THE PRIMARY APPLICATION OF THE HYDROCYCLONE FOR THE SEPARATION OF BIOLOGICAL SOLIDS FROM DISPERSED BACTERIAL SYSTEMS

By

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CHAPTER I

INTRODUCTION

As the world's population continues to increase placing more stress upon the environment, more efficient use of our natural resources, including our disappearing fresh water supply, will be required. To insure that maximum benefits are derived from these natural resources, more specifically the disappearing fresh water supply, more stringent standards will necessarily be placed upon effluents being discharged into these water supplies. To meet these requirements more efficient and more economical waste treatment systems must be developed. Our present methods of treating wastes will in most cases be unable to produce effluents of the required quality or will be able to do so only at a great cost.

One major problem confronting the sanitary engineer is solid-liquid separation. This process is usually included in both water treatment (drinking water) and wastewater treatment. In the water treatment process flocculated turbidity is separated from clear water. In the wastewater treatment process both primary and secondary separation are often required.

The activated sludge process is a commonly used secondary treatment process which generally produces high quality effluents when properly operated. Pipes (1) has stated that the primary factor controlling the performance of the activated sludge process is the separation of the sludge solids from the effluent in the secondary sedimentation process. Nearly all secondary treatment configurations include a solid-liquid separation device. Many such separation techniques have been tried with varying degrees of success. Some of these techniques include centrifugation, flotation, the addition of polyelectrolytes, microscreening, diatomaceous earth filtration, chemical clarification (lime or alum), fiber filtration, vacuum filtration, electrodialysis, countercurrent extraction, and gravity sedimentation with many variations. Gravity sedimentation has been utilized far more than any of the other processes in biological treatment configurations, not necessarily because it is more efficient than the others, but because it requires less maintenance and is more economical to operate. If a useable solid-liquid separation device is to be developed for incorporation into the secondary treatment configuration, it must compete primarily with gravity sedimentation.

This investigation deals with a separation device commonly used by many industries but not yet successfully applied to solid-liquid separation in wastewater treatment. This device is the hydrocyclone, commonly referred to as hydroclone or cyclone.

This investigation involved three types of hydrocyclones (Figure 1), two of which are of conventional design and one of which differs from the conventional hydrocyclones with the addition of a contamination trap (2) that was developed by the Oklahoma State University Mechanical Engineering Laboratories. The solid-liquid system utilized in the study was the dispersed bacterial system with solids ranging from approximately 30 mg/l to 850 mg/l. Attempts were made to determine the feasibility of using the hydrocyclone to separate the bacteria from the

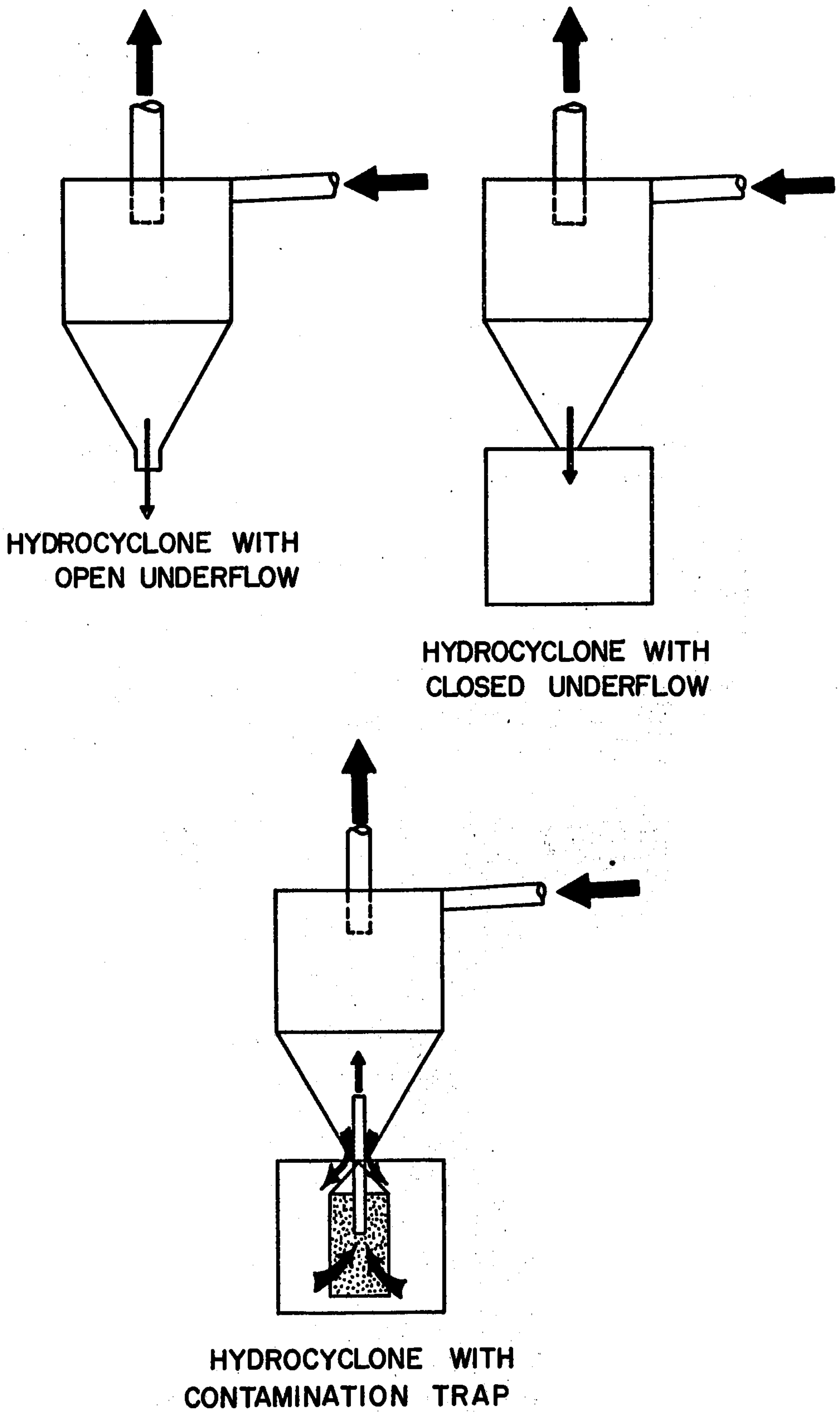

Figure 1. Typical Hydrocyclone Configurations.

liquid medium (tap water) in this system. Hydrocyclone parameters were varied in an attempt to indicate direction for design of more efficient systems.

The goal of this study was simply to determine the feasibility of utilizing the hydrocyclone to separate the solids from a dispersed bacterial system. No attempt was made to derive design equations, either theoretically or empirically.

CHAPTER II

LITERATURE RESEARCH

A. General

A great deal of work has been done to develop solid-liquid separation techniques, much of which has resulted in industrial application. The application of these techniques to the separation of biological solids in wastewater treatment has attained varying degrees of success.

One major problem encountered in the activated sludge process, seldom found in most industrial applications, is the variable separation characteristics of the material to be separated. Not only are the separation characteristics of the activated sludge variable, but unpredictably so. This fact alone eliminates many of the separation techniques commonly utilized industrially.

The mere fact that there are so many process variables in most waste treatment systems (hydraulic loading, organic loading, temperature, pH, etc.) causes the physical properties, therefore, the separation characteristics of the bacteria, to vary. Much work has been done to determine what effects these process variables have on sludge formation, the separation characteristics of the sludge formed, and what steps can be taken to improve these characteristics (1), (3), (4), (5), (6), (7), (8), (10), (11). Dick (12) has stated that the size and cost of treatment facilities are often controlled by settling characteristics of the sludge.

B. Factors Affecting Sludge Formation

Pipes (1) has done a considerable amount of work to simply define some of the factors affecting sludge formation, and to determine what effect these factors have on sludge formation. He makes an attempt to describe the various sludge types commonly encountered in the activated sludge process which separate poorly. He also attempts to define the process properties which cause the sludge to separate poorly, and corrective measures to be taken which might improve the sludge condition.

Pipes and Jones (13) and Richards and Sawyer (14) have related poor settling characteristics of sludge to specific microbial populations which develop in the system. The activated sludge process is dependent upon the bacterial populations which develop within it to utilize soluble organic material from the waste stream. The nature of this process allows heterogeneous populations to develop with frequent predominance changes occurring. Often a particular species or group of bacteria will predominate which has poor settling characteristics. These predominance changes often occur due to changes in process variables such as temperature, pH, hydraulic loading, organic loading, etc.

Reed and Murphy (11) have studied the effect of temperature on settling of activated sludge. They developed an equation for zone settling velocity of activated sludge based on experimental data. They found the influence of temperature on settling velocity to decrease as the concentration increased. They did, however, conclude that the compression or thickening of sludge is fully independent of temperature.

Ford and Eckenfelder (6) indicate that the oxygen tension in the system affects the settleability of activated sludge. They conclude that an aeration period serves to improve sludge settleability after an anaerobic period.

C. Separation Techniques

1. Gravity Sedimentation

Gravity sedimentation is the principal method of solid-liquid separation used in the wastewater treatment process. It is the process with which any other method would have to compete both economically and with comparable separation efficiency.

As early as 1904 attempts were made by Hazen (15) to describe settling tank theory. He proposed that settling basin efficiency is dependent primarily upon basin depth and overflow rate and is independent of detention time. Camp (16) described the theoretical settling pattern of discrete particles in an ideal rectangular basin as straight lines where all particles with similar settling velocities move in parallel paths.

Both of the above authors recognized that an ideal settling basin should be as shallow as possible to reduce detention times. Several instances (17), (18), (19), (20) have been reported in which tray settling principles were incorporated in the design of sedimentation basins. However, difficulties encountered in proper distribution of flow to a large number of shallow trays and problems of sludge removal from shallow trays have limited the practical application of this theory.

More recent attempts to incorporate shallow depth settling principles are the "Tube Settling" techniques reported by Culp and others (10), (21), (22). They report the incorporation of inclined tubes into clarifiers resulting in lower detention times, decreasing the required size of clarifiers, and improvement in their separation efficiency.

As mentioned earlier, the separation characteristics of a sludge are often poor. To improve the settling characteristics of a sludge, polyelectrolytes have been incorporated. Pipes and Hermann (7) have stated that the introduction of a flocculating agent can agglomerate filamentous growth in an activated sludge system into a settleable floc. They compare the cost of two cationic polymers and alum. The added cost of treatment by the alum process was determined to be approximately \$9.50 per million gallons treated, whereas they found the cost of treatment for the two cationic polymers to be approximately \$6.50 per million gallons treated and \$20.00 per million gallons treated.

Braithwaite (4) reported the successful incorporation of polyelectrolytes into an activated sludge plant at the city of Warren, Michigan. He reported a great improvement in sludge thickening at this plant. He reported that it was often impossible to thicken the sludge before incorporation of the polyelectrolytes.

Goodman and Witcher (5) reported that synthetic polymers can be of significant benefit in numerous areas of wastewater treatment, including sludge conditioning, elutriation, sludge index control and pressure flotation.

2. Air Flotation

It has been reported (23) that good separation (95+%) with a solids concentration of four to six percent will occur with a properly designed and operated flotation unit.

Geinopolos and Katz (24) have reported similar results. They report that in a conventional air flotation system a thickened activated sludge can be removed as a float with a solids concentration of from four to five percent. In their studies they found the solids concentration to be dependent upon many of the same variables that influence gravity sedimentation, primarily temperature.

3. Centrifugation

The first reported work on the use of a centrifuge for sludge dewatering was conducted by Schaefer (25) in 1902 at Cologne, Germany. A perforated basket centrifuge was used to dewater digested domestic wastewater sludges.

In 1920 an imperforate basket machine was installed in Milwaukee, Wisconsin (1), to thicken sludge. It soon proved not to be an economical method of dewatering activated sludge.

In 1934 an imperforate basket centrifuge developed by American Centrifugal Company was tested at Collingswood, New Jersey (26). This unit was capable of producing excellent solids concentration in the cake but recoveries on primary and activated sludge did not exceed 75 percent of the total solids.

The first unit to be operated with a continuous feed and discharge of solids was a Bird solid bowl conveyor centrifuge tested by the Dorr Company in the 1930's. The unit was tested on raw and digested sludges at Rahway, New Jersey, New Haven, Connecticut, and Cedar Rapids, Iowa (27).

In 1937, DeLaval introduced the disc type valve centrifuge to thicken activated sludge in Peoria, Illinois (28). This machine achieved thickened sludges of 4.8 percent solids and 75 percent recovery. Low capacity and plugging of the machine proved to be a problem with this unit. By 1950, DeLaval had installed an improved high capacity disc nozzle centrifuge at Sioux Falls, South Dakota, to thicken activated sludge (29). Reportedly, this unit attained removals of 97 percent with a cake concentration of 5.2 percent solids. High operating costs and maintenance problems resulted in abandoning this type of centrifuge for thickening waste activated sludge. It proved impractical to feed raw primary sludge to this type of unit because of the small clearances and the buildup of grease on the discs.

In 1954 the Bird Machine Company installed a solid-bowl conveyor centrifuge in Daly City, California, for the San Mateo Sanitary District (27). This unit, and others like it, were recovering 50 to 70 percent of the feed solids while discharging a cake of 20 to 35 percent total solids. This appears to have been the start of a gradual acceptance of the solid-bowl centrifuge by the sanitary industry.

4. Other Methods

Tchobanoglous and Eliassen (30) reported the use of graded sand filters to treat settled activated sludge effluent. Initial solids concentrations of 7 mg per 1 to 14 mg per 1 were used in their experiments. These initial solids concentrations were reduced to values as low as 0.7 mg per 1 in many of their filter runs. The major problem encountered was the plugging of the filters. The filter life was dependent upon the amount of solids in the filtered fluid.

Microscreening has been investigated for possible use for solids reduction from wastewater (31). Suspended solids reductions of 70 percent to 90 percent were reported. A cost for a 10 million gallon per day plant was estimated to be 1.5¢ per 1000 gallons. This report also included diatomaceous earth filtration as a possible method for solid-liquid separation. They reported an 85 percent reduction in turbidity at an approximate cost of 5¢ per 1000 gallons for both vacuum filters and pressure filters.

5. Hydrocyclones

The design of hydrocyclones is still in a rather unsophisticated state, even though their use dates back to pre-World War II days in Holland (32). Most equations that have been developed to predict hydrocyclone performance prove to be either incapable of extension or contain terms that are difficult or impossible to determine. Campbell (33) presents an equation for the prediction of hydrocyclone performance containing the number of turns taken by a particle in the hydrocyclone as a variable.

A major problem encountered in hydrocyclone design has been the inability to "scale up" designs based on equations developed for a particular size hydrocyclone. One technique used to avoid this problem has been to use several smaller capacity units rather than one larger hydrocyclone. One such unit is the Type TM by Dorr-Oliver Incorporated, consisting of 24 or 32 miniature cyclones installed in a common housing, operating in parallel, with provisions for introducing the feed and withdrawing the products (32).

Hydrocyclone design for a new application is largely a matter of judgment. There has been a great deal of work done to develop hydrocyclone theory to a state that will allow reliable theoretical design of units based on treatment requirements and input parameters. This will be discussed in the next chapter.

Hydrocyclones have been used for many industrial purposes. Bergman and others (34) report the use of three inch cyclones to recover barite from Gulf Coast muds in oil well drilling operations. They reported that a single cyclone could readily concentrate as much as 50 tons per day. To achieve more capacity, he recommended the operation of cyclones in parallel.

Lummus and Scott (35) reported the use of an 8 inch cyclone to separate the sand cuttings from drilling fluids in oil well drilling operations. They reported reclaiming 82 to 98 percent of the lost circulation materials from drilling fluids having a density range of 8.5 to 10.5 pounds per gallon.

