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BIOLOGICAL REGENERATION  
OF ACTIVATED CARBON

by  
Robert S. Sturgis

A Thesis  
Presented to the Graduate Committee  
of Lehigh University  
in Candidacy for the Degree of  
Master of Science  
in  
Civil Engineering

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CERTIFICATE OF APPROVAL

This thesis is accepted and approved in partial fulfillment of the requirements for the Degree of Master of Science in Civil Engineering.

9/10/73  
(date)

Dr. Robert L. Johnson  
Professor-in-Charge

Dr. David A. VanHorn  
Chairman of the Department  
of Civil Engineering

## ABSTRACT

Regeneration of activated carbon used in advanced wastewater treatment has been accomplished by biological means. This process may replace or supplement thermal regeneration systems which are commonly advocated.

Pilot investigations with expanded columns used recirculating aerated water upward through the columns to maintain aerobic bacterial activity. The biological activity restored the capacity for adsorbing greater quantities of COD/pound of activated carbon (greater than 2.0 pounds COD/pound activated carbon). This is much greater activated carbon capacity than previously reported in the literature.

There are indications that at pH 6 and at a temperature of 40°C there is enhanced biological regeneration of the activated carbon. Carbon losses from the system were very low, less than 1%. Operation costs of such biological regeneration systems would be minimal. The only significant costs are for air flow (0.2 cfm/sf) and recirculation pumping.

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LIST OF SYMBOLS

AC	Activated Carbon
BOD	Bio-Chemical Oxygen Demand
°C	Degree Celsius
COD	Chemical Oxygen Demand
C	Concentration of solute in bulk solution
cfm/sf	Cubic Feet/Minute/Square Foot
DO	Dissolved Oxygen
DWV	Drain-Waste-Vent
ft	Feet
fps	Feet/Second
gal	Gallons
GPM	Gallons/Minute
HP	Horse Power
ID	Internal Diameter
IN	Inch
k	Adsorption Coefficient
kwh	Kilowatt Hours
lb	Pounds Weight
l	liter
MGD	Million Gallons/Day
mg	Milligrams
mg/l	Milligrams/Liter
ml	milliliter
<u>M</u>	molar
m	Mass of Carbon Adsorbent
m	meter

n	Adsorption Coefficient
<u>N</u>	Normal
pH	Negative Logarithm of Hydronium Ion Concentration
PSI	Pounds/Square Inch
PVC	Poly-Vinyl Chloride
TOC	Total Organic Carbon

## 1 INTRODUCTION

### 1.1 PERSPECTIVES OF ACTIVATED CARBON UTILIZATION

Optimum design and operation of wastewater treatment plants requires that the latest technology and equipment be employed if the continued protection and eventual rehabilitation of the Nation's waters are to be effected. Conventional wastewater treatment consisting of primary and secondary treatment has proven to be inadequate in achieving the desired water quality.

Advanced treatment utilizing activated carbon for removal of residual organic and biologically resistant refractories following conventional primary and secondary treatment has proven successful. In addition, physico-chemical processes applied to raw wastewater utilizing activated carbon for organics removal following coagulation, sedimentation and filtration, have also proven successful as an alternate process to conventional treatment schemes. The same physico-chemical processes are commonly referred to as Advanced Wastewater Treatment when applied to effluent from conventional treatment. In each case the treatment scheme is designed around the adsorption capacity of activated carbon for the removal of the dilute, dissolved organics and other refractory materials.

In all engineering applications, one of the major parameters affecting the use of activated carbon for Advanced Wastewater Treatment (AWT) is cost--first cost plus operating and maintenance costs. Physico-chemical systems have roughly equal first costs (comprised of equipment, physical plant and buildings) with conventional treatment plants of similar

performance, except for the high price of carbon which is around 30¢-40¢ per pound. Operating and maintenance costs are dependent upon the system configuration, but one of the largest costs outside of labor is the carbon replacement. Carbon losses are primarily due to attrition in handling and thermal regeneration. Additional replacement is required for the loss in adsorption capacity of the carbon after repeated usage.

Due to the high cost of the activated carbon, it is mandatory to regenerate the carbon after exhaustion of the initial adsorption capacity. The main practical system utilized thus far has been thermal regeneration. Thermal regeneration consists of three steps: 1) dewatering of the activated carbon slurry, 2) baking and pyrolysis of adsorbed organics and 3) reactivation of the carbon. The thermal regeneration system, comprised of dewatering devices, multiple hearth furnace, conveying equipment, storage facilities and other appurtenances, has a built-in carbon loss of 5% to 10% due to oxidation of the carbon in the furnace. If the treatment system is to maintain the design efficiency, makeup of fresh carbon after every regeneration is required.

Another interesting aspect of activated carbon utilization has been the observation that the effluent from conventional treatment systems is usually too dilute to support further biological treatment units, but that after the carbon has concentrated the organics onto the surface of the granules, biological activity has flourished within the carbon beds. This biological activity has been interpreted to non-adverseley affect the carbon's removal efficiency. If this activity improves system performance then the overall treatment cost and efficiency

should be improved by enhancing biological metabolism of the adsorbed organic materials. It has been found possible to favorably stimulate the biological activity for these purposes through simple, ordinary environmental controls--such as dissolved oxygen concentration, pH and temperature adjustment. Since the biological activity on the activated carbon surface may become quite complex and extensive, it has been postulated that thermal regeneration may be complemented or replaced by adjustment of environmental conditions to stimulate the ubiquitous bacteria's metabolism of adsorbed organics.

Previous research has centered on utilization of activated carbon primarily in downflow packed bed adsorption systems, where biological activity has at best been merely tolerated, if not actively discouraged. Adequate recognition of the benefits of biological activity on activated carbon will allow a better definition of the real life design adsorption capacity of activated carbon. A larger maximum adsorption capacity may allow longer carbon utilization periods for contacting with the wastewater before thermal regeneration is necessary. In some cases, such as small installations, it may be economical to completely eliminate thermal regeneration.

The research described in this thesis was addressed to the problem of identification of those parameters that affect biological activity within the activated carbon columns. The intent was to maximize this action for purposes of complementing, and/or replacing the expensive, conventional thermal regeneration operation.

Preliminary parameters investigated included contact time, regeneration time, pH and temperature. These variables were investigated by contacting columns of activated carbon with secondary effluent and regeneration was accomplished by recirculating aerated water upward through the carbon columns after the waste load was removed.

## 1.2 INTENT OF RESEARCH

The intent of this research was to evaluate an alternative to costly thermal regeneration of activated carbon. Costs at the Lake Tahoe Treatment Plant indicate that the cost of regeneration and its attendant make-up carbon was 39% of the total treatment costs (Ref. 1, Table 21).

Results to date indicate the feasibility of activated carbon regeneration by stimulating aerobic biological activity in the carbon columns. It was found that a loading capacity of greater than two (2) pounds of dissolved COD per pound of activated carbon could be consistently achieved with proper air, pH and temperature control during the biological regeneration.

## 2 LITERATURE REVIEW

### 2.1 USE OF ACTIVATED CARBON: EVIDENCE OF BIOLOGICAL ACTIVITY ON AND WITHIN

Use of activated carbon for advanced wastewater treatment is predicated upon the phenomenon of adsorption. The adsorption phenomenon is the adherence of solute molecules onto a solid surface due to the surface attractive forces. These forces are proportional to the size of the surface area. Activated carbon commonly has a surface area in excess of 1000 m<sup>2</sup>/gram. This huge specific surface area is the major reason the carbon is so effective as an adsorbent.

Various investigators (1,2,3,4,5,6) have reported that in practice, more organics and refractories have been removed than would be expected from adsorption alone. The observations (7,8,9,10) of bacteria and slime growths on the carbon beds and the larger than expected capacity of some activated carbon beds has led to the speculation that the biological activity is in some way responsible (1,2,3, 5,9,10,11,12,13,14,15).

The relative importance attributed to these observations varies. Bishop, et al (10) chlorinated the influent to carbon beds to prevent the accumulation of bacteria, slime, etc.; Joyce and Sukenik (5) only admitted of the possibility that biological activity occurred. Hsieh (9) stated that the presence of the biological activity complicated the treatment and complicated the use of adsorption isotherms for prediction of carbon performance. Friedman, Weber, Bloom and Hopkins (2) found a great increase in the adsorption capacity of activated carbon used in an



upflow, aerated carbon column, due to the presence of flourishing bacterial growths within the contactors. As this phenomenon was heretofore unexpected by most investigators it is appropriate to consider the flow scheme used in the activated carbon unit operations as applied to advanced wastewater treatment, and thence to consider the ramifications of biological activity within carbon contactors.

## 2.2 ACTIVATED CARBON UTILIZATION IN ADVANCED WASTEWATER TREATMENT

Activated carbon unit operations in advanced wastewater treatment is somewhat complicated by the fact that the operations of various systems is dependent upon the flow scheme within the carbon contactors; downflow packed contactors have quite different design parameters and operational problems than do upflow, expanded contactors. Both system configurations however are dependent on two unit operations: 1) an adsorption process and 2) a regeneration process.

As previously indicated, the adsorption phenomenon has been interpreted by various investigators (1,7,9,16,17,18,19,20,21) as a surface phenomenon. A useful analytical device, in this light, is the adsorption isotherm. The adsorption isotherm is an equilibrium, temperature dependent relationship between the amount of an adsorbed substance and the concentration of that substance in the bulk solution (16, p 138). In very dilute solutions, a logarithmic plot often yields a linear relationship. Mattson and Mark (17) present a very thorough discussion of this subject. A useful expression of this line is the Freundlich equation:

$$x/m = kC^{(1/n)} \quad (2.1)$$

where

x = weight of adsorbed solute

m = weight of carbon adsorbed

k,n = constants of the particular system

C = concentration of solute in bulk solution

Transposing to a logarithmic formulation yields:

$$\log(x/m) = \log k + (1/n)\log C \quad (2.2)$$

wherein (1/n) is the slope of the line (16, p 137).

For single-solute adsorption, Keinath and Weber (11), based on a Langmuir isotherm, have developed a predictive model for the activated carbon contactor. While ignoring biological activity, this model may have some practical use if extended to multi-component solutions. They conclude however, that:

"To date, experimental evidence has been insufficient to confirm or refute the proposed procedure for predicting breakthrough curves for multiple-solute systems."

Wang (18, p 19) also comments upon this:

"...it is concluded that for multi-component organic wastes, the optimum pH for adsorption should be experimentally determined because numerous competing adsorption mechanisms are involved."

Hsieh (9, p 508) found interesting temperature effects indicating adsorption was greater and faster at 30°C than at either 60°C or 3°C. He also discussed the use of adsorption isotherms for analysis of multi-component wastes, and concluded that the wide scatter that is usually found is caused in part by the error in treating a multi-solute as a pseudo-single solute solution.

The second unit operation of interest is the regeneration of activated carbon once the adsorption capacity has been exhausted. Various methods of reactivating the carbon have been proposed, but thermal regeneration has been the only practical method utilized.

The use of chemical oxidants to reactivate the carbon was investigated (22) but it was found that of the oxidants tested, only hydrogen peroxide was effective, and only for the first regeneration. After the second contacting with a waste stream, the hydrogen peroxide was ineffective (22, p 23). Culp and Culp (16, p 163) comment most succinctly on methods of regenerating activated carbon.

..."thermal regeneration is universally used for this purpose at the present time."

The steps in thermal regeneration consist of dewatering, pyrolysis of the adsorbates, and reactivation of the carbon. A direct fired multiple hearth furnace has proven most successful for this purpose (1,4,5,13,16). Although less than stoichiometric air is used in the thermal regeneration it is sufficient for some combustion of the carbon, as well as the pyrolysis of the adsorbates. This causes a 5% to 10% loss of activated carbon through combustion on every passage through the multiple hearth furnace (1,4,5,13,16). The carbon losses and the expensive upkeep for a multiple hearth furnace are two of the major expenses in the regeneration unit operation.

### 2.3 TOTAL COSTS FOR THERMAL REGENERATION

Since only a few granular activated carbon plants for wastewater treatment have been built, it is somewhat imprecise to generate

cost data from such a small base. However, there are two published cost breakdowns for a pressure downflow packed bed system and one cost breakdown for an upflow fluidized bed system. The accounting procedures used in the three discussions of activated carbon costs are different, different years with different inflation and labor adjustments were used in the reports and different regions of the country are involved ranging from Trenton, N. J. to Pomona, California.

Considering the two downflow systems, there are three major factors to consider: 1) the loading capacity of the carbon, expressed as pounds of COD removed/pound of activated carbon, 2) the capital and construction cost/unit volume of wastewater treated and 3) the operating and maintenance costs/unit volume of wastewater treated.

Referring to data compiled over a 4½ year operating period at the Lake Tahoe plant (a 7.5 MGD pressure downflow plant) Culp and Culp (16, p 175) found that the average loading of COD was 0.45 lbs COD/lb activated carbon. Also, the cost of regeneration of activated carbon was \$0.0323/pound. Tables 1 and 2 from the same source summarize the costs. Note that the cost of regeneration plus carbon replacement is 39% of the total actual operating costs.

TABLE 1<sup>1</sup>  
ACTUAL TAHOE COSTS FOR CARBON REGENERATION, MARCH 1, 1969-FEB. 28, 1969

<u>ITEM</u>	<u>TOTAL COST (\$)</u>	<u>UNIT COST (\$/LB)</u>
LABOR	4,090	0.0241
FUEL	355	0.0021
POWER	141	0.0008
MAINTENANCE	905	0.0053
TOTAL	5,491	0.0323

<sup>1</sup>Taken from Culp and Culp (16, Table 8-4)

TABLE 2<sup>1</sup>  
TOTAL CARBON TREATMENT COSTS AT TAHOE, AT 7.5 MGD RATE BASED ON  
ACTUAL COSTS FOR MARCH 1, 1968 TO FEB. 28, 1969

<u>ITEM</u>	<u>COST PER MG (\$)</u>
CAPITAL COST	21.10
REGENERATION	7.36
MAKEUP CARBON	6.76
MAINTENANCE	<u>0.89</u>
TOTAL COST PER MILLION GALLONS	36.11

<sup>1</sup>Taken from Culp and Culp (16, Table 8-5).

The EPA manual (23) is based on different assumptions, and furthermore recommends that the carbon replacement cost be 20% of the operating costs, and be 12% of the capital costs compared to a carbon cost of 34% of the capital cost at Lake Tahoe.

The upflow, expanded bed concept was described by Weber, Hopkins and Bloom (20) for the ELSA system at Trenton, N. J. They reported from pilot plant operations that removals at 0.6 pounds of TOC per pound of activated carbon was effected, with unused capacity remaining. Scaled up to a 10 MGD plant, they found that an upflow fluidized bed system accrues a 0.73¢/1000 gal cost advantage over a pressure downflow system. Costs would be 19.75¢/1000 gal for the upflow system, and 20.48¢/1000 gal for the downflow system (20, p 551). The carbon makeup rate would be 5% and the regeneration installed cost would be \$129,000 for the 10 MGD plant. This is 19% of the physical costs of the plant.

#### 2.4 PROCESS PARAMETERS

Parameters that have to be considered for design are the rate of flow, the expected short term variations, the concentration of organics

and refractories, the carbon type and physical properties, the load of organics removed per pound of carbon, the idle carbon inventory, the type of regeneration, the capacity of the carbon after numerous cycles of contacting and regeneration and the losses for each regeneration. The design manual (23) by the Environmental Protection Agency outlines a procedure for establishing these parameters.

### 3 DESCRIPTION OF RESEARCH

The experimental apparatus was installed at the Bethlehem Sewage Treatment Plant, a traditional, high-rate trickling filter facility. The plant was overloaded with both domestic and industrial wastewater. The design capacity is 10 million gallons per day (MGD) but the plant has been operating at 15 MGD for some time. The wastewater influent to the experimental apparatus was the final effluent from the treatment plant prior to chlorination.

#### 3.1 RESEARCH PROCESS FLOW SCHEMES

There were two flow schemes involved in this research. The first was the contacting to expend the activated carbon adsorption capacity and the second was the regeneration to restore the capacity of the activated carbon.

##### 3.1.1 Contacting Scheme

The treatment plant effluent was withdrawn from the recirculation pump suction line. The wastewater was pumped up to the equipment room where the experimental apparatus was located. This influent flowed into a constant head reservoir which fed a variable speed pump<sup>a</sup> supplying the activated carbon columns. Effluent from the activated carbon columns flowed into a second constant head reservoir from which samples were taken and the overflow from this reservoir then discharged to the plant wet well. Later modifications due to related research efforts at the treatment plant made available effluent from a dual media filter. When this filtered wastewater was available

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<sup>a</sup>Teel 1P817, Dayton 3M293

it was fed directly to the influent constant head reservoir. This procedure eliminated the need for the sample filter pretreatment step in the COD determination as discussed in the following section (3.3).

There was no attempt made to regulate the pH, temperature, or solids load of the activated carbon column influent, except as noted previously in connection with the dual media filter. At first, hydrogen sulfide generation within the activated carbon columns was a problem and chlorination of the column influent was effected by a chemical feed pump.<sup>a</sup> This practice was eventually discontinued and further hydrogen sulfide was not encountered in significant concentrations.

Flow rate control to the columns was of three types: 1) speed control of the supply pump which was limited by the 35 psi maximum operating pressure of the pump seals, 2) the installation of flow control valves<sup>b</sup> and 3) by the installation of throttling ball valves on the supply line for each column. Breakup of occasional agglomerations within the columns was found to be necessary every few weeks and an air tap was set into the base of all of the columns for this purpose. A flow schematic is shown in Fig. 1.

### 3.1.2 Regeneration Scheme

The second major flow system was for regeneration. The first system that was used consisted of removing the caps from the columns, and inserting a porous stone diffuser on the end of a piece of plastic pipe into the carbon, until it was near the bottom. By

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<sup>a</sup>MEC-O-MATIC, 475-C

<sup>b</sup>Dole Mfg. Co.



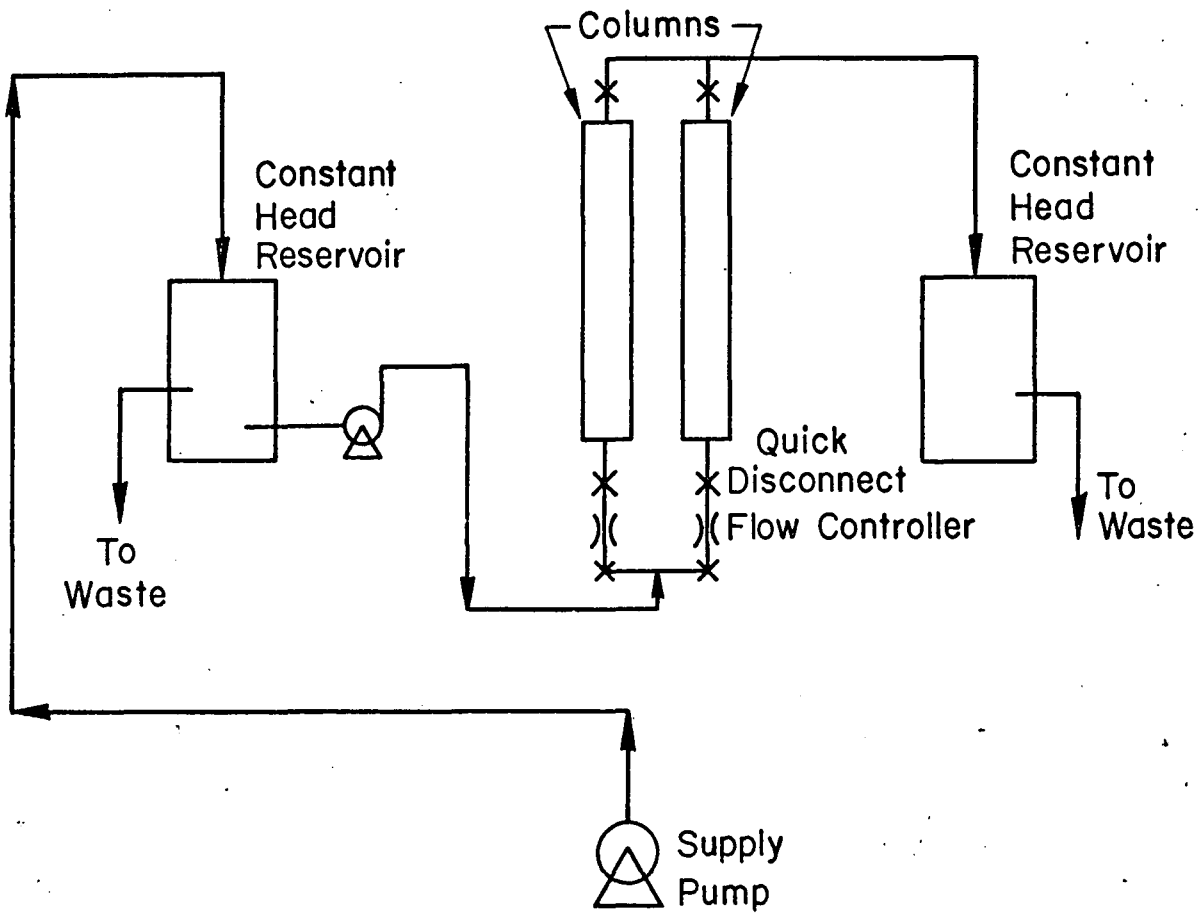


Fig. 1 Contacting Schematic

inserting the air supply assembly while the column was filled with fluid, and with the air flow maintained down through the pipe and out of the diffusers, it was a simple matter to locate the diffuser at the bottom of the column. This system was abandoned due to two reasons. First, there was inadequate freeboard and as a result, the agitation of the water was sufficient to cause activated carbon to overflow the columns. Second, associated with this occurrence was the occasional rise of an agglomeration of activated carbon which boiled out over the top of the columns.

Modifications to this basic system were ineffectual, leading to the fabrication of another system. The carbon columns again had the tops removed, and an extension of the column which was open to the atmosphere was sealed in place on top. The extension had a 1/2 inch connection which was covered by a screen to prevent carbon particles from entering the recirculation lines. Recirculating tap water flowed upward through the columns. Problems associated with this system were due to the head limitations of the submersible pumps<sup>a</sup> and clogging of the screen with carbon particles and adsorbed material that had been scoured off. Dissolved oxygen concentrations were maintained by insertion of the stone diffusers into the constant head reservoir in which the submersible pumps were located. It was simple to monitor the dissolved oxygen level and control the dissolved oxygen level using the air supply rate. Flow regulation was accomplished by adjustment of the position of the constant head reservoir. This system was further modified to improve the regeneration operation.

