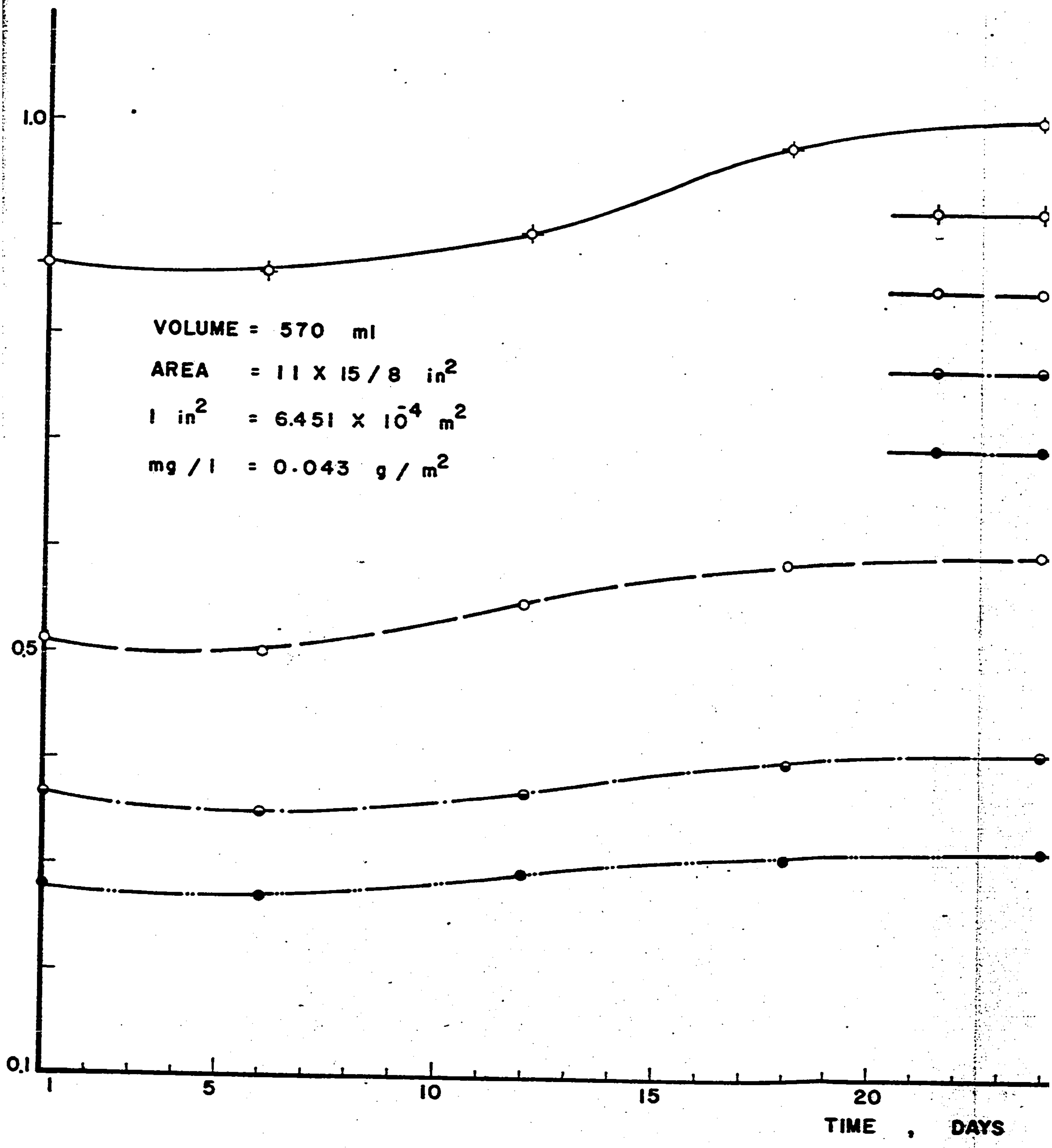