Haas and others (36) discussed a hydrocyclone developed to remove precipitated fission and corrosion products from uranyl sulfate solutions in aqueous homogeneous nuclear reactions. Tests were performed on 0.16 inch, 0.25 inch, 0.4 inch and 0.5 inch diameter hydrocyclones. They found they could attain acceptable separation of particles approximately 1 micron in diameter.

Some of the industrial applications of the hydrocyclone reported in the literature but not discussed in detail (37), (38) are listed as follows:

1. Classifiers in closed circuit grinding as in cement mills, cyanidation mills, flotation plant regrind circuits, and iron-ore circuits.

2. Desliming ground ore prior to flotation, tabling and other concentration processes in which the slime fraction is detrimental.

3. Removing undesirable minus 200-mesh fines from glass sand, recovering and classifying sand to be used for construction, classifying bentonite and pumice slurries at 10 microns, and degritting clay slurries, slaked lime, and whiting.

4. The manufacture of evaporated salt. Used to classify sodium chloride slurry at about 200-mesh, the overflow fraction being returned to the evaporator for further crystal growth.

5. Pulp and paper industry cyclones are used for removal of undesirable coarse and heavy particles from dilute pulps.

6. Impurities in the food industry products are removed from starch by groups of 15-mm diameter cyclones.

7. In coal preparation, cyclones are used to make possible a closed water circuit. The wash water which formerly contaminated streams is now treated by cyclones to recover the fine coal and the cyclone overflow is clean enough for reuse as wash water.

8. Recovery of solids from water used to scrub flue gas.

9. Cleaning of wash water used in wet screening.

10. Used to separate minerals, i.e., coal from shale due to differences in specific gravity.

11. Removal of fine particles from green liquor in the recausticizing steps of sulfate kraft mills.

12. Separation of starch from gluten.

CHAPTER III

THEORETICAL CONSIDERATIONS

A. General

A hydrocyclone is a vortical separator whose dispersion medium is a liquid. Its separation characteristics are due to the high particle settling velocities which result from forces that occasionally reach a value of several thousand times the force due to gravity.

The hydrocyclone shown in Figure 2 is a classical configuration. It consists of a cylindrical section (A) mounted above a truncated cone (B). The inlet nozzle (C) enters the cylindrical section (A) tangentially at the top. The overflow nozzle (D), commonly known as the vortex finder, extends partially into the top center of the cylindrical section (A). An opening at the apex of the truncated cone serves as the underflow nozzle (E). Shown at the apex of the cone is the collection pot (F). The purpose of the collection pot (F) is to collect the particles that are discharged from the underflow nozzle (E). The collection pot may or may not be included in particular hydrocyclone configurations, this being the distinction between open and closed underflow units.

Figure 3 illustrates the general flow patterns resulting in particle separation found within the hydrocyclone. The fluid enters the hydrocyclone tangentially through the inlet nozzle. The high velocity at which the fluid enters tangential to the cylindrical section creates

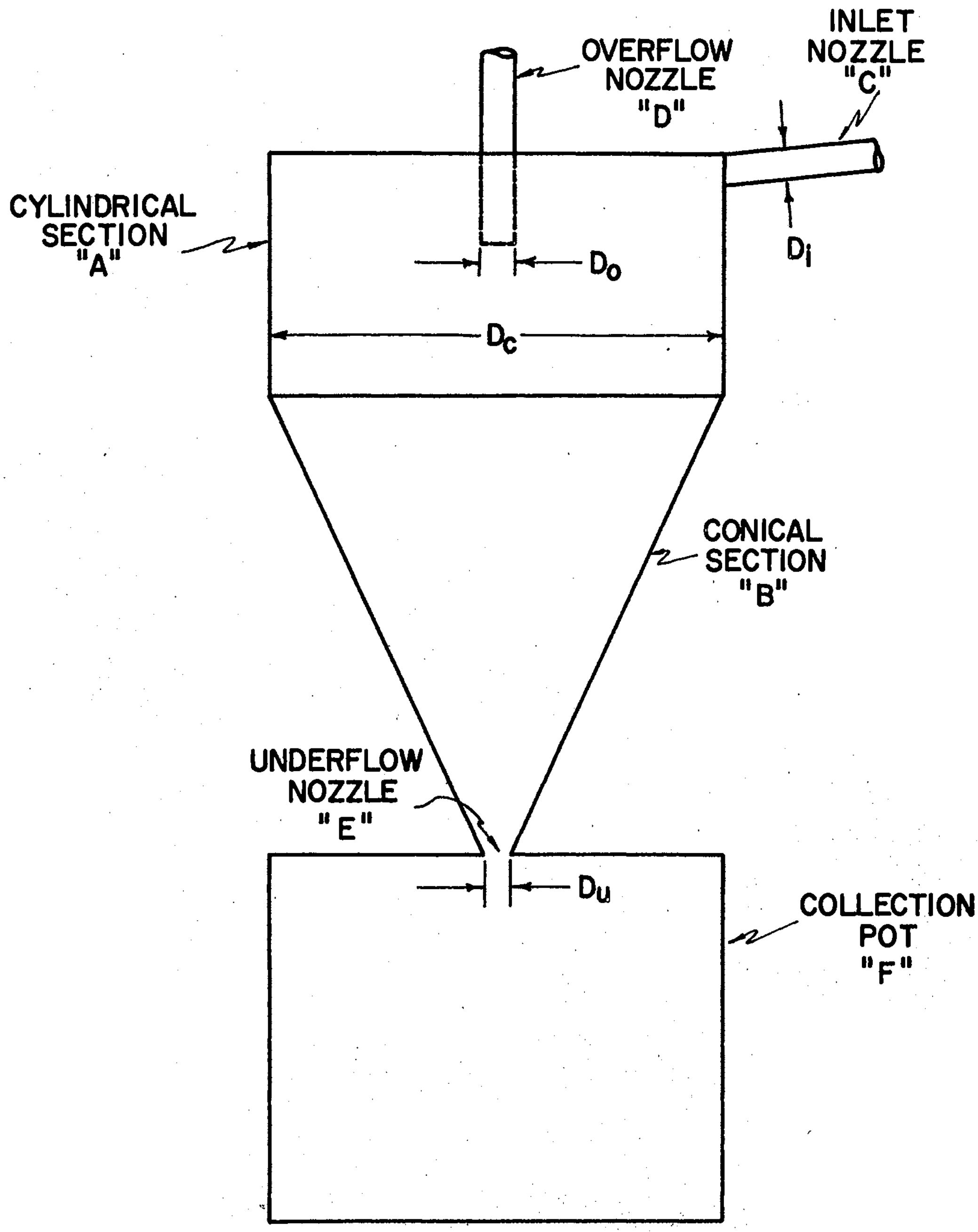

Figure 2. Classical Hydrocyclone Configuration.

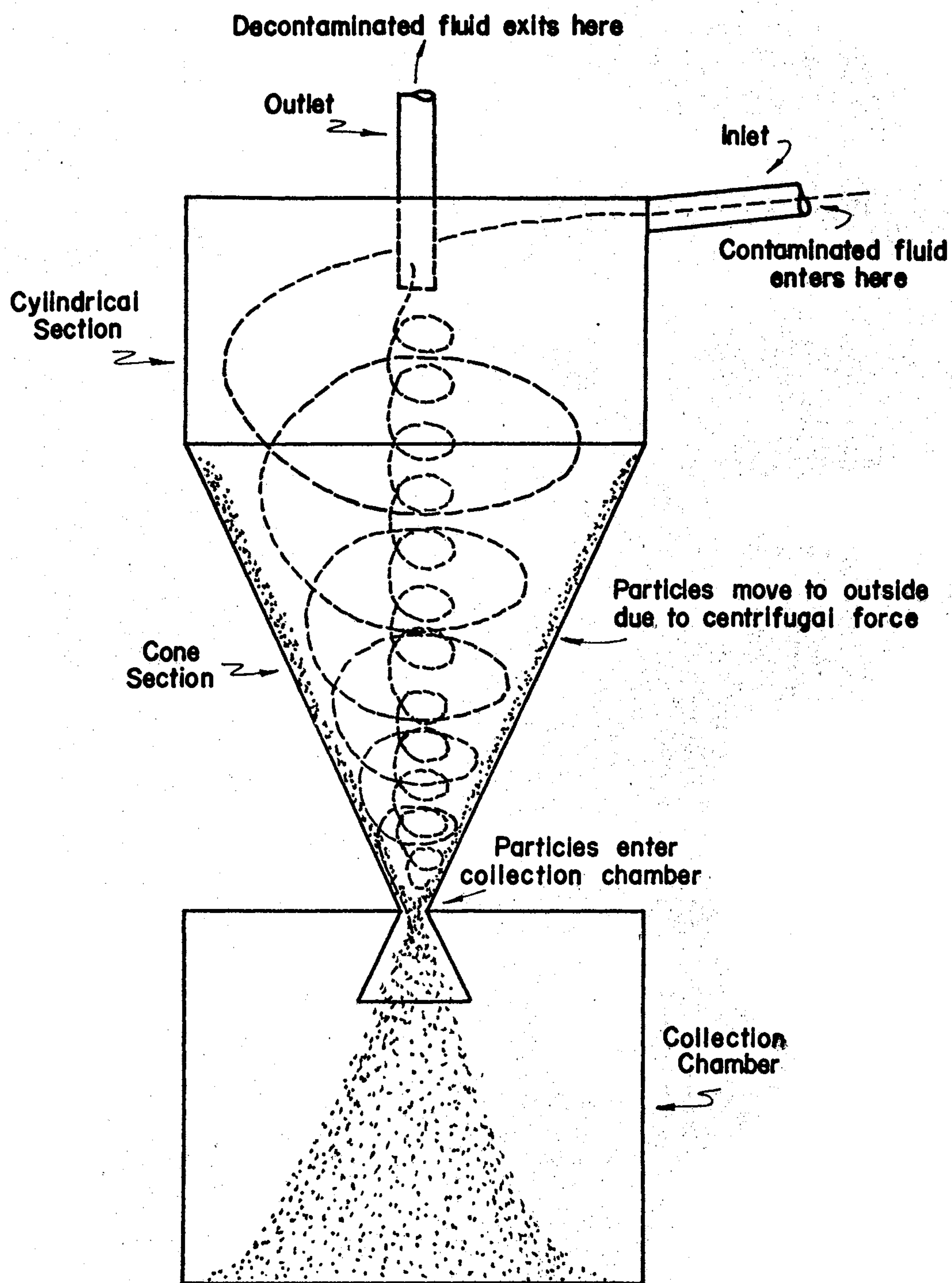

Figure 3. General Flow Patterns in a Hydrocyclone.

a spiral pattern of high centrifugal force. This high centrifugal force causes particles of sufficient size and gravity to be moved outwardly toward the cyclone walls and be discharged spirally through the apex of the cone. However, most of the fluid moves radially inward generating a forced vortex finally being discharged through the overflow nozzle. It has been estimated that only 3 to 10% of the fluid passing through the hydrocyclone actually enters the collection pot, where, ideally all of the particles to be separated enter and remain (36), (39).

B. Hydrocyclone Dynamics

1. Separation Efficiency

From the literature, the most commonly used method of expressing the separation efficiency of the hydrocyclone is the d_{50} point. The d_{50} point is defined as the point at which the hydrocyclone allows 50% (by weight) of a specific particle size to pass through the underflow nozzle and 50% to pass through the overflow nozzle.

Matschke and Dahlstrom (38), through work on miniature hydrocyclones in the 10 to 30 mm size, have shown the equation

$$d_{50} = \frac{C\ (D_o D_f)^{0.65}}{(Q)^{0.6}} \left[\frac{1}{(\rho_s - \rho_l)} \right]^{0.50} \qquad (3\text{-}1)$$

where

d_{50} = Diameter of particle at 50% point, microns,

C = Constant,

D_o = Diameter of overflow nozzle, inches,

D_f = Diameter of inlet nozzle, inches,

Q = Flow rate, gallons per minute,

ρ_s = Density of solid particles, pounds mass per cubic inch,

ρ_l = Density of liquid dispersion medium, pounds mass per cubic inch,

can be used to predict the solid separation efficiency of the miniature hydrocyclone with a reasonable amount of confidence. They have stated that the largest particles found in the overflow fluid would be approximately twice the d_{50} value for particles of similar specific gravities.

Haas and others (36) have suggested the possible influence of viscosity in the equation,

$$d_{50} = \frac{C\, D_c^{0.5}\ \mu^{0.5}}{\Delta P^{0.25}\,(\rho_s - \rho_l)^{0.5}}\ , \qquad (3\text{-}2)$$

where

d_{50} = Diameter of particle at 50% point, microns,

C = Constant,

d_c = Diameter of hydrocyclone, inches,

μ = Absolute viscosity, pounds mass per inch second,

ΔP = Differential pressure, pounds per square inch,

ρ_s = Mass density of solids, pounds mass per cubic inch,

ρ_l = Mass density of liquid dispersion medium, pounds mass per cubic inch.

This equation is of limited value, however, because it was not developed from experimental data but was based upon certain assumptions.

2. Flow Capacity

From experimental data, Dahlstrom (40) developed an equation involving flow capacity;

$$\frac{Q}{(\Delta P)^{0.5}} = k\ (D_o D_f)^{0.9} \quad , \tag{3-3}$$

where

Q = Total flow rate, cubic inches per second,

ΔP = Differential pressure, pounds per square inch,

k = Constant for flow capacity correlation,

D_o = Diameter of overflow nozzle, inches,

D_f = Diameter of inlet nozzle, inches.

The expression $\frac{Q}{(\Delta P)^{0.5}}$ is called the capacity ratio. It simply states flow capacity is a function of the square root of energy loss. This term should remain constant for any particular constant dimension hydrocyclone.

Haas and others (36) developed a similar equation for miniature hydrocyclones smaller than one inch. This equation,

$$\frac{Q}{(\Delta P)^{0.44}} = k\ D_c^{1.8} \ , \tag{3-4}$$

where

Q = Total flow rate, cubic inches per second,

ΔP = Differential pressure, pounds per square inch,

k = Constant for flow capacity correlation,

D_c = Hydrocyclone diameter, inches,

is of limited usefulness due to the fact so few hydrocyclone parameters are included making actual prediction of hydrocyclone performance rather unreliable.

A more comprehensive expression developed by Yoshioka and Hotta (41)

$$\Delta P = \frac{kQ^2}{D_c^{0.9} D_f^{1.2} D_o^{1.9}} , \qquad (3\text{-}5)$$

where

ΔP = Differential pressure, pounds per square inch,

k = Constant for flow capacity correlation,

Q = Total flow rate, cubic inches per second,

D_c = Hydrocyclone diameter, inches,

D_f = Diameter of overflow nozzle, inches,

D_o = Diameter of inlet nozzle, inches,

is an attempt to develop an equation which includes enough critical hydrocyclone parameters to permit dependable prediction of hydrocyclone performance.

The constant for flow capacity correlation, k, used in equations (3-3) through (3-5) is a function of the cone angle, the distance between the conical section and the vortex finder, surface finish, and type of underflow discharge.

