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APPLICATION OF HYDROCYCLONES FOR THE TREATMENT OF WASTEWATER IN GOLD PLACER MINING

HSING KUANG LIN

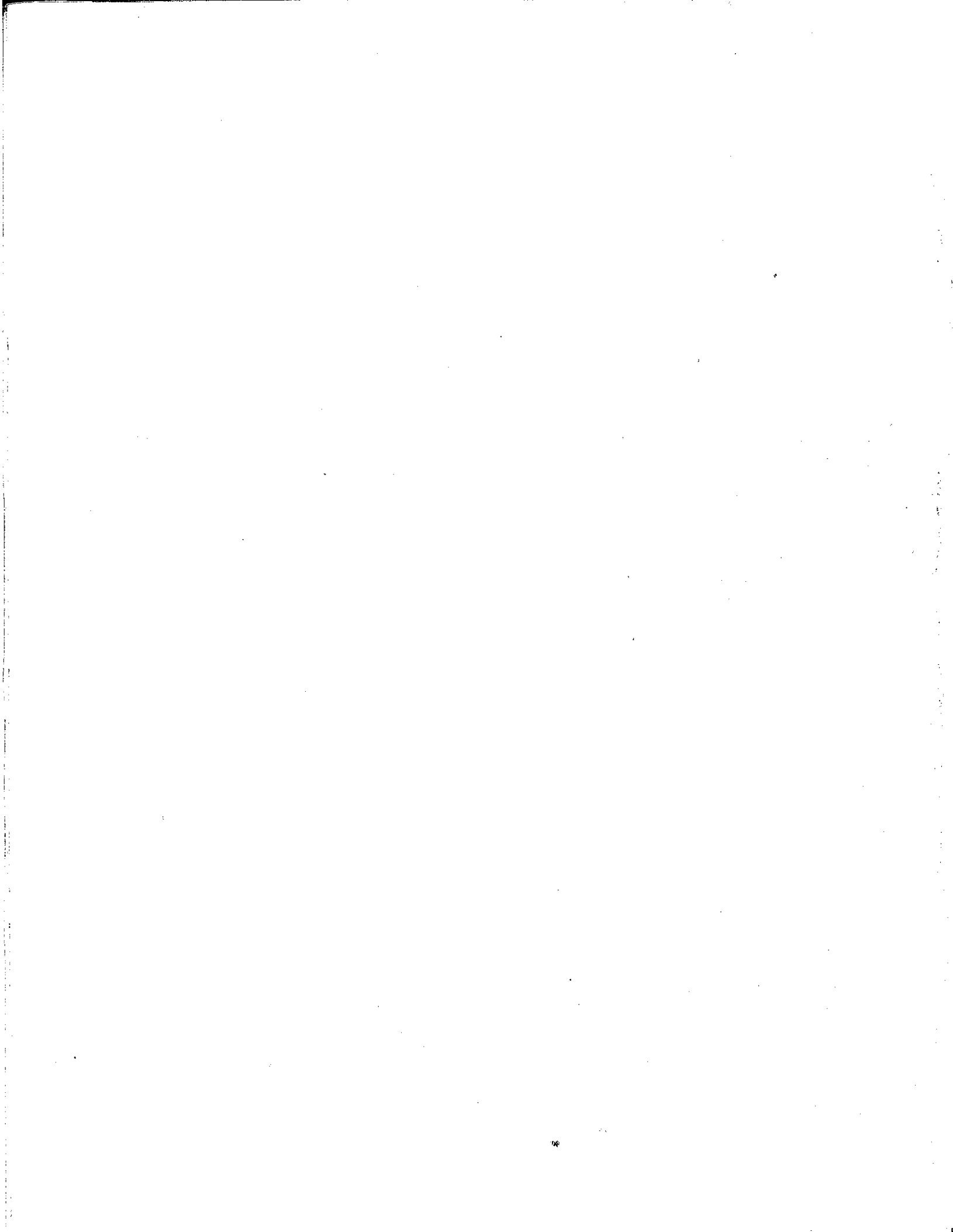
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APPLICATION OF HYDROCYCLONES FOR THE TREATMENT OF
WASTEWATER IN GOLD PLACER MINING

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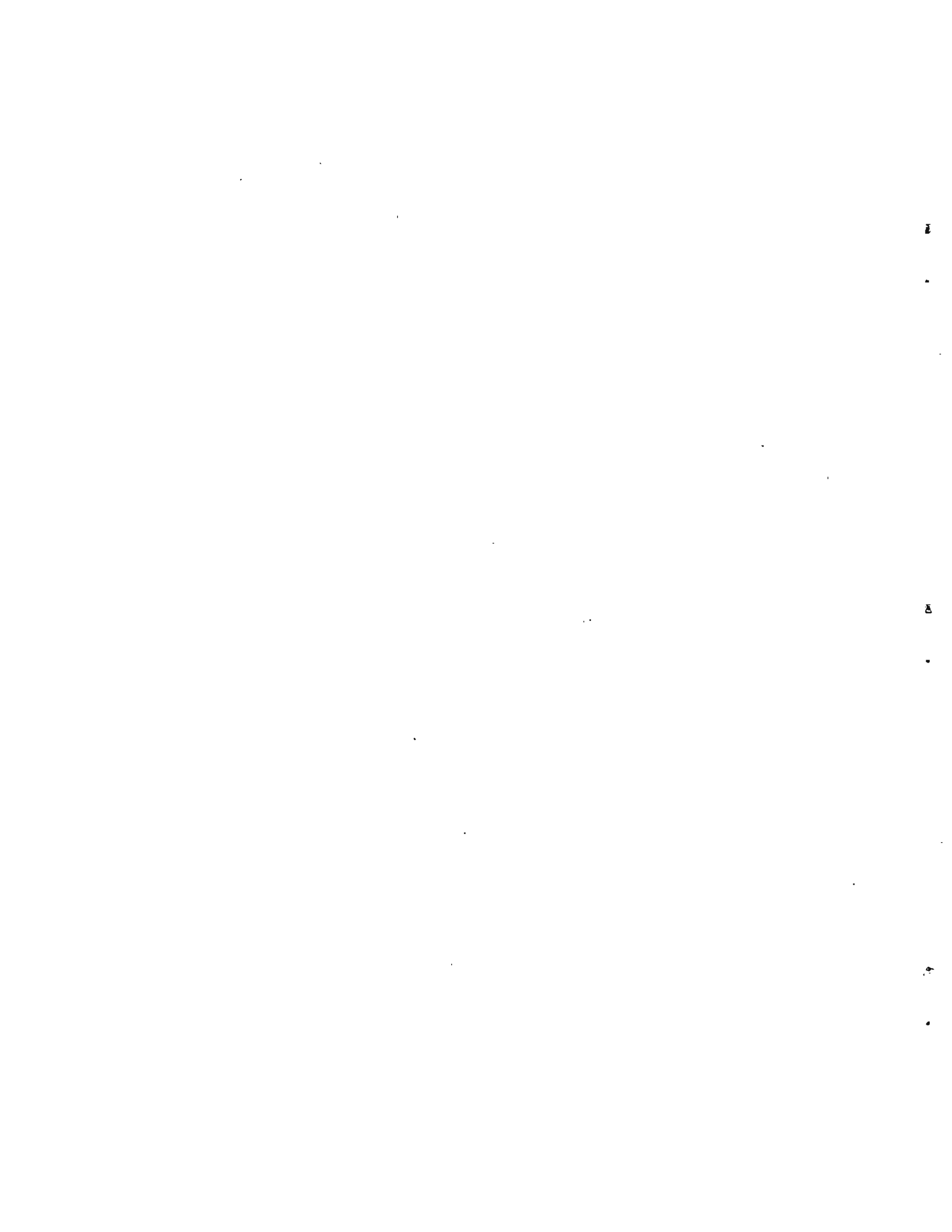
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APPLICATION OF HYDROCYCLONES FOR THE TREATMENT OF
WASTEWATER IN GOLD PLACER MINING

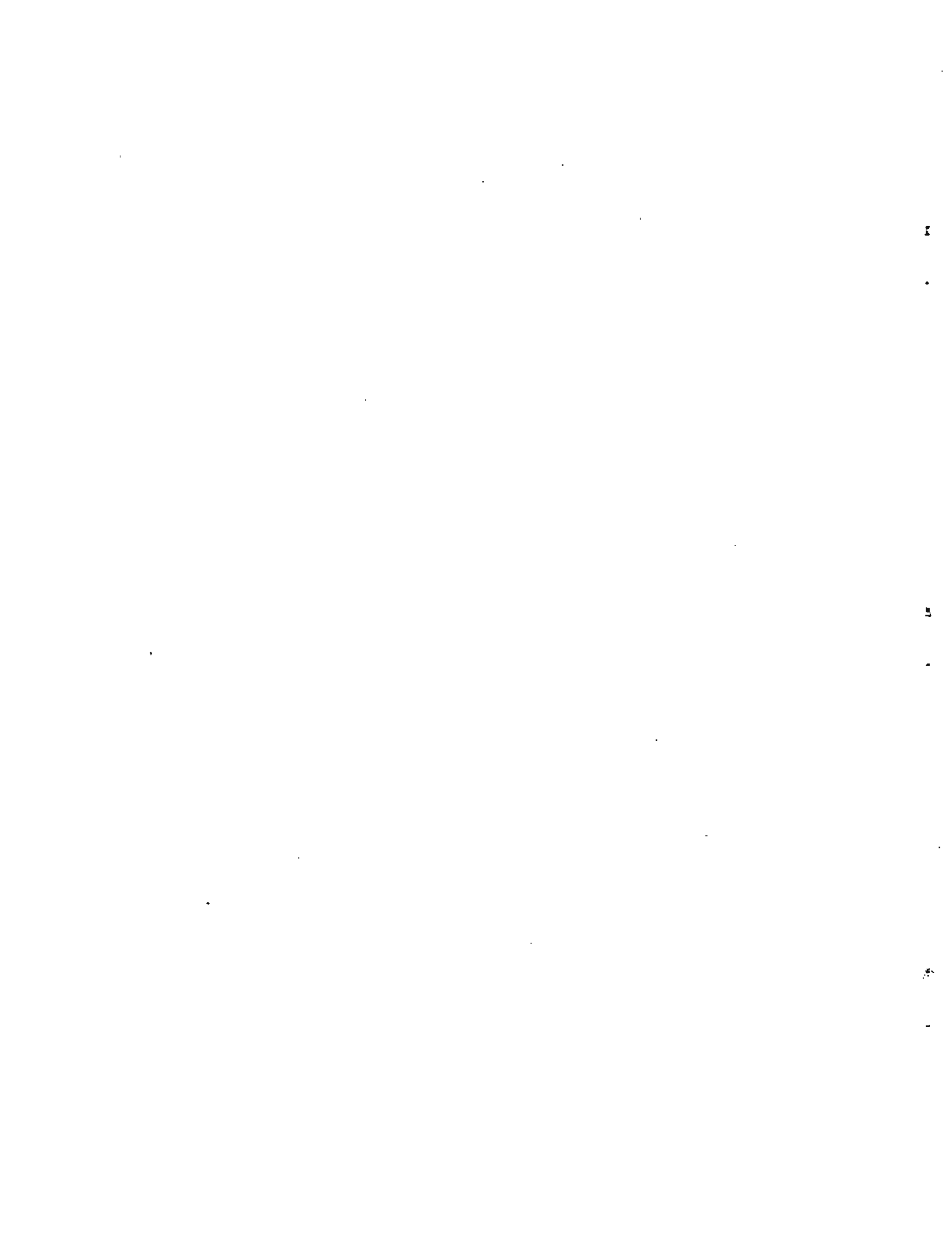
A
THESIS

Presented to the Faculty of the
University of Alaska in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE

BY
HSING KUANG LIN, M.S.
Fairbanks, Alaska

May 1979



ABSTRACT

This is a report on experimental application of hydrocyclones for the wastewater treatment in placer mining, with emphasis on their use in combination with a kind of large molecular weight flocculant. The simultaneous flocculating and clarifying of placer mining effluents was tested and evaluated.

Tests showed that Superfloc 84 can be used as a flocculant to improve the thickening performance of the hydrocyclone. This thickening improvement demonstrates that, contrary to previously held theories, floc can be capable of resisting the shear forces in the hydrocyclone.

For the 4-inch-diameter hydrocyclone used in this study, more than 80% of solids coarser than 16 microns in diameter can be removed without the addition of flocculants. The optimum flocculant dosage and feed pressures for the removal of fine solids also were determined. Based on the data obtained, a flowchart of a closed circuit system for the treatment of placer mining effluents was recommended.

ACKNOWLEDGEMENTS

I wish to express my deepest appreciation to my committee chairman, Dr. Pannasani D. Rao, as well as the two other members of my committee, Dr. Ernest N. Wolff and Dr. Earl H. Beistline, for their helpful guidance and assistance during the course of this thesis.

I wish to extend my acknowledgements to Dr. Donald J. Cook for his encouragement and to the U. S. Bureau of Mines for its financial assistance.

Thanks are also due many individuals for their cooperation in the collection of samples.

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CHAPTER 1

INTRODUCTION

When this country was young and inhabited by few people, the streams, rivers, and lakes were able to provide all the clean water needed by man and take away all the wastes created by him. However, with growing population and increasing demand for goods and services, the public, industry and government at all levels have become aware of the need to manage more effectively the water resources of this country.

In the past, the disposal of the utilized water in placer mining operations was usually a fairly simple matter. Ditches were often used to drain the utilized water into the nearest stream or river. The concept of "water is water" was generally accepted without too much concern over what was in it, since low-cost products and services, rather than clean water, were what the public wanted.

During the last two decades, this country has seen a dramatic change in its attitude toward water. Society is now demanding cleaner streams, rivers, and lakes, free from pollutants that can interfere with multiple use of these resources. New laws have been adopted that prohibit everyone from discharging water into streams unless it is free from pollutants. These new laws also have affected the placer mining industry, in that mine operators can only discharge the utilized water when it, too, is free of pollutants. Thus, removal of pollutants from the utilized water is one of the more serious problems facing the placer mining industry today.

Legislation and Regulations

The Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500) is one of the most important regulations concerning the environmental consequences of the mining industry. Its goal was described as follows:

"The objective of this Act is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters ...

It is the national goal that the discharge of pollutants into the navigable waters be eliminated by 1985 ... " Under this Act, the effluent limitation requirements are: (1) (2)

- 1: Best practicable control technology currently available (BPCTCA) shall be achieved not later than July 1, 1977.
- 2: Best available technology economically achievable (BATEA) shall be applied not later than July 1, 1983.
- 3: New source effluent limitations and/or standards, to be applied to the construction of all new operations which is begun after proposed standards are first published.

It is hoped that with application of the above criteria, the national goal of zero source pollution will be met.

Based on the BPCTCA, the U.S. Environment Protection Agency (EPA) published the interim effluent limitations and guidelines for mining and mill industries excluding the coal industry. Among these guidelines, the limitation of less than 20 mg/liter of suspended solids has the most important effect on the placer mining industry (3).

In May 1976, the EPA issued the first batch of National Pollutant

Discharge Elimination System (NPDES) permits. Under these permits the effluent limitations are: (4)

- 1: The volume of settling ponds should be large enough to contain the water supply of one day's operation or the maximum concentration of settleable solids from mining shall not exceed 0.2 ml/liter.
- 2: The turbidity at a point 500 feet downstream from the discharge shall not be higher than 25 Jackson Turbidity Units compared with the turbidity in the receiving stream.

In Alaska, under section 303 of the Federal Water Pollution Act Amendment, which encourages states to set their own water quality standards, the Alaska Department of Environmental Conservation (ADEC) responds to set the standards for the prevention and abatement of water pollution.

In October 1973, ADEC issued its water quality standards as Alaska Administrative Code (AAC) Title 18, Chapter 70, and amendments were made in January 1979. According to this code, the limitations for effluents from placer mining are: (5)

- 1: The turbidity shall not be 25 NTU greater than that in receiving water.
- 2: The temperature shall not exceed 25°C.
- 3: The pH value shall be within the range 5.0-9.0.
- 4: The dissolved oxygen shall not cause detrimental effects on established water supply treatment levels.
- 5: There shall be no imposed load of sediment that will affect established water supply treatment levels.

Among these limitations, the turbidity problem is most serious for the placer mining industry in Alaska.

The Purpose and Scope of Study

Two of the serious problems in Alaskan placer mining are insufficiency of water for continuous operation of mining and the turbidity problem in the effluent. The purpose of this study is to investigate the application of hydrocyclones for a closed circuit water system to help solve these problems.

The scope of this study includes:

- 1: Review of the theories of hydrocyclones.
- 2: Preliminary tests of the hydrocyclone used in this study.
- 3: Determination of:
 - (a) The separation efficiency of the hydrocyclone on different particle sizes of solids.
 - (b) Effect of temperature on separation efficiency.
 - (c) Effect of feed concentration on separation efficiency.
- 4: Tests of the hydrocyclone with different feed pressures and flocculant loadings.
- 5: Proposal of a flowchart for a zero discharge closed circuit system for placer mining in Alaska.

Description of Areas from which Samples were Obtained

Samples were collected from the Circle and Livengood districts (Figure 1) in August 1979.

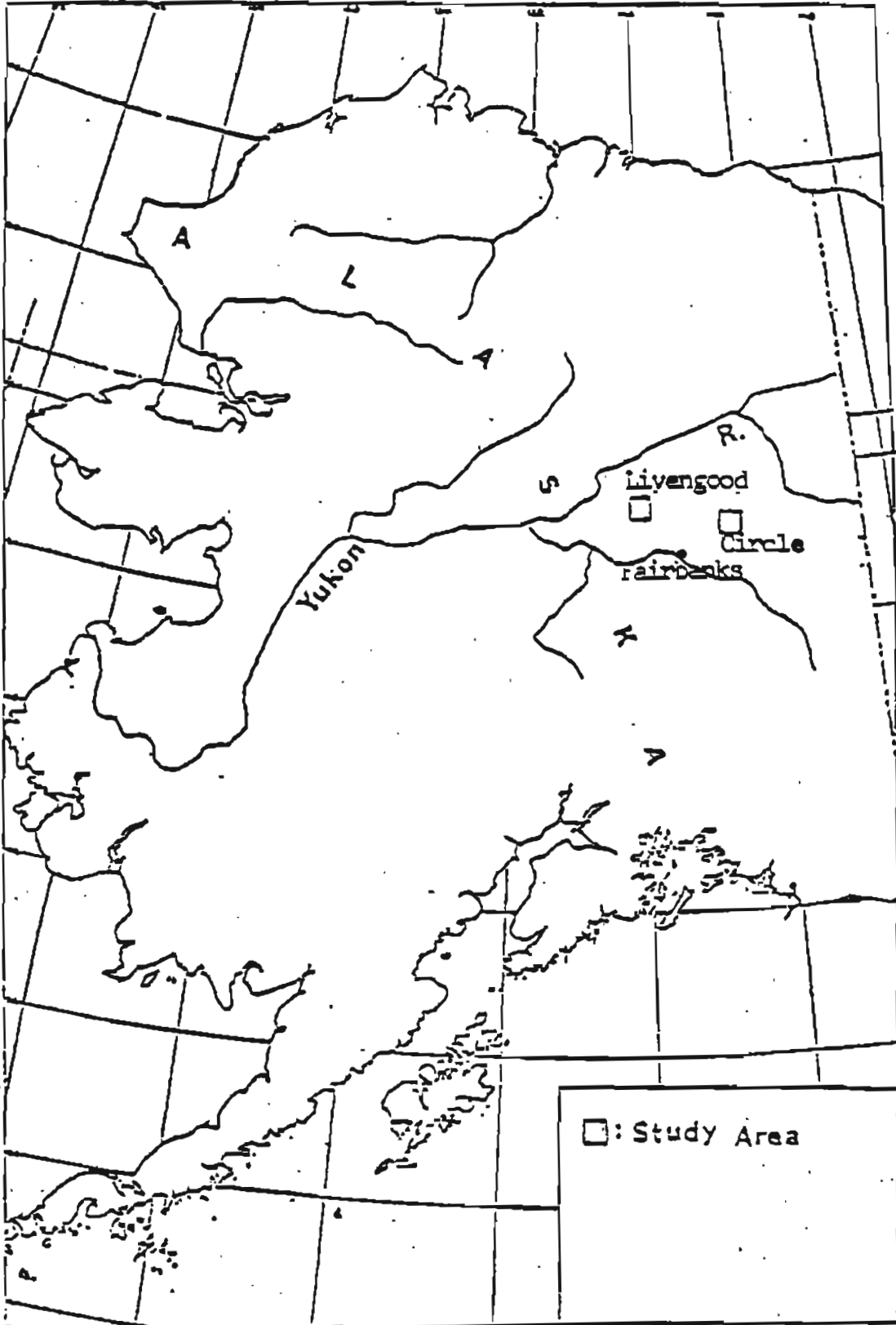


Figure 1. Index map shows mining areas studied.

Circle District

The Circle district lies between latitude $65^{\circ}15'$ and $65^{\circ}51'$ N. and longitude $143^{\circ}53'$ and $145^{\circ}47'$ W.

According to Mertie, ⁽⁶⁾ unconsolidated alluvial deposits ranging from Pleistocene to Recent in age lie above the consolidated bedrocks. These bedrocks have been mapped as the following geological formations: ⁽⁶⁾

Granitic rocks: Mesozonic

Chert formations: Mississippian

Rampart group: Lower Mississippian

Limestone: Devonian or Silurian

Noncalcareous sedimentary and greenstone: Devonian to Ordovician

Birch Creek Schist: Pre-Cambrian

It is the granite rocks which are believed to play a very important role in the processes of mineralization. These granitic rocks are composed of biotite and hornblende granites with minor proportion of quartz monzonite, quartz diorite, diorite, and gabbro. The unconsolidated alluvial deposits consist of gravel, sand, and silt and are covered with black muck composed of silt and peaty material as well as a few beds of sand or gravel. The latter gravel deposits conform closely with the general run of fluviatile deposits found elsewhere. "Some of the fluviatile deposits were formed by ancient or present streams that drained areas mineralized with gold; these deposits also contain gold, and where the auriferous content is sufficiently high they constitute commercial gold placers." Overlying the gravel stratum is a layer of overburden or muck of 3 feet to several tens of feet in thickness.

Wastewater was obtained on a mining site at Bonanza Creek depicted

in Figure 2. At this station, a bulldozer was utilized to transport gold-bearing gravel to the sluice plate and sluice box. The tailings were removed by a front-end-loader. Wastewater sample was collected at a distance of about 100 feet from the discharge end of the sluice box during the period of sluicing operation.

Livengood District

The Livengood district lies between latitude $65^{\circ}10'$ and $65^{\circ}35'$ N. and longitude $147^{\circ}40'$ and $149^{\circ}30'$ W.

Gold occurs in the gravel layer that overlies bedrock. The bedrock is composed of metamorphosed clastic facies of sedimentary rocks, metadiorite, metabasalt, serpentinite, peridotite, and silica-carbonate-talc schists (7). The gold-bearing gravel ranging from 4 to 20 feet in thickness is usually overlain by overburden composed of barren alluvium and loess. The overburden in this area may be up to 100 feet (8).

The wastewater sample was obtained on a mining site at Ruth Creek depicted in Figure 3. At this station a bulldozer was employed to strip the overburden and a front-end-loader for transportation of the gold-bearing gravel to the sluice box. Both machines were used to remove the tailings and stack them off the mining limits. Wastewater sample in this district was also collected at a distance about 100 feet from the discharge end of the sluice box in a relatively fast stream.

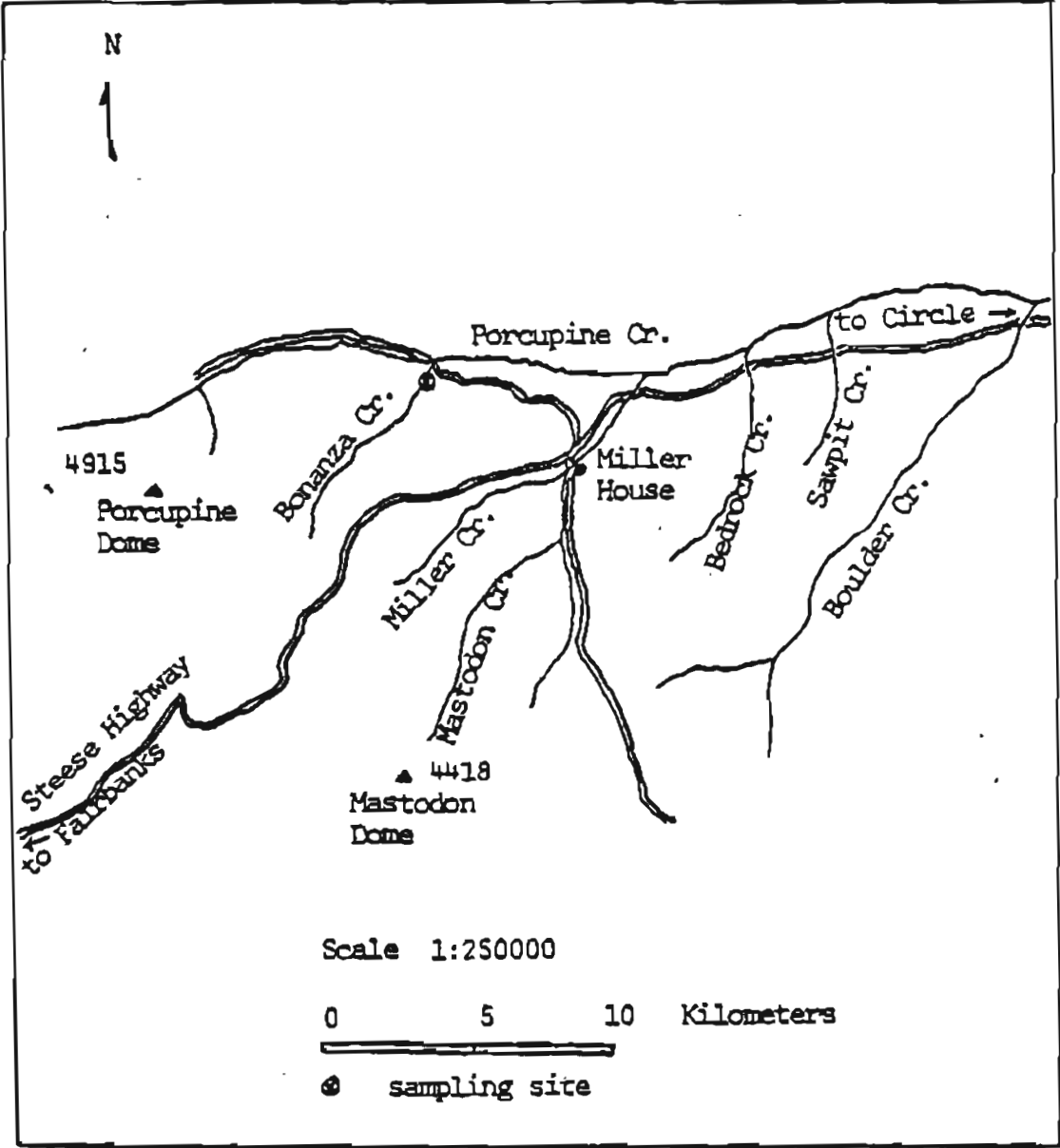


Figure 2. The sampling site at Circle district.

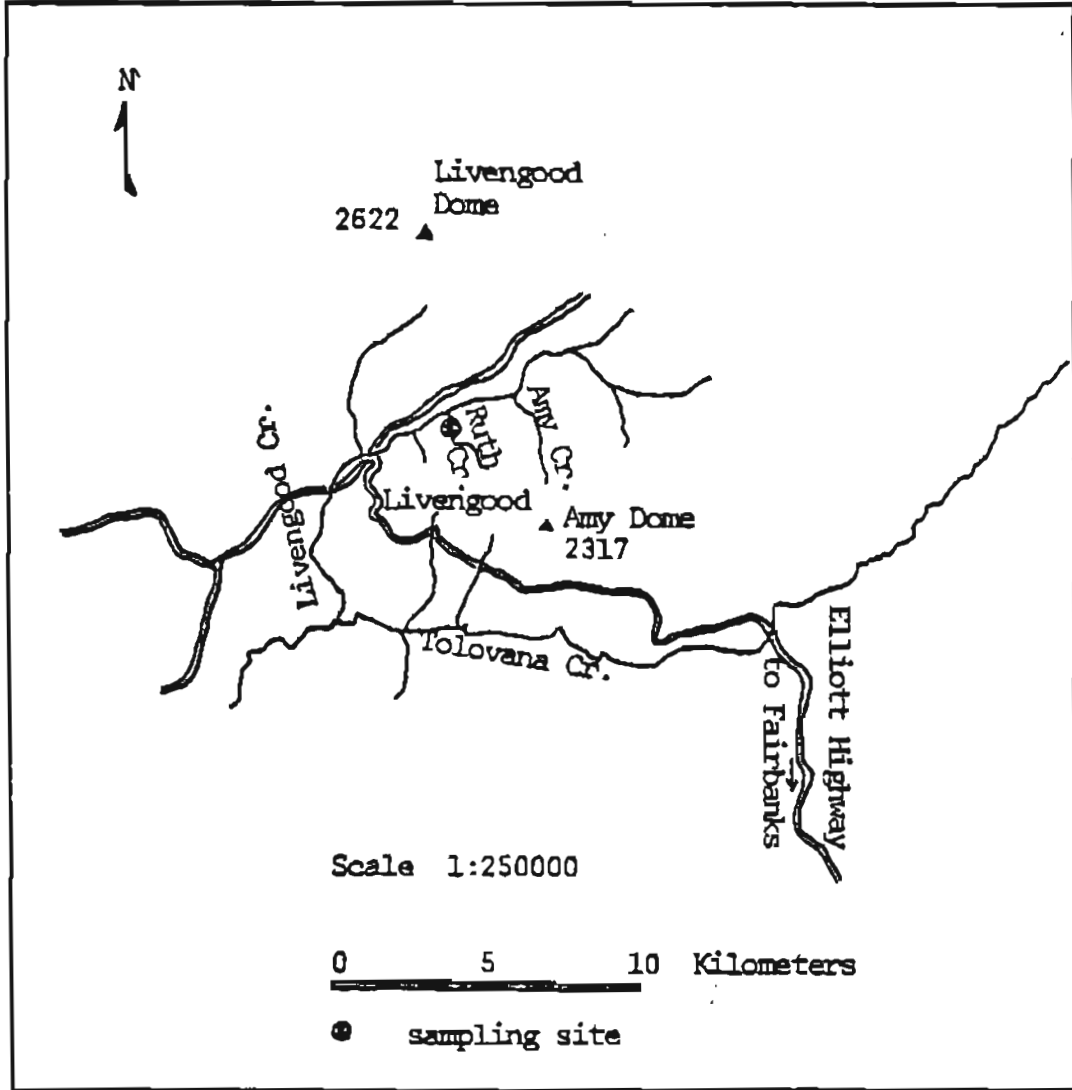


Figure 3. The sampling site at Livengood district.

