D.R. Woods
Process Design and Engineering Practice
Prentice Hall, 1995

Minichapter 5

Selecting Options for the Separation of Components from Heterogeneous

Often we need to separate or concentrate species. They may occur in a single homogeneous phase (like a glass of Coke that is to be separated into components); they may occur as an intimate mix of two or more different phases (like a mixture of sand and gold or a mixture of sand and water). If the starting mixture is a heterogeneous phase, then we start with the ideas given in this chapter. If the initial mixture is homogeneous, then we start with the ideas in Chapter 4.

As with homogeneous phase separation, to separate a heterogeneous mixture, we primarily exploit the differences in properties among the different species. Having said that, we have some very sloppy guidelines for initially selecting separation equipment that:

- consider the types of phases present: gas-liquid; liquid-liquid, etc.
- make an initial selection based on feed concentration and particle size.

Later, as we consider the options in more depth, we consider the types of property differences that can be exploited and the types of product required. In this chapter we focus on how to select feasible equipment.

5.1 OVERVIEW TO SELECTING OPTIONS FOR SEPARATIONS

In selecting separation options, we should keep an open mind. Tradition, as exemplified by this text, may suggest certain options. However, new developments are occurring rapidly. Individuals and companies have their "favorite" separation technique and thus may prefer to work with the familiar. The purpose of this textbook is to provide shortcut methods that will allow you to rough-size many options before deciding. Hence, in selecting options, choose about three to consider in more detail for any separation.

Next, think of combinations of options. Perhaps a screen followed by sedimentation is an appropriate choice for a liquid-solid system.

The general criteria for selecting options include the properties of the species, the feed and product constraints, and the characteristics of the equipment.

5.1-1 A First Selection: Exploit the Size and Concentration for the System

For heterogeneous systems, the type of system has a major impact on what options to consider. Hence, it is appropriate first to identify whether we are separating:

- a gas-liquid system,
- a gas-solid system,
- a liquid-liquid system,
- a liquid-solid system, or
- a solid-solid system.

Once this is established, an initial guess may be made by considering the size of the "particulate" phase and the feed concentration. To some extent this focus on the particle size *early in the screening process* is misleading because we may need to exploit differences in properties other than size in order to make an option work. (For example, a big and small particle of different materials might have the same settling velocities; hence, sedimentation could not be used.) Nevertheless, particle size and concentration give us an initial idea about the probable options for different systems.

The particles in any system can be drops, bubbles, mist, dust, gas, liquid, or solid; they can be big—like a bottle—or small—like suspended clay particles that make drinking water look murky. In the context of separation we usually think of particles as having a size greater than about 0.1 μm.

A. Separating Gas-Liquid Systems. Figure 5–1 shows sketches of the equipment options usually available to separate gas-liquid mixtures: cyclones, knock out pots, scrubbers, and burners. Figure 5–2 illustrates the ballpark region when the different types might be applicable. Actually, since gas-liquid separations are surprisingly difficult, most of our effort is spent trying to prevent the unwanted formation of mists or bubble dispersions. For example, when liquid is drained from a tank, vortex breakers are put in the exit pipe to prevent the overhead gas vapor from being caught in the vortex and entrained. Demisters mainly function to increase the size of drops or bubbles so that the separation can occur rapidly by the action of gravity on the drops.

When a separation is required, cyclones can be used but they have not always worked satisfactorily. The most common device is a knock out pot, which provides sufficiently slow gas velocity for the drops to settle out by gravity. Thus, this exploits difference in settling velocity. For low concentrations, this separation can be achieved by baffles. The terms in brackets in this figure refer to the removal efficiency.

B. Separating Gas-Solid Systems. Figure 5–3 lists options for this type of separation. These include cyclones, electrostatic precipitators, scrubbers, and bag filters. Figure 5–4 illustrates regions of applicability for removing a dust from a gas. This suggests that the particle size seems to be the major variable, since for both wet scrubbers and electric precipitators almost any inlet loading can be handled. The smaller the particle size to be removed, the greater the energy requirement.

Example 5–1: A stream contains 10 g/m^3 of a 20 μm dust. What options might we consider?

An Answer: A relatively high-energy cyclone (since the point is in the lower portion of the application region), a relatively low-energy bag filter (since the point is near the top of the application region), and a low-voltage electrostatic precipitator.

Comment: The lower one is in any region, the more energy is required.