3. Particle Dynamics Within the Hydrocyclone

Kelsall (42) has presented curves describing relative velocity patterns within the hydrocyclone. Figure 4-A illustrates the relative pattern of the tangential velocity existing in a hydrocyclone. The vertical velocities found in a vortical field are shown in Figure 4-B. Figure 4-C represents the radial velocity patterns in a vortical field. The particles suspended in the fluid are influenced by these fluid

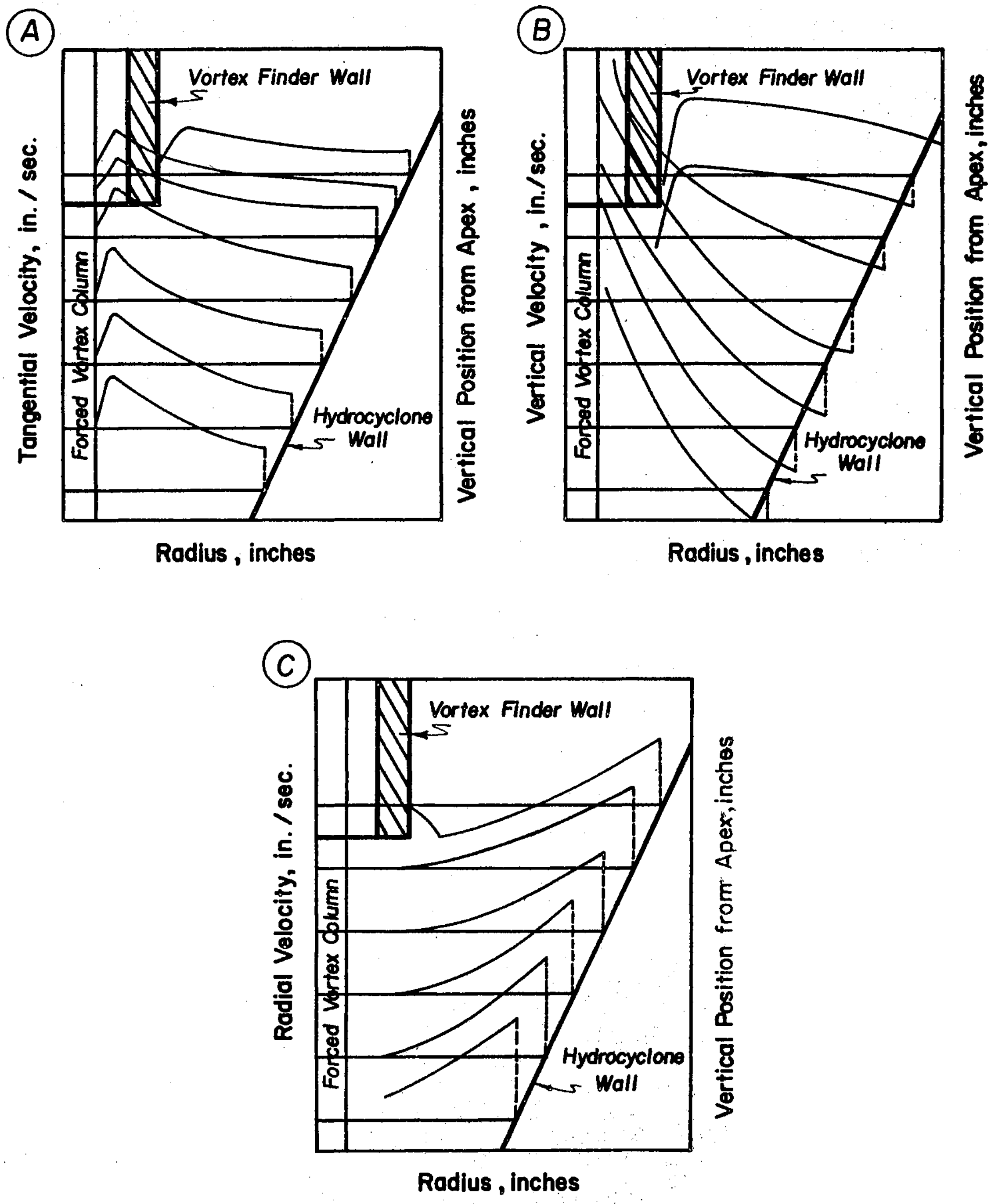

Figure 4. (A) Tangential Velocity Versus Radius, (B) Vertical Velocity Versus Radius, (C) Radial Velocity Versus Radius.

velocities. These velocity patterns subject the suspended particles to three forces:

1. Centrifugal force--an inertia force related to the tangential velocity of the particles,

2. Radial Stokes force--caused by the radially moving fluid dragging the particles,

3. Axial Stokes force--caused by the axially moving fluid dragging the particles.

It is the vector sum of these three forces at any given time that determines the particle movement within the hydrocyclone.

4. Factors Affecting Separation Efficiency

The basic factors affecting the separation efficiency are the fluid properties, the particle properties, flow parameters, and hydrocyclone parameters. Kelsall (43) has described the effect of each of these factors. Figure 5 generally describes these factors in relation to the separation efficiencies.

5. The Collection Pot

Haas and others (36) have reported that the settling of particles in a collection pot could improve the efficiency of the hydrocyclone. The particles that are discharged from the underflow nozzle are moved to the walls of the collection pot, due to the centrifugal forces on the particles, and downward along the walls. An equal volume of fluid returns through the overflow nozzle by means of the vortex path.

One problem that arises in the use of the collection pot is that the poor settling characteristics of some particles might allow them to be returned to the overflow nozzle. One attempt to correct this problem has been the addition of a contamination trap, developed by the School

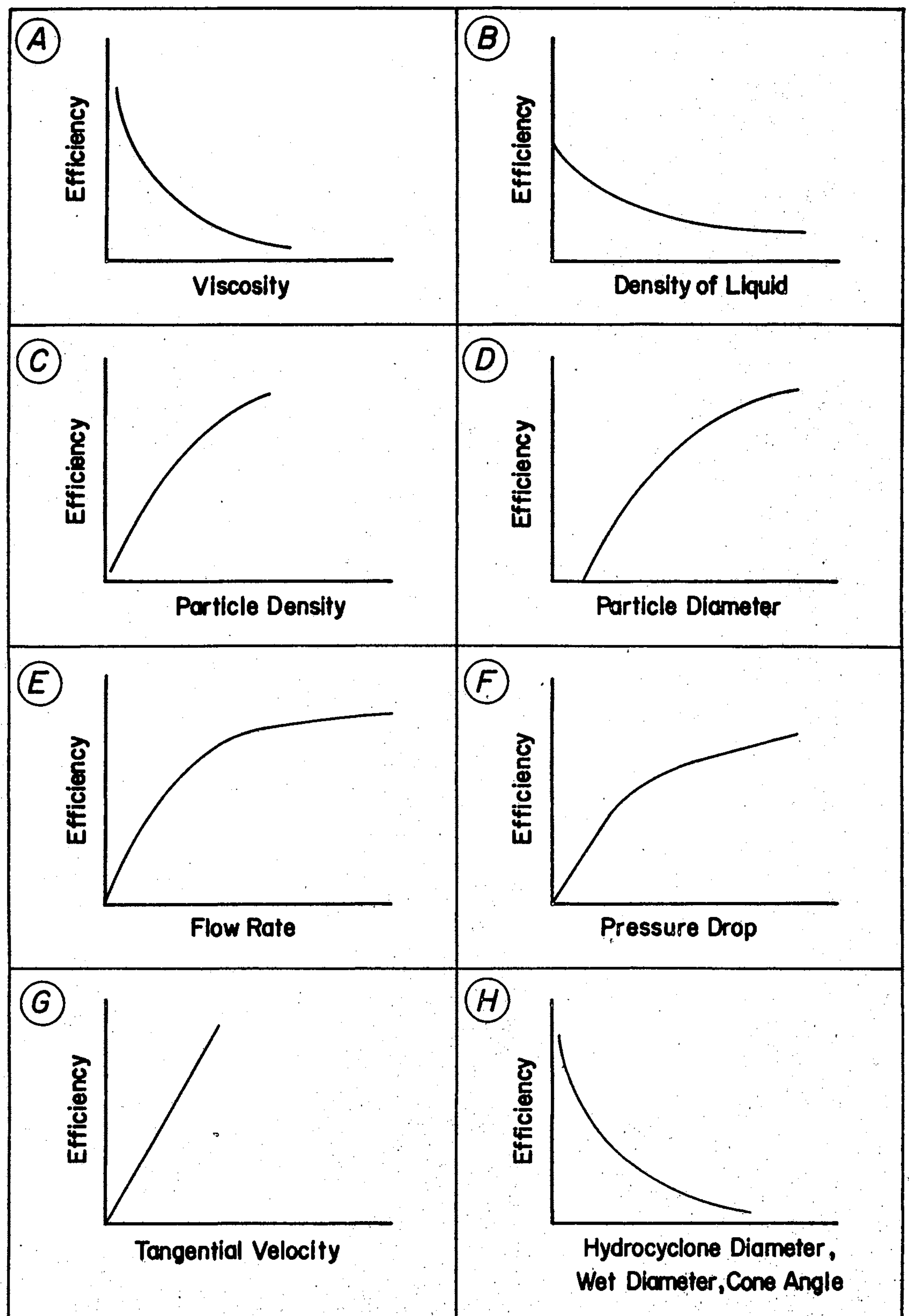

Figure 5. Parameters Affecting Separation Efficiency of the Hydrocyclone.

of Mechanical and Aerospace Engineering at Oklahoma State University (2), to the system to "trap" the particles that are difficult to settle. This contamination trap does not function as a full flow filter because as mentioned earlier only about 3 to 10% of the fluid actually enters the collection pot and is acted upon by the trap. The majority of the solids are acted on by the contamination trap because ideally they have been concentrated in the collection pot by centrifugal forces.

6. General Design Considerations

Matschke and Dahlstrom (38) have given a summary of geometric guides for design. They are as follows:

1. Cyclone included angle should be kept as low as possible (10 to 20 degrees).

2. The bottom of the vortex finder should be 6 inches or one cyclone diameter, whichever is less, from the transition point between the conical section and cylindrical sections.

3. The vortex finder should extend just below the bottom of the inlet nozzle to the cyclone.

4. The inlet angle should allow the entering fluid to descend at least one inlet nozzle diameter in the first revolution.

5. Inlet, overflow, or vortex finder dimensions are determined with respect to cyclone diameter according to the following equations:

$$\frac{2D_f + D_o}{D_c} = 0.35 \text{ to } 0.70 \quad , \tag{3-6}$$

and

$$\frac{D_o}{D_f} = 1.0 \text{ to } 1.6 \quad , \tag{3-7}$$

where

D_f = Diameter of inlet nozzle, inches,

D_o = Diameter of overflow nozzle, inches,

D_c = Diameter of hydrocyclone, inches.

6. Distance between the top of the inlet port and cyclone top should be kept at a minimum to minimize secondary flows that result in an overall decrease in efficiency.

CHAPTER IV

MATERIALS AND METHODS

A. Experimental Apparatus

1. Hydrocyclones

The hydrocyclones used in this study were of three designs. The first unit tested was a 6 gallon per minute, 44 psi pressure drop unit borrowed from the Mechanical and Aerospace Engineering Department at Oklahoma State University (Figure 6). This unit was originally designed and constructed to test the feasibility of cleaning dirty scrub water used in industrial sweepers.

The second hydrocyclone used was specifically designed for this project (Figure 7). The design was a judgment design based upon past experience of hydrocyclone design and operation at the Oklahoma State University Mechanical and Aerospace Engineering Laboratories, and from characteristics of available pumps. The design was to be approximately a 2 gallon per minute, 75 psi pressure drop unit.

When the second hydrocyclone failed to perform as expected a third hydrocyclone was built. It was a modification of the second unit, the only change being to reduce the minimum diameter of the cone, D_u, from 1/8 inch to 1/16 inch.

In all three hydrocyclones a valve was placed into the bottom of the collection pot to facilitate sampling and to expedite draining and cleaning the unit at the termination of an experiment.

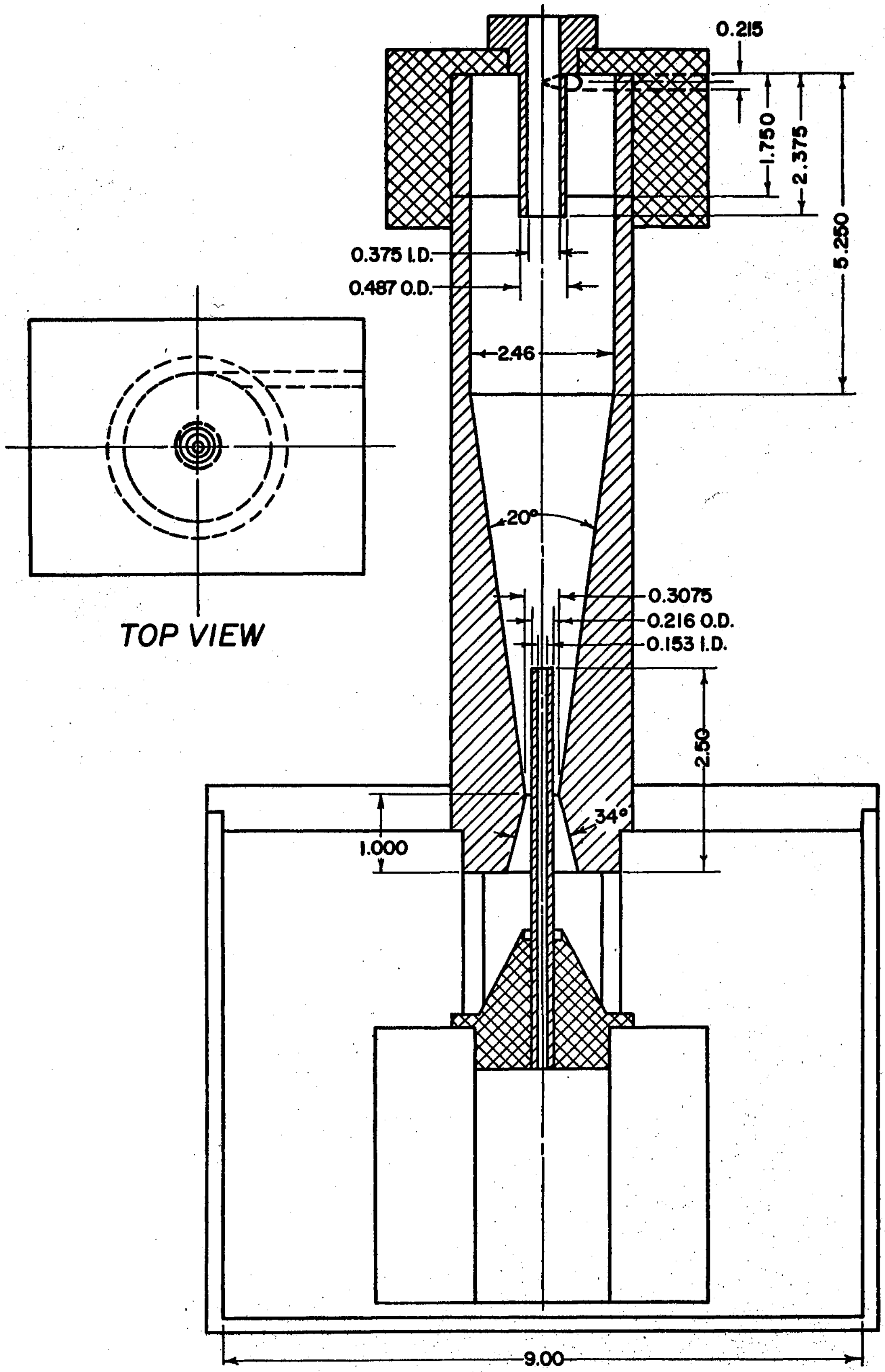

Figure 6. Hydrocyclone #1.