CHAPTER 2

THEORETICAL ASPECTS OF HYDROCYCLONES

The liquid cyclone usually is known as the hydraulic cyclone through the prevalence of applications where water is used as the fluid medium. "Hydraulic cyclone" has been abbreviated to "hydrocyclone" and sometimes even "hydroclone." However, "hydrocyclone" is the most common term used both in industry and in research.

The first hydrocyclone patent was granted to Bretney in the United States in 1891 (9). However, the hydrocyclone has been utilized in industry only since 1935 whereas the gas cyclone has been known and in general use throughout industry for more years.

Application of the hydrocyclone in the pulp and paper industry was developed in 1935 before serious thought was given to its use in other industries (10, 11). In the late 1940's and early 1950's, numerous commercial installations were in successful operation, and reported in the technical literature of several different fields: coal preparation (12), mineral dressing (13), the clarification of process water (14), food industry, and other fields.

Principal Features of a Hydrocyclone

The hydrocyclone is a device in the form of a cylindro-conical vessel into which the fluid to be processed is injected under pressure. The tangential injection of the fluid into a vessel produces the rotation of fluid and high centrifugal force within the vessel. This

centrifugal force and rotational motion cause relative movement of materials suspended in the fluid thus permitting separation of these materials from each other or from the fluid. The rotating fluid is forced to spiral towards the center to escape, which the suspended solids are forced to move in an outward radial direction due to the centrifugal force. Another force acting on the suspended solids in an inward radial direction is the drag force of the moving fluid. The magnitude of these forces is dependent mainly on the size and shape of the solids, density of the solids and of the fluid, viscosity of the fluid, feed pressure, and the dimensions of the hydrocyclone. Solids of sufficient size and density are ejected outward to the walls and spirally discharged to the underflow. Most of the water with uneliminated fine solids moves radially inward, along the path of the outer spiral to a second inner spiral at the hydrocyclone core, and passes out the overflow. The inner spiral is the most critical to fluid movement because of its small radius and higher tangential velocity. The centrifugal force which furnishes the elimination power will attain a maximum at this inner spiral. A typical hydrocyclone is shown in Figure 4.

The operating characteristics of a hydrocyclone in wastewater treatment are summarized as follows:

- (1) **Simplicity and low cost:** The complete absence of moving parts and ease of construction make the hydrocyclone attractive from the point of view of both initial capital and operating costs. Capital and operating costs are naturally variable depending on design, material of construction, use for

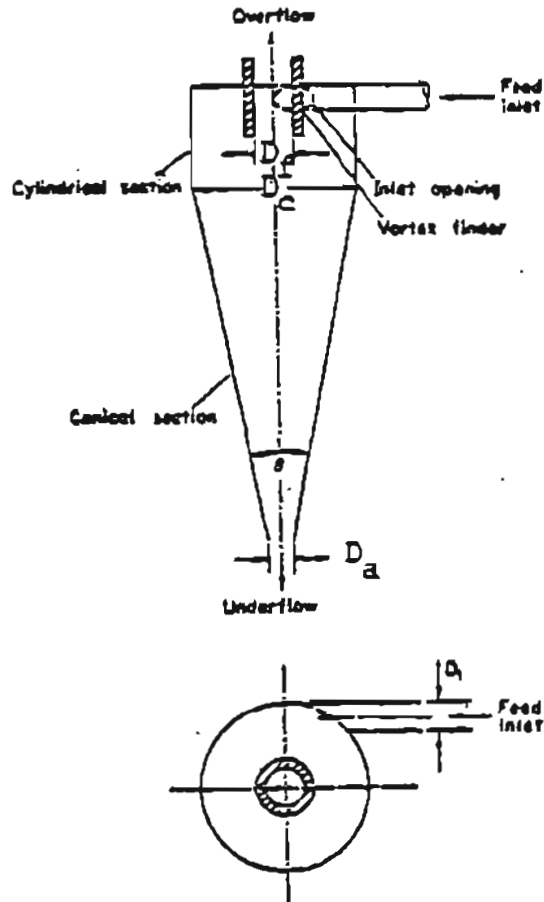


Figure 4. Principal features of a hydrocyclone.

special features, etc. However, according to Brodley (15), a figure often used in comparing the hydrocyclone with a gravitational classifier is that the hydrocyclone costs 20 to 50 percent of the cost of an equivalent classifier.

- (2) **Small space requirement:** A hydrocyclone usually is installed with its axis vertical, hence the floor space required is extremely small for the capacity involved. It is not uncommon for the floor space to be decreased by a factor of 10^5 by the use of hydrocyclones instead of settling tanks (15).
- (3) **Limitation of separating effect:** A hydrocyclone requires water pressure energy to achieve rotational motion and centrifugal acceleration. Achievement of high separational affect, that is, separation of fine solids, is possible by increasing the pressure employed. This utilmately becomes uneconomical, and single hydrocyclones rarely are operated with a feed pressure higher than 50 psig in industrial application. Classification size is increased by an increase in hydrocyclone diameter. The throughput capacities of hydrocyclones fall off very rapidly with a decrease in diameter of hydrocyclone. Therefore, for affective separation of solids, a practical limit of classification size is approximately 5 microns.
- (4) **Erosion:** Hydrocyclones have stationary walls, while the liquid and solids rotate within them. The erosion problem in hydrocyclones is therefore severe.

A Review of the Performance of Hydrocyclones

Hydrocyclone operation still is not an exact science and many aspects of design and operation remain controversial. Workers in many countries have paid considerable attention to both theory and practice. Most of these workers have developed their own theories. In this study, only a few of them will be discussed.

Flow Pattern in a Hydrocyclone

In 1952, Kalsall measured tangential velocity V_t and vertical velocity V_v at selected points in the hydrocyclone by following the motion of suspended solids using an optical device (16). The relative values of these components are given in Figures 5 and 6. Below the bottom of the vortex finder, at any horizontal level, starting from near the conical wall, the tangential velocity increases with decrease in radius (r) according to the relationship

$$V_t \cdot r^n = \text{constant, where } 0 < n < 1$$

This holds to regions of the envelope of maximum tangential velocity (See Fig. 7) where V_t reaches a maximum value. At this envelope, the centrifugal acceleration, V_t^2/r reaches a maximum value. As the radius is further decreased, the tangential velocity decreases in the relationship of $V_t = k \cdot r$, where k is constant

Above the bottom of the vortex finder, tangential velocity increases from the hydrocyclone wall toward its axis but decreases rapidly as the wall of the vortex finder is approached.

From analysis of results of testing different hydrocyclones ranging from 3.0 - 6.0 inches, Lilge concluded (17):

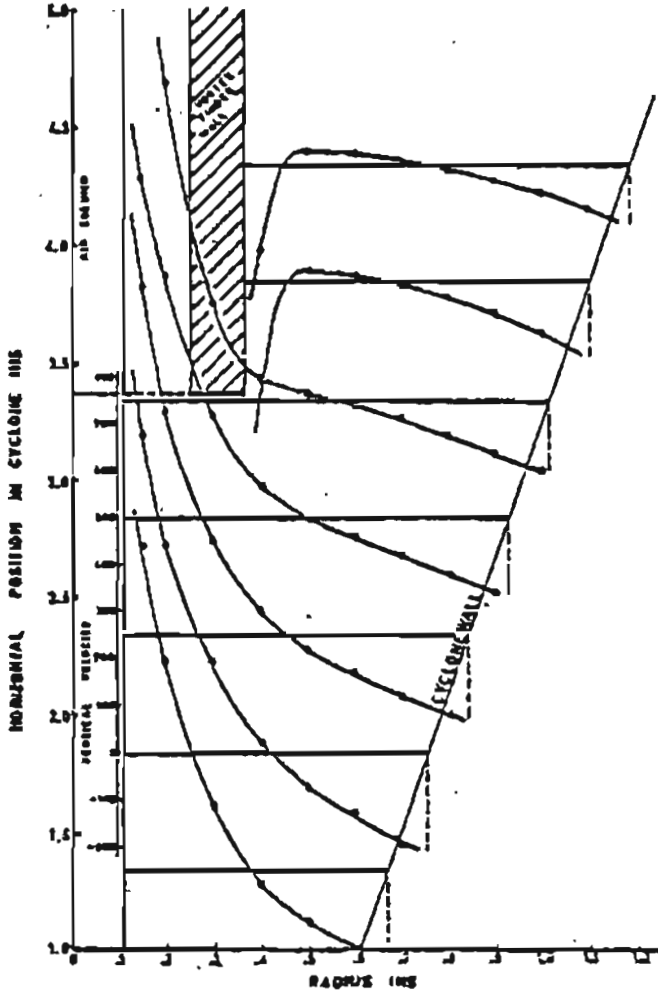


Figure 5. Vertical velocities in a hydrocyclone (in arbitrary units), taken from Kelsall. (15)

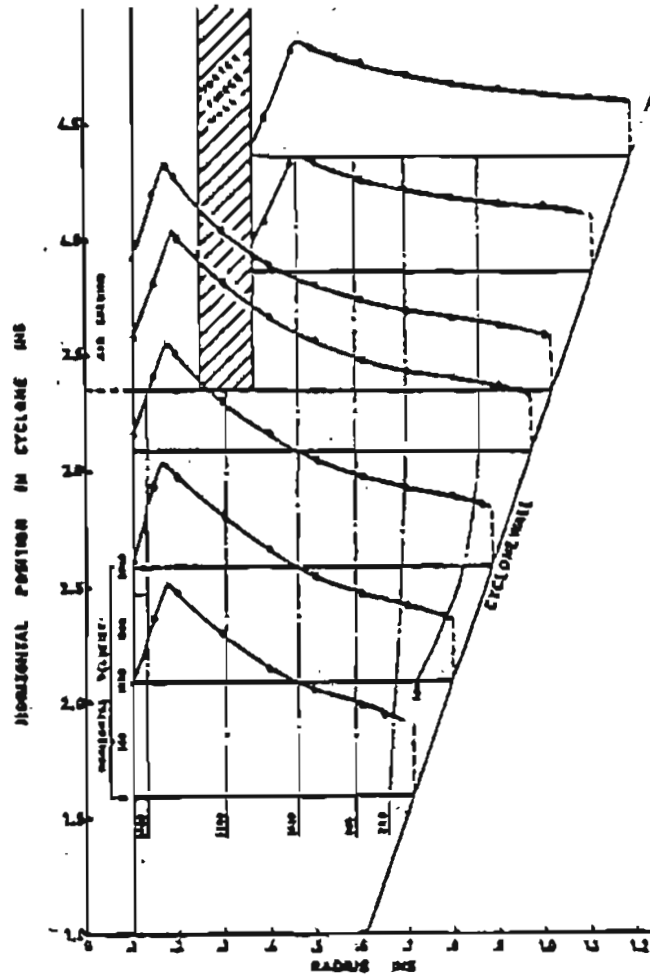


Figure 6. Tangential velocities in a hydrocyclone
(in arbitrary units), taken from Kelsall. (16)

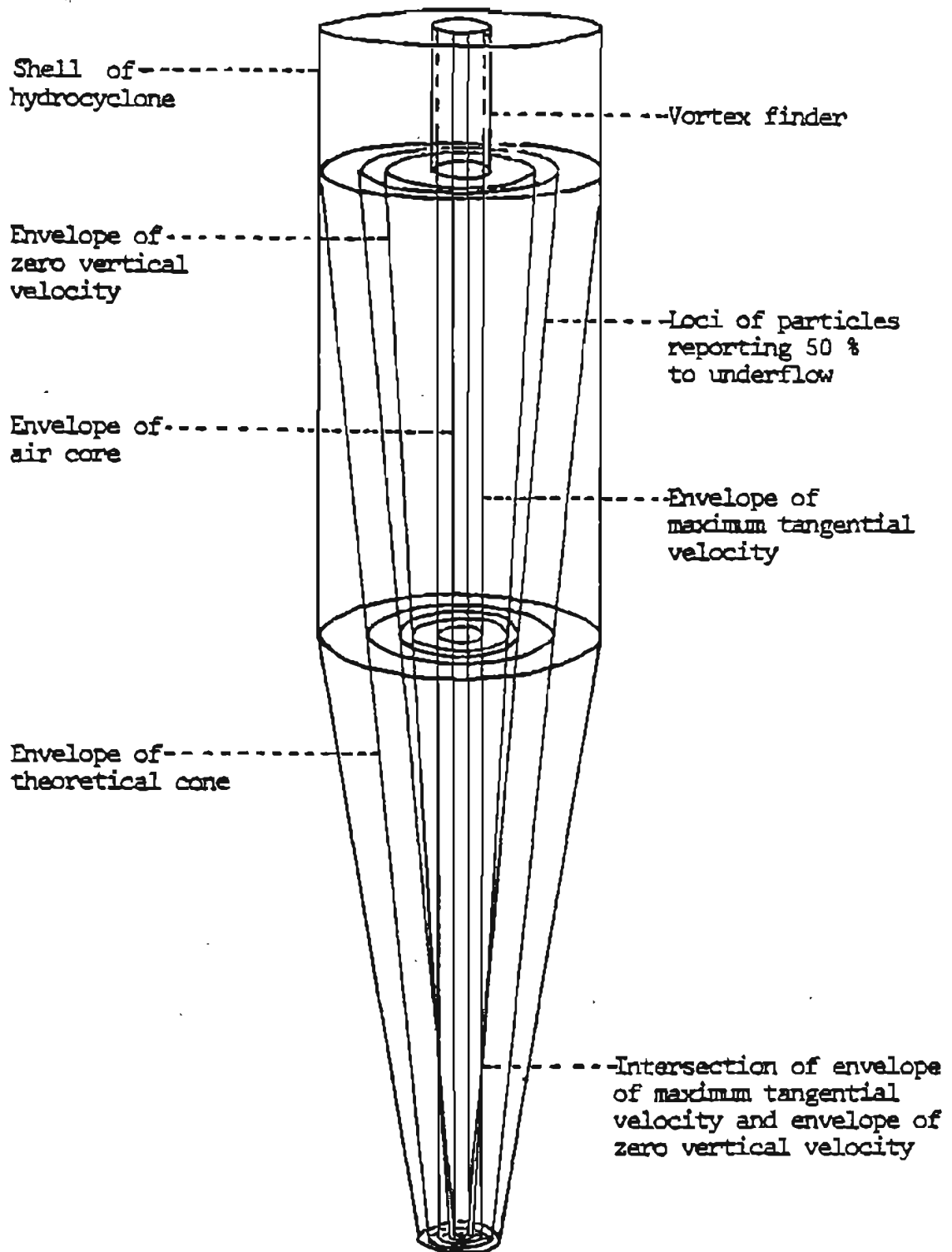


Figure 7. The representation of envelopes of velocities in the hydrocyclone. (17)

- (1) The maximum tangential velocity in the conical portion of a hydrocyclone occurs at $0.167 r_C$.
- (2) The radius of the air column is $0.083 r_C$.

Where r_C is the radius of the hydrocyclone at the cylindrical portion.

The same relationships were obtained when the underflow diameter was reduced progressively until no fluid was reported to underflow.

Beneath the bottom of the vortex finder, the greatest downward velocities occur near the conical wall at any horizontal level and the downward velocity decreases as r decreases, becoming zero at the envelope of zero vertical velocity, then upward movement increases until the greatest upward velocity is found at the wall of the air column in the center of the hydrocyclone.

In regions between the conical wall and the envelope of zero vertical velocity, all liquid flows downward, toward the apex (underflow); between the envelope and the central axis, all liquid flows upward, toward the vortex finder (overflow). The suspended solids are discharged with the underflow, unless these solids move inward through the envelope of zero vertical velocity before the underflow opening of the hydrocyclone is reached.

Above the bottom of the vortex finder, downward velocity decreases to zero as r decreases. Then the movement becomes upward, increasing to a maximum, then returning to zero. A large downward velocity is found near the wall of the vortex finder. This large downward velocity corresponds to a short circuit flow caused by the decreasing tangential velocity. Thus, the separation efficiency is relatively low in this region.

The relationship between V_v and V_t , which is independent of the feed pressure, can be expressed as (16):

$$\frac{V_v}{V_t} = \tan \frac{\theta}{2}$$

Where θ is the angle of the conical portion of the hydrocyclone.

The inward radial velocity V_r at any horizontal level near the conical wall tends to be:

$$V_r = V_v \tan \frac{\theta}{2}$$

As r decreases, V_r decreases and becomes zero in regions near the wall of the air column. At levels above the bottom of the vortex finder, radial movement of the liquid may be outward due to recirculatory flows.

Forces Acting on the Solids within a Hydrocyclone

The total force F acting on the solids is made up of three components:

$$F = F_d + F_v + F_c$$

where F_d : drag force

F_v : vertical force

F_c : centrifugal force

The drag force acting on the solids at any point within a hydrocyclone can be expressed as (18):

$$F_d = \frac{52.4}{2g} C_d A \gamma_f V^2$$

where g : gravitational acceleration, ft/sec.²

C_d : drag coefficient

A : cross sectional area of solid, ft²

γ_f : specific gravity of fluid

V : velocity of solid, ft/sec.

The magnitude of F_v determines the time of residence of a solid within a hydrocyclone on either side of the envelope of zero vertical velocity. The vertical force affects the velocity of solids, V , thus affecting F_d also. If the component of F_d in a radial direction F_{dr} is considered:

$$F_{dr} = \frac{62.4}{2g} C_d A \gamma_f V_r^2 \quad (1)$$

where V_r is radial velocity

The centrifugal force is

$$F_c = \frac{62.4}{g} U (\gamma_s - \gamma_f) \frac{V_t^2}{r} \quad (2)$$

where U is volume of solid and

γ_s is specific gravity of solid.

At the position where

$$F_{dr} = F_c$$

$$\text{Thus } \frac{62.4}{2g} C_d A \gamma_f V_r^2 = \frac{62.4}{g} U (\gamma_s - \gamma_f) \frac{V_t^2}{r}$$

$$\text{or } C_d A \gamma_f V_r^2 = 2 (\gamma_s - \gamma_f) U \frac{V_t^2}{r} \quad (3)$$

This equation is the Cone Force Equation.

For spherical solids, it becomes

$$3 C_d \gamma_f V_r^2 = \frac{4 (\gamma_s - \gamma_f) d V_t^2}{r}$$

where d is diameter of solid.

For different solids and liquids, the values of C_d , γ_s , γ_f , effective values of d , and dimensions of the hydrocyclone (such as the ratio of diameter of apex to diameter of vortex finder) all contribute

to determine the relative magnitudes of drag, centrifugal or vertical forces. Because it is difficult to define all these variables with precision, the prediction of overall performance of a hydrocyclone without limitations and disadvantages has not yet been possible.

Separation Effectiveness of a Hydrocyclone

The separation effectiveness of a hydrocyclone can be expressed in two ways:

- (1) Actual separation effectiveness E_a : defined as the fraction of the feed solids which go to the underflow.
- (2) Corrected or reduced separation effectiveness E_c : defined

as

$$E_c = \frac{E_a - R_f}{1 - R_f}$$

Where R_f is flow ratio defined as the ratio of underflow rate to total flow rate.

In industrial application of the hydrocyclone, actual separation effectiveness often is used, but in the study of "how centrifugal force, drag force or vertical force acts on the solids," corrected separation effectiveness is preferred.

The term, d_{50} , very frequently is used instead of actual separation effectiveness or corrected separation effectiveness. It is defined as the particle diameter which distributes 50 percent to overflow and 50 percent to underflow. Many workers (16, 17, 19, 20) assumed that solids attain an equilibrium radial position in hydrocyclones where the terminal velocity is equal to fluid radial velocity. Different solids have different equilibrium radial positions. If this radius is less than the radius of zero vertical velocity, the solid will go to the overflow being in an

upward stream, while those with the radius larger than that of zero vertical velocity will go to the underflow. The solid with its radius coincident with that of zero vertical velocity is assumed to be of the size equal to d_{50} .

Dahlstrom developed one of the earliest expressions of d_{50} from a 9-inch-diameter cyclone (21). The equation is

$$d_{50} = \frac{81 (D_i D_f)^{0.68}}{Q_t^{0.53}} \left(\frac{1.73}{\rho_s - \rho_f} \right)^{0.5} \quad (4)$$

Where D_i , D_f are diameters of hydrocyclone inlet and vortex finder respectively. Q_t is total flow rate

Units in this equation are d_{50} — microns
 D_i, D_f — inches
 Q — gallons/min
 ρ_s, ρ_f — g/cm³

By imparting viscosity, μ , and diameter of hydrocyclone, b_c , Yoshioka and Hotta (19) carried out a series of tests of different hydrocyclones with diameters ranging from 3 — 6 inches to develop the equation

$$d_{50} = 6.3 \times 10^6 \left(\frac{\mu}{\rho_s - \rho_f} \right)^{0.5} \frac{D_c^{0.1} D_i^{0.6} D_f^{0.8}}{Q_t^{0.5}} \quad (5)$$

where units: d_{50} — microns
 μ — kg/m.sec
 ρ_s, ρ_f — kg/m³
 D_c, D_i, D_f — meters
 Q_t — l/sec

Bradley (20) did not agree with Yoshioka's assumption made for equation (5), which was "the locus of zero vertical velocity coincided with the surface of an imaginary cone whose apex is at the apex of the hydrocyclone cone and whose base is at the bottom of the vortex finder," and he introduced Q and a factor α into the equation, it became

$$d_{50} = 2.7 \left(\frac{\tan \frac{\theta}{2} \cdot \mu \cdot (1-R_f)}{D_c \cdot Q_t \cdot (\rho_s - \rho_f)} \right)^{0.5} \cdot \left(\frac{2.3D_f}{D_c} \right) \cdot \frac{D_i^2}{\alpha} \quad (6)$$

A year later, Bradley (21) revised equation (6) by introducing the concept of "conical classification surface," (22) then the equation read

$$d_{50} = \frac{3 (0.28)^n \cdot D_i^2}{\alpha} \left(\frac{\tan \frac{\theta}{2} \cdot \mu \cdot (1-R_f)}{D_c \cdot Q_t \cdot (\rho_s - \rho_f)} \right)^{0.5} \quad (7)$$

where α and n are factors dependent on hydrocyclone design and fluid properties.

Starting from Stokes' Law, Rietema (23) introduced pressure drop p , and length of hydrocyclone L , and found

$$d_{50}^2 \cdot \frac{(\rho_s - \rho_f)}{\mu} \cdot L \cdot \frac{p}{(\rho_f \cdot Q_t)} = \frac{36}{\pi} \cdot \frac{V_v}{V_i} \cdot \frac{r_c}{D_i}$$

where V_i is inlet velocity.

Then, Rietema stated that above a certain minimum Reynolds Number, $\frac{V_v}{V_i}$ is practically constant for a particular cyclone so that $\frac{36}{\pi} \cdot \frac{V_v}{V_i} \cdot \frac{r_c}{D_i}$

is constant and termed the "characteristic cyclone number," C_{y50} .

Evidently, C_{y50} is dependent only upon the geometric proportions of the hydrocyclone, but independent of pressure drop and Reynolds Number. A good hydrocyclone design should give a minimum value of C_{y50} which satisfies the requirements of low d_{50} , low p , and large Q_t .

In 1976, Plitt (24) processed the data obtained from tests carried out using 1½ to 6-inch-diameter hydrocyclones. The equation relating the d_{50} size to hydrocyclone variables was determined to be

$$d_{50} = \frac{35 D_c^{0.46} \cdot D_i^{0.6} \cdot D_f^{1.21} \exp(0.063\phi)}{D_a^{0.71} h^{0.38} Q^{0.45} (\rho_s - \rho_f)^{0.5}} \quad (8)$$

Where h is the distance from the bottom of the vortex finder to the top of apex.

Units used in equation (8) are:

d_{50} — microns

D_c, D_i, D_f, D_a, h — inches

$\rho_s - \rho_f$ — g/cm^3

ϕ — percent solids by volume

Q — $ft^3/min.$

Plitt then stated that the solid content of the feed was the variable which influenced the magnitude of d_{50} the most. He concluded that the principal reason for this is an increase in the effective pulp viscosity with increasing solids content. Hindered settling and underflow crowding may also be factors which lead to this effect.

There is an interesting relation between total flow rate, Q_t , and d_{50} . The generally accepted relationship in practice is an exponent for Q_t numerically greater than 0.5, (25) that is

$$d_{50} \propto Q_t^{-x} \quad \text{where } x < 0.5$$

But in some equations such as equations (5), (6), and (8), $x = 0.5$ or less can be seen.

Many efficiency equations could not be mentioned in this study, such as Haas equation (26), Lilge equation, Gelder equation (27), etc. Although some efficiency equations will give a result tolerably close to practice under certain conditions, there is no efficiency equation without disadvantages in application or limitations in theoretical or empirical development.

Specification of the Hydrocyclone Used in this Study

A Krebs Cyclone, Model D4B-12^o-827 was used in this study with its specifications as follows:

$$D_i : 1.5''$$

$$h : 20''$$

$$\theta : 12^{\circ}$$

$$D_a : 0.35'', 0.60'', 0.85'' \text{ respectively}$$

$$D_e : 0.75'', 1.00'', 1.25'' \text{ respectively}$$

$$D_c : 4''$$

CHAPTER 3

EXPERIMENTAL PROCEDURES AND RESULTS

Arrangement of Apparatus

Figure 8 is a photograph of the closed circuit cyclone testing system used in this study. The circuit consists of a Denver 2 x 2 SRL sand pump, delivering into a tangential entry into a 4" hydrocyclone from an open reservoir tank that receives both overflow and underflow discharge from the hydrocyclone. A pressure guage set right before the hydrocyclone indicates the feed pressure. Feed pressure can be adjusted by the setting of the valve between the pump and the pressure guage. Since the hydrocyclone discharges to an open tank, the feed pressure (guage reading) is, for practical purposes, the pressure drop which is defined as the pressure differential between the cyclone inlet and overflow. In such cases then, the pressure drop and hydrocyclone feed pressure are synonymous. Where the hydrocyclone overflow discharges against a head (back pressure against the hydrocyclone overflow), the terms are not synonymous.

Flow Rate and Flow Ratio

The tests to determine flow rate and flow ratio were conducted with clear water. Overflow and underflow were discharged to two different tanks by using two flexible pipes under free discharge conditions of operation. Table 1 shows the results.

As would be expected, total flow rate Q_t is an exponential function

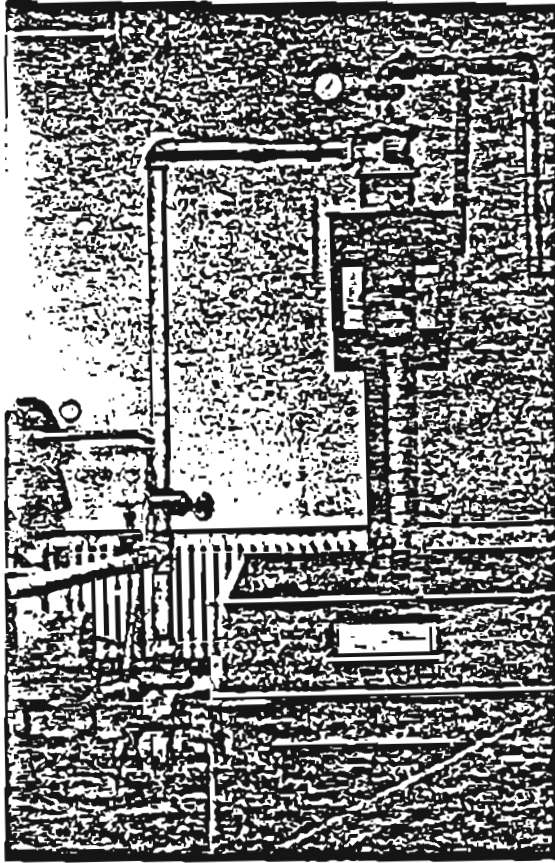


Figure 8. Photograph of hydrocyclone circuit.

TABLE 1

The Flow Rates and Flow Ratios Under Different Conditions

P (psi)	D _a (inch)	D _f (inch)	Q _u (gallons/min)	Q _o (gallons/min)	Q _t (gallons/min)	R _f
5	0.35	0.75	1.3	14.5	15.8	0.080
5	0.35	1.00	0.7	19.5	20.2	0.034
5	0.35	1.25	0.6	22.2	22.8	0.027
5	0.60	0.75	8.4	8.8	17.2	0.49
5	0.60	1.00	4.9	16.5	21.4	0.23
5	0.60	1.25	4.1	21.4	25.5	0.16
5	0.85	0.75	16.0	4.8	20.8	0.77
5	0.85	1.00	12.2	10.4	22.6	0.54
5	0.85	1.25	8.8	19.5	28.3	0.31
10	0.35	0.75	1.6	19.4	21.0	0.078
10	0.35	1.00	0.8	26.1	26.9	0.031
10	0.35	1.25	0.8	32.3	33.1	0.023
10	0.60	0.75	10.8	13.0	23.8	0.45
10	0.60	1.00	6.4	22.6	29.0	0.22
10	0.60	1.25	4.9	26.5	34.4	0.14
10	0.85	0.75	20.1	7.3	27.4	0.73
10	0.85	1.00	16.6	15.2	31.8	0.52
10	0.85	1.25	11.2	26.9	38.1	0.29
15	0.35	0.75	1.8	22.8	24.6	0.074
15	0.35	1.00	1.0	32.2	33.2	0.030
15	0.35	1.25	1.0	39.6	40.6	0.025
15	0.60	0.75	13.1	16.0	29.1	0.45
15	0.60	1.00	7.6	32.1	39.7	0.21

TABLE 1
(Cont.)