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<sup>a</sup>Little Giant Pumps

The final regeneration system that was devised and which has worked quite adequately since, was a simple modification of the second system. The column extensions were abandoned and the original caps were kept in place. The constant head reservoir was installed at the level of the tops of the column to allow minimum head loss and tap water was again recirculated upflow through the column. The water would overflow through the top cap into the constant head reservoir, where the diffusers would saturate the water with dissolved oxygen. The submersible pump would then pump it down to the bottom of the column and thence upflow through the activated carbon. The flow rate was maintained near incipient fluidization of the upper 2 to 3 inches of the carbon bed. The final flow scheme used is shown in Fig. 2.

### 3.2 EQUIPMENT DETAILS

#### 3.2.1 Columns

The activated carbon columns were constructed of two materials. The columns were operated in sets of two, in parallel. One set of columns was fabricated from 2-3/4 inch ID plexiglass. The second set of columns was fabricated from 3-1/16 inch ID PVC. The columns were all 6 feet long, with insert male adaptors at both ends, and capped by either drain waste vent (DWV) caps, or schedule 80 caps. Details of the columns are shown in Fig. 3.

All columns had stainless steel screens shown in Fig. 4 mounted in plastic holders within the caps for support of the carbon. The first five batch operations were run with 4.62 pounds of activated carbon in each column. The last two runs had only 3 pounds of activated

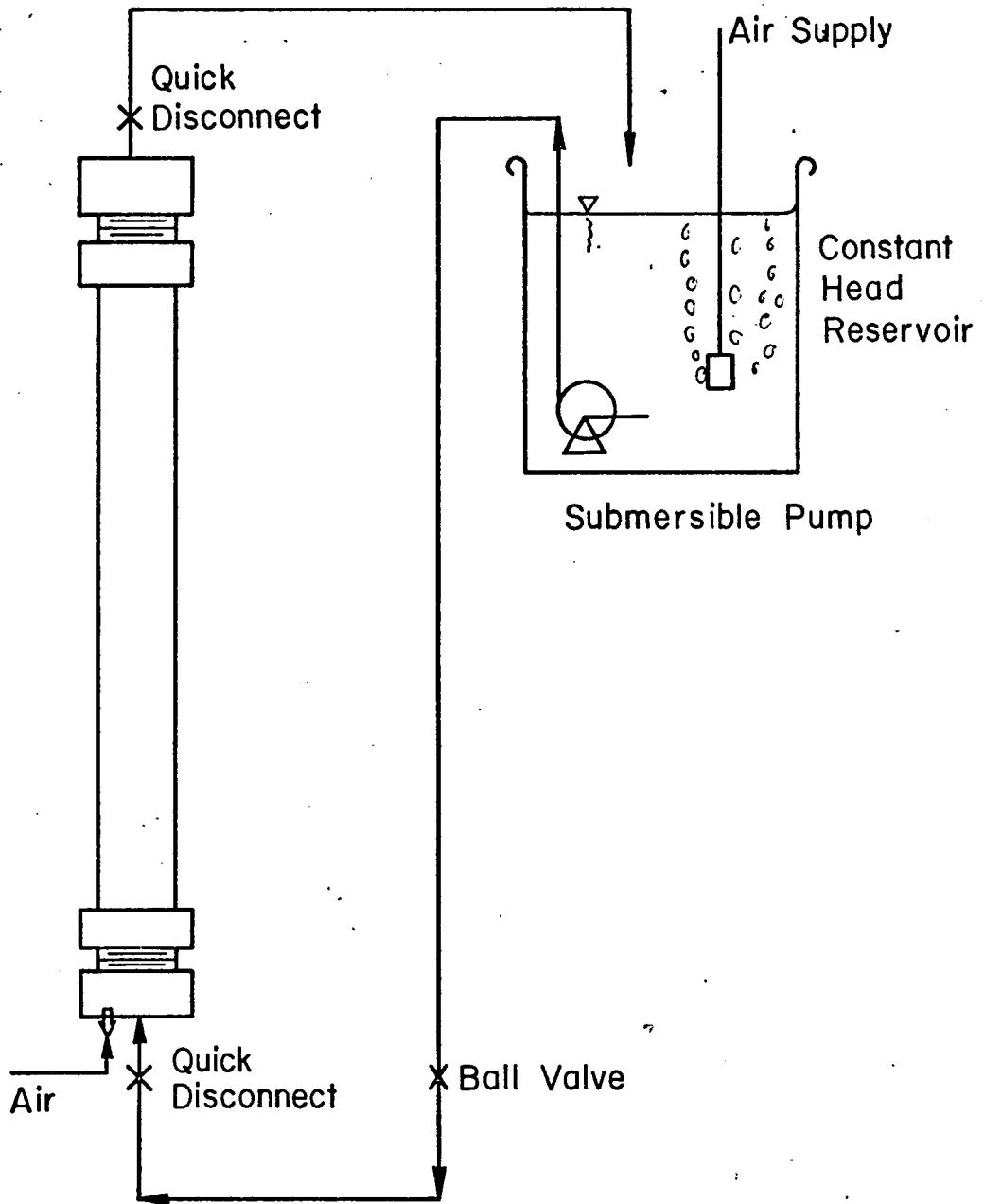


Fig. 2 Regeneration Schematic

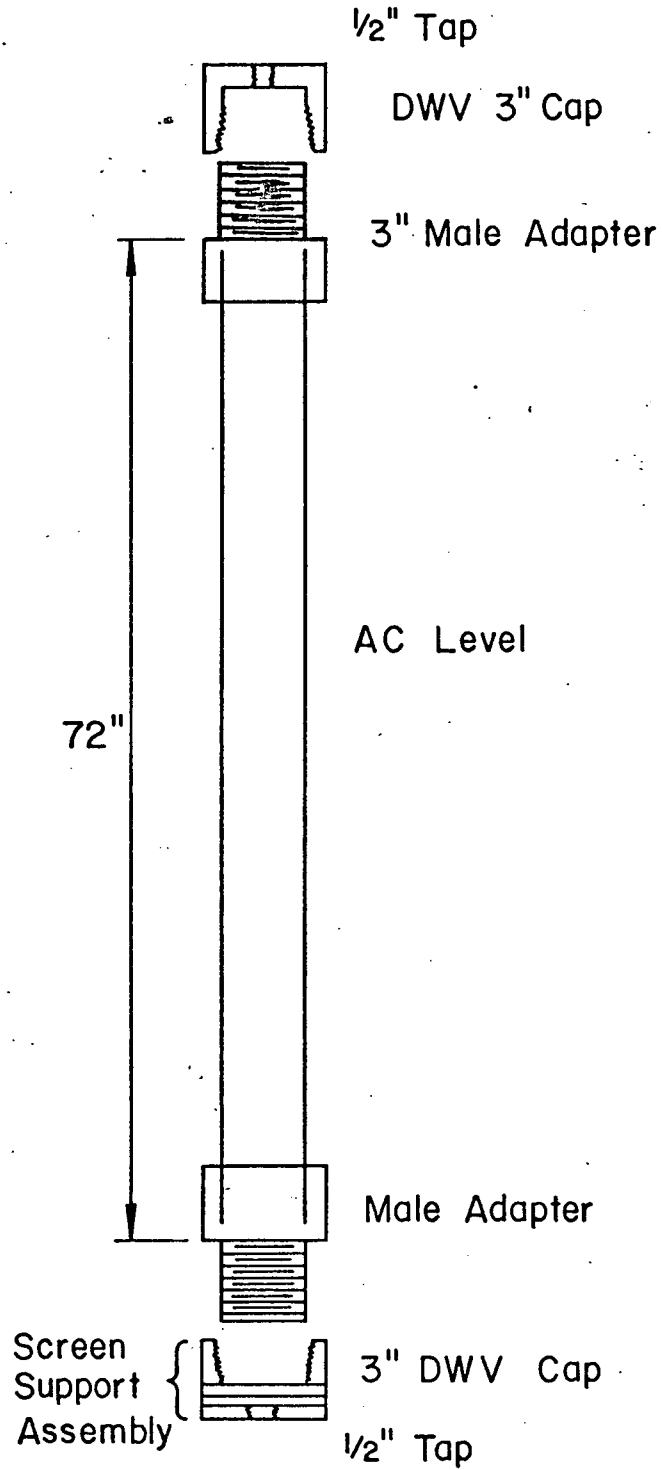


Fig. 3 Column Detail

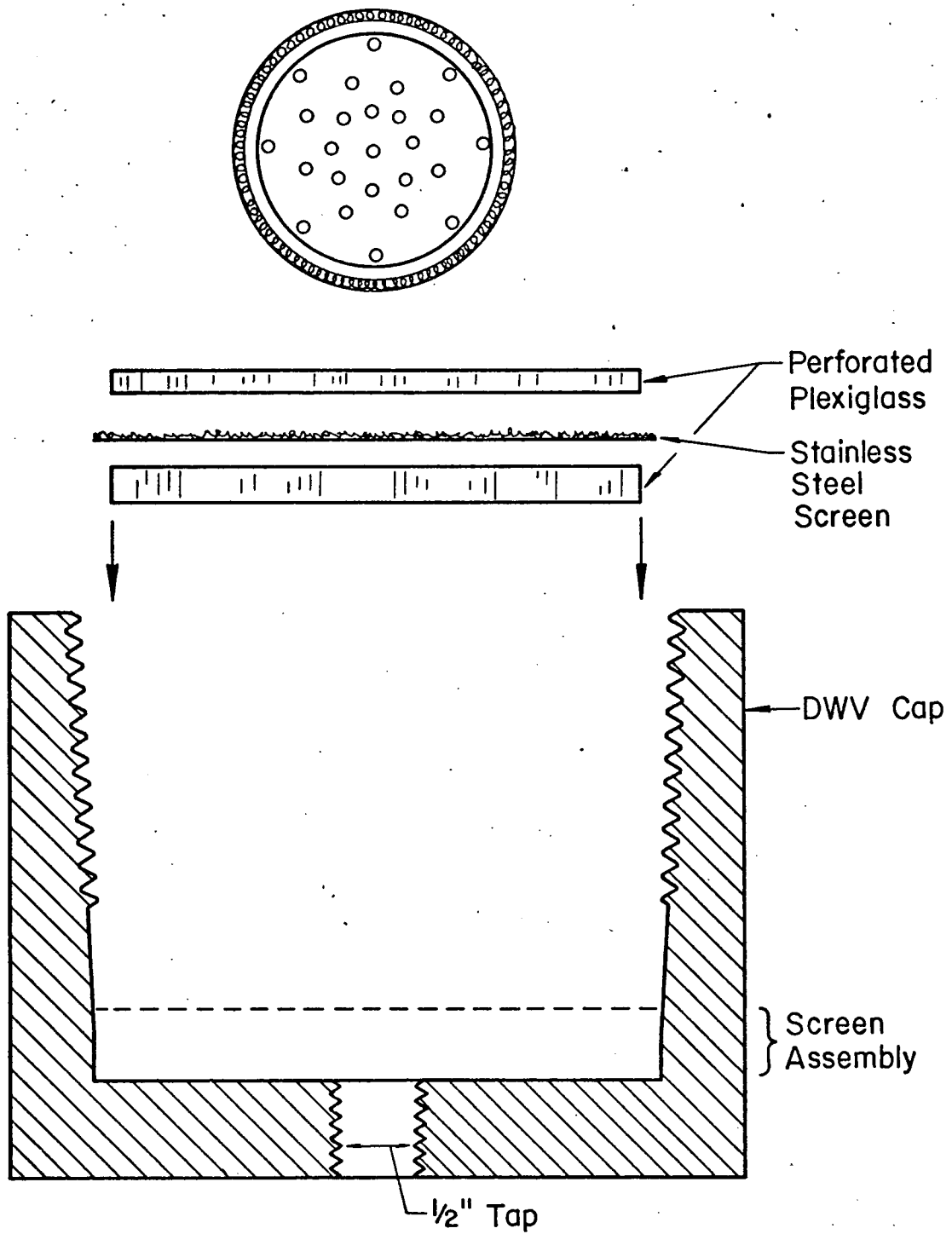


Fig. 4 Cap Detail

carbon to allow for more expansion during regeneration. The performance was altered only with respect to the ease of operating the system.

### 3.2.2 Air Supply

There were two different air supplies. One was located at the Bethlehem Sewage Treatment Plant and one was located in the laboratory on the Lehigh campus. The compressor<sup>a</sup> discharged into a holding tank<sup>b</sup> equipped with a pressure switch to activate the compressor drive motor. The air pressure was reduced through a pressure reducer valve<sup>c</sup> and was monitored by a dial gage. The air was distributed to the two columns through rotameters<sup>d</sup> to the stone diffusers in each regeneration constant head reservoir using Tygon tubing. Piping details and a rotameter calibration curve are shown in Fig. 5 and Fig. 6 respectively.

### 3.2.3 Guillotine Sampler

Composite influent and effluent samples were taken by a unique, clock-timer acutated guillotine sampler that was developed especially for this research project. This sampler consisted of a solenoid acutated scissors mechanism that pinched off rubber sample lines which were connected to each of the influent and effluent constant head reservoirs. The composite sampler was fabricated in essentially three pieces: the timer mechanism, the solenoid action and the scissor action mechanism, or guillotine. The sampler details are shown in Fig. 7. It was found necessary to insert a heavy duty spring (about 20 lbs/in) to protect the solenoid mechanism from shock loads. The system was fail safe,

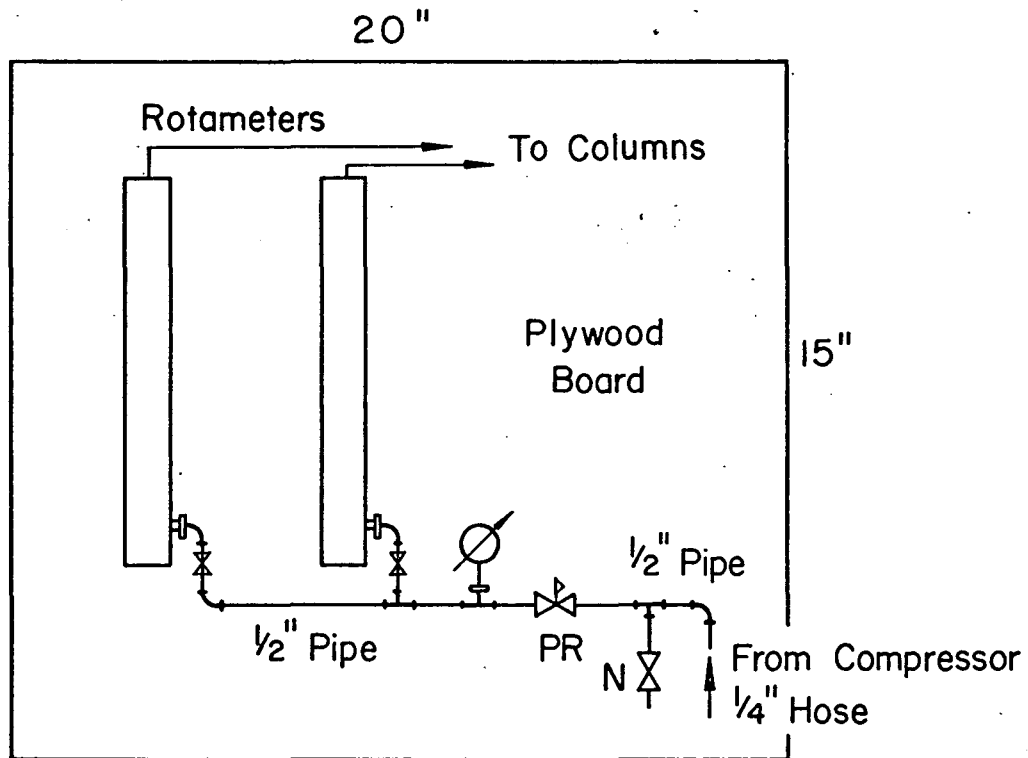
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<sup>a</sup>Bell and Gossett SYC 8-1

<sup>b</sup>Satellite Stamping PN 1Z984

<sup>c</sup>Watts B5

<sup>d</sup>Brooks E/C



N Needle Valve  
 PR Pressure Regulator

Fig. 5 Air Supply Detail



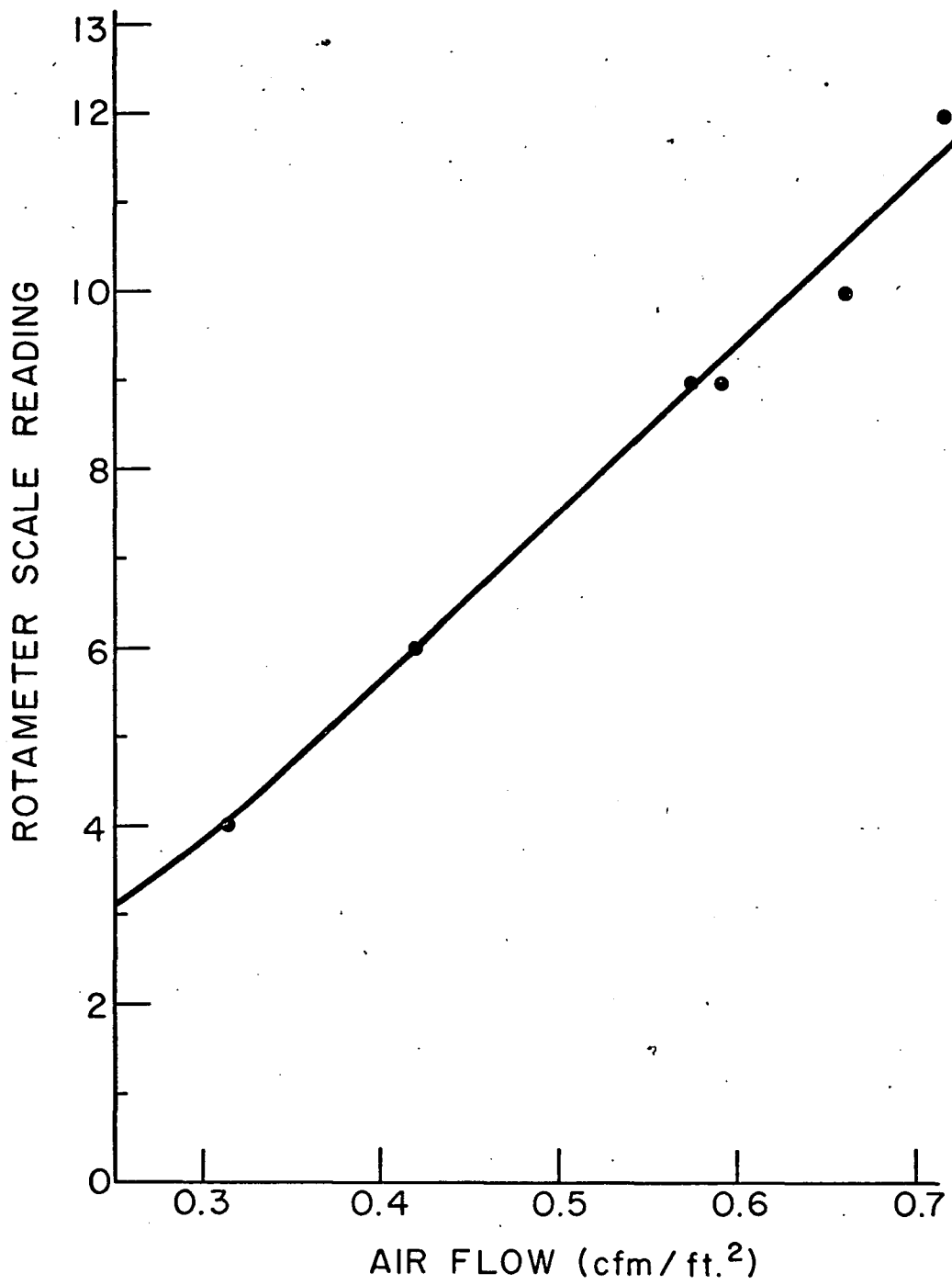


Fig. 6 Rotameter Calibration Curve

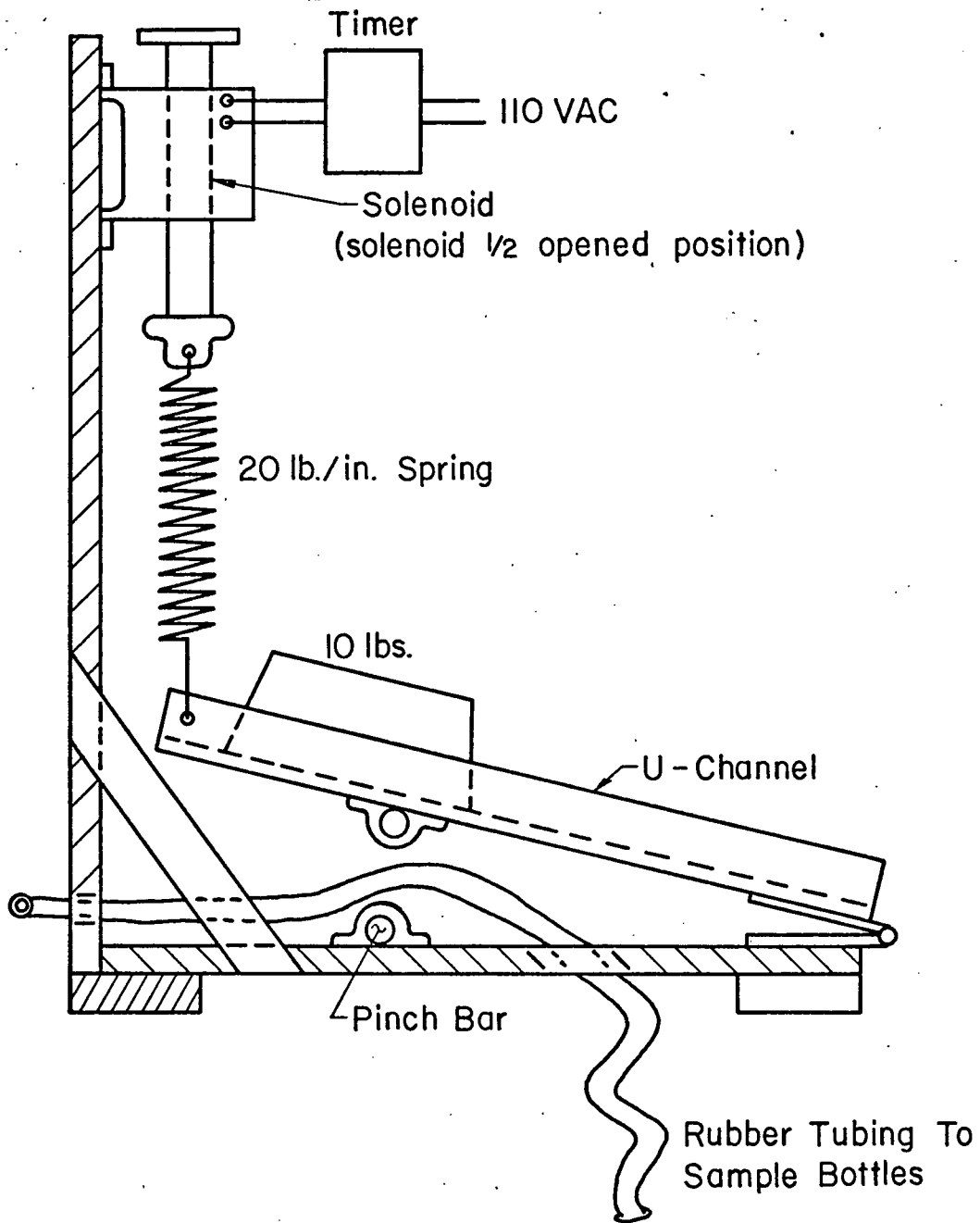


Fig. 7 Guillotine Sampler

since the scissors were counter weighted and would keep the sampler closed in the event of power or equipment failures.