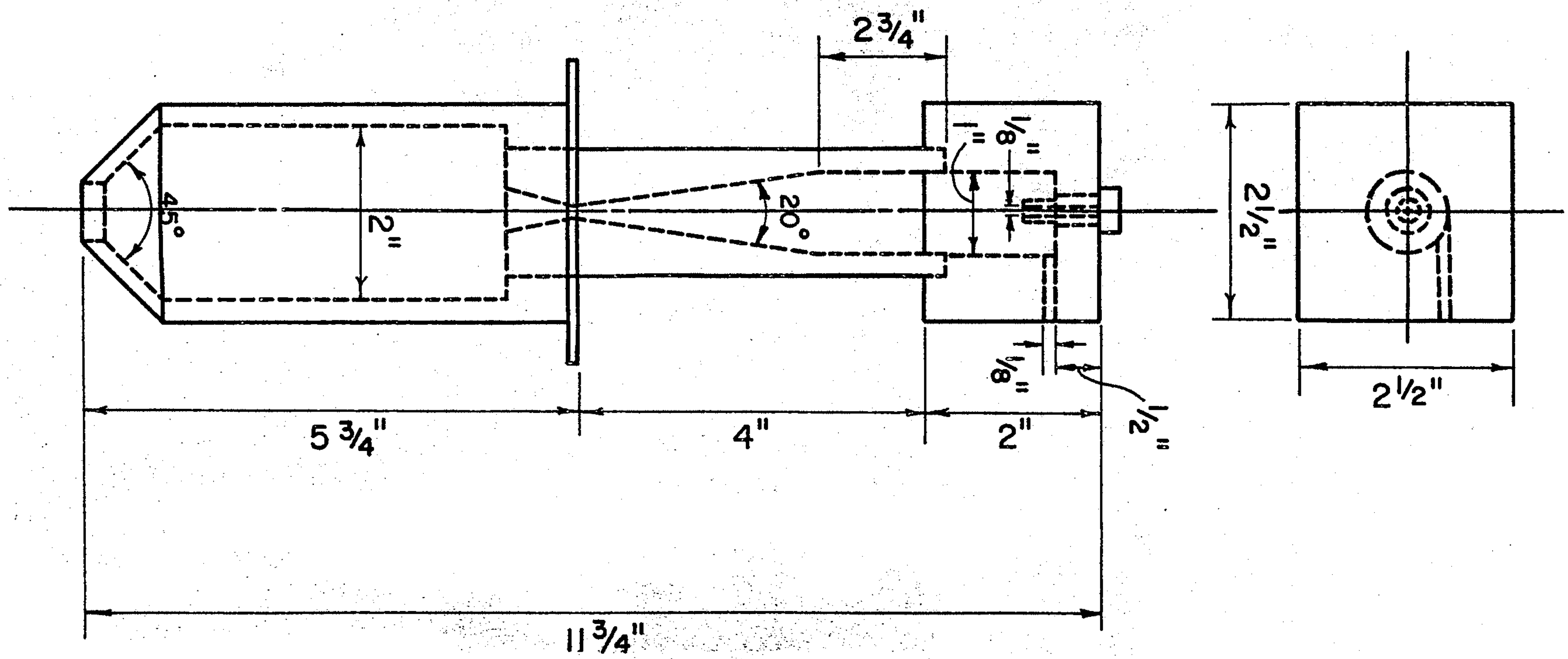

Figure 7. Hydrocyclones #2 and #3.

The critical dimensions for the three hydrocyclones used in this study are shown below.

Hydrocyclone	D_i	D_o	D_c	D_u	ϕ
#1	0.215"	0.375"	2.460"	0.3075"	20^o
#2	0.125"	0.125"	1.000"	0.125"	20^o
#3	0.125"	0.125"	1.000"	0.0625"	20^o

By definition

D_i = Feed inlet diameter,

D_o = Overflow outlet (vortex finder) diameter,

D_c = Maximum cone diameter,

D_u = Underflow diameter (minimum cone diameter),

ϕ = Cone angle.

Hydrocyclone #1 was run at several different ΔP's both with and without the contamination trap to determine the effect this would have on the system's separation efficiency. Experiments were conducted with this hydrocyclone varying the initial bacterial solids concentration to determine the effect of solids concentration on the separation efficiency of the system.

As mentioned earlier, experiments were conducted on hydrocyclone #1 both with and without the contamination trap. From experimental data obtained from the Oklahoma State University Mechanical and Aerospace Laboratories, taken from dust removal experiments, it was noted that separation efficiencies approaching those obtained with the contamination trap could be obtained without the contamination trap if the collection pot were drained at a rate of 3 to 10% of the flow rate through the hydrocyclone.

Based on this information, experiments were conducted on hydrocyclone #1 without the contamination trap, draining the collection pot at various flow rates.

Hydrocyclones #2 and #3 were designed for use without a contamination trap and for continuous collection pot drainage. Experiments were conducted with hydrocyclones #2 and #3 at various ΔP's, initial bacterial concentrations, and collection pot drainage rates.

2. Pumps

The pumps used were of two types: 1. Centrifugal pump, 2. Roller pump. The centrifugal pump was driven by a ¼ horsepower, 110 volt a.c. motor. The roller pump was driven by a 1 horsepower, 110-220 volt a.c. motor. These pumps were placed in series, the centrifugal pump first, followed by the roller pump, followed by a valve. This configuration allowed maximum flexibility and control of the pressure drop and flow rate through the system.

From this configuration the pumps could be operated separately or together, depending upon the pressure drop and flow rate requirements, with further control being offered by the valve located between the pumps and the hydrocyclone. This configuration allowed the pressure drop and the flow rate to be varied from zero to the maximum for the system.

The pumps and the configuration described above were selected to meet the design pressure drop and flow rate requirements of hydrocyclone #1. The pump characteristics were a determining factor in the design of hydrocyclones #2 and #3.

3. Reservoir

The reservoir utilized was a cylindrical polyethylene tank of the following dimensions:

Diameter--14½"
Height--20"

An open-close valve was placed between the reservoir and the pumps. This allowed the reservoir to be easily emptied and cleaned. The reservoir was mounted on a wheeled cart to allow it to be moved about the laboratory when filled.

Marks were made 7" and 14" from the bottom of the reservoir to indicate the 5 gallon and 10 gallon levels. These were the two volumes utilized in all experiments conducted in this study. From the known volumes and flow rates the cycle times were calculated.

4. Growth Vessels

The vessels used to grow the bacterial systems were identical to the reservoir with one exception; there was no open-close valve. Two such vessels were used throughout this investigation. They, like the reservoir, were mounted on a wheeled cart for convenience and mobility.

5. System Configuration

The general configuration is shown in Figure 8.

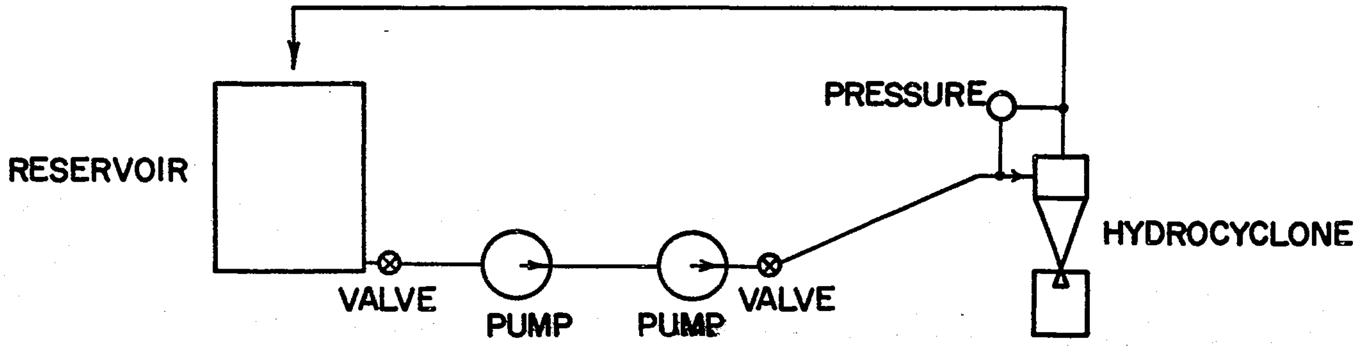

Figure 8. Hydrocyclone System Configuration.

B. Synthetic Waste

The synthetic feed used throughout this investigation had the following chemical make-up:

Constituent	Concentration
Feed:	
Sucrose	1000.0 mg/l
$(NH_4)_2SO_4$	500.0 mg/l
$MgSO_4 \cdot 7H_2O$	100.0 mg/l
$MnSO_4 \cdot 7H_2O$	10.0 mg/l
$CaCl_2$	9.5 mg/l
$FeCl_3 \cdot 7H_2O$	0.5 mg/l
KH_2PO_4	17.5 mg/l
Buffer:	
KH_2PO_4	527.0 mg/l
K_2HPO_4	1070.0 mg/l

The major constituents of the synthetic feed and their concentrations are based on those commonly used in the bioenvironmental laboratories at Oklahoma State University.

The constituents were weighed and mixed together resulting in a dry feed. This dry feed was then weighed and added to the reaction vessels at the desired concentration which was usually 1000 mg/l of sucrose but was often doubled to increase the concentration of the microorganisms.

C. The Bacterial System

The bacterial systems used in this investigation were heterogenous dispersed systems varying in solids concentration from 30 mg/l to 850 mg/l. The systems were grown in the growth vessels described previously. The initial "seed" was taken from an abandoned project in the Oklahoma State University bioenvironmental engineering laboratories. All following systems were seeded with 1000 ml of the supernatent from the system preceding it. The desired growth usually occurred within 1 to 2 days, depending upon the required concentration. Aeration was provided by compressed air.

After each experiment the bacterial systems were disposed of, saving 1000 ml for seeding the next system, to insure that flocculation would not occur as it often does in "old" bacterial systems.

D. Experimental Procedures

1. Preparatory Procedures

A considerable amount of data had to be obtained on the physical system in each configuration that was to be investigated before data from experiments on bacterial systems could be obtained and reduced.

Curves were obtained for each configuration to be investigated describing pressure drop across the hydrocyclone vs flow rate. The technique used to obtain these curves involved determining the time required to fill a 10 gallon container at a given pressure drop across the hydrocyclone. The pressure drop was then varied by opening or closing the valve located between the pumps and the hydrocyclone. The time required to fill the 10 gallon container, at the new pressure drop, was then determined. This process was repeated until enough values were obtained to plot a graph of ΔP vs flow rate. Thus the flow rate could be obtained simply by reading ΔP from the pressure gauge and converting to flow rate from the graph.

From a knowledge of the flow rate and the volume of fluid in the system, the time required for one cycle through the system could be computed where

$$\text{Cycle time (minutes)} = \frac{\text{Volume (gals.)}}{\text{Flow rate (gal./min.)}}.$$

Also needed for the design of hydrocyclones #2 and #3 were pump curves without the hydrocyclones in the system. These were obtained in nearly the same manner as the curves described above. The only difference is the absence of the hydrocyclone in the system. From these pressure vs flow rate curves the design flow rate and pressure drop were selected for hydrocyclones #2 and #3 within the capabilities of the pumps.

One to two days prior to an experiment, depending upon the desired bacterial concentration, a growth vessel was prepared (seeded and fed) as described earlier.

When the biological solids approached the desired concentration experiments involving separation of these solids by passage through the hydrocyclone were begun.

2. Hydrocyclone Experiment

The experimental procedures for all hydrocyclone configurations investigated were basically the same.

The bacterial systems of the desired biological solids concentration were transferred to the reservoir. The reservoir was always filled to either the 5 or 10 gallon mark. These volumes were chosen according to the flow rate selected for each particular experiment. At the lower flow rates the 5 gallon volume was generally used to decrease the cycle time, thereby shortening the time required to complete the experiment. The 5 gallon volume was most often used with hydrocyclones #2 and #3 since their flow rates were always below 2 gallons per minute, whereas the 10 gallon volume was utilized with hydrocyclone #1 which had flow rates between 5 and 6 gallons per minute for all experiments.

After filling the reservoir to the desired level samples were drawn to determine the initial biological solids concentration. Also an Imhoff Cone was utilized to insure that the system was truly dispersed and that no gravity settling would occur.

After initial biological solids samples were drawn the pumps were started, ΔP was set to the desired value (by opening or closing the valve between the pumps and the hydrocyclone), and the timer was started. Samples were periodically taken from the reservoir mixed liquor for biological solids determination and the time of sampling recorded. The experiments were continued until enough data had been obtained to describe the separation characteristics of the particular hydrocyclone configuration being investigated.

Upon termination of each experiment, approximately 1000 ml of the mixed liquor was taken from the reservoir to seed the growth vessel. The remainder of the supernatent in the reservoir was then discarded.

Experiments were conducted on hydrocyclone #1, both with the contamination trap and without the contamination trap draining the collection pot at various flow rates.

After each experiment with hydrocyclone #1 with the contamination trap, the trap (0.4 μ paper filter) was removed and cleaned by washing in hot water.

All experiments with hydrocyclones #2 and #3 were conducted as described above. Investigations were made at various drainage rates of the collection pot.

E. Analytical Procedures

1. Flow Rate

All flow rates were determined by timing the flow into a known volume with a stop watch. This was repeated several times to improve accuracy.

2. Biological Solids

The concentration of biological solids in the reservoir was determined by filtering a known volume through a 0.45 μ Millipore Filter as described in Standard Methods (44).

Also, the optical density of the mixed liquor was employed to determine the course of growth in each growth vessel and to determine the concentration of biological solids in the reservoir as a check on the filtration method. It also gave a quick indication as to the progress of an experiment. Percent transmittance was measured and converted to optical density in accordance with the equation

$$OD = -\log_{10}T,$$

where

OD = Optical Density,

T = % Transmittance.

A Bausch and Lomb spectrophotometer was used.

From data obtained in each experiment, optical density vs biological solids concentration (as determined by filtration) was plotted. From these graphs, biological solids concentration could be determined by knowing the optical density of the mixed liquor. Graphs plotted from data obtained in these experiments all appeared to be linear indicating that the concentration of biological solids in the mixed liquor was directly proportional to the optical density for the concentrations investigated.

CHAPTER V

EXPERIMENTAL RESULTS

A. General

The results of this investigation are shown in Figures 9 through 19. The experimental results for hydrocyclone #1 are found in Figures 9 through 13. The data obtained from hydrocyclone #2 are found in Figures 14 through 18. Figure 13 displays the results from experiments with hydrocyclone #3.

B. Hydrocyclone #1

Figure 9 shows the results of an experiment conducted to provide a method for determining the flow rate through hydrocyclone #1. The flow rate can be determined by reading the pressure drop across the hydrocyclone and converting it to flow rate from the graph in Figure 9. This was the method used to determine the flow rate for all experiments conducted on hydrocyclone #1. The reservoir volume, which was 10 gallons in all experiments conducted on hydrocyclone #1, divided by the flow rate gives the cycle time (time required for the entire reservoir volume to pass through the hydrocyclone one time).

After the preliminary experiment was conducted to determine the calibration curve for hydrocyclone #1, experiments were begun to determine its separation characteristics.