P (psi)	D _a (inch)	D _f (inch)	Q _u (gallons/min)	Q _o (gallons/min)	Q _t (gallons/min)	R _f
15	0.60	1.25	6.1	36.7	42.8	0.14
15	0.85	0.75	24.5	9.2	33.7	0.73
15	0.85	1.00	20.7	18.9	39.6	0.52
15	0.85	1.25	13.9	37.3	53.2	0.30
20	0.35	0.75	2.0	26.1	28.1	0.071
20	0.35	1.00	1.2	37.6	38.8	0.030
20	0.35	1.25	1.2	46.2	47.4	0.025
20	0.60	0.75	15.2	17.9	33.1	0.46
20	0.60	1.00	8.7	32.8	41.5	0.21
20	0.60	1.25	6.7	43.1	49.8	0.14
20	0.85	0.75	29.7	9.7	39.4	0.75
20	0.85	1.00	22.8	21.4	44.2	0.52
20	0.85	1.25	15.9	37.3	53.2	0.30
30	0.35	0.75	2.4	31.8	34.2	0.069
30	0.35	1.00	1.6	45.7	47.3	0.033
30	0.35	1.25	1.5	56.3	57.8	0.026
30	0.60	0.75	19.4	22.9	42.3	0.46
30	0.60	1.00	10.3	38.9	49.2	0.21
30	0.60	1.25	8.9	51.2	60.1	0.15
30	0.85	0.75	37.6	13.2	50.8	0.74
30	0.85	1.00	29.5	26.1	55.6	0.53
30	0.85	1.25	19.0	46.4	65.4	0.29

TABLE 1.

(Cont.)

P (psi)	D _a (inch)	D _f (inch)	Q _u (gallons/min)	Q ₀ (gallons/min)	Q _t (gallons/min)	R _f
35	0.35	0.75	2.5	34.9	37.4	0.067
35	0.35	1.00	1.7	48.7	50.4	0.033
35	0.35	1.25	1.6	60.8	62.4	0.025
35	0.60	0.75	20.7	24.4	45.1	0.46
35	0.60	1.00	11.5	43.1	54.6	0.21
35	0.60	1.25	9.2	56.7	65.9	0.14
35	0.85	0.75	41.4	14.4	55.5	0.74
35	0.85	1.00	32.4	28.7	61.1	0.53
35	0.85	1.25	20.4	50.0	70.4	0.29

of a pressure drop. Again, pressure drop and feed pressure are synonymous under free discharge conditions. A linear relationship can be obtained when Q_t is plotted vs pressure drop on full-log scale. This relationship is depicted in Figure 9 and can be expressed as follows:

$$Q_t = P^x$$

Where x has been reported in the range of 0.38-0.50 (16, 28, 29)

If the diameters of apex orifice and vortex finder D_a and D_f are considered as the two other variables, then

$$Q_t = K.D_a^y.D_f^z.P^x \quad (9)$$

units:

D_a, D_f — inches

Q_t — gallons/min

P — psi

The data, excluding the feed pressure of 5 psi were processed using a linear regression program shown in Appendix 1. The linear regression coefficient K for equation (9) was found to be 11.1 and x , y , and z were 0.49, 0.23, and 0.75 respectively. The equation thus became

$$Q_t = 11.1 D_a^{0.23} D_f^{0.75} P^{0.49}$$

The error defined as $(SSE/(n-2))^{0.5}$ is 2.2 gallons/min where SSE is the sum of squares of errors and n the number of data. The accuracy defined as $1 - (\text{error}/\text{average flow rate})$ would be 95% for this equation.

By using the similar program, with an accuracy of 97% the R_f can be expressed as:

$$R_f = 0.5D_a^2 + 0.55D_f^2 + 1.85D_a - 0.75D_f - 1.5D_aD_f + 0.05$$

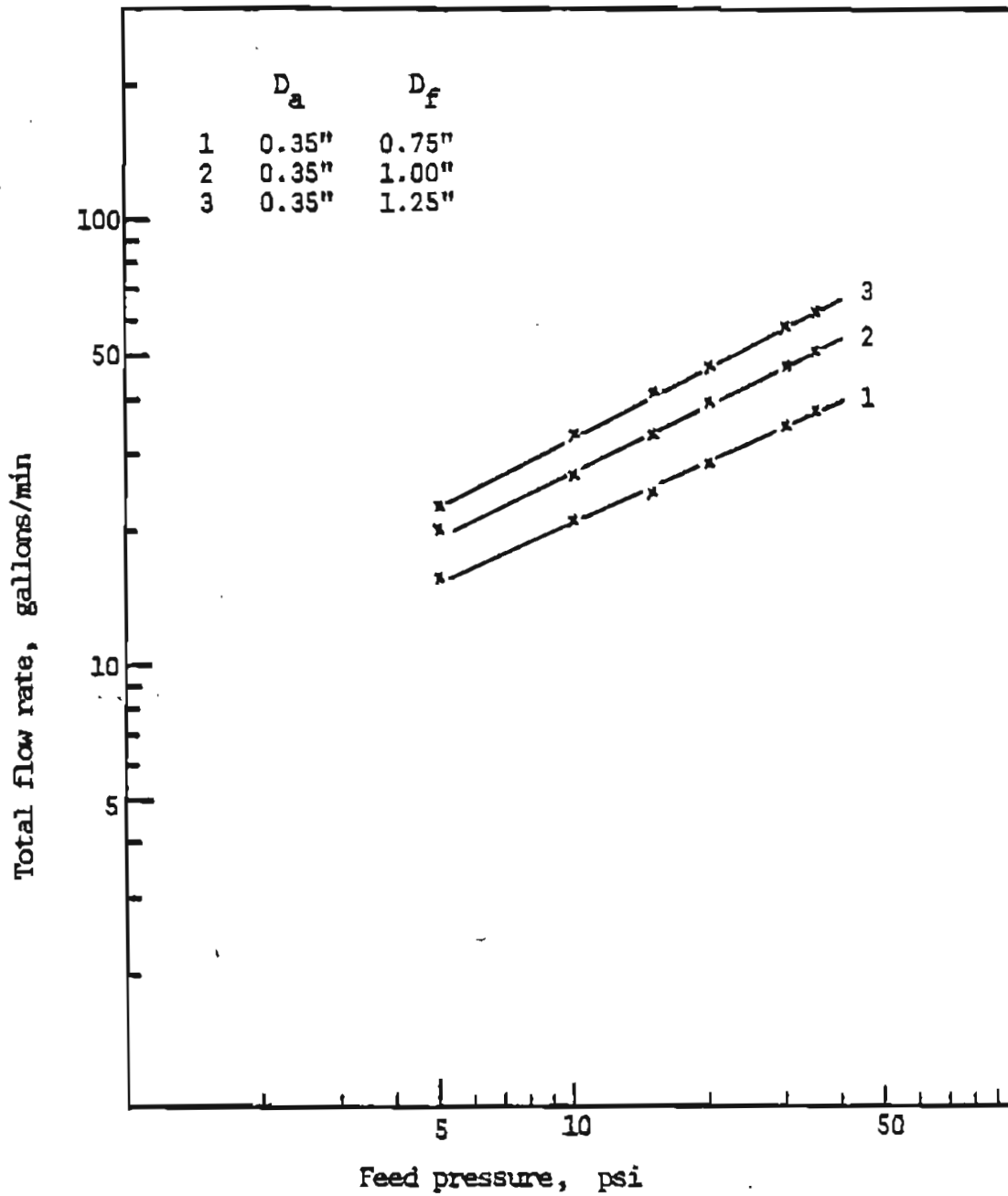


Figure 9. The effect of feed pressure on the total flow rate.

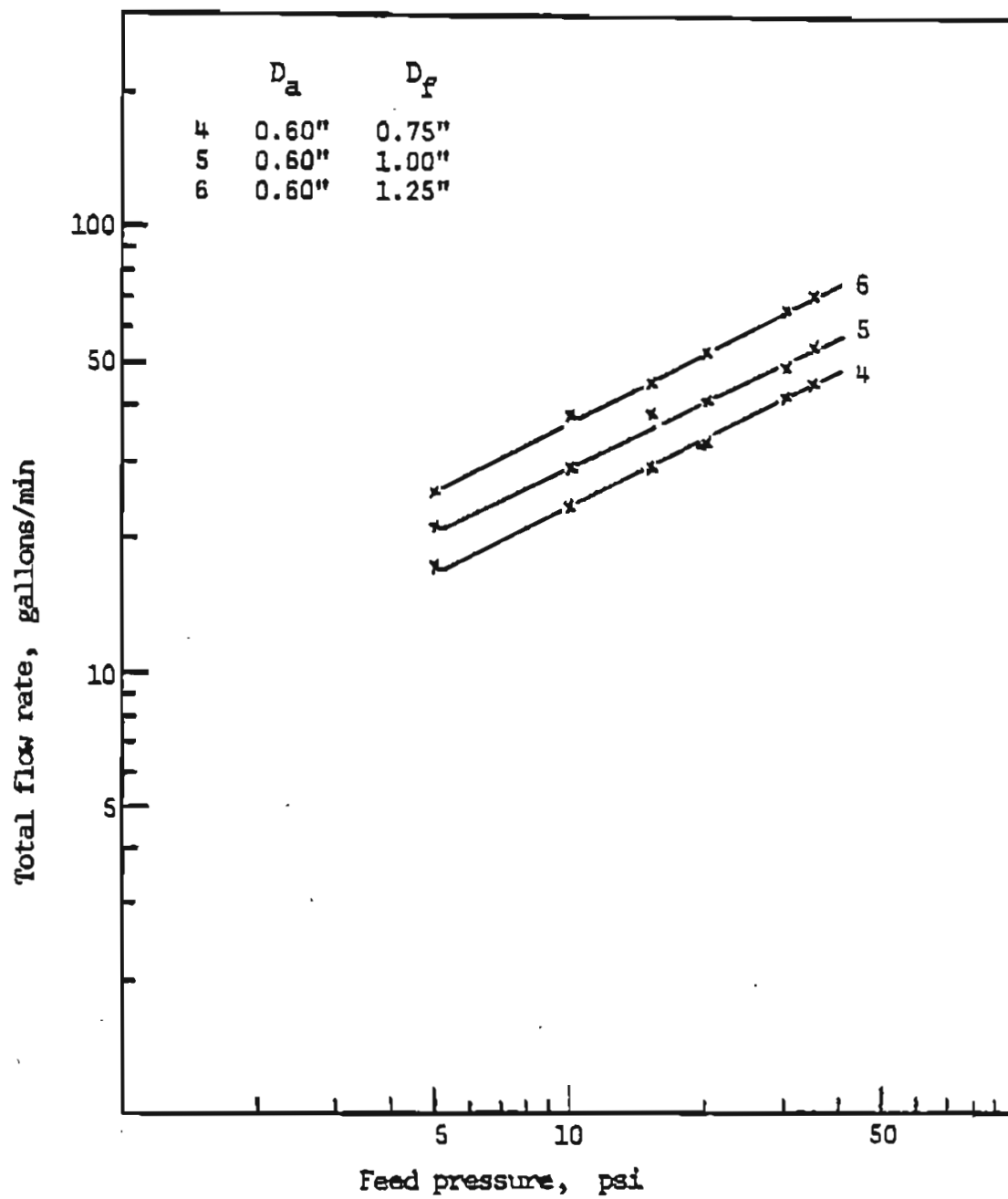


Figure 9. (cont.)

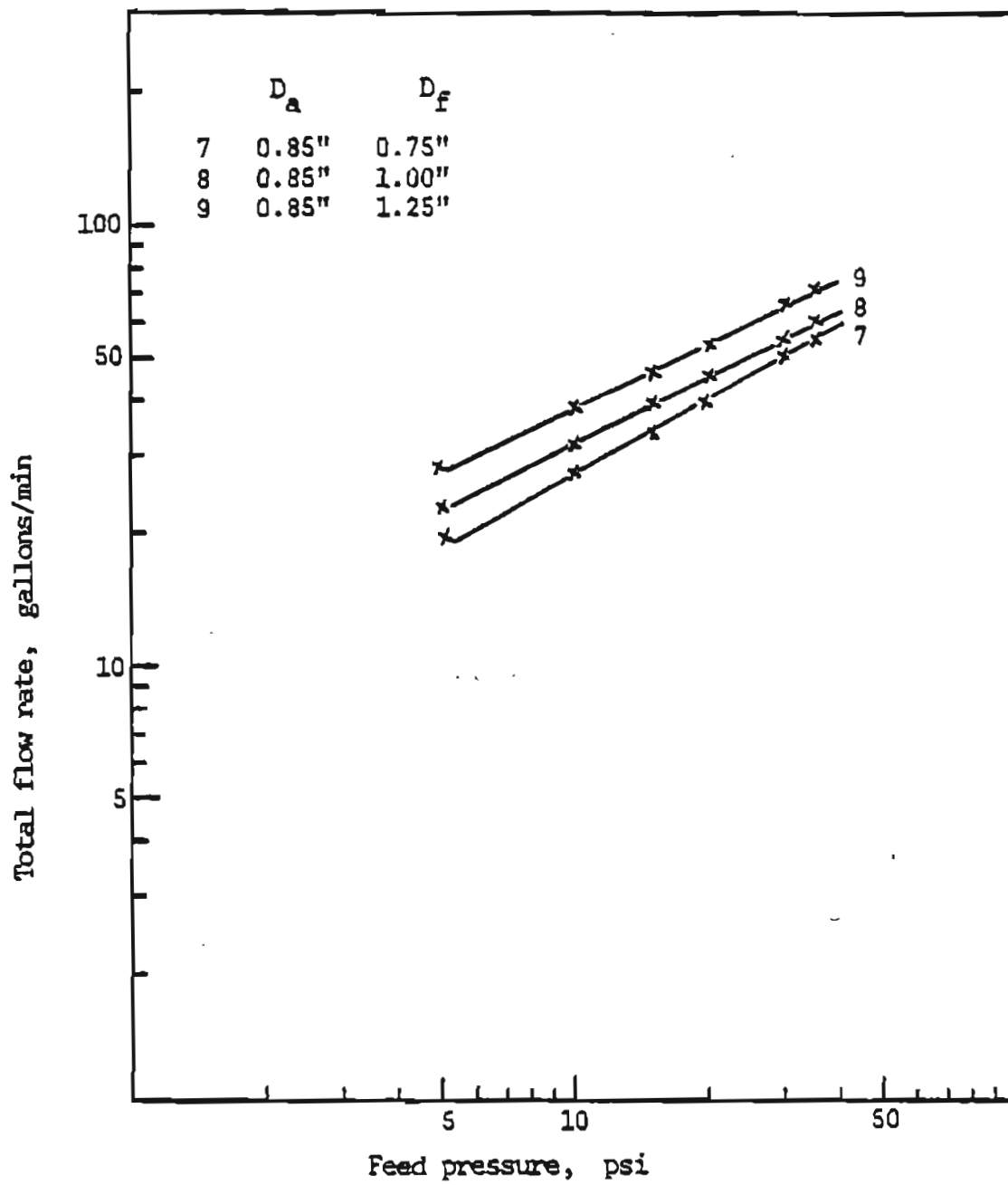


Figure 9. (cont.)

It can be seen that diameters of vortex finder and apex orifice are the important variables which affect the flow ratio. For a large enough feed pressure (not less than 10 psi) and D_a (not less than 0.60 inch), flow ratio is constant and independent of feed pressure when D_a and D_f are specified. When 5 psi of feed pressure is employed, the flow ratio is slightly larger than that in higher feed pressure. In this case, the presence of an air column plays an important role and it is dependent on the feed pressure conditions. At low feed pressure to a particular hydrocyclone, the air column is not well developed and fluid is easier to get through the apex orifice, thus flow ratio is higher. As the feed pressure increases, the air column develops. However, further increase in feed pressure might cause the obscuration of the apex orifice by the larger air column and the flow ratio might decrease.

The Method Used for Particle Size Analysis

In 1936, Wadell (30) derived an expression from Stokes' Law for the settling velocity of a particle intermediate in shape between a disc and sphere. This is considered to be a better approximation of the average shape of a mixture of particles of varying shapes. The values of Wadell settling times of different size particles are shown in Table 2 (31).

Settlement size analysis by pipette is based on these data. It has been reported that it offers better over-all results for a moderate range of silt and clay concentration (6 - 24 g/liter) with the particle size in the range of 2 - 62 microns than the hydrometer analysis does (32).

The principle of pipette analysis is depicted as follows:

To analyze particle size distribution for material finer than 62

TABLE 2

Times of Settling Computed According to Wadell's
Modification of Stokes' Law at 20°C⁽³¹⁾

Diameter microns	Velocity cm/sec	Depth cm	Time of Settling		
			hr	min	sec
62.4	0.223	20	0	1	0
31.2	0.0558	10	0	2	59
15.6	0.0139	10	0	11	59
7.8	0.00349	10	0	47	51
3.9	0.00087	10	3	12	
2.0	0.000217	7	8	58	

microns, a 20 ml aliquot is first removed from 1000 ml of the homogenized suspension 1 minute after mixing, at the depth of 20 cm under the surface. This sample represents 1/50 of total particles in the suspension. Thus, an aliquot can be taken at a specified time and depth so that a known portion of the coarsest particles are excluded from the sample. The total weight of sediment represented in this aliquot is subtracted from the amount of total particles to get the weight of the coarser particles. The exact pipette analysis procedure is as follows:

- 1: Prepare 0.55% dispersing solution by using Calgon (sodium hexametaphosphate) as dispersing agent.
- 2: Obtain 200 ml thoroughly mixed water sample and mix it with 100 ml of dispersing solution in a mixer for 5 minutes.
- 3: Screen the dispersed sample with a sieve of 230 ASTM mesh (62 microns opening). The underflow goes to a 1,000 ml graduated cylinder.
- 4: Use washing bottle to wash -230 mesh material through the sieve into underflow.
- 5: Fill the graduated cylinder exactly to 1,000 ml with the dispersing solution.
- 6: Remove the sieve and wash the retained fraction of solids into a pre-weighed filter paper.
- 7: Dry and weigh the filter paper and +230 mesh material, then record the weight.
- 8: Weigh and record 4 aluminum pans to the nearest 0.0001 gram.
- 9: Mix the sample in graduated cylinder completely by inversion for one minute with a rubber stopper covering the opening of graduated cylinder.

- 10: Immediately after mixing ceases, set timer on clock.
- 11: After a one minute period, remove the initial aliquot portion of 20 ml from 20 cm below the surface to the aluminum pan with a 20 ml transfer pipette fitted with a suction bulb.
- 12: Remove the 31, 16, and 8 micron aliquot portions according to the times and depths indicated in Table 2.
- 13: Dry the aliquots in an oven at 90°C, then cool in a desiccator and weigh to the nearest 0.0001 gram.
- 14: Calculate the fraction weight of different size of solids and total weight of solids in the water sample.

Blank tests of aluminum pans with 20 ml dispersing solution within them were conducted and dried with the aliquots simultaneously in the oven for all pipette analyses. The weight of dispersing agents in the aliquots were subtracted from the weights of dried aliquots.

Particle Size Distribution of Samples

The particle size distribution of samples from both the Circle district and the Livengood district were conducted by pipette analysis. Table 3 shows the results.

A pycnometer was employed to measure the specific gravity of dry solids. Dry solids were obtained by drying the water samples in an oven at 60°C. It is found that the specific gravity of solids from the Circle district (2.68) is only slightly higher than that of the Livengood district (2.62).

TABLE 3

Particle Size Distribution of Samples

Particle size micron	<u>Circle District</u>		<u>Livengood District</u>	
	Concentration gm/l	Wt. %	Concentration gm/l	Wt. %
+62	2.63	17.3	3.56	8.5
-62 +31	2.03	13.3	9.89	23.6
-31 +16	3.37	22.1	8.62	20.5
-16 + 8	3.32	21.8	6.05	14.4
- 8	3.88	25.5	13.83	33.0
	<u>15.23</u>	<u>100.0</u>	<u>41.95</u>	<u>100.0</u>

The Effect of Design Variables on Hydrocyclone Performance

Diameter of apex orifice:

Three apex orifices with variable diameters were utilized in this study. As Van Ebbenhorst Tengbergen and Rietewa (33) have stated, "the minimum total amount of underflow necessary is equal to the amount of solids separated plus the total amount of liquid which is entrained in the pores between the solids." It can be said that flow ratio is a useful guide for the approximate selection of apex orifice size to meet the particular need. In general, flow ratio should be slightly higher than the solid fraction in the slurry.

Diameter of vortex finder:

To allow an opportunity for the re-entrainment of the particles in the short circuit flow it is usual to remove the overflow stream by means of a vortex finder. When solids flow down the outside wall of the vortex finder, re-entrainment occurs. Therefore, an increase in the length of vortex finder allows more time for this re-entrainment and increases the separation effectiveness of the coarse particles. The diameter of vortex finder has a large influence on the flow rate and flow ratio. This can be found in Table 1. It also affects the value of d_{50} , and generally speaking, the larger the diameter of the vortex finder, the coarser the d_{50} and the greater the proportion of solids reporting to overflow.

The effects of diameter of the apex orifice and the vortex finder on the hydrocyclone performance at variable feed pressure for samples from the Circle and Livengood districts are shown in Figures 10 and 11

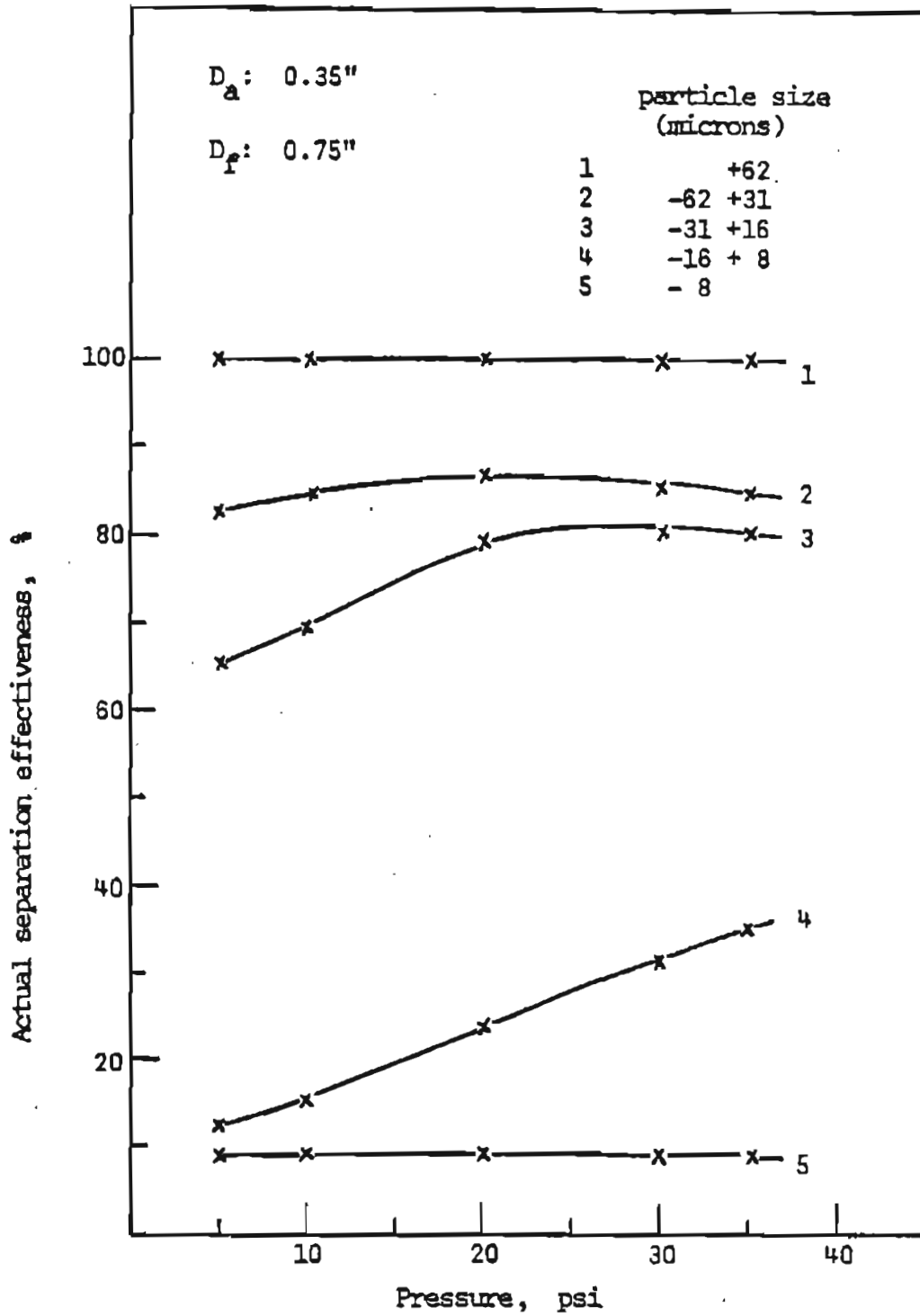


Figure 10. The effect of feed pressure on the separation effectiveness (Circle district sample).

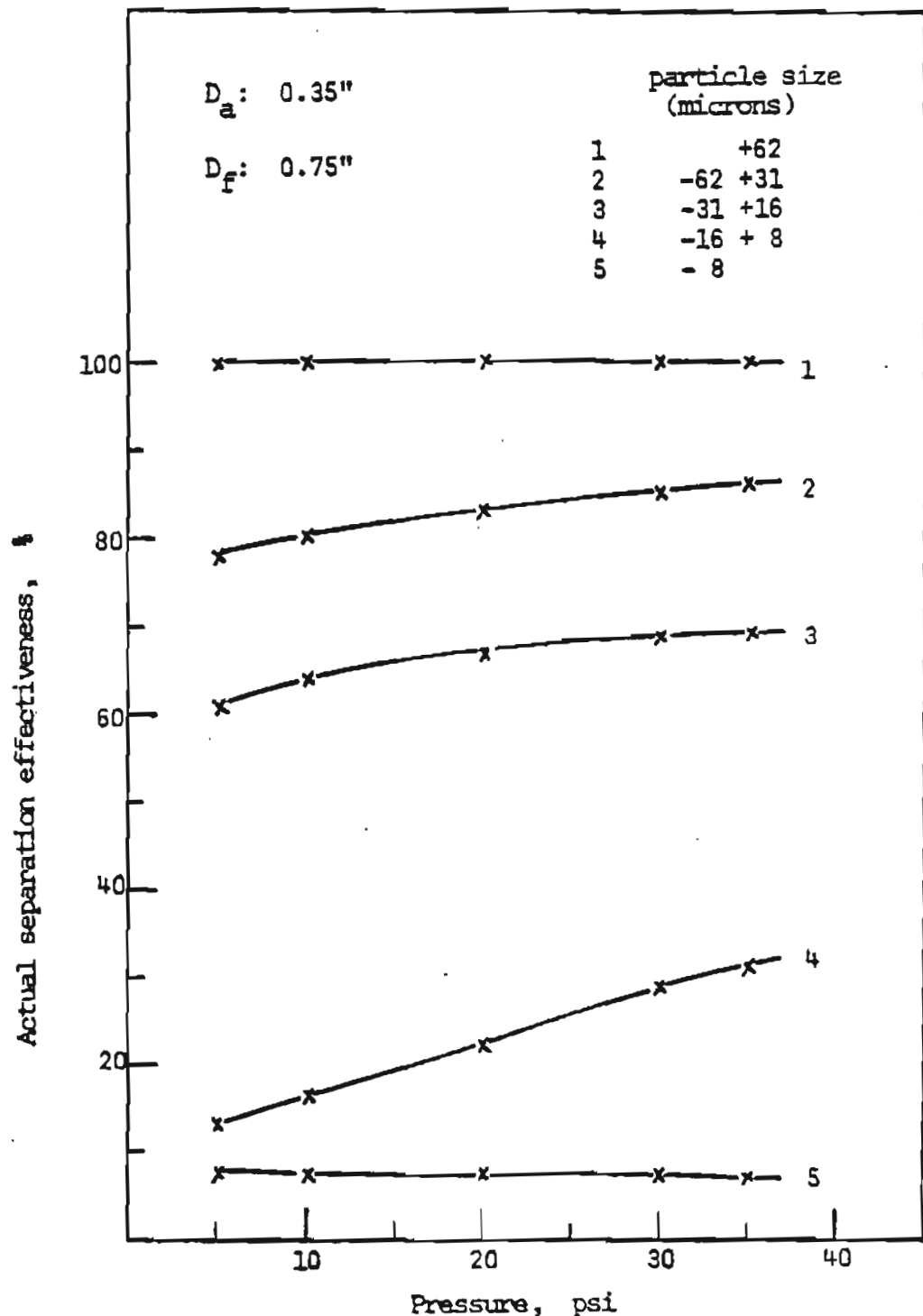


Figure 11. The effect of feed pressure on the separation effectiveness (Livengood district sample).

and Appendices 2 and 3. It was found that a D_a of 0.60" and a D_b of 1.25" forms best combination for this study. The reasons are:

- 1: Relatively high actual separational effectiveness for solids coarser than 16 microns.
- 2: Relatively low flow ratio.
- 3: This diameter of apex orifice is large enough to allow continuous and easy underflow discharge. Even at a feed concentration of 10% solid by weight, this D_a is large enough to prevent a "roping" discharging condition exists. Roping discharge is an indication that a larger amount of solids is reporting to underflow than the apex orifice can discharge; therefore, the remainder must report to overflow, reducing the effectiveness of separation.