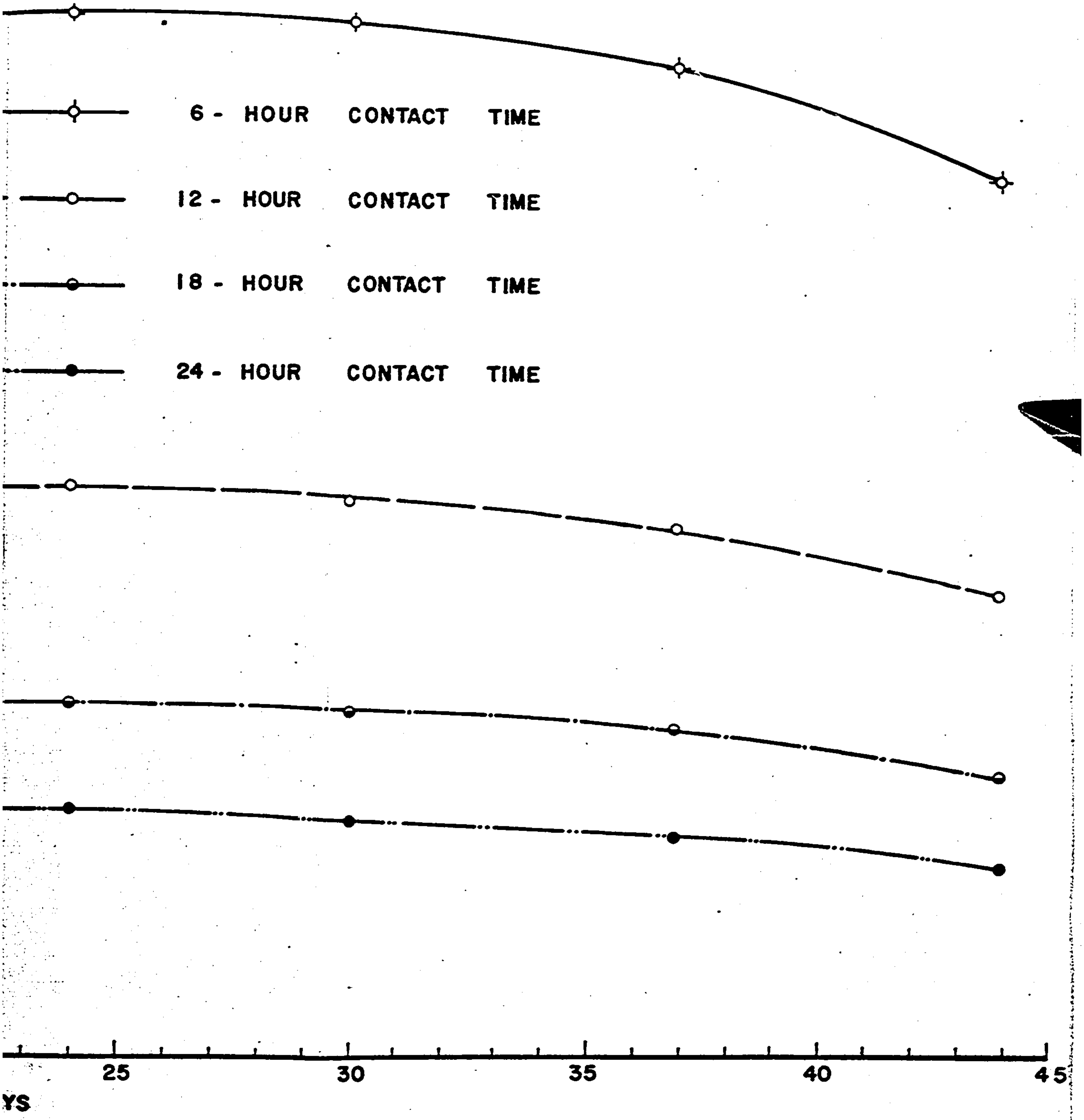