Experiment #1, the results of which are shown in Figure 10-A, was conducted at a pressure drop of 40 psi, which converts to 5.1 gpm, and

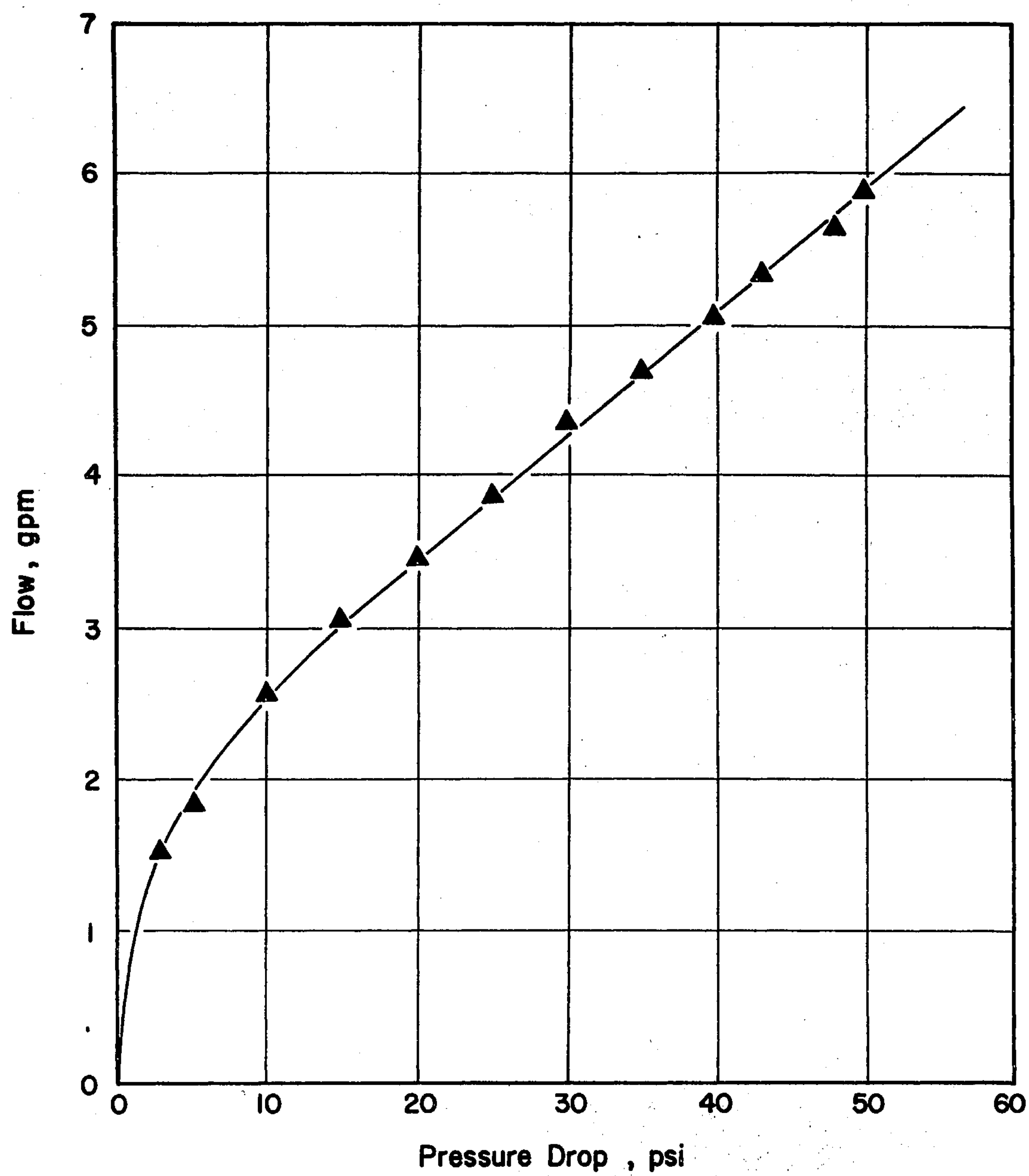

Figure 9. Flow Rate Versus Pressure Drop for Hydrocyclone #1.

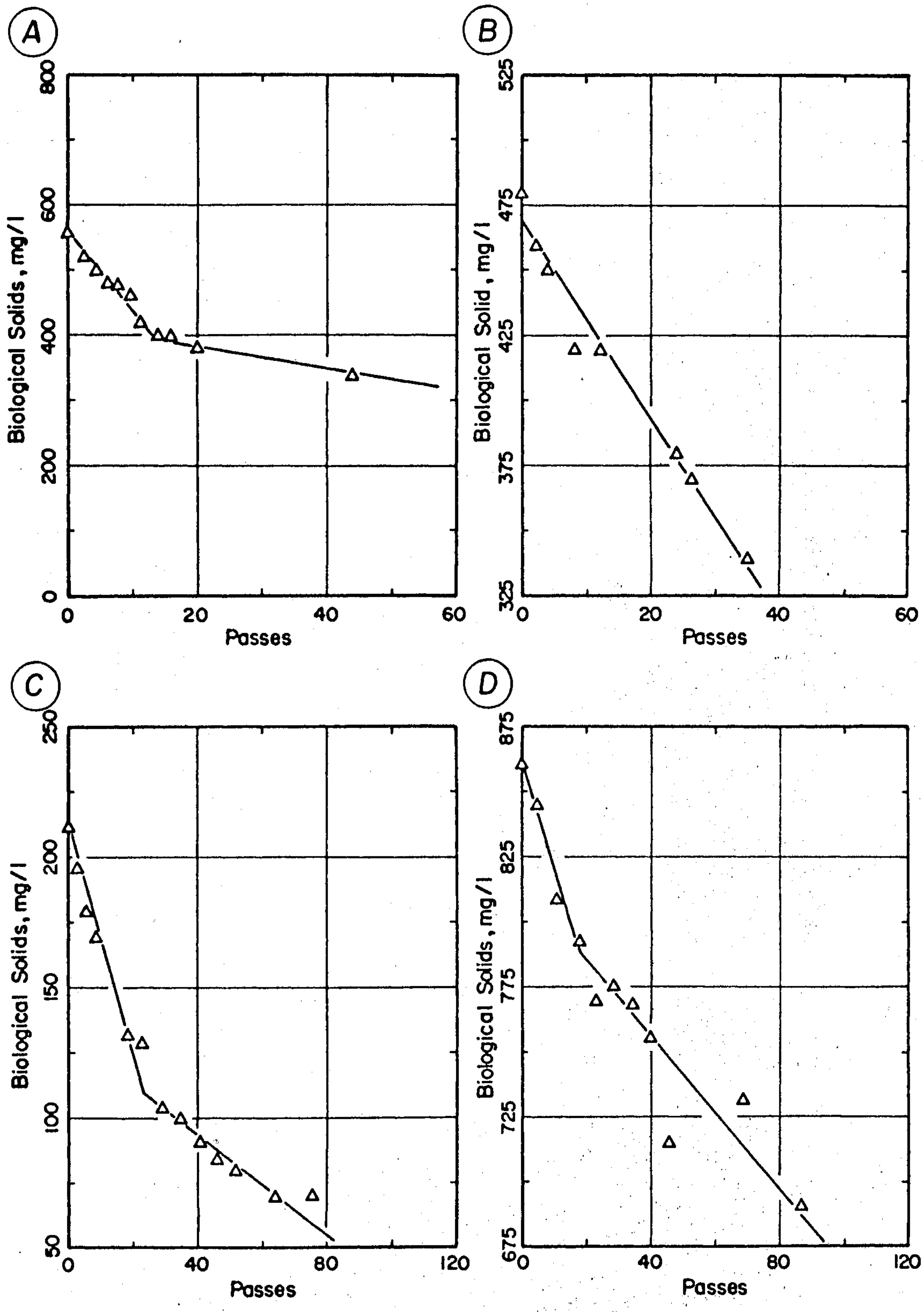

Figure 10. Results, Hydrocyclone #1 with Contamination Trap.

an initial biological solids concentration of 560 mg/l. The removal curve obtained appears to be a two phase curve; the first phase, from 0 to 14 passes, having a separation rate of approximately 10.45 mg/l/pass, and the second phase, from 14 passes until termination, having a separation rate of approximately 1.75 mg/l/pass.

Experiment #2, Figure 10-B, was conducted at a pressure drop of 45 psi which converts to 5.45 gpm, and an initial biological solids concentration of 480 mg/l. The separation rate in this experiment was approximately 4.56 mg/l/pass.

Experiment #3, Figure 10-C, was conducted at a pressure drop of 46 psi, which was a flow rate of 5.55 gpm, and an initial biological solids concentration of 212 mg/l. As in Experiment #1 the separation curve is a two phase curve, the first phase occurring from 0 until 20 passes and the second phase occurring from 20 passes until termination. The separation rate of the first phase was 3.45 mg/l/pass.

Experiment #4, Figure 10-D, was conducted at a pressure drop of 48 psi which was a flow rate of 5.7 gpm, and an initial biological solids concentration of 860 mg/l. Again a two phase separation curve was obtained. The first phase, from 0 to approximately 20 passes, had a separation rate of 3.45 mg/l/pass. The second phase, from 20 passes until termination, had a separation rate of 2.48 mg/l/pass.

A pressure drop of 48 psi, therefore a flow rate of 5.70 gpm, and an initial biological solids concentration of 452 mg/l were utilized for Experiment #5, Figure 11-A. As before, a two phase curve was obtained, the first phase occurring between 0 and 50 passes and the second phase occurring from 50 passes until termination. The separation

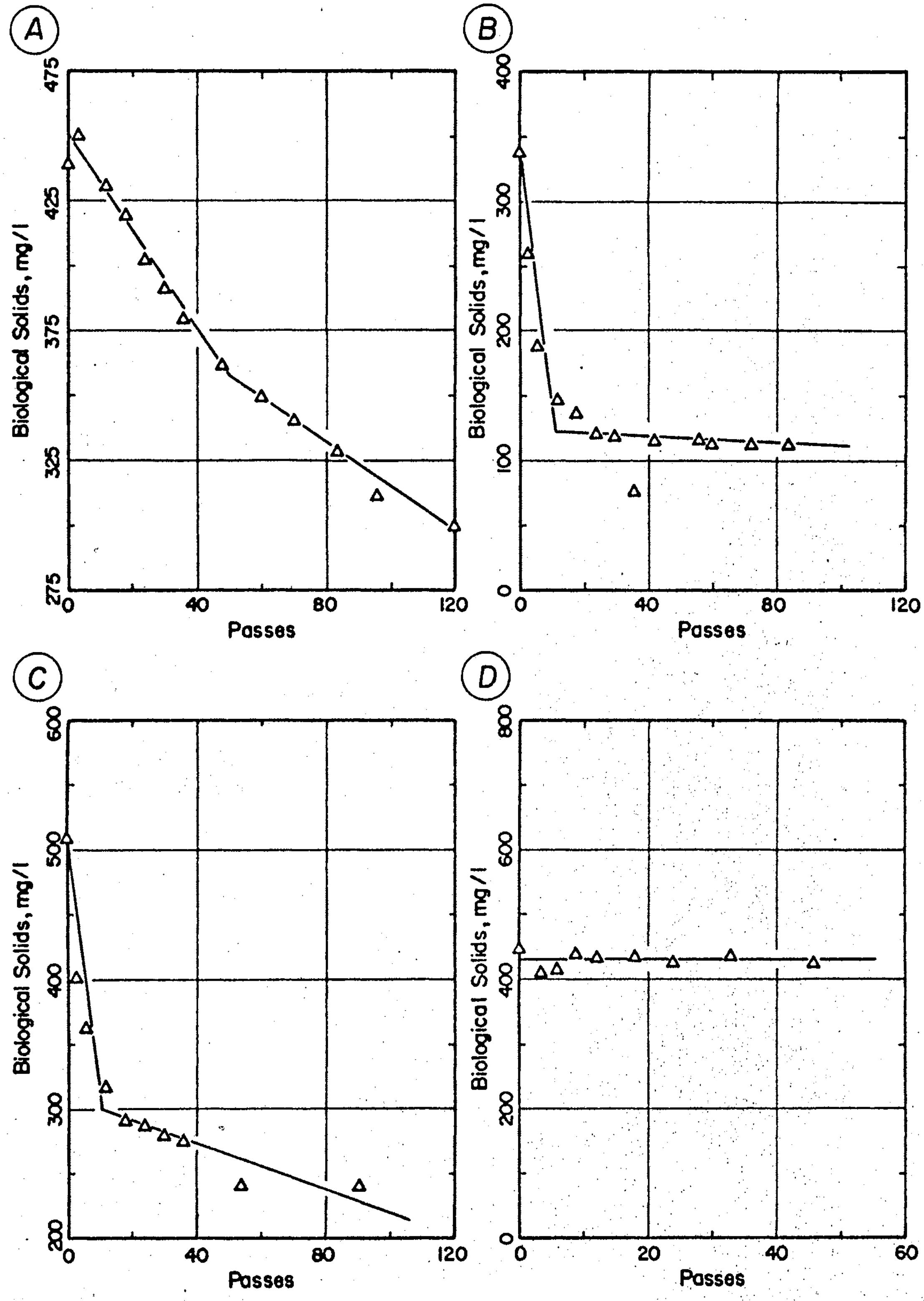

Figure 11. Results, Hydrocyclone #1, (A), (B), and (C) with Contamination Trap, $Q_u = 0$, (D) without Contamination Trap, $Q_u = 0$.

rate of the first phase was 1.67 mg/l/pass. The separation rate of the second phase was 0.89 mg/l/pass.

At this point in the investigation it was determined that the contamination trap (paper filter) should be replaced with a new one. Figure 12 shows how the efficiency of the system decreased with each experiment, even though the filter was washed in hot water after each run. The filter apparently became loaded with biological solids, decreasing its separation efficiency. The curve would indicate that the efficiency of the filter drops off very rapidly for the first three runs. There appeared to be a "break point" at approximately three runs, after which the removal rate decreased at a much slower rate.

Experiment #6, Figure 11-B, was conducted with a new filter. The pressure drop was 52 psi, the flow rate was 6 gpm, and the initial biological solids were 340 mg/l. As before, the reservoir volume was 10 gallons. The two phase curve was observed again in this experiment. The first phases occurred between 0 and 12 passes and the second phase occurred from 12 passes until termination. The first phase separation rate was 25.3 mg/l/pass. The separation rate for the second phase was 0.15 mg/l/pass.

Experiment #7, Figure 11-C, was performed at a pressure drop of 52 psi, 6 gpm, and an initial biological solids concentration of 508 mg/l. As in all previous results, with the exception of Experiment #2, a two phase curve was observed. The first phase occurred between 0 and 12 passes, and the second phase occurred from the 12th pass until the termination of the experiment. The separation rate of the first phase was 24.2 mg/l/pass. The rate of separation for the second phase was 1.34 mg/l/pass.

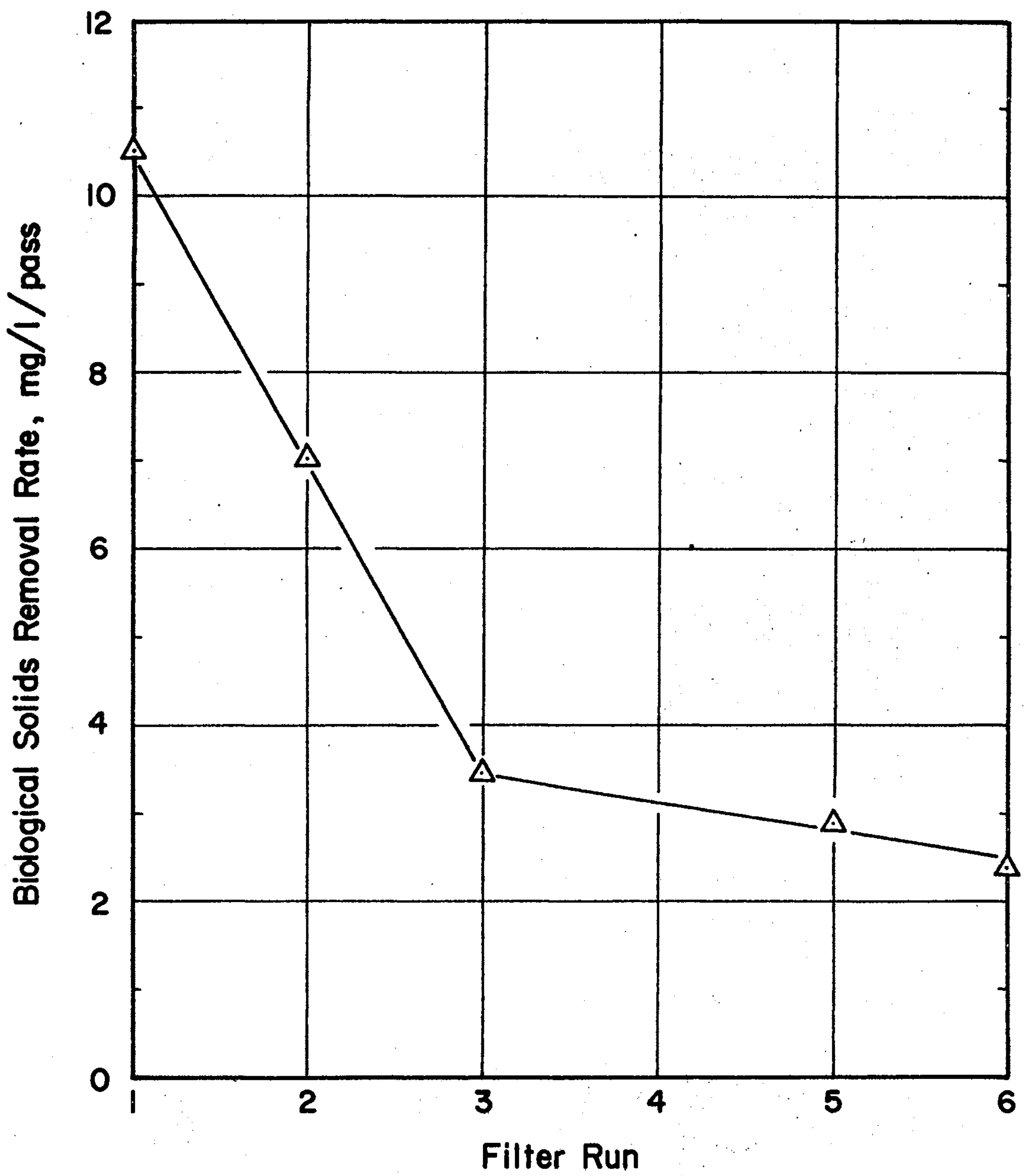

Figure 12. Filter Efficiency Versus Runs.