For all further tests, this combination of D_a and D_f was employed. No further changes in diameter were made after the optimum combination was determined.

In comparing the test results, it was found that the sample from the Circle district gave slightly better separation effectiveness than the Livengood district sample. The author believes that the slightly higher specific gravity of Circle district sample played an important role in this effect.

Some other design variables such as hydrocyclone diameter D_c , body dimensions of hydrocyclone, and inlet diameter D_i are fixed in this study, hence, no attempt is made to evaluate the effects of varying these design variables.

The Effect of Operating Variables on Hydrocyclone Performance

Feed pressure

Feed pressure is an important factor which affects flow rate and d_{50} . The former is shown in Table 1, Figure 9 and equation (9). The latter can be expressed as (34):

$$d_{50} = p^{-n} \quad 0.25 < n < 0.27$$

In other words, increase in the feed pressure decreases the d_{50} .

Figures 10 and 11 and Appendices 2 and 3 show that the separation effectiveness of some critical size solids increases sharply with the increase in feed pressure. For the solids whose size is smaller than critical size, increasing feed pressure does not affect separation effectiveness much. This can be explained by saying that the increasing feed pressure still does not provide large enough inlet energy for the finer solids to be separated.

Temperature

Few workers have considered the effect of temperature as a variable in the hydrocyclone operation. But in Alaska, especially in field work, temperature might be an operating factor which can not be ignored.

In these tests, samples were cooled to desired temperatures and run through the hydrocyclone.

Temperature rises about 1°C after completion of the test. The effect of temperature on the separation effectiveness is given in Figures 12 and 13.

For critical size solids, in the range of 31 and 8 microns in

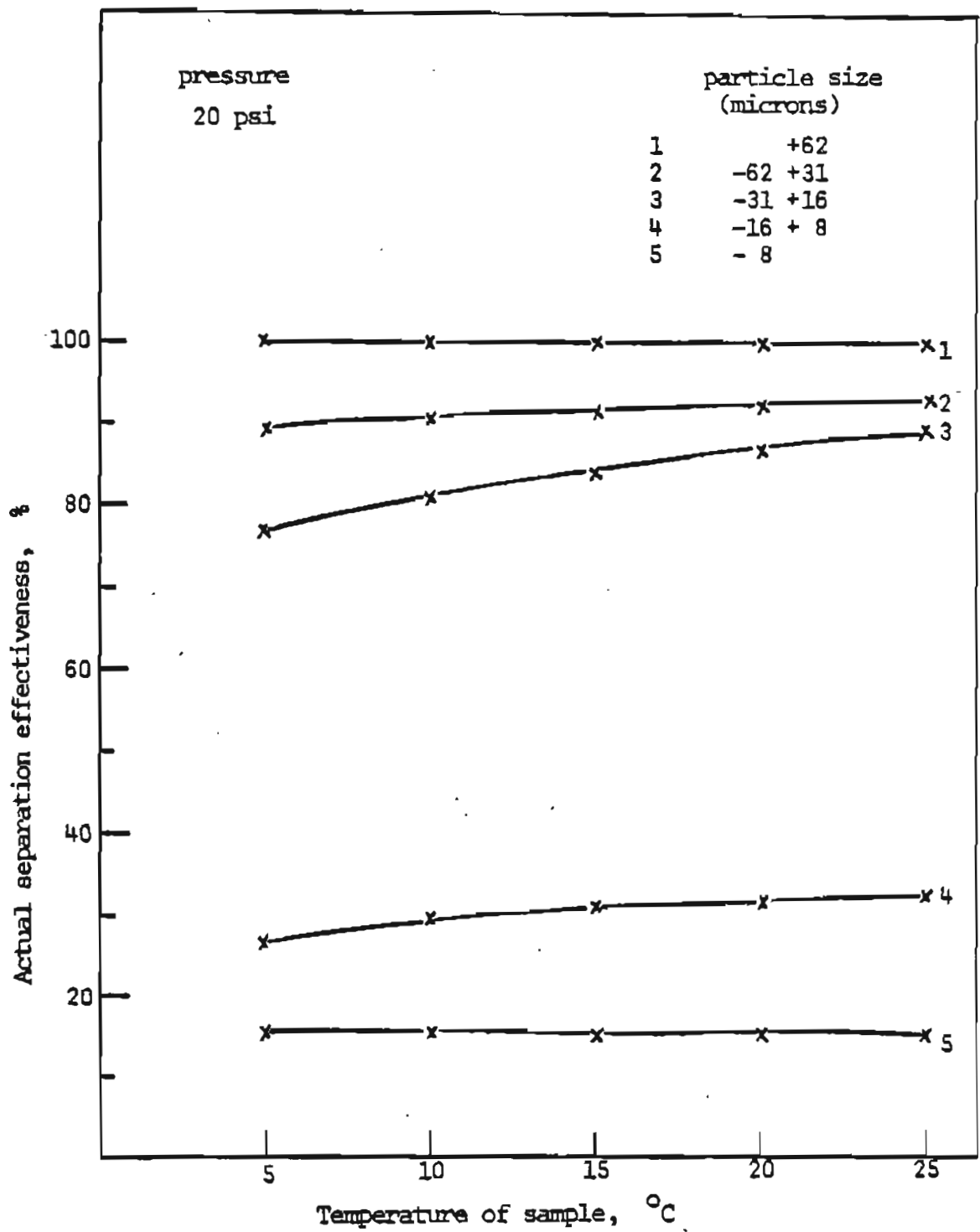


Figure 12. The effect of temperature on the separation effectiveness (Circle district sample).

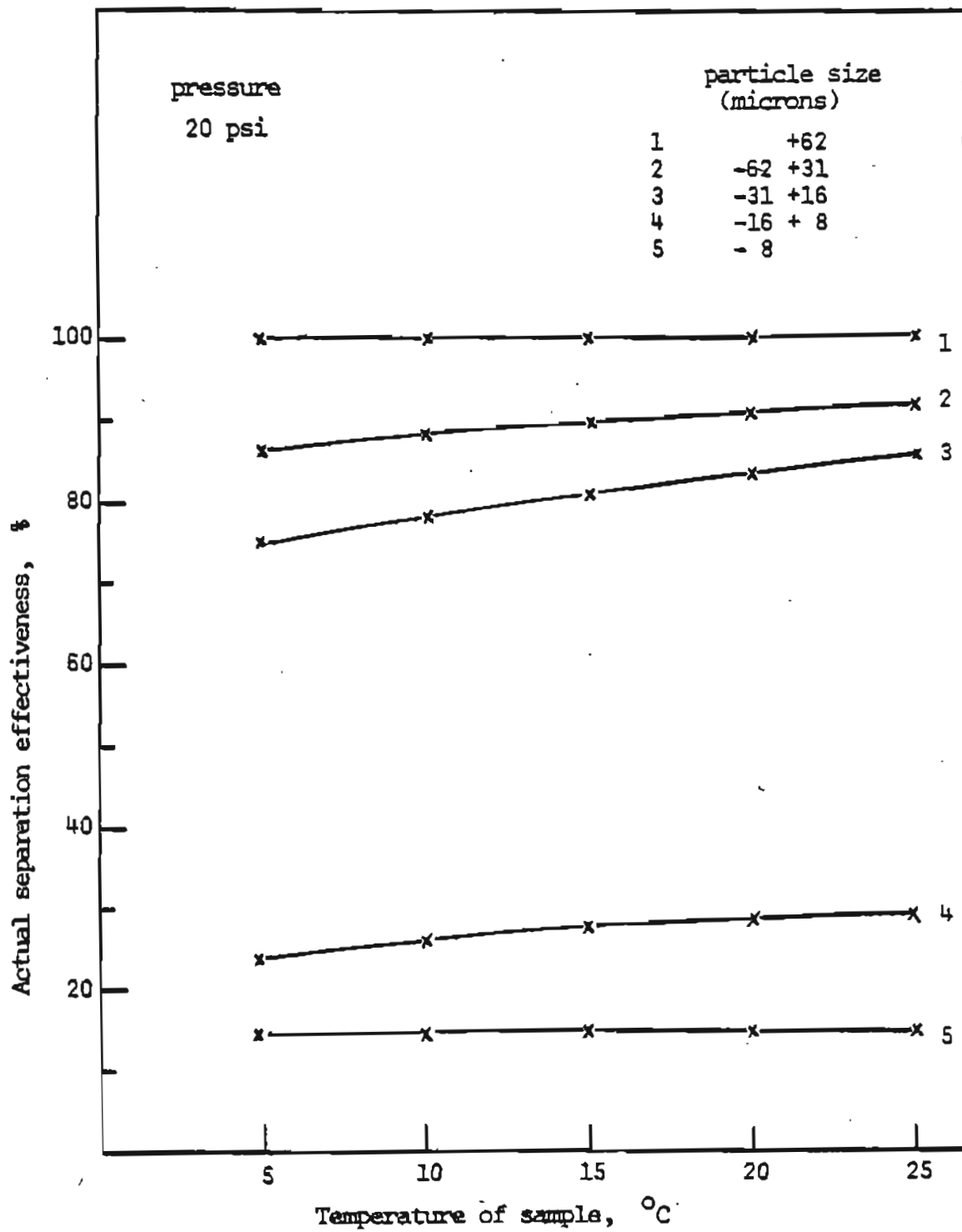


Figure 13. The effect of temperature on the separation effectiveness (Livengood district sample).

this case, separation effectiveness tends to increase as the temperature increases. This is caused by the following factors:

- 1: specific gravity of the fluid
- 2: viscosity of the fluid

Both of these two factors are decreasing as temperature increases. But the rate of change of specific gravity of water is much smaller than that of viscosity in the range of 5°C - 25°C tested in this study (see Table 4). The author does not believe the small rate of change of specific gravity of water can be one of the key factors which cause the higher separation effectiveness with increase in temperature for some critical size particles.

According to either Stokes' Law, suitable for laminar flow

$$V_t = \frac{1}{18 \mu} (\rho_s - \rho_f) d^2 \frac{V_i^2}{r}$$

where V_t is terminal velocity and V_i is inlet velocity
or Newton's Law

$$V_t = 1.82 \left(\left(\frac{\rho_s - \rho_f}{\rho_f} \right) d \frac{V_i^2}{r} \right)^{0.5}$$

suitable for turbulent flow, the increases of V_t caused by the change of ρ_f as temperature changes from 5° to 25°C is less than 0.3% which would not offer a significant change in separation effectiveness.

To judge the effect of viscosity of fluid, Reynolds Number in hydrocyclones shall be considered first. It is defined as (36, 37)

$$R_e = \frac{V_i \cdot D_c \cdot \rho_f}{\mu}$$

The values consequently are in the range $10^5 - 10^6$, and 2×10^5 in this study, which implies turbulent flow in the inlet pipe. If

TABLE 4

Specific Gravity and Viscosity of Water at 1 atm. (35)

Temp °C	Specific gravity	Change rate of sp. g. % per °C	Viscosity centipoise	Change rate of viscosity % per °C
4	0.99998	0.002	1.567	3.03
6	0.99994	0.005	1.472	2.91
8	0.99985	0.007	1.386	2.85
10	0.99970	0.010	1.307	2.75
12	0.99950	0.013	1.235	2.67
14	0.99925	0.015	1.169	2.56
16	0.99895	0.018	1.109	2.53
18	0.99860	0.020	1.053	2.42
20	0.99821	0.022	1.002	2.36
22	0.99777	0.024	0.955	2.29
24	0.99730	0.026	0.911	2.23
26	0.99679		0.871	

turbulent flow continues within the hydrocyclone body, according to Newton's Law, terminal velocity of solids in the hydrocyclone is independent of the viscosity of the fluid. Thus, centrifugal force and separation efficiency of solids are independent of the viscosity of the fluid. However, a powerful centrifugal field has a stabilizing effect on turbulence (23). Laminar conditions are known to be maintained at higher than the transitional Reynolds Number for flow in a curved channel and hydrocyclone conditions accentuate this effect. Lilge (17) has pointed out that the flow in the body of a hydrocyclone can certainly not be presented by a single Reynolds Number. The change of viscosity of the fluid therefore could be the main reason for the increasing separation effectiveness of some solids as the temperature of slurry increases.

Feed concentration

The change of feed concentration can affect the flow ratio, total flow rate, and separation effectiveness.

In this test, samples of known concentration were left in quiescent settling conditions for over 2 days. Desired concentrations can be obtained by removing calculated amount of supernatant with a siphon.

It is shown in Figures 14, 15, 16, and 17, that when the feed stream commences to show an increase in the solids concentration, it will permit an increased flow ratio and flow rate under the same operating conditions.

The explanation given is that when the solids are accelerated to the conical wall of the hydrocyclone, they cause turbulence

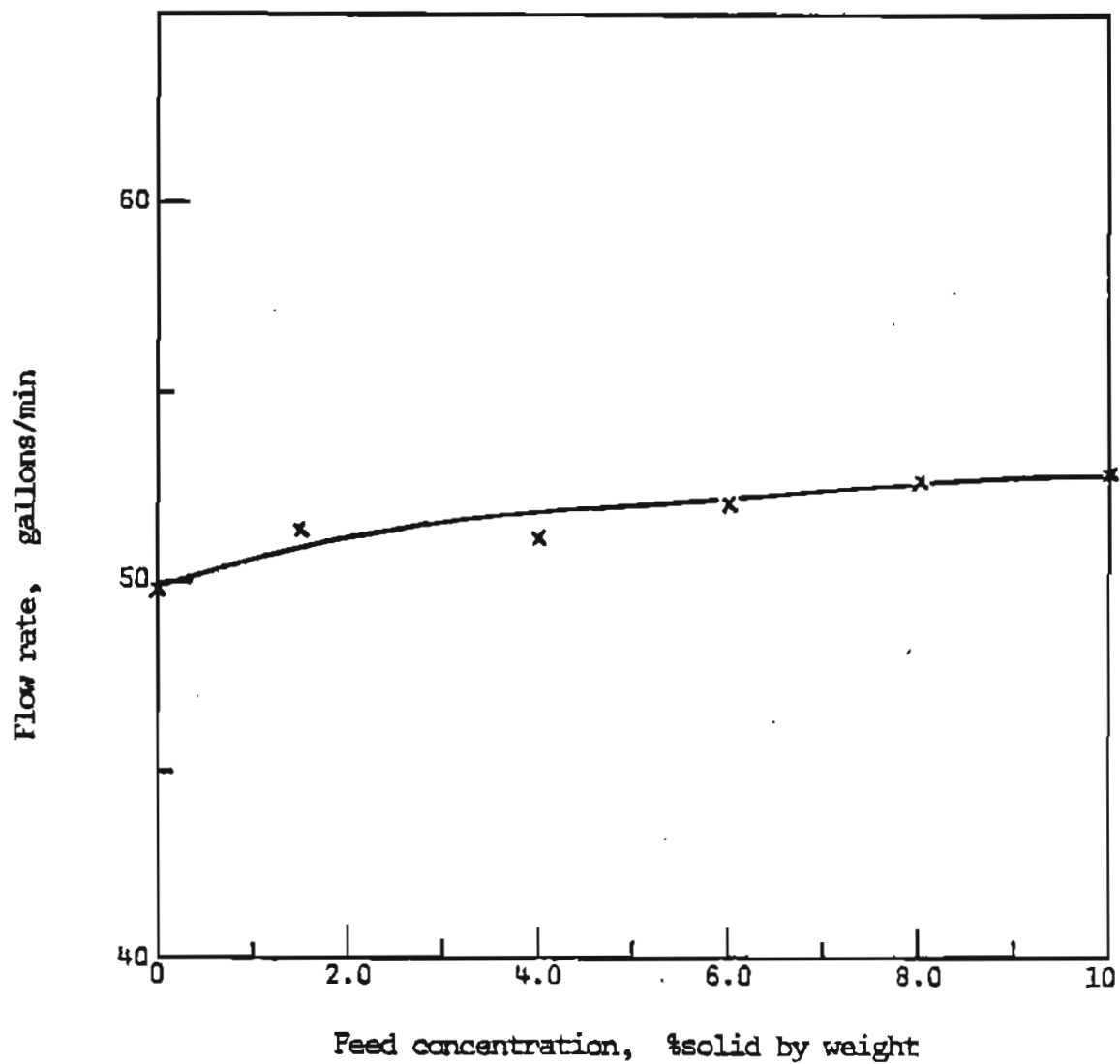


Figure 14. The effect of feed concentration on the flow rate (Circle district sample).

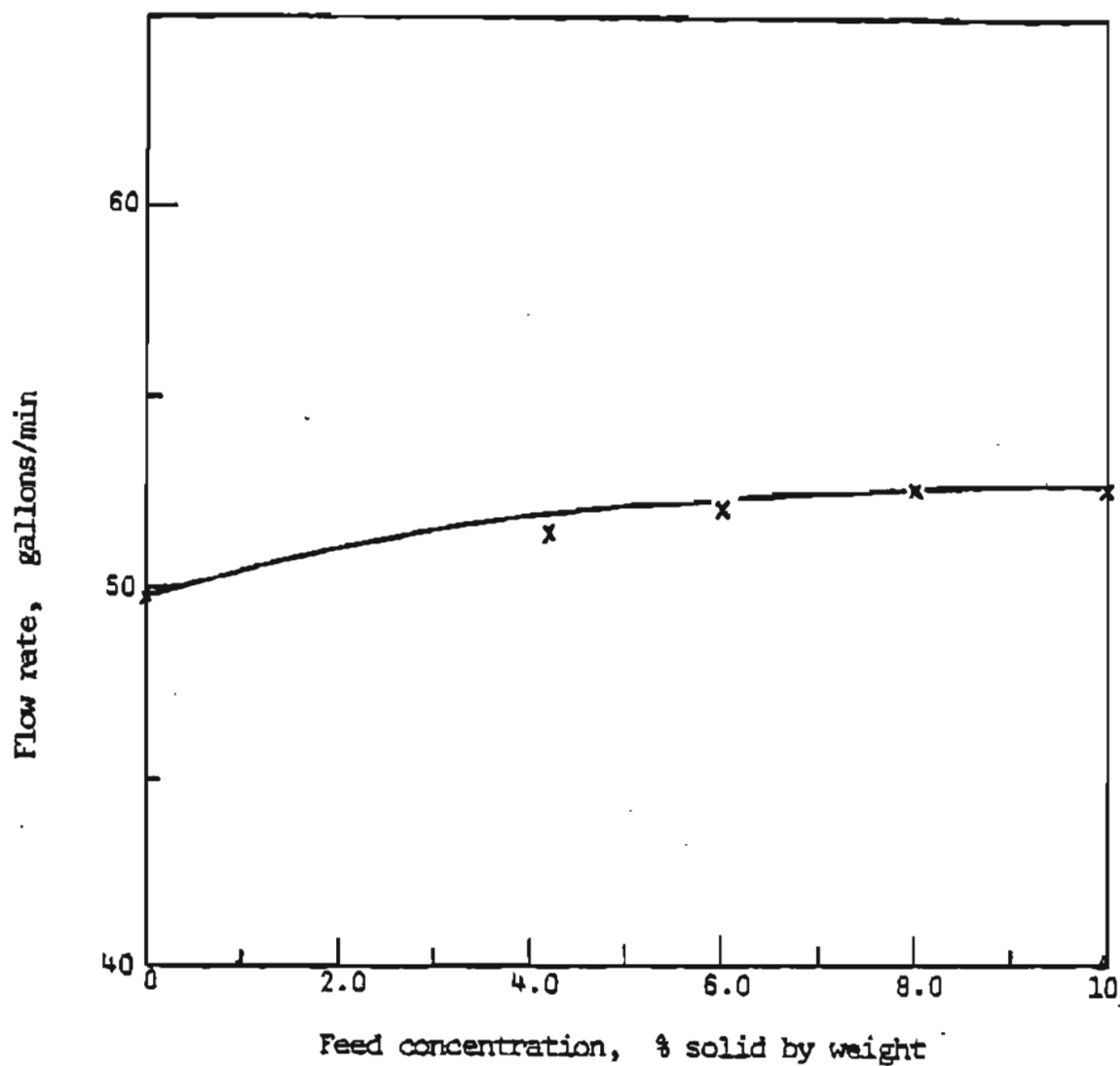


Figure 15. The effect of feed concentration on the flow rate (Livengood district sample).

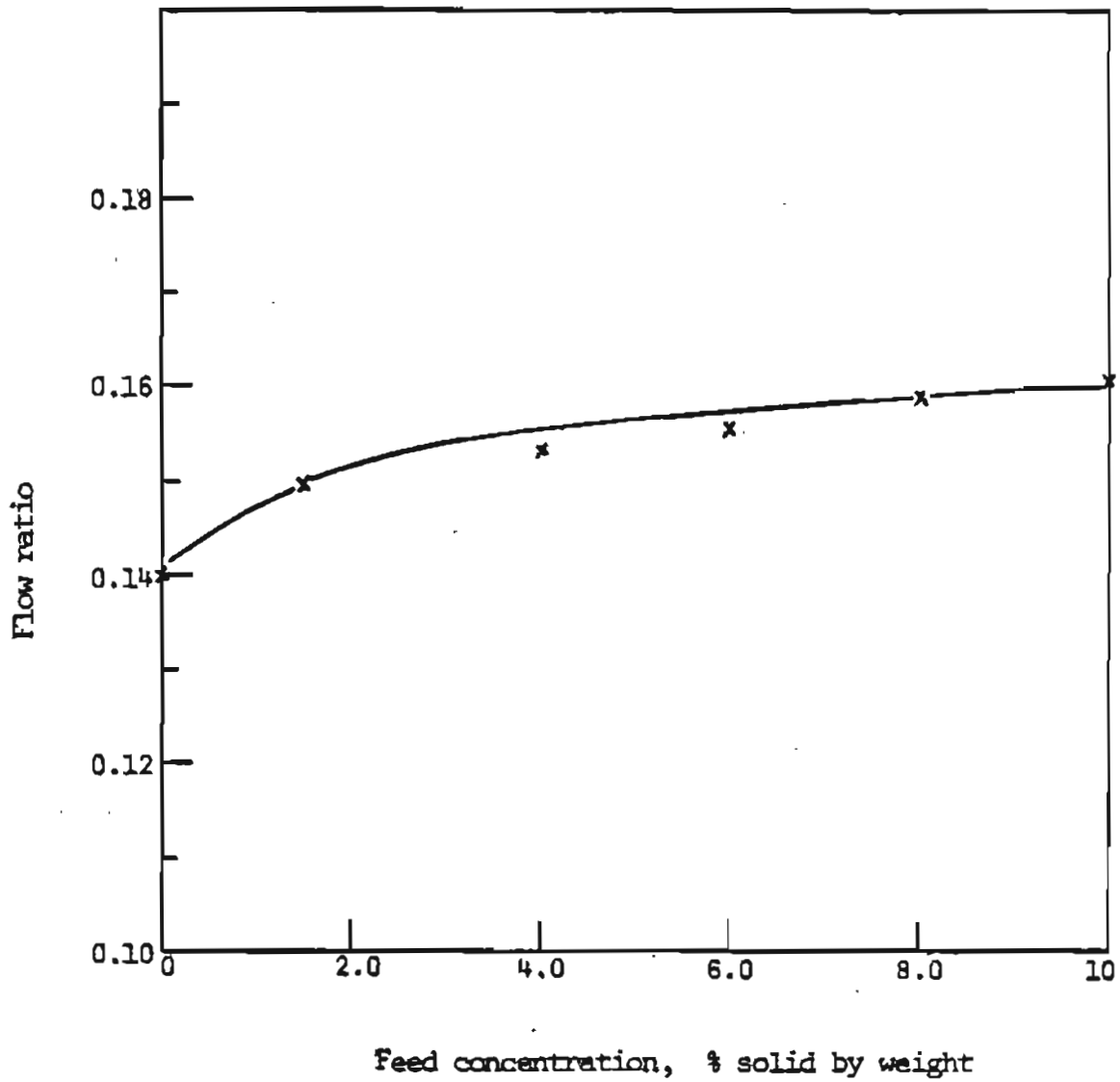


Figure 16. The effect of feed concentration on the flow ratio (Circle district sample).

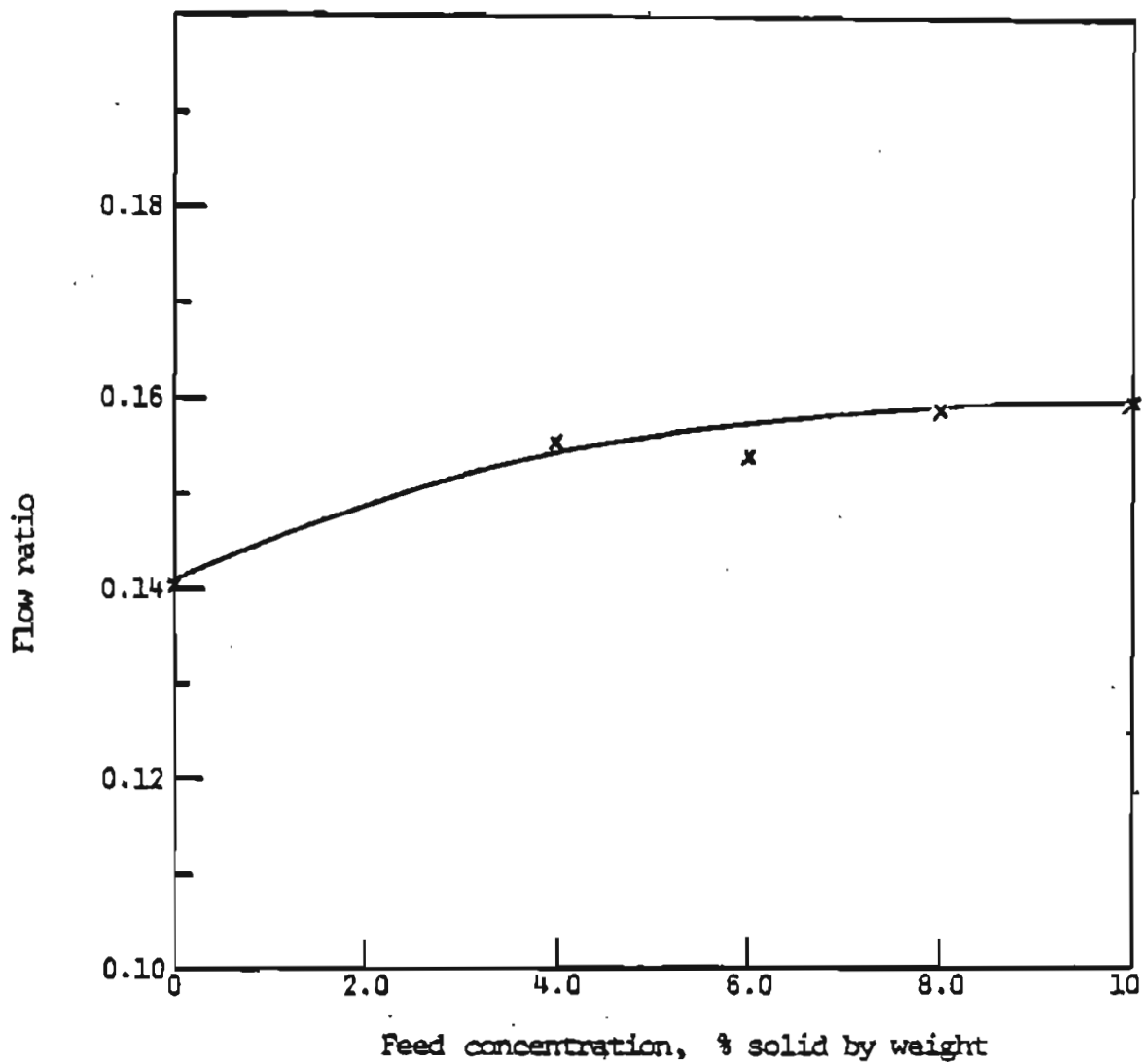


Figure 17. The effect of feed concentration on the flow ratio (Livengood district sample).

which decreases the tangential velocity of the fluid and other solids when these solids and fluid flow to the surface of solids. Retardation of tangential flow must be compensated by increased vertical or radial flows, giving a stronger downward flow and a greater proportion of the feed passes to the underflow at the same feed pressure. This means an increase in both flow ratio and total flow rate.

Another possible reason is that a solid particle will flow down the hydrocyclone wall and then to the apex faster than a same size "fluid particle" because of its higher density. Thus both flow ratio and total flow rate increase as the feed concentration increases.

The concentration of the solids in the feed should affect the separation effectiveness of critical size solids if a high enough feed concentration is employed. This is because it causes:

- 1: Higher viscosity.
- 2: Higher density of fluid when fine solids are suspended in it.
- 3: Hindered settling effects due to the crowding of the solids.

The effect of the first two factors was explained previously. As for the third factor, the turbulence caused by the solids will decrease the separation efficiency as other solids pass through this turbulence. This turbulence is more significant when solids reach the cyclone wall because of the greater horizontal relative motion between the solids on the wall and the fluid or spiral solids.

Dahlstrom (38) has stated that there is a negligible effect of varying feed concentration on the separation effectiveness in a 9-in hydrocyclone performance. However, there is an evident change of separation effectiveness of solids ranging from 16 to 31 microns at variable feed pressures in samples from the Circle and the Livengood districts (Figures 18 - 23). The rate of change becomes significant when feed concentration is above 10% by weight.

The Effect of Feed Concentration on the Recovery of Gold

A 10"x3.5"x43" sluice box was employed to model the sluicing operation of placer mining. The arrangement is shown in Figure 24.