FIGURE 14 - OXYGEN UPTAKE RATES


6 - HOUR CONTACT TIME
12 - HOUR CONTACT TIME
18 - HOUR CONTACT TIME
24 - HOUR CONTACT TIME
25
30
35
40
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YS

RATES

Figure 11, it can be seen that the acids and the BOD from the bottom deposit were imparted to the water body in different proportions. This difference may be explained by the fact that the matter that reaches the water from the sludge consists mostly of non-biodegradable materials. Considering Figure 12 which shows the observed value of BOD and turbidity, it appears that the BOD from the deposit is independent of the turbidity imparted to the water.

In general, for this system in which no additional sludge is added, the BOD imparted to the overlying water remains rather constant over most of the period.

4-2-6 Dissolved Oxygen Concentration

The degree to which the dissolved oxygen content of the overlying water is affected as a result of the woody benthal decomposition was studied by using the reactor for the four contact times as previously described with increasing age of sludge. Table IX, Appendix, gives the observed results of these tests. In Figure 13 the variation of oxygen demand with contact time and sludge age is shown. The curves demonstrate a definite lag phase of low uptake for about six days which is followed by a fairly rapid increase in oxygen consumption. The peak dissolved oxygen demands as shown in Figure 13 for different contact times occur on the twenty-fourth experimental day before a definite decreasing trend began.

The rate of oxygen utilization of the river water alone which is shown on Figure 13 was in every case much less than that for the

