THE SIZING AND SELECTION OF HYDROCYCLONES

By Richard A. Arterburn

For many years, hydrocyclones, commonly referred to as cyclones, have been extensively utilized in the classification of particles in comminution circuits. The practical range of classification for cyclones is 40 microns to 400 microns, with some remote applications as fine as 5 microns or as coarse as 1000 microns. Cyclones are used in both primary and secondary grinding circuits as well as regrind circuits. The information given in this paper is intended to provide a method, at least for estimating purposes, of selecting the proper number and size of cyclones and to determine the proper level of operating variables. Generally, it is recommended that cyclone suppliers be consulted for sizing confirmation. Some cyclone suppliers employ digital computers to aid in the sizing and selection of cyclones.

CYCLONE DESCRIPTION AND BASIC OPERATION

Figure 1 shows a cutaway view of a typical cyclone. During operation, the feed slurry enters the cyclone under pressure through the feed pipe into the top of the cylindrical feed chamber. This tangential entrance is accomplished by two types of design, as shown in Figure 2. Since the majority of research has been done with the involuted type, the graphs and relationships shown may not be strictly applicable to other designs.

As the feed enters the chamber, a rotation of the slurry inside of the cyclone begins, causing centrifugal forces to accelerate the movement of the particles towards the outer wall. The particles migrate downward in a spiral pattern through the cylindrical section and into the conical section. At this point the smaller mass particles migrate toward the center and spiral upward and out through the vortex finder, discharging through the overflow pipe. This product, which contains the finer particles and the majority of the water, is termed the overflow and should be discharged at or near atmospheric pressure.

The higher mass particles remain in a downward spiral path along the walls of the conical section and gradually exit through the apex orifice. This product is termed the underflow and also should be discharged at or near atmospheric pressure.

BASIC PARAMETERS FOR STANDARD CYCLONE

The definition of a "standard cyclone" is that cyclone which has the proper geometrical relationship between the cyclone diameter, inlet area, vortex finder, apex orifice, and sufficient length providing retention time to properly classify particles. As with the involuted type design, the graphs and mathematical relationships shown for proper selection and sizing of cyclones apply to the "standard cyclone" geometry.

The main parameter is the cyclone diameter. This is the inside diameter of the cylindrical feed chamber.

The next parameter is the area of the inlet nozzle at the point of entry into the feed chamber. This is normally a rectangular orifice, with the larger dimension parallel to the cyclone axis. The basic area of the inlet nozzle approximates 0.05 times the cyclone diameter squared.

The next important parameter is the vortex finder. The primary function of the vortex finder is to control both the separation and the flow leaving the cyclone. Also, the vortex finder is sufficiently extended below the feed entrance to prevent short circuiting of material directly into the overflow. The size of the vortex finder equals 0.35 times the cyclone diameter.

The cylindrical section is the next basic part of the cyclone and is located between the feed chamber and the conical section. It is the same diameter as the feed chamber and its function is to lengthen the cyclone and increase the retention time. For the basic cyclone, its length should be 100% of the cyclone diameter.

The next section is the conical section, typically referred to as the cone section. The included angle of the cone section is normally between 10° and 20° and, similar to the cylinder section, provides retention time.

The termination of the cone section Is the apex orifice and the critical dimension is the inside diameter at the discharge point. The size of this orifice is determined by the application involved and must be large enough to permit the solids that have been classified to underflow to exit the cyclone without plugging. The normal minimum orifice size would be 10% of the cyclone diameter and can be as large as 35%. Below the apex is normally a splash skirt to help contain the underflow slurry.

PERFORMANCE

In determining the proper size and number of cyclones required for a given application, two main objectives must be considered. The first is the classification or separation that is required, and the second is the volume of feed slurry to be handled. Before determining whether these objectives can be achieved, it is necessary to establish a base condition as follows:

1. Feed liquid – water at 20° C.
2. Feed solids – spherical particles of 2.65 sp gr.
3. Feed concentration – less than 1% solids by volume
4. Pressure drop – 69 kPa (10psi).
5. Cyclone geometry – "standard cyclone" as described above

CLASSIFICATION

Historically, classification has been defined as the particle size of which 1% to 3% reports to the cyclone overflow with coarser particles reporting to the cyclone underflow. Recent investigations have defined classification as the particle size of which 50% reports to the overflow and 50% to the underflow, or the so-called $D50_C$ point. Figure 3 shows the typical relationship between particle diameter and the percent recovered to underflow. The portion of the curve near the 50% recovery level is quite steep and lends itself readily to determining an accurate particle diameter. Examination of the recovery curve near the 97% to 99% recovery level shows that the curve is nearly horizontal and a small differential could change the micron diameter considerably.

[Note: The particle size shown on Figure 3 and also used for calculations in this paper is defined as the minimum particle diameter of a given size band. For example, a particle that passes a 150 mesh screen (105 microns) but is retained on a 200 mesh screen (74 microns) would actually have a diameter between 74 microns and 105 microns. For this paper, the size of 74 microns would be used for particles in this size range.]

Figure 3 also shows that the actual recovery curve does not decrease below a certain level. This indicates that a certain amount of material is always recovered to the underflow and bypasses classification. If a comparison is made between the minimum recovery level of solids to the liquid that is recovered, they are found to be equal. Therefore it is assumed that a percent of all size fractions reports directly to the underflow as bypassed solids in equal proportion to the liquid split. Then each size fraction of the actual recovery curve is adjusted by an amount equal to the liquid recovery to produce the "corrected recovery" curve shown in Figure 3.

As the $D50_C$ point changes from one application to another, the recovery curves shift, along the horizontal axis. In order to determine a single graph which represents the corrected recovery curve, the particle size of each size fraction is divided by the $D50_C$ value and a "reduced recovery" curve can be plotted, as shown in Figure 4.

Investigations have shown that this curve remains constant over a wide range of cyclone diameters and operating conditions when applied to a slurry containing solids of a single specific gravity and a typical or normal size distribution such as those encountered in most grinding circuits. Equation 1 gives a mathematical relationship which can be used to calculate the reduced recovery. This recovery, along with the bypassed solids, is used to predict the complete size distribution for the underflow product.

$$R_r = \frac{e^{4X} - 1}{e^{4X} + e^4 - 2} \qquad \text{(eq. 1)}$$

Where R_r = Recovery to underflow on corrected basis.
X = Particle diameter $/D50_C$ particle diameter.

In designing comminution circuits the objective is to produce an overflow from the cyclone which has a certain size distribution, normally defined as a given percent passing a specified micron size. An empirical relationship shown in Table 1 is used to relate the overflow size distribution to the $D50_C$ required to produce the specified separation. The relationship of this table is for typical or average grinding size distributions and may vary slightly depending upon the grinding characteristics of the ore itself.

The separation a cyclone can achieve can be approximated using Equation 2. The $D50_C$ (base) for a given diameter cyclone is multiplied times a series of correction factors designated by C_1, C_2, and C_3.

(Eq. 2)

$$D50_C(application) = D50_C(base) \times C_1 \times C_2 \times C_3$$

Table 1. Relationship of $D50_C$ to Overflow Size Distribution

Required Overflow Size Distribution (Percent Passing) of Specified Micron Size	Multiplier (To Be Multiplied Times Micron Size)
98.8	0.54
95.0	0.73
90.0	0.91
80.0	1.25
70.0	1.67
60.0	2.08
50.0	2.78

Example: Produce an overflow of 80% passing 149 microns (100 mesh).