A gold-bearing gravel sample from the Circle district was screened. The portion of 48x65 mesh was concentrated by panning roughly, then dried in an oven. This treated sample, containing 0.05 oz/ton of gold, was ready for the sluicing operation.

For each test, three pounds of treated sample was adjusted to 30% solid by weight and put into tank A (see Figure 24). Wastewater from the Circle district with an adjusted solid content from 0 to 10%, was put into tank B. The slurries from both tank A and B were pumped simultaneously to the sluice box. The sluicing operation continued for 2 minutes for each test.

The concentrates on the bottom of the sluice box were washed carefully, dried, and weighed. Initially a sink-float test was conducted for the analysis of gold content. But it was found impractical because of the high content of heavy minerals. Acid digestion followed by atomic absorption spectrophotometry was used to determine the concentration of gold in the products. The gold concentrations of these products are

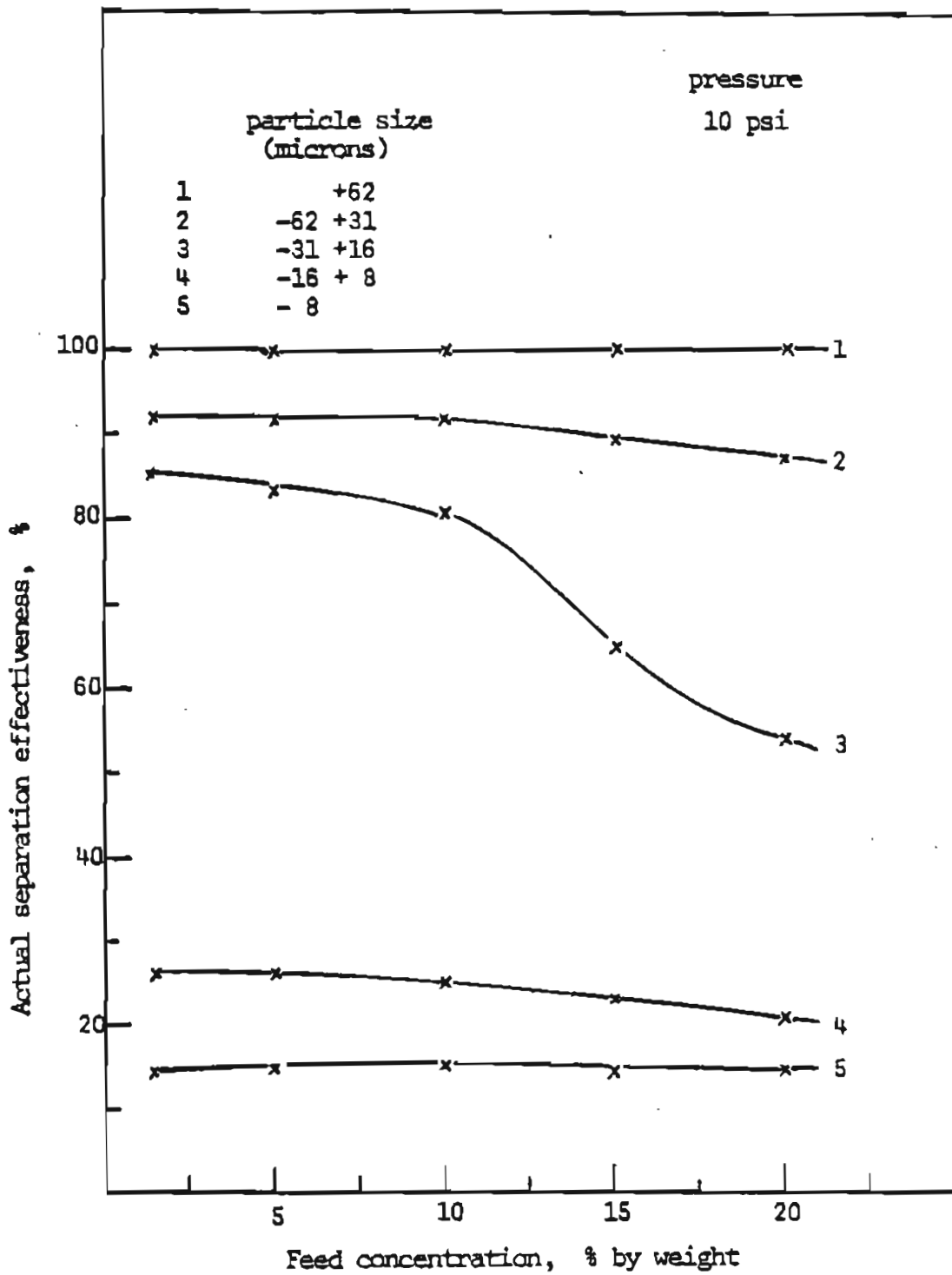


Figure 18. The effect of feed concentration on the separation effectiveness at 10 psi (Circle district sample).

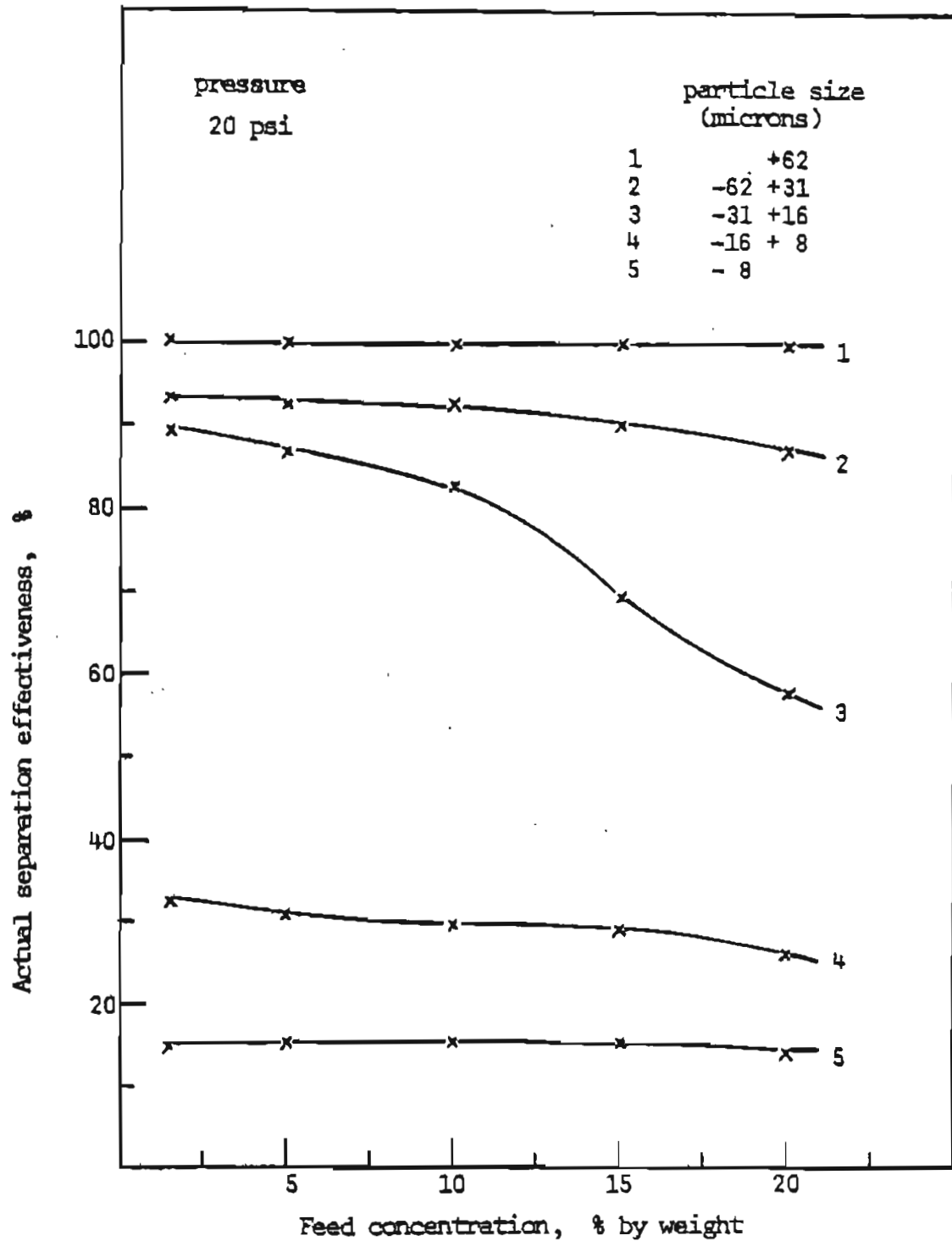


Figure 19. The effect of feed concentration on the separation effectiveness at 20 psi (Circle district sample).

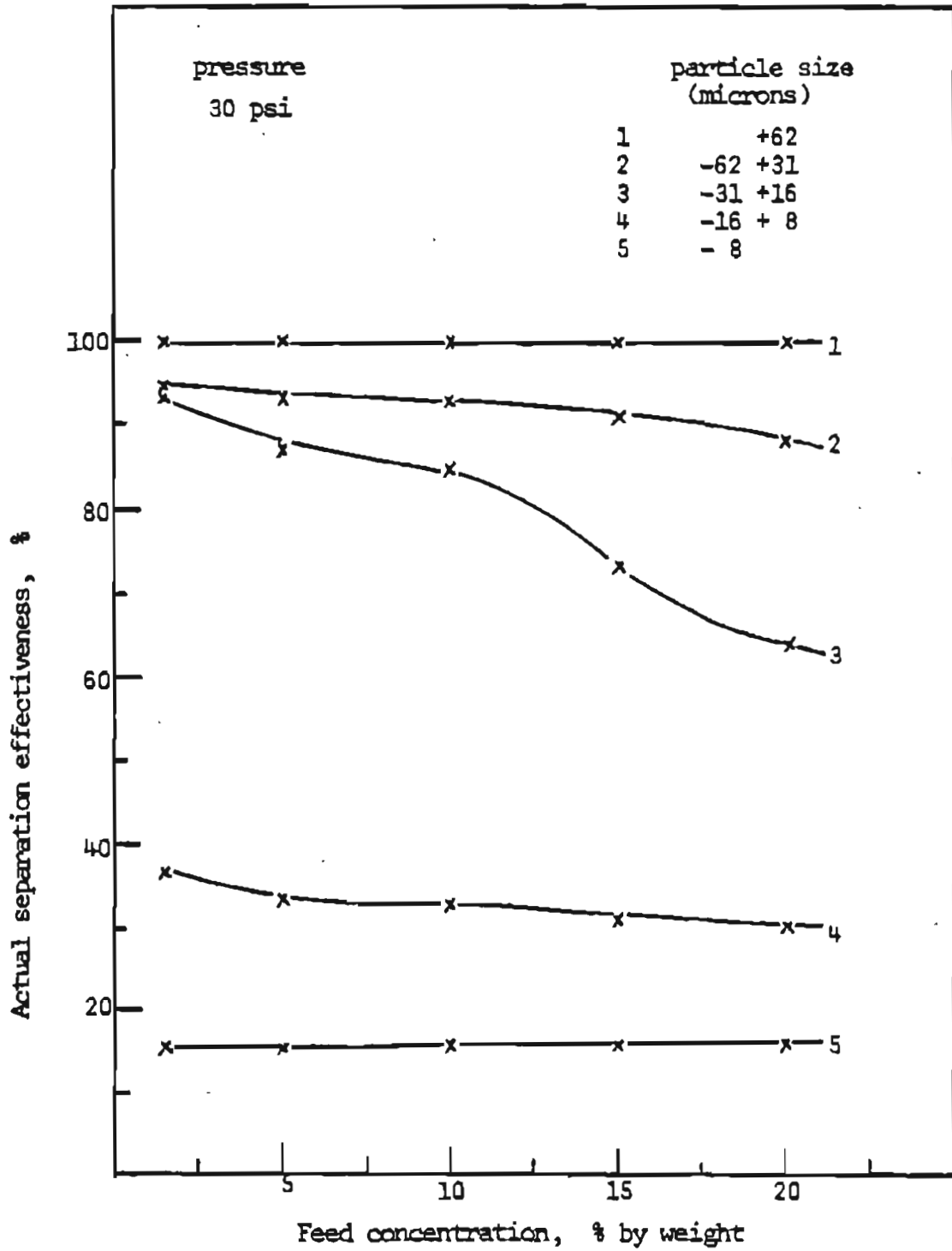


Figure 20. The effect of feed concentration on the separation effectiveness at 30 psi (Circle district sample).

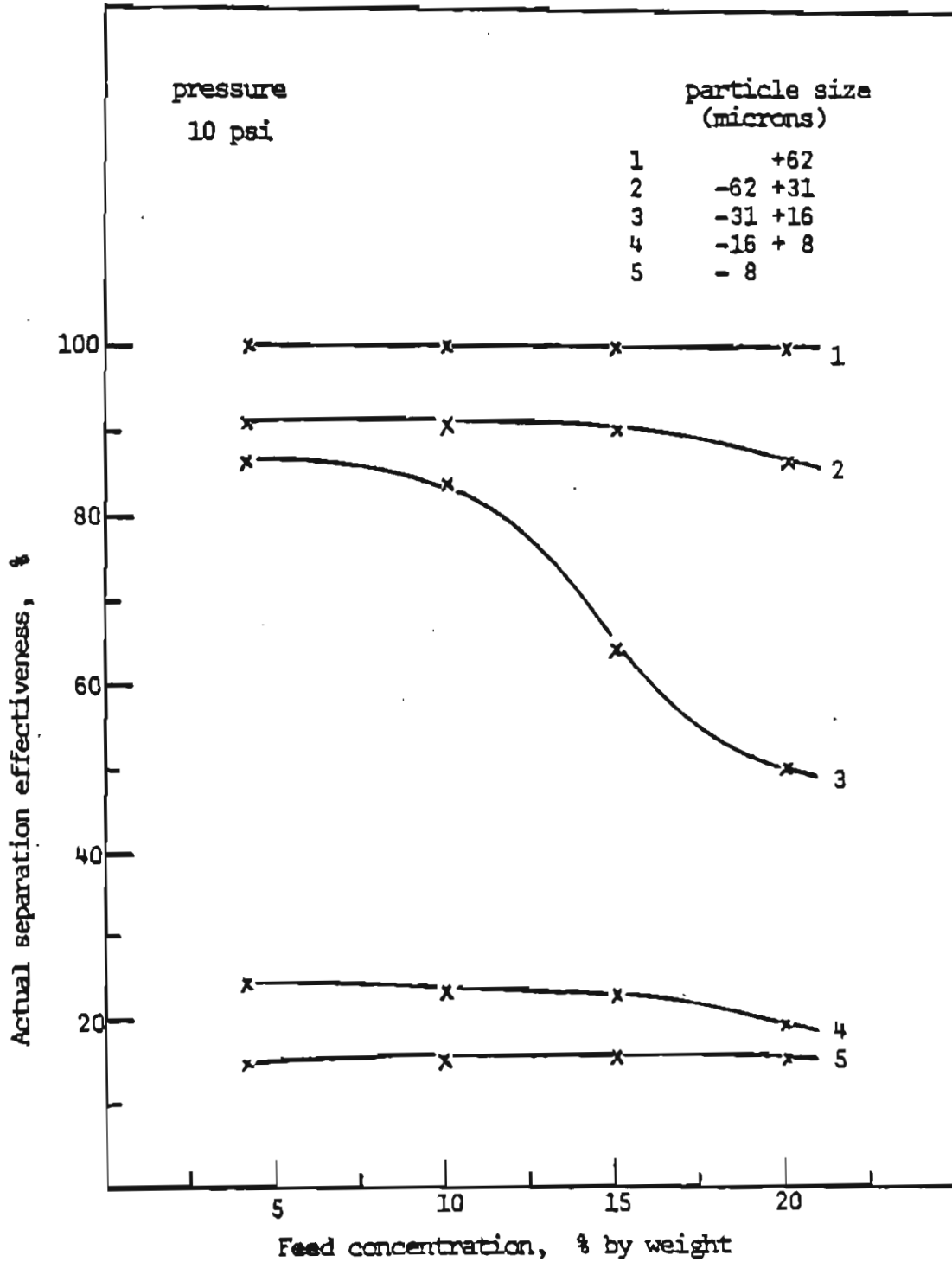


Figure 21. The effect of feed concentration on the separation effectiveness at 10 psi (Livengood district sample).

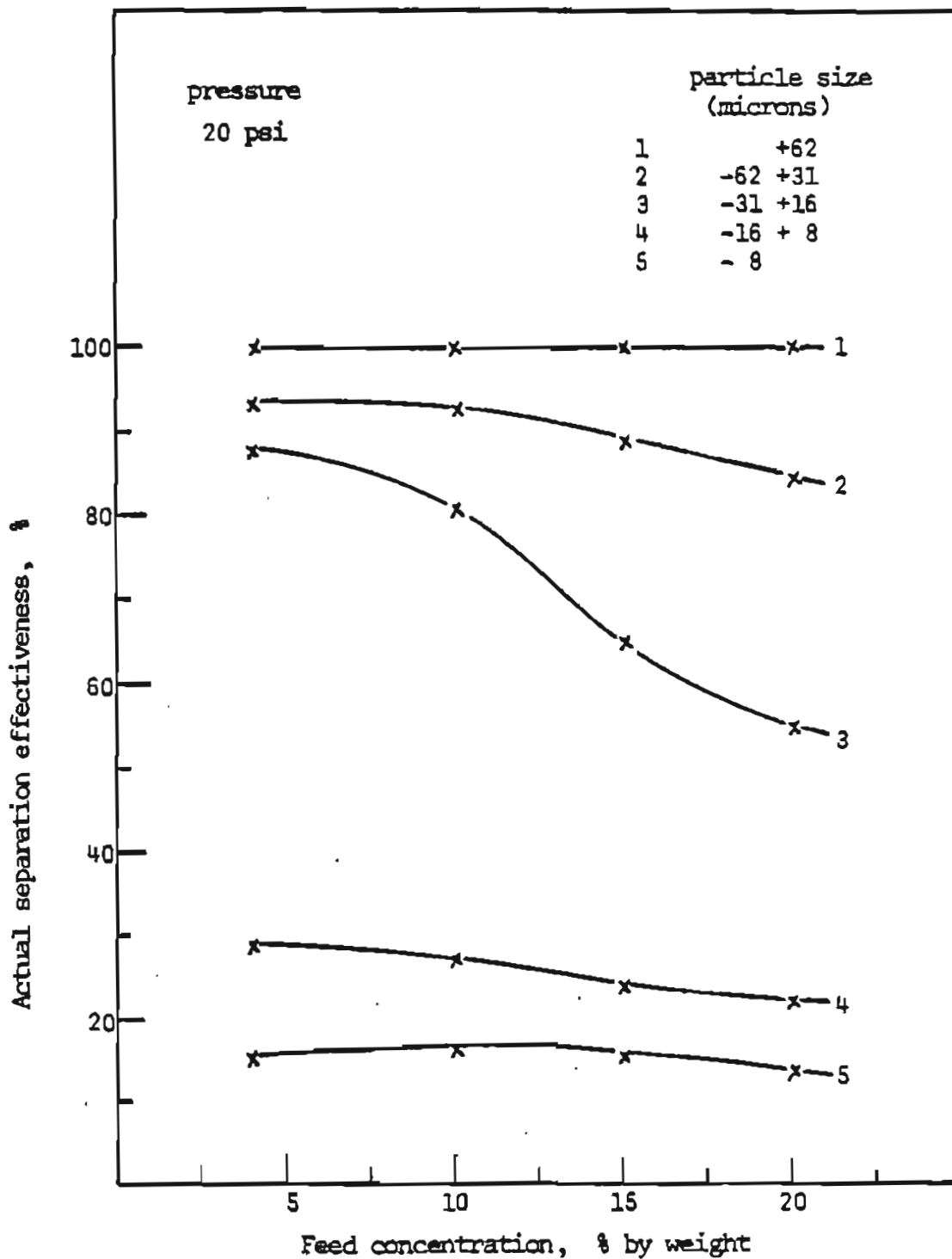


Figure 22. The effect of feed concentration on the separation effectiveness at 20 psi (Livengood district sample).

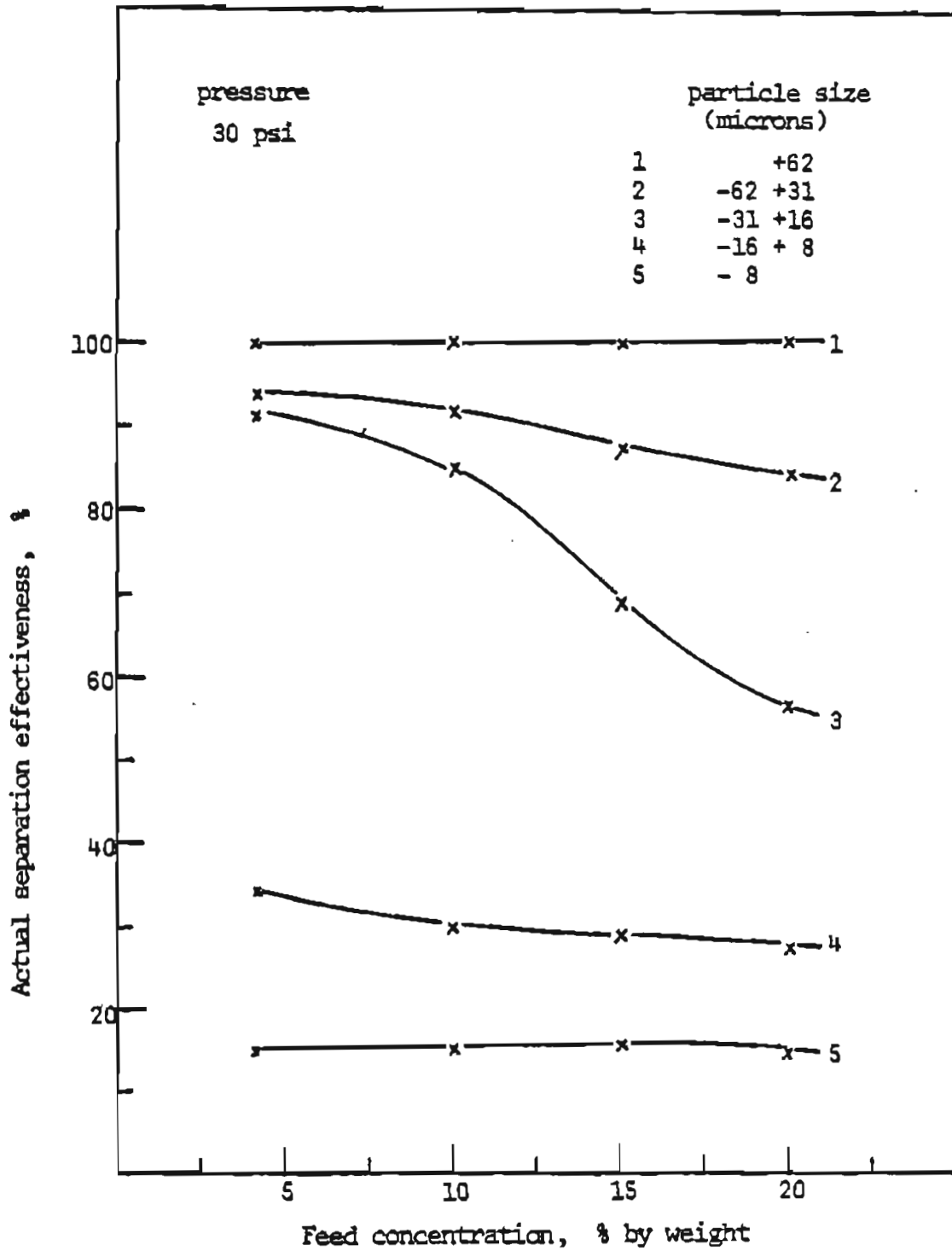


Figure 23. The effect of feed concentration on the separation effectiveness at 30 psi (Livengood district sample).

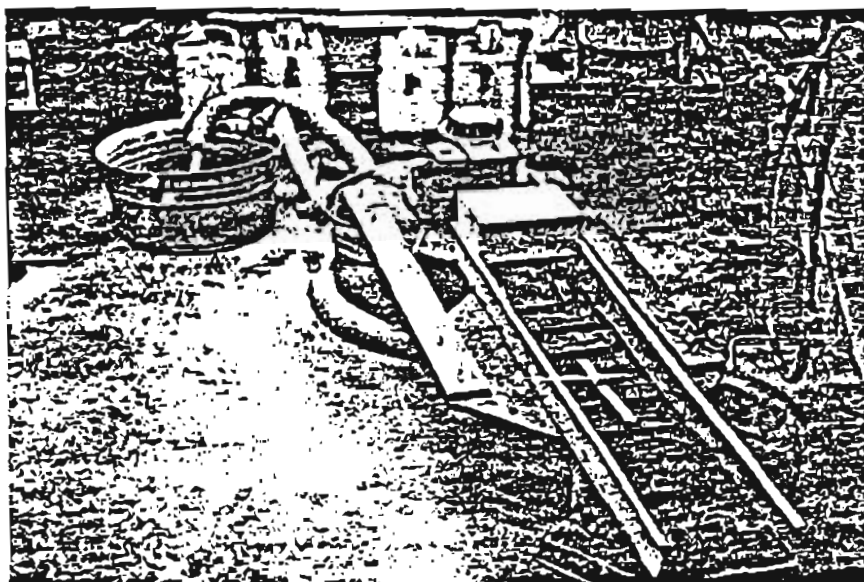


Figure 24. Photograph of the sluice box.

0.23 - 0.28 oz/ton. Figure 25 shows the effect of solid concentration of the slurry on the gold recovery in placer mining. The difference in the average relative recovery of gold for each of two solid concentrations in sluicing water is less than 3%. It may be concluded that under the conditions tested there is no significant change of relative recovery of gold as solid concentration in sluicing water increases to 10%.

