# A FEASIBILITY STUDY OF HYDROCYCLONE SEPARATION IN MUNICIPAL WASTEWATER TREATMENT

By

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# A FEASIBILITY STUDY OF HYDROCYCLONE SEPARATION IN MUNICIPAL WASTEWATER TREATMENT

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# Chapter I

# INTRODUCTION

Population increases and industrialization have caused ever-increasing over-burdens on the hydrologic cycle of this planet. The lag between industrial development and the development of suitable waste abatement techniques has brought about the pollution crisis entangling man today. The intensity of this dilemma can be reduced by future planning, and considerations of the side effects of ever-increasing new products and industries, as well as by research into the treatment of refractory, and into better treatment methods of non-refractory compounds. The underlying aim is the discovery of complete water renovation methods.

In the treatment of municipal wastewater, separation of suspended solids from the liquid has been accomplished by gravity sedimentation for a long time. The advent of tube clarifiers has given much promise to improved gravity basins. However, much research is warranted in developing better means for suspended solids-liquid separation. The hydrocyclone is one device to this end. It was invented just prior to World War II. Now its application is quite widespread among all industries.

This study was made to determine the feasibility of applying the hydrocyclone in the treatment of municipal wastewater (where the suspended solids are both organic and inorganic, and the range of particle sizes is from colloidal to fine).

# CHAPTER II

# LITERATURE SURVEY

One of the main objectives of water and wastewater treatment is the separation of solids from the liquid. Solids in the water may be dissolved, suspended, or settleable; they may be organic or inorganic, ionized or un-ionized. Biological treatment processes are employed for the removal of dissolved organics, and physical and chemical treatment processes are employed for the removal of the rest. Chemical treatment consists of chemical additions, formation of flocs, or conversion of the chemical nature of the solids. Physical treatment includes sedimentation, centrifugation, flotation, etc.

Gravity sedimentation has been the most common physical method used in treatment plants for solids separation. It is the most economical with regard to operation and maintenance costs, and does not require skilled operators. However, it has its disadvantages; it requires a large space, and high capital outlay. Fischerstrom (1), and Hansen, et al. (2) point out eddy currents, density currents, wind effects, short circuitings, and dead corners among the many difficulties of gravity sedimentation basins.

Shallow depth sedimentation by tube clarifiers requires much shorter detention times. Culp, et al. (3) conducted conductivity analyses at inlets and outlets of tubes 2½ inches in diameter. A minimum of short circuiting existed in that the volumetric displacement efficiency was 84 percent compared to 63 percent for ideal basins.

Control of turbulence and removal of sediments were formerly the main problems in shallow depth sedimentation (4). However, the use of tube clarifiers set at an angle seem to have solved these problems. Inlet and outlet conditions are important so that no great velocity gradients are established across inlet and outlet faces of the tubes. As the horizontal angle ($\theta$) increases to the point where settled sludge begins to move downward, additional flocculation occurs as the heavier flocs settle and collide with the smaller, upward-moving flocs, contributing to a higher efficiency.

Hansen, et al. (5), Yao (6), and Culp, et al. (7) report maximum efficiencies at $\theta = 35$ to $45^{0}$, and maximum self-cleaning of pipes at $\theta$ about $60^{0}$. Also, tube length and diameter, flow rate, nature of settleable solids, and nature and quantity of chemicals added, all affect their performance. Tube clarifiers show great promise for future use. They are as simple to operate as conventional sedimentation basins, but require a detention time of few minutes as compared to few hours; therefore, much smaller basins are required.

Flotation has been used to some extent in various industries and to a lesser degree in wastewater treatment--mainly for sludge thickening. Varblik (8) reports that in this process, the solids have to be of low specific gravity or very close to that of water, flocculant, hydrophobic, and without free ions on their surfaces. Free ions on particles of solids would tend to establish primary bonds between the solids and water surrounding them. In order for the air bubbles to attach to the solids to float them for removal (by increasing their buoyant force) they will have to break the solid-liquid bonds and establish solid-air bonds. Eckenfelder, et al. (9), and Katz, et al. (10) point out that excess air bubbles would cause turbulence and breakage of flocs, while insufficient amounts would leave some solids unfloated. Mulbarger, et al. (11) report that flotation efficiency depends among other things on chemical dosages, net mass loading, detention time, air bubble size and their distribution, and amount of pressure applied in mixing.

Flotation requires air compressors and pressurization pumps, high capital cost, and power cost.

Physical removal of solids by centrifugation has been practiced some in wastewater treatment plants. Centrifuges have to be designed and selected in order to match the requirements of the particular solids to be removed. Landis (12), and Keith, et al. (13) pointed out that the solid-bowl conveyor centrifuges do not separate soft, gelatinous solids efficiently, since the conveyor is not able to move these solids out of the bowl. They are good only for solids that pack to a hard-firm cake. Disc-type centrifuges separate soft fluffy solids at low concentrations and high volumes, properly. Basket centrifuges have to be cleaned regularly to prevent excessive solids contamination with the clear outflowing liquid. Ambler (14) reports that efficiency of centrifuges depends on one or more of the following factors: particle size and distribution, solids shape and plasticity, density differential between solids and the liquid, and fluctuations of feed solids concentration. The high shear forces in a centrifuge eliminate the advantages of floc formation for removal to some extent.

The cyclone is a device used extensively in industries for solid-liquid or solid-gas separation. The use of hydrocyclones started years after dry cyclones had been in operation. The hydrocyclone was first used commercially by the Dutch States Mines in Holland just prior to World War II, and further developed during the war in Holland (15). The main action in a hydrocyclone is classification as opposed to thickening. However, the classification can be extended down to a few microns. The hydrocyclone diameter is frequently selected according to the solids size to be separated. Because of greater centrifugal force, separations are generally obtainable at a finer size in small-diameter hydrocyclones than in larger units.

Once the hydrocyclone has been selected, the main control over the size of separation is in the diameter of feed entrance and vortex finder. In general, the smaller the openings, the finer the size of separation obtained, but if the orifices are reduced in size beyond a critical point, the separation again becomes coarser. The feed diameter is normally about the same size as the overflow (vortex finder) diameter. Usually they are about 1/5 to 1/6 of the hydrocyclone diameter. The size of the underflow diameter should be such that the percent underflow is kept to a minimum and at the same time large particles are not directed to the vortex finder. The inlet pressure is converted to centrifugal force by the shape of the hydrocyclone, and heavier particles are forced toward the sides (16). Pressure drops range from 10 to over 100 psi across the inlet and overflow openings. Increased pressure at the feed line permits increased throughput, and therefore higher capacity. The increased velocity produces higher centrifugal forces within the hydrocyclone, which tends to decrease the size of separation. However, this effect is partly offset by the shorter retention time in the hydrocyclone. The particles of the medium are retained in the hydrocyclone longer than the fluid; therefore, density of the medium in the separation zone is greater than the feed density.

The flow pattern inside a hydrocyclone has been a controversial issue for some time, and there are still questions about it which are not satisfactorily answered. The flow pattern inside a hydrocyclone has rotational symmetry, except in the region immediately near the inlet nozzle. The liquid and particles velocity at any point in a hydrocyclone can be described in axial, radial, and tangential velocities. There are five distinct regions in the flow pattern of a hydrocyclone (Figure 1)(17). These are: the outer region, free vortex region, central core region, the apex zone, and the short circuit region. Mizrahi (17) describes these regions as follows:

1. The outer region consists of the conical wall boundary layer in which a strong downward current runs parallel with the wall. The thickness of this layer depends much on the vortex, cone angle, roughness of the wall, and pressure drop across the cyclone.

2. In the non-ideal free vortex region, the tangential velocity at any point depends on its radius. This region can be subdivided into two zones separated by a "zero-vertical-velocity" conical envelope, the outer zone having a downward current and the inner zone an upward current. In the upper part of the hydrocyclone, the radial velocity is relatively very small, and a cylindrical "mantle" zone exists with practically no radial flow. The liquid, therefore, passes from the inlet to the overflow, mainly through the lower part of the hydrocyclone.

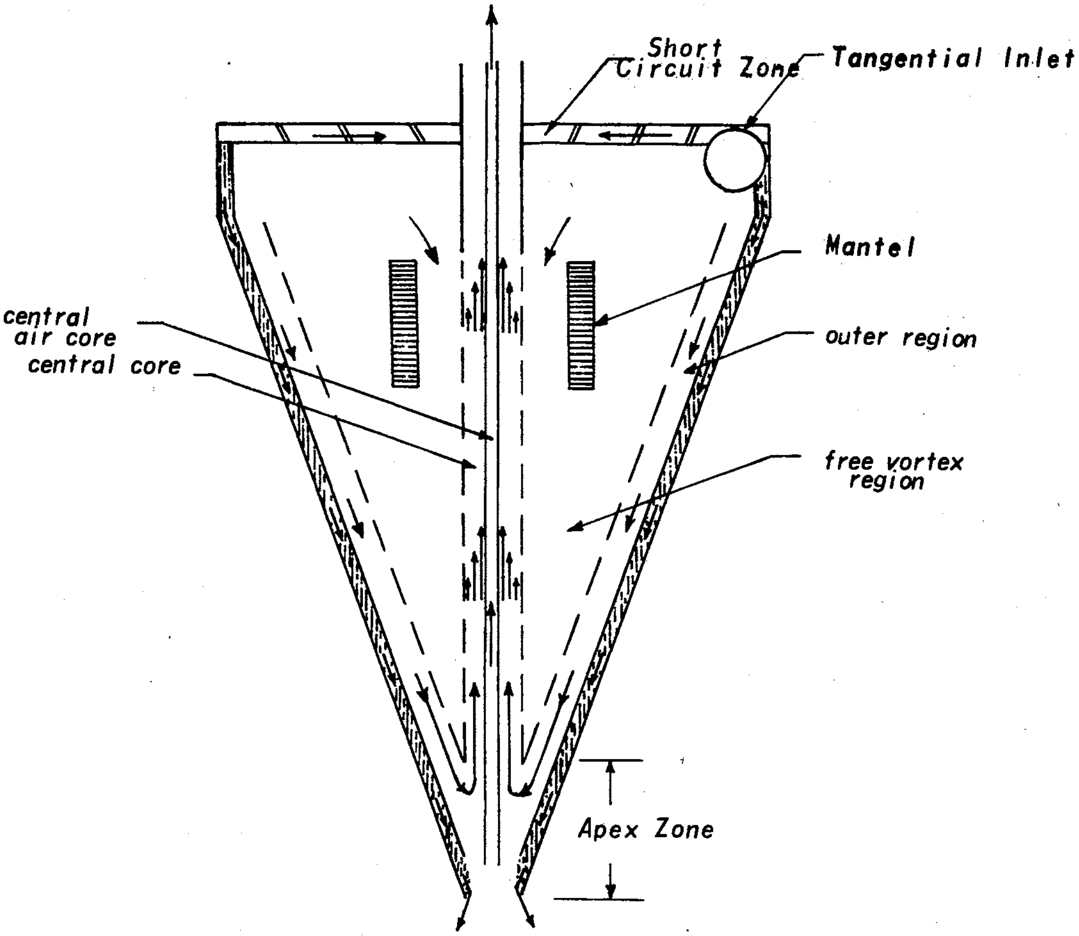

Figure 1. Longitudinal View of Flow Pattern in Hydrocyclone (17).

3. Central Core. An air column of variable diameter in most cases occupies the axis of the central core, and the center of both outlet nozzles. There is no data available on the diameter of this air column. For all practical purposes, the outer limit of the central core can be taken as the inner diameter of the overflow nozzle. The axial velocity in the central core decreases with increasing radius, and the radial velocity is negligible. The upward axial velocity in this region is much higher than the downward axial velocity in the outer region.

4. The Apex Zone. In this part of the hydrocyclone, all of the above three regions meet. This part is the most complex and least known region of the hydrocyclone, yet it has a major influence on separation results. In this region, where the tangential velocity, the solids concentration, and the wall effects are at their maximum, there is a strong radial inflow and reversal in the vertical velocity of much of the fluid.

5. In the short circuit region near the upper wall, there is an undesirable radial secondary flow between the inlet and the overflow nozzles. Since this radial secondary flow is driven by the centrifugal pressure gradient of the vortex, it is evident that wherever this centrifugal pressure gradient is decreased (by wall friction) there will be a radial flow. The standard cylindrical-shaped vortex finder produces the least short circuiting. This current can also be minimized by constructing the inlet nozzle as near as possible to the upper wall, which should also have the smoothest surface. Also, the vortex finder cylinder is extended below the inlet nozzle level to reduce short circuiting (18).

To this general description, two other phenomena should be added: 1) the local circulation eddies near the vortex finder and the mantle, and 2) the turbulence diffusion counteracting any separation process, which may be of secondary importance, but explains the internal recirculation of certain particles in the hydrocyclone. The above description of the hydrocyclone flow pattern holds only for dilute pulps having Newtonian rheological character. Higher pulp concentrations, about eight percent solids by volume or more, lead to additional effects such as hindered settling, hindered discharge, thixotropic effects (a reversible gel-sol transformation under isothermal shearing stress followed by rest), appreciable wall friction by the separated particles, etc. The separation curve of a cyclone is the combined result (Figure 2)(17) of the following mechanisms: the classification in the outer region which has the greatest effect, the central core sorting and subsequent recirculation and accumulation of part of the particles and, to a much lesser extent, the short circuiting effect. In design it is possible to enhance some particular effect and significantly reduce the importance of others.

A parameter commonly used for hydrocyclone performance is $d_{50}$; it represents the diameter size of the particles (in microns), 50 percent of which goes through the underflow and 50 percent through the overflow openings. Therefore, the smaller the $d_{50}$, the finer separation the hydrocyclone performs and a higher efficiency is attained. Fitch and Johnson (19) prefer to use a particle size which registers almost completely to the underflow opening (about 95 percent). Fontein, et al. (20) use a clarification number which is the ratio of the difference in gravimetric concentrations of solids in the inflow and the overflow over that of the inflow. A more reliable method involves the construction of efficiency curves (18) which gives the efficiency of elimination of the whole range of particle sizes present in the hydrocyclone feed (efficiency being clarification number, times the percent overflow rate of the inflow rate). Kelsall (18) also reports long, narrow rectangular feed openings give slightly improved efficiencies when compared with circular openings of the same cross-sectional area. The flow rate of a hydrocyclone depends on pressure drop, inflow diameter, and the length.

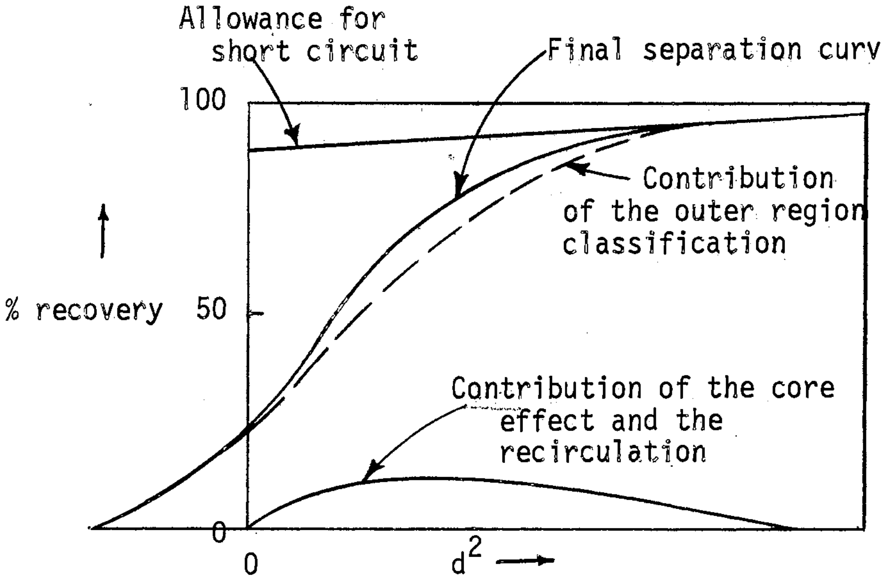

Figure 2. Separation Curve for Hydrocyclone; Percentage Recovery vs. Particle Diameter Squared (17).

The resistance of a hydrocyclone can be characterized by the dimensionless flow coefficient, $\alpha$ (20); it represents the ratio between the capacity of the hydrocyclone and the quantity of medium which would theoretically pass through an opening as large as the feed opening of the hydrocyclone at equal pressure drops.

$$\alpha = \frac{Q}{a_f\sqrt{2g\frac{\Delta_p}{\gamma_f}}}$$

where Q is the flow rate of the hydrocyclone, $a_f$ is the area of feed opening, $\Delta_p$ is the pressure drop across the inlet and overflow of the hydrocyclone, $\gamma_f$ is the specific gravity of medium, and g is the acceleration of gravity. Therefore, higher $\alpha$ values represent lower resistance, and vice versa. The air core in the center core is somewhat conical near the underflow opening. The core is not stable at very low feed pressures, but does become so as soon as rotation has grown strong enough. Its diameter is determined in the first place by the diameter of the vortex finder; it is practically independent of the size of underflow diameter (17). Increasing the back pressure decreases the air core diameter drastically down to eliminating it completely. When the air core diameter is larger than that of the underflow opening, the percent underflow is minimal. It is maximum when the ratio of air core diameter to underflow diameter is the smallest. In order to keep the underflow percentage constant, it is necessary to enlarge the underflow opening with a rise in pressure drop. If the diameter is kept constant, the underflow rate can only increase when the rotation flow is retarded. When the feed of a hydrocyclone consists of a suspension of solid particles in water, suspended particles with specific gravity larger than unity move to the wall of the hydrocyclone under the influence of the centrifugal force. Hence, in the first instance, the solid particles are concentrated at the wall of the hydrocyclone; thereafter they follow a certain course along the wall to the underflow opening. At not too low feed concentrations, the wall will be covered by a continuously flowing layer of particles already concentrated.

The clarification number which is a measure of thickening properties of a hydrocyclone, first increases considerably, then less and less with rising pressure drops. The influence of the pressure drop upon the clarifying properties of a hydrocyclone is greatly dependent on the particles to be thickened. At lower pressure drops, the rapid increase of the clarification number with increasing pressure drops is due to the fact that the increased pressure drop causes higher rotation of the larger and heavier particles. Afterward, it becomes more and more difficult to separate ever smaller particles in the underflow of a cyclone.