Multiplier from Table 1 at 80% passing = 1.25.

Micron size for application = 149 microns (100 mesh).

$D50_C$ required = 1.25x149 = 186 microns for application.

This $D50_C$ (base) is the micron size that a "standard cyclone" can achieve operating under the base conditions and is given in Figure 5 or calculated from Equation 3. For example, a 25.4 cm (10 in.) diameter cyclone has a base $D50_C$ point of 24 microns.

$$D50_C(base) = 2.84 \times D^{0.66} \quad \text{(Eq. 3)}$$

Where D = Cyclone diameter in cm.

The first correction (C_1) is for the influence of the concentration of solids contained in the feed slurry. The graphical representation of this correction is shown in Figure 6 and can be calculated using Equation 4. Figure 6 indicates that the level of percent solids is extremely important in determining the proper separation, as the higher the concentration the coarser the separation. It should be pointed out that this correction is a relative measure of slurry viscosity and is affected by such things as the size of particles present as well as particle shape. For example, a feed that contains a large amount of clay would tend to shift this curve to the left and result in a coarser separation, whereas the absence of fines would shift the curve to the right and result in a finer separation. Many other

variables such as liquid viscosity also affect this correction.

$$C_1 = \left(\frac{53-V}{53} \right)^{-1.43} \quad \text{(Eq. 4)}$$

Where C_1 = Correction for the influence of cyclone feed concentration.
V = Percent solids by volume of cyclone feed.

The second correction is for the influence of pressure drop across the cyclone as measured by taking the difference between the feed pressure and the overflow pressure. Pressure drop is a measure of the energy being utilized in the cyclone to achieve the separation. It is recommended that pressure drops, whenever possible, be designed in the 40 to 70 kPa (5 to 10 psi) range to minimize energy requirements as well as reduce wear rates. This is especially true for coarse separations usually associated with primary or secondary grinding circuits.

The correction for pressure drop is shown in Figure 7 and can be calculated from Equation 5. As indicated, a higher pressure drop would result in a finer separation and lower pressure drop in a coarser separation.

$$C_2 = 3.27 \times \Delta P^{-0.28} \quad \text{(Eq. 5)}$$

Where C_2 = Correction for influence of pressure drop.
ΔP = Pressure drop in kPa.

The next correction is for the effect that specific gravity of the solids and liquid have on the separation. Since the cyclone does not actually achieve a size separation but rather a mass separation, the specific gravity of the particle is extremely important in determining the separation. It is especially meaningful in applications where the mineral has a higher specific gravity than the gangue material which allows better liberation of mineral particles at a coarser overall separation size.

It has been found that Stoke's law can be applied to determine particle diameters which would produce the same terminal settling velocity for a particle of known specific gravity in a liquid of known specific gravity as compared to a particle of 2.65 specific gravity in water. This relationship is shown in Figure 8 and can be calculated using Equation 6.

$$C_3 = \left(\frac{1.65}{G_S - G_L} \right)^{0.5} \quad \text{(Eq. 6)}$$

Where C_3 = Correction for influence of specific gravity
G_S = Specific gravity of solids
G_L = Specific gravity of liquid (normally 1.0)

The cyclone diameter, along with the three corrections of percent solids, pressure drop, and specific gravity, are the main variables necessary for preliminary sizing and selection of cyclones. Other variables, such as the vortex finder and inlet size, also have an effect on separation. For example, a larger vortex finder size would tend to coarsen the separation, whereas a smaller size would tend to achieve a finer separation. Due to this fact, most cyclones have a replaceable vortex finder with different sizes available. Vortex finder diameters vary from a minimum of about 25% of the cyclone diameter to a maximum of about 45%. The inlet area also shows the same effect as the vortex finder, but not as pronounced.

The apex size also has an effect on separation but the effect is minor unless the apex is too small and becomes a physical constraint, forcing material into the overflow.

Cyclone retention time is also a minor factor influencing cyclone performance. Within limits, increased retention time would help achieve a finer separation; whereas reduced retention time would coarsen the separation. The retention time of the cyclone can be altered by either changing the length of the cylindrical section or by changing the cone angle.

There are numerous other variables which also have an effect of separation; however, these variables are relatively minor and may be neglected for the preliminary sizing and selection of cyclones.

FLOW RATE

The second main objective which must be considered is to provide adequate cyclone capacity for the application. The volume of feed slurry that a given cyclone can handle is related to the pressure drop across the cyclone. The relationship between flow rate and pressure drop for several different sizes of standard cyclones is shown in Figure 9. As shown, the flow rate increases as the pressure drop increases. In order to utilize this graph, the pressure drop used for calculating the separation is used to determine the flow rate for the cyclone diameter which was also used for determining the separation. The flow rate is then divided into the total flow for a specific application to determine the number of units necessary.

Since the flow rate given in Figure 9 is for water rather than slurry, it should be mentioned that slurry normally increases the capacity of a cyclone over that shown for water; however, for preliminary estimates this factor can be neglected. This will result in the number of cyclones calculated being slightly higher than those actually needed. Approximately 20% to 25% standby cyclones are recommended for operational as well as maintenance flexibility.

The vortex finder size and inlet area of a cyclone also have an effect on the volumetric flow rate that a given cyclone can handle. Larger vortex finders or inlet areas would increase the capacity, whereas smaller vortex finders or inlet areas would decrease the capacity. The shaded area in Figure 9 corresponding to each standard cyclone gives the approximate range of capacity for each cyclone.

APEX SELECTION

The proper selection of apex size is critical to proper cyclone performance. For each application a circulating load is normally given which establishes the amount of solids which must pass through the cyclone underflow. Experience has shown that an underflow density of 50% to 53% solids by volume is typical for primary grinding circuits, whereas an underflow density of 40% to 45% solids by volume is normal for regrind circuits. Therefore, an underflow density can be assumed which establishes the total flow rate that must report through each cyclone apex. Figure 10 shows the approximate flow rate for a given diameter apex orifice.

OPERATIONAL AND DESIGN CONSIDERATIONS

One of the most important considerations is to insure that cyclones are installed properly. A detailed list of "Do's and Don'ts" is given in a later chapter.

FEED PIPING AND DISTRIBUTION

A most important consideration for a given cyclone system is proper delivery of the slurry to the cyclone or cyclones. It has been found that a pipe size which produces a line velocity of 200 to 300cm/sec (7 to 10 ft/sec) is high enough to prevent particles from settling, even in horizontal sections, but low enough to minimize wear. Normally for a single cyclone installation the inlet pipe size of the manufacturer's recommendation produces a velocity in this area.

If the slurry is to be distributed to a number of cyclones operating in parallel, extreme care should be given to the design of the distribution system, and a radial type of manifold is recommended. This is a system where the cyclones are fed from a central circular chamber. When properly designed the central chamber becomes a mixing area and the line velocity should be lowered to approximately 60 to 90 cm/sec (2 to 3 ft/sec). This will help insure that each cyclone is fed with the same slurry concentration as well as the same particle size distribution and also will reduce wear rates. Using the radial manifold also makes it easier to install standby cyclones.

Should an inline type manifold be utilized, the cyclones do not receive good distribution. It is typical that the high mass particles or coarser particles tend to pass the first cyclones and report to the final cyclone. This results in the last cyclone receiving a higher feed concentration of coarser particles, which accelerates the

wear of the last cyclone as well as produces a coarser separation due to the higher feed density. Also, the last cyclone, once shut off, becomes difficult to restart because the solids will tend to pack into the feed pipe.