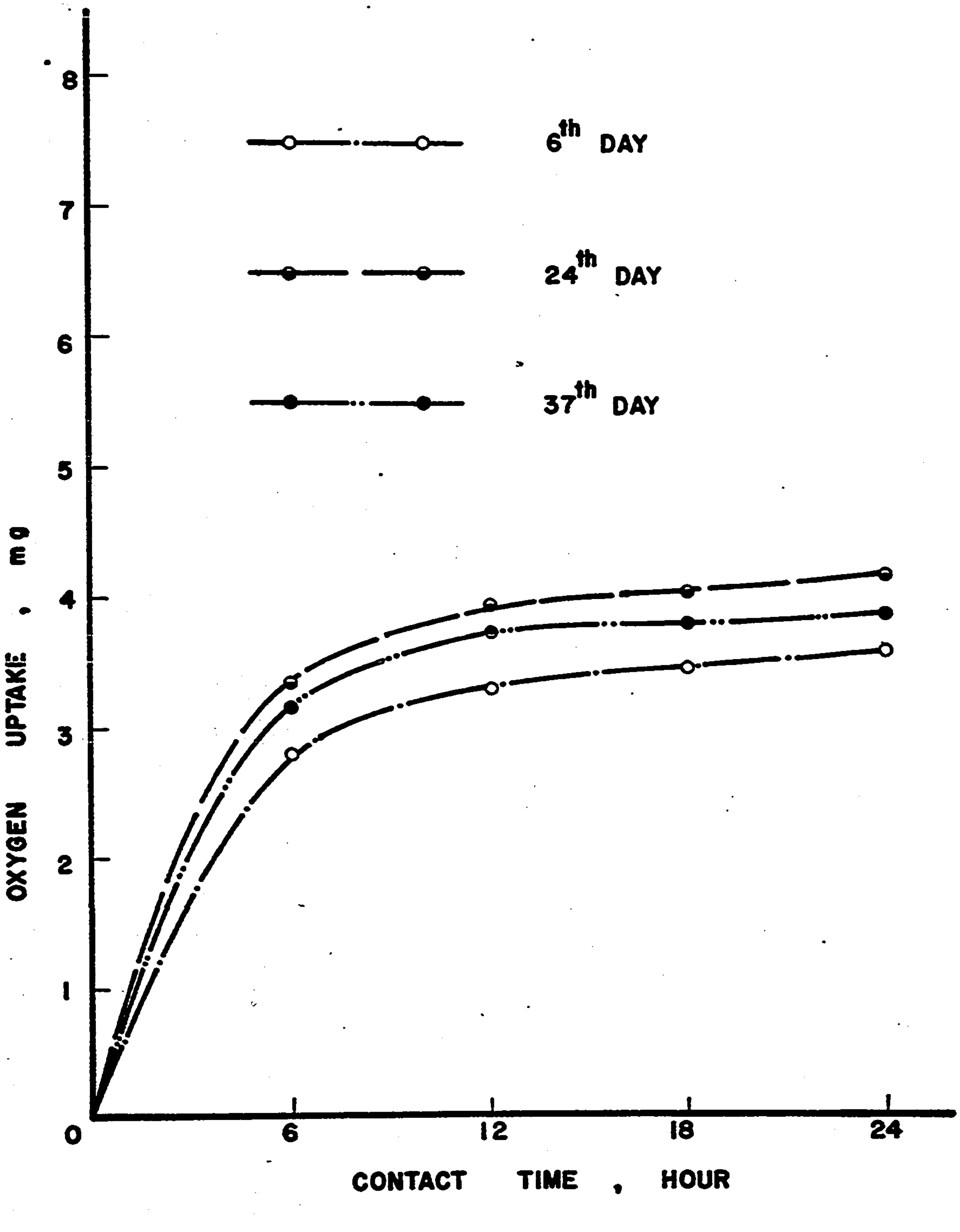

FIGURE 15 - OXYGEN DEPLETION AS A FUNCTION OF CONTACT TIME. (DATA SELECTED ON THE 6th, 24th, AND 37th DAY FROM FIGURE 13)