In industry, feed concentrations of 30 to over 100 grams per liter are employed, and usually efficiencies of over 90 percent are achieved. In wastewater treatment, feed concentrations of 0.150 to 0.600 grams per liter is the trend, and much lower efficiencies are obtained.

Higher temperatures of the medium and the resultant drop in viscosity causes greater effectiveness of centrifugal forces on particles, and lesser effectiveness of inwardly directed entraining forces on them. Therefore, a higher clarification number corresponds to a higher temperature of the medium.

A rough-walled hydrocyclone has a lower efficiency than a smoother one. The rotation flow is retarded by the roughness, thus affecting the relation between the centrifugal force exerted on particles and the entraining force. The centrifugal force decreases, while the entraining force is affected to a lesser degree.

Fontein, et al. (20) also report that at a given feed velocity, the tangential velocities in a hydrocyclone are smaller at lower values of Reynolds number,

$$N_R = \frac{v_f \, D_c \, \gamma_f \, L}{\eta}$$

for it was found that the resistance of a hydrocyclone diminishes at decreasing values of $N_R$.

The relationship between the flow rate of a hydrocyclone and the inflow-overflow pressure drop has been found to have the form (21)(22):

$$Q = K \, \Delta P^m \qquad m = 0.40 \text{ to } 0.50$$

K and m depend on all diameter sizes of hycrocyclone, viscosity and specific gravity of medium and particles.

Hydrocyclones as means of solid-liquid separation (or classification) have the advantages of simplicity in construction and operation, small size and high rate of flow per unit space, rather high efficiencies (22)(23)(24); they can be designed to handle high temperatures and high pressure streams; also, they can be built of almost any kind of corrosion-resistant material. Compared to a centrifuge or continuous filter, a hydrocyclone has no moving parts and no mechanical seals. Sludge handling is very convenient, since it leaves as a slurry stream. There are no maintenance or cleaning problems. The unit cost is very low, and they can be operated in parallel or series to meet any specific flow conditions. The use of screens prior to the inlet is required to eliminate inflow, outflow, or underflow cloggings. Corrosion is about the only problem in the use of hydrocyclones, and the use of highest corrosion-resistant materials for construction of hydrocyclones is desirable.

Molyneux (25) describes the Daynor hydrocyclone. The cylindrical part of the hydrocyclone is divided into two chambers by means of a horizontal plate which has a central orifice. The inlet nozzle is below the plate, and the clarified liquid leaves from the upper chamber (above the plate). In the normal hydrocyclone, the air of the air core enters the vessel through overflow and/or underflow and/or feed liquid. It is either at atmospheric or below atmospheric pressure. The variations in feed quality and quantity develop instability in the central core, and render varying efficiencies. The advantage of Daynor consists of means whereby this central vortex is maintained under pressure and its diameter varied to conform with variations in feed quality and quantity.

# CHAPTER III

# MATERIALS AND METHODS

## A. Hydrocyclones

This study is comprised of two phases, at the end of which the best design of a hydrocyclone for treatment of the municipal wastewater of Stillwater, Oklahoma, was to be achieved. The first phase consisted of tests of eight different hydrocyclones to determine the most efficient one. The second phase consisted of two hydrocyclones, units Nos. 7 and 10. Unit No. 10 was designed on the basis of results of the first phase experiments. The hydrocyclones were designed under the supervision of Dr. W. G. Tiederman, College of Engineering, Oklahoma State University, Stillwater, Oklahoma.

Figure 3 is a schematic diagram of the hydrocyclone. The two types of hydrocyclone configurations used in this study were those with and without contamination traps. The contamination traps were filters installed to screen the underflow stream after it leaves the collection pot. In the first phase of the study, no contamination traps were used. In the second phase, two types of contamination traps: a sand filter and a diatomaceous earth filter were used.

Table I presents the dimensions of the eight hydrocyclones, units two through nine, which were tested in the first phase. Table II shows the parameter dimensions of hydrocyclone No. 10, which was tested in

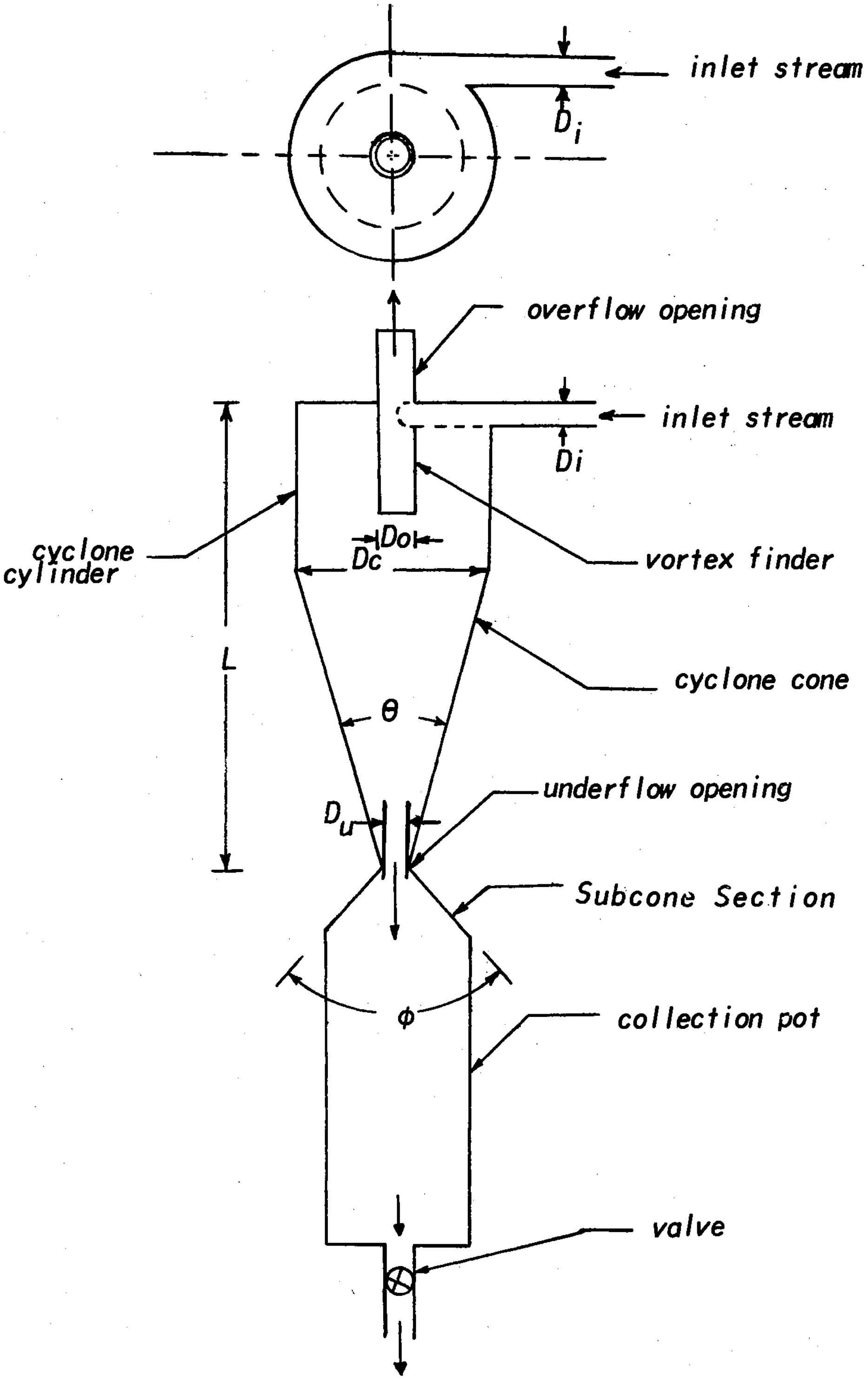

Figure 3. Schematic Diagram of Hydrocyclone.

## TABLE I

## CRITICAL DIMENSIONS OF HYDROCYCLONES NOS. 2 THROUGH 9

| Unit No. | $D_c$ in. | $D_i$ in. | $D_o$ in. | $D_u$ in. | L in. | $\Delta P$ psi | $\theta$ |
|---|---|---|---|---|---|---|---|
| 2 | 1½ | 0.30 | 0.36 | 0.188 | 9 | 14.5 | $20^o$ |
| 3 | 1 | 0.28 | 0.24 | 0.125 | 6 | 28 | $20^o$ |
| 4 | 1½ | 0.42 | 0.36 | 0.188 | 6 | 11.5 | $20^o$ |
| 5 | 1 | 0.20 | 0.34 | 0.125 | 6 | 41 | $20^o$ |
| 6 | 1½ | 0.30 | 0.51 | 0.188 | 6 | 13 | $20^o$ |
| 7 | 1 | 0.28 | 0.34 | 0.125 | 4 | 30 | $20^o$ |
| 8 | 1½ | 0.42 | 0.51 | 0.188 | 9 | 7 | $20^o$ |
| 9 | 1 | 0.20 | 0.24 | 0.125 | 6 | 74 | $20^o$ |

## TABLE II

## CRITICAL DIMENSIONS OF HYDROCYCLONE NO. 10

| Unit No. | $D_c$ in. | $D_i$ in. | $D_o$ in. | $D_u$ in. | L in. | $\Delta P$ psi | $\theta$ |
|---|---|---|---|---|---|---|---|
| 10 | 1½ | 0.30 | 0.36 | 0.188 | 6 | 20 | $20^o$ |

the second phase of the study. All of the hydrocyclones tested were operated under 4.0 gpm inflow rate in both phases.

## B. Wastewater

The municipal wastewater of the Stillwater, Oklahoma, treatment plant was used as inflow suspension to the hydrocyclones. The wastewater was collected from the grit chamber prior to the preaeration basin of the wastewater treatment plant. All samples were collected from the plant during early afternoon, so as to obtain a stronger waste. No additives were added to the wastes, except flocculants in the case of chemical treatment.

## C. Contamination Traps

Two types of filters were employed as contamination traps: sand filter and diatomaceous earth filter. Both of the filters were used in continuous recycle studies (phase 2). Figures 4 and 5 show their dimensions and configurations as part of the continuous recycle system.

The diatomaceous earth powder was purchased from Eagle-Picher Industries, Inc., under the name of "Celatom Diatomite," manufactured for swimming pool filtration systems. The filter was operated as a vacuum filter under atmospheric pressure. Diatomite slurry was added to the filter from time to time during operation in order to prevent clogging of the filter by underflow solids. This provided a more convenient operation than backwashing.

The sand filter consisted of fine grade beach sand, which was supported on a layer of gravel in the cylinder, Figure 5. This filter was also operated under atmospheric pressure. It was not backwashed during operation, but was backwashed afterward.

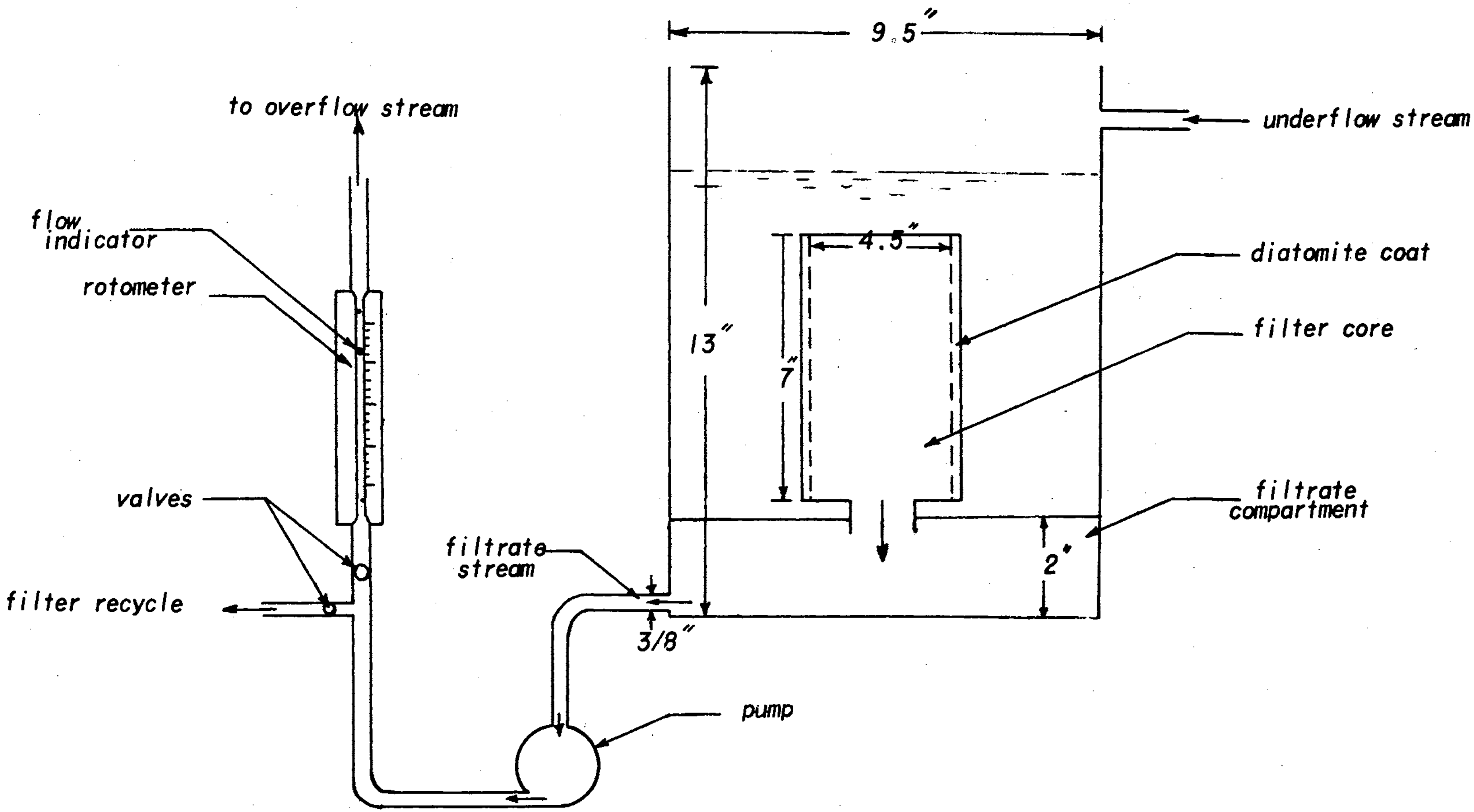

Figure 4. Schematic Diagram of Diatomaceous Earth Filter Configuration.

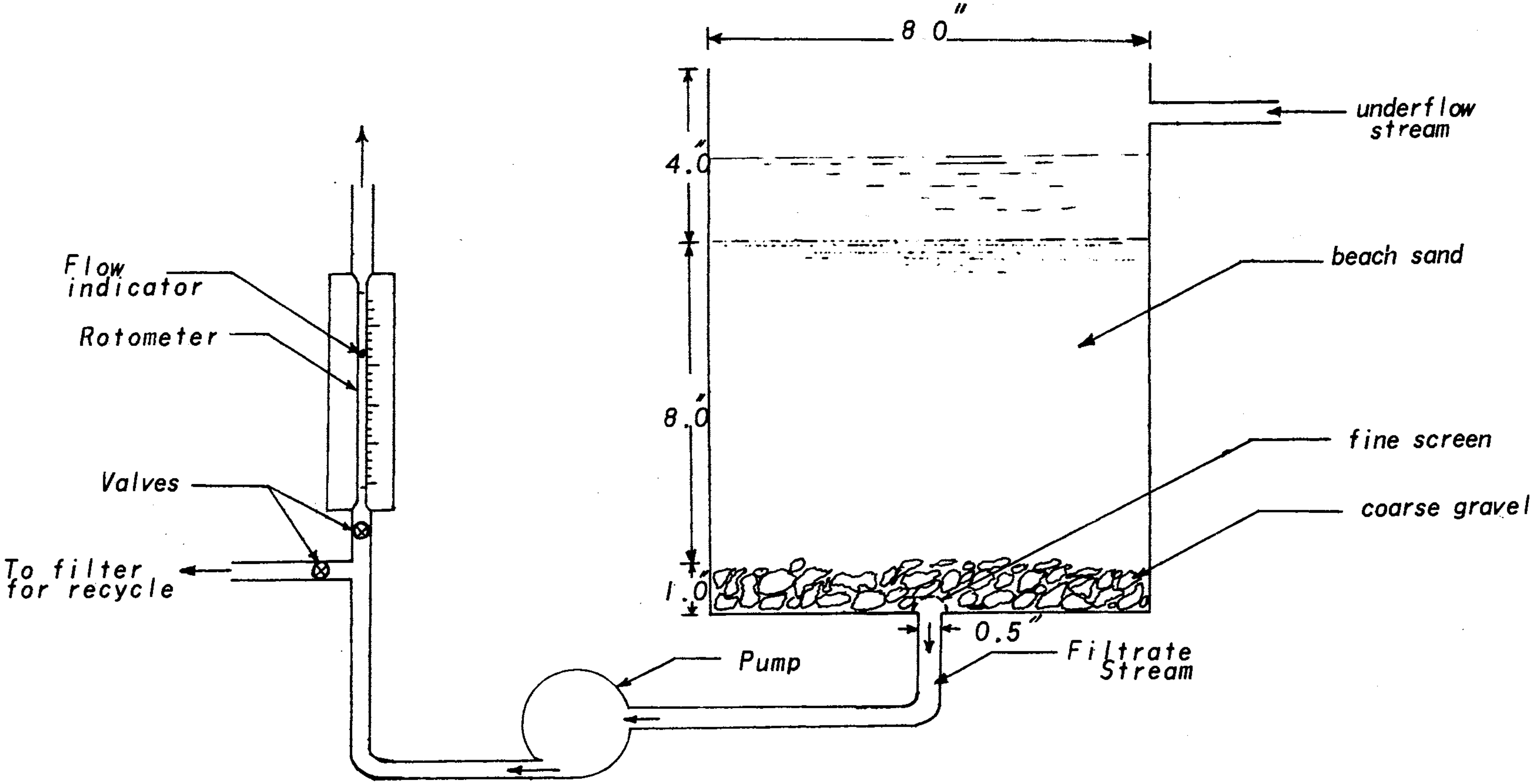

Figure 5. Schematic Diagram of Sand Filter Configuration.