For applications where the separation is not critical or one in which the feed concentration is extremely low, an inline manifold is acceptable and is much less expensive than the radial type.

MATERIALS OF CONSTRUCTION

Cyclone Construction varies greatly from one manufacturer to another, but the majority of the designs includes metal housings with replaceable liners with replaceable liners with the most suitable liner material varying from one application to another. It is also common to utilize several different lining materials within the same cyclone to optimize wear characteristics.

Natural gum rubber is the most common material utilized due to its relatively low cost, excellent wear, ease of handling, and it is not fragile. Applications where gum rubber is not suitable are those where the temperatures exceed 60°C or there are large amounts of hydrocarbons present in the slurry such as oil or other detrimental chemicals.

Ceramic materials have found acceptance as cyclone liners for the apex orifice as well as other areas which exhibit severe abrasion. These include areas such as the lower cone liner and vortex finder.

Nihard has also proven to be an acceptable wear material, especially for vortex finders and other areas which require strength as well as abrasion resistance.

Other elastomer materials such as neoprene and nitrite are also utilized when hydrocarbons are present or when the temperature exceeds 60°C. Urethane has found acceptance, especially in areas where the solids are relatively fine.

PRESSURE DROP CALCULATIONS

As mentioned earlier, the pressure drop across a cyclone is measured by taking the difference between the feed pressure and the overflow pressure. If the overflow is discharged at near atmospheric pressure as

recommended, the feed pressure is the same as the pressure drop.

Cyclone selection provides the pressure drop required, and for pump calculations this must be converted to meters of slurry which can then be added to the static and friction heads to determine the total dynamic head for the pump. Equation 7 is used for conversion of pressure drop to meters of slurry.

$$M = \frac{\Delta P \times 0.102}{G} \qquad \text{(Eq. 7)}$$

Where M = Meters, slurry.
ΔP = Pressure drop, kPa.
G = Sp gr of slurry.

As stated, it is recommended that both the overflow and underflow products be discharged at atmospheric pressure. Should the overflow be discharged against a positive head, some of the fluid which normally reports to the overflow is forced to report to the underflow. This does not have a major effect on classification but does increase the amount of bypass solids and reduces underflow density.

Should the overflow be discharged at a point lower than the feed entrance, a possible siphon can be established which would cause a breakdown in classification and could bring larger particles into the overflow. A large siphon effect could actually dislodge a worn liner which in turn would plug the overflow piping. Siphons can be prevented by installing a vent pipe on the overflow piping of each cyclone.

The underflow should also be discharged at or near atmospheric pressure. Should the underflow be discharged at a negative pressure, the effect would be similar to a positive pressure at the cyclone overflow. If the underflow is discharged against a positive pressure, the amount of flow is reduced and a larger apex must be selected in order to insure that the classified solids can discharge freely.

SUMP/PUMP DESIGN

Another chapter covers the selection and sizing of slurry pumps and should be consulted for more detailed information concerning sump/pump design. Specifically

regarding cyclone applications, the feed slurry being delivered to a cyclone should be as steady as possible with regard to both volumetric flow rate and slurry density. Unsteady feed conditions such as severe pump surging or extreme variations in slurry density are very detrimental to good cyclone performance. In general, a sump/pump system for a cyclone application should have a sump with as much depth as possible and a minimum cross-sectional area consistent with the pump manufacturer's recommended retention time. A sump of this design will normally eliminate pump surging by allowing small variations in sump level well above the minimum pump suction level. The small cross-sectional area will reduce the buildup of solids in the bottom of the sump and help prevent large sections of the settled solids to slough into the pump suction and plug either the cyclone feed line or the cyclone apex. Therefore, a tall sump with a small cross-sectional area provides much smoother operation.

APEX DISCHARGE PATTERN

An Important part of cyclone operation is being able to observe the type of pattern that the cyclone apex is producing. An apex operating at atmospheric pressure should produce a cone shaped discharge with an angle of 20° to 30° and a hollow center. If the cyclone consistently produces a high angle cone spray, the apex orifice should be reduced in size to maximize the slurry density being discharged. On the other hand, should the cone spray be void of the hollow center and resemble a "rope", then the apex is too small and oversize material may be reporting to the cyclone overflow. In this case, a larger apex orifice should be installed.

EXAMPLE PROBLEM

Example – Primary Grinding Circuit

Problem: Select the proper size and number of cyclones for a rod mill/ball mill circuit where new feed to the rod mill is 250 metric tons per hour (MTPH) solids. Both mill discharges join together at cyclone feed sump and are pumped to cyclones. Overflow is to be 60% - 200 mesh (74

microns) at a minimum of 40% solids by weight. Underflow becomes ball mill feed. Specific gravity of solids is 2.9 and estimated circulating load is 225%.

STEP 1. Calculate material balance from known information. Overflow must be 250 MTPH at 40% solids.

Overflow:

MTPH solids = 250
MTPH water = 375
MTPH slurry = 625
% solids, wt = 40
Sp gr slurry = 1.355
1/sec slurry = 128 (2030 USGPM)
  (1/sec = liters per second)

Underflow: (based on 2.25 x overflow):

MTPH solids = 562
MTPH water = 187
MTPH slurry = 749
% solids, wt = 75 (assumed at
Sp gr slurry = 1.966
1/sec slurry = 106 (1676 USGPM)

Feed (sum of overflow and underflow):

MTPH solids = 812
MTPH liquid = 562
MTPH slurry = 1374
% solids, wt = 59.1
Sp gr slurry = 1.632
1/sec slurry = 234 (3706 USGPM)
% solids, vol. = 33.2 (necessary for
               separation
               calculations)

STEP 2. Calculate required $D50_C$ for specified overflow of 60% passing 74 microns.

From Table 1:

Multiplier at 60% passing = 2.08
Specified micron size = 74 microns
$D50_C$ (application) = 2.08x74 = 154 microns

STEP 3. Calculate cyclone diameter required.

First, calculate C_1, C_2 and C_3:

C_1 = Correction for feed density = 4.09

(from Figure 6)
C_2 = Correction for ΔP = 1.1 (from Figure 7). Pressure drop assumed at 50 kPa (7 psi) which would be low energy and good maintenance.
C_3 = Correction for sp gr solids = 0.93 (from Figure 8)

Second, calculate cyclone diameter:

$D50_C$ (application) = $D50_C$ (base) x
$$C_1 x C_2 x c_3$$
(from Equation 2)
154 = $D50_C$ (base) x 4.09xl.lx0.93
$D50_C$ (base) = 37 microns

Therefore, from Figure 5 use 51 cm cyclones (20 in.).

STEP 4. Calculate number of units required.

From Figure 9:

Flow rate for 51 cm cyclone at
50 kPa = 40 1/sec
Total feed flow = 234 1/sec

Therefore, number of units = 234/40 = 5.85 or use 6 cyclones in operation.

STEP 5. Calculate proper apex size.

Total underflow = 106 1/sec
Underflow per unit = 106/6 = 18 1/sec
From Figure 10 each apex should be
9.5 cm (3 ¾ in.)

CONCLUSION

It has been the intent of this paper to provide a method for determining the proper size and number of cyclones required for the design of a comminution circuit. The parts of a cyclone and the geometry which comprise a standard cylone were described. Cyclone performance, as well as the fundamental variables of cyclone diameter, feed concentration, pressure drop, and specific gravities, has been explained. Both graphical representations and mathematical relationships have been given for each of the fundamental variables, and cyclone and apex capacities have been presented.