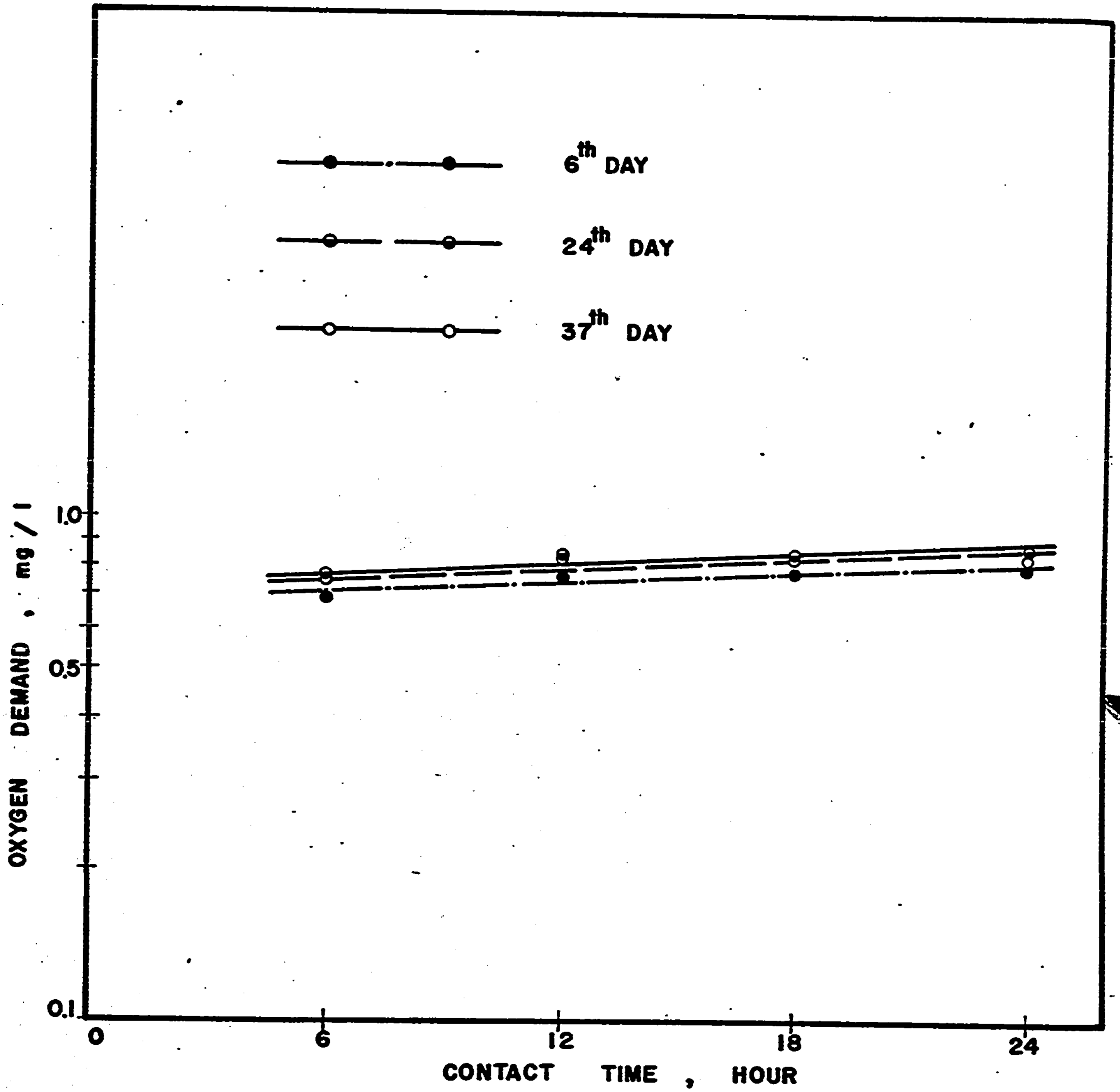

FIGURE 16 - THE VARIATION OF OXYGEN DEMAND WITH CONTACT TIME . (VALUES SELECTED ON THE 6th, 24th, AND 37th DAY FROM FIGURE 13) .

system containing sludge. The major portion of the demand was caused by the presence of the sludge. Considering the five-day BOD leaching from deposit which shows a relatively constant and fairly low oxygen uptake by suspended matter, it could be postulated that the superficial layer of sludge drew a significant amount of dissolved oxygen from the overlying water.

Perhaps the most striking evidence of the behavior of woody sediments revealed by the analysis is the relatively steady rate at which benthal oxidation takes place. The oxygen utilization rates are shown in Figure 14. The unit of the rate is gram of oxygen consumed per square meter of sludge water surface per day. The maximum mean uptake rates for 6- , 12- , 18- , and 24- hour detention period are 1.01; 0.60, 0.41, 0.32 g/m^2/day respectively. Selecting the 6- hour contact time for example, the oxygen consumption rate as shown in Figure 14 ranges from 0.866 to 1.01 g/m^2/day. This low and fairly constant rate of benthal oxygen utilization which implies a relatively steady process is caused by the composition of the woody sludge.

A comparison of uptake rate with other systems is shown in Table II. The peak demand rate obtained by McKeown and others with the shallow deposit of wood origin having pH value of 6.3 and a sludge water contact area of 190 cm^2 was 0.6 g/m^2/day, and that for an area twice this value, it decreased to approximately 0.44

Table II Comparison of Uptake Rates for Several Systems on Shallow Benthal Deposits

Sludge Classification	pH of Sludge	Depth cm	Area cm^2	Nature of Reactor	Method of Agitation	Oxygen Uptake $gm/m^2/day$	Author
Paper mill waste	7.1 (Adjusted)	Shallow deposit		Batch-system	Rotated by magnetic stirrer	1.68 (new benthal deposit) 1.008(old benthal deposit)	Hane and Irvine (1968)
Wood origin	6.3	Shallow deposit	199	Continuous flow system		0.60	McKeown et al (1968)
		"	380	horizontal		0.44	
		2.1	380	tube		1.12	
		0.8	380	assembly		0.92	
Paper mill waste deposits (with some domestic sewage)	4.9	3.8	20.2	Continuous and constant flow system		2.20	Lardieri (1954)
Paper mill waste deposits	5.7	1.9	133.0	Continuous flow system, horizontal tube assembly	Backward and forward agitating	1.01	This Study
Sewage sludge	6.2	1.5	540	Continuous flow system		3.47	Baity (1938)
		2.0	540			3.78	
Sewage sludge	7.0	2.55	526	Continuous flow respirometer		1.70	Fair et al (1941)
		1.42	526			1.08	

pH value of the paper-waster sludge deposits. Adjustment of the pH to 7.0 and buffering of the deposits has been reported as responsible for doubling the oxygen demand rate of such deposits (Lardieri). Bacteria are sensitive to pH; waste products of bacterial growth may inhibit or even poison the organisms producing them.