The hydraulic loadings on the filters for the different underflow rates experimented are shown in Table III.

## D. Analytical Procedures

### 1. Coagulation Chemicals

Two kinds of coagulants were used: solutions of ferric sulfate crystals $\left[Fe_2(SO_4)_3\right]$, and Calgon WT-2600, a polyelectrolyte. Other coagulants were tested through jar studies, including alum, lime, Calgon polymers WT-2630, WT-2660, WT-2870, WT-2690, WT-2700, WT-2900, and WT-3000; also Hercofloc polymers 828.1, 814, 810, 822, 836, and 816. The Calgon polymers are produced by Calgon Corporation, and Hercofloc polymers by Hercules, Inc.

TABLE III

HYDRAULIC LOADINGS OF THE CONTAMINATION TRAPS

| Underflow Rate | | Diatomaceous Filter | | Sand Filter | |
|---|---|---|---|---|---|
| percent | gpm | gpm/ft$^2$ | gpd/ft$^2$ | gpm/ft$^2$ | gpd/ft$^2$ |
| 2.5 | 0.10 | 0.145 | 209 | 0.290 | 418 |
| 5.0 | 0.20 | 0.290 | 418 | 0.580 | 836 |
| 10.0 | 0.40 | 0.580 | 836 | 1.16 | 1672 |

gpm = U. S. gallons per minute
gpd = U. S. gallons per day

## 2. Jar Studies

The jar studies were performed by using a Phipps and Bird, Inc., laboratory stirrer. The coagulants had been dissolved in distilled water in desired concentrations, ready to be applied to the samples. Six 500-ml samples in glass beakers were placed on the stirring apparatus. Desired amounts of coagulants were added to each beaker and stirred at 100 rpm for one minute, then the stirrer was slowed down to 20 rpm for twenty minutes or longer. The fastest settling time and the least turbidity of water were the criterion for determining the optimum coagulant dosages.

## 3. Flocculation

For all runs, a volume of ten gallons was placed in the inflow tank. In case of chemical treatment, optimum amounts of inorganic and then organic (polyelectrolyte) coagulant solutions were added to the reservoir, one at a time. Meanwhile, the batch and chemicals were mixed rapidly by a variable speed mixer with shop-made propellers of seven-inch diameter at 100 rpm for one minute. Vertical baffles were installed in the inflow tank, which enhanced flocculation considerably. After one minute of rapid mixing, the stirrer was set at 40 rpm to facilitate formation of flocs. After 15 to 30 minutes of slow (40 rpm) mixing, the hydrocyclone inlet pump was started, and throughout the experimentation, the slow mixing was continued in order to keep the flocs in suspension and provide a uniform feed to the hydrocyclones.

## 4. Pumps

Two pumps were used in the system; one for pressurization of inflowing feed being a roller pump driven by a one-horsepower, 110-220 volt A. C. motor. A bypass valve provided flexibility of inflow pressure and flow rate through the hydrocyclones. This pump was calibrated for pressure drop vs. flow rate by measuring volumes of water flown through the system for definite periods of time at given pressure drops. A second pump, a conveyor type driven by a 1/4-horsepower, 115 volt, A. C. motor, was employed to pump the filtered underflow back through a vertical rotometer to the inflow tank. This was used only in continuous recycle experiments.

## E. <u>Experimental Procedures</u>

### 1. Three Consecutive Single-Pass Studies

In the first phase, the eight hydrocyclones were tested by three consecutive single-pass runs. These experiments included both chemical treatment and no chemical treatment of wastewater for all hydrocyclones. Figure 6 shows a schematic flow diagram of single-pass runs. The inflow tank was filled to the 10-gallon mark. In the case of chemical treatment, the coagulants were added to the tank and flocculated as described previously. The by-pass valve and underflow and overflow valves were set to produce 4.0 gpm of inflow rate and 0.2 gpm (5 percent) underflow rate for all experiments. A vertical flow-meter indicated the underflow rate, and the pressure drop across a calibrated orifice as measured by a mercury manometer, indicated the overflow rate. Just prior to the start of each experiment, the collection pot of the underflow was filled to the top by wastewater in order to obtain a uniform performance of the hydrocyclone throughout the experiment. The underflow and overflow streams were allowed to fall freely under atmospheric pressure into the receiving containers. The inflow samples were taken

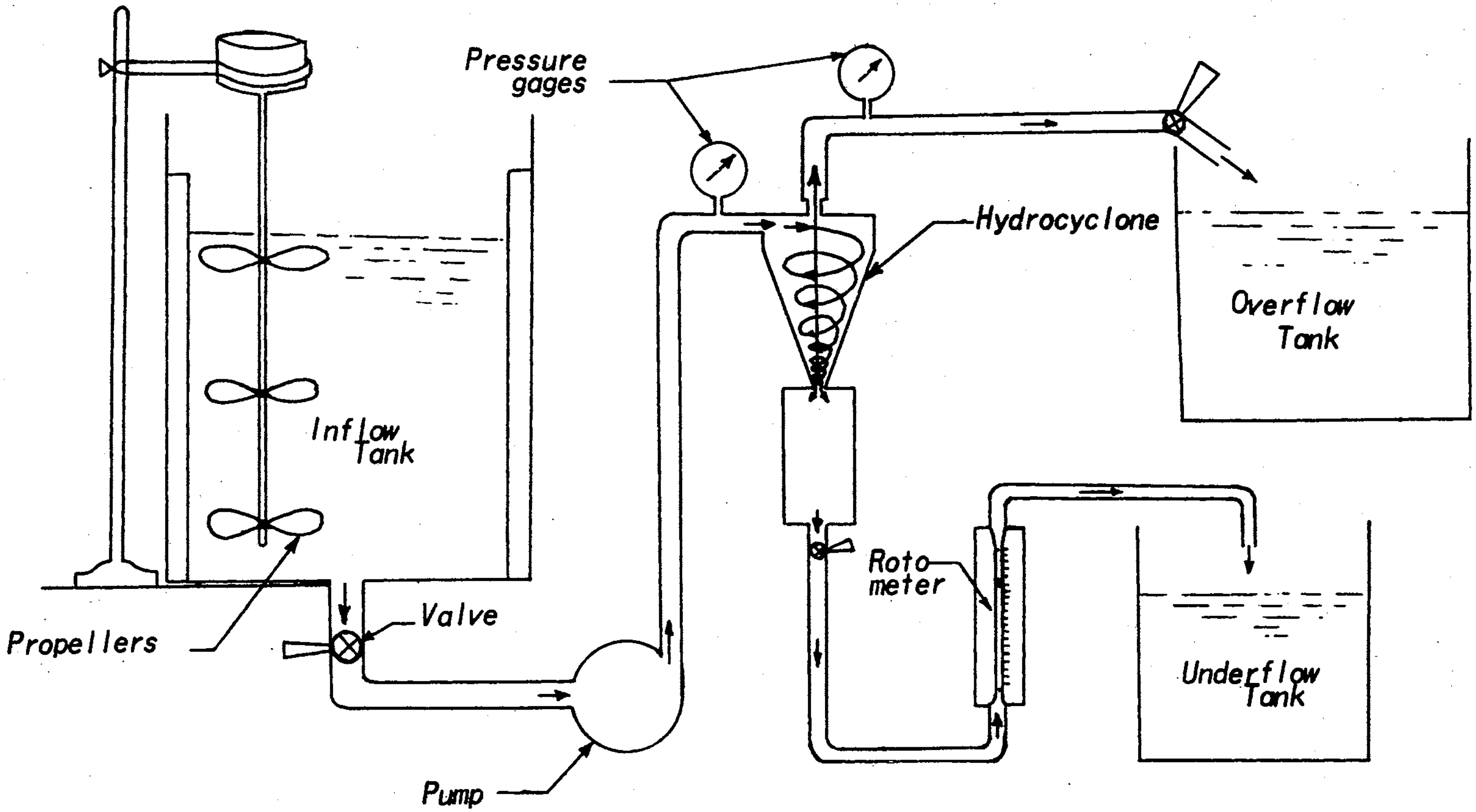

Figure 6. Schematic Flow Diagram of Single-Pass Experiments.

approximately half-way below the sewage level in the inflow tank, but overflow and underflow samples were taken directly from the flowing streams. The samples were taken in duplicate.

### 2. Continuous Recycle Studies

A schematic flow diagram of continuous recycle runs is shown in Figure 7. In these experiments, batches of 10 gallons of wastewater were placed in the inflow tank. Chemical treatment and flocculation were followed in all experiments; underflow and overflow samples were taken directly from the streams, and that of inflow, from the inflow tank half-way below the sewage level. Identical duplicate experiments were performed using the diatomaceous earth filter and the sand filter. The percent underflows were 2.5 percent, 5.0 percent, and 10.0 percent for each filter on each unit. The underflow was passed through the filter and pumped back through a rotometer and the overflow stream to the inflow tank.

Diatomaceous slurry was added to the filter from time to time. The percent underflow was kept constant for each experiment by maintaining the water level over the filter at a constant height, while the rotometer indicated flow of the correct percentage of underflow to the overflow stream. A by-pass valve on the underflow pump allowed adjustments of flow through the rotometer. Samples were taken at 5-minute intervals from the overflow stream and inflow tank. Occasional samples of unfiltered and filtered underflow were taken directly from the streams. The overflow stream and inflow tank samples provided a check and balance system, since they should be very similar.

Samples taken from both phases of the study were subjected to gravimetric analysis, using Millipore filters of 0.45 μ. Samples of

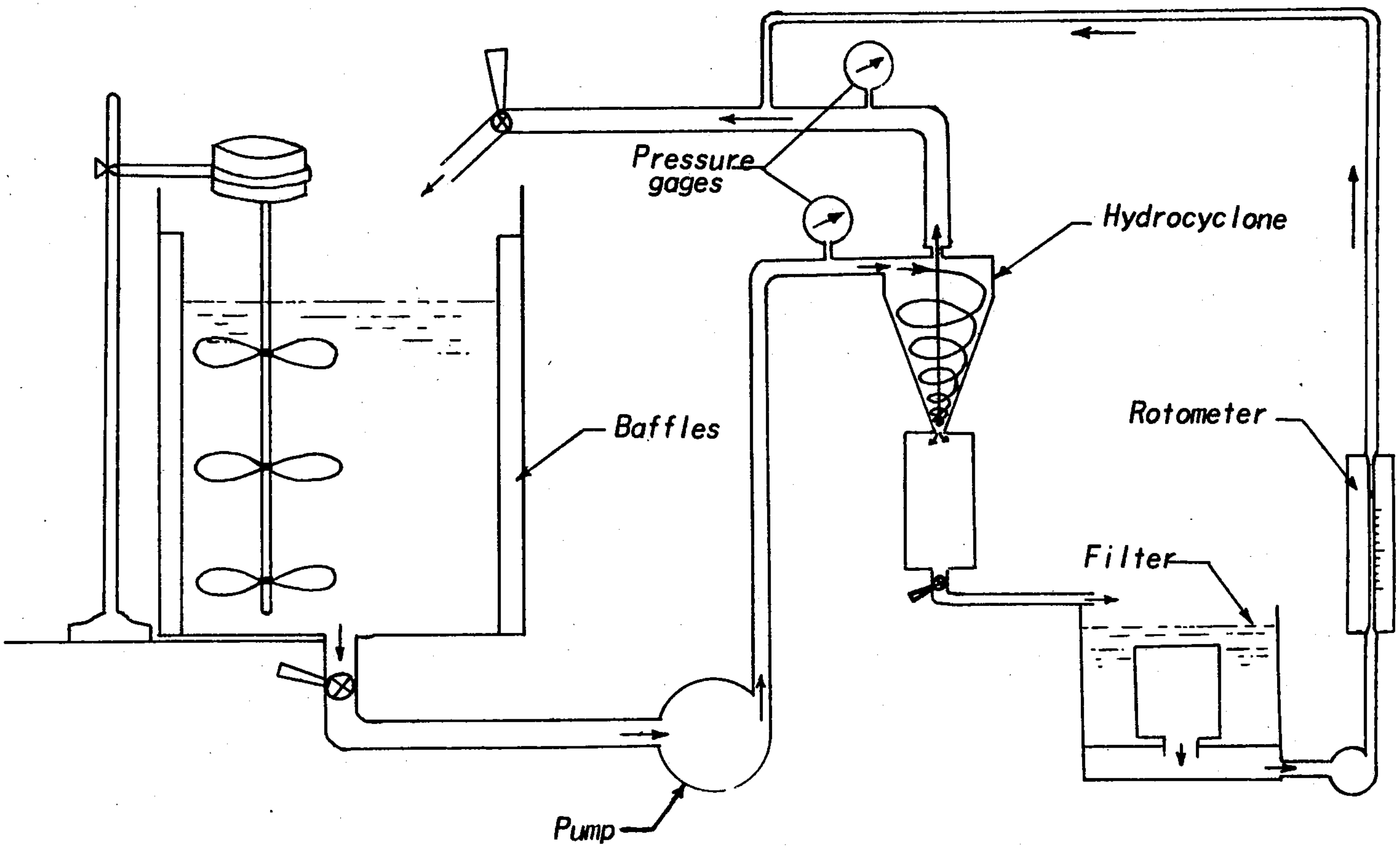

Figure 7. Schematic Flow Diagram of Continuous Recycle Experiments.

25 ml were passed through Millipore filters by a vacuum system, then oven-dried and put in desiccators; afterward weighted by digital balance to one hundred thousandths of a gram. The samples of the second phase were tested for chemical oxygen demand (COD) as well, by the procedure described in Standard Methods, 13th edition, for wastewater (32).

### 3. Gravity Sedimentation

Gravitational settling of wastewater with and without chemical treatment was tested by filling a 2-liter graduated cylinder with the treated or untreated sewage. Samples for suspended solids and COD tests were taken from the top layer of the cylinder at 5-minute intervals.

# CHAPTER IV

# EXPERIMENTAL RESULTS

## A. General

This chapter consists of four sections. The first section reports the results of three consecutive single-pass experiments. In this section, results of nine hydrocyclones on chemically treated and untreated wastewater are reported. Also, comparative performance of units Nos. 7 and 10 with and without the effect of chemicals are presented.

In the second section, results of continuous recycle experiments are reported for hydrocyclones Nos. 7 and 10. Each hydrocyclone is evaluated for 2.5 percent, 5.0 percent, and 10.0 percent underflow rates with diatomaceous earth filter, and analyzed for suspended solids and COD removal. Further, unit No. 10 results with different underflow rates and sand filter are presented in this section.

The third section presents the results of gravity settling with and without chemical treatment of wastewater. The data reports the effects of chemicals in settling as reflected by suspended solids and COD removal.

The fourth section reports the results of jar test studies. Two types of organic polyelectrolytes, Calgon and Hercofloc, are reported here. Three types of inorganic coagulants: alum, lime, and ferric sulfate, were tested in conjunction with the polyelectrolytes which are reported in this section. These results are not quantitative, and are based on visual judgments.

## B. Single-Pass Studies

The results of three consecutive single-pass experiments are tabulated in Table IV. The percent efficiencies are given for one single-pass. The coagulants used were 8 mg/l of Calgon WT-2600 and 60 mg/l ferric sulfate. The suspension was flocculated before pumping through the hydrocyclones. The percent efficiencies of each unit varied within ± 5 percent, depending on the initial amount of solids loading. Higher initial solids produced higher efficiencies. In this report, efficiency is presented by clarification number, which is the ratio of difference of inflow and overflow suspended solids concentration over that of inflow concentration. The underflow rate of all experiments in this section was maintained constant at 5 percent.

Hydrocyclone No. 2 produced an 8 percent efficiency with an initial suspended solids of about 230 ppm and no chemical treatment. Flocculation increased its efficiency to 20 percent for the same initial suspended solids (S.S.). It was observed that part of the flocs were broken after going through the pump and hydrocyclone. Breakage of flocs was observed in all experiments with hydrocyclones. The back pressure was about 5 psig. Pressure drop across the inflow-overflow lines was 15 psig. The efficiency of each single-pass in all hydrocyclones decreased with increasing numbers of passes. In other words, the first pass efficiency was always greater than that of the second or third pass for all hydrocyclones.

Hydrocyclone No. 3 produced a pressure drop of 28 psig. A back pressure of 8 psig was applied. It produced an efficiency of 10 percent with no coagulation, and 20 percent under coagulation conditions when the initial S.S. was about 300 ppm in both cases.

TABLE IV

SINGLE-PASS EFFICIENCIES OF THE HYDROCYCLONES ON TREATED AND UNTREATED WASTEWATER

| Unit No. | $D_c$ in. | $D_i$ in. | $D_o$ in. | L in. | $\Delta P$ psi | back press. psig | percent E without chemicals | percent E with chemicals | initial S.S. (ppm) |
|---|---|---|---|---|---|---|---|---|---|
| 2 | 1½ | 0.30 | 0.36 | 9 | 14.5 | 5 | 8 | 20 | 230 |
| 3 | 1 | 0.28 | 0.24 | 6 | 28 | 8 | 10 | 20 | 300 |
| 4 | 1½ | 0.42 | 0.36 | 6 | 11.5 | 10 | 5 | 10 | 350 |
| 5 | 1 | 0.20 | 0.34 | 6 | 41 | 10 | 15 | 15 | 300 |
| 6 | 1½ | 0.30 | 0.51 | 6 | 13 | 8 | 5 | 10 | 300 |
| 7 | 1 | 0.28 | 0.34 | 4 | 30 | 15 | 15 | 30 | 200-350 |
| 8 | 1½ | 0.42 | 0.51 | 9 | 7 | 15 | 0 | 10 | 300 |
| 9 | 1 | 0.20 | 0.24 | 6 | 74 | 2 | 10 | 20 | 250-350 |
| 10 | 1½ | 0.30 | 0.36 | 6 | 20 | 10 | 20 | 40 | 250-500 |

Hydrocyclone No. 4 registered a low pressure drop of 12 psig; a back pressure of 10 psig was applied. Efficiencies of 5 and 10 percent resulted from untreated and chemically treated wastewaters, respectively. The initial suspended solids was about 350 ppm in both cases.

Hydrocyclone No. 5 did not show any improvement in efficiency due to chemical treatment. In both cases, an efficiency of 15 percent and

41 psig pressure drop at 10 psig back pressure and about 300 ppm initial suspended solids, resulted.