Other design and installation information such as feed distribution systems, materials of construction, pressure drop calculations, sump/pump design, and apex pattern were discussed. An example problem for a primary rod mill/ball mill grinding circuit was also given.

Although the method for determining the proper size and selection of hydrocyclones in this paper has proven to be quite accurate, the engineer should still be aware of the fact that variations in ore characteristics have an effect on cyclone performance. In cases where the slurry characteristics are questionable, pilot plant information should be used to provide more accurate cyclone sizing and selection.

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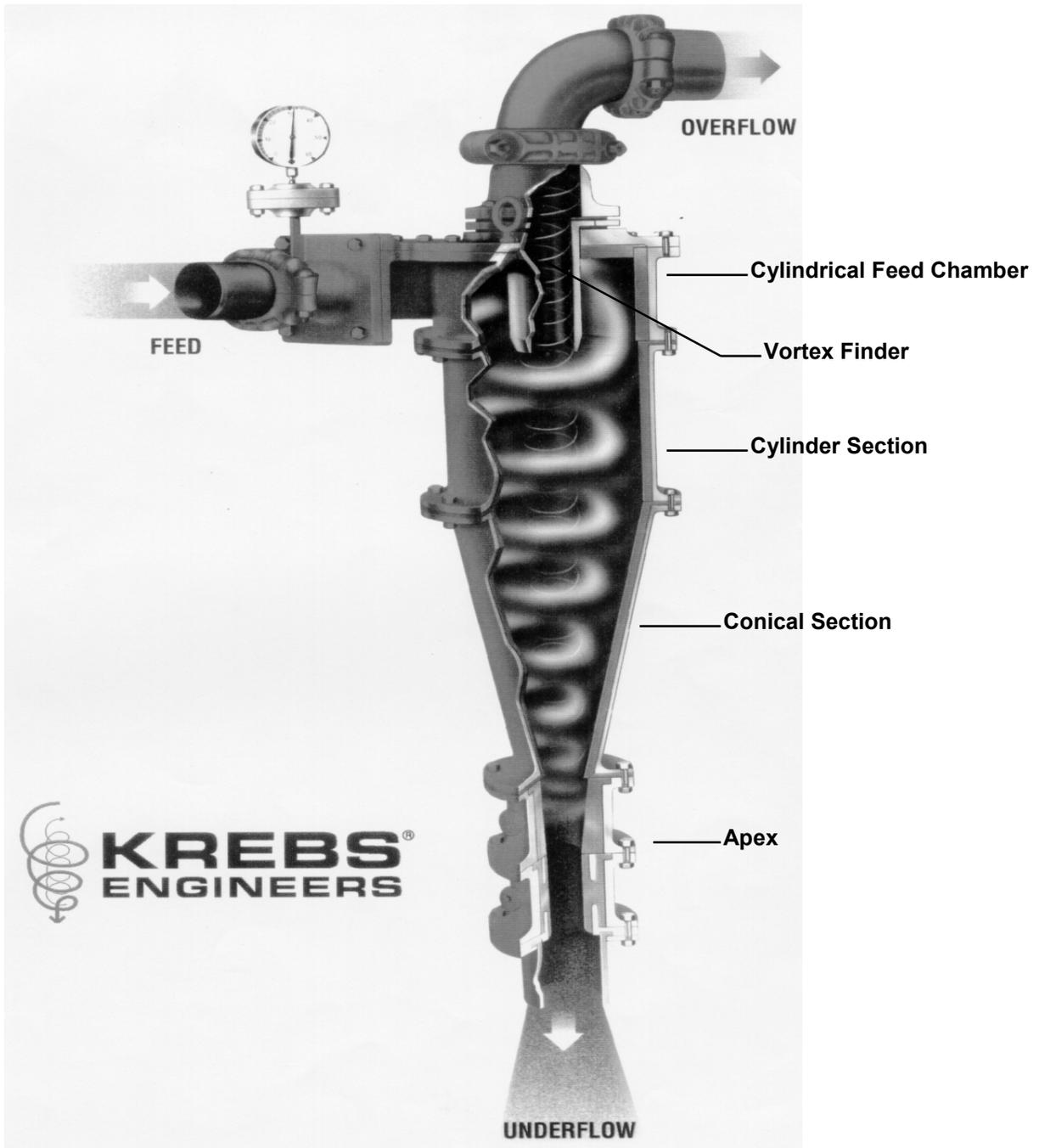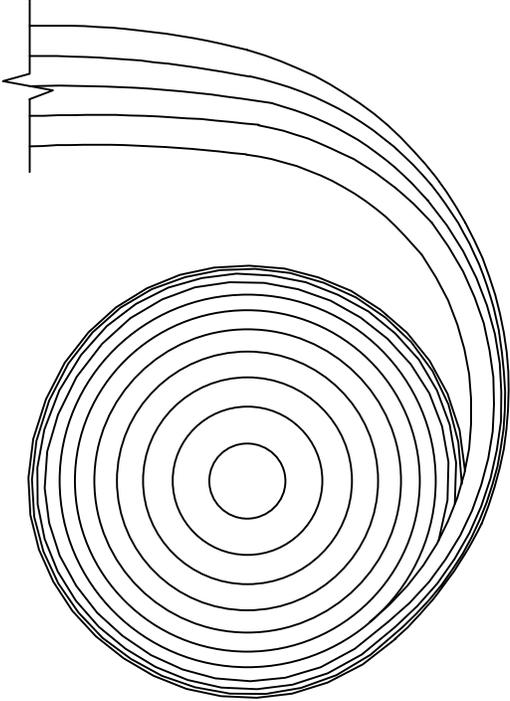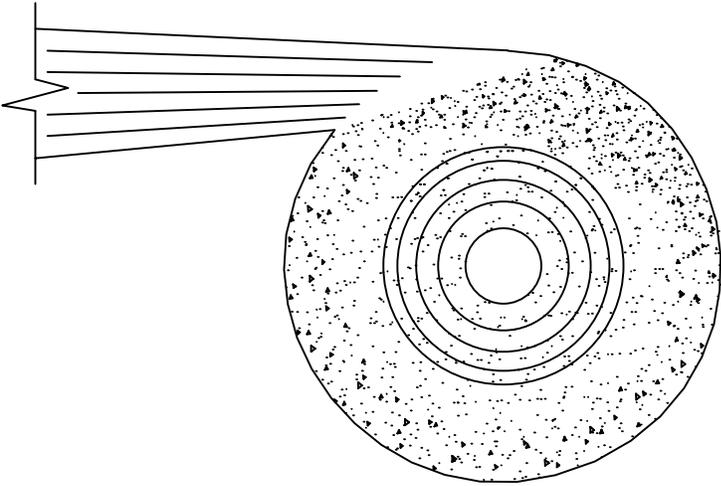
FIGURE 1
CYCLONE CUTAWAY

OVERFLOW

FEED

Cylindrical Feed Chamber

Vortex Finder

Cylinder Section

Conical Section

Apex

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UNDERFLOW

Figure II
Involuted Feed vs. Tangential Feed

Involuted Feed

Tangential feed

Graph I
Particle Diameter VS. Particle Recovery

Particle Recovery (% to Underflow)

Particle Diameter (Microns)