Experiments #8 through #12 were conducted with hydrocyclone #1 to determine the separation efficiency of this hydrocyclone at various underflow rates without a contamination trap. All experiments in this series were conducted at a pressure drop of 52 psi which is a flow rate of 6 gpm. The results from these experiments are shown in Figure 11-D and Figure 13-A, B, C, and D. No separation was obtained in any of the experiments in this series, as can be seen from the figures.

Experiment #8 had an initial biological solids concentration of 408 mg/l and an underflow of 0 gpm. Experiments #9 and #10 had an initial biological solids concentration of 425 mg/l. Experiment #9 had an underflow rate of 0 gpm and Experiment #10 had an underflow rate of 0.198 gpm which was approximately 3.3% of the hydrocyclone flow rate. Experiments #11 and #12 had an initial biological solids concentration of 300 mg/l. Experiment #11 had an underflow rate of 0.273 gpm, which was approximately 4.5% of the hydrocyclone flow rate, and Experiment #12 had an underflow rate of 0.29 gpm, which was approximately 4.8% of the hydrocyclone flow rate.

C. Hydrocyclone #2

Hydrocyclone #2 was designed and built specifically for this investigation. To insure that the pumps available would be able to deliver the design pressure drop at the design flow rate, an experiment was conducted to determine the pump characteristics. The results of this experiment are shown in Figure 14.

From the above experiment, it was determined that the available pumps could easily produce a pressure drop of 75 psi at 2 gpm.

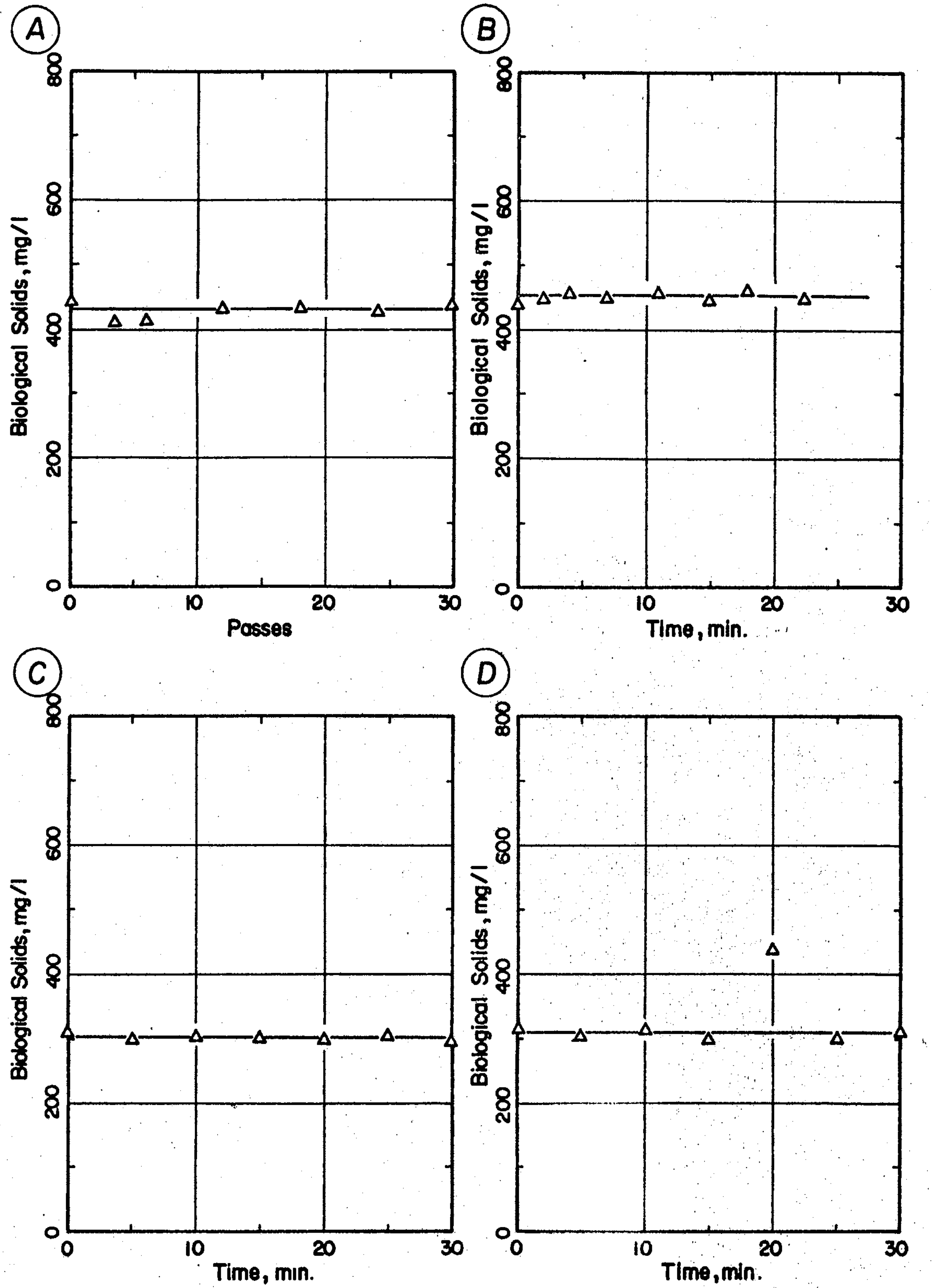

Figure 13. Results, Hydrocyclone #1 Without Contamination Trap, (A) $Q_u = 0$, (B) $Q_u = 3.4\%\ Q$, (C) $Q_u = 4.6\%\ Q$, (D) $Q_u = 5.1\%\ Q$.

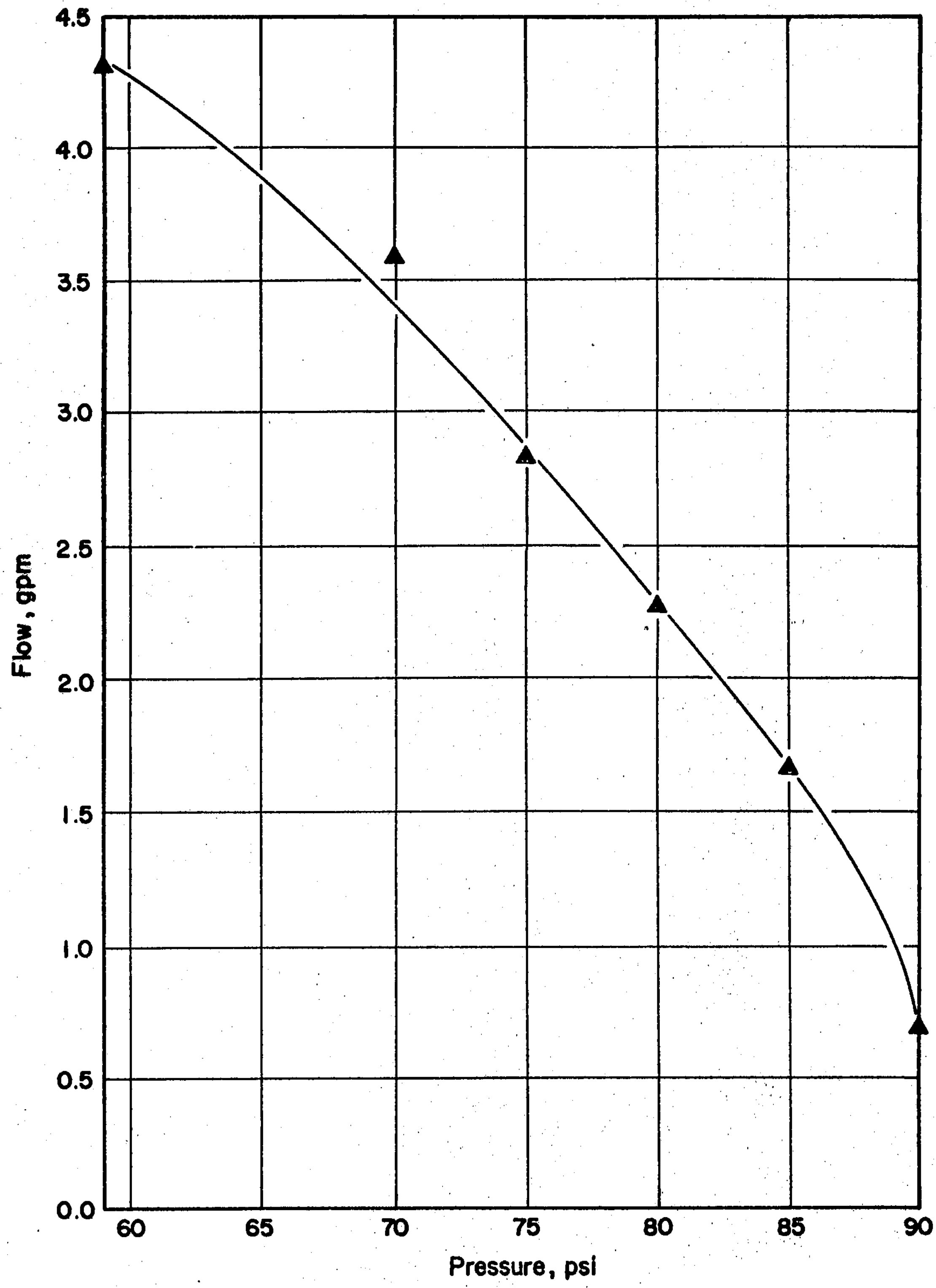

Figure 14. Pump Curve for Design of Hydrocyclone #2.

Therefore, hydrocyclone #2 was designed to operate at this pressure drop and flow rate. However, the hydrocyclone was unable to produce a flow rate of 2 gpm at 75 psi pressure drop. In fact, a flow rate of only 1.34 gpm was produced at a pressure drop of 90 psi, which was the maximum output of the available pumps. A possible explanation for this apparent deficiency in flow rate at the design pressure drop could be due to the oscillation that occurred in the pressure gauge, making accurate pressure readings difficult. Any attempts to reproduce experiments in this investigation should be based on flow rate.

Sixteen experiments were conducted to determine the separation characteristics of hydrocyclone #2. The results of these experiments are shown in Figures 15 through 18. All of the experiments, with the exception of Experiment #4 (Figure 15-D) were conducted at a pressure drop of 80 psi and a flow rate of 1.31 gpm (as obtained by determining the time required to fill a known volume). Experiment #4 was conducted at a pressure drop of 90 psi which produced a flow rate of 1.34 gpm. The reservoir volume for all experiments of hydrocyclone #2 was 5 gallons. The initial biological solids and the underflow rate were varied for each experiment. As the figures show, no separation occurred in any of the experiments conducted with hydrocyclone #2.

The input parameters and the figure in which the results can be found are as follows:

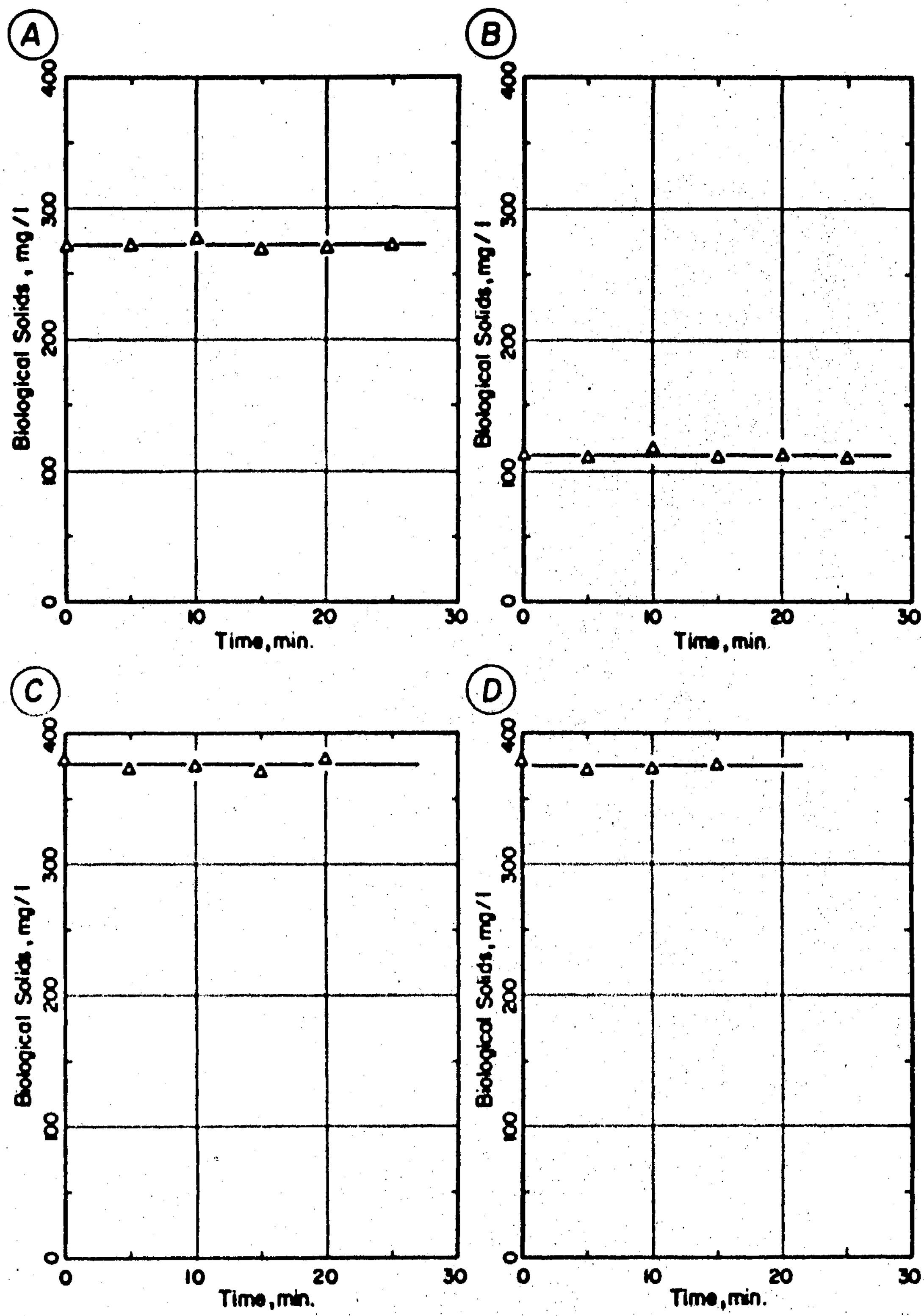

Figure 15. Results, Hydrocyclone #2, Q_u = 0.