The effects of chemical treatment of wastewater on performance of unit No. 6 was negligible as in units Nos. 4 and 5. A 5 percent and a 10 percent efficiency for untreated and treated wastewater, respectively, resulted. The hydrocyclone operated under a 13 psig pressure drop and a back pressure of 5 to 10 psig.

Hydrocyclone No. 7 produced the highest efficiency of the first eight hydrocyclones tested. It produced a 15 percent efficiency on untreated wastewater, and 30 percent on coagulated wastewater. It had a pressure drop of 30 psig; a back pressure of 15 psig was applied. The range of influent suspended solids concentration for this performance was between about 200 to 350 ppm.

Hydrocyclone No. 8 was not satisfactory, as it yielded 0 percent and 10 percent solids separation efficiency for untreated and treated wastewater, respectively. It had a low pressure drop of 7 psig, and was operated at 15 psig back pressure.

Hydrocyclone No. 9 had the highest pressure drop of the hydrocyclones, 74 psig. The applied back pressure was between 0 to 2 psig. It resulted in 10 percent and 20 percent efficiencies for untreated and treated wastewater, respectively. The influent solids concentration applied to this unit was between 250 and 350 ppm.

Hydrocyclone No. 10 was designed on the basis of results obtained from the above eight hydrocyclones. Its configuration is not similar to that of No. 7, since No. 10 is two inches longer and one-half inch larger in diameter; however, their inlet and vortex finder diameters are each within 0.02 of an inch of one another, and their pressure drops within 5 psi. This unit produced a 20 percent and 40 percent efficiency for untreated and treated wastewater. It has a 20 psig pressure drop, and was operated under 10 psig back pressure.

Figure 8 presents the results of three consecutive single-pass experiments on units Nos. 7 and 10. Both are chemically treated, and the underflow rate is 5.0 percent. The chemical dosages were 8 ppm Calgon WT-2600, and 60 ppm ferric sulfate. The solids concentration for unit 7 starts at 227 ppm at inflow, and yields 160 ppm in the overflow after the first run, 145 ppm after the second run, and 130 ppm after the third run. Solids concentration for unit 10 starts with 470 ppm in inflow to 282 ppm for first, 232 ppm for second, and 210 ppm for third run in overflow stream. The slope of the curve for unit No. 10 is much steeper than that of unit No. 7, even though both yield an overall 50 percent efficiency for three passes. Unit No. 7 produces 30 percent efficiency for first pass, 10 percent for the second and third passes. Unit No. 10 produces 40 percent efficiency for first pass, 20 percent for second pass, and 10 percent for third pass.

Figure 9 shows data on unit No. 10 operated at 5.0 percent underflow rate with and without chemical treatment. The untreated curve starts with 342 ppm suspended solids in raw sewage to 270 ppm after first, 240 ppm after second, and 225 ppm after third pass. Efficiencies of 20 percent for first, 12 percent for second, and 6 percent for third pass resulted. The chemically treated wastewater curve is the same as shown in Figure 8, unit No. 10, with efficiencies of 40 percent, 20 percent, and 10 percent for first, second, and third passes, respectively. An overall efficiency of 51 percent for chemically treated, and 32 percent for untreated wastewater resulted for three

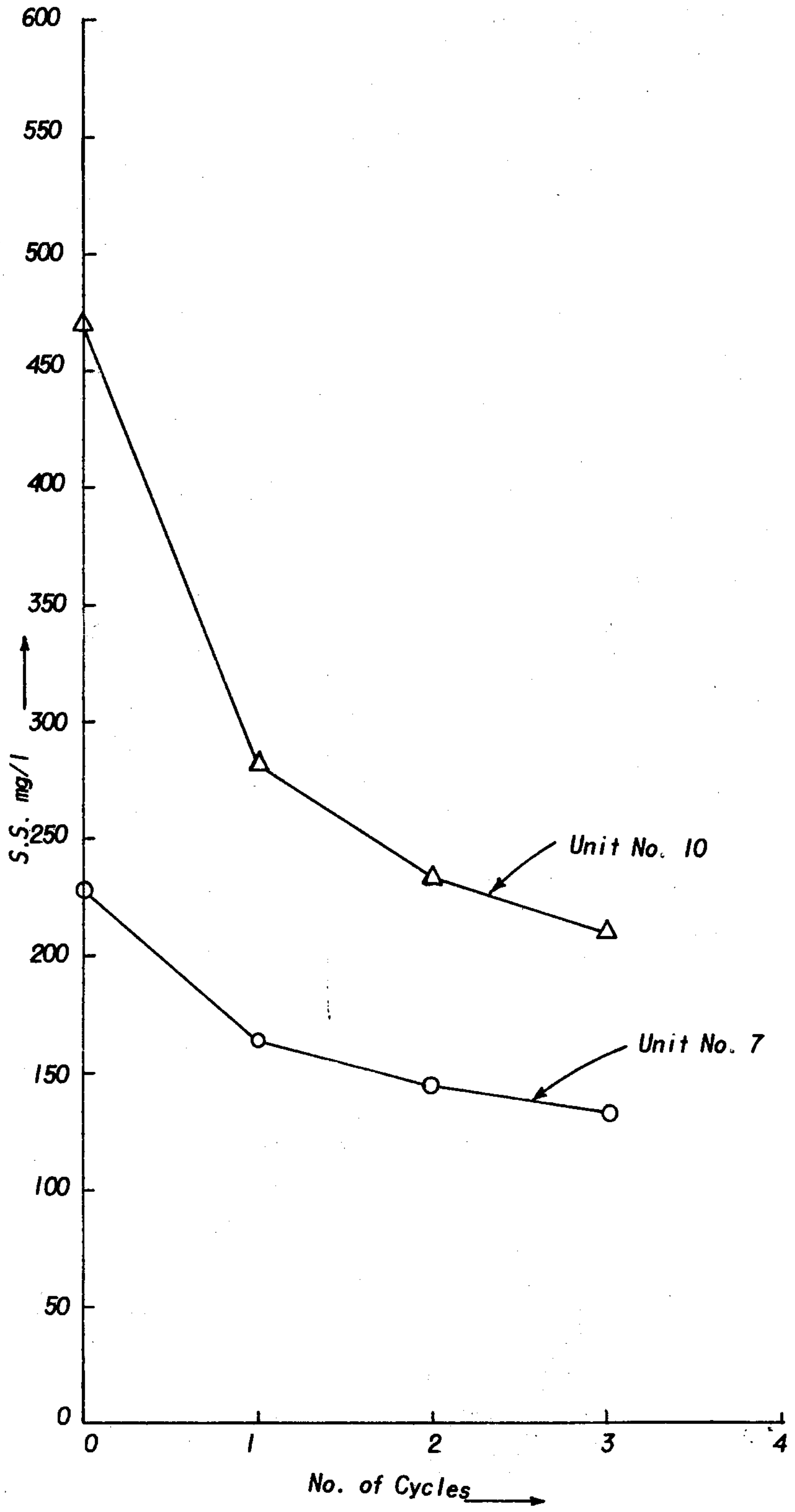

Figure 8. Single-Pass Results, Hydrocyclone Nos. 7 and 10, Five Percent Underflow Rate.

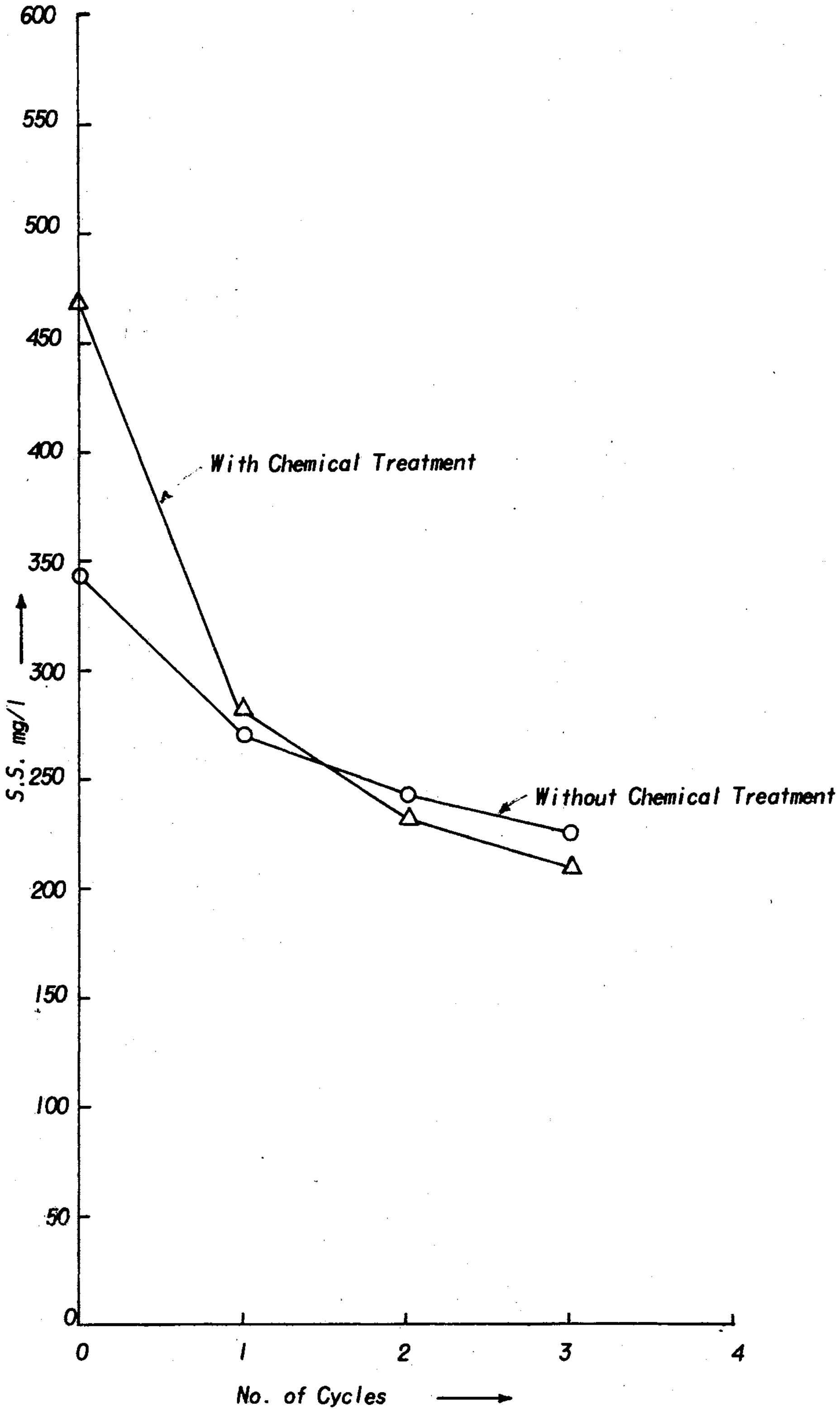

Figure 9. Single-Pass Results, Hydrocyclone No. 10, Five Percent Underflow Rate, With and Without Coagulation.

passes through hydrocyclone No. 10.

## C. Continuous Recycle Studies

This section presents results of experiments performed with diatomaceous earth filter first, and then the results of the sand filter studies.

The diatomaceous earth filter was of the vacuum type with about 1/8 to 1/4-inch coating on the filter core (a cylinder). The diatomite slurry was added to the filter from time to time during the operation in order to prevent clogging. All experiments in this section were performed on chemically treated wastewater. The chemical dosages were 60 ppm ferric sulfate and 8 ppm Calgon WT-2600. The mixing propellers kept rotating at 40 rpm during the experiments in order to provide a homogeneous feed to the hydrocyclones.

Figure 10 presents the results of a 30-minute continuous recycle of 10 gallons of chemically treated wastewater through unit No. 7 at a 5.0 percent underflow rate. The initial solids concentration was 307 ppm; after five minutes (two cycles) it was 210 ppm. From then on, the suspended solids concentration decreased at a constant linear rate to 102 ppm after 30 minutes recycling (12 passes). An overall efficiency of 69 percent was achieved. For the 10-gallon batch and 5 percent (0.2 gpm) underflow rate through diatomite filter for 30 minutes, six gallons of underflow wastewater passed through the diatomite filter.

Figure 11 presents data on a run through hydrocyclone No. 7. The conditions and arrangements of previous tests are duplicated here, except that the underflow rate is reduced to 2.5 percent (0.1 gpm) for this experiment. Figure 11 shows an initial suspended solids concentration of about 275 ppm gradually and uniformly reduced to 123 ppm in

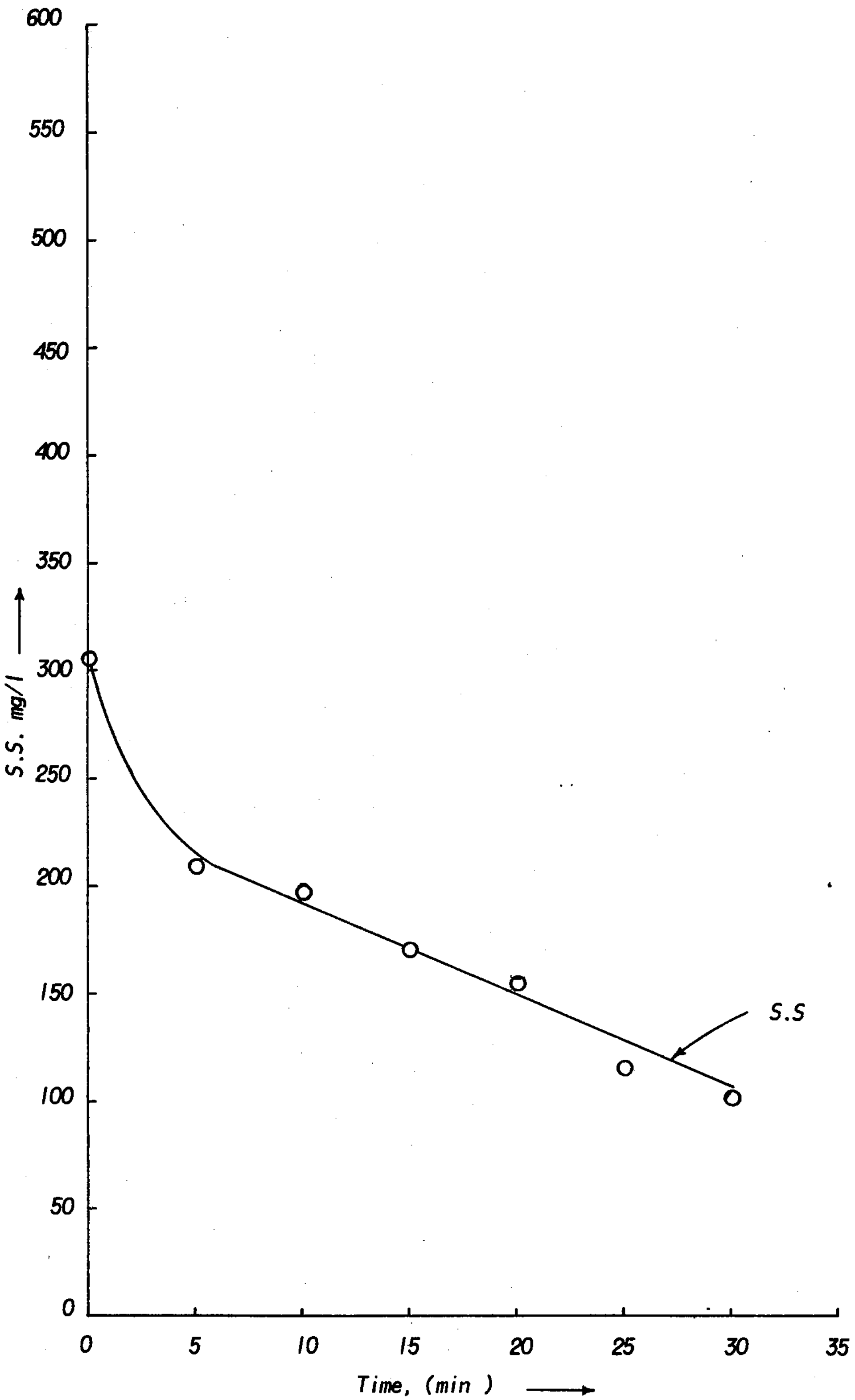

Figure 10. Continuous Recycle Results, Hydrocyclone No. 7, Five Percent Underflow Rate, Diatomaceous Earth Filter.