Actual
Recovery

D50 Point

Corrected
Recovery
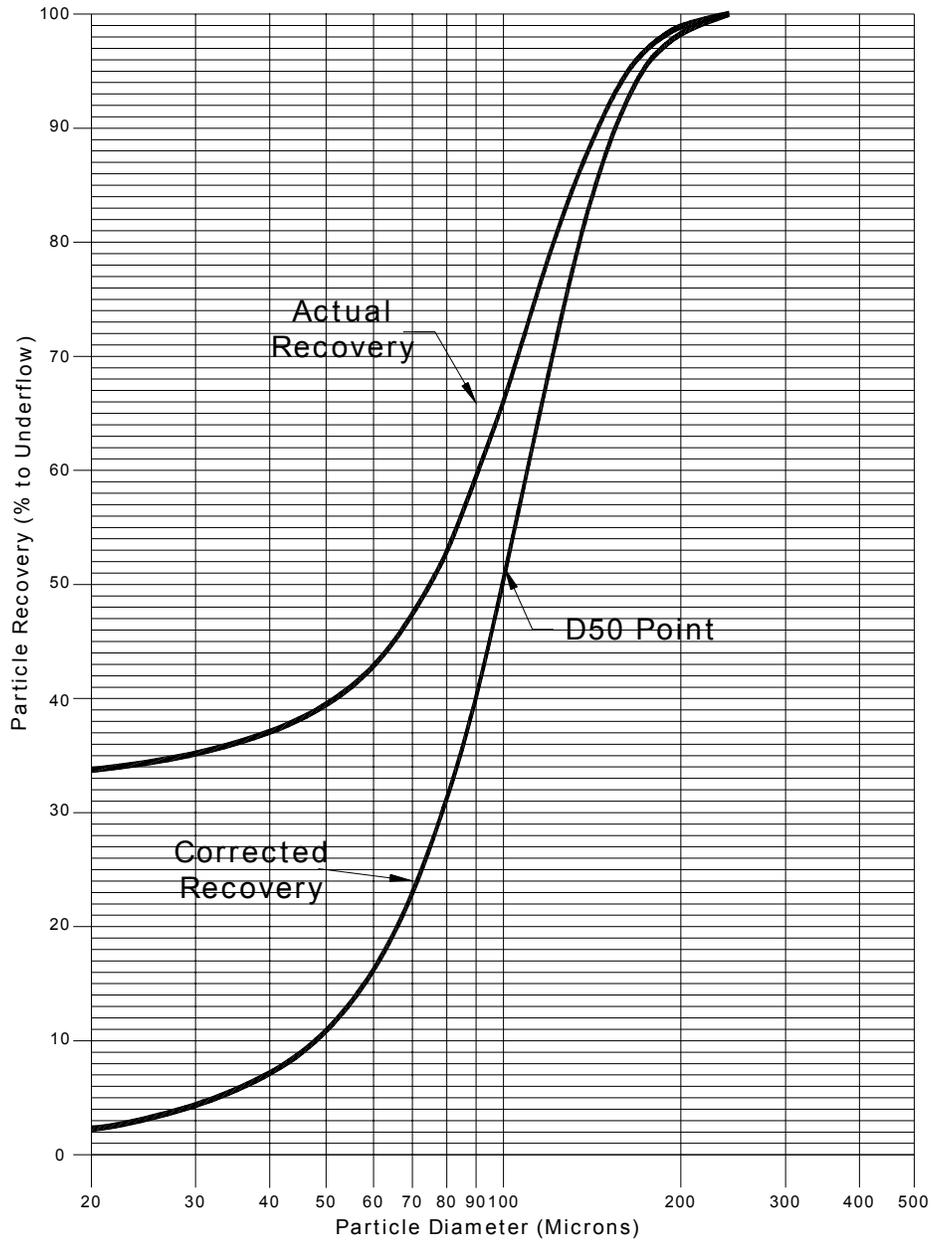
Figure 3. Particle Recovery Curves

Graph II
Reduced Recovery
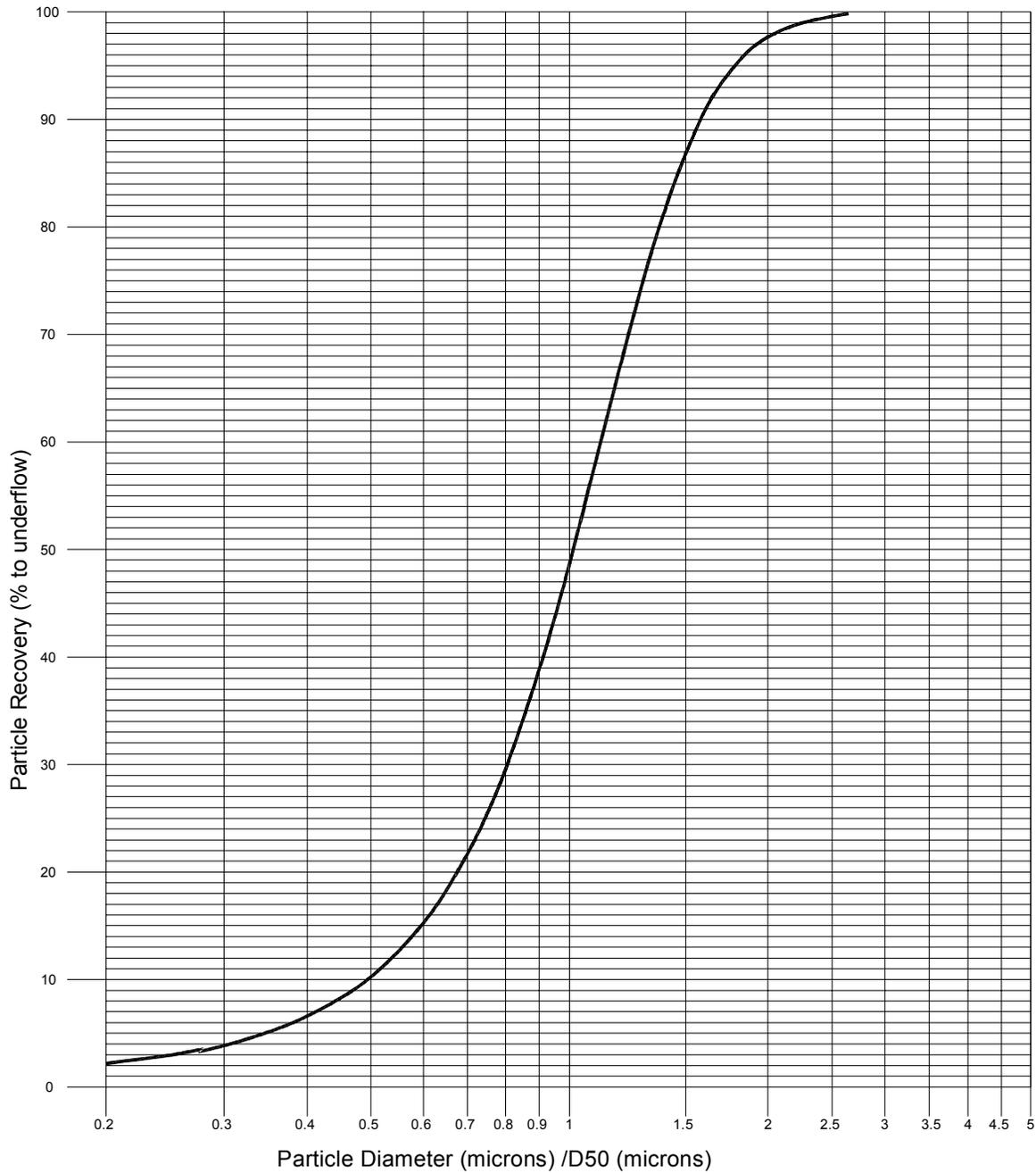
Figure 4. Reduced Particle Recovery Curve