Flocculation Test in the Hydrocyclone

The mechanisms of flocculation of suspended particles in a slurry can be classified as two types:

- 1: Flocculation by charge neutralization: The repulsive interactions between similarly charged suspended particles act to prevent flocculation. The repulsive surface charges can be neutralized by the addition of an electrolyte. The reduction of electrostatic surface charge (zeta potential) then permits the universal van der Waals forces to operate between the atoms of various particles and form particle aggregates. The lime additions used by thickener operators promotes flocculation by this mechanism.
- 2: Flocculation by interparticle bridging: When long-chain macromolecules are employed as flocculants, they attach to the surface of suspended particles at one or more absorption sites, and that part of a chain extends into the bulk solution. When other particles with some vacant absorption sites contact these extended segments, attachment can occur. Thus, larger flocs can grow and the long-chain macromolecules

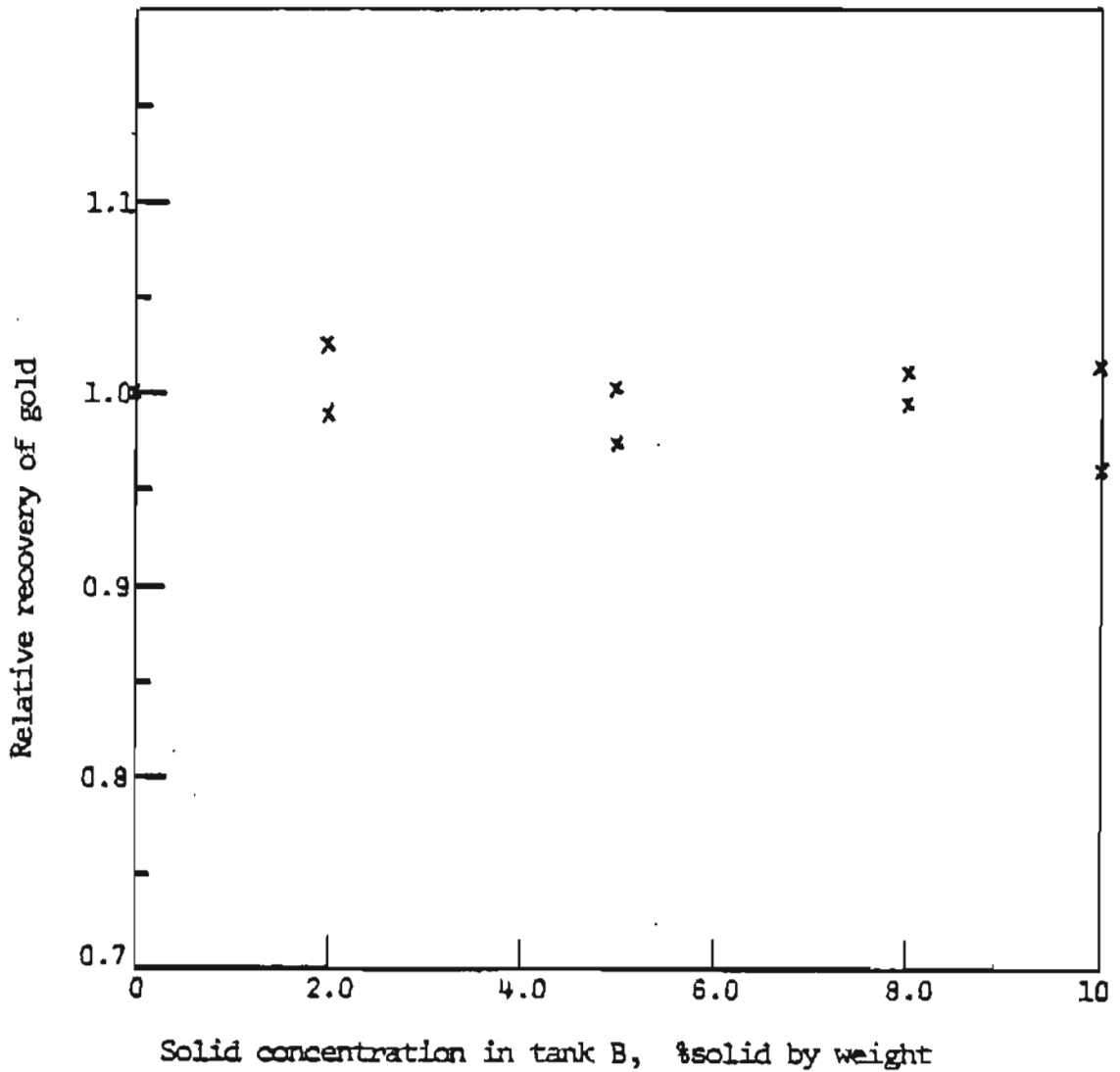


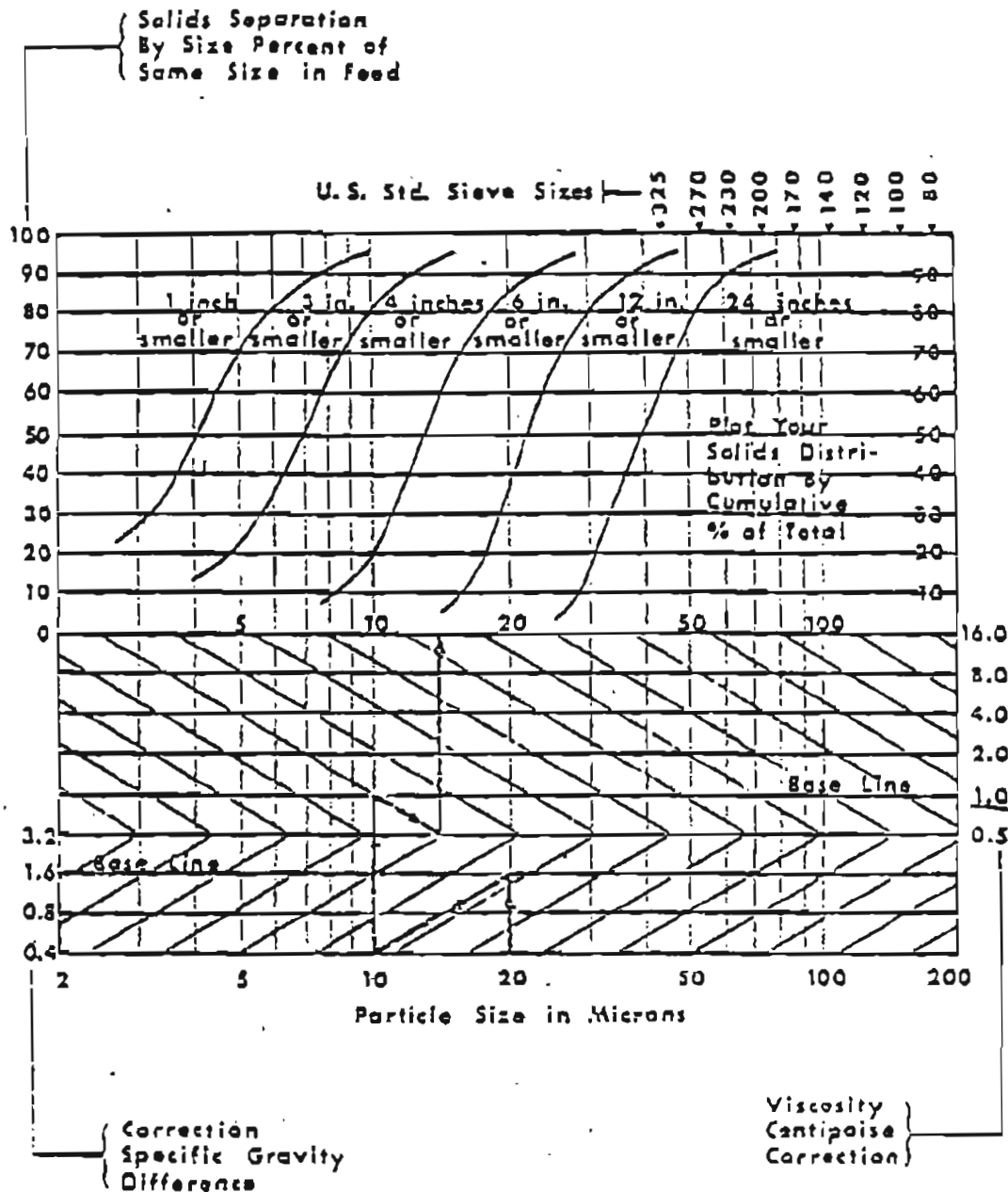
Figure 25. The effect of solid concentration of the slurry on gold recovery. (Two sets of points represent two runs)

serve as bridges (39, 40).

In the hydrocyclone, it was always assumed that the existence of shear force would prevent the formation of flocs (13, 15, 16). Thus, if no floc structure is retained the thickening hydrocyclone must be designed so that its separation size is below the size of the smallest particle to be recovered. To obtain a smaller separation size requires the formation of higher centrifugal force, which necessitates the use of a smaller diameter hydrocyclone. Small hydrocyclones have, in turn, low throughput capacities which render them impractical for many industrial thickening applications. Figures 26 and 27 show the separation sizes and capacities of different diameter hydrocyclones.

During the past decade synthetic long-chain polymers with extremely high flocculating capabilities have been developed. The flocs formed by these new polymeric flocculants are larger and more shear-resistant than those formed by the use of electrolytes (42). Investigations were carried out to study whether the flocs formed by a selected synthetic polymer were stable enough to resist the liquid shear force in the hydrocyclone.

According to Chang and Yang (43, 44) among 15 various non-ionic, anionic, and cationic synthetic polymers tested, Superfloc 84, a product of the American Cyanamid Company, was found to be best for the flocculation of suspended solids in the wastewater of the placer mining operations in both Circle and Livengood districts. This polymer resulted not only in the least residual turbidity with the least amount of dosage, but also produced the fastest settling rate flocs to each tested sample. Therefore, Superfloc 84 was selected as the flocculant subjected to the



THE ABOVE CHART IS FOR GUIDANCE ENGINEERING PURPOSES ONLY. FINAL SIZING OF CYCLONES MUST BE DETERMINED BY TESTS ON THE EXPECTED SLURRY OR PRIOR EXPERIENCE IN SIMILAR SITUATIONS.

Figure 25. Separation performance of various size hydrocyclones. (41)

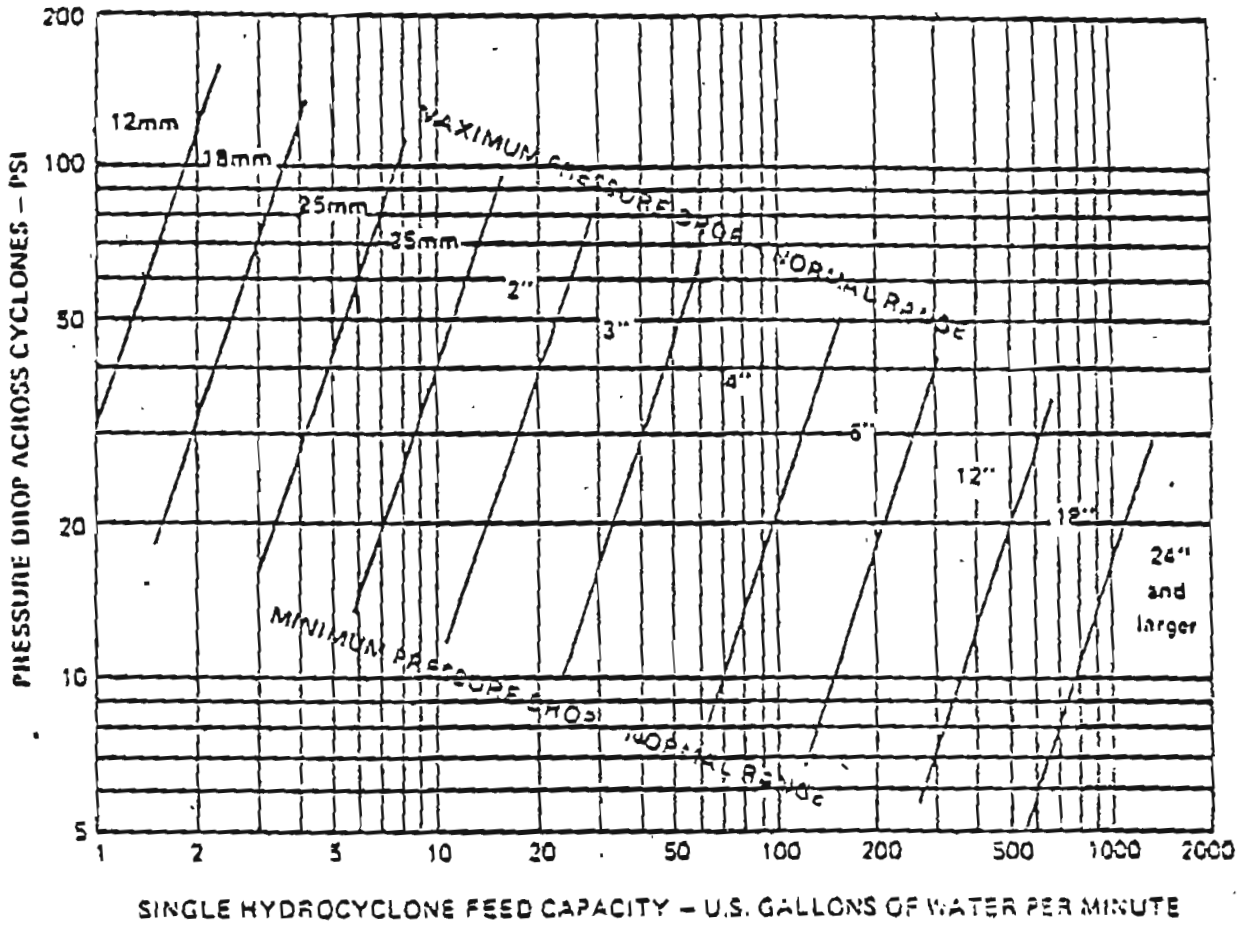


Figure 27. Hydrocyclone capacity nomograph (41)

following tests.

The solids coarser than 16 microns in water samples were removed by running the hydrocyclone three times. These processed samples were adjusted to 10% solid by weight to be the feed slurries. Calculated amounts of 0.5% Superfloc 84 solution were added to slurries so that desired flocculant loadings could be reached. The hydrocyclone was run right after the addition of the flocculant solution. Figures 28 and 29 show the flocculation in the hydrocyclone with various feed pressures. It can be seen that 10 psi is the optimum pressure for sample from the Circle district and 5 psi for the Livengood district sample. Beyond these optima, the increasing liquid shear force tends to break the formed flocs and reduce the separation effectiveness. At the lower range of flocculant loading, increase in flocculant dosage may enhance the flocculation which causes the higher separation effectiveness. Eventually optimum dosage is reached. Further increase in flocculant loading will decrease the flocculation thus reducing the separation effectiveness. The reason is that when the flocculant loading is greater than optimum loading, the extended segments of polymer may eventually absorb on other sites on the original particle rather than absorb on the sites of other particles. Therefore, the polymer wraps the discrete particle and is no longer capable of serving as a bridge. Separation effectiveness is also reduced by the increase in liquid viscosity resulting from the presence of unabsorbed flocculant.

Inspection with the zeta potential meter showed that the suspended solids of both samples were negatively charged. Superfloc 84 being a non-ionic flocculant, the flocculation can not be explained by charge

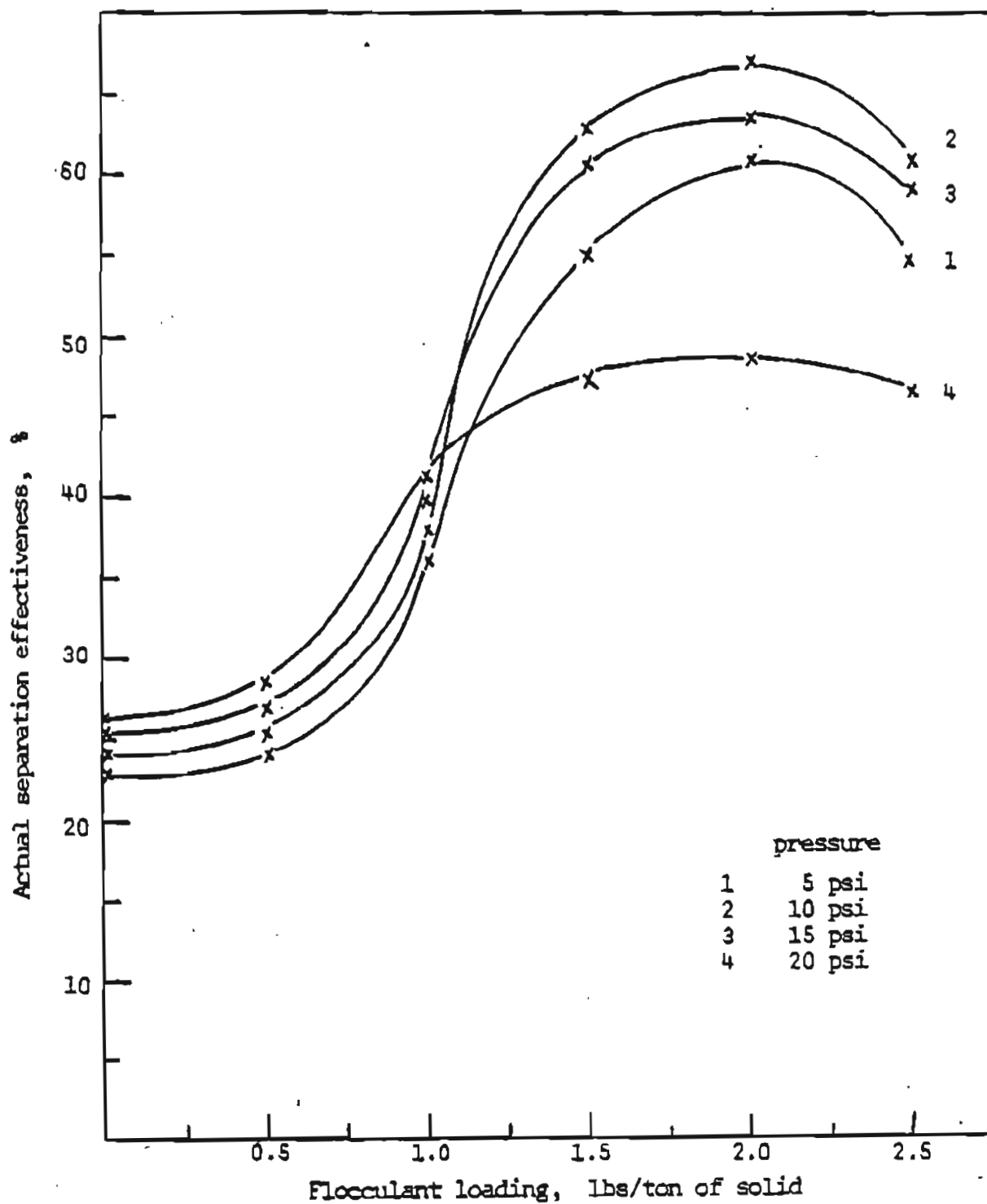


Figure 28. The effect of flocculant loading on the separation effectiveness (Circle district sample).

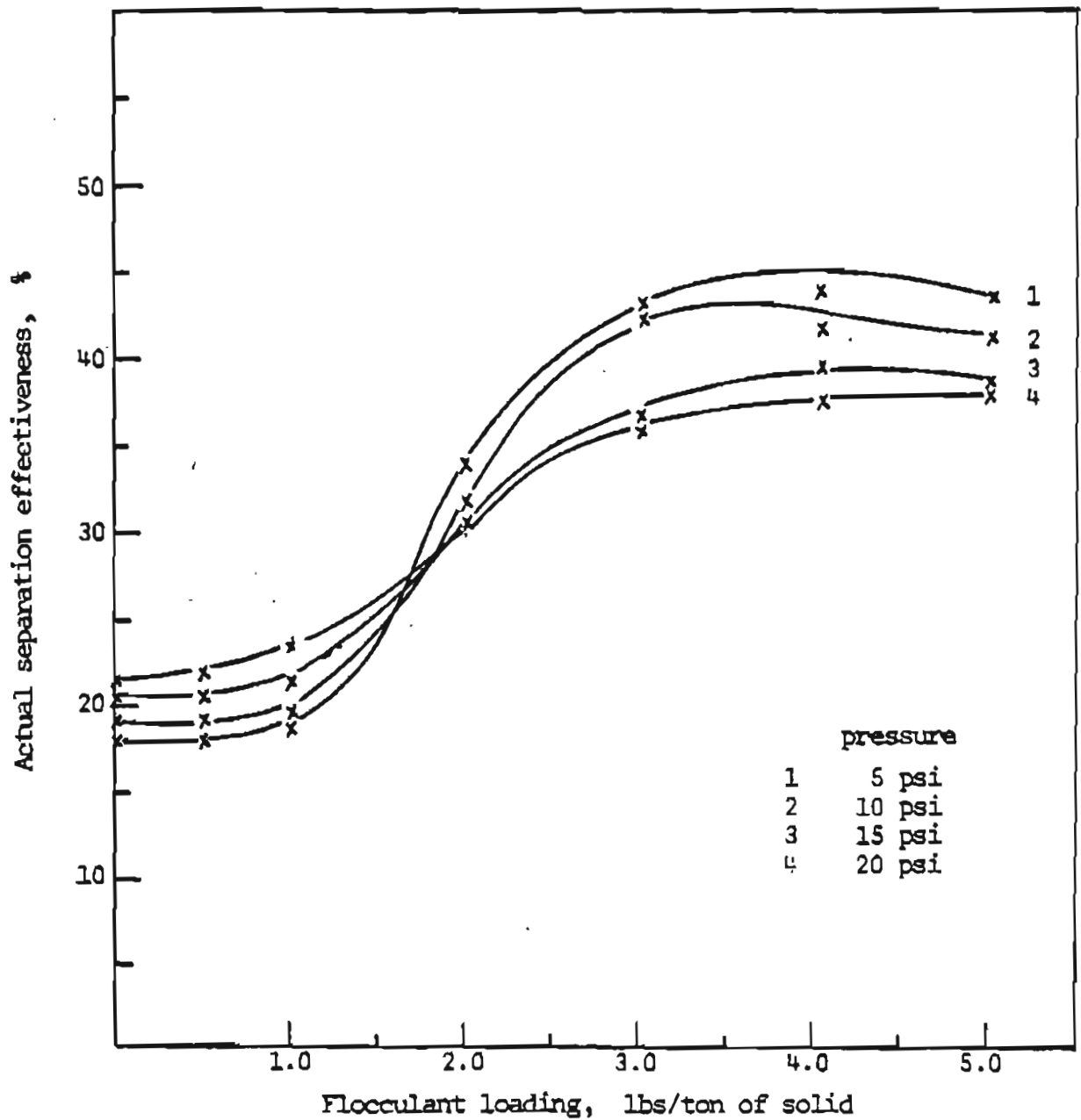


Figure 29. The effect of flocculant loading on the separation effectiveness (Livengood district sample).

neutralization. Thus, interparticle bridging dominates the flocculation. The main type of bonding between the flocculant and solids may be hydrogen bonding or chemical bonding rather than electrolytic bonding. The floc formed from the Circle district sample has higher physical strength than that of the Livengood district sample. Therefore, the higher shear-resistant ability of flocs formed from the Circle district sample, (10 psi rather than 5 psi) is believed to cause the higher actual separation effectiveness of solids in the Circle district sample. The different surface characteristics of solids of different samples probably contribute to these various results.

A Recommended Flowsheet of Recirculating System of Wastewater in Placer Mining

A flowsheet of wastewater treatment in placer mining suggested by this study is given in Figure 30.

The wastewater discharged from a sluice box passes through a 50-100 feet transitional zone where coarser particles dropout and are removed by a bulldozer or a dragline. A feed pond for the hydrocyclone is built at the end of the transitional zone. The number of hydrocyclones arranged in parallel is dependent on the amount of wastewater discharged from the sluice box. The feed pond for hydrocyclones should be large enough in volume for at least 3 minutes operation plus storage capacity with a static head of at least 5 feet so that the pump will not suck air under minor fluctuation. The underflow of the hydrocyclones is led to a settling pond. The overflows of hydrocyclones and the settling pond are pumped back to the water reservoir for sluicing. When the solid content

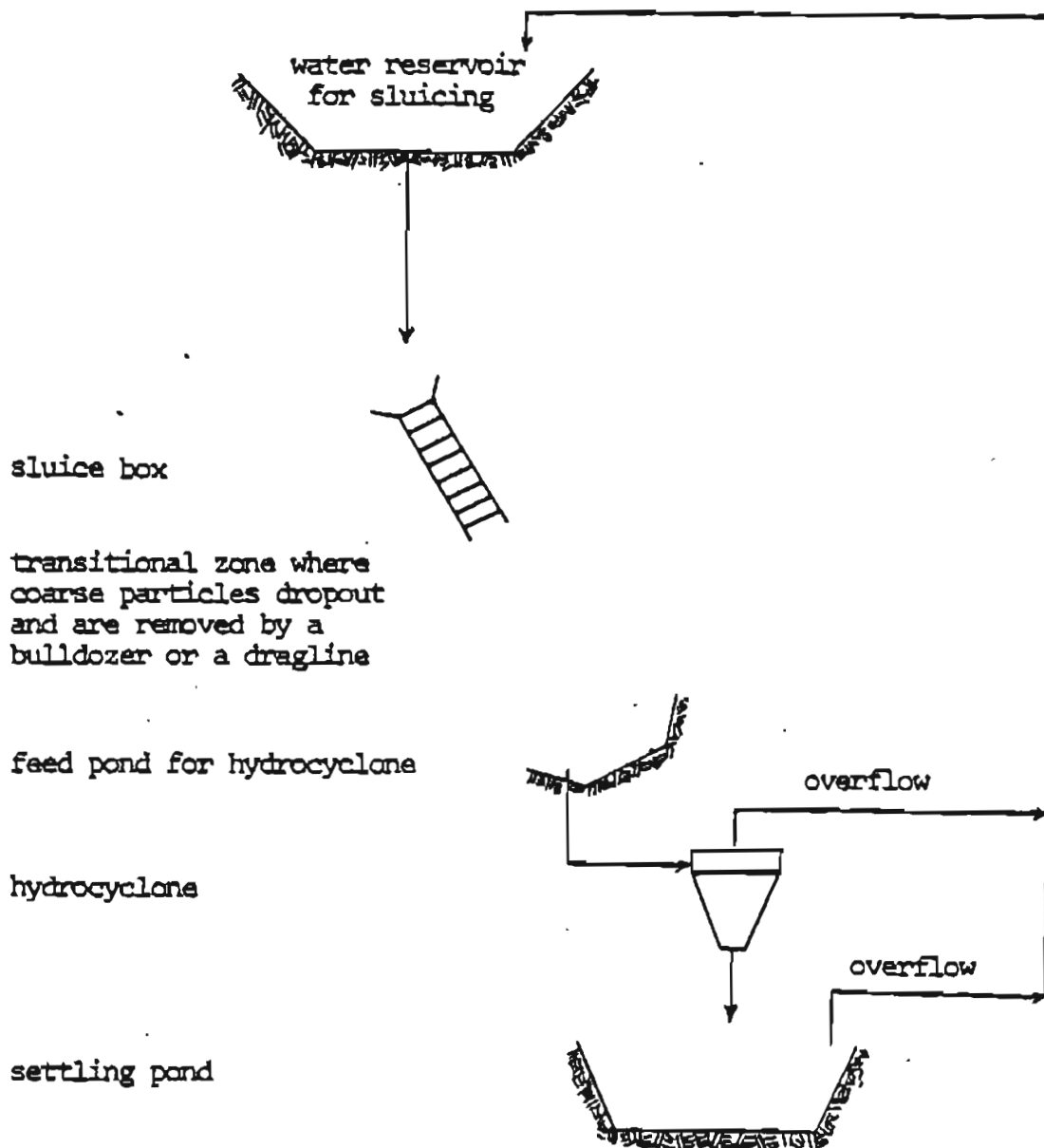


Figure 30. A recommended flowsheet of wastewater treatment in placer mining.

of wastewater in the hydrocyclone feed pond is built up to a certain level, flocculant is injected to the hydrocyclone feed pond. No additional time is needed to agitate, therefore, a continuous operation can be maintained.

According to Yang (44), the fraction of particles finer than 37 microns (400 mesh) in gold-bearing gravel at the Circle district is less than 1%. Based on the laboratory tests, it was found that the particles coarser than 16 microns in the gold-bearing gravel can be removed by the combination of a 50-100 feet transitional zone and hydrocyclones without the addition of flocculants. Therefore, only less than 1% of the solids need to be flocculated. If the optimum dosage of 2 lbs/ton can be achieved in the field work, the estimated amount of flocculant needed for sluicing a ton of gold-bearing gravel would be less than 0.04 pound.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Suspended solids have been proved to contribute the major impact of placer mining on the creek water quality in Alaska (43, 44). Settling ponds have been employed for the removal of these solids. However, settling ponds need large area to effectively reduce the turbidity of effluent to meet the EPA regulation. The use of the gravitational settling with the addition of flocculants has been studied in the laboratory (43,44). It may be effective in reducing the turbidity of the effluent below the current limitations permitted in field work and the problem of space needed still exists. The continued use of flocculants in this case will cause a relatively high reagent cost. The Federal Water Pollution Act expects the discharge of pollutants into navigable waters to be eliminated by 1985. Although this goal could be achieved by simple polymer flocculation in conjunction with settling ponds (43), it can be expensive. Thus, it would appear that the hydrocyclone plus flocculants could reduce the cost of wastewater treatment in placer mining and the requirements of zero discharge could be met this way since most of the water is reused.

For the conditions, under which the tests reported were carried out, the following statements can be made:

- 1: The total flow rate of the 4-inch-diameter hydrocyclone used in this study can be expressed as:

$$Q_t = 11.1 D_a^{0.23} D_f^{0.75} P^{0.49}$$

- 2: The D_a of 0.60" and D_f of 1.25" is the best combination for the 4" hydrocyclone. Solids coarser than 16 microns can be easily removed.
- 3: Higher inlet energy caused by higher feed pressure will increase the separation effectiveness.
- 4: The change of viscosity rather than density is the main cause for the increase in separation effectiveness as temperature increases.
- 5: High viscosity and density of fluid as well as hindered settling effects due to the crowding of solids can result from the high feed concentration. The feed concentration of 15% solid by weight is high enough to cause a sharp decrease in separation effectiveness for the particle sizes 16 - 31 microns.
- 6: As the recovery of 48x65 mesh gold in a 10"x3.5"x43" sluice box is not adversely affected by a sluicing water solid concentration of 10% by weight, it is reasonable to conclude that the recovery of coarser gold will also be unaffected.
- 7: The shear-resistance of flocs is dependent on their physical strength. High feed pressure can break the flocs. 10 psi and 5 psi are the optimum feed pressures for the Circle district and the Livengood district samples respectively when Superfloc 84 is employed as the flocculant.
- 8: 2.0 and 3.0 lbs/ton of Superfloc 84 are optimum flocculant loadings for the Circle district and Livengood districts samples respectively. Overloading with flocculant will

decrease the separation effectiveness of solids due to the decreased ability of the flocculant to serve as bridges.

Recommendations

In order to apply the polymer flocculation in a hydrocyclone to the plant condition for the wastewater treatment of the placer mining, some further studies are recommended:

- 1: Flocculation tests of new synthetic flocculants.
- 2: Tests of large diameter hydrocyclones.
- 3: A pilot plant test program.
- 4: Economical evaluation for building a full scale plant.

Appendix 1. Data processing of flowrate of the hydrocyclone.