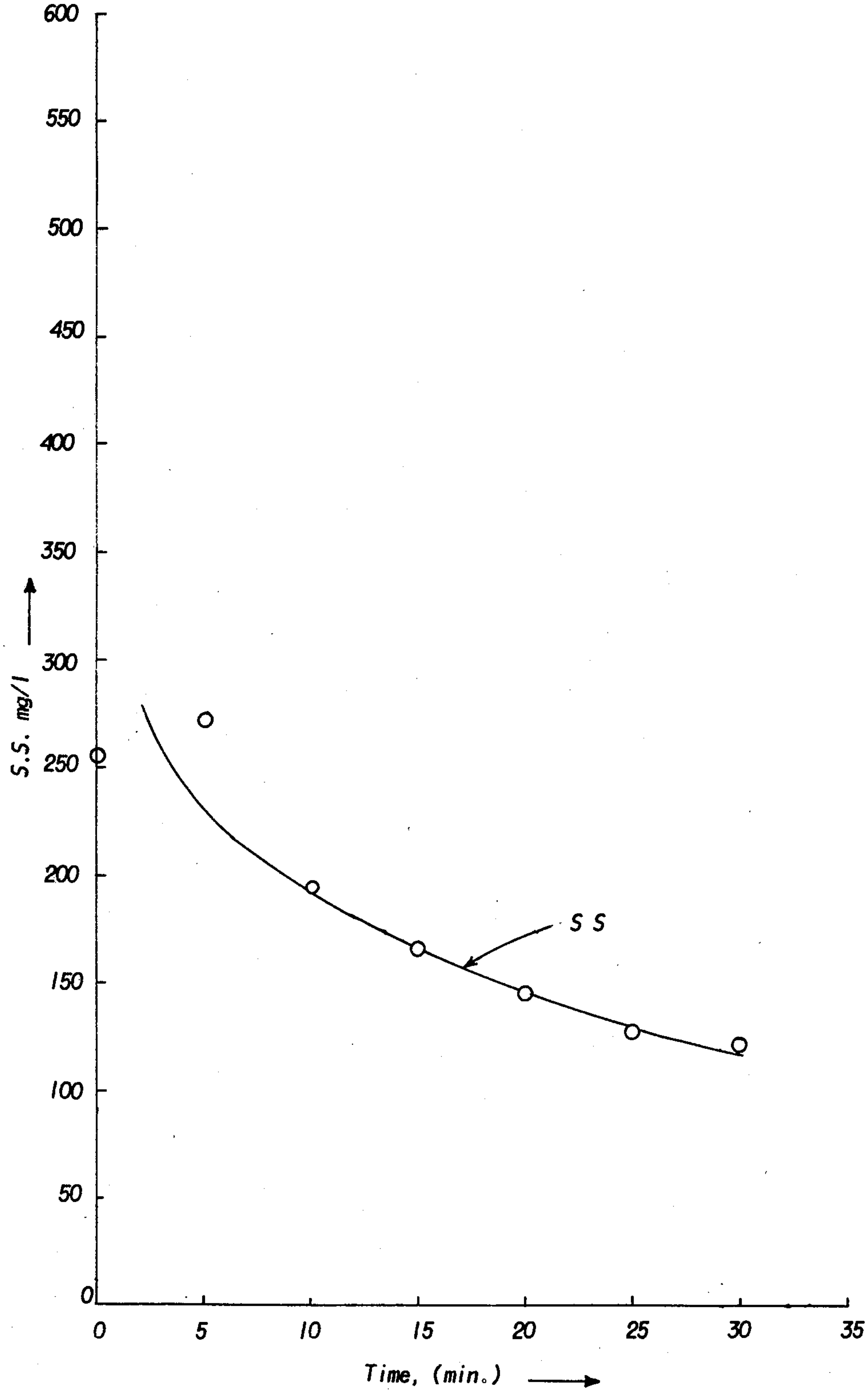

Figure 11. Continuous Recycle Results, Hydrocyclone No. 7, 2.5 Percent Underflow Rate, Diatomaceous Earth Filter.

30 minutes (12 recycles). The overall efficiency was 64 percent. In this experiment, three gallons of underflow wastewater had run through the diatomite filter since the underflow rate was 2.5 percent.

Figure 12 is a combination of Figures 10 and 11 drawn on the same coordinate system for comparison purposes. The S.S. concentration for 2.5 percent underflow rate experiment levels off earlier than that for five percent underflow rate. The solids separation of the 5.0 percent underflow rate experiment is also more rapid for the first five minutes (two cycles) than for the 2.5 percent experiment, as is shown by the slopes of the curves during that period.

Figure 13 is another run through unit No. 7 at 5.0 percent underflow rate. The details of the experiment are exactly the same as those presented in Figure 10. In this experiment, COD removal was measured, as well. The suspended solids removal curve starts at 237 ppm; after five minutes it is 180 ppm, and from then on it decreases rather linearly to 104 ppm at 30 minutes. An overall 60 percent efficiency resulted.

Chemical oxygen demand removal for this experiment was 53 percent. The initial COD was 540 ppm; 424 ppm at five minutes; 360 ppm at 10 minutes; from then on decreasing linearly to 255 ppm at 30 minutes. The slope of the COD removal curve is steeper than the suspended solids removal curve in this experiment. The chemical oxygen demand removal in these experiments is due solely to removal of organic solids by the hydrocyclone and filter, aided by chemical coagulation; the wastewater was not subjected to biological treatment.

Figures 14 through 17 show the results of hydrocyclone No. 10 with varying underflow rates through the diatomite filter. The results were analyzed for solids and COD removal.

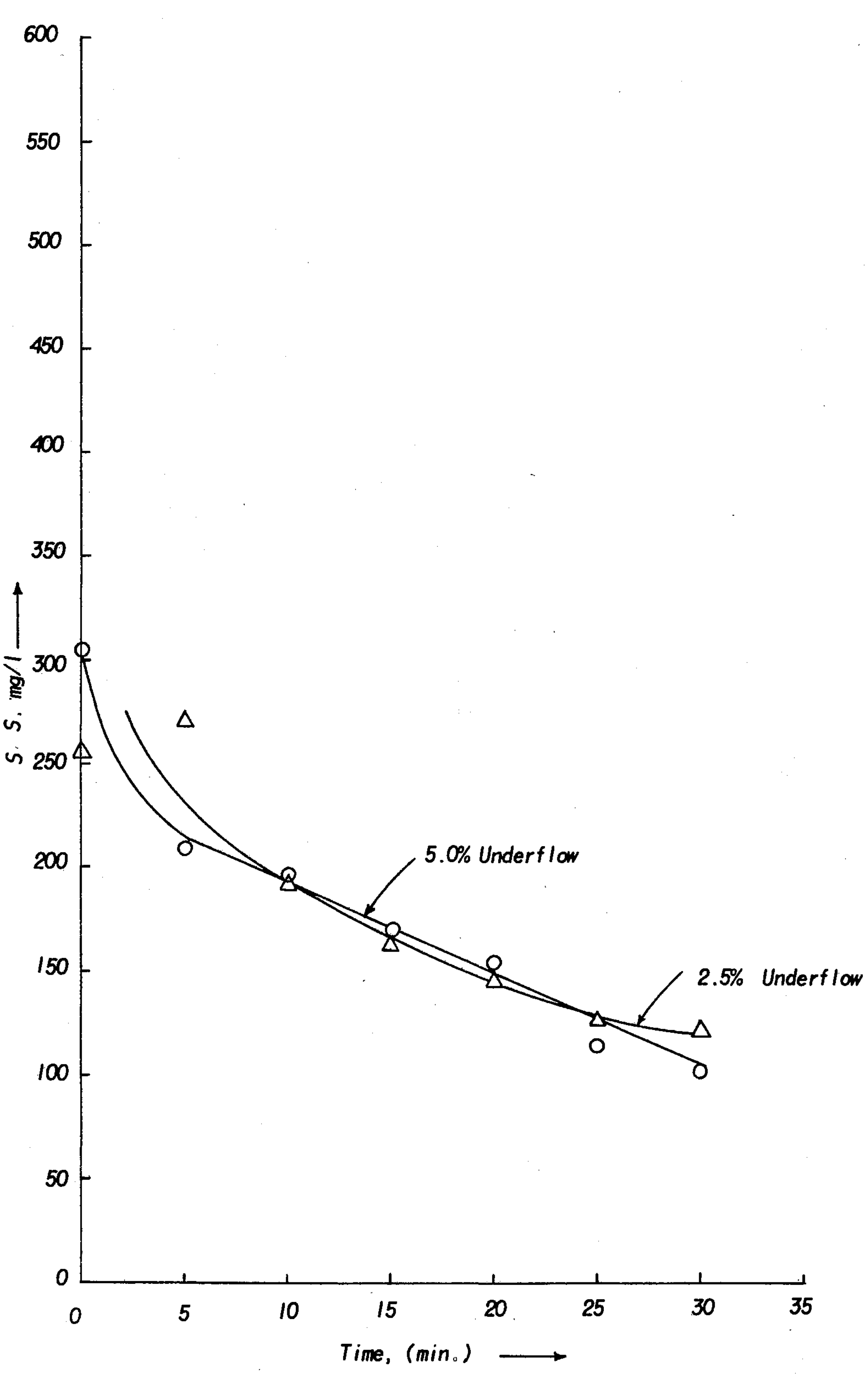

Figure 12. Continuous Recycle Results, Hydrocyclone No. 7, 2.5 and 5.0 Percent Underflow Rates, Diatomite Filter.

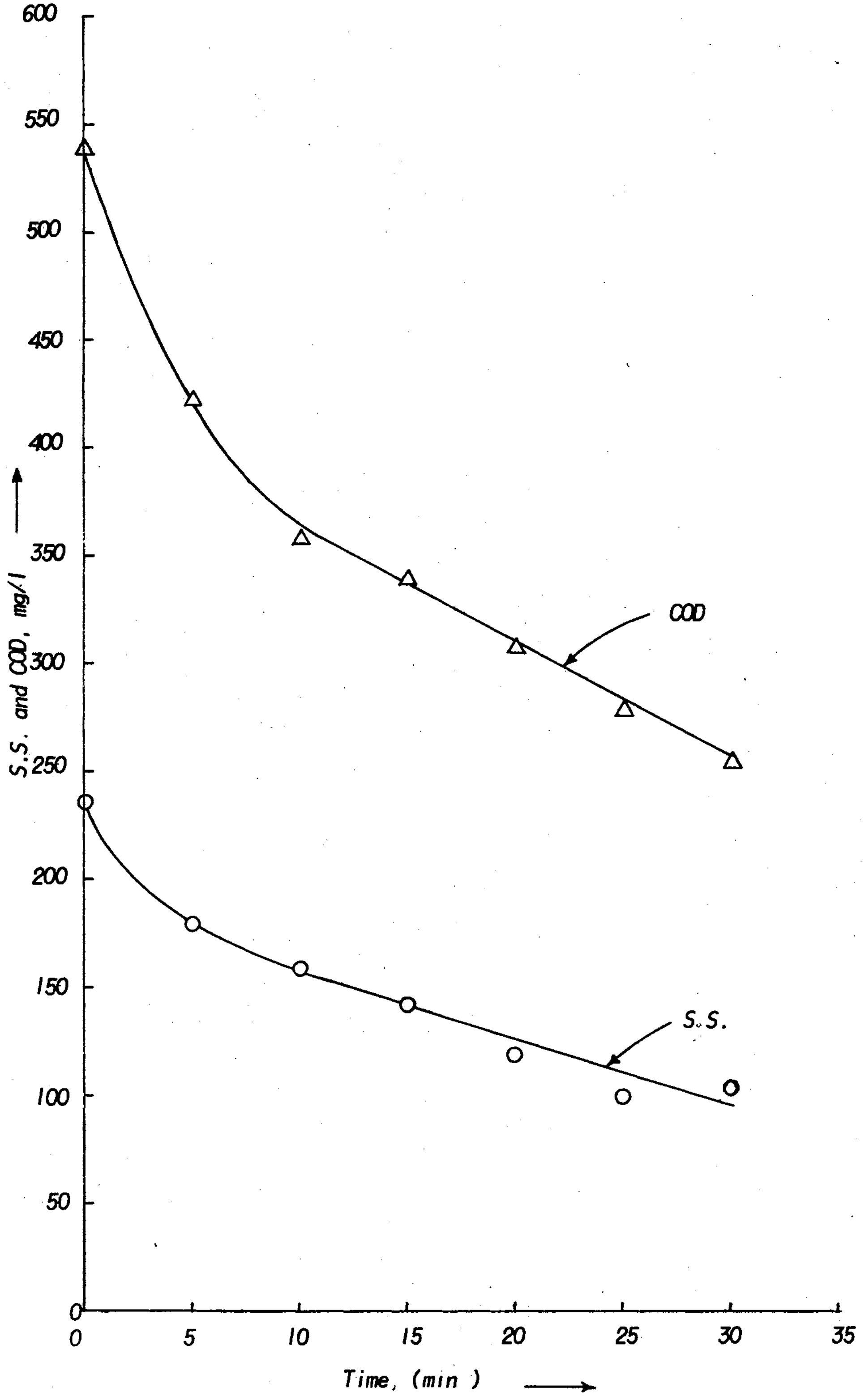

Figure 13. Continuous Recycle Results, Hydrocyclone No. 7, 5.0 Percent Underflow Rate, Diatomite Filter.

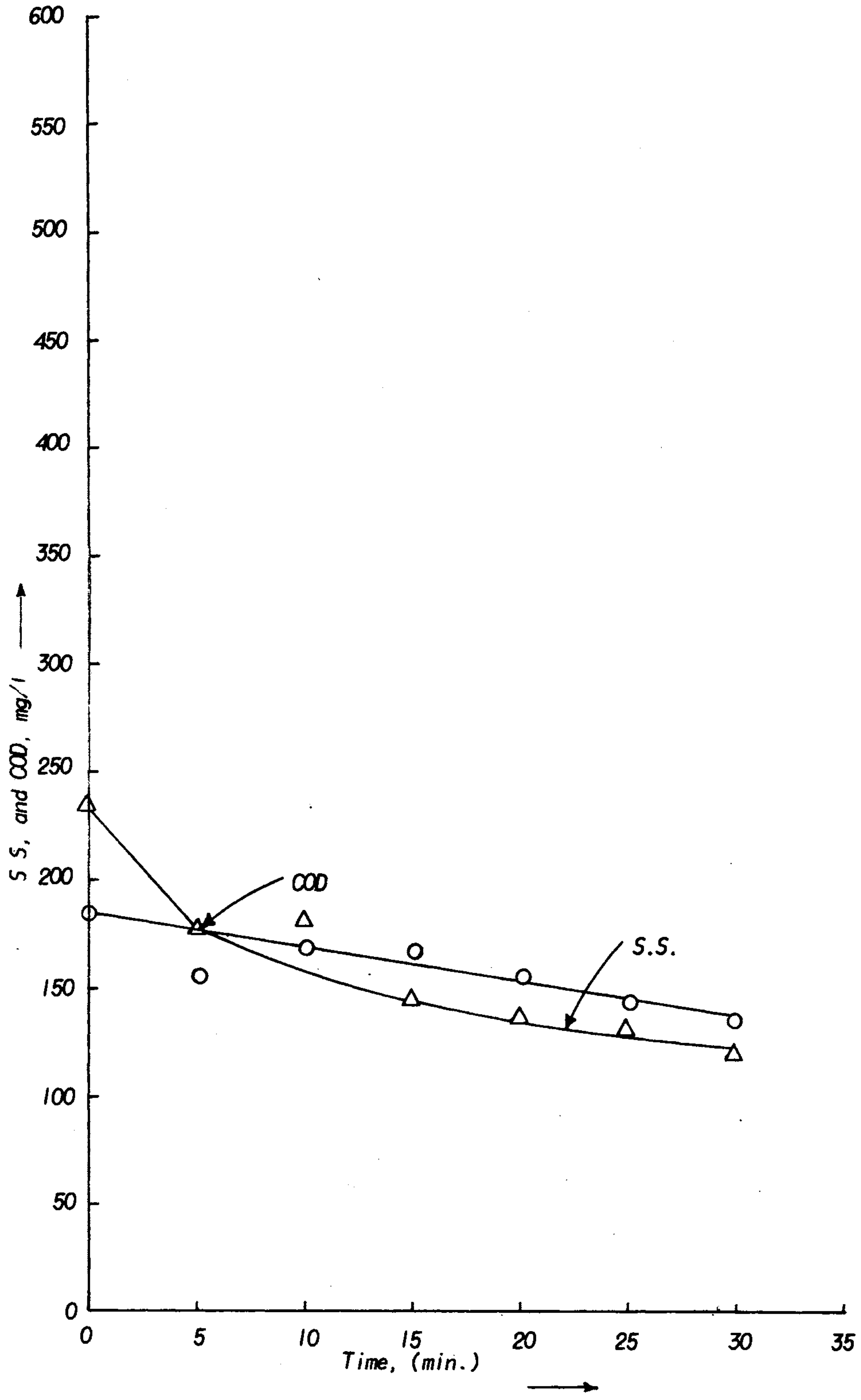

Figure 14. Continuous Recycle Results, Hydrocyclone No. 10, 2.5 Percent Underflow Rate, Diatomite Filter.

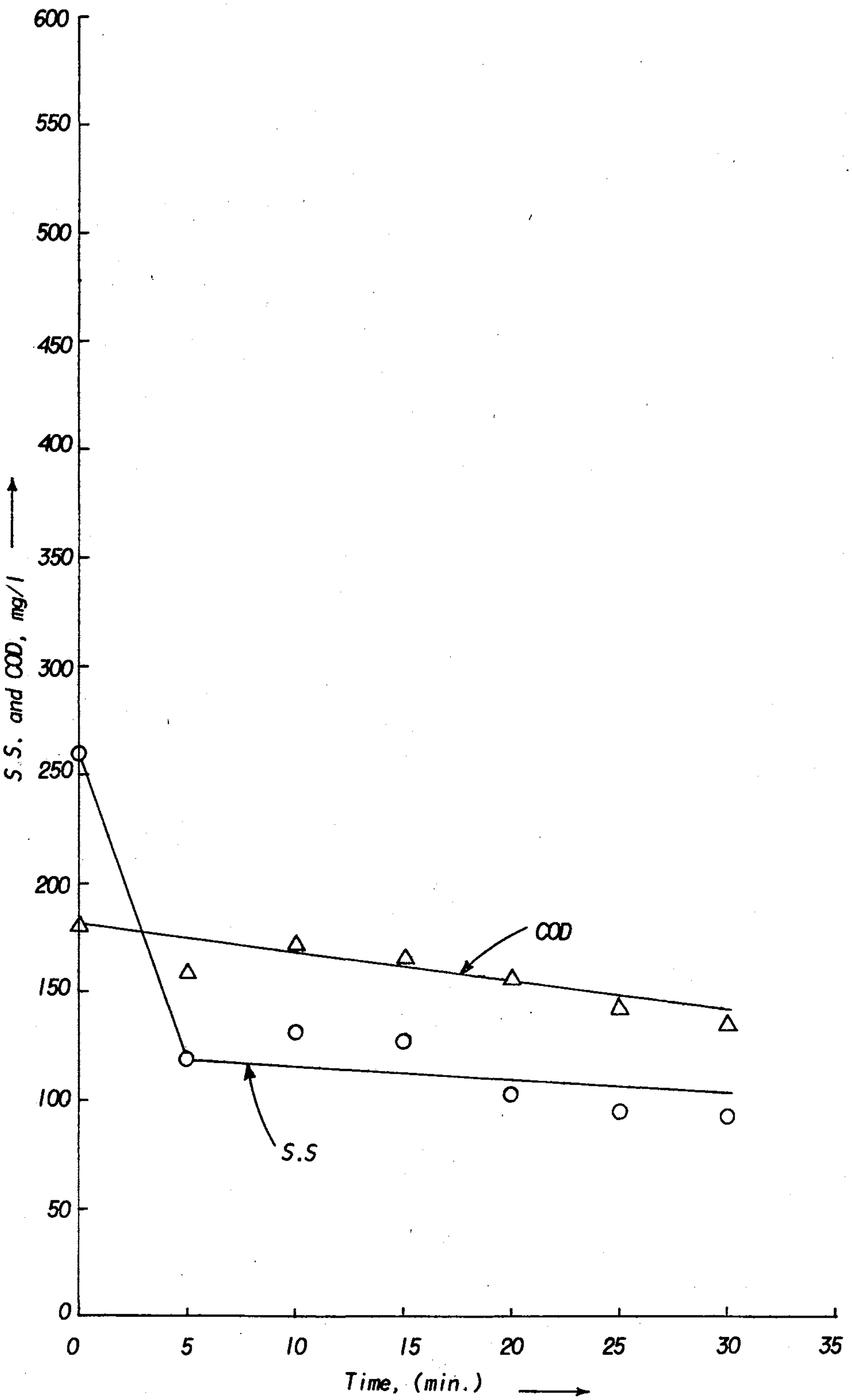

Figure 15. Continuous Recycle Results, Hydrocyclone No. 10, 5.0 Percent Underflow Rate, Diatomite Filter.