Another feature to note is that most devices are about 90 to 99% efficient in *mass* removal. The part that is not removed will be the smaller-sized particles. Thus, one can use Figure 5–4 by moving to the left *one* cycle on the abscissa to obtain the concentration and go to the limit of the device application region. Read the particle size from the ordinate.

Example 5–2: An inlet gas stream has 1 g/m^3 of dust of about 1 μm diameter. What device is appropriate and what are the characteristics of the exit gas leaving the separator?

An Answer: From Figure 5–4, we could use a high voltage electrostatic precipitator, a moderate-energy venturi scrubber or a high-energy bag filter. If we used the electrostatic precipitator, the exit stream might be about 10^{-1} g/m^3 of about 0.1 μm particles.

C. Separating Liquid-Liquid Systems. Liquid-liquid systems can be separated by decanters, hydrocyclones, flotation, deep bed filtration. Figure 5–5 illustrates the equipment in general. Figure 5–6 shows the options. The usual size of drops in an oily emulsion or dispersion is about 200 μm. The basic device is gravity settling or decantation. This can be augmented by adding coalescence promoters, electrodes, and/or plates. A hydrocyclone or centrifugal device exploits the same general principle. As the concentrations and size become smaller, the options shift to coagulation (increasing the size of the particles by clustering the particles together to form a larger one), entrapment (such as filters, solvent extraction, and flotation) combinations. Combustion and high gradient magnetic separation (HGMS) are options for very dilute and very small systems.