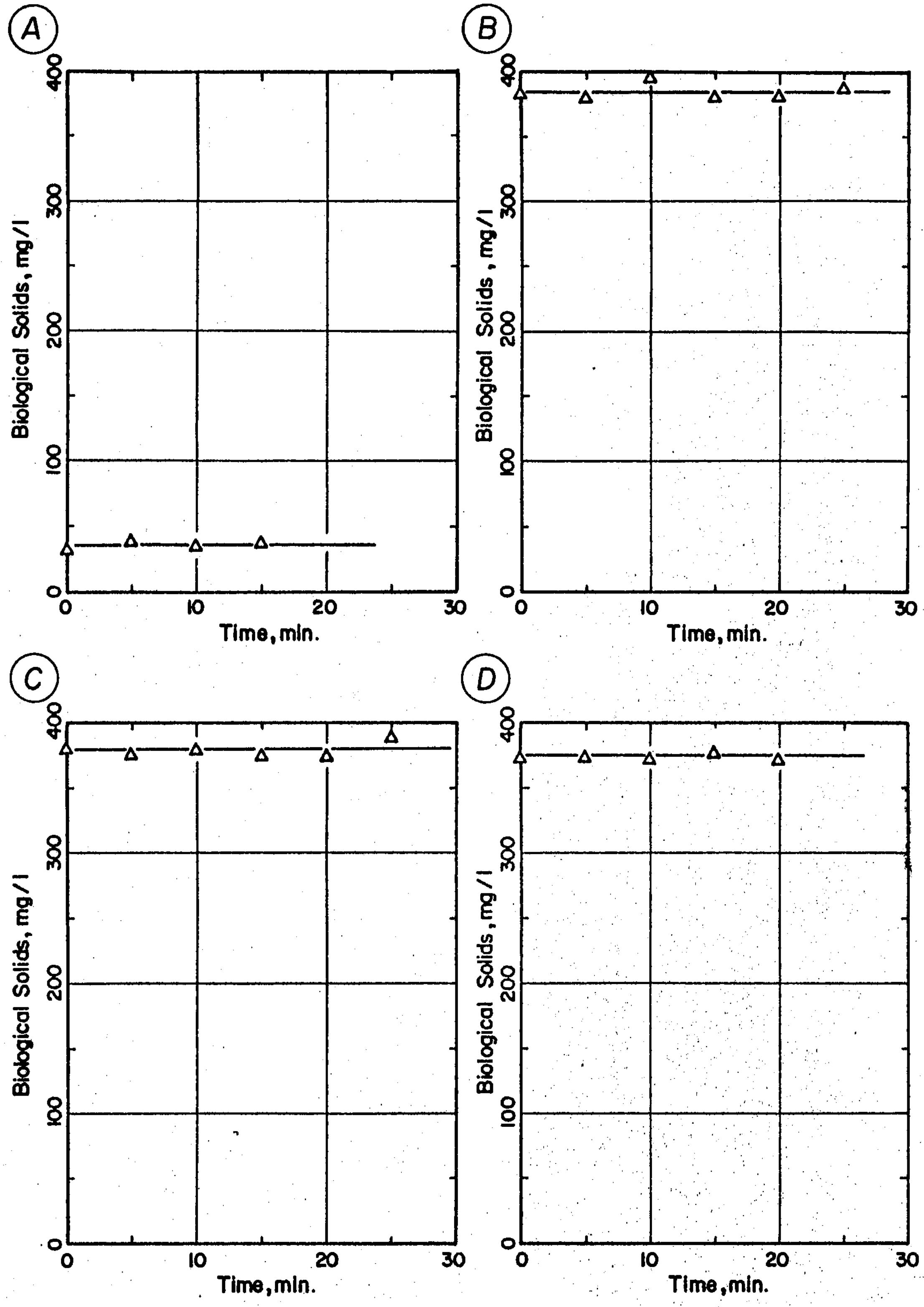

Figure 16. Results, Hydrocyclone #2, (A) Q_u = 10.1% Q, (B) Q_u = 7.6% Q, (C) Q_u - 5.4% Q, (C) = 4.2% Q.

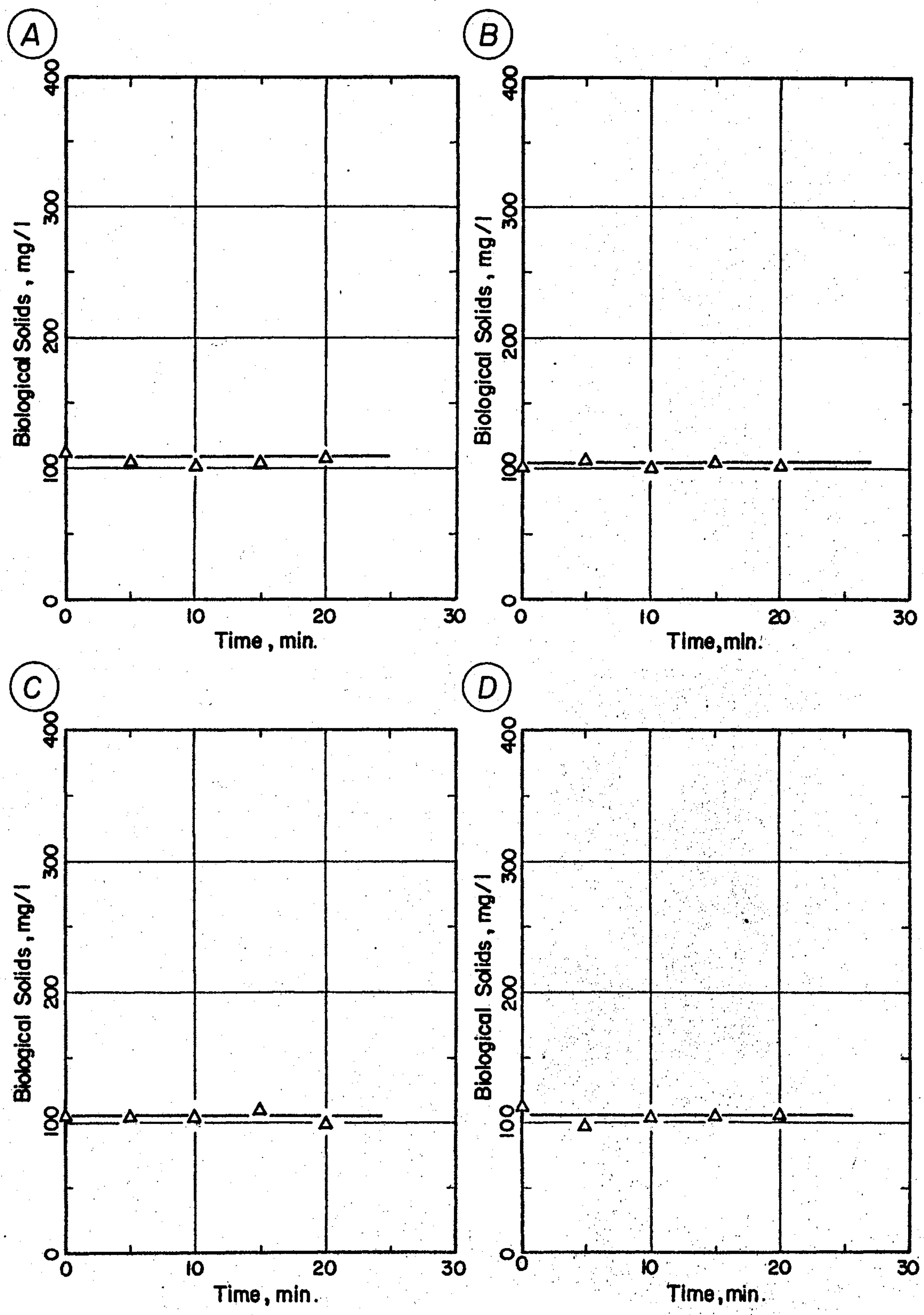

Figure 17. Results, Hydrocyclone #2, (A) Q_u =13.7 Q, (B) Q_u = 10.9% Q, (C) Q_u = 8.4% Q, (D) Q_u = 7.6% Q.

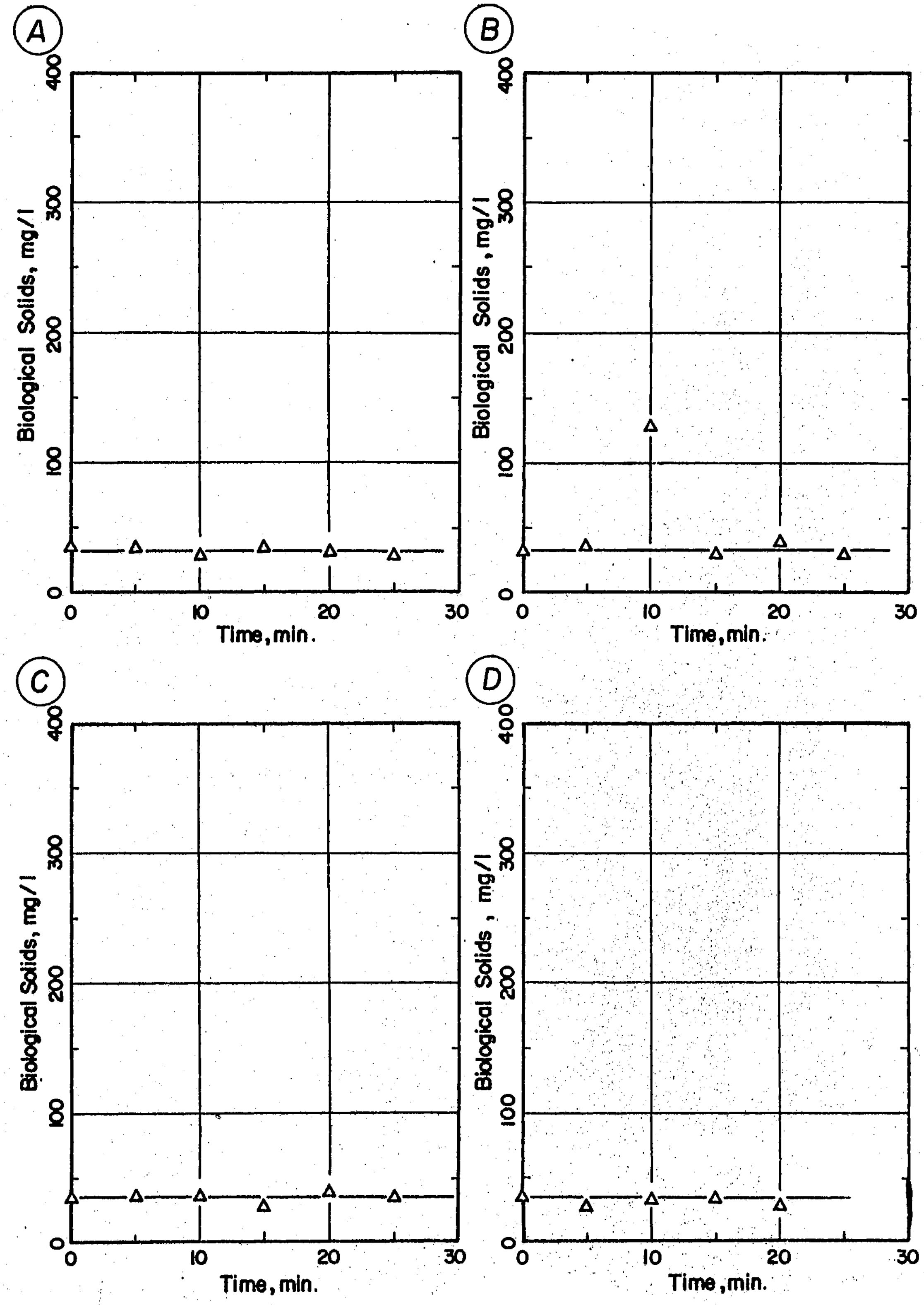

Figure 18. Results, Hydrocyclone #2, (A) Q_u = 10.1% Q, (B) Q_u = 7.6% Q, (C) Q_u = 5.4% Q, (D) Q_u = 4.2% Q.

Experiment	Figure	Flow Rate, Q (gpm)	Underflow, Q_u (gpm)	Initial Solids (mg/l)
1	15-A	1.31	0.000	240
2	15-B	1.31	0.00	113
3	15-C	1.31	0.00	381
4	15-D	1.34	0.00	377
5	16-A	1.31	0.00	37
6	16-B	1.31	0.18	383
7	16-C	1.31	0.13	380
8	16-D	1.31	0.11	373
9	17-A	1.31	0.18	110
10	17-B	1.31	0.14	103
11	17-C	1.31	0.11	105
12	17-D	1.31	0.10	105
13	18-A	1.31	0.14	35
14	18-B	1.31	0.10	33
15	18-C	1.31	0.07	35
16	18-D	1.31	0.06	37

D. Hydrocyclone #3

When hydrocyclone #2 did not produce the desired results it was modified by reducing the minimum diameter of the cone, D_u, from 1/8 inch to 1/16 inch. It was decided that possibly too much of the liquid flowing through the system was entering the collection pot causing many of the solids to be discharged through the overflow. By reducing the minimum diameter of the cone the amount of fluid entering the collection pot was reduced. There were no other modifications made.

All experiments conducted on hydrocyclone #3 were at a pressure drop of 90 psi and a flow rate of 1.34 gpm. The initial biological solids and the underflow were varied.

The input parameters and the figure in which the results can be found are as follows:

Experiment	Figure	Flow Rate, Q (gpm)	Underflow, Q_u (gpm)	Initial Solids (mg/l)
1	19-A	1.34	0.00	209
2	19-B	1.34	0.11	212
3	19-C	1.34	0.074	215

As is shown in the figures, no separation occurred in the experiments on hydrocyclone #3.