#### 3.2.4 Dual Media Filter

The dual media filter shown in Fig. 8 was fabricated from 10 inch ID schedule 80 steel pipe with blind flanges and tapped to accept 3/4 PVC tubing. The filter was equipped with backwash lines, pressure gages and a clear sight-glass to monitor the efficiency of the backwashing procedure. The media was installed over an inlet section which was fabricated from a PVC funnel. The underdrain media was 3/4 - 1/2 inch gravel up to the top of the inlet funnel. Three additional layers of gravel, each 3 inches deep 1/2 - 1/4 inch, 1/4 - 1/8 inch and 1/8 - 1/16 inch made up the balance of the underdrain gravel.

The upper filtering media was twenty inches (20") of anthracite coal with an effective size of 1.84 mm and a uniformity coefficient of 1.20. All fines from the coal were washed out prior to installation of the filter. The twelve inch (12") layer of sand below the anthracite coal had an 0.5 mm effective size and a uniformity coefficient of 1.30.

### 3.3 ANALYTICAL METHODS AND TEST PROCEDURES

#### 3.3.1 Chemical Oxygen Demand

The COD was used to monitor the performance of the apparatus during the contacting phase. The method for dilute samples as outlined in Standard Methods (25) was used. Due to the variation of the suspended solids concentration, a filter<sup>a</sup> pre-treatment was necessary prior to the COD analyses. When the dual media filter was placed in operation,

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<sup>a</sup>Reeves Angle Filterpaper, 984 AH

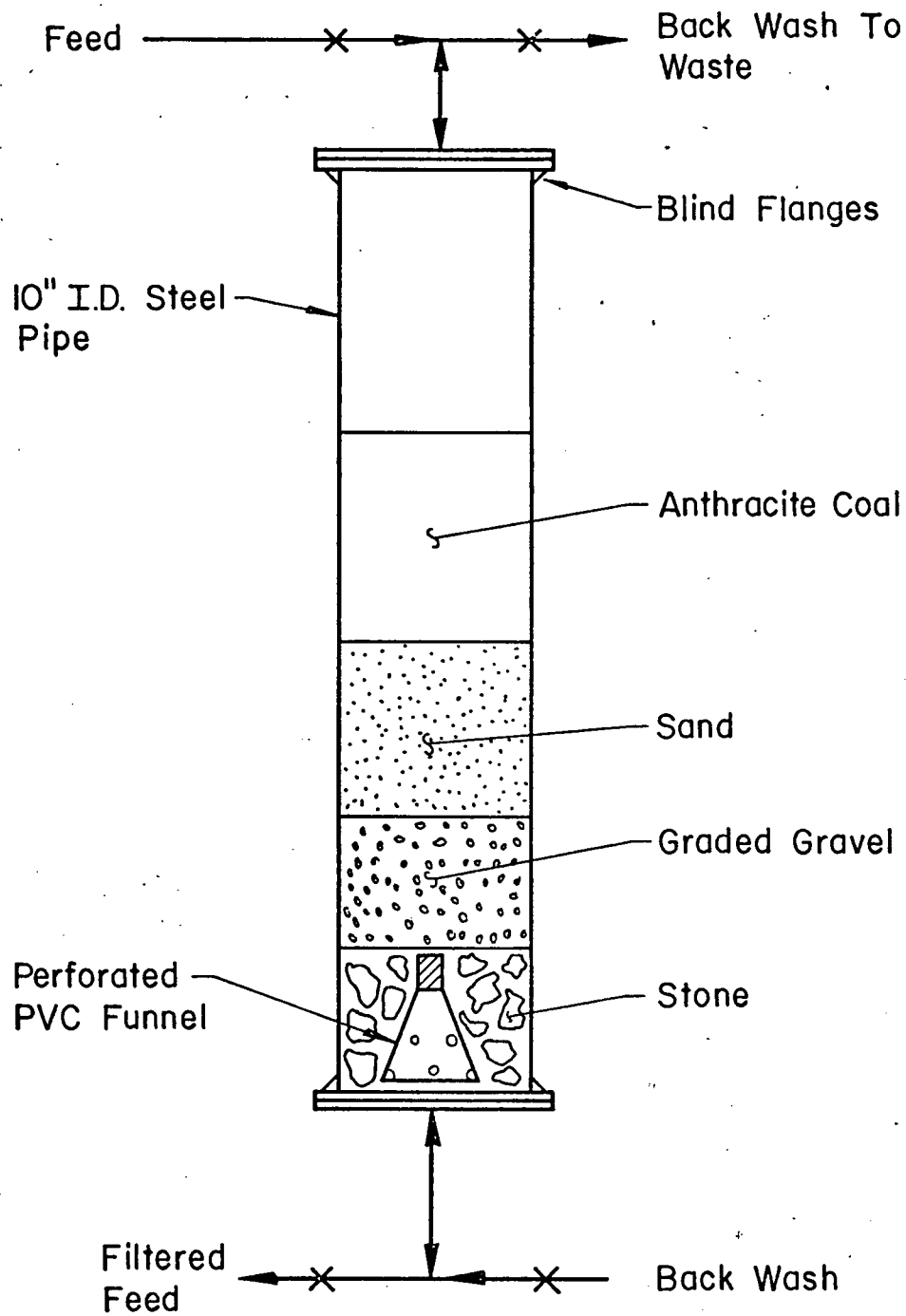


Fig. 8 Dual Media Filter

and the filtered wastewater was available for contacting, this analytical procedure was discontinued.

The COD test was also employed in determining adsorption isotherms. The first experiments used total COD, but it was determined that using only the dissolved COD would yield more consistent results. The activated carbons used in the isotherm experiments were Filtrasorb<sup>a</sup> 400, of sizes 100x200 and 8x30. The 100x200 size activated carbon yielded the most consistent results. The procedure for running the COD adsorption isotherms was that as outlined by the Atlas Chemical Co. (26) for use specifically with activated carbon.

### 3.3.2 Iodine Number Test

The Iodine Number Test was used to monitor the regeneration process. The procedure was that of Culp and Culp (16, p 249) with modifications of the normality of the iodine solution and the sample volume to be titrated, as recommended by Culp and Culp. The use of a ball mill to pulverize the carbon sample is to be recommended, as use of mortar and pestle for more than a few carbon samples becomes tiresome.

### 3.3.3 Dissolved Oxygen

Dissolved oxygen (DO) tests were made to determine the amount of DO in the regeneration system recirculation fluid. This determination was accomplished using a commercially available instrument<sup>b</sup>, with atmospheric calibration. The DO in the regeneration system was monitored periodically, and was above 7.0 mg/ at all times.

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<sup>a</sup>Calgon product

<sup>b</sup>Yellow Springs Instrument Co.

#### 3.3.4 Activated Carbon Selection

Activated carbon selection has been thoroughly outlined in the EPA's "Process Manual for Carbon Adsorption". The parameters of especial interest were size distribution and COD adsorption capacity. Several carbons were investigated and it was found<sup>a</sup> that the Filtrasorb 400<sup>b</sup> gave the best overall performance for this research. The 8x30 size was used in all subsequent experiments.

#### 3.3.5 Sampling Procedures and Preservation

Carbon samples were taken from the columns during regeneration by insertion of a thief grab sampler through the top of the carbon columns. Samples taken were approximately 5 grams of carbon. It was found that for the activated carbon samples, oven drying at 100°C for one day and storage in a dessicator at room temperature was adequate.

Composite samples of the influent and effluent wastewaters were taken by the guillotine sampler previously described.

It was found that storage of the wastewater samples in glass bottles with ground glass stoppers (300 ml BOD bottles) was adequate when two (2) drops of concentrated sulfuric acid were added for preservation and samples were stored at 10°C.

Influent and effluent composite samples, after the initial testing of the apparatus, were taken on a daily schedule. The composite samples were taken in 1 gallon glass jugs and then transferred into 300 ml BOD bottles for transport to the laboratory.

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<sup>a</sup>Results of unpublished research by A. G. Collins, Dr. R. L. Johnson, 1972

<sup>b</sup>Calgon product

### 3.4 OPERATION OF THE RESEARCH SYSTEM

#### 3.4.1 Numbering of Runs

Numbering of runs was based on a decimal system. The leading digit to the left of the decimal point refers to the number of the activated carbon batch. The first number to the right of the decimal point displays the number of complete cycles through contact and regeneration. For instance, the first batch of carbon was referred to as run 1.1 during the initial contacting, and the initial regeneration. The second time through, it was referred to as run 1.2. The numbering for the third batch of activated carbon added a second number to reflect the pH of the regeneration. One column was regenerated at pH 6 and was referred to as 3.16, the other column in the set was regenerated at pH 8 and was referred to as 3.18. The second time through the contacting-regeneration cycle, the batches were referred to, respectively, as 3.26 and 3.28.

TABLE 3  
EXPERIMENTAL RUNS CONDUCTED

<u>RUN NUMBER</u>	<u>CYCLES</u>	<u>CONDITIONS</u>
1.1	1	Batch 1 Ambient pH & Temperature
1.2	2	Batch 1 Ambient pH & Temperature
1.3	3	Batch 1 Ambient pH & Temperature
2.1	1	Batch 2 Ambient pH & Temperature
2.2	2	Batch 2 Ambient pH & Temperature
3.16	1	Batch 3 pH 6, 30°C
3.18	1	Batch 3 pH 8, 30°C
3.26	2	Batch 3 pH 6, 40°C
3.28	2	Batch 3 pH 8, 30 C

### 3.4.2 Environmental Control Parameters

Control of pH during regeneration was maintained by manual addition of sodium hydroxide or sulfuric acid into the constant head reservoir. After the system was started, the temperature was found to be  $30^{\circ}\text{C} \pm 2^{\circ}\text{C}$ . A temperature of  $40^{\circ}\text{C}$  was maintained by the addition of heater elements to the constant head reservoir, and temperature was controlled by a commercial manual temperature controller.<sup>a</sup>

### 3.4.3 Monitoring Operations

COD was used to monitor the performance of the contacting operations. On the first run (i.e., 1.1) composite samples were analyzed twice a day. All subsequent runs had composite samples taken daily, 6 days per week. The COD determination was run as soon as possible after the samples were taken, but in some cases the acidified, preserved samples were stored at  $10^{\circ}\text{C}$  for up to two days. This procedure did not appear to adversely influence the results, as the samples did not decompose to any significant extent.

Iodine numbers were determined during regeneration of the carbon on a 5 day schedule. The first determination was done immediately at day 0 and subsequent determinations were done after contacting 5, 10, 15, and 20 days following inception of regeneration. Replicates were run on the carbon taken from both columns.

Temperature was monitored for runs 1.1 through 3.18. Temperatures were controlled at  $40^{\circ}\text{C}$  only for run 3.26 and 3.28. The pH was monitored periodically for runs 1.1 through 1.3 and 2.1 through 2.2.

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<sup>a</sup>Yellow Springs Instrument Co., Model 51A



The temperature control system is shown in Fig. 9. For runs 3.1 through 3.2 the pH was manually adjusted on a daily basis by addition of 1N NaOH and 1N H<sub>2</sub>SO<sub>4</sub>.

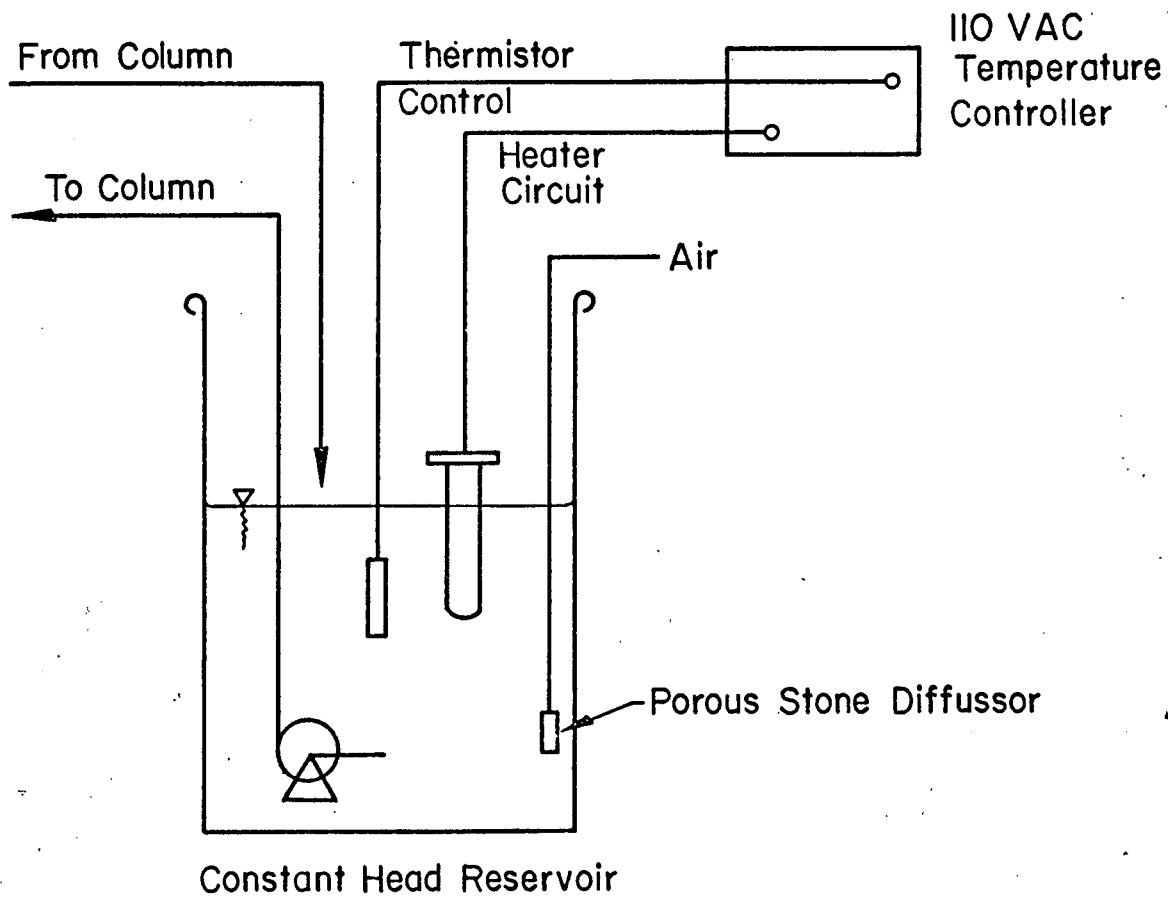


Fig. 9 Temperature Control System

## 4 ANALYSIS OF RESULTS AND DISCUSSION

### 4.1 COD REMOVAL DURING CONTACT PHASE

The influent wastewater to the apparatus and the effluent from the apparatus was continuously sampled as outlined previously for COD determinations. A plot of the influent and effluent COD concentration from run 1.1 is included shown in Fig. 10. Similar plots for all runs, 1.1 through 3.2 are included in the appendix.

Upon examination of the widely varying COD of the influent and effluent streams from the apparatus, it was determined that a clearer representation of the data could be achieved by plotting the mass of COD applied to and removed by the activated carbon against the cumulative time of contacting. This procedure was carried out for each of the runs. The plots for all runs are included in the appendix and Fig. 11 is a typical plot, in this case for run 1.1. This method of analysis also incorporates the effect of flow rate variations which occurred during the contacting period.

In viewing the removal efficiency of the columns, it must be remembered that the aim of this research was only to evaluate the effectiveness of the biological regeneration. The research apparatus was not designed to provide long enough contact times to achieve good removal efficiencies in terms of the effluent COD concentrations. However, the mass of COD removed per unit of activated carbon--the apparent activated carbon capacity--can be evaluated from this data.

Table 4 summarizes the apparent activated carbon capacity during the various contacting periods. Figure 12 is a plot of the

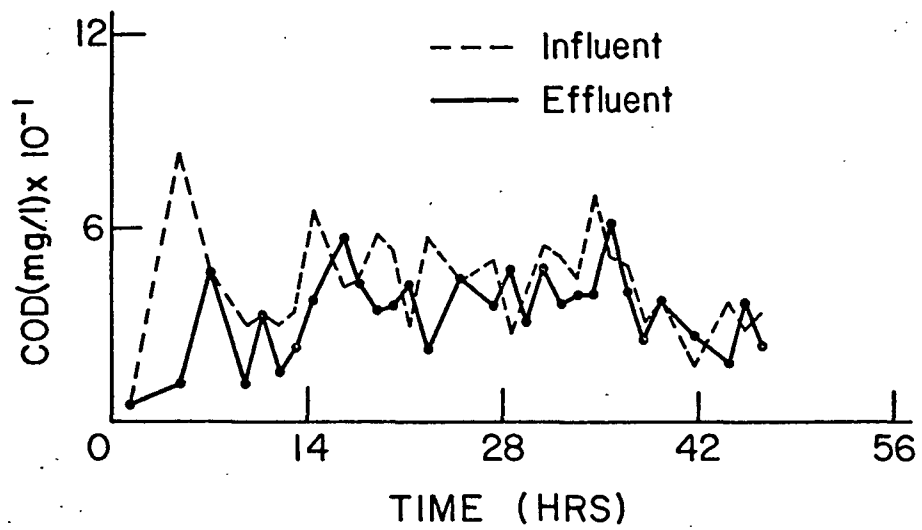


Fig. 10 Influent-Effluent COD vs. Time

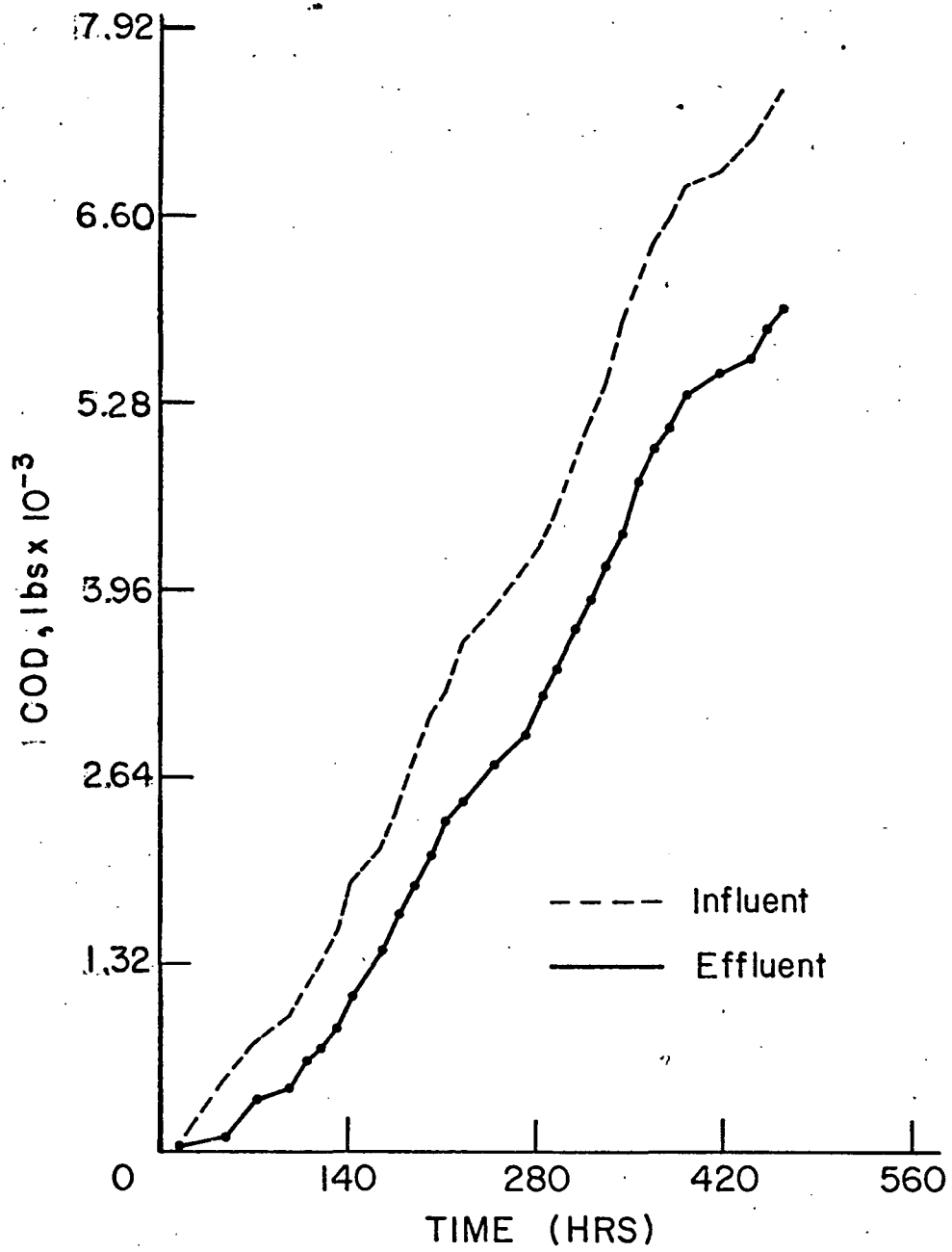


Fig. 11 Influent-Effluent Summed COD vs. Time

TABLE 4  
SUMMARY OF COD REMOVAL AND CARBON CAPACITIES

RUN	ARTH. MEAN COD CONCENTRATION		APPARENT CARBON CAPACITY (1b COD/1b CARBON)					CARBON CAPACITY (1b COD/1b AC)	TOTAL TIME CONTACTED (HOURS)
	INFLUENT (mg/l)	EFFLUENT (mg/l)	24 HRS	48 HRS	72 HRS	240 HRS	360 HRS		
1.1	42.5	32.9	.0331	.073	.120	.765	1.274	1.87	466
1.2	156.2	111.3	.0611	.134	.329	1.922	3.187	3.19	486
1.3	187.5	157.8	.0533	.135	.228	1.574	2.540	3.07	392
2.1	57.4	25.5	.0433	.108	.215	1.146	2.007	2.00	348
2.2	178.4	142.3	.025	.035	.120	1.831	3.021	3.65	435
3.1	93.3	59.7	.022	.084	.167	1.242	1.486	1.49	285
3.2	163.5	127.7	.006	.022	.046	0.868		0.87	292