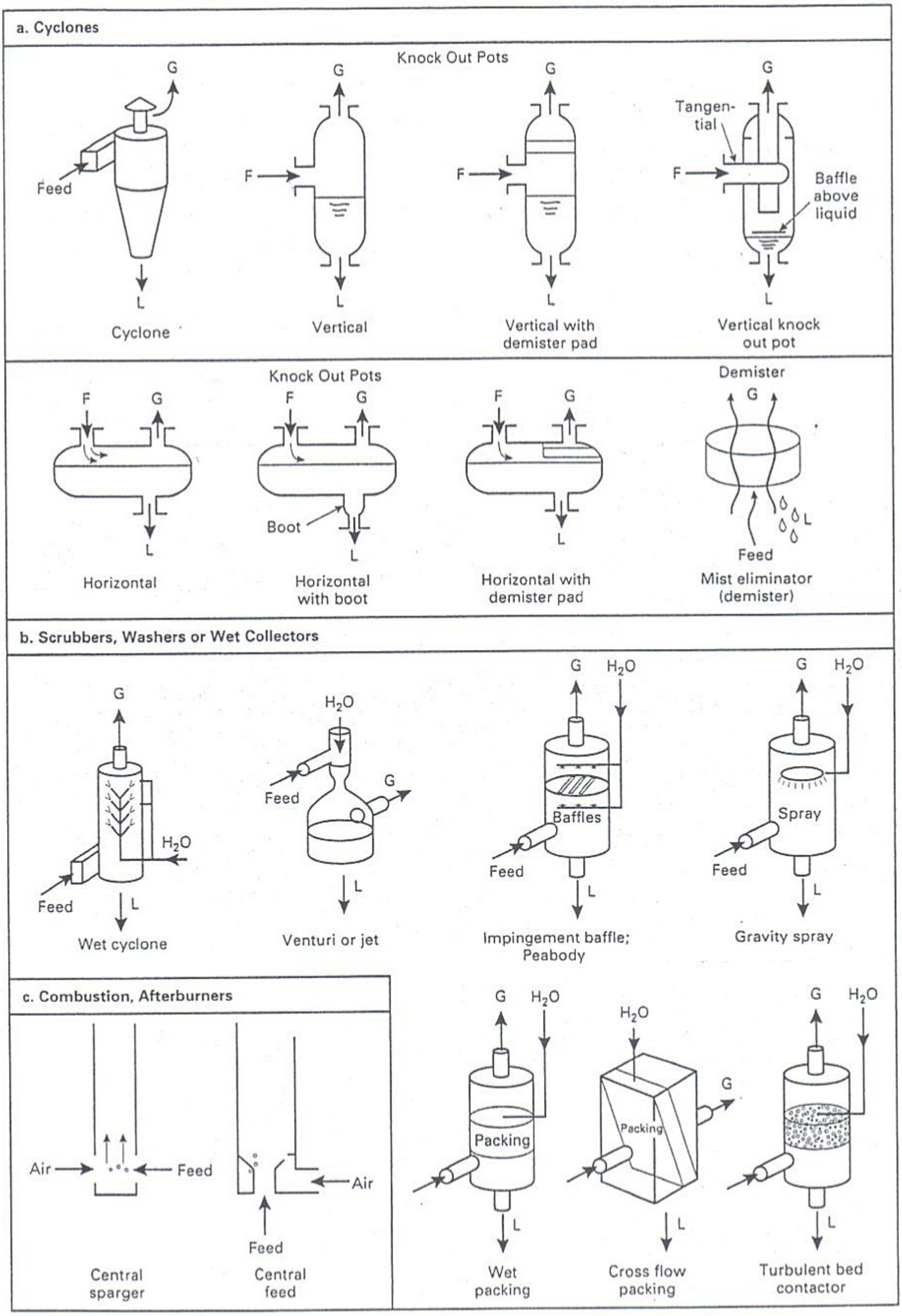

Figure 5–1 Equipment Options for Separating Gas-Liquid Systems

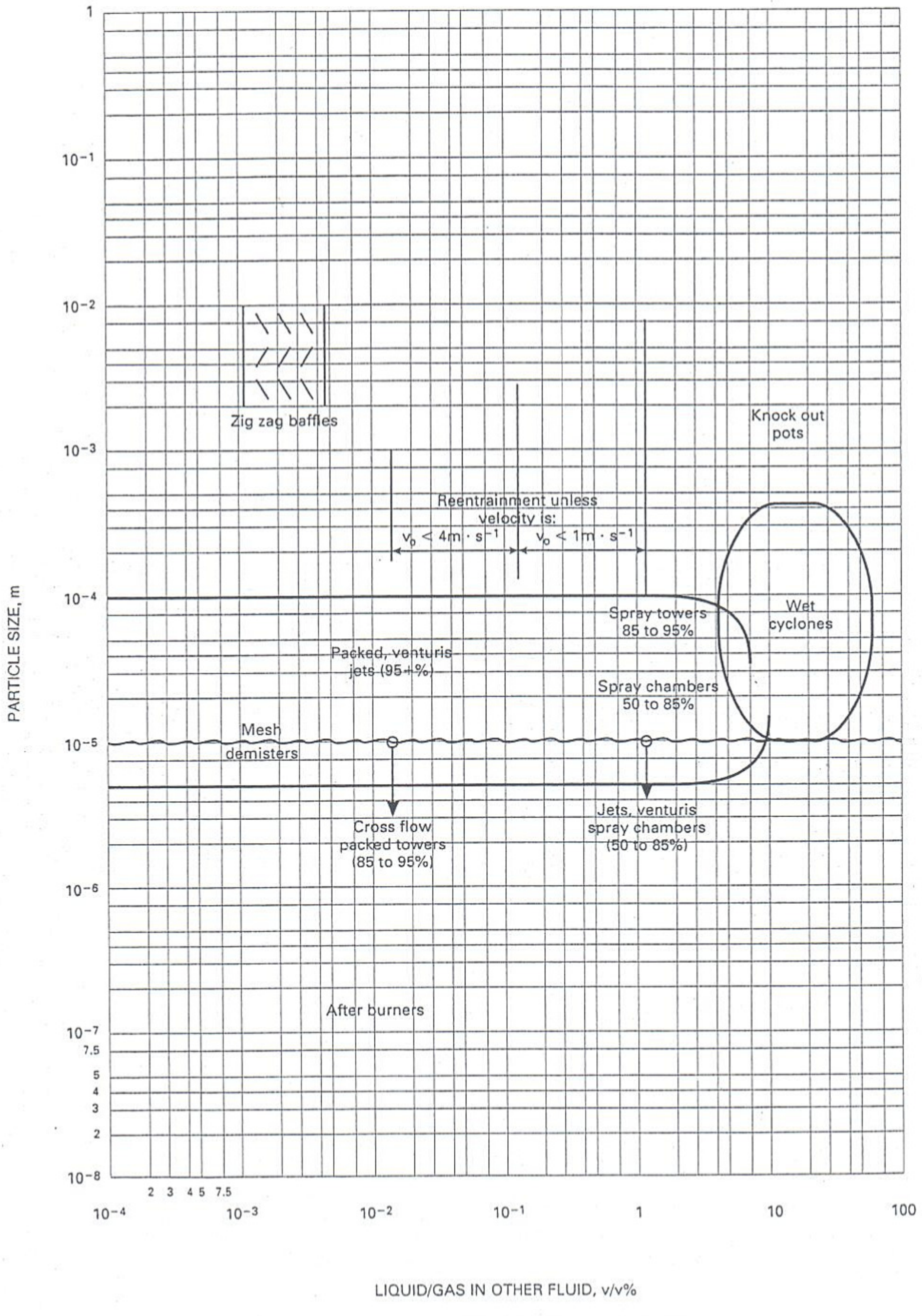

Figure 5–2 General Regions of Applicability for Gas-Liquid Separations: Based on Particle Size and Concentration (Bracketed Terms = % Removal Efficiency)