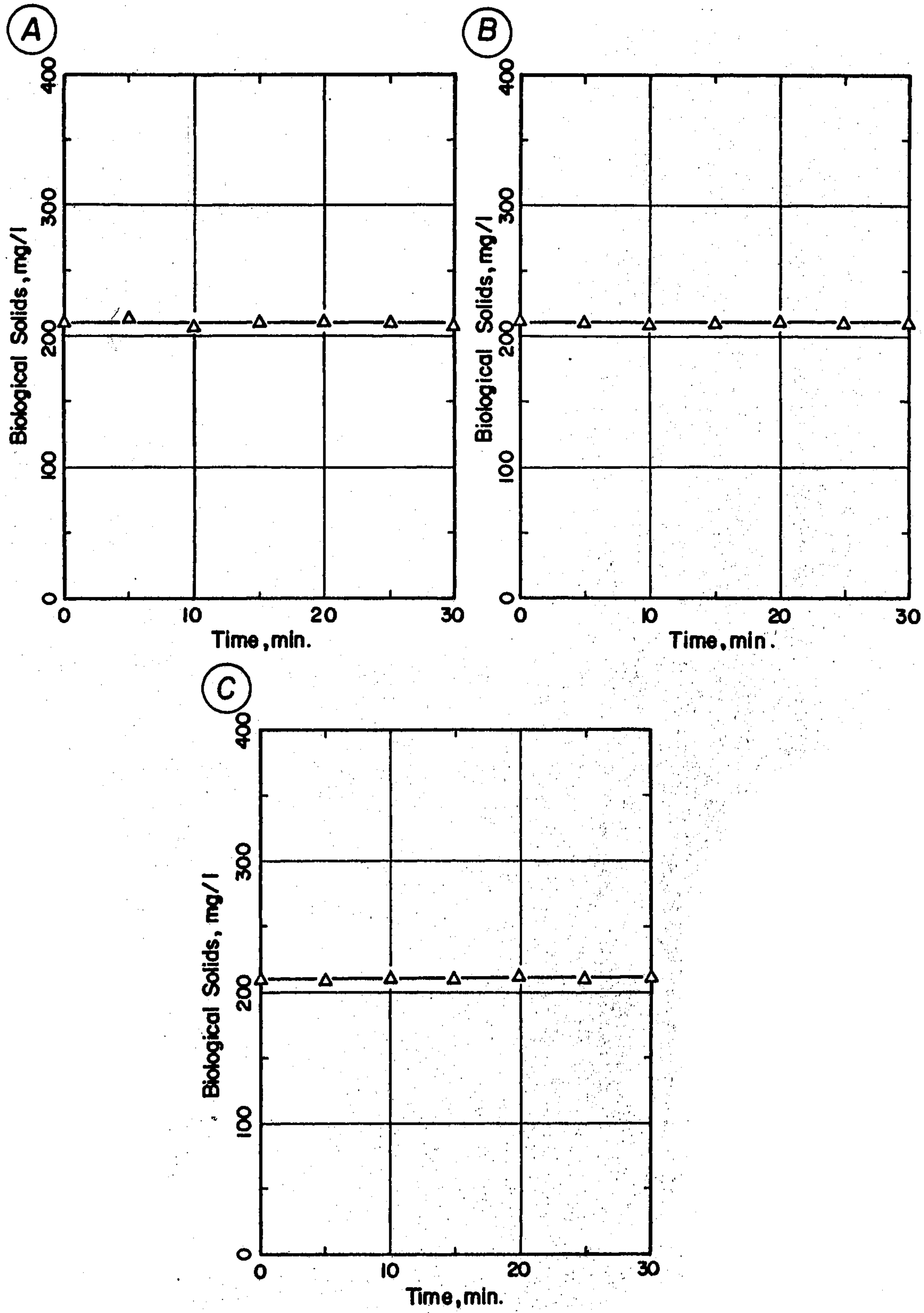

Figure 19. Results, Hydrocyclone #3, (A) $Q_u = 0$, (B) $Q_u = 8.2\%\ Q$, (C) $Q_u = 5.5\%\ Q$.

CHAPTER VI

DISCUSSION

The purpose of this investigation was to determine the feasibility of utilizing the hydrocyclone for separating the biological solids from a dispersed bacterial system. The results obtained in these experiments indicate that the hydrocyclone, in the configurations investigated, has limited application in this area.

The only hydrocyclone configuration in which any separation occurred was hydrocyclone #1 with the contamination trap. Hydrocyclones #2 and #3 were unable to separate the biological solids from the mixed liquor in any of the experiments conducted.

Based upon these results, it was considered that possibly the only separation occurring in hydrocyclone #1 was that due to the mixed liquor being filtered by the contamination trap. Based on calculations made by Tiederman (39), the amount of fluid entering the collection pot in hydrocyclone #1 was approximately 2% of the hydrocyclone flow rate, Q. Assuming this to be true, a separation efficiency for the contamination trap of 93.5% in Experiment #1, to an efficiency of 50% in Experiment 5 occurred. This drop in efficiency with each experiment seems to be feasible and Figure 12 tends to strengthen this idea.

Experiments #6 and #7, however, produced results which tend to show some separation by the hydrocyclone other than that removed by the contamination trap. Again, if 2% of the flow is assumed to have been acted upon by the contamination trap, 6.8 mg/l/pass would have been the separation rate for Experiment #6, as compared to the observed rate of 25.3 mg/l/pass, and a separation rate of 10.6 mg/l/pass would have occurred in Experiment #7, as compared with the observed rate of 24.2 mg/l/pass.

One possible explanation for this increased efficiency in Experiments #6 and #7 might be that the added pressure drop, therefore an increase in flow rate, increased the inlet momentum of the hydrocyclone to a high enough value to allow separation of the biological solids from the mixed liquor in these two experiments.

Another possibility lies in the fact that the first contamination trap used, Experiments #1 through #5, was "seasoned" by operating the hydrocyclone with a solution of clay suspended in water for a short time. The second trap, Experiments #5 and #6, was not "seasoned" in this manner. The first contamination trap (the "seasoned" trap) could possibly have been loaded with clay particles to its capacity causing it to be ineffective in the first series of experiments.

Two phase separation curves were observed in all experiments conducted with hydrocyclone #1 with the contamination trap, with the exception of Experiment #2. In all cases where this was observed, the first phase was observed to have a more rapid separation rate than the second. The only explanation that could be given for this two phase separation was that the biological solids built up to a finite level on the contamination trap at which point much of the efficiency of the trap was lost. With this hypothesis in mind, the separation rates of the first five experiments were multiplied by the number of passes occurring to the break point which was then multiplied by 37.85 l (reservoir volume, 10 gallons) giving the weight of biological solids that had been separated by the first phase. The valves were all very near 4000 mg. The two phase separation curves observed in Experiments #6 and #7 could also be explained by this hypothesis. Assuming 2% of the total hydrocyclone flow was acted upon by the contamination trap in both of these experiments, and a trap efficiency of 100%, the same type of calculations as above yield nearly the same results, approximately 4000 mg of solids removed by the filter in the first phase.

This characteristic of the contamination trap would indicate that there are likely to be several problems in the development of a useable hydrocyclone system. A contamination trap that must be cleaned after short periods of operation will be of limited use in an actual full scale unit. Several possibilities do exist, however, that could feasibly overcome these problems.

One such solution might be to have two or more units so that one could carry the load while the other was being cleaned.

Another possibility might be to develop a continuous bleed system where the solids buildup could be continuously bled from the contamination trap.

In all of the experiments conducted without the contamination trap the results were the same; no separation occurred. Experiments of this nature were conducted with all three hydrocyclones at various underflow rates.

One possible explanation for the inability of the hydrocyclones in this configuration to separate the biological solids might be that insufficient flow rate occurred in the hydrocyclones to provide the necessary inlet momentum. Hydrocyclones #2 and #3 were to operate at a pressure drop of 75 psi and 2 gallons per minute. They failed to produce this flow rate at a pressure drop of even 90 psi. At 90 psi the flow rate in both hydrocyclones #2 and #3 was 1.34 gpm. The pumps used in this investigation were unable to deliver a greater flow rate or pressure drop, therefore hydrocyclones #2 and #3 were never operated at their design flow rate of 2 gallons per minute.

CHAPTER VII

CONCLUSIONS

The results of this investigation support the following conclusions:

(1) At the pressure drops and flow rates investigated a contamination trap was necessary for separation of the biological solids from a dispersed bacterial system.

(2) The contamination trap has a finite holding capacity, after which the separation efficiency of the system is greatly decreased.

(3) Before any separation will occur due to the effect of the hydrocyclone, very high inlet momentums must be obtained. In order to generate sufficient inlet momentum, the system must be operated at high pressure drops and flow rates.

CHAPTER VIII

SUGGESTIONS FOR FUTURE STUDY

From the results of this investigation, the following suggestions are made for future study on the utilization of the hydrocyclone for separation of biological solids from a dispersed bacterial system:

(1) The design and construction of hydrocyclones that operate at pressure drops in excess of 100 psi.

(2) Methods for continuously bleeding the biological solids from the contamination trap, and development of contamination traps that lend themselves to continuous bleeding.

(3) Study power requirements for typical hydrocyclone configurations.

(4) Develop design equations for the prediction of hydrocyclone performance on dispersed biological systems.

SELECTED BIBLIOGRAPHY

(1) Pipes, Wesley O., "Types of Activated Sludge which Separate Poorly." Jour. Water Pollution Control Federation, 41, 5, 714-724 (1969).

(2) Maciula, L. Andrew, and Reed, Robert E., Stillwater, Oklahoma, Assignors to Oklahoma State University, Stillwater, Oklahoma, Patent 3,529,724.

(3) Walker, and Dougherty, "Use of Polyelectrolyte Coagulants to Enhance Settling Characteristics of Activated Sludge." Engineering Bulletin of Purdue University, 715 (May 4, 5, and 6, 1965).

(4) Braithwaite, L., "Polymers as Aids to the Pressure Flotation of Wastes Activated Sludge." Water and Sewage Works, 545-547 (December, 1964).

(5) Goodman, Brian L., and Witcher, Preston C., "Polymer-Aided Sludge Elutriation and Filtration." Jour. Water Pollution Control Federation, 37, 12, 1643-1656 (1965).

(6) Ford, Davis L., and Eckenfelder, Wesley W., "Effect of Process Variables of Sludge Floc Formation." Jour. Water Pollution Control Federation, 39, 11, 1850 (1967).

(7) Singer, Philip C., Pipes, Wesley O., and Hermann, Edward R., "Flocculation of Bulked Activated Sludge with Polyelectrolytes." Jour. Water Pollution Control Federation, 40, 2 Part 2, R1 (1968).

(8) Tenny, Echelberger, Coffey, and McAloon, "Chemical Conditioning of Biological Sludges for Vacuum Filtration." Jour. Water Pollution Control Federation, 42, R1 (1970).

(9) Sirnon, E. R., and Lee, D., "Sludge Density Control with Sonar." Jour. Water Pollution Control Federation, 42, 298 (1970).

(10) Culp, Gordon L., Hsiung, Kou-ying, and Conley, Walter R., "Tube Clarification Process." Jour. San. Engr. Div., ASCE, 95, SA5, 829-847 (1968).

(11) Reed, Sherwood C., and Murphy, R. Sage, "Low Temperature Activated Sludge Settling." Jour. San. Engr. Div., ASCE, 96, SA4, 747-763 (1969).

(12) Dick, Richard I., "Role of Activated Sludge in Final Settling Tanks." Jour. San. Engr. Div., ASCE, 96, SA2, 423-436 (1970).

(13) Pipes, Wesley O., and Jones, P. H., "Decomposition of Organic Wastes by Sphaerotilus." Biotechnology and Bioengineering, 87 (1963).

(14) Richards, E., and Sawyer, G. C., "Further Experiments with Activated Sludge." Jour. Society of Chemical Industries, 41, 61 (1922).

(15) Hazen, A., "On Sedimentation." Transactions American Society of Civil Engineers, 53, 45 (1904).

(16) Camp, T. R., "Sedimentation and the Design of Settling Tanks." Transactions American Society of Civil Engineers, 111, 895 (1946).

(17) Eliassen, R., Discussion, Transactions American Society of Civil Engineers, 111, 947 (1946).

(18) Camp, T. R., Discussion, Transactions American Society of Civil Engineers, 111, 952 (1946).

(19) Schmitt, E. A., and Voight, O. D., "Two Story Flocculation-Sedimentation Basin for the Washington Aqueduct." Jour. American Water Works Association, 41, 837 (1949).

(20) Dresser, H. G., "Trays Nearly Triple Settling Tank Capacity." Engineering News Record, 147, 32 (November 29, 1951).

(21) Hansen, S. P., Culp, G. L., and Stukenberg, J. R., "Practical Application of Idealized Sedimentation Theory in Wastewater Treatment." Jour. Water Pollution Control Federation, 41, 8, Part 1, 1421-1444 (1969).

(22) Culp, G. L., and Hsiung, K., "Tube Clarification Process Operating Experiences." Jour. San. Engr. Div., ASCE, 95, SA5, 829-847 (1969).

(23) ________, "Analysis of Flotation Thickening of Waste Activated Sludge." Water and Sewage Works, 111, 1, 68-69 (1965).

(24) Geinopolos, A., and Katz, W. J., "A Study of a Rotating Cylinder Sludge Collector in Dissolved-Air Flotation Process." Jour. Water Pollution Control Federation, 36, 1, 712-721 (1964).

(25) Keefer, C. E., and Krotz, H., "Experiments on Dewatering Sewage with a Centrifuge." Jour. Water Pollution Control Federation, 1, 1, 120 (1929).

(26) Pecker, J. S., "Centrifugals." Jour. Water Pollution Control Federation, 8, 11, 991 (1936).

(27) Albertson, O. E., and Guidi, E. E., "Centrifugation of Waste Sludge." Jour. Water Pollution Control Federation, 41, 4, 607-628 (1969).

(28) Kraus, L. S., and Longby, J. R., "Concentrating Activated Sludge with a Continuous Feed Centrifuge." Jour. Water Pollution Control Federation, 11, 1, 9 (1939).

(29) Bradney, L., and Bragstad, R. E., "Concentration of Activated Sludge by Centrifuge." Jour. Water Pollution Control Federation, 27, 4, 404 (1955).

(30) Tchobanoglous, G., and Eliassen, R., "Filtration of Treated Sewage Effluent." Jour. San. Engr. Div., ASCE, 96, SA2, 243-265 (1970).

(31) ________, "Water Pollution Control Research Series Advanced Waste Treatment Research, Summary Report Advanced Waste Treatment." U. S. Dept. of the Interior FWPCA, Publication WP-20AWTR-19, 9-27 (July, 1964 - July, 1967).

(32) Tangel, O. F., and Brison, R. J., "Wet Cyclones." Chemical Engineering, 62, 2, 234-238 (1955).

(33) Campbell, John M., "Centrifugal Mist Extractors." The Oil and Gas Journal, 54, 101-102 (March 26, 1956).

(34) Bergman, W. E., Engle, S. J., Marwill, S. J., Porter, E. W., "Liquid Cyclone Cuts Cost of Treating Drilling Fluids." The Oil and Gas Journal, 54, 9, 114-116 (October 15, 1956).

(35) Lummus, J. L., and Scott, P. P., Jr., "Cyclones Score 77 to 100 Per Cent." The Oil and Gas Journal, 55, 106-110 (February 25, 1957).

(36) Haas, P. A., Nurmi, E. O., Whatley, M. E., and Engle, J. R., "Midget Hydrocyclones Remove Micron Particles." Chemical Engineering Progress, 53, 4, 203-207 (1957).

(37) Tangel, O. F., Brison, R. J., "Wet Cyclones." Chemical Engineering, 62, 2, 234-238 (1955).

(38) Matschke, D. E., and Dahlstrom, D. A., "Miniature Hydrocyclones - Energy Requirements and Solid Elimination Efficiency." Chemical Engineering Progress, 34, 12 (December, 1958, and January, 1959).

(39) Tiederman, William G., Personal Contact, October 14, 1970.

(40) Dahlstrom, D. A., "Cyclone Operating Factors and Capacities on Coal and Refuse Slurries." Transactions of the American Institute of Mining Engineers, 184, 331-344 (1949).

(41) Yoshioka, N., and Hotta, A., Chemical Engineering (Japan), 632-640 (1955).

(42) Kelsall, D. F., "A Study of the Motion of Solid Particles in a Hydraulic Cyclone." Transactions Institution of Chemical Engineers, (London), 30, 87-108 (1952).

(43) Kelsall, D. F., "A Further Study of the Hydraulic Cyclone." Chemical Engineering Science, 2, 254-272 (1953).

(44) _______, Standard Methods for the Examination of Water and Wastewater, 12th Ed., APHA, New York, (1965).

APPENDIX

TABLE OF TERMS

C = Constant,

d_{50} = Diameter of particle at 50% point, microns,

D_c = Diameter of hydrocyclone, inches,

D_f = Diameter of inlet nozzle, inches,

D_o = Diameter of overflow nozzle, inches,

D_u = Diameter of underflow (minimum cone diameter), inches,

k = Constant for flow capacity correlation,

L_c = Length of cone, inches,

Lcyl. = Length of cylindrical section,

μ = Mu, absolute viscosity, pounds mass per inch, second,

O.D. = Optical density,

ΔP = Differential pressure (pressure drop across hydrocyclone), pounds per square inch,

ϕ = Phi, cone angle,

Q = Flow rate through hydrocyclone, gallons per minute,

Q_u = Flow rate from collection pot underdrain, gallons per minute,

ρ_l = Rho, density of liquid dispersion medium, pounds mass per cubic inch,

ρ_s = Rho, density of solids, pounds mass per cubic inch,

T = Percent transmittance.

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