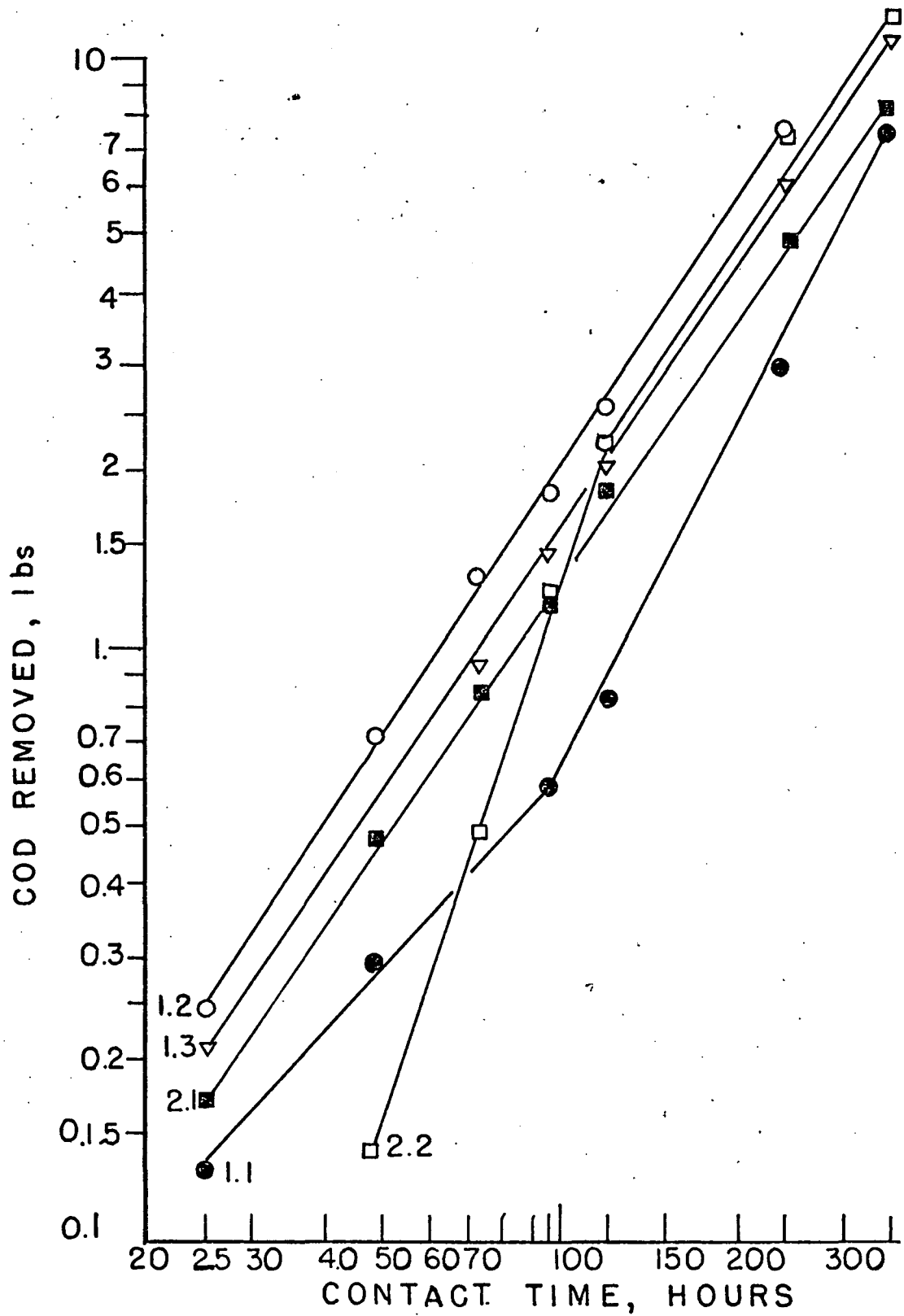


Fig. 12 COD Removed vs Contact Time

COD removal capacity vs contact time for the various batches of carbon.

#### 4.2 EFFECTIVENESS OF BIOLOGICAL REGENERATION

In addition to the apparent capacity of the activated carbon determined from the contacting period of each run, it was desired to have some standard laboratory measure of the activated carbon capacity. This would be necessary to evaluate the adequacy of the biological regeneration.

One type of laboratory determination is the adsorption isotherm. Initially it was thought that isotherms could be determined after various periods of regeneration. From each isotherm it was hoped that the carbon capacity could be determined and compared.

Although normal procedures would require pulverizing the carbon to a powder, a procedure using specific sizes of carbon was used instead. The main reason that the carbon was not pulverized for the isotherm determination was because the pulverizing would expose new carbon surfaces, not previously available, which would tend to show more recovery of the adsorption capacity than was really available in the granular carbon used in the columns.

Because of the kinetic limitations, the true capacity would not be measured by this procedure, but rather some fraction of the capacity would be determined. By using uniform sizes and times of testing, this fraction would be constant and the relative values would allow comparisons to be made.



Using the procedure previously outlined, COD adsorption isotherms were run on the first batch of activated carbon, denoted run 1.1. The isotherms were determined at 20°C for 0, 1, 3, 5, 7 and 10 days of regeneration. The results were not as precise as expected and there was a great deal of scatter of the data points. A typical example is shown in Fig. 13 for virgin carbon. The remainder of the adsorption isotherms appear in the appendix. After day 10, this procedure of monitoring the regeneration process using adsorption isotherms was discontinued.

Since only a relative measure of carbon capacity recovery during regeneration was desired, it was decided to try another standard test, the iodine number. Iodine numbers were determined on a 5 day schedule for all carbon regenerations. Carbon samples of 5 grams each were taken after 0, 5, 10, 15 and 20 days of regeneration. The first regeneration run 1.1, indicated that the iodine number did not change much beyond 10 days. Consequently, regeneration was continued for only 15 days on all subsequent regenerations.

Figures 14 through 17 show the iodine number during each regeneration period. Those runs which had parallel units in operation are designated left or right in the figures.

As can be seen, even with a straight forward test, there is appreciable variation which can not be explained specifically. In particular, the iodine numbers for run 3 are lower than the previous run by a factor of almost one-half.

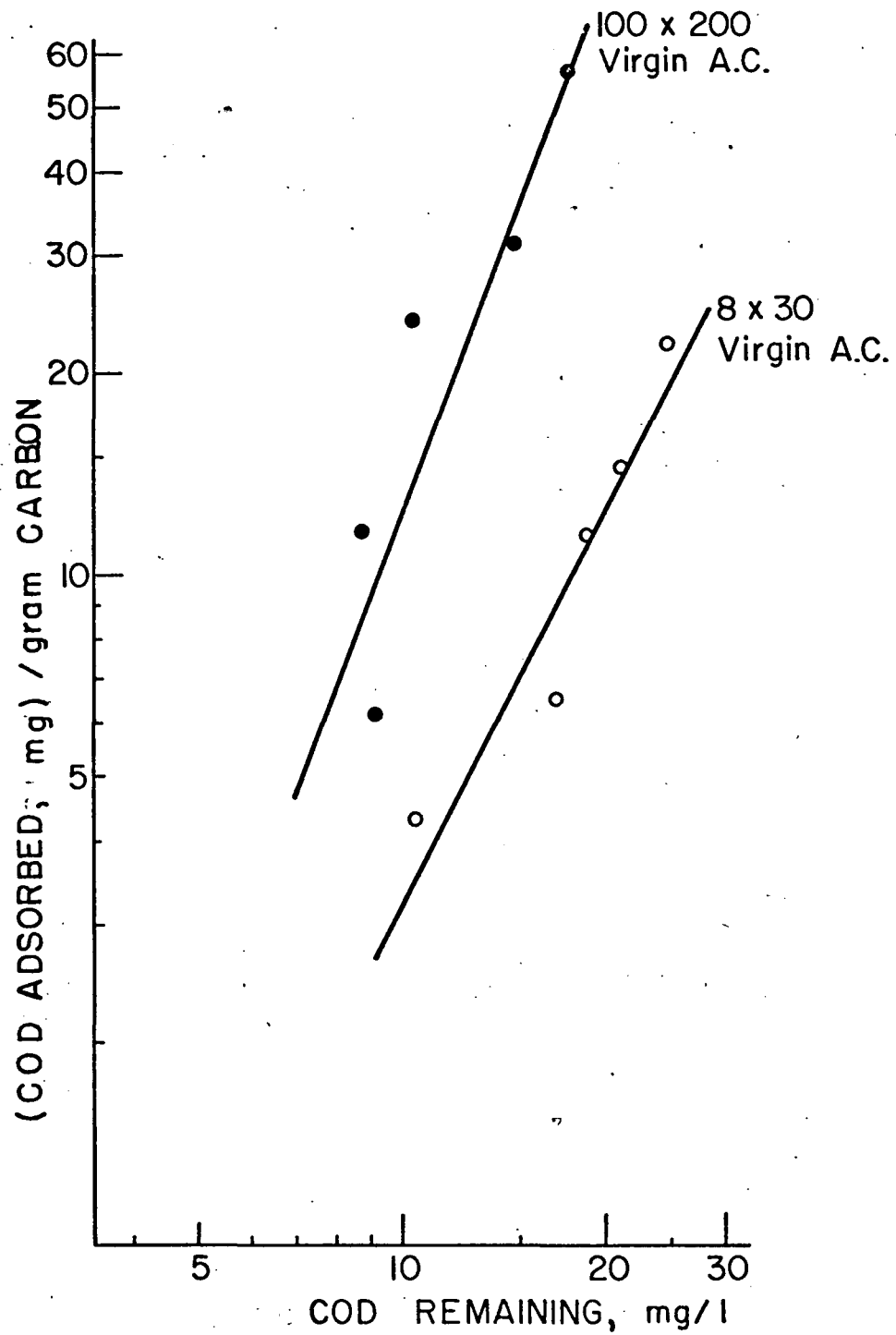


Fig. 13 COD Adsorption Isotherm, Virgin Carbon

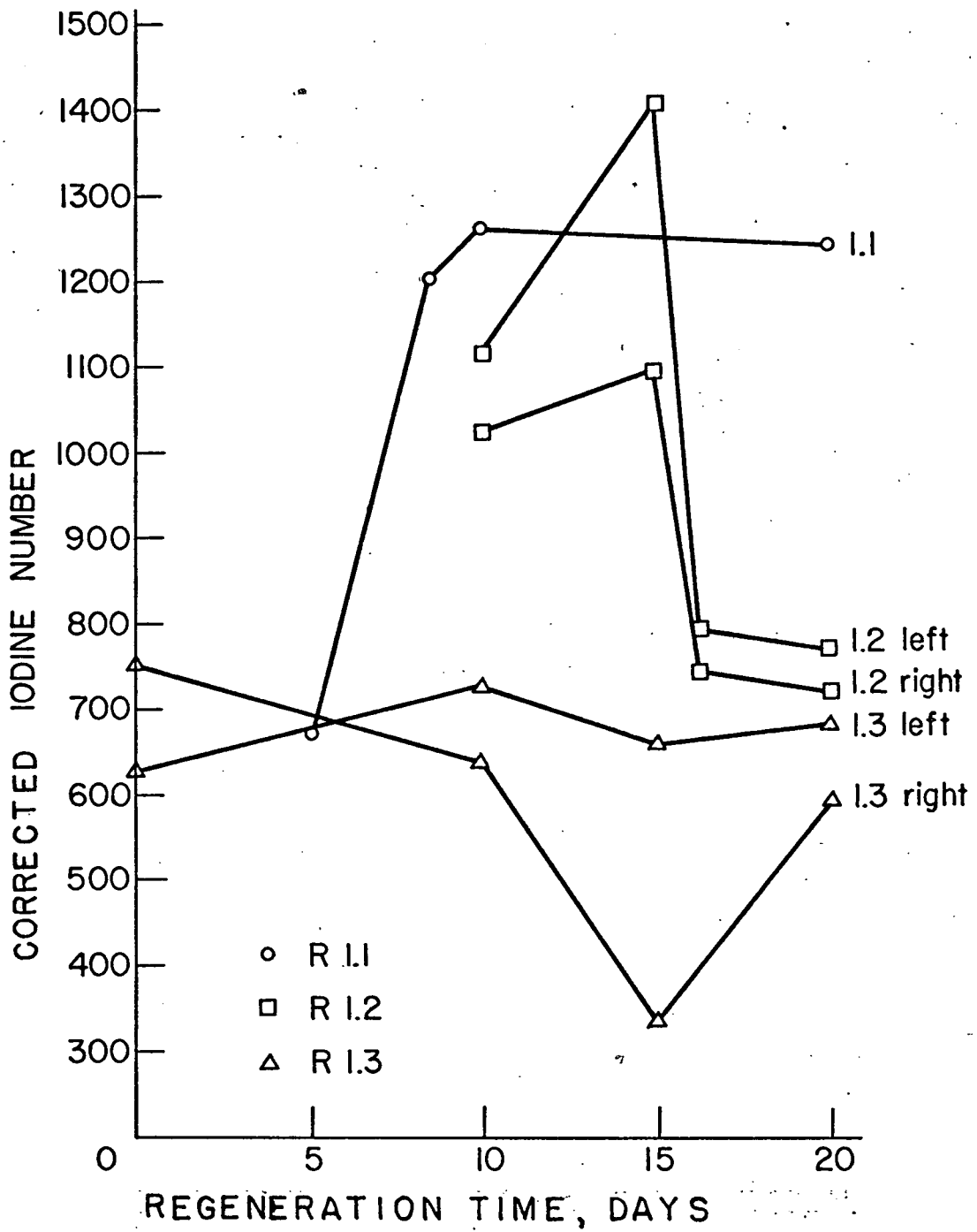


Fig. 14 Iodine Number vs. Time Regenerating Run 1.1, 1.2, 1.3

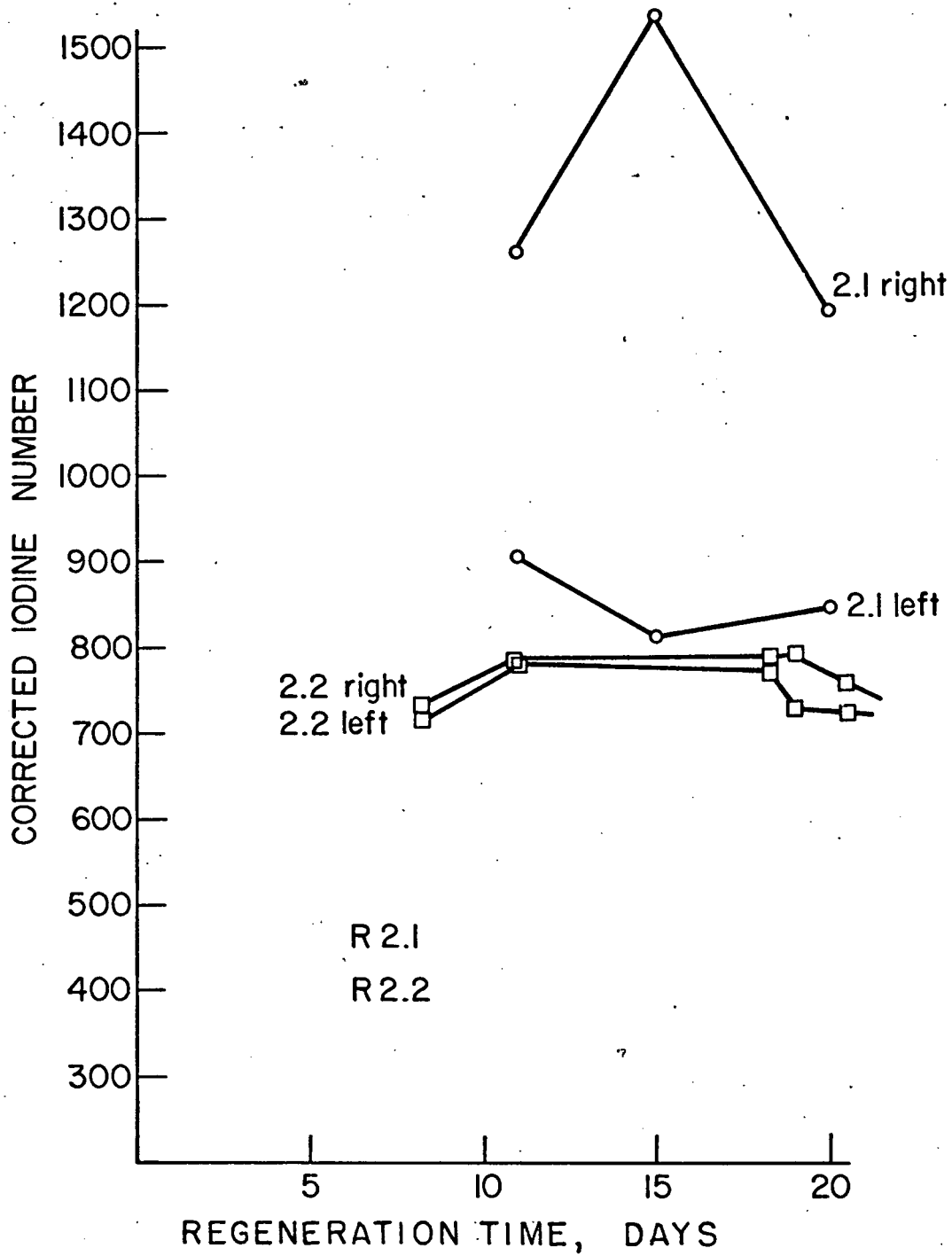


Fig. 15 Iodine Number vs. Time Regenerating, Run 2.1, 2.2

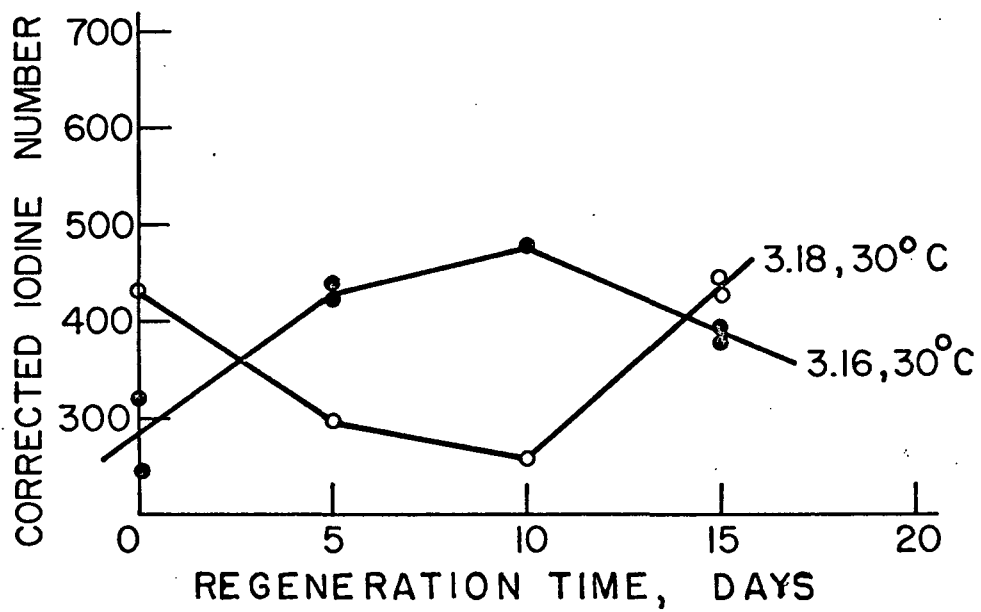


Fig. 16 Iodine Number vs. Time Regenerating, Run 3.1

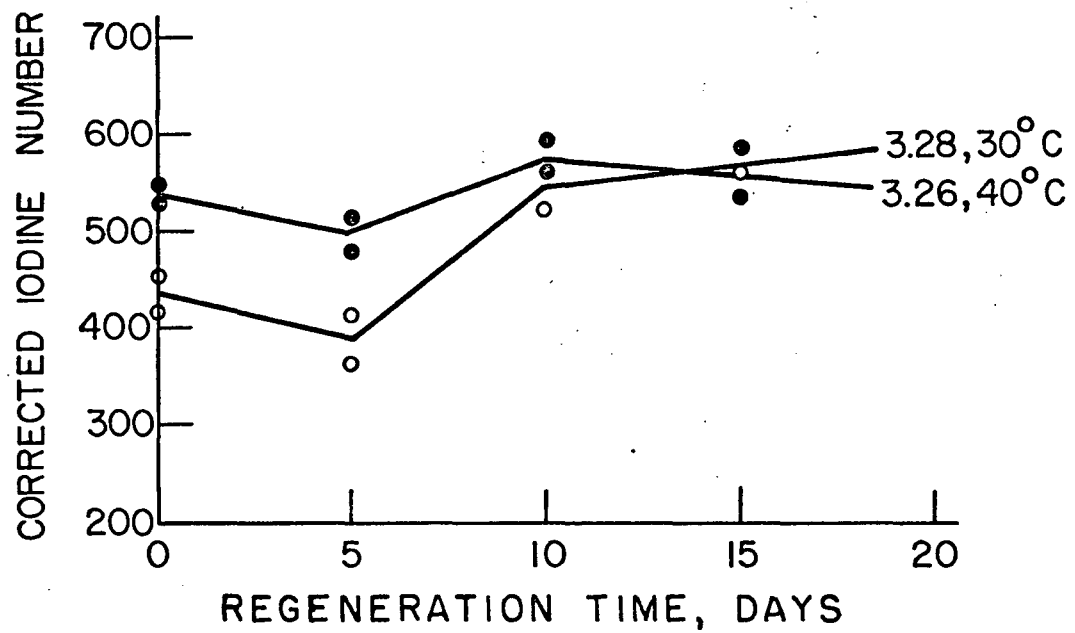


Fig. 17 Iodine Number vs. Time Regenerating, Run 3.2

One possible explanation of this change in iodine number for batch 3 is an accident which occurred in the storage area. A cylinder of anhydrous hydrochloric acid developed a leak in this storage area and it is possible that the escaping gas contacted the carbon and caused a drastic change in surface activity of the carbon. Another possible cause would be the adjustment of the recirculating water to a pH of 6.0 or 8.0 which might have caused the change. None of these can be proven, but further checking should be done of the possible effect due to the pH of the recirculating water.

Although the data from the iodine number determinations varies appreciably, it does show some longer term trends in the biological regeneration scheme. Figures 18 through 20 show the variations of the iodine number for each batch of carbon respectively over the various contact and regeneration cycles. There is a general trend of decreasing iodine numbers during the continuous contact and regeneration cycles. This is in contrast with the apparent continuous increases in carbon capacity when measuring the COD removed, as shown in Fig. 21. This indicates that the iodine number is not a particularly precise test for carbon capacity, particularly where biological activity is involved.

#### 4.3 RATE OF COD REMOVAL

Table 5 summarizes the iodine numbers for each batch of carbon and the observed capacity of the carbon to remove COD when put back into contacting service. This data shows an increasing COD removal with a continued decline in the iodine number during regeneration and contacting periods.