CHAPTER FIVE

CONCLUSIONS

Laboratory studies have been conducted to determine the effects imposed by benthal deposits of wood origin on the overlying water. Natural water from the Ottawa River was used in the experiments. The temperature in the test was held constant. The water in the laboratory reactor was well mixed by a gentle periodic agitation. The conditions of the test were such that they could represent the effects of material which had been scoured from the river and redeposited. Based upon the results of the experiments described, the following conclusions may be reached:

1. The rate of oxygen consumption is relatively steady over the period between the sixth to thirty-seventh day. The peak rate of demand found was 1.01 g per day per square meter of deposit. This value is the average over a six-hour period when oxygen-saturated river water is introduced at the beginning of the period at a temperature of 20°C.

2. Except in the initial stages the BOD transferred to the overlying water remains constant at about 10 mg/l.

3. The decrease in pH during the contact time increases gradually to about 1.2 units at the maximum. However, the change in pH began to lessen after thirty-seven days.

4. Due to the combined facts of less decrease in pH and minute increase in BOD, it may be consluded that the stabilization of the more available organic matter was approached at the final stage.

5. The solids imparted to the overlying water increase with time of contact. The amount of dissolved solids imparted, however, remains about constant at 15 mg/l and does not change appreciably with sludge age and contact time.

6. The high increments in solids contribute to the high value of turbidity and apparent color.

7. BOD, turbidity and solids behave dissimilarly. From this it may be inferred that the bottom deposits that reach the overlying water are not, in general, readily biodegradable solids.

8. The foreward and backward mixing device used in this study is believed to provide better mixing that results in a higher rate of deceomposition.

It is apparent from this study that a single deposition of woody sludge introduces adverse effects on the river water both physically and chemically. In a river which receives woody deposits continuously and where only small quantities of sludge are removed by freshets or tides, the residue exerts a continuous influence. Also, material which is deposited, becomes inactive, and then is scoured and redeposited downstream to decompose further may in time spread the effect of the wasterdischarge over long reaches of the river.

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APPENDIX

Table III Summary Studies on Experimental System Using River Water

Contact Time hours	Dissolved Oxygen mg/l			pH Value			Turbidity JTU		
	Initial	Final	Depletion	Initial	Final	Decrement	Initial	Final	Decrement
6	8.60	8.20	0.40	8.39	8.25	0.14	19.0	18.0	1.0
12	8.50	7.90	0.60	8.15	7.90	0.25	16.0	14.0	2.0
18	8.05	6.95	1.10	8.32	7.90	0.42	17.5	14.0	3.5
24	8.10	6.20	1.90	8.43	7.60	0.83	22.0	17.0	5.0

Table IV Summary Data on Solids Study

Time days	Contact Time hours	Total Solids mg/l			Total Volatile Solids mg/l			Dissolved Solids mg/l		
		Initial	Final	Increment	Initial	Final	Increment	Initial	Final	Increment
1	6	127	152	25	63	80	17	73	83	10
	12	102	132	30	49	67	18	68	87	19
	18	138	191	53	68	105	37	60	98	38
	24	88	169	81	47	99	52	61	92	31
6	6	92	116	24	40	55	15	88	95	7
	12	97	125	28	46	72	26	76	92	16
	18	93	142	49	45	76	31	82	104	22
	24	100	153	53	48	81	33	74	103	29
12	6	95	114	19	42	53	11	73	68	5
	12	91	124	33	40	57	17	71	87	16
	18	86	121	35	45	67	22	68	81	13
	24	102	162	60	52	82	30	83	104	21
18	6	86	110	24	46	64	18	69	83	14
	12	91	111	20	47	61	14	69	79	10
	18	85	133	48	38	64	26	58	74	16
	24	88	140	52	44	78	34	65	80	15
24	6	90	110	20	31	46	15	69	83	14
	12	76	115	39	34	60	26	52	68	16
	18	81	115	34	43	63	20	66	71	5
	24	90	132	42	34	57	23	72	90	18