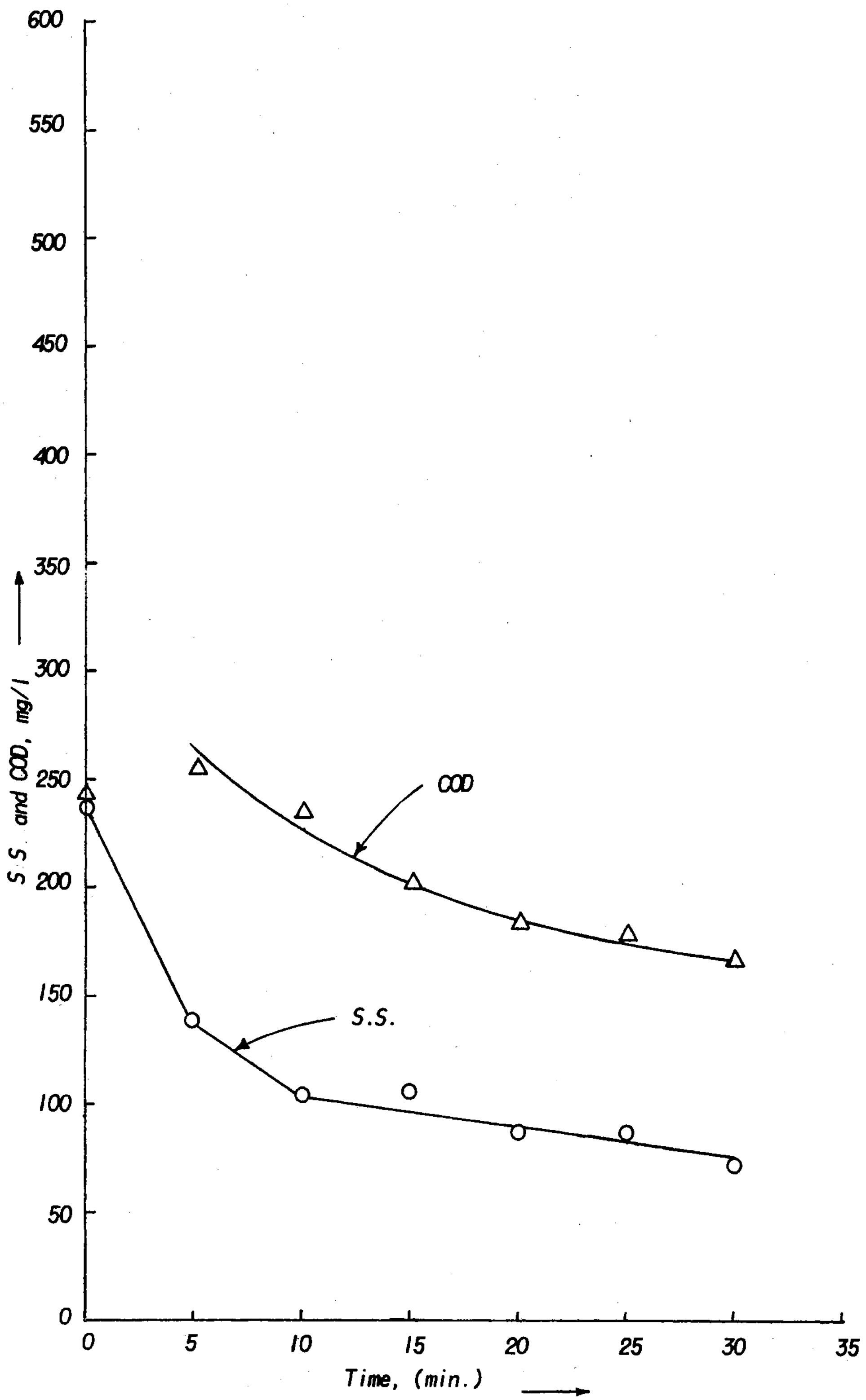

Figure 16. Continuous Recycle Results, Hydrocyclone No. 10, 10.0 Percent Underflow Rate, Diatomite Filter.

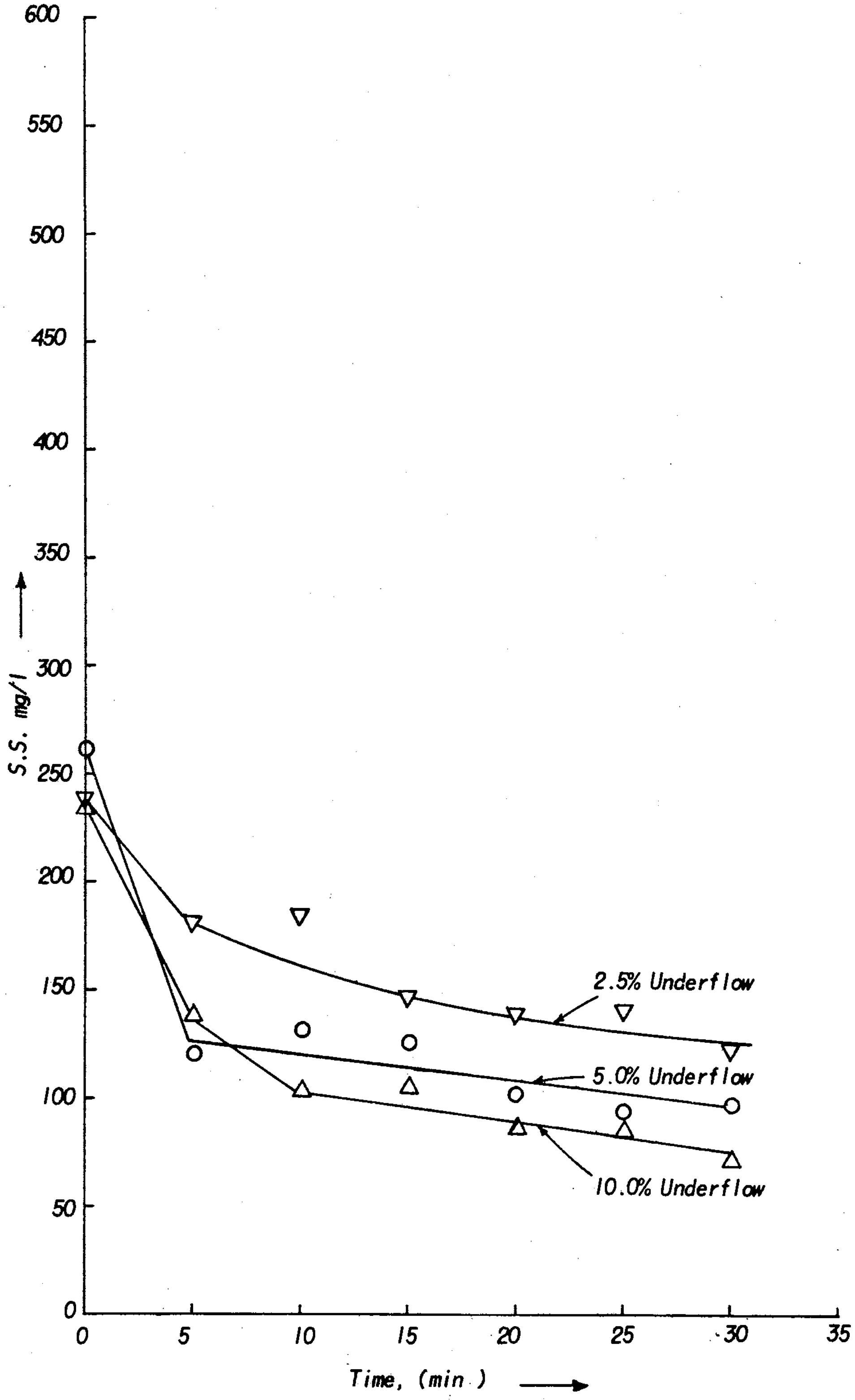

Figure 17. Continuous Recycle Results, Hydrocyclone No. 10, 2.5, 5.0 and 10.0 Percent Underflow Rates, Diatomite Filter.

Figure 14 presents the data obtained for 2.5 percent (0.1 gpm) underflow rate. The initial solids concentration in the feed at zero time was 235 ppm; at five minutes (two passes) the solids concentration was 180 ppm. From then on it decreased rather linearly to 121 at 30-minute intervals. An overall efficiency of 47.3 percent solids removal is indicated by the data.

The COD removal curve exhibited a rather linear removal. The initial inflow COD of flocculated wastewater was 185 ppm; it decreased linearly to 135 ppm in 30-minute recycle (12 passes). The overall COD removal efficiency was 27 percent. Since the experiment was performed with 2.5 percent underflow rate for 30 minutes on a 10-gallon batch, 3.0 gallons of underflow wastewater was passed through the filter.

Figure 15 presents data on a 5.0 percent underflow rate through the diatomite filter. The initial solids concentration was 260 ppm; at five minutes it was 120 ppm, and from then on it decreased gradually to 94 ppm in 30 minutes. An overall solids removal efficiency of 65 percent resulted.

The COD curve followed a rather linear decrease from an initial COD of 185 ppm to 135 ppm in 30 minutes. An overall COD removal efficiency of 30 percent was achieved. Also, a total of six gallons of the underflow wastewater was passed through the diatomite filter during the 30-minute test.

Figure 16 illustrates the results of a 10 percent underflow experiment. The suspended solids decreased from 235 ppm at zero time to 185 ppm after five minutes; then a gradual decrease to 75 ppm at 30 minutes occurred. An overall solids removal efficiency of 69.0 percent resulted.

The COD removal curve followed a continuous smooth curve from an initial COD of 255 ppm to 165 ppm at the 30-minute interval. An overall COD removal efficiency of 36 percent developed. At a 10 percent underflow rate and a 10-gallon batch feed, 12 gallons of underflow wastewater was passed through the filter during the 30-minute test.

Figure 17 presents the results of solids removal for 2.5 percent, 5.0 percent, and 10.0 percent underflow rates discussed above, on the same coordinate system for comparison purposes. It can be seen that the removal characteristics are very similar for the 5.0 percent and 10.0 percent underflow rates. Very little suspended solids are removed after the first five minutes. However, unit No. 10 with a 2.5 percent underflow rate, removed the solids continuously and gradually throughout the experiment.

Figures 18 through 21 present the results of continuous recycle studies with unit No. 10, using a gravity sand filter as contamination trap.

Figure 18 illustrates the results for a 2.5 percent underflow rate experiment. The solids concentrations follow a continuous smooth curve. The initial solids concentration is 399 ppm; it decreased gradually and uniformly to 248 ppm at 30 minutes, and 234 ppm at 45-minute intervals. The suspended solids removal efficiencies were 39.5 percent for 30 minutes, and 42.0 percent for 45-minute recycles. The amount of underflow wastewater passed through the sand filter was 30 percent of the total capacity for 30 minutes, and 45 percent for 45-minute recycle times.

The COD decreased rather linearly from about 625 ppm at zero time to 515 ppm at 30 minutes, and 485 ppm at 45-minute intervals. The COD removal efficiency was 16.7 percent for 30 minutes, and 22.5 percent for the 45-minute recycle.

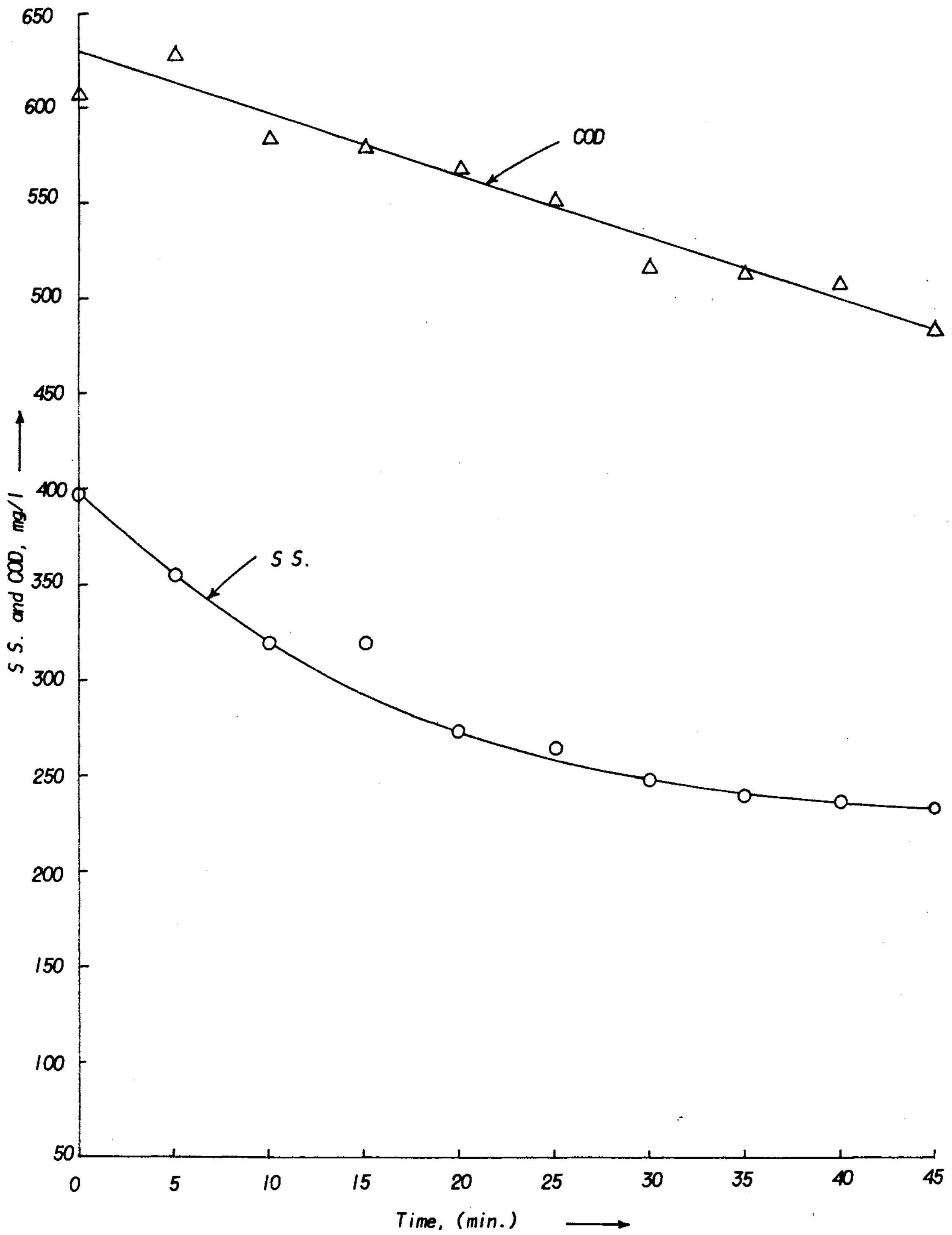

Figure 18. Continuous Recycle Results, Hydrocyclone No. 10, 2.5 Percent Underflow Rate, Sand Filter.

Figure 19 presents the data for a 5.0 percent underflow rate. The initial solids concentration was 382 ppm; at five minutes it was 282 ppm, and from then on it decreased rather linearly to 153 ppm at 30 minutes, and 90 ppm at 45-minute intervals. The solids removal efficiency was 66.0 percent for 30 minutes, and 73.3 percent for the 45-minute recycle.

COD removal followed a continuous smooth curve. At zero time it was 600 ppm; at five minutes, 488 ppm; at 30 minutes, 333 ppm; and at 45 minutes, 280 ppm. COD removal efficiencies were 46 percent for 30 minutes, and 55 percent for 45-minute recycles. A total amount of six gallons (60 percent) for 30 minutes, and nine gallons (90 percent) for 45-minute runs of underflow wastewater were passed through the sand filter.

Figure 20 presents data on a 10 percent underflow rate experiment. The solids concentration was 404 at zero time; it decreased abruptly to 287 ppm and 170 ppm at five- and 10-minute intervals, respectively. From then on, the solids followed a rather linear gradual decrease to 98 ppm at 30-minute and 60 ppm at 45-minute intervals. The solids removal efficiencies of 70 percent for 30-minute and 80 percent for 45-minute recycles were obtained.