*LIST MINL699

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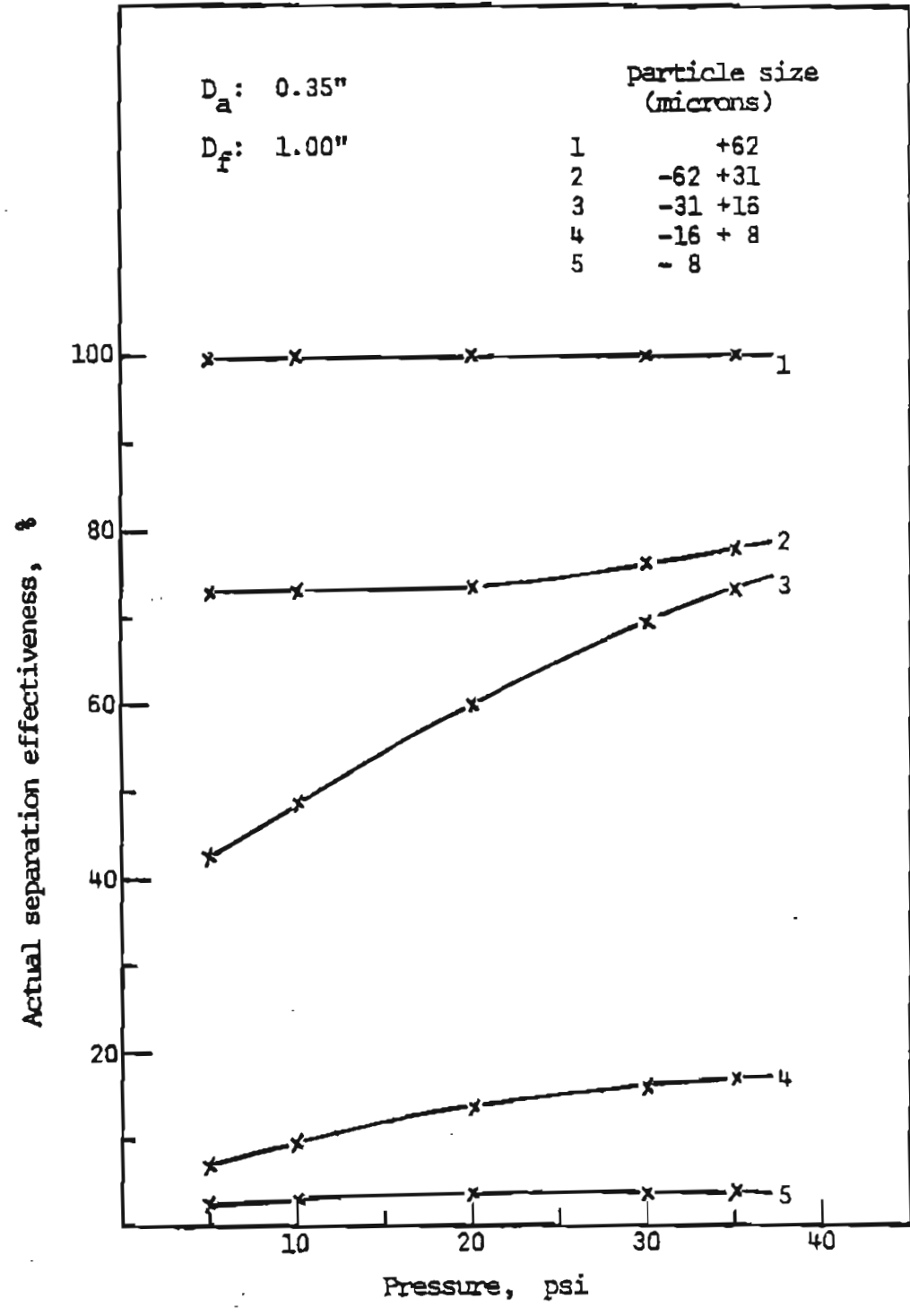
010*#RUN#DATA A '08'
020 DIMENSION P(54), DF(54), DA(54), QT(54), XQT(54)
030 DO 10 N=1,54
040 READ(08,20) P(N), DA(N), DF(N), QT(N)
050 20 FORMAT(4F8.0)
060 10 CONTINUE
070 XSSQT=1000000.
080 DO 1 J=47,52
090 RX=J*0.01
100 DO 2 K=20,25
110 RY=K*0.01
120 DO 3 L=70,78
130 RZ=L*0.01
140 DO 4 M=108,115
150 RK=M*0.1
160 SQT=0.
170 XXQT=0.
180 DO 5 I=10,54
190 XQT(I)=RK*(DA(I)**RY)*(DF(I)**RZ)*(P(I)**RX)
200 XXQT=(XQT(I)-QT(I))**2
210 SQT=SQT+XXQT
220 5 CONTINUE
230 IF (SQT. LT. XSSQT) GO TO 30
240 GO TO 4
250 30 XSSQT=SQT
260 AK=RK
270 AY=RY
280 AX=RX
290 AZ=RZ
300 4 CONTINUE
310 3 CONTINUE
320 2 CONTINUE
330 1 CONTINUE
340 WRITE(6,12) XSSQT, AK, AX, AY, AZ
350 12 FORMAT(2X, 'E=', F8.2, 2X, 'K=', F6.2,
360 2X, 'X=', F4.2, 2X, 'Y=', F4.2, 2X, 'Z=', F4.2)
370 STOP
380 END

```

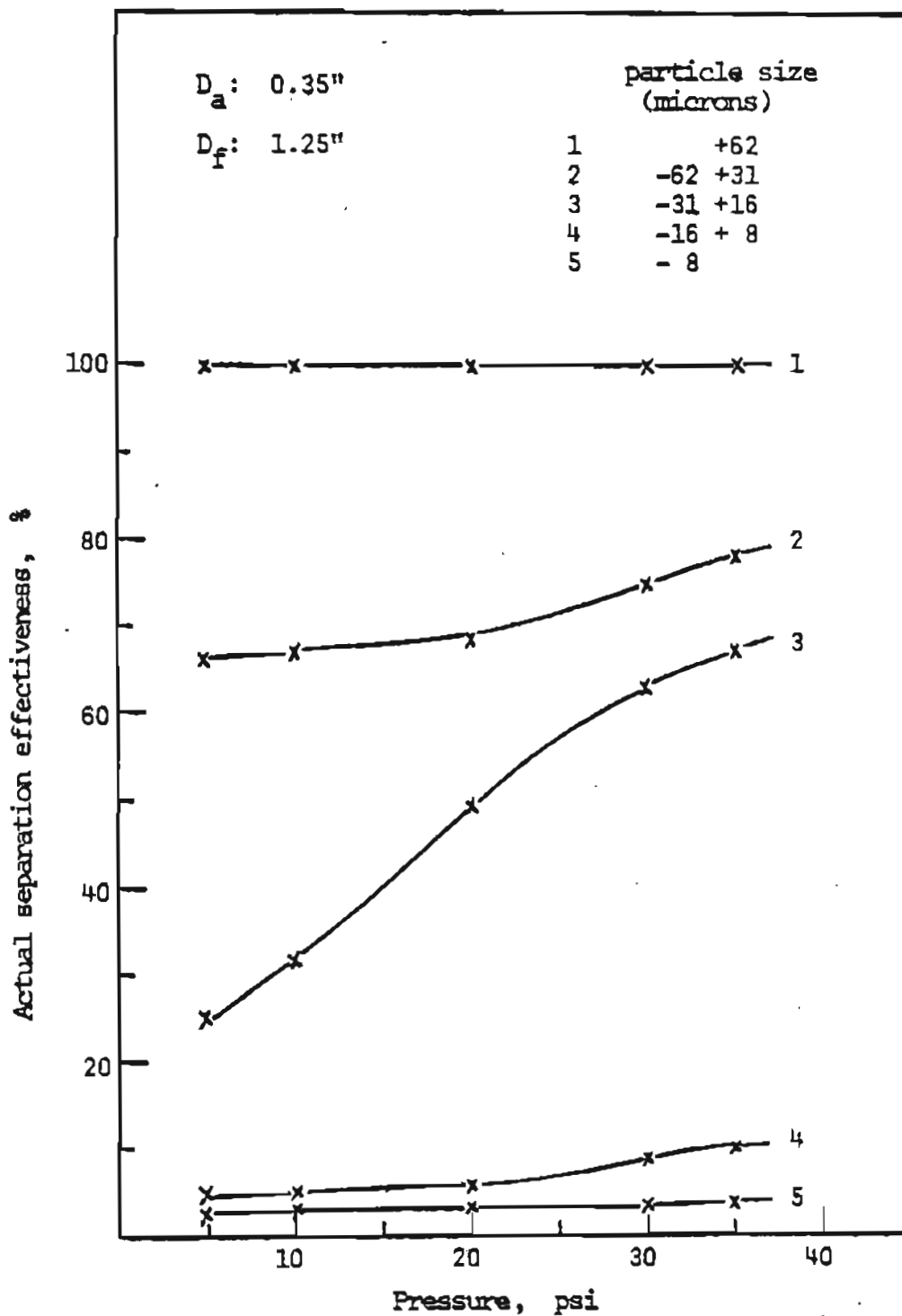
*PRN

E= 219.47 K= 11.10 X=0.49 Y=0.23 Z=0.75

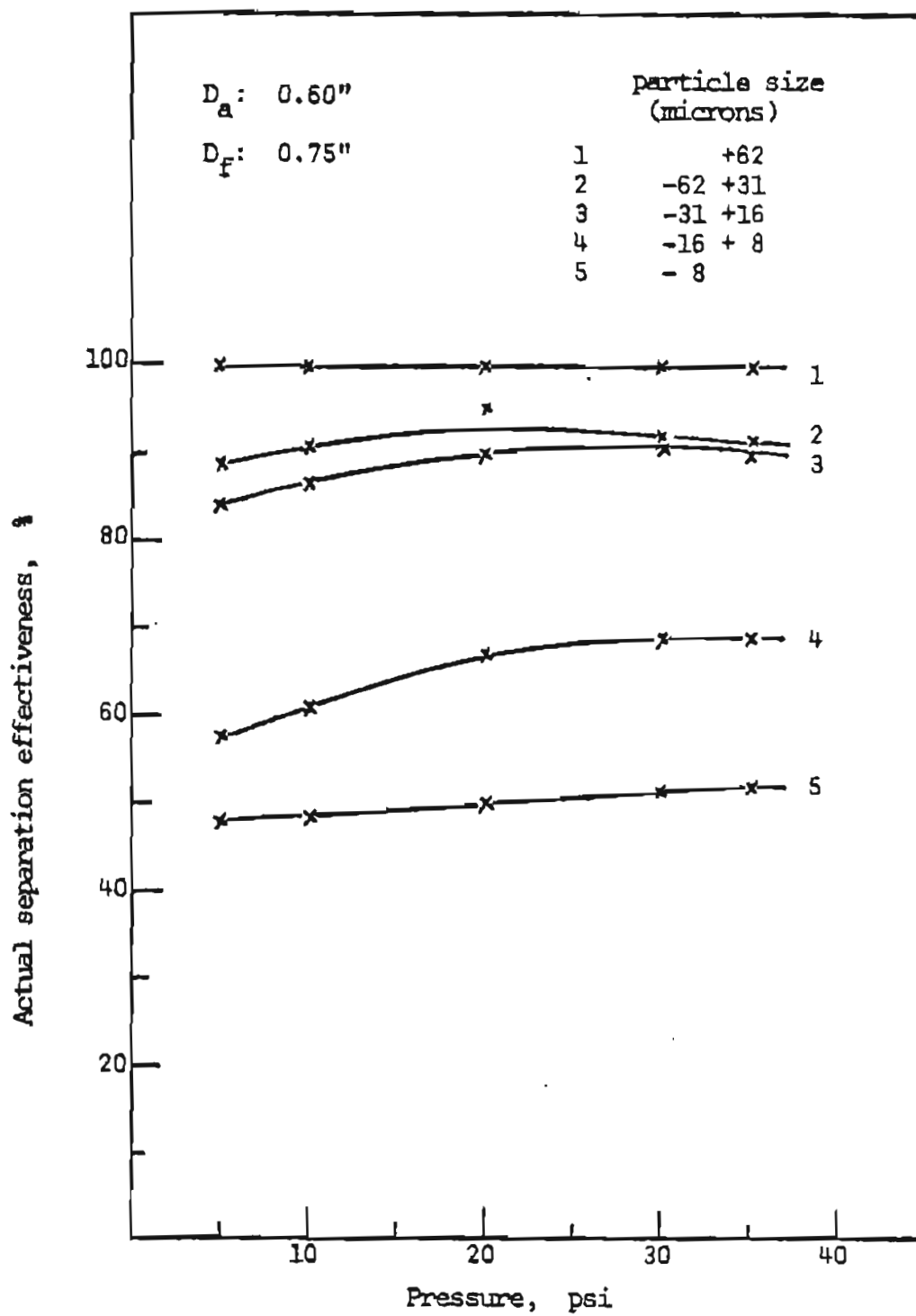
Appendix 2. The effect of feed pressure on the separation effectiveness (Circle district sample) for different combinations of D_a and D_f , compare with Figure 10.



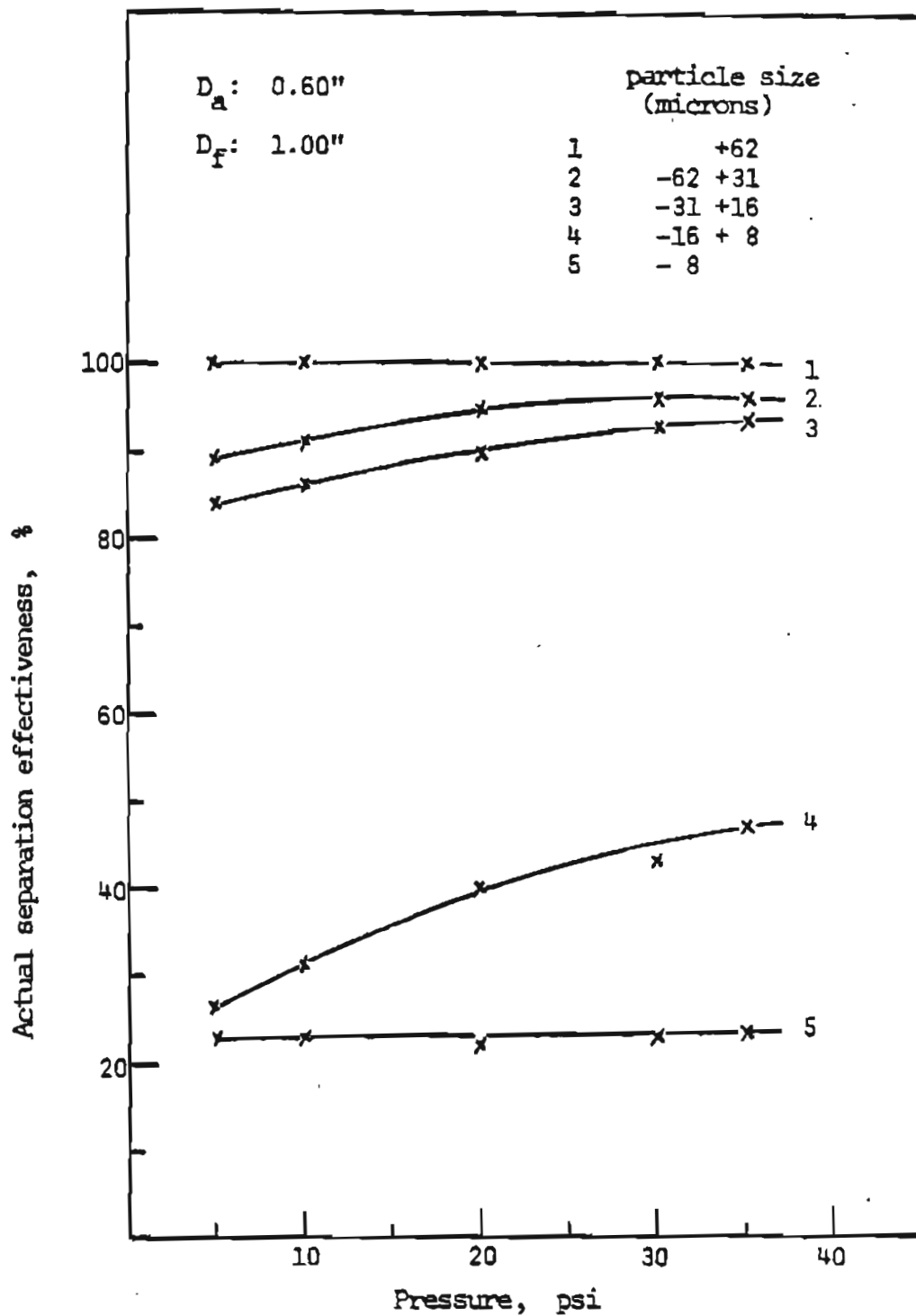
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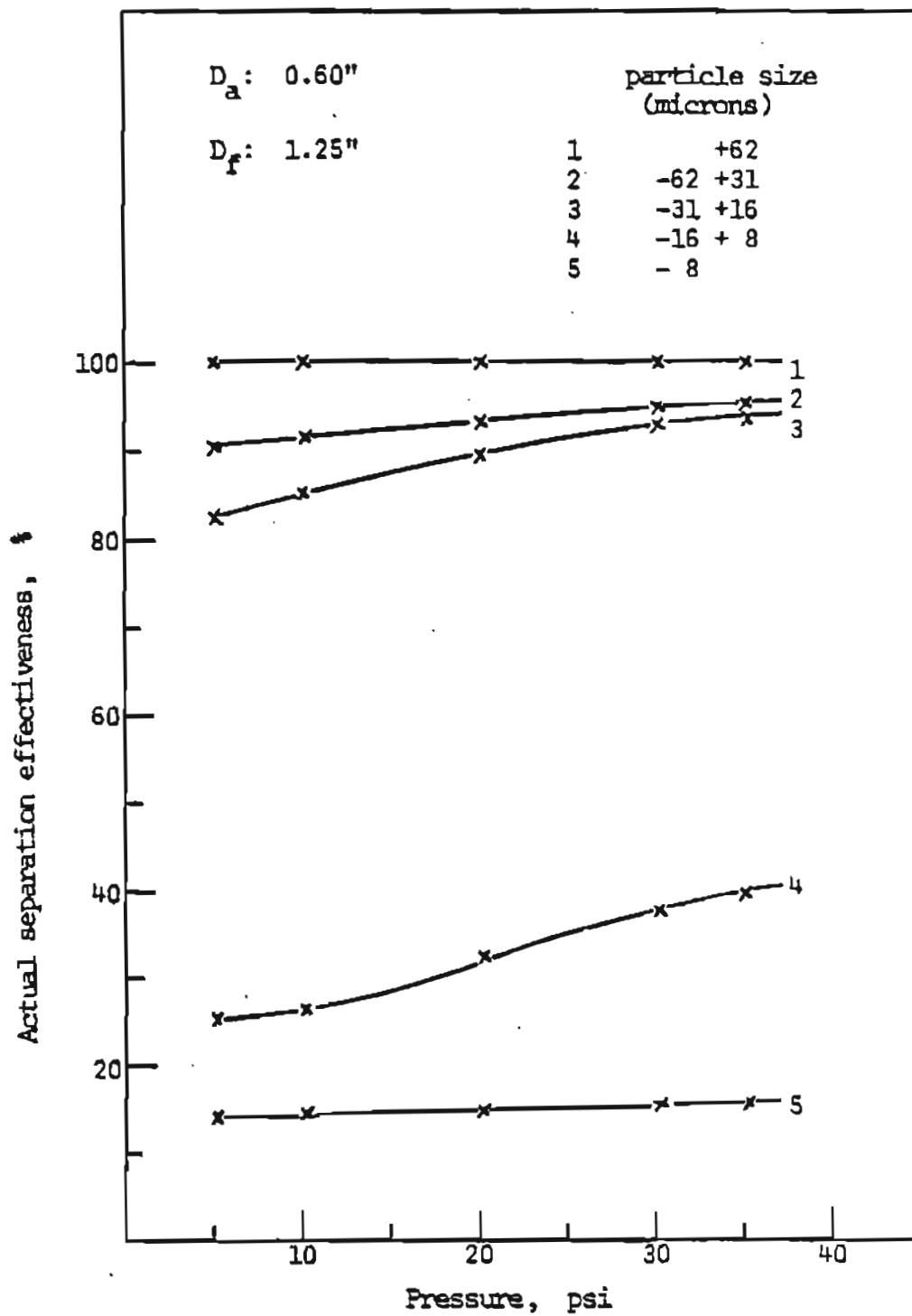