Graph III
Cyclone Diameter VS. D50
(For "Typical" Cyclones)
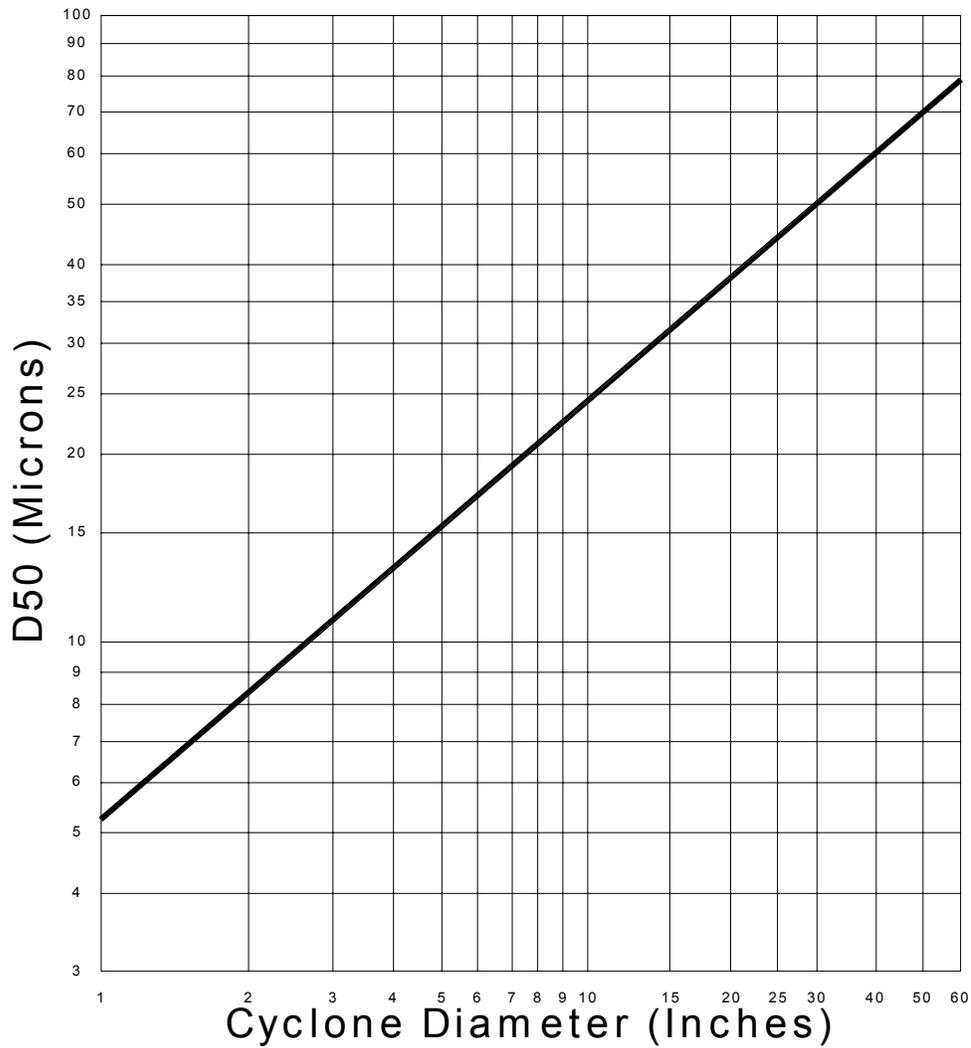
Figure 5. Cyclone Diameter versus D50_c for Standard Cyclone

Graph IV
Correction For Feed Concentration
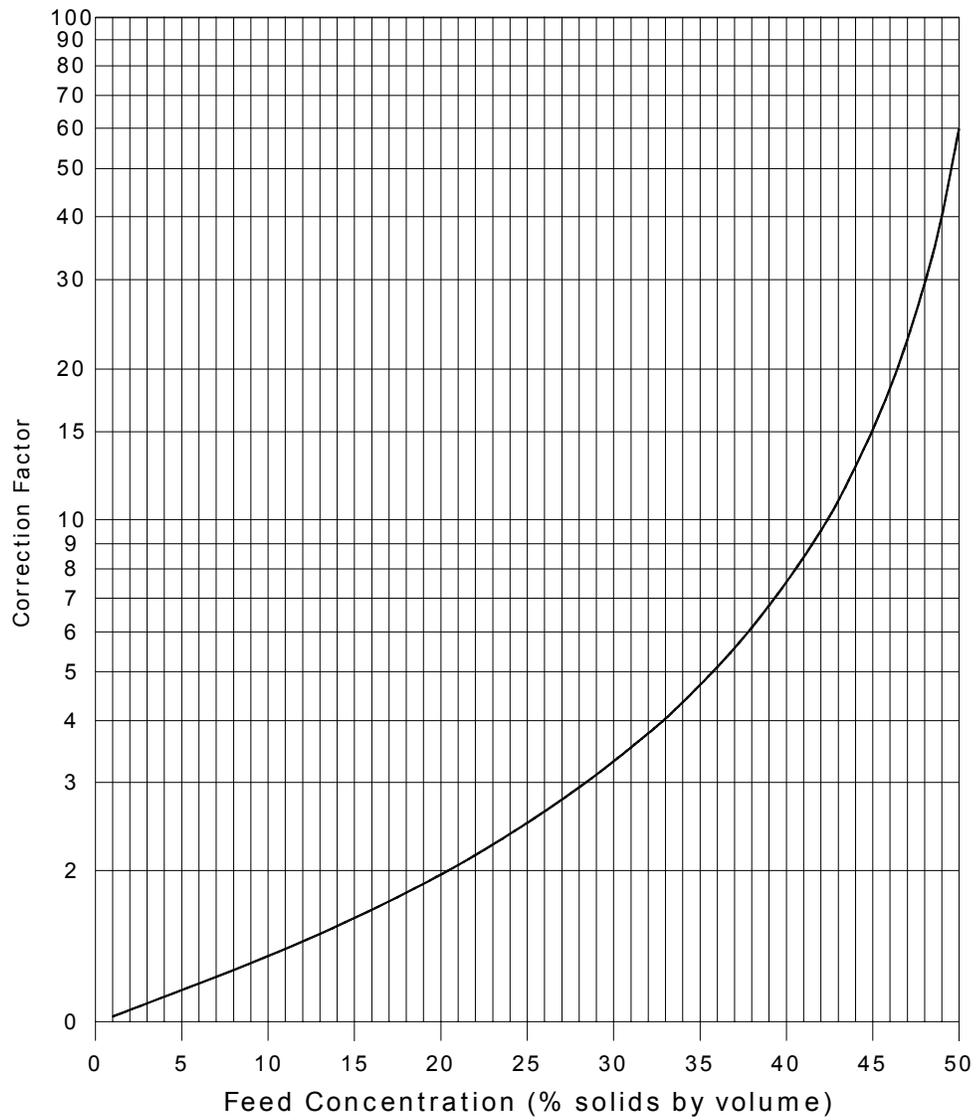
Figure 6. Influence of Feed Concentration on Separation