The COD removal followed a continuous smooth curve. The initial COD was 584 ppm; in a 15-minute interval it had decreased at a constant rate to 340 ppm; and from then on it followed a gradual linear decrease to 300 ppm at 30-minute and 212 ppm at 45-minute intervals. An overall efficiency of 53 percent for 30-minute and 64 percent for 45-minute recycles was obtained for COD removal. In this experiment, the 10-gallon batch was recycled twelve times through the cyclone, and 12

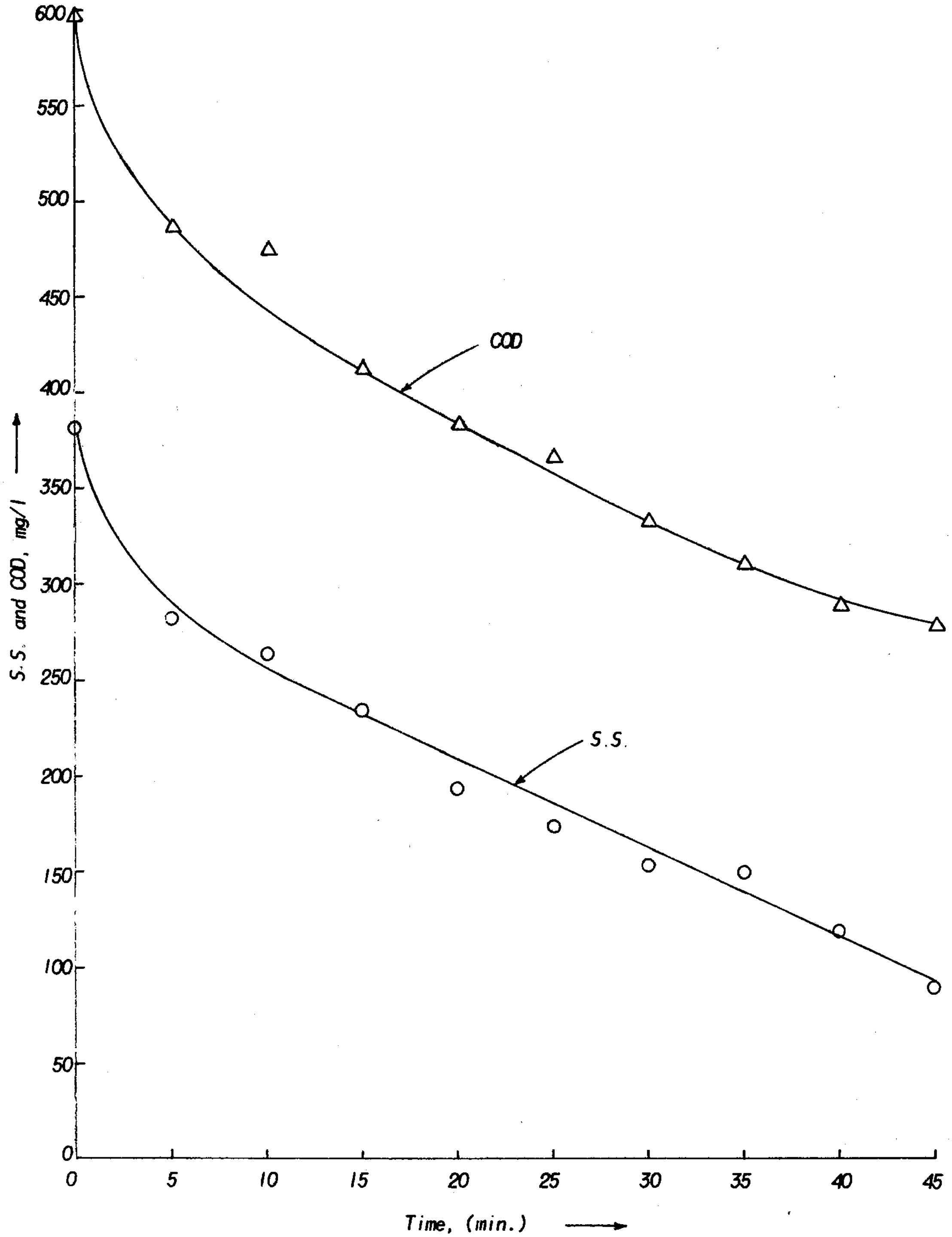

Figure 19. Continuous Recycle Results, Hydrocyclone No. 10, 5.0 Percent Underflow Rate, Sand Filter.

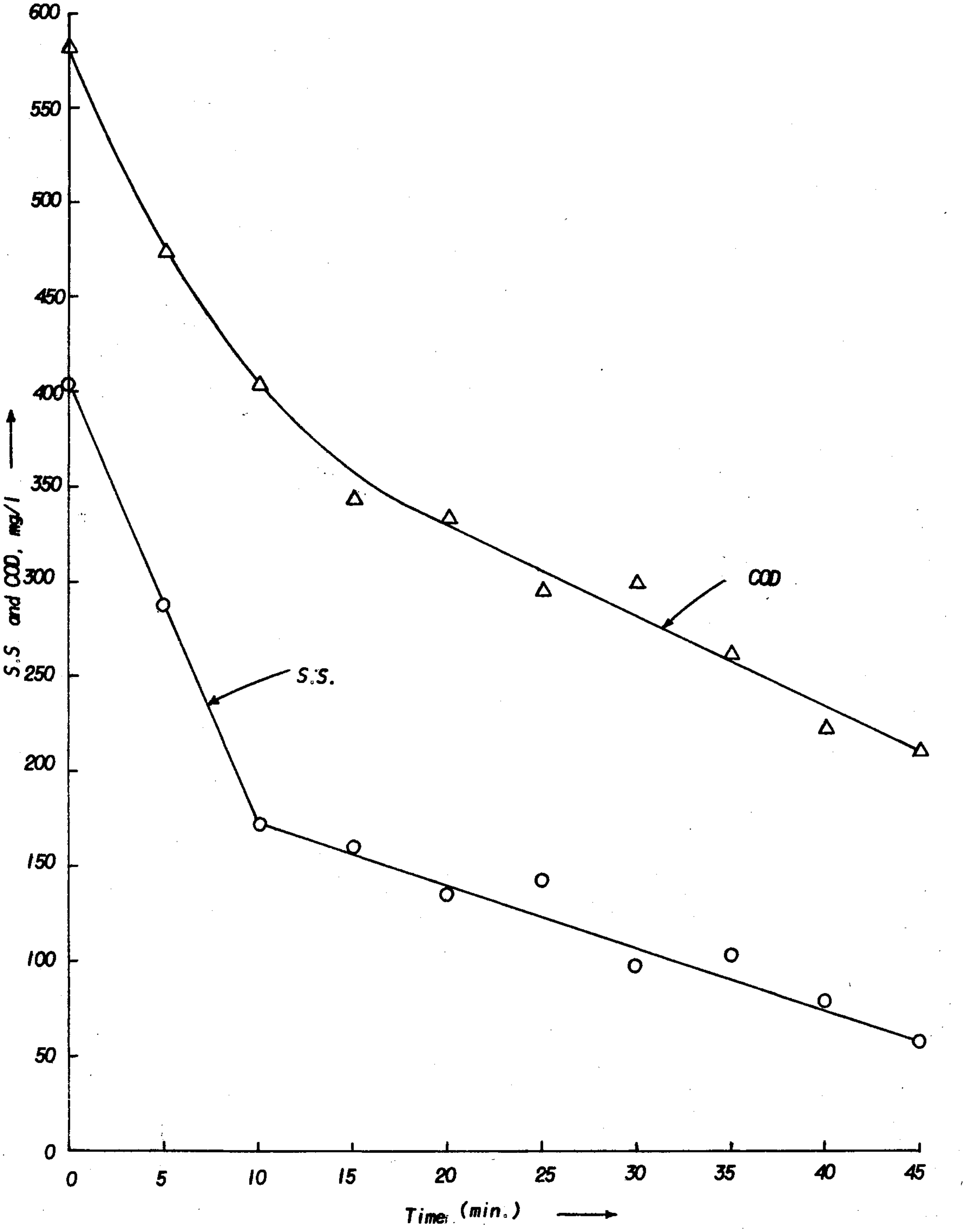

Figure 20. Continuous Recycle Results, Hydrocyclone No. 10, 10.0 Percent Underflow Rate, Sand Filter.

gallons of underflow wastewater was passed through the sand filter in 30 minutes. The corresponding figures for 45 minutes were 18 times and 18 gallons, respectively.

Figure 21 illustrates solids removal curves for unit No. 10 at various underflow rates on the same coordinate system for comparison purposes. The 2.5 percent underflow rate data follows a smooth continuous curve with minimal gradual changes of slope throughout the experiment, while the five percent and 10 percent underflow rate experiments show a major solids removal in the first five to 10 minutes of the run (2 to 4 passes) followed by a minor gradual removal through the rest of the experiment.

## D. Gravity Sedimentation

Figures 22 through 24 present results of gravity sedimentation of the wastewater with and without chemical treatment. The results are analyzed for suspended solids and COD removal.

Figure 22 illustrates the results with no chemical treatment. There are two separate experiments shown here. In both experiments, the solids follow a continuous smooth curve. Efficiencies depend on initial solids concentrations. The first curve starts at 355 ppm; it reaches 220 in five minutes, and 135 ppm in 30 minutes. The resultant efficiency is 62 percent. The second curve starts at 260 ppm and uniformly decreases to 120 ppm in 30 minutes; an efficiency of 54 percent resulted.

The COD removal of the first experiment started at 612 ppm; in five minutes it reduced to 456 ppm, and in 30 minutes, to 352 ppm. The resultant efficiency was 42.5 percent. The COD of the second experiment

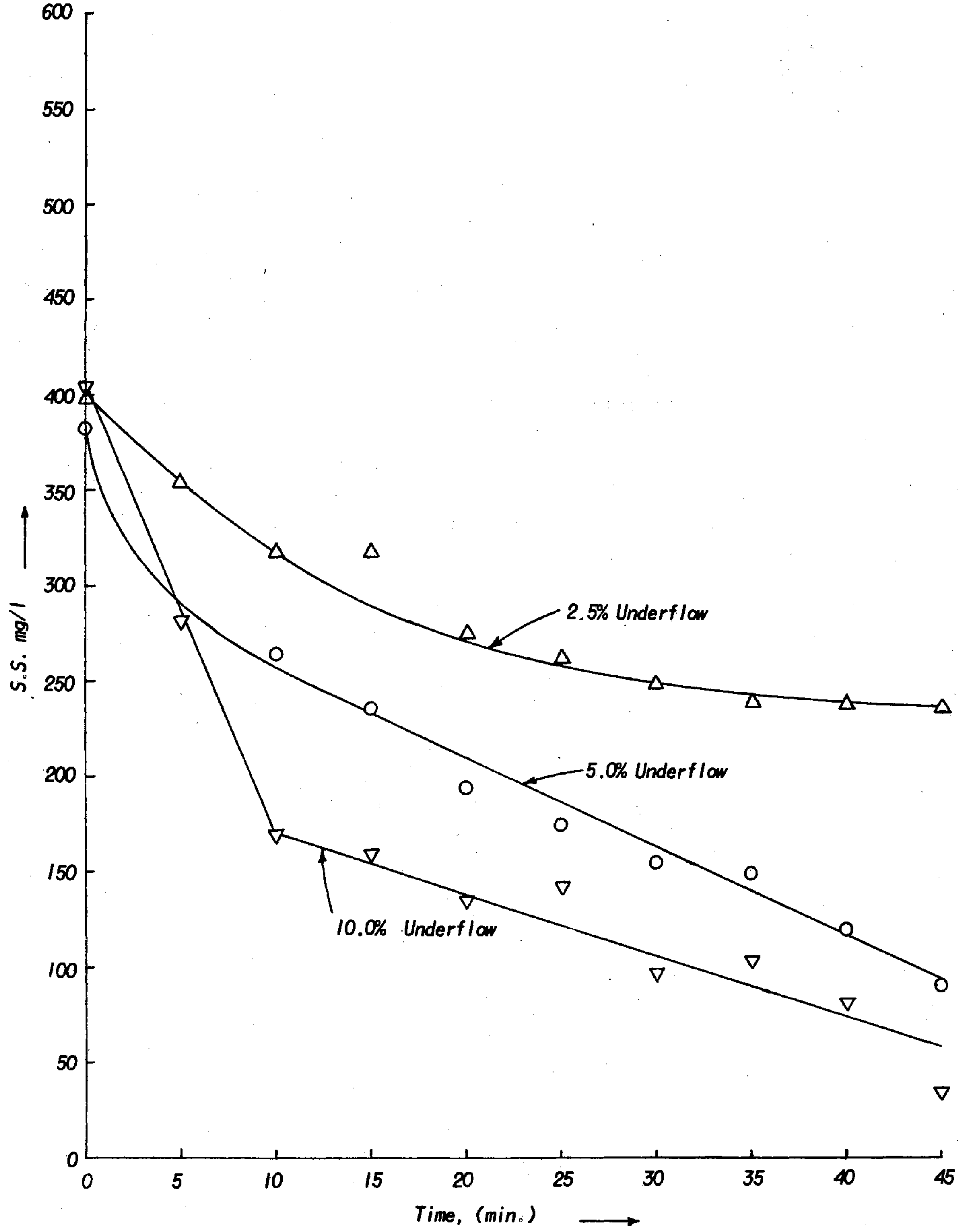

Figure 21. Continuous Recycle Results, Hydrocyclone No. 10, 2.50, 5.0, and 10.0 Percent Underflow Rates, Sand Filter.

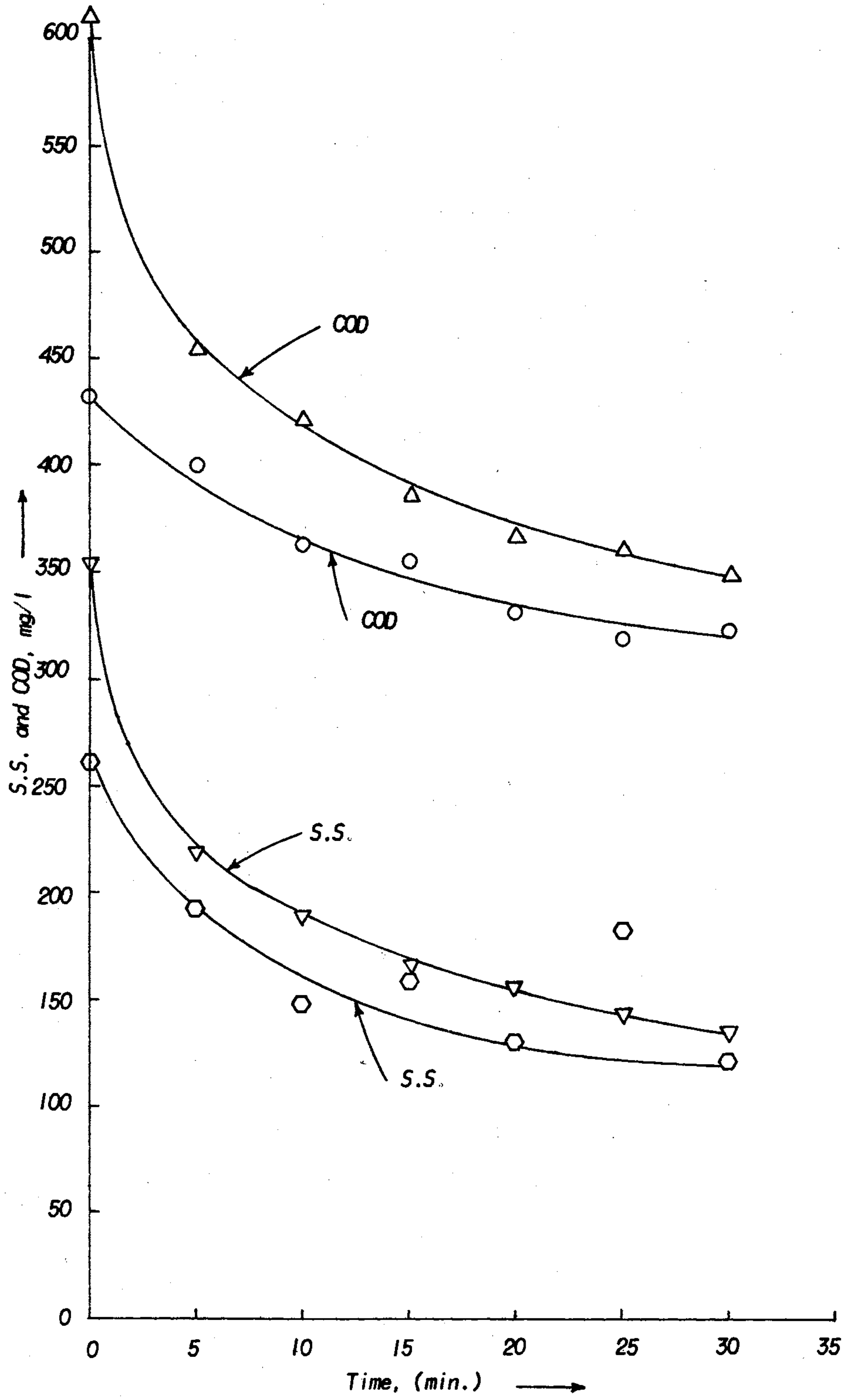

Figure 22. Gravity Sedimentation, No Chemical Treatment.

initially was 432 ppm; it decreased uniformly to 324 ppm in 30 minutes. An overall 26 percent COD removal efficiency resulted for the second experiment.

Figure 23 presents the results of sedimentation of chemically-treated wastewater. The chemicals and dosages were 60 ppm ferric sulfate and 8 ppm Calgon WT-2600. The solids and COD removal data followed a sharp decline in the first five to 10 minutes; afterward they barely decreased. The initial solids concentration was 275 ppm; it was 60 ppm in five minutes, 31 ppm in 10 minutes, 8 ppm in 30 minutes, and 2.5 ppm in 45 minutes of sedimentation. The efficiencies of solids removal were 97.1 percent and 99.3 percent for 30 and 45 minutes, respectively.

The COD removal curve was 436 ppm at zero time; it decreased to 180 ppm in five minutes, 140 ppm in 10 minutes, and 116 ppm in 45 minutes. An overall efficiency of 71 percent for 30 minutes, and 73 percent for 45 minutes was obtained.

Figure 24 shows the solids removal curves for treated and untreated wastewater from Figures 22 and 23, plotted on the same coordinate system for comparison purposes. Both curves are smooth and continuous, but the curve with chemicals has a much steeper slope initially, levelling off after 10 minutes. Even though its initial solids is much lower than that for the untreated curve, it yields an efficiency of 97 percent, compared to 62 percent for untreated wastewater.