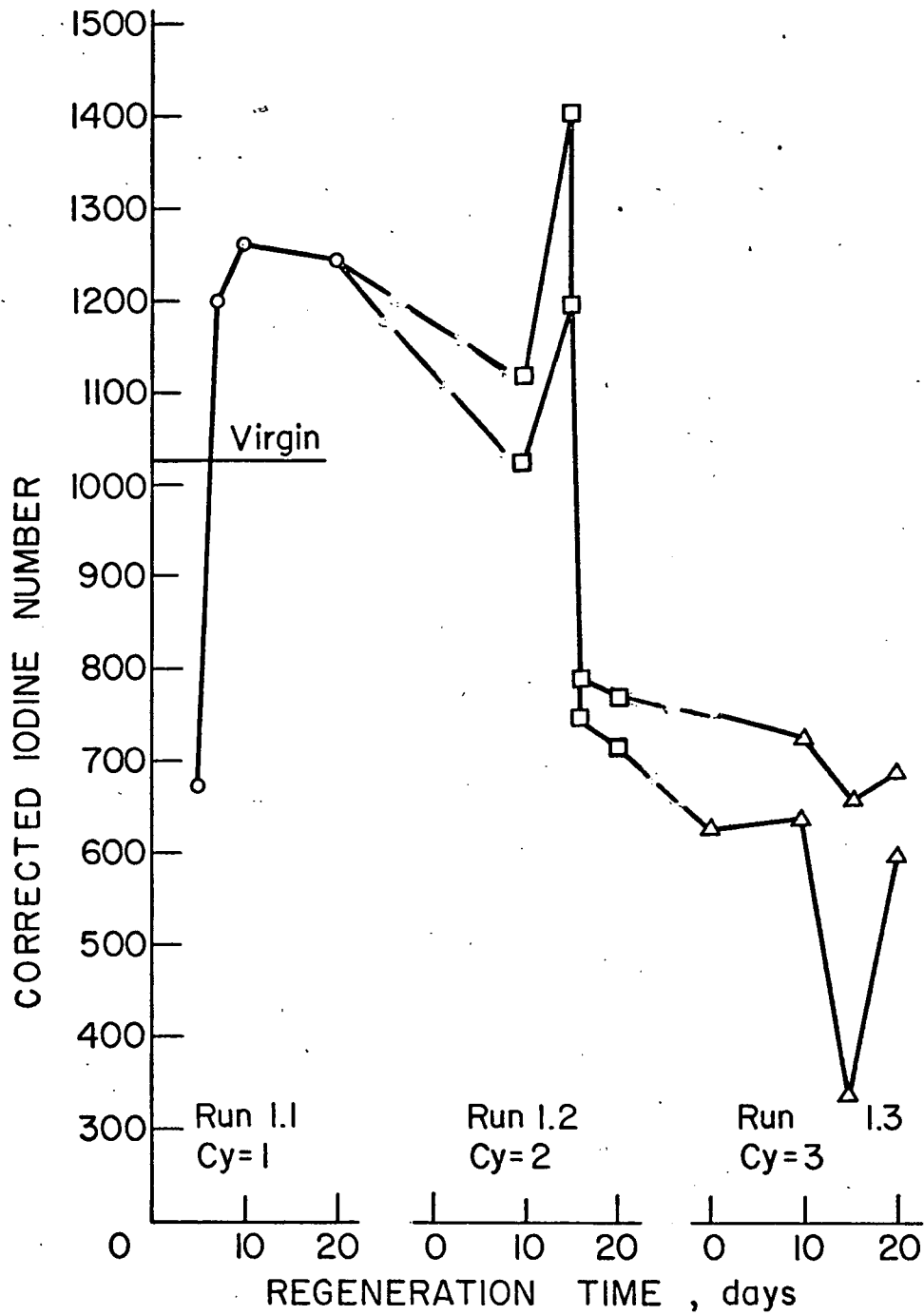


Fig. 18 Iodine Number vs. Regeneration Cycles, Run 1



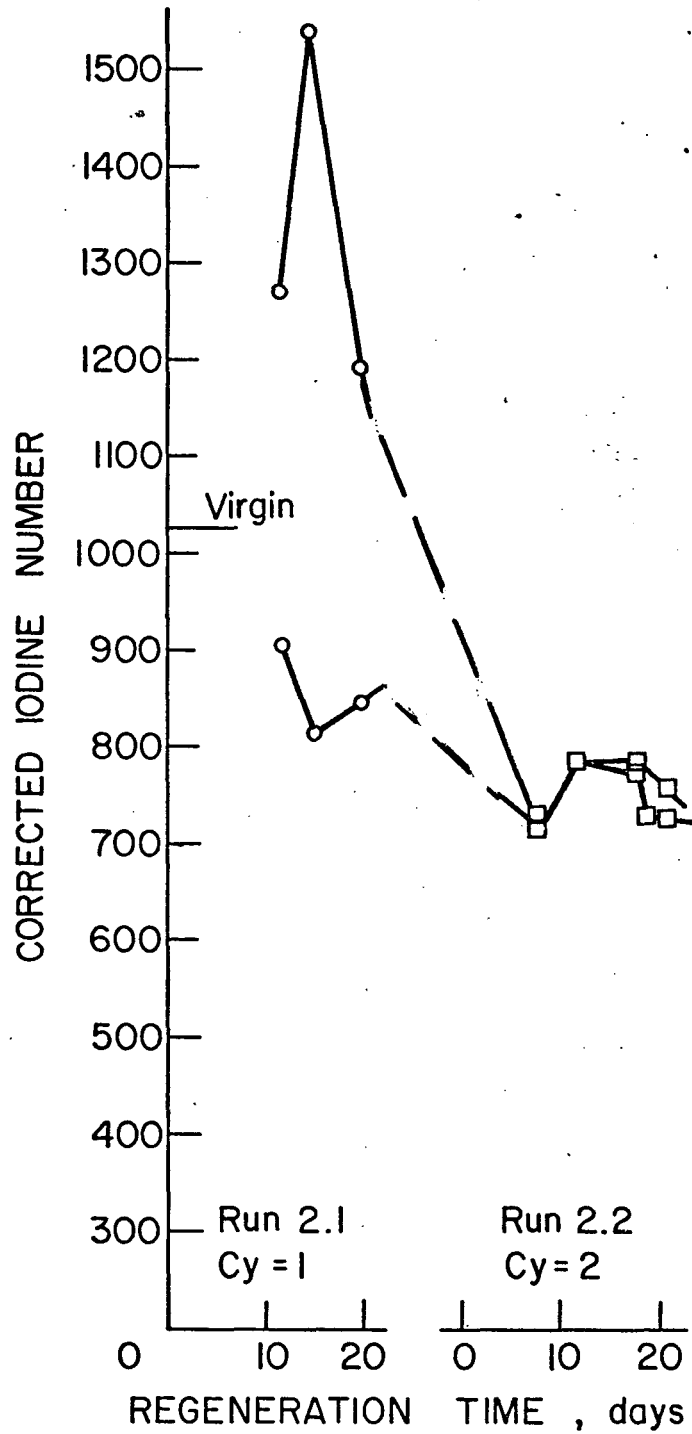


Fig. 19 Iodine Number vs. Regeneration Cycle, Run 2

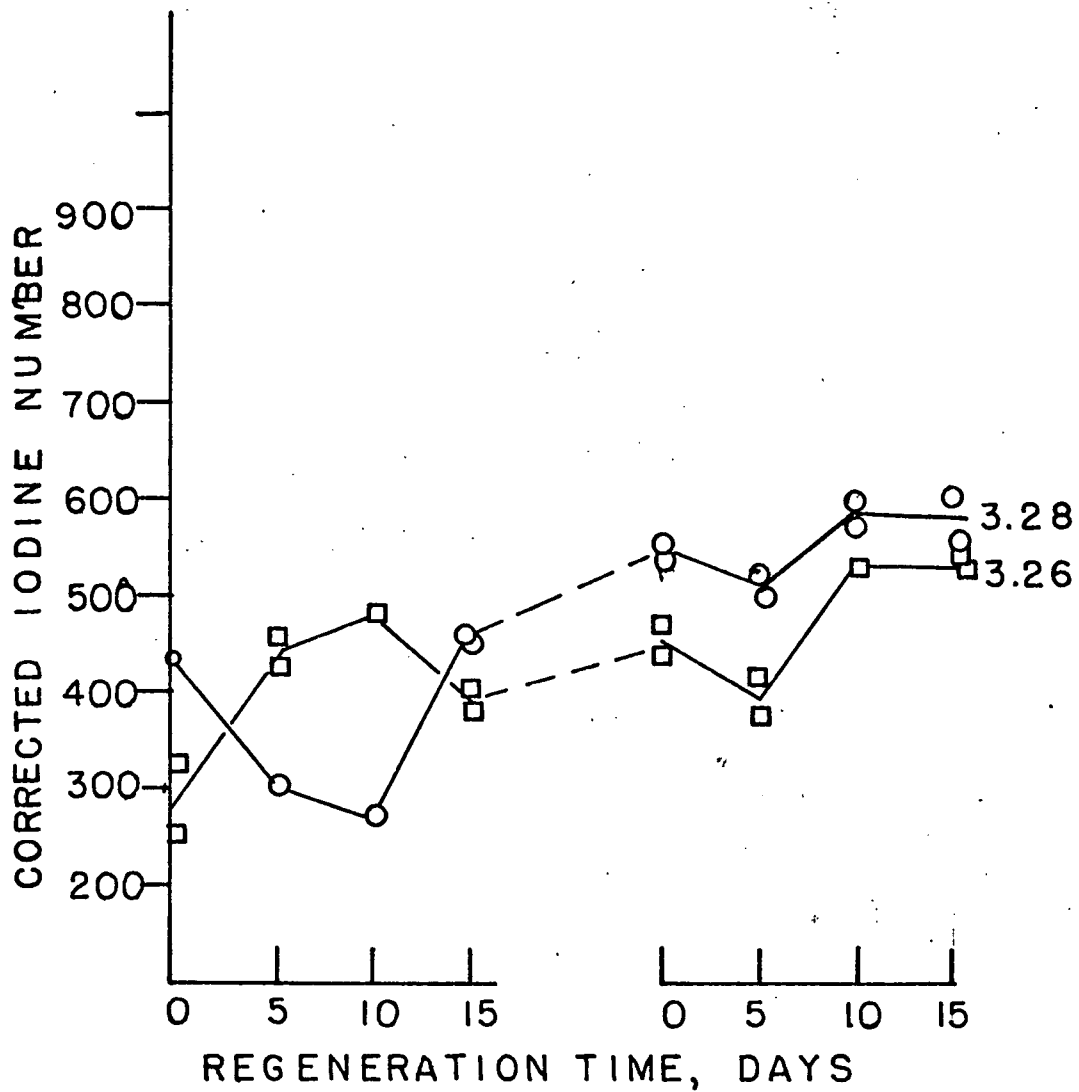


Fig. 20 Iodine Number vs Regeneration Cycles, Run 3

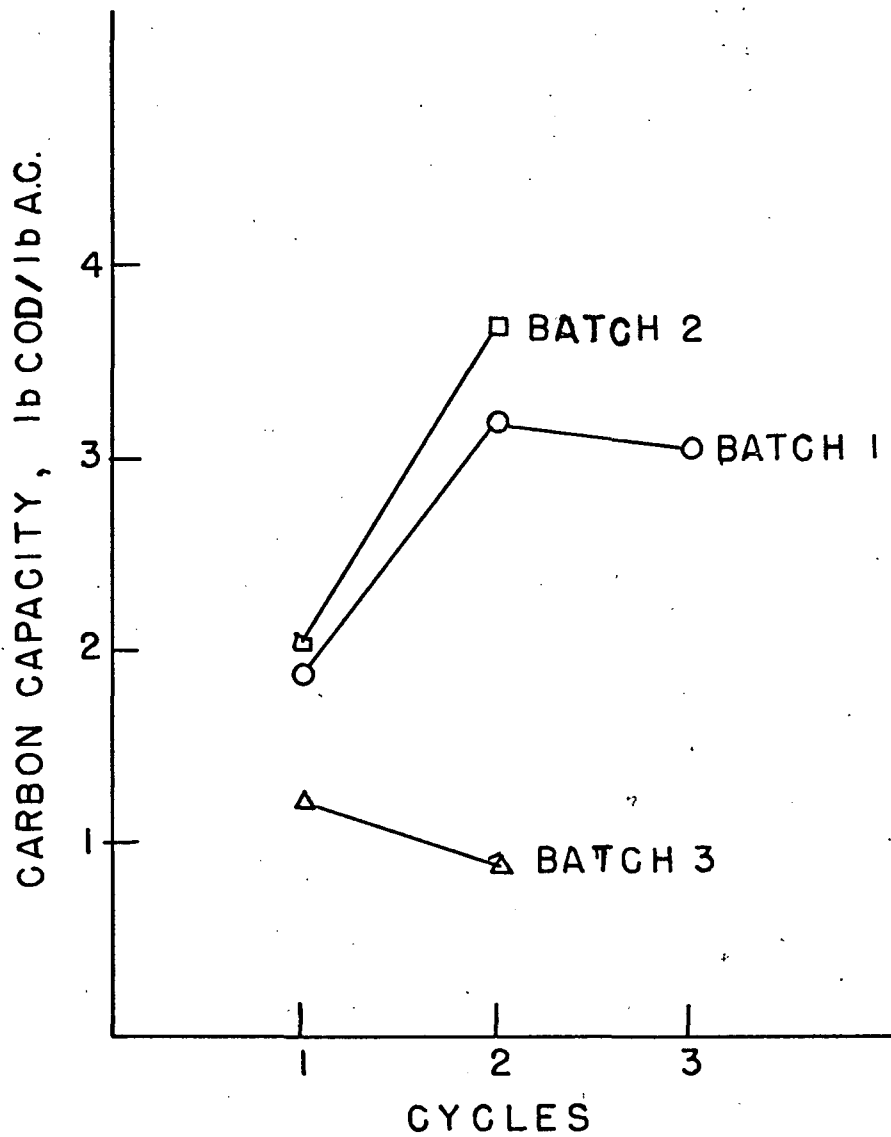


Fig. 21 Carbon Capacity vs Cycles

It was also interesting to compare the apparent rate of COD removal by the different batches of activated carbon. This was accomplished by determining the rate of COD removal for each run. The removal rate was an arithmetic average of the lbs of COD removed/lb of activated carbon per hour determined at each sampling period. This data (shown in Table 5) shows an increase of rate for the first two cycles of contacting and regeneration. Additional research using more cycles is needed to determine if this trend is continued.

TABLE 5  
APPARENT COD REMOVAL RATES

<u>RUN</u>	<u>IODINE NUMBER*</u>	<u>CAPACITY 1b COD/1b AC</u>	<u>CONTACT TIME (HR)</u>	<u>1b COD/1b AC/HR (x10<sup>-3</sup>)</u>
1.1	1132	1.87	466	4.013
1.2	810	3.19	392	8.138
1.3	745	3.07	486	6.317
2.1	870	2.00	348	5.747
2.2	775	3.65	435	8.390
3.10	435	1.49	285	5.228
3.20	638	.87	292	2.979

\*After 15 days regeneration

#### 4.4 EFFECT OF pH AND TEMPERATURE ON REGENERATION

The data shown in Fig. 16 and Fig. 17 for the variation in iodine number during regeneration when the pH was adjusted indicate very little effect of the change in pH.

Comparing the performance of the regeneration for carbon batches 1, 2 and 3 shown in Figs. 18 through 20 it can be seen that the iodine numbers are slightly lower at any given time for batch 3 with adjusted pH, compared to the first and second batches which had unadjusted pH. This is probably due to an accidental discharge of anhydrous hydrochloric acid into the laboratory which was previously mentioned. This accident reduced the virgin activated carbon iodine number to 315, a factor which was unknown until run 3 was underway.

Observations of the temperature dependency of the regeneration yield much the same conclusions as did the pH dependency observations. The condition of the activated carbon due to the accidental contact with the anhydrous hydrochloric acid probably was such a dominant factor that both temperature and pH effects were too small to be recognized.

#### 4.5 DISCUSSION OF RESULTS

One of the major problems that occurred in the analysis of the experimental results was that of separating COD removal due to adsorption and that due to biological metabolism. From Fig. 12, showing the COD removal vs. time of contacting, it is clear that there is a trend to remove additional COD as the contact period increases.

However this was not the main aspect of the research project. The research was addressed to the problem of using in situ biological regeneration of spent activated carbon. The initial use of COD adsorption isotherms to monitor regeneration performance was unsuccessful as was the subsequent use of iodine numbers.

It appears that neither standard laboratory determination will yield precise, reliable results. The only true indicator of how a biologically regenerated carbon will perform is to put it back into contacting service.

The mass of COD adsorbed per unit mass of carbon, the capacity, is a direct function of the equilibrium COD concentration in the solution after adsorption. Although the column operation was never at equilibrium, the same effect would be seen in that a higher influent COD concentration would result in more COD being removed.

In other words, the influent COD concentration is also a factor to consider when determining the activated carbon capacity to be used in design or discussions. With this consideration in mind, it can be seen that batch 1 and batch 2 had similar performances and indicated that as time progresses the COD removal increases. In all cases however, the influent COD increased from one cycle to the next, which would explain a portion of the increase in apparent capacity. Results from batch 3 are probably of little value due to the previously mentioned accidental contacting with anhydrous hydrochloric acid.

#### 4.6 ESTIMATED OPERATING COSTS FOR BIOLOGICAL REGENERATION SYSTEM

Patterson (26) has given procedures for estimating the operating and maintenance costs for wastewater treatment plants. The essentials of that procedure, as applied to activated carbon treatment, are given in Table 6. The assumptions used were: 1) adequate pumping for 1 MGD through the plant is necessary, 2) recirculation pumping for the regeneration process is at 30 feet of head at a flow rate of 0.000475 times the plant capacity, which was the operating conditions of the laboratory regeneration, 3) power costs 1.5¢/kwh, 4) aeration is accomplished by air compressors and 5) manpower requirements are the same as for typical conventional primary and secondary treatment plants with a typical hourly wage rate (1971) of \$3.68/hr.

This cost estimate given in Table 6 includes maintenance and operations personnel requirements, pumping costs and aeration costs. These are the only major costs involved in a plant of 1 MGD capacity. The total operating cost, 1971 dollars, is \$25,000 per year.

TABLE 6

## ANNUAL OPERATING AND MAINTENANCE COSTS FOR 1 MGD ACTIVATED CARBON PLANT

PUMPING includes upflow operations at 30 feet head, recirculation at  $4.7 \times 10^{-4}$  the plant capacity, power cost 1.5¢/kwh

ANNUAL OPERATING	450 manhours @ 3.68/hr	= 1656
MAINTENANCE	370 manhours @ 3.68/hr	= 1361
POWER	from Patterson charts	= 9000
OTHER MISC. COSTS	from Patterson charts	= 360
	PUMPING SUB-TOTAL	<u>\$12,377</u>

AERATION includes diffused air compressors and appurtenances, air supply at 0.2 cfm/33 gpm recirculation scaled up to 1 MGD plant, i.e., air rate of 420 cfm

ANNUAL OPERATING	1000 manhours @ 3.68/hr	= 3860
MAINTENANCE	490 manhours @ 3.68/hr	= 1803
POWER	from Patterson charts	= 5200
OTHER MISC. COSTS	from Patterson charts	= 2000
	AERATION SUB-TOTAL	<u>\$12,683</u>

ANNUAL OPERATING AND MAINTENANCE COSTS FOR 1 MGD PLANT \$25,060



#### 4.7 OPERATING DIFFICULTIES OF THE RESEARCH SYSTEM

As with almost all experimental apparatus, there were operating problems during the research program. This section is included as a guide to future research and also as a guide to future design of pilot plant or large scale installations. Operational problems of the system can be characterized in three areas: mechanical, contacting and regeneration.

Various sorts of mechanical difficulties were initially encountered at both the laboratory where the regeneration occurred and at the treatment plant. In particular, the nature of the wastewaters processed and the generally corrosive atmosphere encountered at the research installation, (e.g., high humidity, little air circulation, and occasional hydrogen sulfide) present very harsh corrosion conditions. It has been recommended that as far as possible, all materials be plastic since very satisfactory performance was encountered with this material for piping and plumbing fittings. Brass, stainless steel, and monel metal are also useful and relatively maintenance free.

Some problems were encountered due to inadequate flushing of thread tape and excess thread materials from the system after initial fabrication. A thorough flushing is recommended. Adequate positive suction head on all pumps was also most helpful. In the air supplies and connections to hydraulic systems, check valves or equivalent protection are mandatory to prevent back-flooding of the rotameters, pressure gages and pressure reducing valves when the air compressor is inoperative, such as when the power is off. An inexpensive replacement for check valves is the routing of the air hoses to an elevation higher than the

uppermost fluid level and thence immediately to the hydraulic apparatus. Utilization of clear Tygon tubing also facilitated visual observation of water in air lines, indicating mechanical failures of the air system.

Lip shaft-seal failures on the supply pumps were encountered after continued operation at the maximum rated pressure due to scour by fines transported along in the wastewater stream. The operation of the dual-media filter reduced this erosion, but it has still continued at a slow rate. Another operational technique that was found beneficial was the immediate flushing of the piping system when the operations of the system were halted for testing and repairs. Following flushing, filling the system with tap water prevented subsequent scaling of the piping and valves which allowed rapid start-up of the system after testing or repairs were completed.

Incipient fluidization was the initial flow regime goal. This was found difficult to achieve. Complete fluidization was far easier to effect. It should be noted that relatively high head losses between the influent distribution manifold and the carbon columns was mandatory to achieve stable and even distribution of flow between the two columns. This was obtained by installation of flow control devices<sup>a</sup> and Teflon coated ball valves on the feed line from the manifold for each column.

At only one time did filamentous slime growths plague the operations of the system and this was encountered only for a period of about a week. Attendant with the slime growth was an infestation

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<sup>a</sup>DOLE flow controllers

of nemotode worms. The combination of these two organisms constituted a major system failure due to severe clogging and agglomeration of the carbon beds. This problem was only encountered one time and is unexplained since no further problems were encountered.

A further work about operations with plexi-glass columns. Do not attempt to relieve channeling and bed separation by tapping the column, such as would be done with the butt end of a screwdriver. This non-recommended procedure on one occasion led to a massive column failure when the entire sidewall of the column fractured into many pieces.

As in contacting operations, incipient fluidization was difficult to achieve during regeneration with the equipment at hand. It was far easier to operate in a fluidized mode. Once fluidized there was never any problem with the recirculation pumps, flow distribution or bed agglomerations.

## 5 CONCLUSIONS AND RECOMMENDATIONS

Research was conducted to determine the feasibility of using in situ biological activity to regenerate the activated carbon used in upflow columns that had been contacted with final effluent from an overloaded conventional high rate trickling filter plant at Bethlehem, Pennsylvania.