Graph V
Correction For Pressure Drop
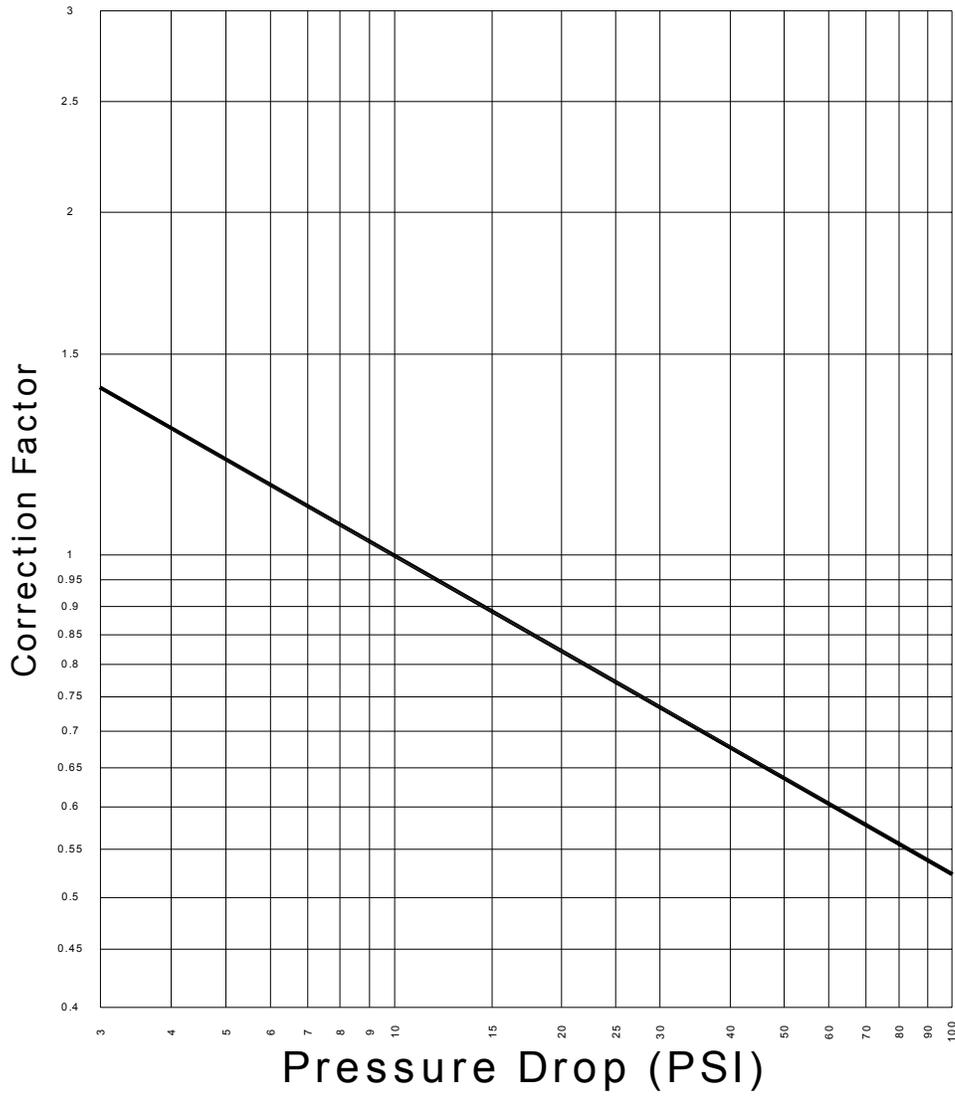
Figure 7. Influence of Pressure Drop on Separation

Graph VI
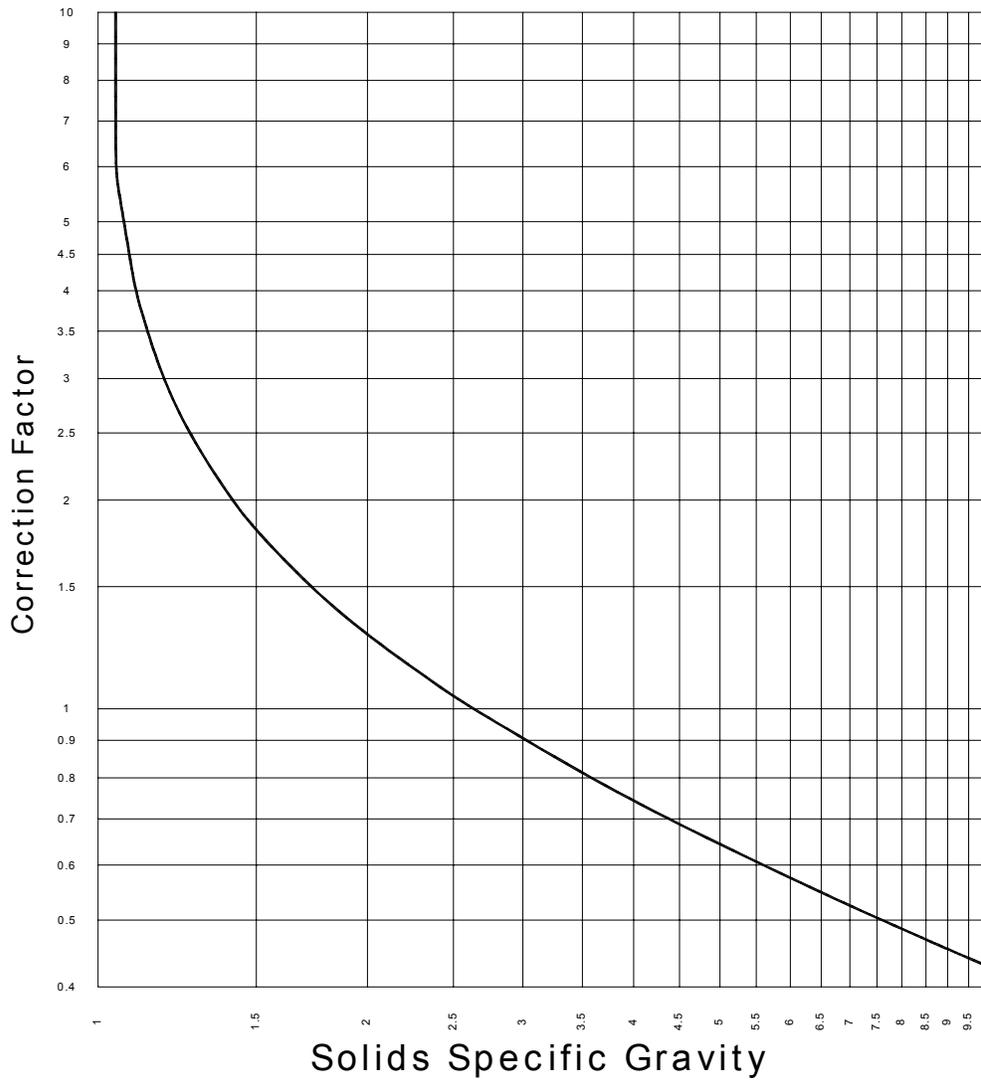## Correction for Solids Specific Gravity
(in water)