Table IV (Cont'd)

30	6	95	113	18	37	43	6	69	80	11
	12	94	106	12	36	47	11	76	81	5
	18	92	122	30	37	45	8	73	97	24
	24	85	135	50	22	40	18	60	86	26
37	6	82	99	17	37	48	11	74	81	7
	12	91	104	13	48	62	14	61	69	8
	18	97	122	25	45	57	12	60	75	15
	24	95	149	54	38	74	36	54	65	11
44	6	81	77	-4	28	27	-1	70	60	-10
	12	81	79	-2	34	43	9	69	63	-6
	18	51	66	15	30	35	5	49	63	14

Table V The Effect of Benthal Decomposition on Turbidity

Time days	Contact time, hours	Initial Value,JTU	Final Value, JTU	Increment JTU	Final Value / Initial Value
1	6	10	34	24	3.40
	12	18	44	26	2.44
	18	18	48	30	2.70
	24	19	62	43	3.26
6	6	20	40	20	2.00
	12	20	44	24	2.20
	18	20	45	25	2.25
	24	20	52	32	2.60
12	6	14	30	16	2.14
	12	18	38	20	2.11
	18	18	40	22	2.22
	24	25	70	45	2.80
18	6	16	30	14	1.88
	12	29	45	16	1.55
	18	17	50	33	2.94
	24	29	67	38	2.31
24	6	18	35	17	1.94
	12	20	40	20	2.00
	18	25	50	25	2.00
	24	20	50	30	2.50

Table V (Cont'd)

30	6	18	33	15	1.83
	12	20	30	10	1.50
	18	18	45	27	2.50
	24	14	53	39	3.79
37	6	16	28	12	1.75
	12	17	30	13	1.76
	18	14	37	23	2.64
	24	20	39	19	1.95
44	6	24	20	-4	0.833
	12	22	17	-5	0.773
	18	14	24	10	1.710

Table VI Summary Data on Apparent Color

Time Days	Contact Time, hours	Initial Value unit	Final Value Unit	Increment Unit	Final Value / Initial Value
1	6	40	120	80	3.00
	12	80	165	85	2.06
	18	80	190	110	2.38
	24	84	240	156	2.86
6	6	60	110	50	1.83
	12	70	140	70	2.00
	18	60	140	80	2.33
	24	70	210	140	3.00
12	6	40	90	50	2.25
	12	60	150	90	2.50
	18	50	140	90	2.80
	24	80	253	173	3.16
18	6	50	120	70	2.40
	12	80	165	85	2.06
	18	60	160	100	2.67
	24	80	218	138	2.73

Table VI Continued

24	6	50	120	70	2.40
	12	80	170	90	2.13
	18	90	195	105	2.17
	24	80	190	110	2.38
30	6	60	100	40	1.67
	12	50	100	50	2.00
	18	70	130	60	1.86
	24	50	170	120	3.40
37	6	60	90	30	1.50
	12	60	120	60	2.00
	18	55	135	80	2.45
	24	70	140	70	2.00
44	6	80	70	-10	0.875
	12	80	65	-15	0.813
	18	40	60	20	1.500

Table VII Summary Data on pH Study

Time (days)	Contact Time hours	Initial Value	Final Value	ΔpH	Time (days)	Contact time hours	Initial Value	Final Value	ΔpH
1	6	6.80	6.20	0.60	24	6	7.40	6.50	0.90
	12	6.85	6.50	0.35		12	7.35	6.50	0.85
	18	6.70	6.20	0.50		18	7.49	6.46	1.03
	24	6.70	6.15	0.55		24	7.50	6.45	1.05
6	6	6.75	6.58	0.17	30	6	7.70	6.70	1.00
	12	6.80	6.55	0.25		12	7.60	6.52	1.08
	18	6.94	6.50	0.44		18	7.60	6.44	1.16
	24	6.90	6.20	0.70		24	7.60	6.46	1.14
12	6	6.90	6.58	0.32	37	6	7.72	6.59	1.13
	12	7.34	6.87	0.47		12	7.70	6.50	1.20
	18	7.35	6.54	0.81		18	7.70	6.49	1.21
	24	7.40	6.47	0.93		24	7.70	6.42	1.28
18	6	7.31	6.60	0.71	44	6	7.77	6.84	0.93
	12	7.40	6.50	0.90		12	7.66	6.58	1.08
	18	7.24	6.48	0.76		18	7.70	6.63	1.07
	24	7.46	6.42	1.04		~~28~~			