Results indicate that regenerating the carbon columns, in an upflow mode, with recirculating water which was saturated with dissolved oxygen, allowed at least three cycles of operation, each cycle consisting of contacting and subsequent regeneration. The data does not allow differentiation between the COD removal by adsorption and that removed by biological activity during contact service. However, the very high total removals indicate a great potential increase in the design capacity to be used in treatment processes with activated carbon.

Temperature and pH effects upon regeneration were studied with run 3. However these results are of doubtful value due to the accidental contacting of anhydrous hydrochloric acid prior to initial contacting.

Costs for a regeneration system similar to that used in this research were estimated using an approach suggested by the Environmental Protection Agency. Operating and maintenance costs for a 1 MGD plant were estimated to be \$25,000 annually.

The following recommendations have been made in order to further define the operating parameters for biological regeneration systems.

1. The process should also be used to investigate the contact and regeneration performance when treating a high quality secondary treatment plant effluent.
2. The biological regeneration process should be carried out with one batch of carbon for extended periods of time, up to 10 cycles, to determine long term performance of the activated carbon. Preferably this system should be designed to give a high level of effluent quality similar to that which would be required in a full scale advanced waste treatment facility.
3. A future pilot scale operation of about 0.5 MGD should be planned.
4. In order to investigate the extent of biological activity in the columns during contacting it is recommended that a continuous mode of operation should be investigated.
5. An analysis should be carried out to determine an optimum system configuration. Parameters to be investigated should include life of carbon in extended use, idle carbon inventory, contactor volumes, regeneration volumes, thermal regeneration volumes (if necessary), number and capacity of standby units, vessel size and number and flow scheme (parallel vs series).

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APPENDIX

TABLE 7 RAW COD DATA  
RUN 1.1

<u>INFLUENT COD</u> (mg/l)	<u>EFFLUENT COD</u> (mg/l)	<u>TIME (HRS)</u>
5.660	5.031	12.000
83.438	11.447	48.900
43.941	46.541	72.000
29.319	11.937	96.000
33.298	33.298	108.000
29.948	15.288	120.000
34.450	23.037	132.000
65.455	37.980	144.000
41.616	56.566	166.000
44.848	42.828	178.000
58.586	34.747	190.000
52.684	35.785	202.000
28.827	42.545	214.000
57.455	22.664	226.000
42.942	44.930	250.000
50.898	35.729	274.000
26.747	47.106	286.000
42.116	30.938	298.000
54.890	47.705	310.000
50.891	36.832	322.000
43.960	39.208	334.000
70.495	39.604	346.000
51.089	61.782	358.000
48.473	40.326	370.000
30.550	26.069	382.000
37.067	37.475	394.000
16.701	26.884	418.000
37.817	18.324	442.000
28.070	36.647	454.000
33.918	23.782	466.000

TABLE 7 (CONTINUED)

RUN 1.2

<u>INFLUENT COD</u>	<u>EFFLUENT COD</u>	<u>TIME (HRS)</u>
(mg/l)	(mg/l)	
118.376	55.128	24.000
137.179	81.624	48.000
151.709	107.692	86.000
116.239	89.957	96.000
176.068	126.923	120.000
220.085	176.923	144.000
190.171	165.385	168.000
196.581	200.855	192.000
345.455	345.455	268.000
280.000	264.545	288.000
208.182	239.091	312.000
275.455	221.818	336.000
127.193	198.465	417.000
105.263	109.649	432.000
155.702	142.544	456.000
196.272	206.140	486.000

RUN 1.3

<u>INFLUENT COD</u>	<u>EFFLUENT COD</u>	<u>TIME (HRS)</u>
(mg/l)	(mg/l)	
215.605	190.775	24.000
216.236	60.148	48.000
144.280	74.170	72.000
54.511	78.947	96.000
216.165	157.519	117.000
83.459	99.248	143.000
132.707	139.098	166.000
226.389	120.139	190.000
164.931	106.250	262.000
171.181	143.750	284.000
68.056	79.861	310.000
135.431	94.796	338.000
184.015	213.011	373.000
172.119	212.268	392.000

TABLE 7 (CONTINUED)  
RUN 2.1

<u>INFLUENT COD</u> (mg/l)	<u>EFFLUENT COD</u> (mg/l)	<u>TIME (HRS)</u>
51.626	.203	18.000
50.813	.203	41.000
51.626	.203	65.000
49.187	28.049	89.000
48.413	10.317	111.000
47.222	15.079	137.000
31.349	46.032	168.000
66.270	49.206	185.000
72.472	61.049	209.000
75.468	50.375	233.000
73.596	45.506	255.000
71.723	40.262	348.000

RUN 2.2

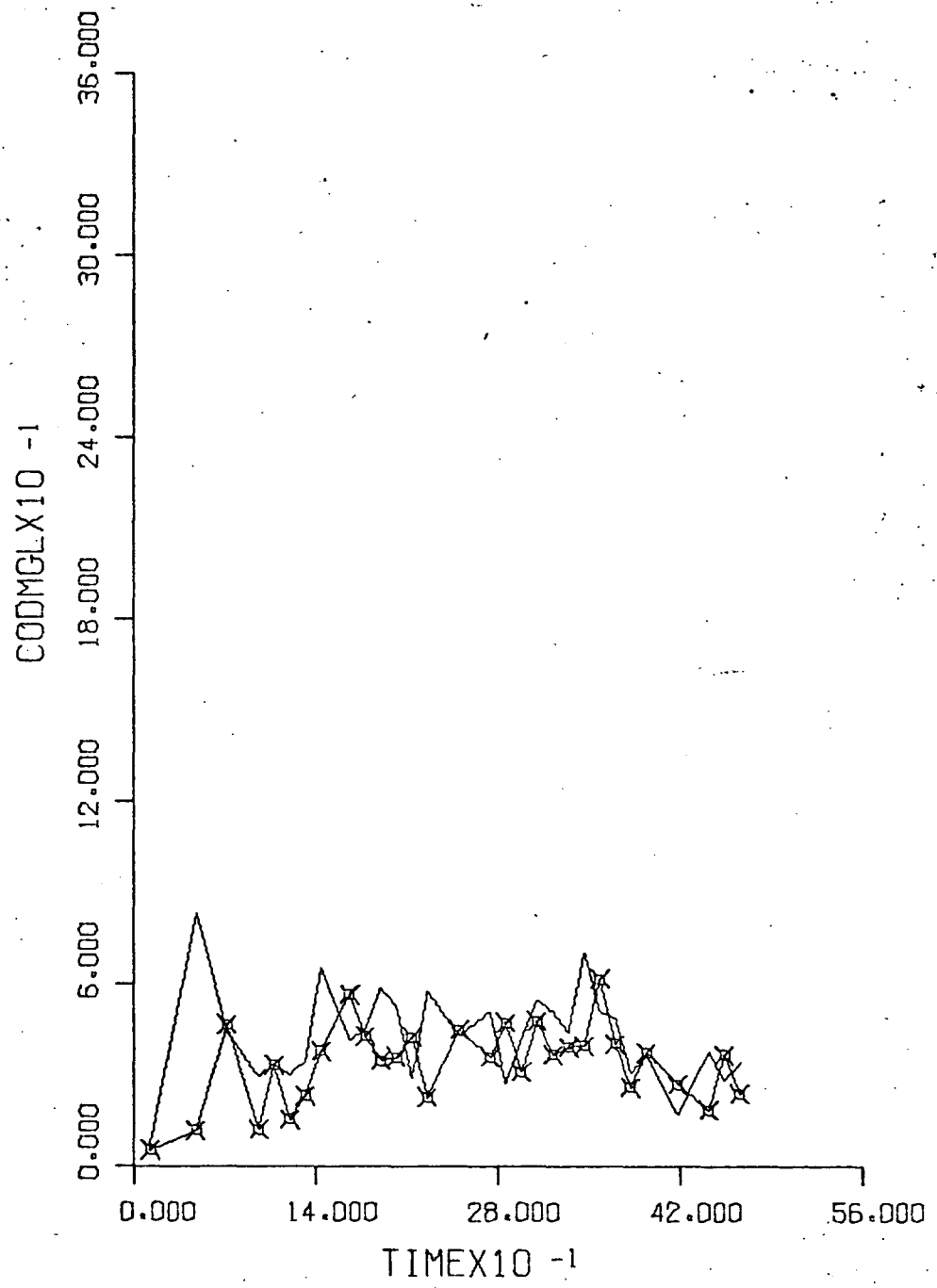
<u>INFLUENT COD</u> (mg/l)	<u>EFFLUENT COD</u> (mg/l)	<u>TIME (HRS)</u>
193.066	62.409	72.000
151.460	58.029	80.000
212.409	125.547	93.000
240.511	218.248	117.000
217.544	178.509	142.000
188.596	116.667	165.000
154.825	147.368	189.000
124.561	92.982	213.000
196.983	253.448	237.000
244.397	222.845	262.000
217.672	259.483	285.000
205.603	213.362	309.000
147.303	131.535	357.000
120.747	157.676	381.000
122.650	35.897	405.000
117.094	48.718	435.000

TABLE 7 (CONTINUED)  
 RUN 3.1

<u>INFLUENT COD</u> (mg/l)	<u>EFFLUENT COD</u> (mg/l)	<u>TIME (HRS)</u>
108.566	101.594	22.000
50.797	1.992	43.000
107.570	51.793	66.000
72.709	64.741	88.000
129.149	79.876	119.000
17.635	10.373	138.000
95.436	106.846	169.000
84.025	72.614	185.000
74.689	59.647	218.000
151.452	79.357	243.000
98.548	87.137	263.000
128.631	109.959	285.000

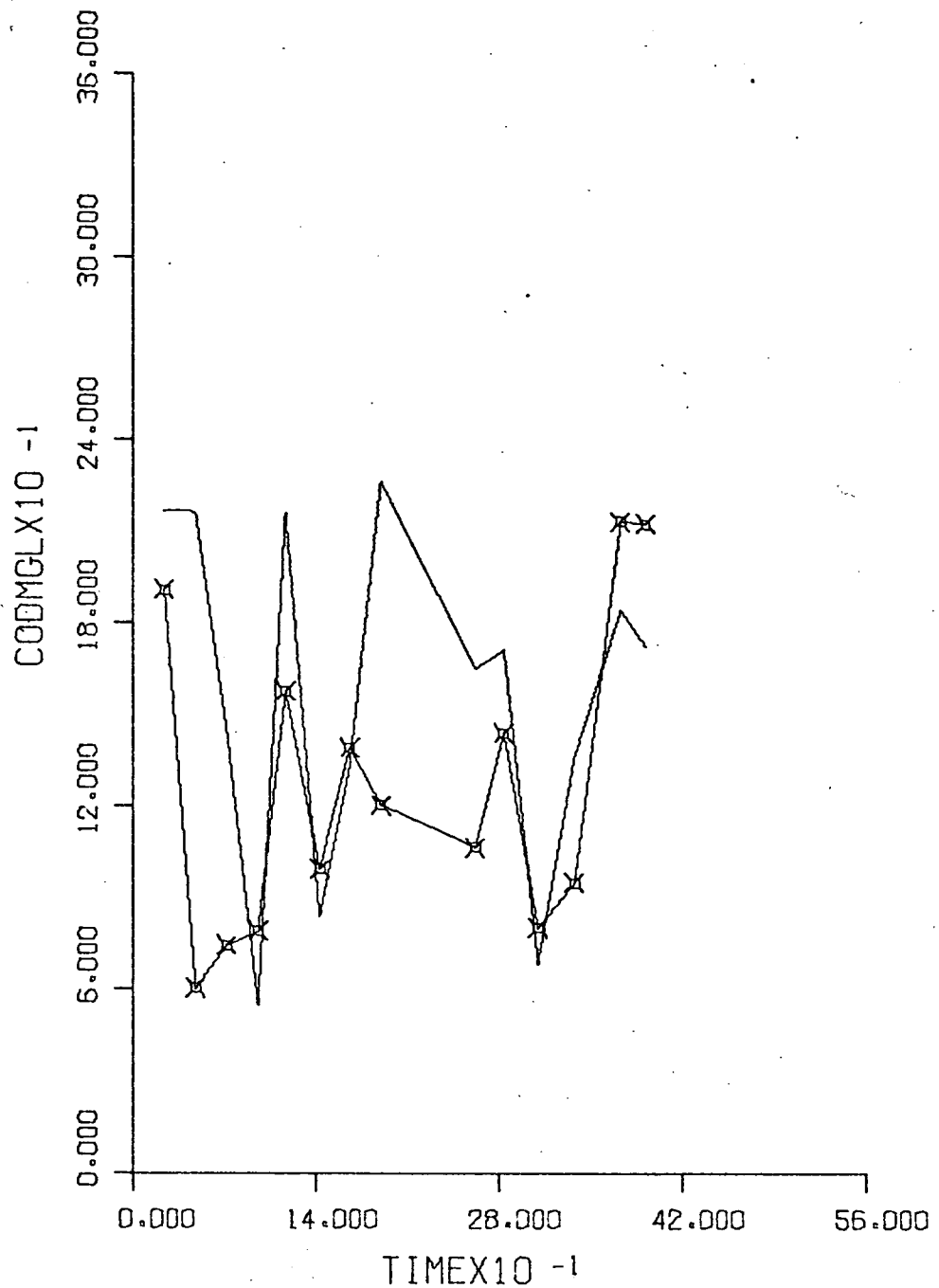
RUN 3.2

<u>INFLUENT COD</u> (mg/l)	<u>EFFLUENT COD</u> (mg/l)	<u>TIME (HRS)</u>
207.819	200.617	24.000
184.418	183.432	49.000
140.039	117.357	73.000
58.185	46.351	96.000
189.349	159.763	120.000
107.495	104.536	144.000
209.684	194.618	168.000
185.786	142.664	240.000
189.010	149.552	292.000