## E. Jar Studies

In this section, the results of two kinds of polyelectrolytes and three inorganic coagulants are reported. The optimum dosages of each

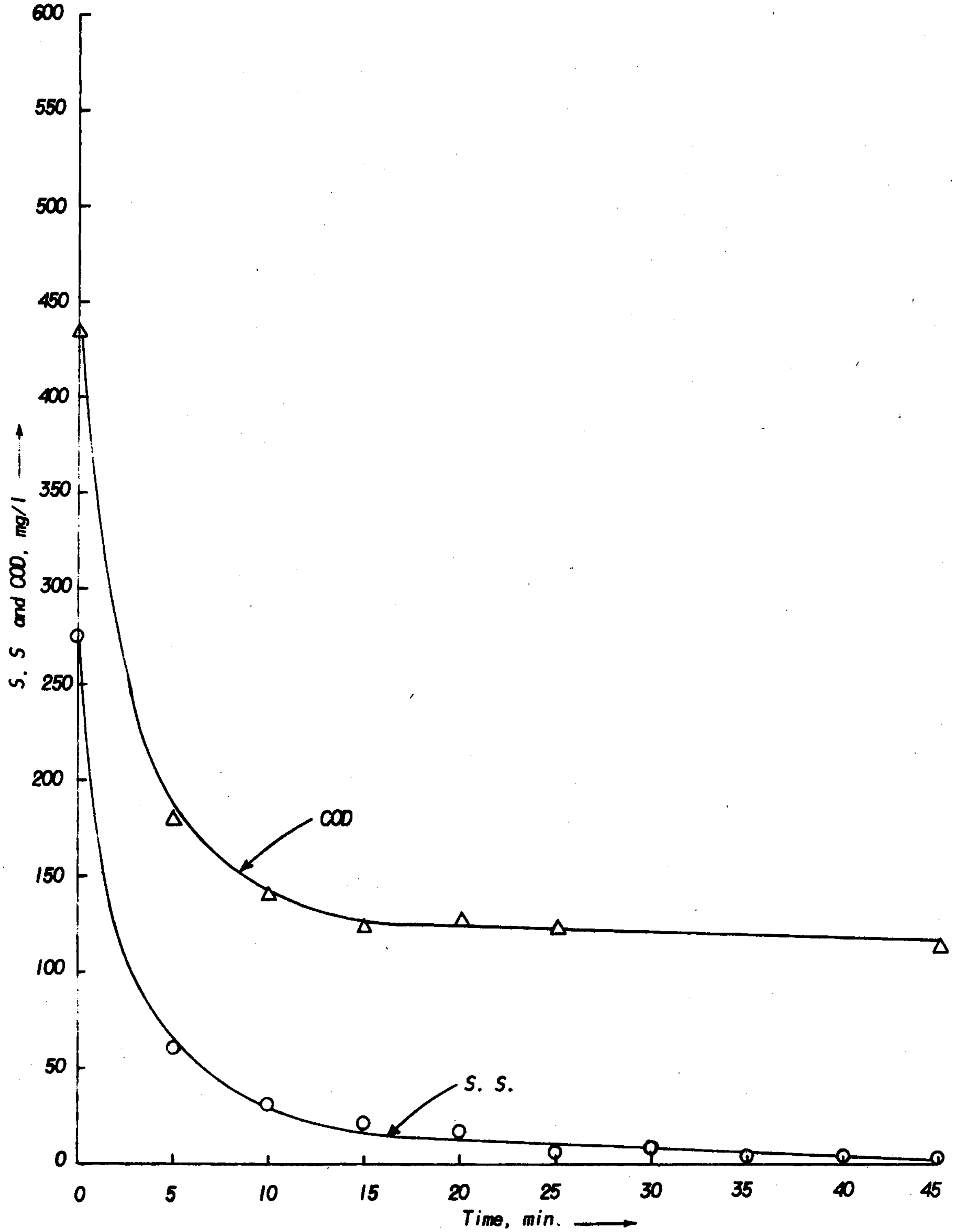

Figure 23. Gravity Sedimentation, With Chemical Treatment.

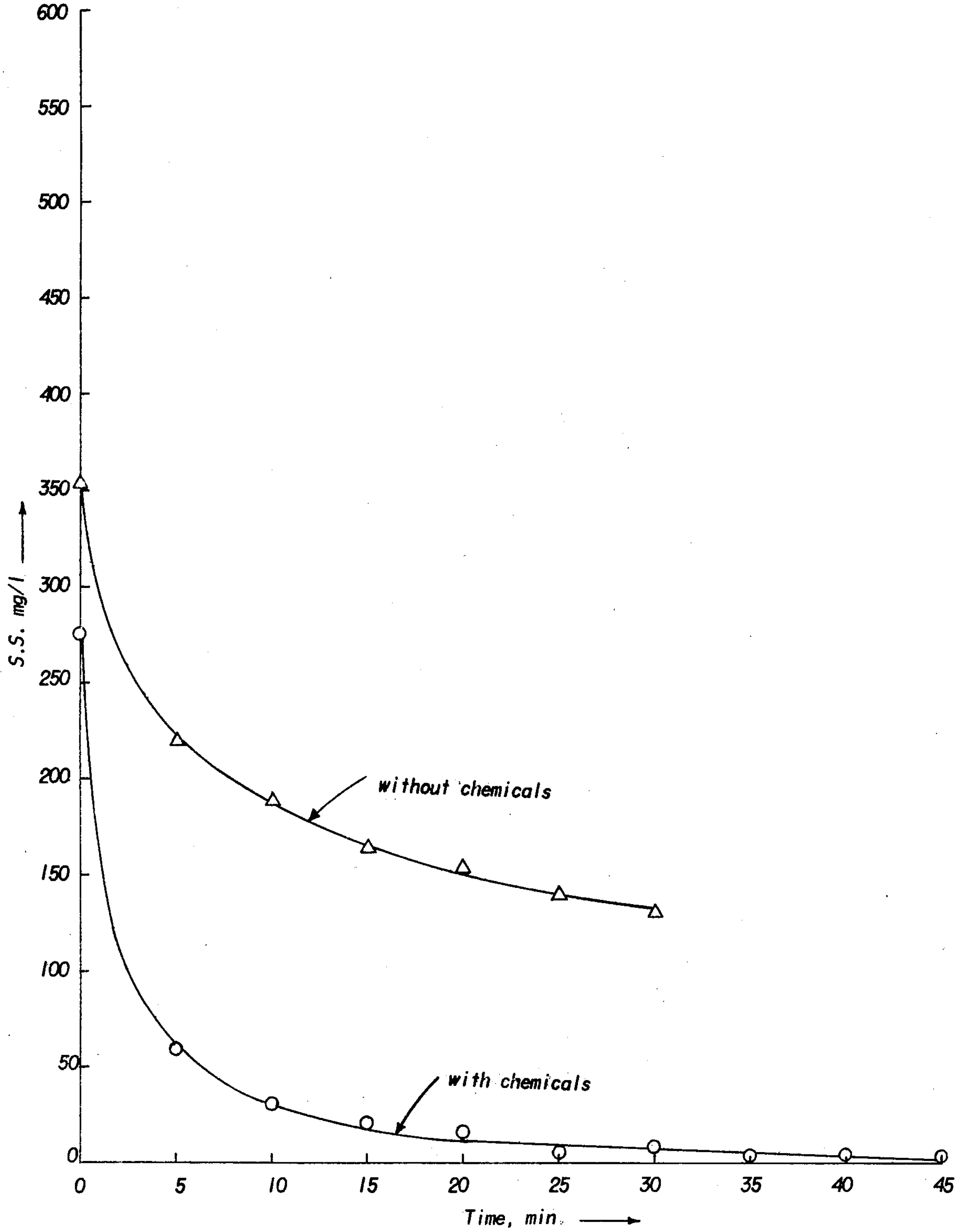

Figure 24. Gravity Sedimentation, With and Without Chemical Treatment.

are shown in Table V. Ferric sulfate was the best flocculant among the inorganic chemicals, and Calgon WT-2600 was the best among the organic chemicals, though Hercofloc 828.1 gave comparable results. It was also found that flocs hardly formed if the inorganic coagulant was not added before the polyelectrolyte. The flocs were large and cohesive, and gave a clear-water appearance to the wastewater.

TABLE V

OPTIMUM DOSAGES OF CHEMICAL COAGULANTS

| Ionic Character | Coagulant | Optimum Dosage (ppm) | Remarks |
|---|---|---|---|
| Neutral | Alum, $Al_2(SO_4)_3$ | 50 | |
| Neutral | Ferric Sulfate, $Fe_2(SO_4)_3$ | 60 | |
| Neutral | Lime, $Ca(OH)_2$ | 50 | Not much effect |
| Cationic | Calgon WT-2600 | 8 | Most effective of all Calgon polymers |
| Cationic | Calgon WT-2630 | 10 | |
| Cationic | Calgon WT-2660 | 12 | |
| Cationic | Calgon WT-2870 | 10 | Not much effect |
| Non-Ionic | Calgon WT-2690 | 10 | |
| Anionic | Calgon WT-2700 | 1.0 | Not much effect |
| Anionic | Calgon WT-2900 | 0.5 | Not much effect |
| Anionic | Calgon WT-3000 | 0.4 | Not much effect |
| High Cationic | Hercofloc 828.1 | 6 | Most effective of all Herofloc polymers |
| Medium Cationic | Hercofloc 814 | 8 | |
| Low Cationic | hercofloc 810 | 11 | |
| High Anionic | Hercofloc 822 | - | No effect |
| Medium Anionic | Hercofloc 836 | - | No effect |
| Low Anionic | Hercofloc 816 | - | No effect |

# CHAPTER V

# DISCUSSION

The performance efficiencies of the hydrocyclones tested are shown in Table IV. Upon chemical treatment of the wastewater, an increase of efficiency occurred for all hydrocyclones except for unit No. 5. The only parameter dimension of this unit different from that of unit 9 is its much larger overflow opening (Table IV). Therefore, it may be concluded that in the case of unit No. 5 either the overflow diameter was too large to force the flocs through the underflow opening, or the 35 psi pressure drop was too large and the flocs were broken to a size finer than the hydrocyclone could have removed.

The rest of the hydrocyclones showed an increased solids removal efficiency of 5 to 20 percent due to chemical treatment. It is also noted that unit No. 9 with a 74-psi pressure drop, increased its efficiency by 10 percent upon chemical treatment, while units Nos. 4 and 6 did not improve as much even though they had lower pressure drops.
In the previous chapter, it was also reported that breakage of flocs did occur in all of the experiments; therefore, it is concluded that flocculation does improve hydrocyclone performance if the broken flocs are not too fine for the hydrocyclone to remove. Also, the lower the pressure drop, the less floc breakage. Figure 9 graphically illustrates the effects of flocculated and non-flocculated wastewater on performance

of hydrocyclone No. 10, a 51 percent solids removal efficiency for treated sewage as compared to 32 percent for untreated sewage resulted.

In the continuous recycle experiments, the underflow rates were varied in order to determine the effects on hydrocyclone performance. Figure 12 compares the performance of hydrocyclone unit No. 7 at 2.5 percent and 5.0 percent underflow rates using a diatomaceous filter as the contamination trap. It is observed that the solids removal curve for 2.5 percent underflow rate levels off earlier than that for the 5.0 percent underflow rate. Figure 17 illustrates solids removal curves for 2.5 percent, 5.0 percent, and 10.0 percent underflow rates of unit No. 10 with the diatomaceous filter. It can be seen that at higher underflow rates, a fewer number of passes are required to obtain the same effluent solids level as those at lower underflow rates. Figure 21 illustrates the above conclusion for unit No. 10 using a sand filter as the contamination trap. Coincidentally, the initial solids concentrations for different underflow rates were all about the same, which leaves the efficiencies outside their relative effects. This figure shows that the solids removal curve for 10.0 percent underflow rate exhibits a much steeper slope for the first 10 minutes than does the curve for 5 percent underflow rate, and the same for the 5 percent underflow rate curve over that of the 2.5 percent underflow rate curve. It is speculated that there is an optimum underflow rate at which the most efficient performance results.

Table VI presents the various efficiencies obtained for units Nos. 7 and 10 with regard to solids and COD removals. At a 5.0 percent underflow rate and no chemical treatment, hydrocyclone No. 10 achieved 20 percent, 12 percent, and 5 percent suspended solids removal

# TABLE VI

## EFFICIENCIES OF MULTI SINGLE-PASSES AND CONTINUOUS FLOW RECYCLES OF HYDROCYCLONES NOS. 7 AND 10 ON THE TREATED WASTEWATER

| | | Single-Passes | | | | | | Continuous Recycle With Chemicals | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | No Chemicals | | | With Chemicals | | | 30 Minutes | | | | | | 45 Minutes | | |
| | | u = 5% | | | | | | Diatomite Filter | | | Sand Filter | | | Sand Filter | | |
| | | 1st Pass | 2nd Pass | 3rd Pass | 1st Pass | 2nd Pass | 3rd Pass | u = 2.5% | u = 5.0% | u = 10.0% | u = 2.5% | u = 5.0% | u = 10.0% | u = 2.5% | u = 5.0% | u = 10.0% |
| Unit No. 7 | percent S.S. removed | 15 | 10 | 5 | 30 | 10 | 10 | 64 | 69 | - | - | - | - | - | - | - |
| | percent COD removed | - | - | - | - | - | - | - | 53 | - | - | - | - | - | - | - |
| Unit No. 10 | percent S.S. removed | 20 | 12 | 5 | 40 | 20 | 10 | 50 | 65 | 70 | 40 | 66 | 78 | 42 | 73 | 80 |
| | percent COD removed | - | - | - | - | - | - | 27 | 30 | 36 | 17 | 46 | 53 | 22 | 55 | 64 |

efficiencies for the first, second, and the third passes, respectively, as compared to 15 percent, 10 percent, and 5 percent for unit No. 7 under the same experimental conditions. For the chemically treated wastewater, the corresponding figures were 40 percent, 20 percent, and 10 percent for unit No. 10, as compared to 30 percent, 10 percent, and 10 percent for unit No. 7, respectively. It should be noted that the chemical treatment of the wastewater increased the single pass S.S. removal efficiency of unit No. 10 by 20 percent as compared to 15 percent for unit No. 7.

The surface area of the sand filter was 0.35 square feet, while that of the diatomaceous earth filter was 0.69 square feet. Therefore, the hydraulic loading on the sand filter was twice as much as that on the diatomite filter for the same underflow rates. A disadvantage of the diatomaceous filter is that its flow-through rate per unit area (hydraulic loading) has to be kept within a minimum and a maximum rate, outside which the filter will either collapse or diatomite will seep through to the filtrate stream.

It was observed that both the diatomite filter and the sand filter had to be backwashed once every 30 minutes on the average. For the diatomite filter, approximately 150 grams of dry diatomaceous earth is washed away after each backwashing. This may be a considerable solid waste disposal problem, unless the diatomite is further used in other processes, or recovered. The sand filter requires about three gallons of clean water for each backwashing process. The use of the filters should be evaluated according to the prevailing circumstances. It may be more economical to discard the underflow slurry rather than recovering it.

Whenever the solids concentration of the underflow stream reaches that of the overflow stream, no further separation will be achieved by the hydrocyclone. These points are in Figures 18, 19, and 20, at 40, 20, and 35 minutes, respectively; they mark the end of solids separation accomplished by both the hydrocyclone and the filter, whereafter separation is done by the filter alone.

The gravity sedimentation experiments of this study were conducted under absolute quiescent conditions. Solids removal efficiency of 97 percent and COD removal efficiency of 71 percent in 30 minutes (Figure 23) were achieved. However, in practice, quiescent conditions are non-existent, and efficiencies of one-half to one-third of those reported here are obtained. As a rule of thumb, about 30 percent COD removal efficiency is expected from primary clarifiers.

The data presented here shows unit 10 with comparable results to be qualified as a primary clarifier by three passes. Further, it is proven that hydrocyclone performance on sewage can be improved by specific designs; unit No. 10 is by no means the ultimate design for this separation. Also, better chemicals may provide a stronger, shear-resistant floc and thereby improve the separation efficiency still further.

Hydrocyclones may be operated in parallel in order to meet high flow rate demands. For instance, a 40 gpm flow rate may be divided equally between ten hydrocyclones of 4 gpm flow rates. The overflow streams may be joined together or extended separately to another set of parallel hydrocyclones, operating in series with the first set of hydrocyclones. The operation in series requires the connection of the preceding overflow streams to the following inflow streams. The underflow streams may assume any desired connection. The hydrocyclone No. 10

produced a 40 percent efficiency of suspended solids removal after the first pass, and only 20 percent and 10 percent for the second and third passes, respectively. If this hydrocyclone is operated three consecutive times in series, the above efficiencies will result after each pass. It is important to determine the range of solids sizes that hydrocyclones are capable of removing, so that a set of hydrocyclones in series may operate on removal of the widest range of solids sizes possible in order to yield the maximum overall efficiency. Therefore, it may be more efficient to operate units Nos. 10 and 7 in series rather than two units of No. 10 in series, and so on.

## TABLE VI

## CONCLUSIONS

The results of this investigation support the following conclusions:

1. The use of a hydrocyclone is feasible as a suspended solids removal unit in municipal wastewater treatment.

2. Chemical coagulation of the wastewater can improve hydrocyclone perfomrance considerably.

3. The underflow rate variations do affect the hydrocyclone performance, though its separation efficiency is not influenced greatly.

4. The hydrocyclone can remove organic solids of municipal wastewater and thereby reduce its organic strength (COD).

5. It is feasible to improve the design of a hydrocyclone for more efficient treatment of municipal wastewater.

# CHAPTER VII

## SUGGESTIONS FOR FUTURE STUDY

The following suggestions for future study of hydrocyclones in municipal wastewater treatment are made, based on the results of this investigation:

1. Determination of the range of solids sizes that different hydrocyclones can remove.

2. Design and investigation of hydrocyclones to operate in series in order to remove as wide a range of solid sizes as possible.

3. Determination of optimum underflow rate and its possible relations with other parameters of the hydrocyclone.

4. Investigation into coagulants producing shear-resistant flocs.

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# APPENDIX

## Table of Terms

$D_c$ = Diameter of Hydrocyclone

$D_i$ = Feed inlet diameter of hydrocyclone

$D_o$ = Vortex finder diameter of hydrocyclone

$D_u$ = Diameter of underflow of hydrocyclone

$L$ = Length of hydrocyclone

$\theta$ = Theta, cone angle of hydrocyclone

$\phi$ = Phi, subcone angle of hydrocyclone

$\Delta_p$ = Pressure drop across inlet and overflow openings of hydrocyclone

$\gamma_f$ = Specific gravity of feed medium to hydrocyclone

$g$ = Acceleration due to gravity

$a_f$ = Area of feed opening of hydrocyclone

$Q$ = Flow rate of hydrocyclone

$\alpha$ = Alpha, flow coefficient

$N_R$ = Reynolds number

$v_f$ = Feed velocity of hydrocyclone

$\eta$ = Nu, the kinematic viscosity of feed medium

$v_t$ = Tangential velocity of a particle in hydrocyclone

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