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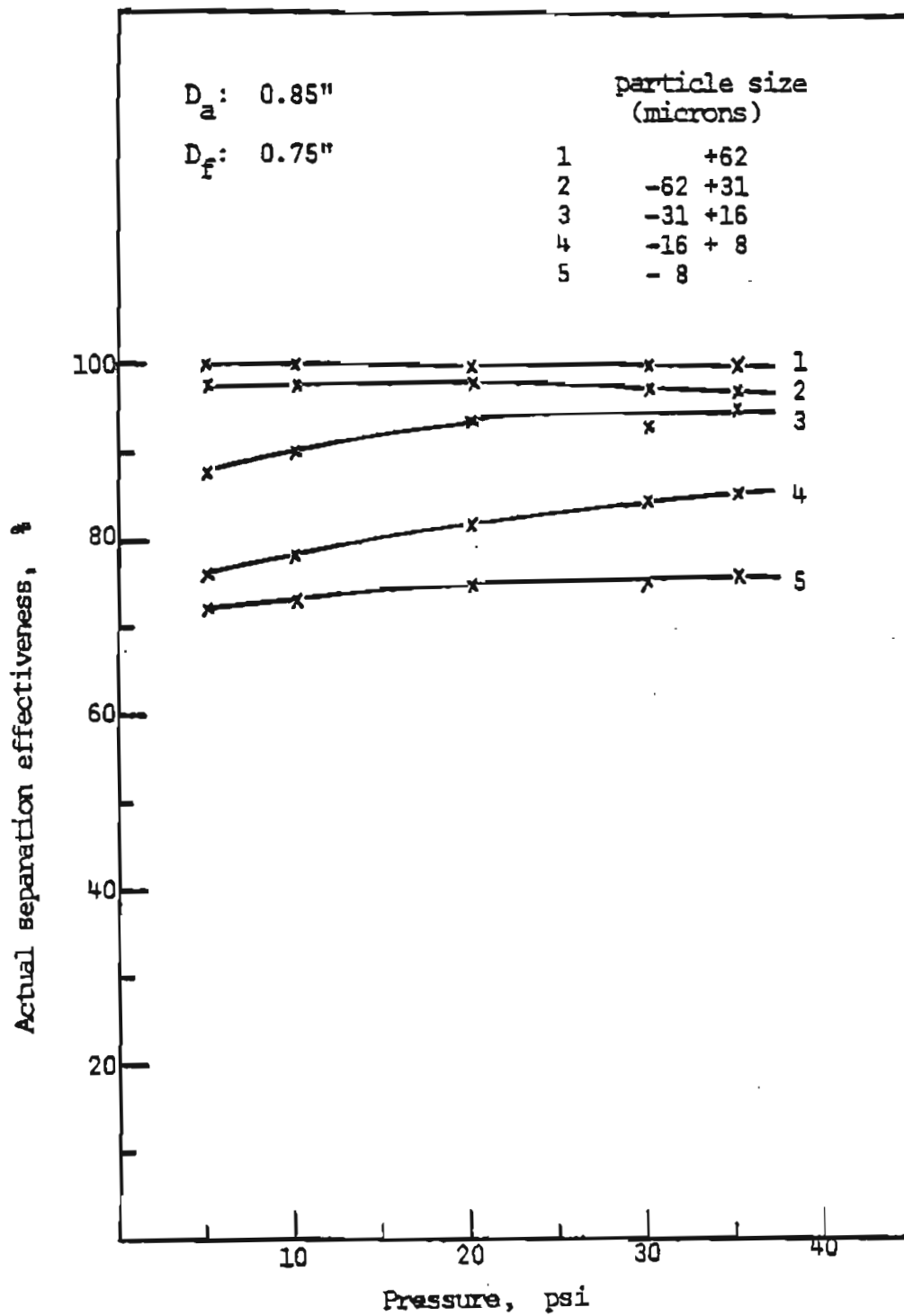
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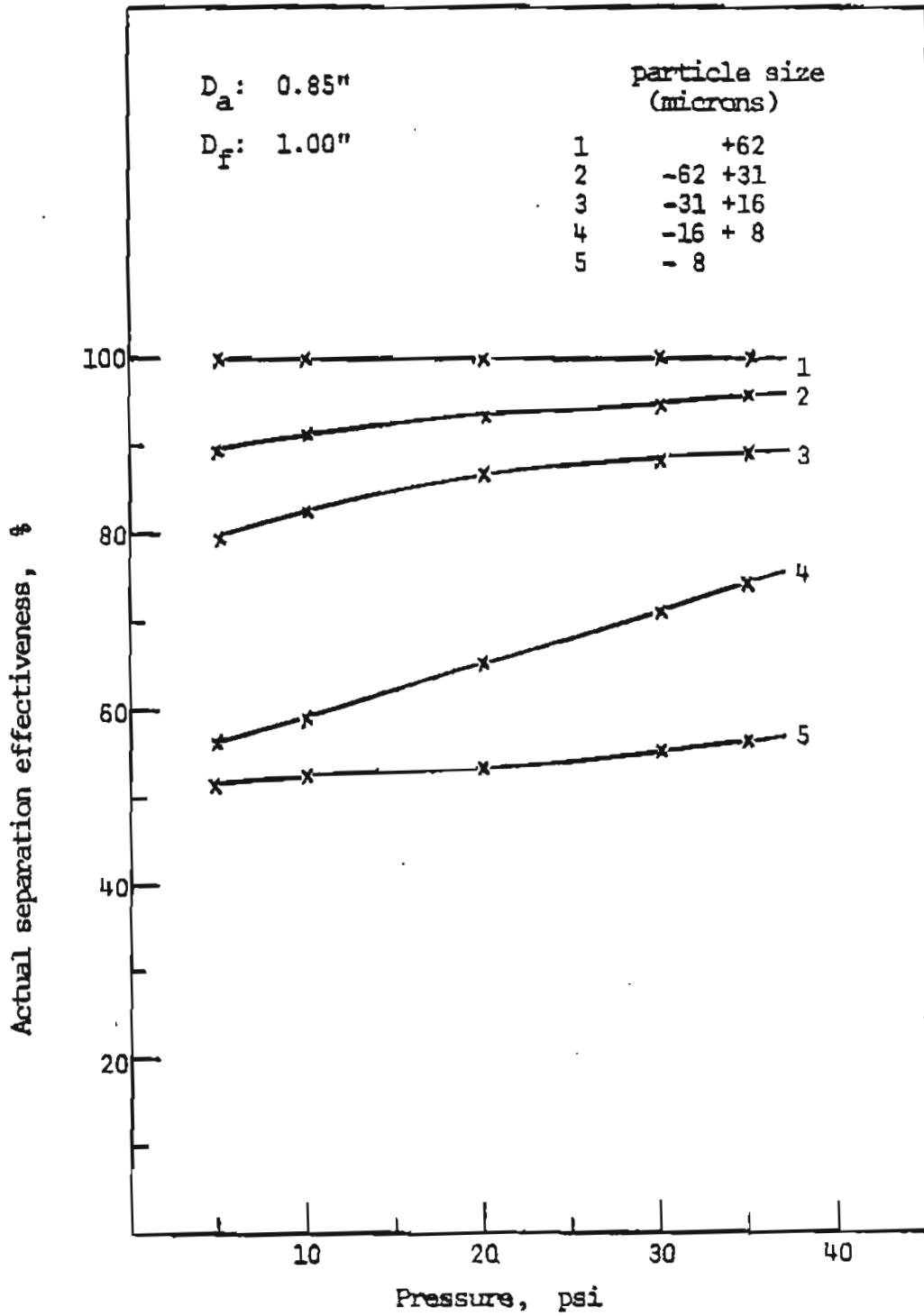
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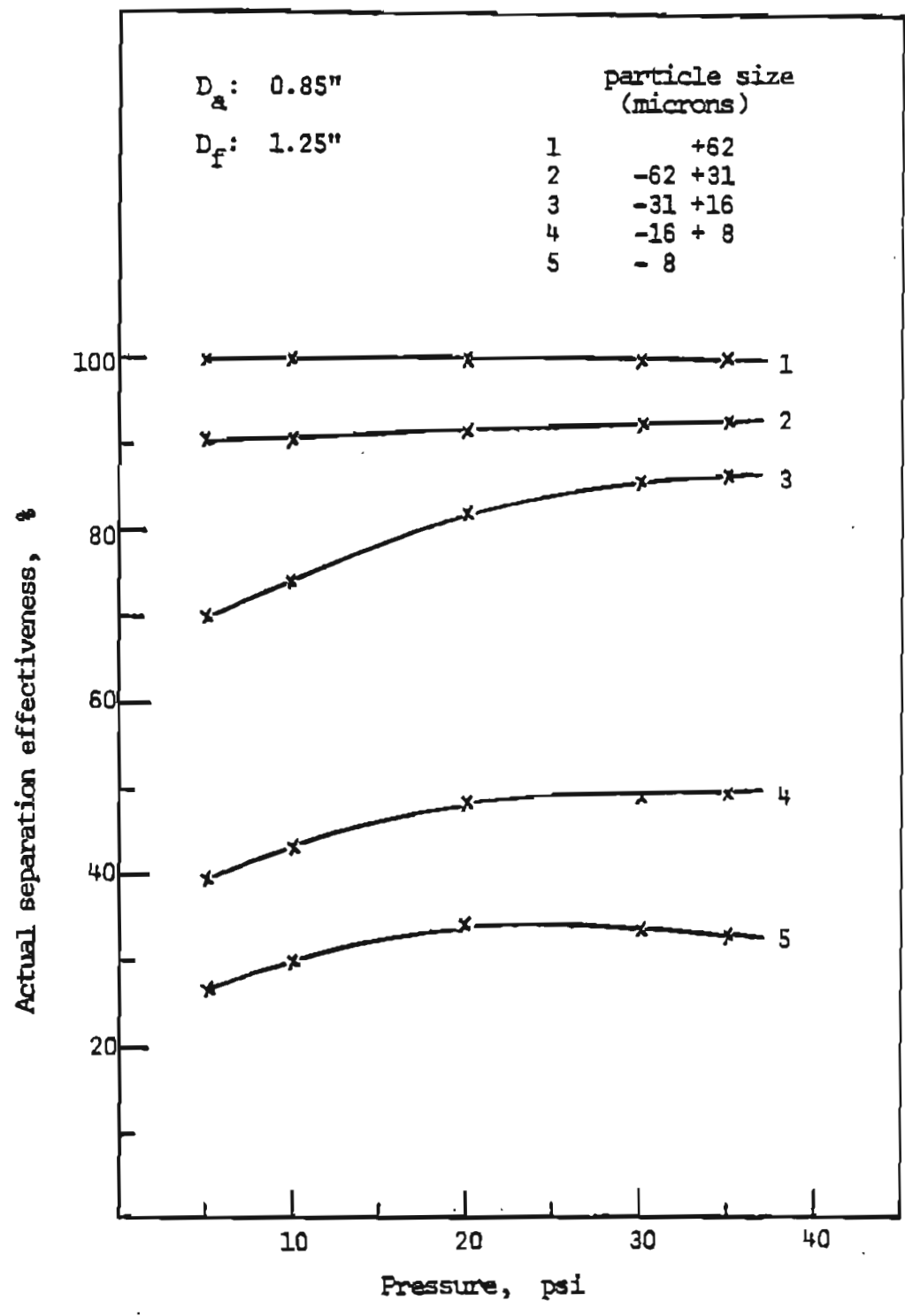
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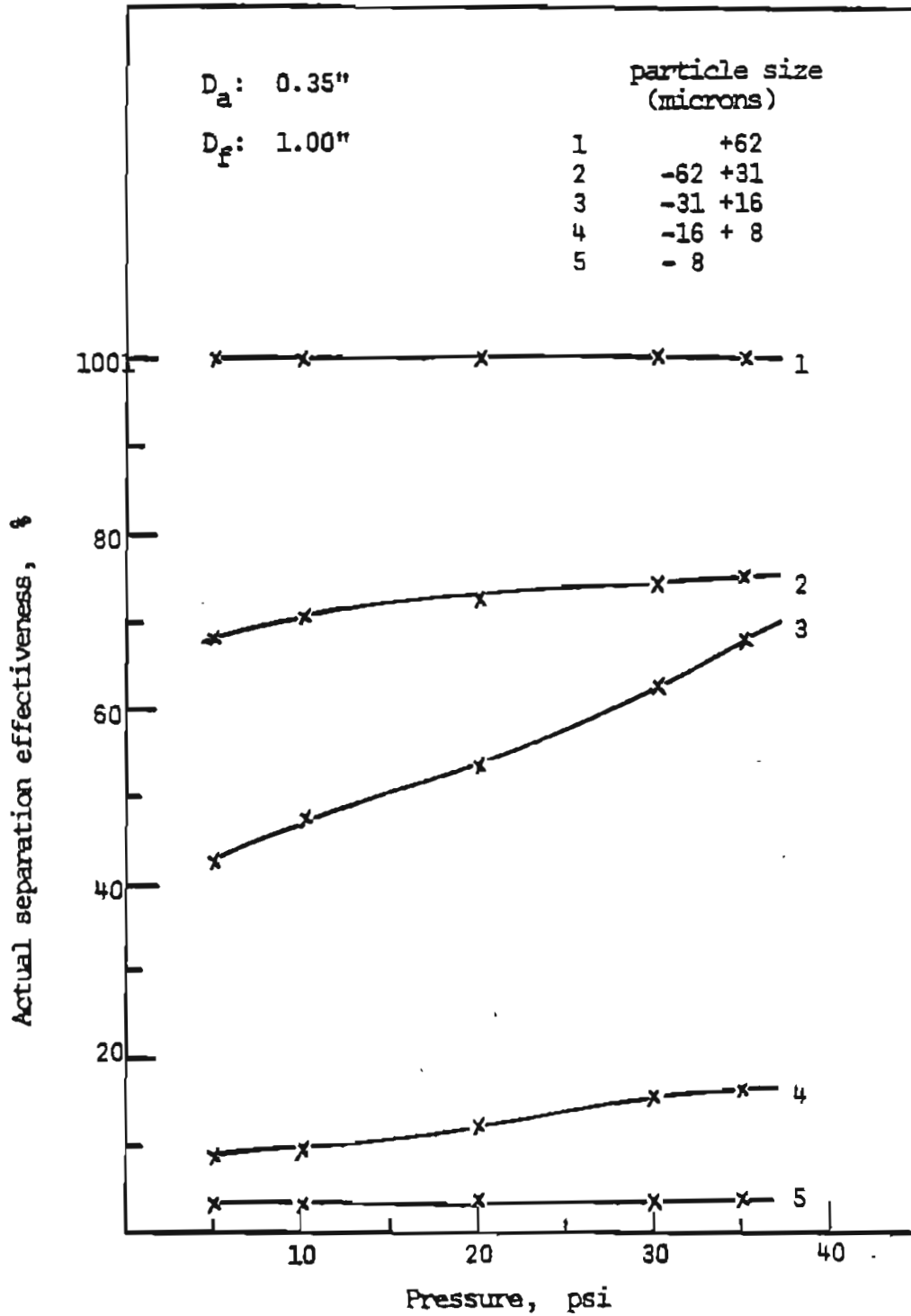
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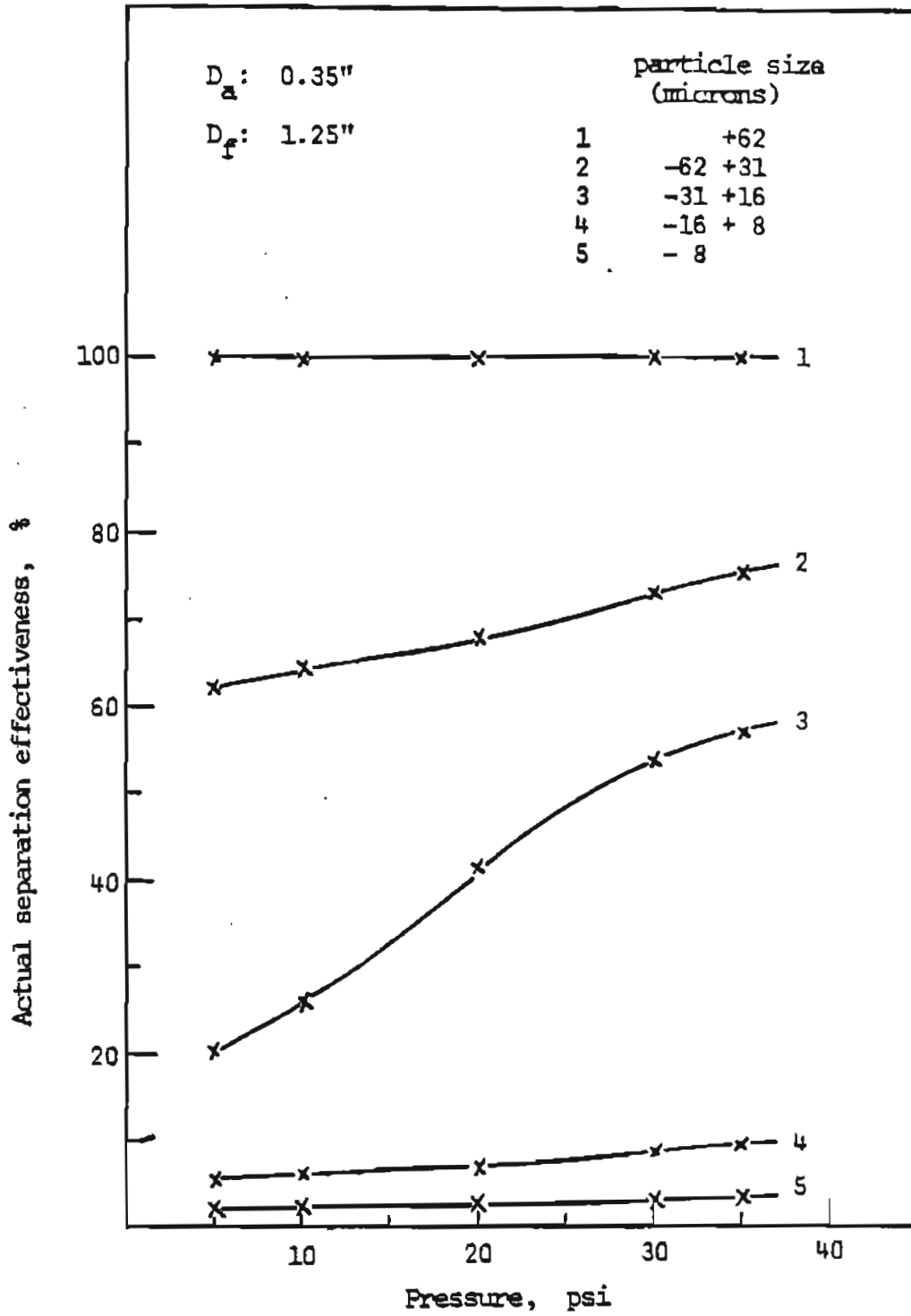
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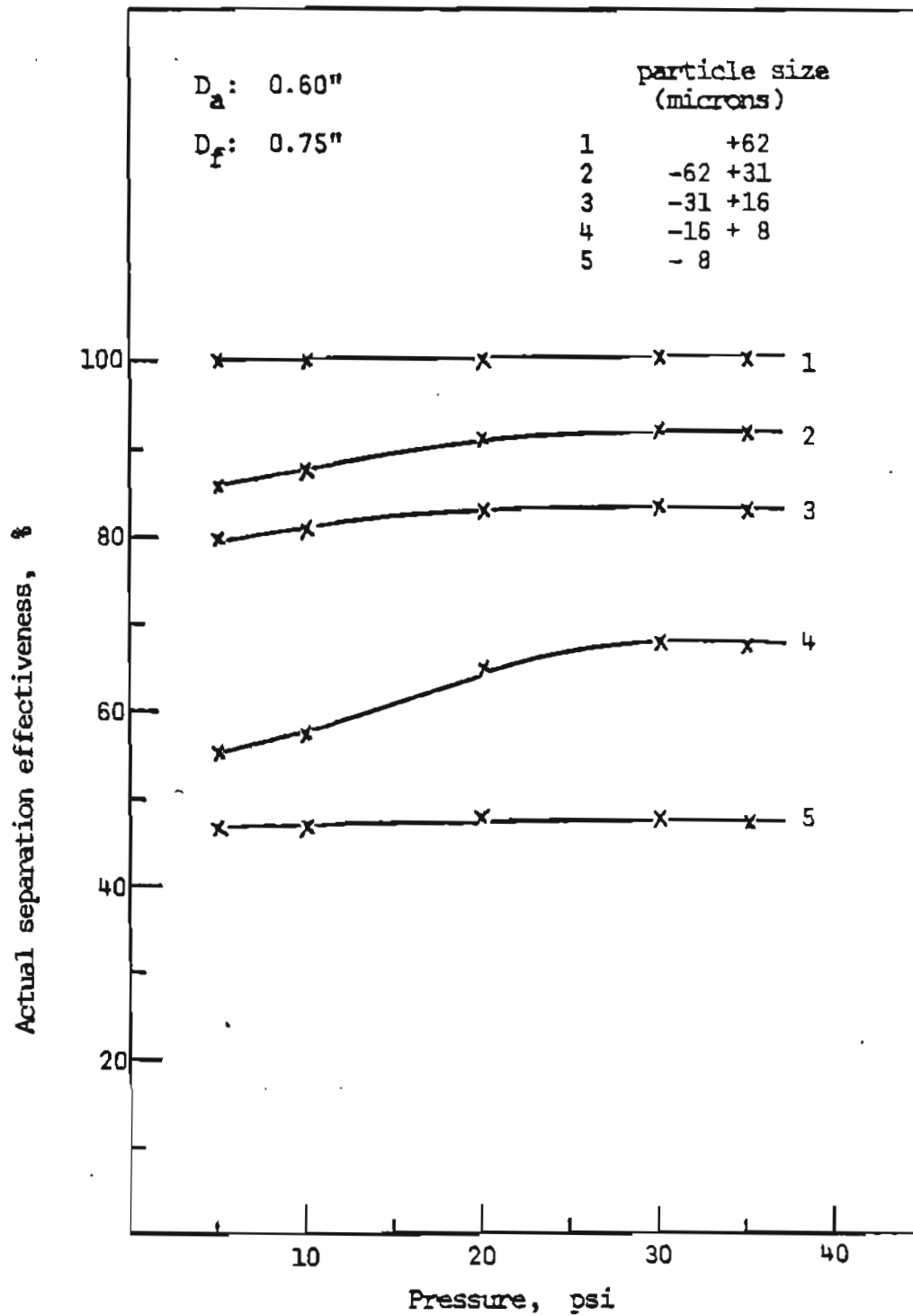
Appendix 3. The effect of feed pressure on the separation effectiveness (Livengood district sample) for different combinations of D_a and D_f , compare with Figure 11.



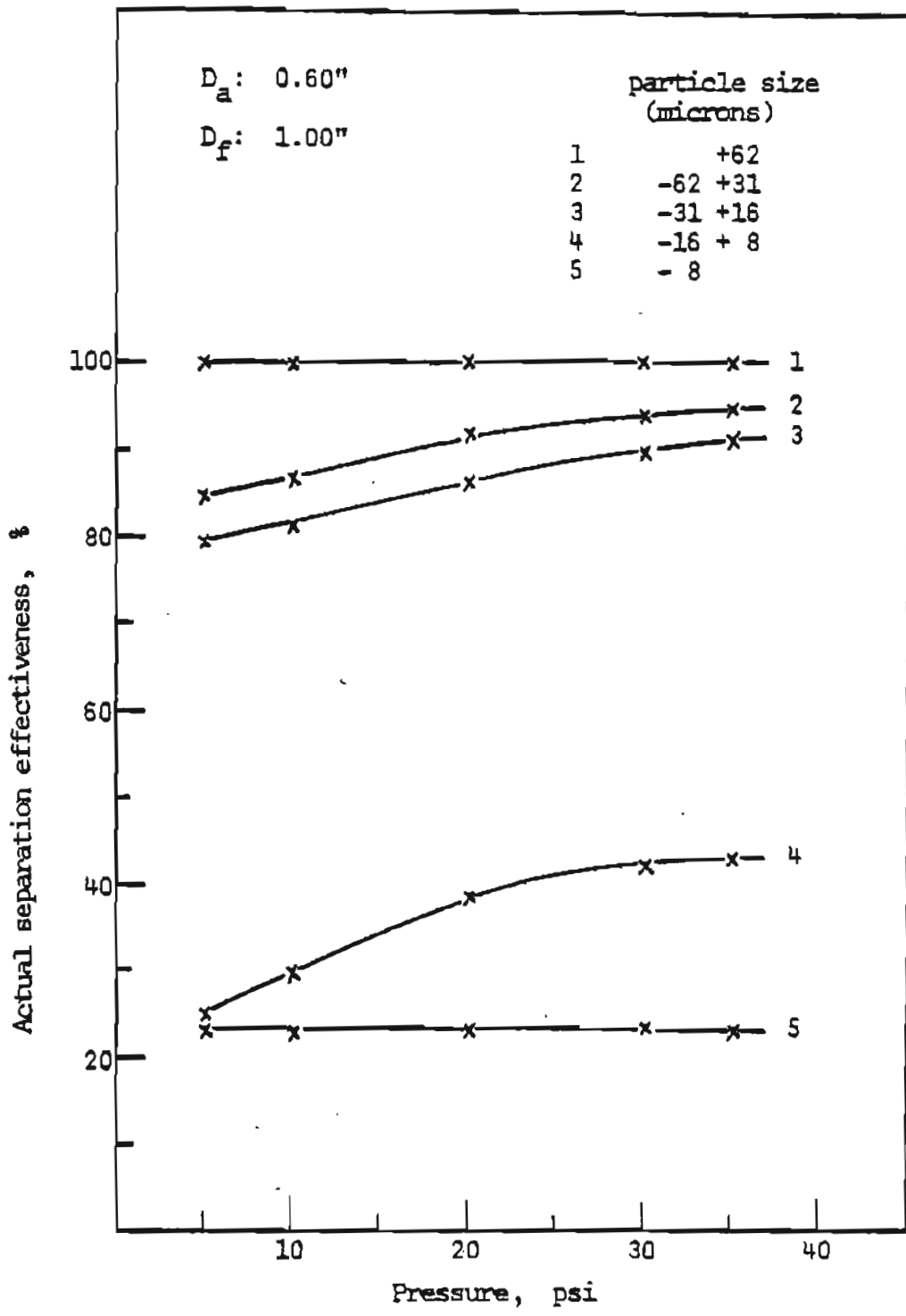
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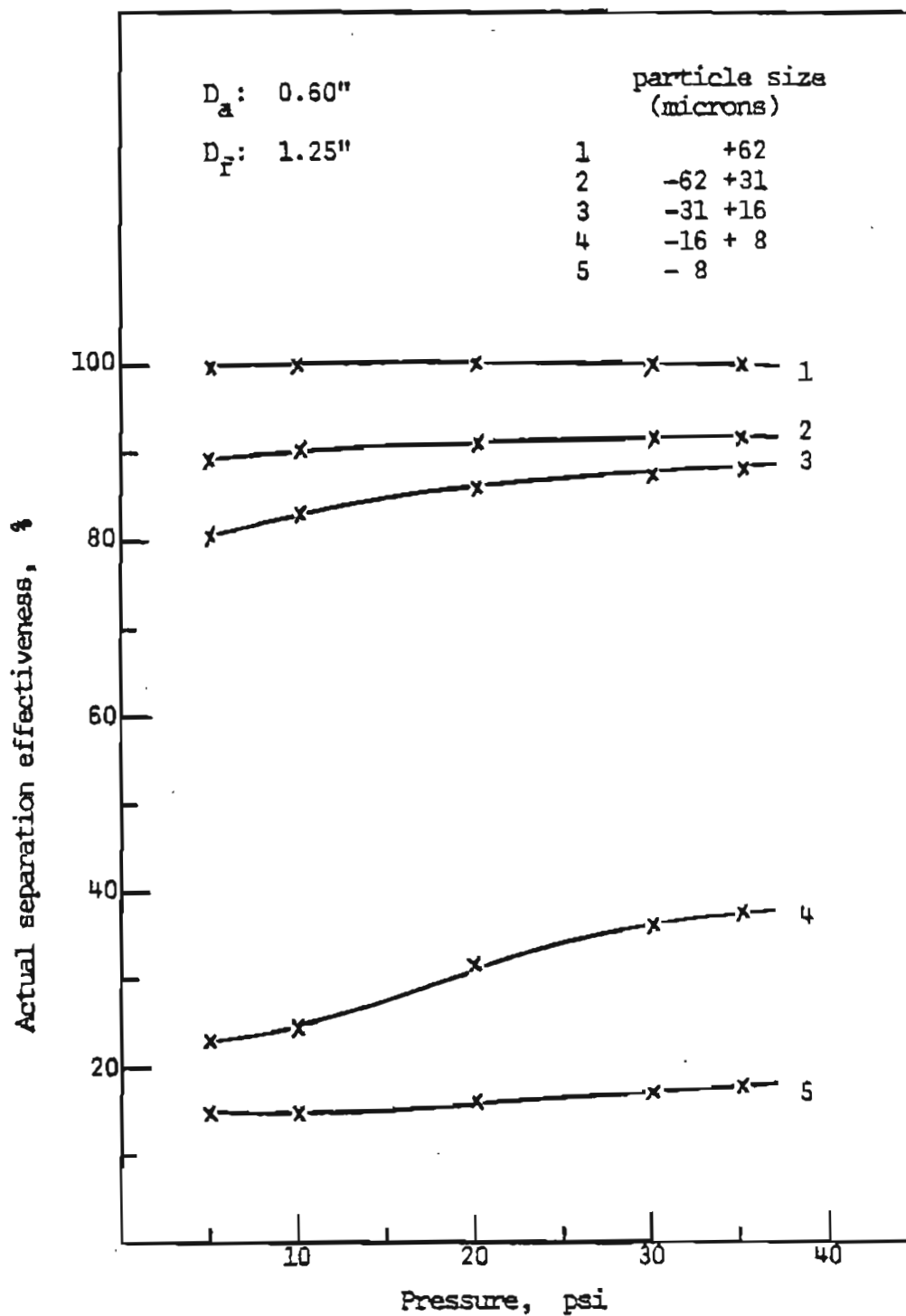
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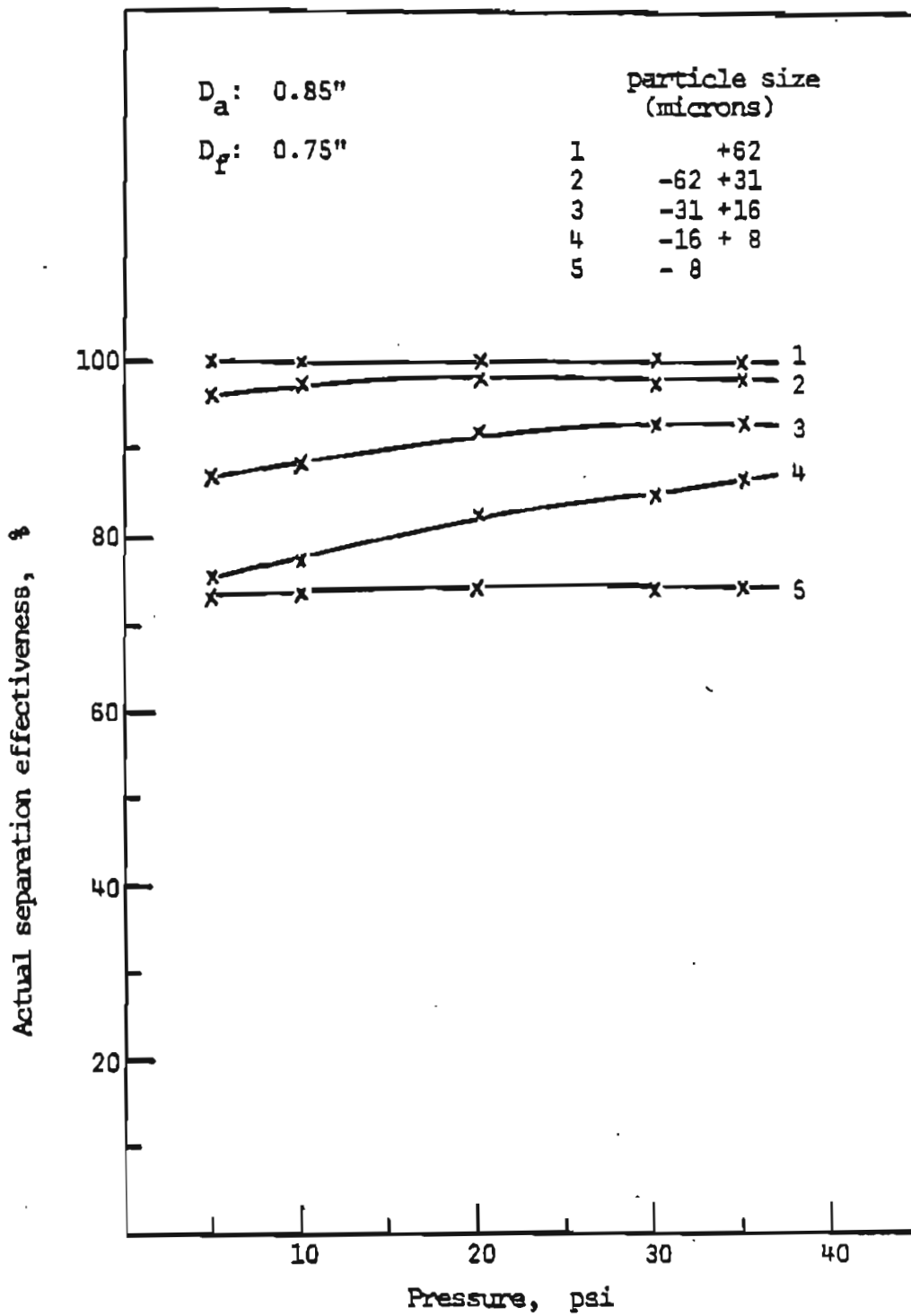
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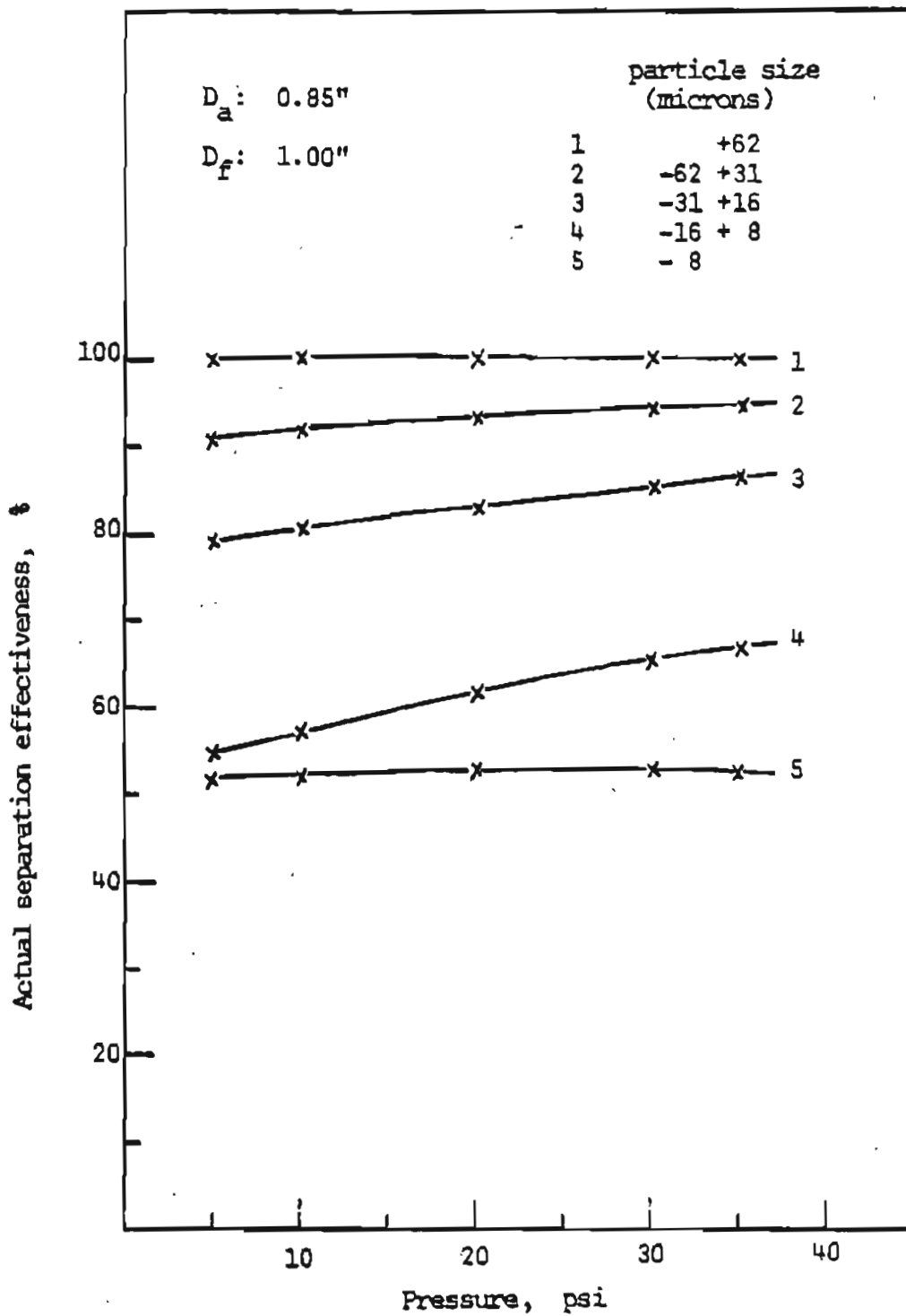
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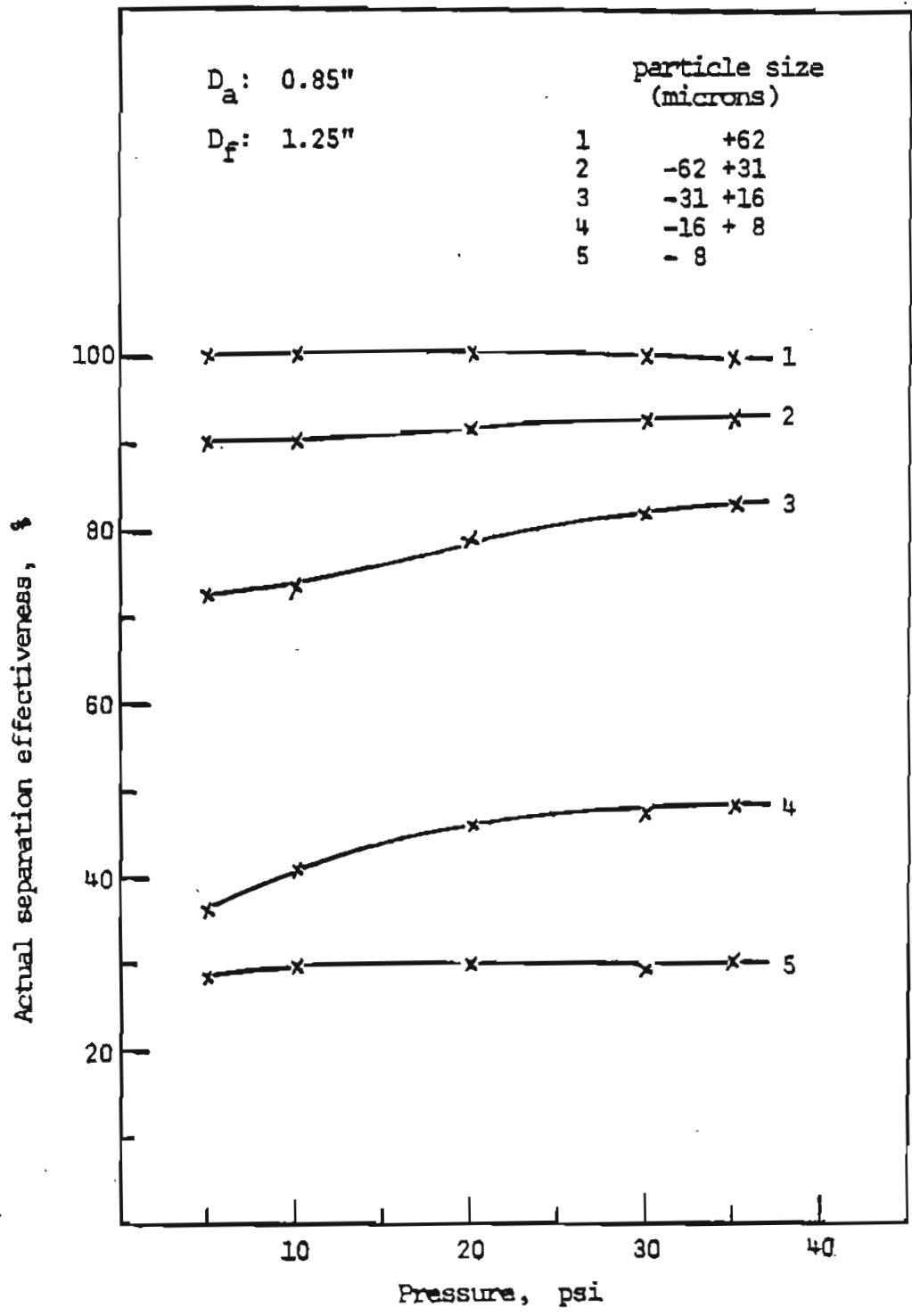
Appendix 3. (cont.)



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Appendix 3. (cont.)



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