Table VIII Five-Day BOD Released from Shallow Deposits

Time days	Contact time, hours	Initial Value mg/l	Final Value mg/l	Increment mg/l	Ratio Increased
1	6	2.4	15.6	13.2	6.5
	12	0.4	14.4	14.0	36.0
	18	2.6	21.6	19.2	8.3
	24	1.6	30.0	28.4	18.8
6	6	1.4	7.2	5.8	5.1
	12	1.2	8.4	7.2	7.0
	18	2.6	9.6	7.0	3.7
	24	1.8	9.6	7.8	5.3
12	6	1.0	7.2	6.2	7.2
	12	1.0	12.0	11.0	12.0
	18	0.6	9.6	9.0	16.0
	24	0.8	14.0	13.6	17.5
18	6	1.0	7.2	6.2	7.2
	12	0.8	9.6	8.8	12.0
	18	1.4	10.8	9.4	7.7
	24	0.8	8.4	7.6	10.5
24	6	1.0	6.0	5.0	6.0
	12	0.6	6.0	5.4	10.0
	18	1.4	7.2	5.8	5.1
	24	<1.2	13.2	12.0	11.0

Table VIII (Cont'd)

30	6	0.8	7.2	6.4	9.0
	12	1.2	7.2	6.0	6.0
	18	1.8	8.4	6.6	4.7
	24	1.4	9.6	8.2	6.9
37	6	1.0	7.2	6.2	7.2
	12	0.8	6.8	6.0	8.5
	18	1.0	8.4	7.4	8.4
	24	1.2	7.2	6.0	6.0
44	6	1.4	0.6	-0.8	-0.43
	12	2.0	2.4	0.4	1.20
	18	1.2	0.6	-0.6	-0.50

Table IX Benthal Oxygen Demand of Shallow Deposits for the Four Contact Times

Time (days)	Contact Time, hours	Initial Oxygen Concentration mg/l	Final Oxygen Concentration mg/l	Oxygen Uptake mg/l	Oxgen Uptake / Initial Oxygen
1	6	8.6	3.60	5.0	0.581
	12	7.8	1.90	5.9	0.756
	18	8.6	1.90	6.7	0.780
	24	7.7	1.20	6.5	0.845
6	6	7.2	2.30	4.9	0.680
	12	7.6	1.80	5.8	0.763
	18	7.3	1.65	5.65	0.775
	24	7.5	1.20	6.3	0.840
12	6	8.1	3.60	4.5	0.556
	12	7.9	0.70	7.2	0.911
	18	8.0	1.10	6.9	0.863
	24	7.7	0.50	7.2	0.935
18	6	7.8	1.55	6.25	0.802
	12	8.0	0.90	7.1	0.840
	18	7.4	0.60	6.8	0.920
	24	7.6	0.60	7.0	0.920
24	6	7.9	1.30	6.6	0.835
	12	8.0	1.20	6.8	0.850
	18	7.8	0.57	7.23	0.926
	26	7.6	0.60	7.0	0.921

Table IX (Cont'd)

30	6	8.3	3.05	5.25	0.633
	12	8.3	1.60	6.70	0.807
	18	8.1	1.20	6.90	0.852
	24	8.2	1.10	7.10	0.866
37	6	8.4	2.90	5.5	0.655
	12	8.5	1.90	6.6	0.777
	18	8.2	1.90	6.3	0.770
	24	8.4	1.70	6.7	0.798
44	6	8.7	3.60	5.1	0.587
	12	8.7	2.85	5.85	0.672
	18	8.4	2.00	6.40	0.762
	24	8.4			