Figure 8. Influence of Solids Specific Gravity on Separation

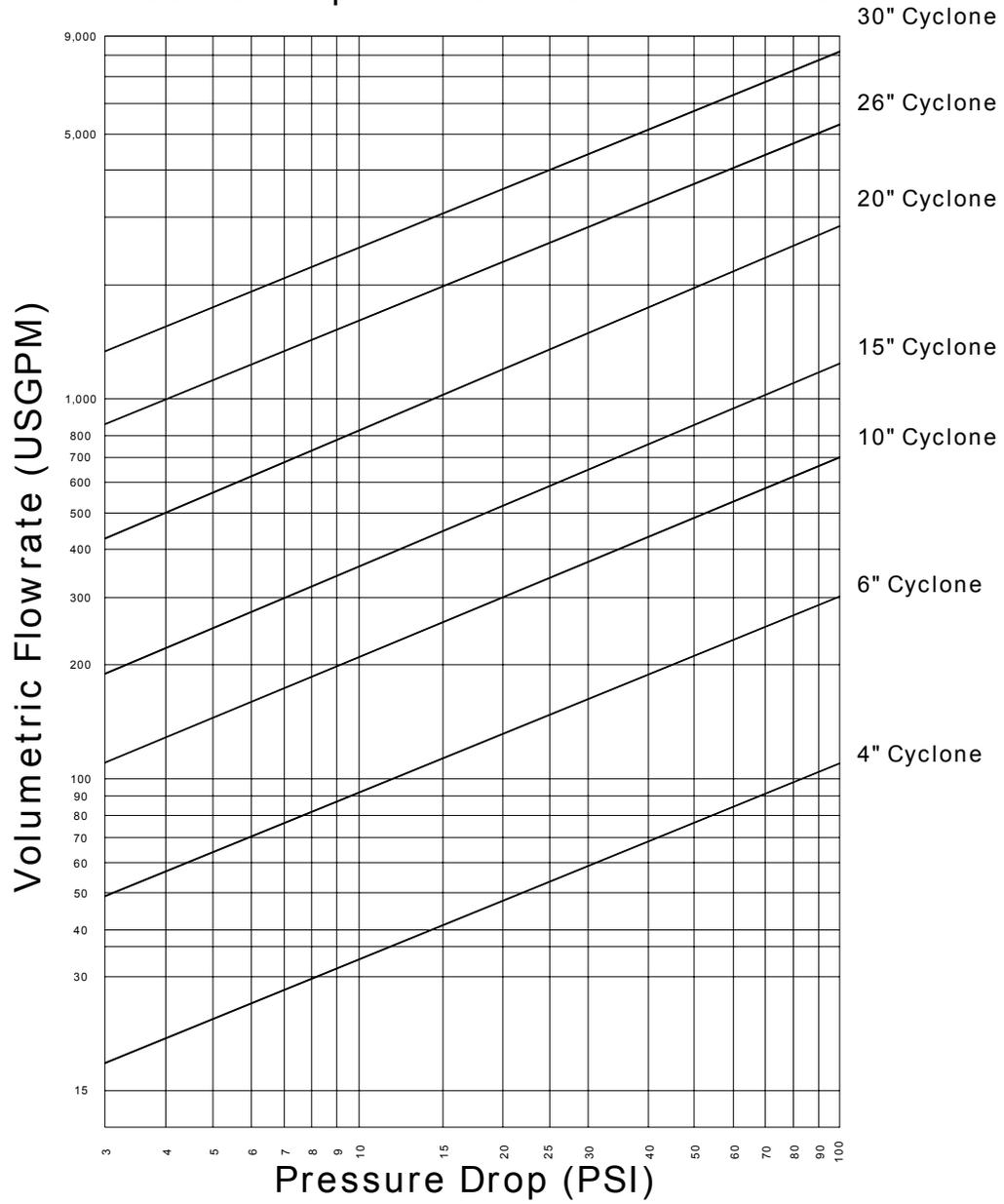# Graph VII
Pressure Drop VS. Volumetric Flowrate

Figure 9. Water Capacity for Standard Cyclone
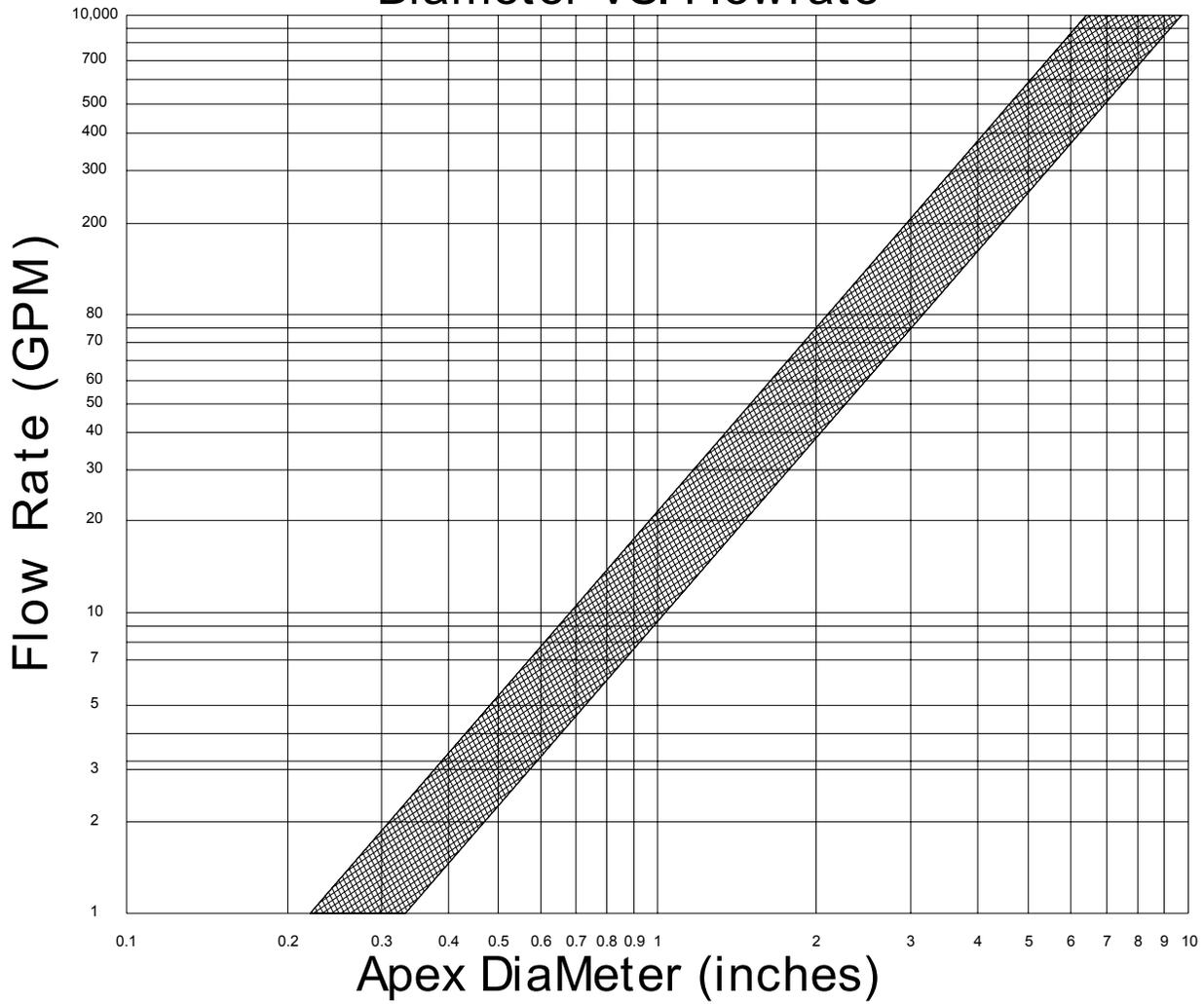
Graph VIII
Apex Capacity
Diameter VS. Flowrate

Figure 10. Apex Capacity Curve