INFL AND EFFL COD VS TIME

RUN 1.1  
 Fig. 22

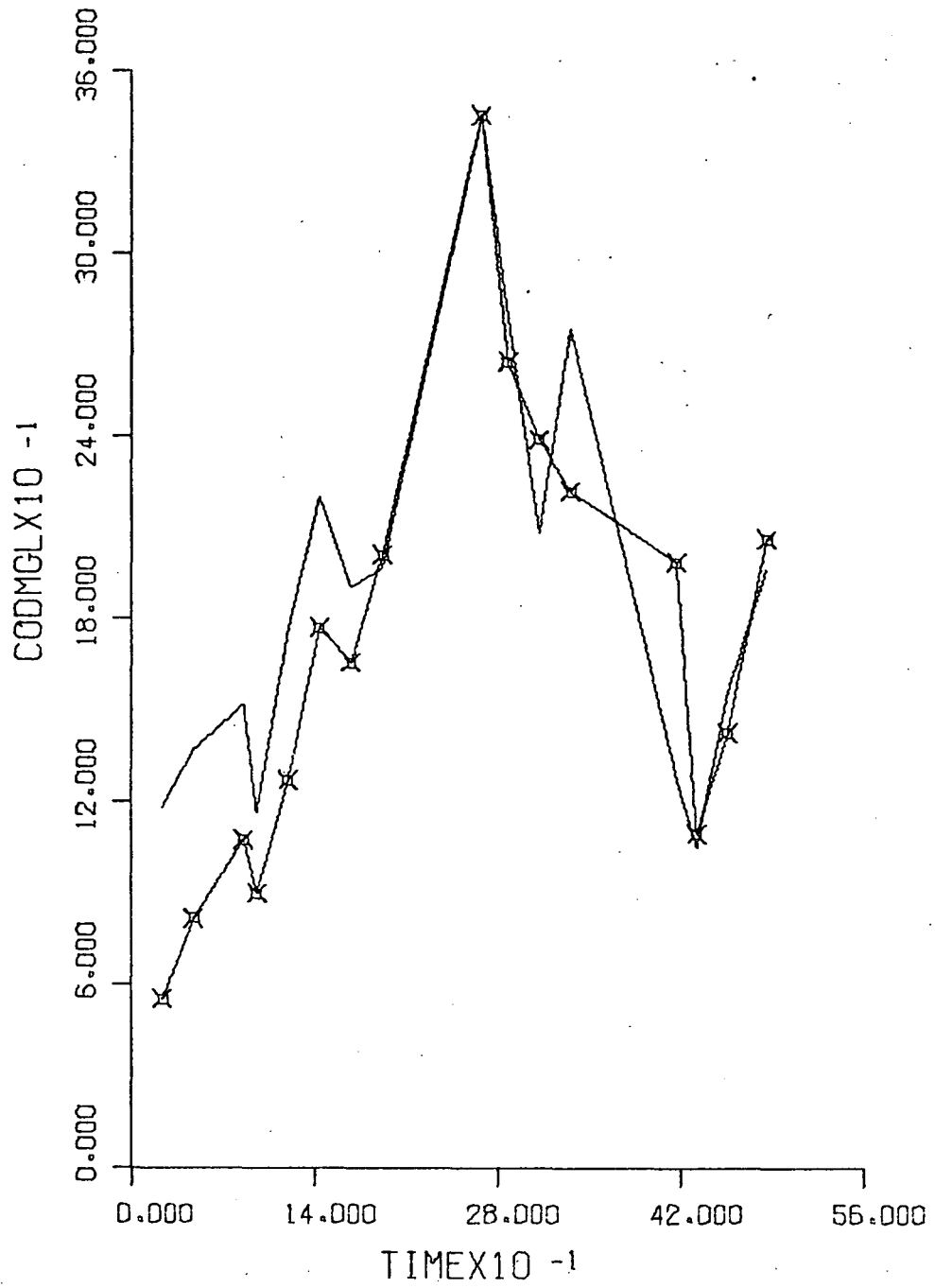


INFL AND EFFL COD VS TIME

RUN 1.2

Fig. 23

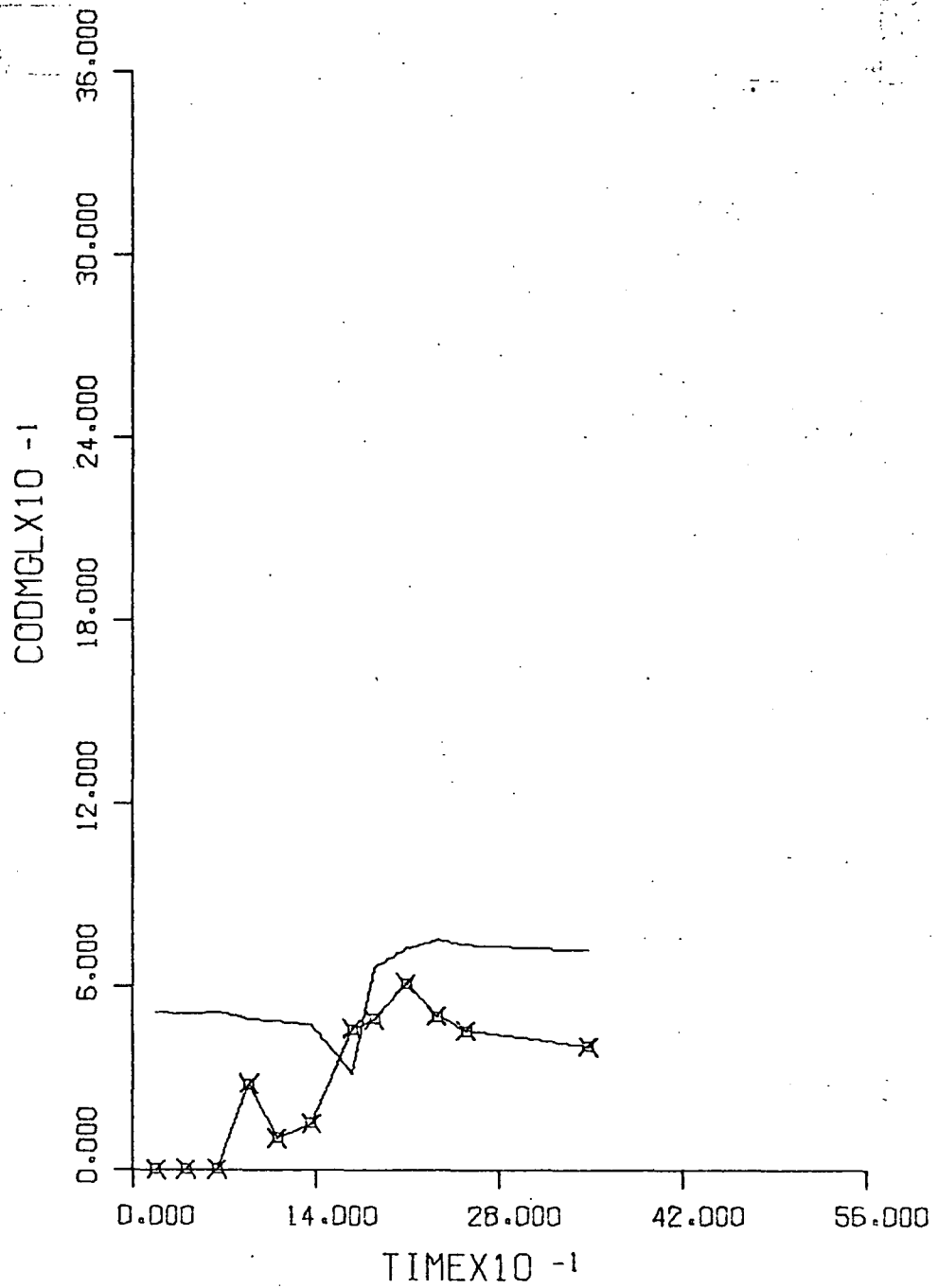




INFL AND EFFL COD VS TIME

RUN 1.3

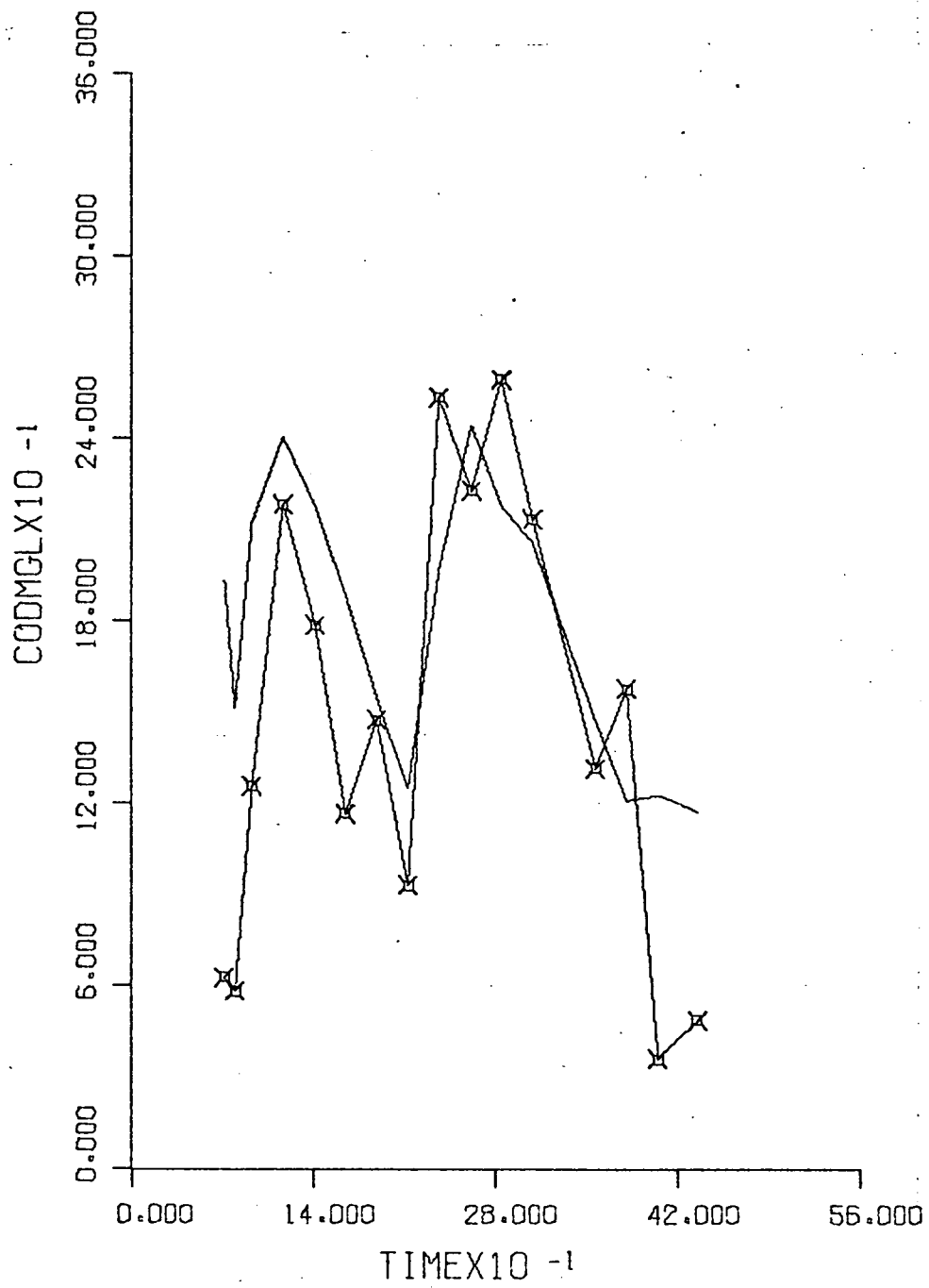
Fig. 24



INFL AND EFFL COD VS TIME

RUN 2.1

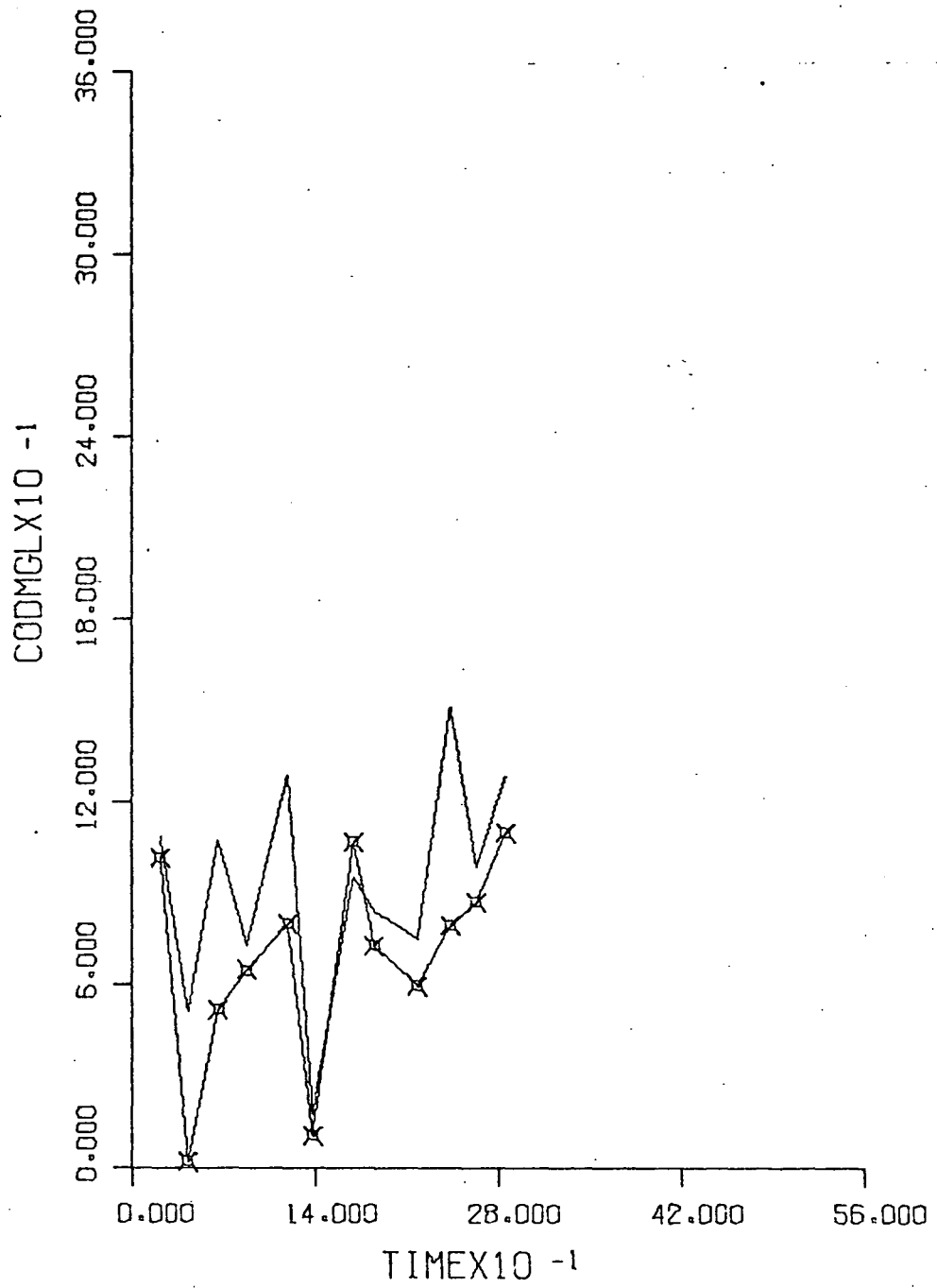
Fig. 25



INFL AND EFFL COD VS TIME

RUN 2.2

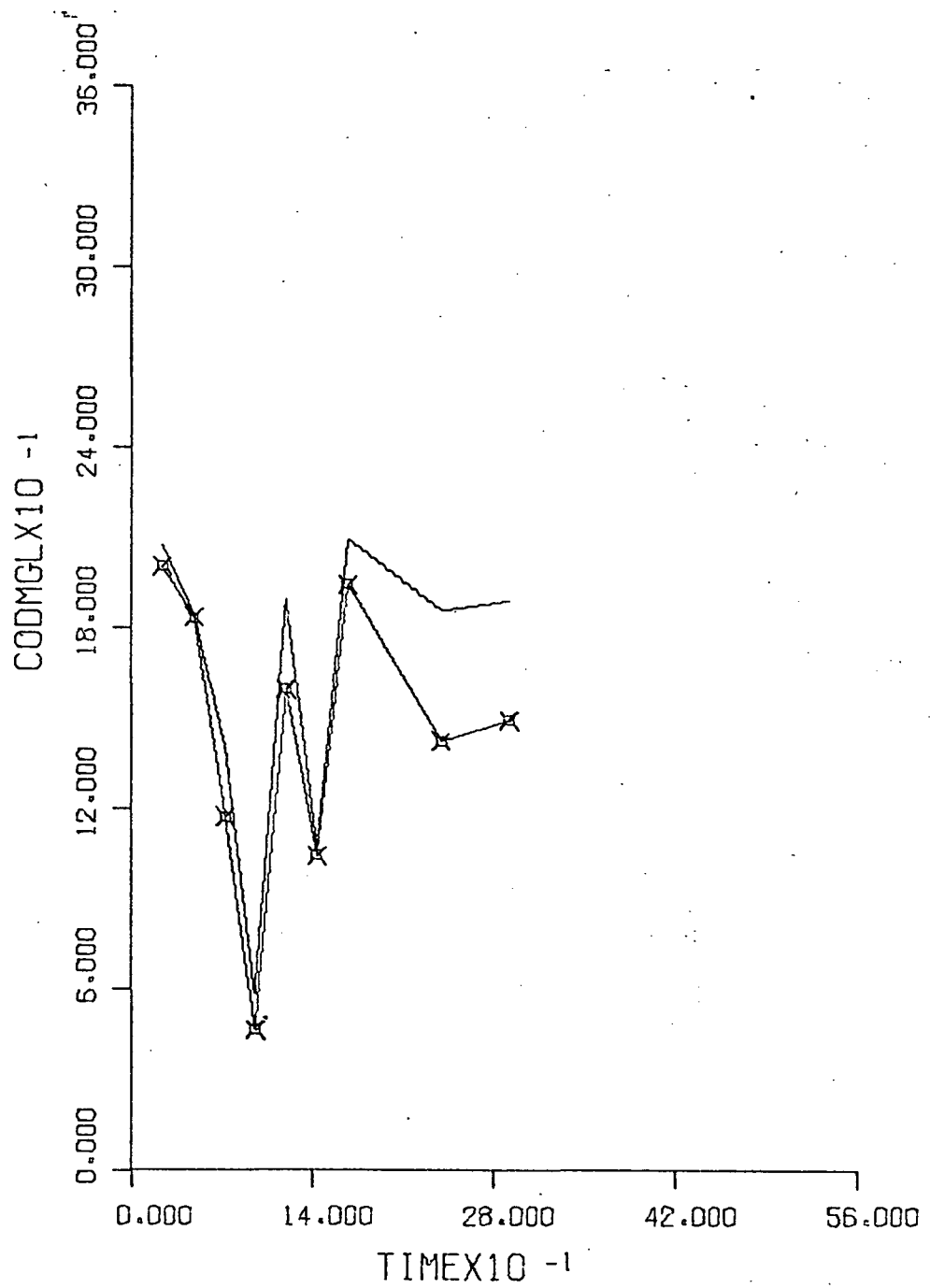
Fig. 26



INFL AND EFFL COD VS TIME

RUN 3.1

Fig. 27



INFL AND EFFL COD VS TIME

RUN 3.2

Fig. 28

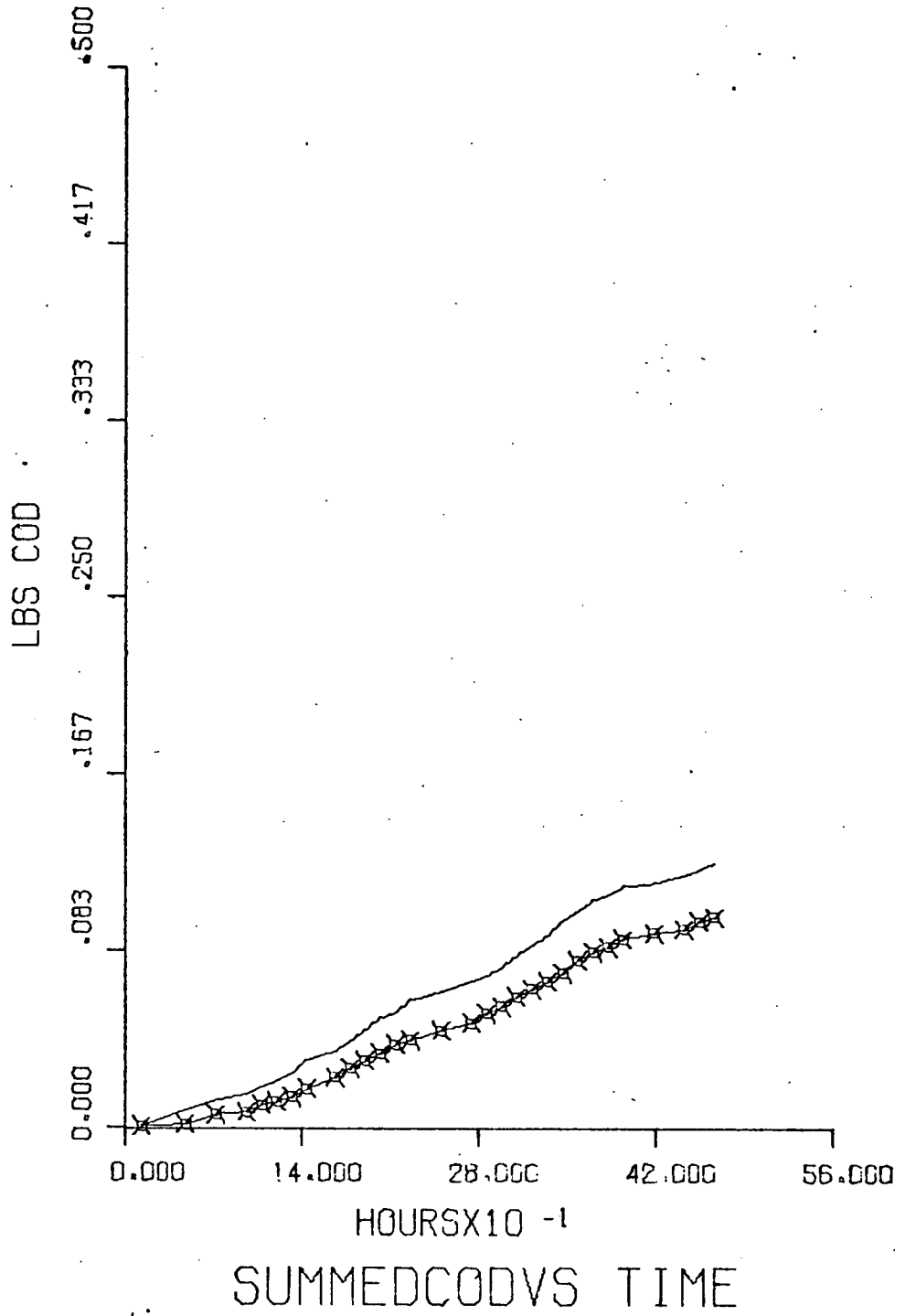
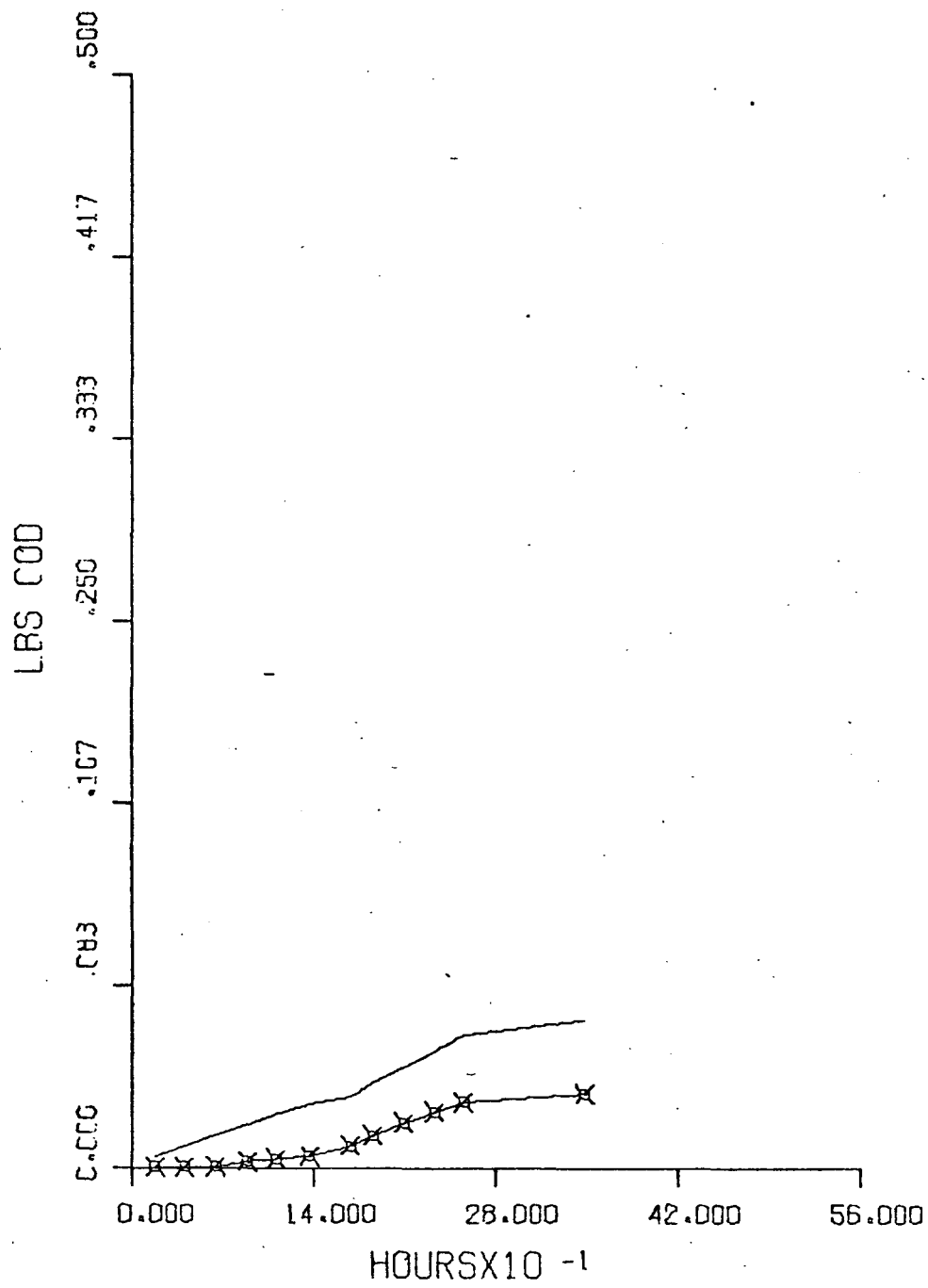


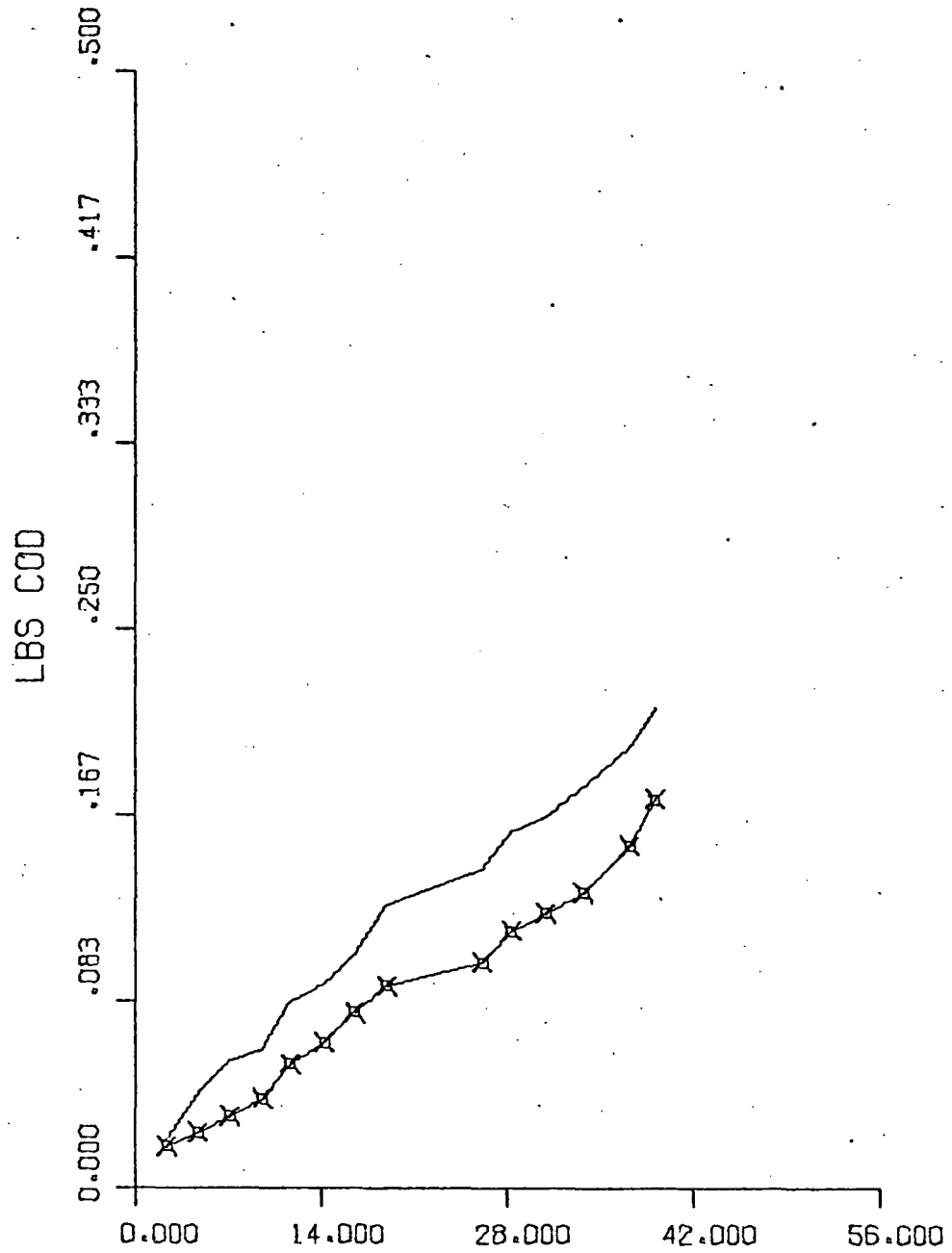
Fig. 29 Summed COD Vs Time, Run 1.1



SUMMEDCODVS TIME

RUN 1.2

Fig. 30

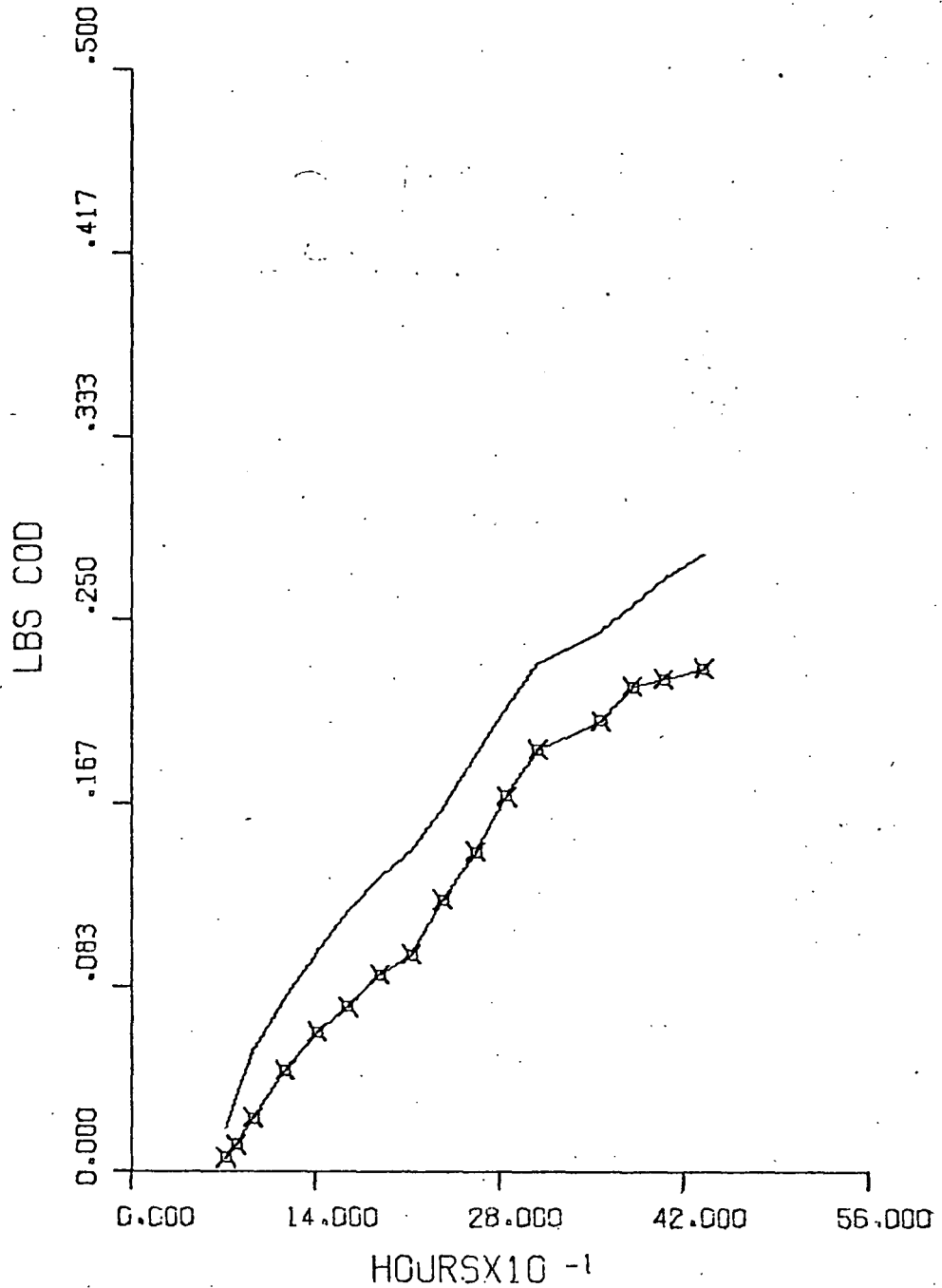


SUMMEDCODVS TIME

RUN 1.3

Fig. 31

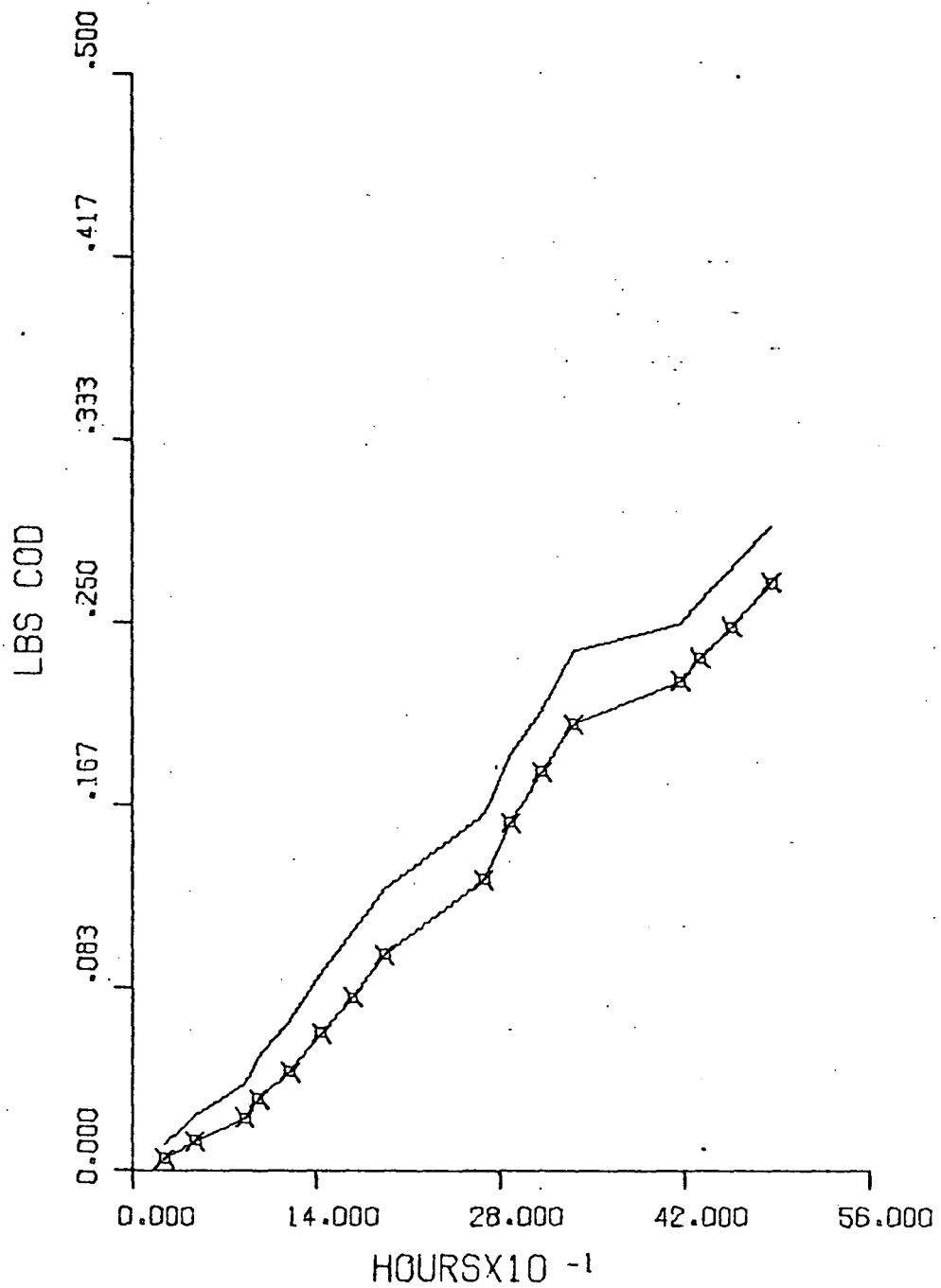




SUMMEDCODVS TIME

RUN 2.1

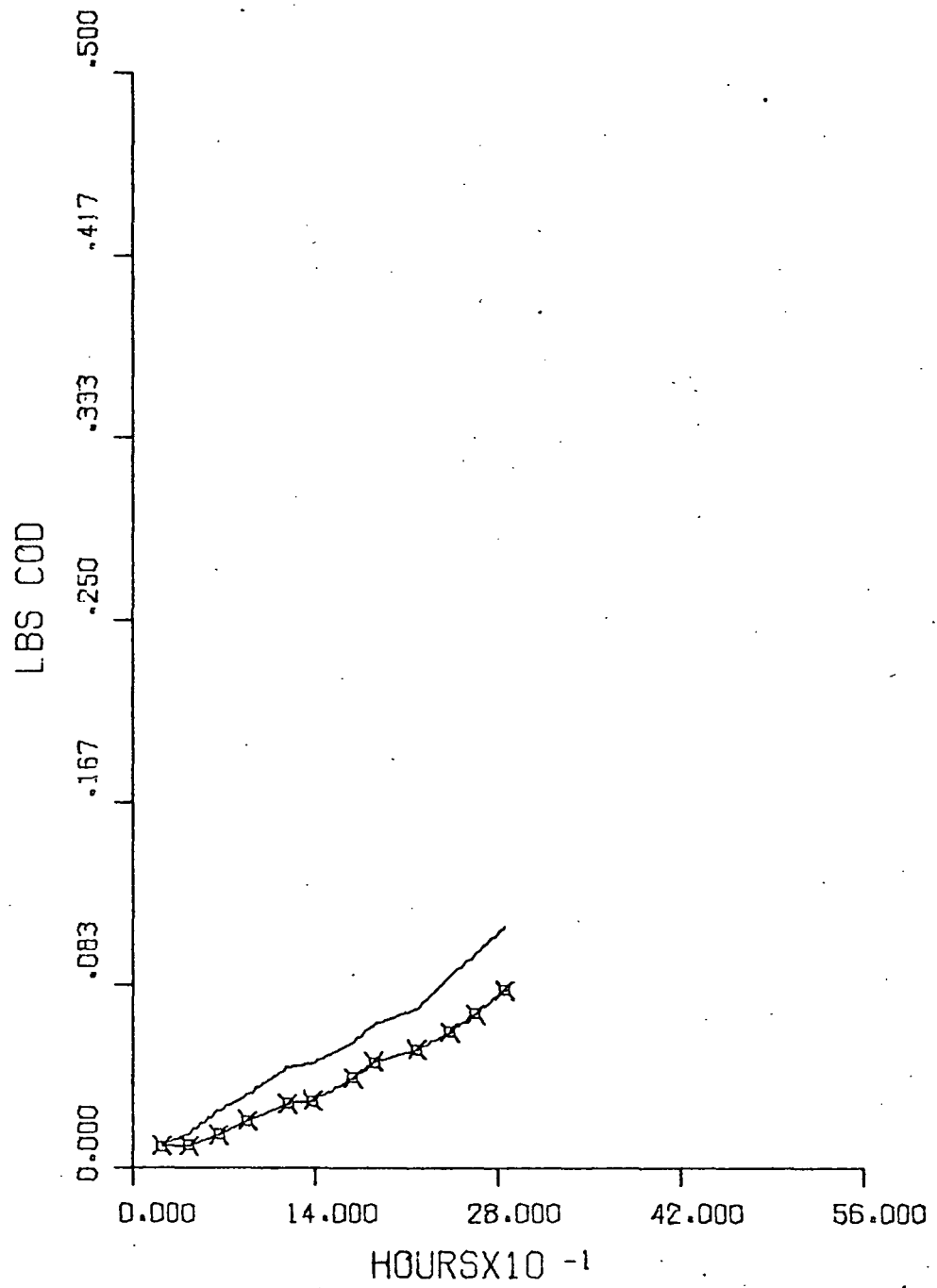
Fig. 32



SUMMEDCODVS TIME

RUN 2.2

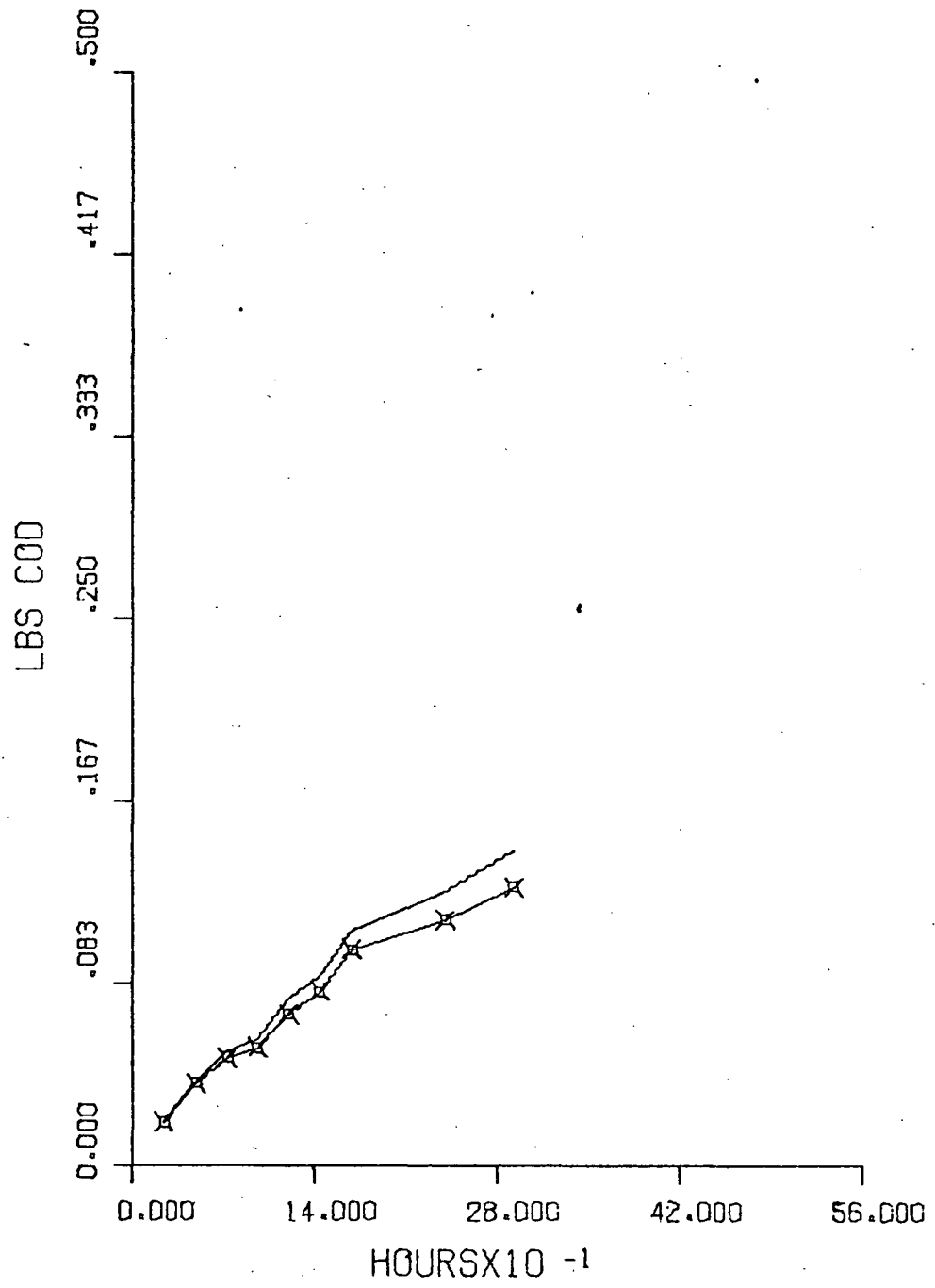
Fig. 33



SUMMEDCODVS TIME

RUN 3.1

Fig. 34



SUMMEDCODVS TIME

RUN 3.2

Fig. 35

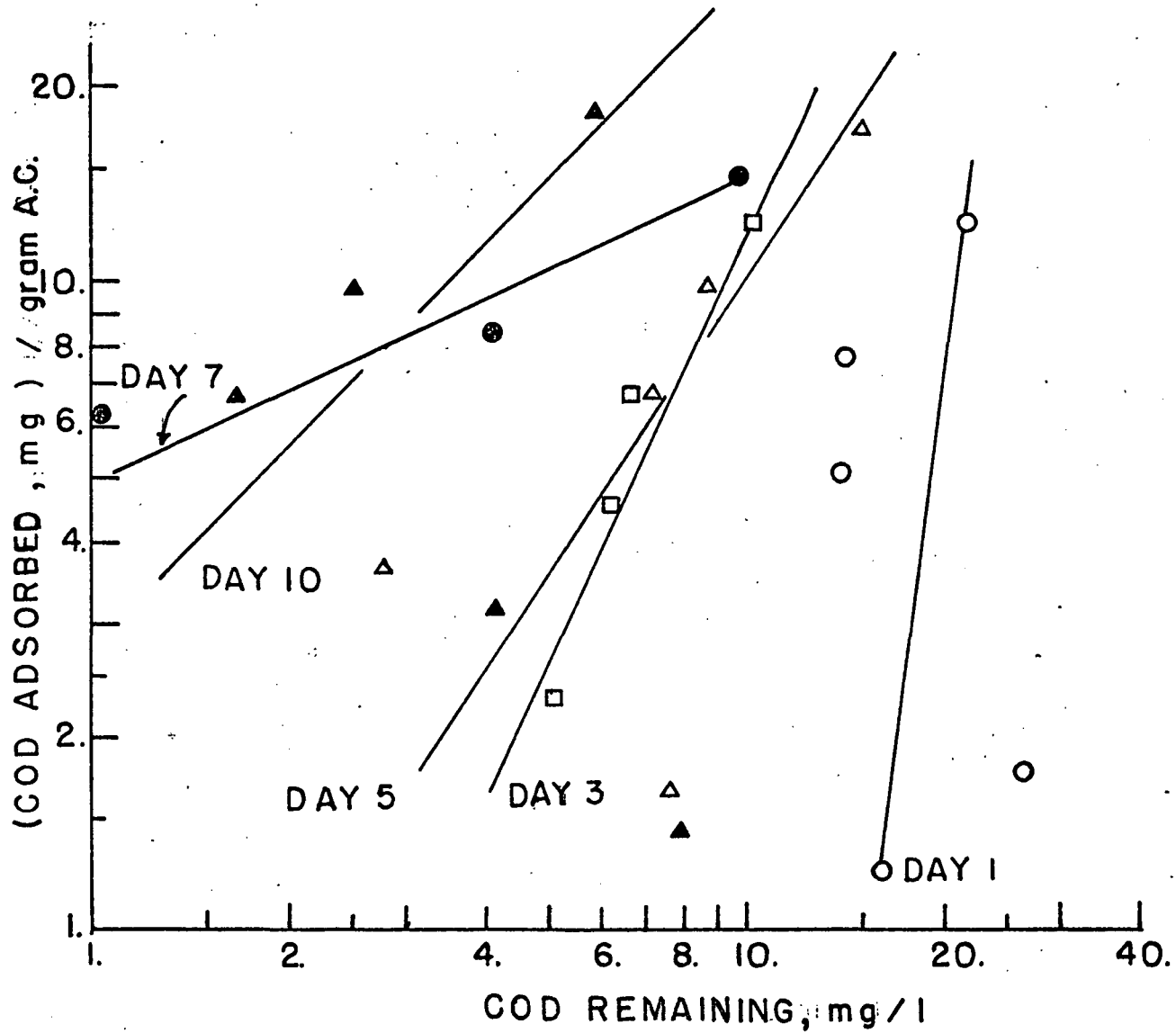


Fig. 36 COD Adsorption Isotherms, Run 1.1

TABLE 8  
RAW IODINE NUMBERS

<u>RUN</u>	<u>TEMP</u>	<u>ELAPSED TIME (HOURS)</u>	<u>pH</u>	<u>IODINE NUMBER</u>
1.1	0.000	5.000	0.000	728.878
1.1	0.000	7.000	0.000	1089.645
1.1	0.000	0.000	0.000	1132.072
1.1	0.000	0.000	0.000	1124.169
2.1	30.000	.600	0.000	1132.072
2.1	30.000	.600	0.000	1201.093
2.1	30.000	456.000	0.000	1110.997
2.1	30.000	288.000	0.000	904.292
2.1	30.000	360.000	0.000	844.833
2.1	30.000	480.000	0.000	870.315
1.2	31.000	240.000	0.000	1050.406
1.2	30.000	360.000	0.000	1082.018
1.2	30.000	360.000	0.000	1113.631
1.2	30.000	240.000	0.000	1125.140
1.2	30.000	336.000	0.000	789.620
1.2	30.000	360.000	0.000	827.844
1.2	30.000	480.000	0.000	768.385
1.2	30.000	480.000	0.000	810.856
2.2	29.000	192.000	-0.000	779.505
2.2	29.000	192.000	-0.000	770.979
2.2	29.000	288.000	-0.000	826.402
2.2	29.000	288.000	-0.000	822.138
2.2	29.000	352.000	-0.000	822.138
2.2	29.000	352.000	-0.000	820.007
2.2	29.000	376.000	-0.000	779.505
2.2	29.000	376.000	-0.000	830.665
2.2	29.000	424.000	-0.000	796.558
2.2	29.000	424.000	-0.000	775.242
1.3	25.000	0.000	0.000	800.822
1.3	25.000	0.000	0.000	677.186
1.3	30.000	240.000	0.000	694.239
1.3	30.000	240.000	0.000	775.242
1.3	28.000	360.000	0.000	365.965
1.3	28.000	360.000	0.000	711.292
1.3	28.000	480.000	0.000	651.606
1.3	28.000	480.000	0.000	745.399

NOTE: pH 0.0 or -0.0 indicates ambient conditions

TABLE 8  
(CONTINUED)

<u>RUN</u>	<u>TEMP</u>	<u>ELAPSED TIME (HOURS)</u>	<u>pH</u>	<u>IODINE NUMBER</u>
3.1	30.000	0.000	8.000	482.000
3.1	30.000	0.000	8.000	482.000
3.1	30.000	120.000	8.000	332.637
3.1	30.000	120.000	8.000	332.637
3.1	30.000	240.000	8.000	288.977
3.1	30.000	240.000	8.000	296.555
3.1	30.000	360.000	8.000	491.400
3.1	30.000	360.000	8.000	472.349
3.1	30.000	0.000	6.000	359.505
3.1	30.000	0.000	6.000	273.437
3.1	30.000	120.000	6.000	472.349
3.1	30.000	120.000	6.000	486.731
3.1	30.000	240.000	6.000	530.848
3.1	30.000	240.000	6.000	530.848
3.1	30.000	360.000	6.000	422.395
3.1	30.000	360.000	6.000	438.383
3.2	40.000	0.000	6.000	587.174
3.2	40.000	0.000	6.000	597.261
3.2	40.000	120.000	6.000	535.310
3.2	40.000	120.000	6.000	573.193
3.2	40.000	240.000	6.000	662.364
3.2	40.000	240.000	6.000	637.344
3.2	30.000	360.000	6.000	654.272
3.2	30.000	360.000	6.000	596.849
3.2	30.000	0.000	8.000	501.573
3.2	30.000	0.000	8.000	464.261
3.2	30.000	120.000	8.000	454.307
3.2	30.000	120.000	8.000	405.995
3.2	30.000	240.000	8.000	644.522
3.2	30.000	240.000	8.000	581.453
3.2	30.000	360.000	8.000	620.888
3.2	30.000	360.000	8.000	638.795

## VITA

Robert Sugden Sturgis was born 6 July 1949 in Woodbury, New Jersey, U.S.A. He grew up in Greenwich, Connecticut, a suburb of New York City. He graduated from the Stamford Connecticut High School system in the top 20 of his class.

His undergraduate studies were in the field of Mechanical Engineering. He received a Bachelor of Science in Mechanical Engineering from Lehigh University in June 1971.

Following two years of graduate study he received a Masters of Science in Civil Engineering, with an environmental engineering major, also from Lehigh University. His future plans include practical experience in design/consulting field.