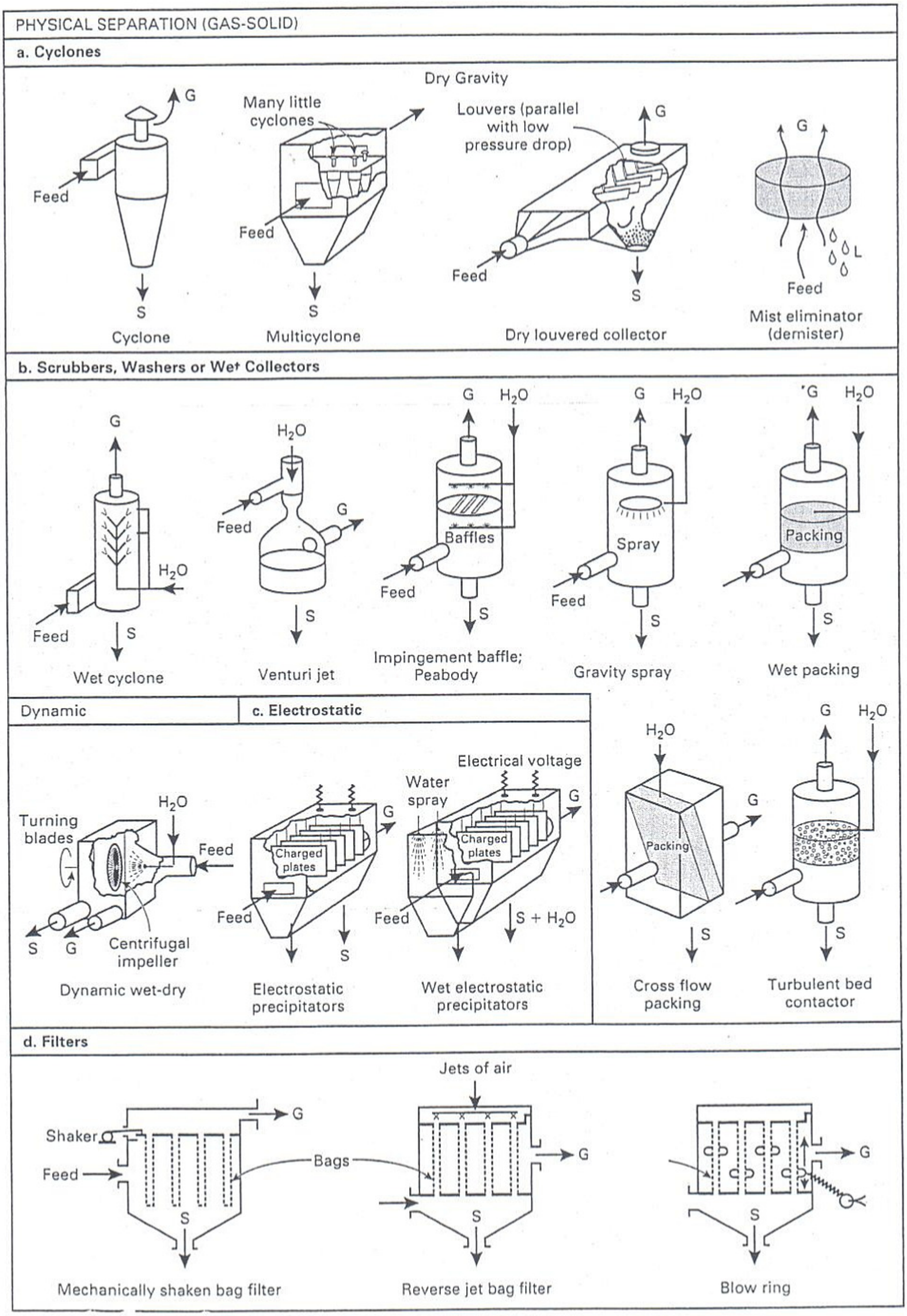

Figure 5–3 Equipment Options for Separating Gas-Solid Systems

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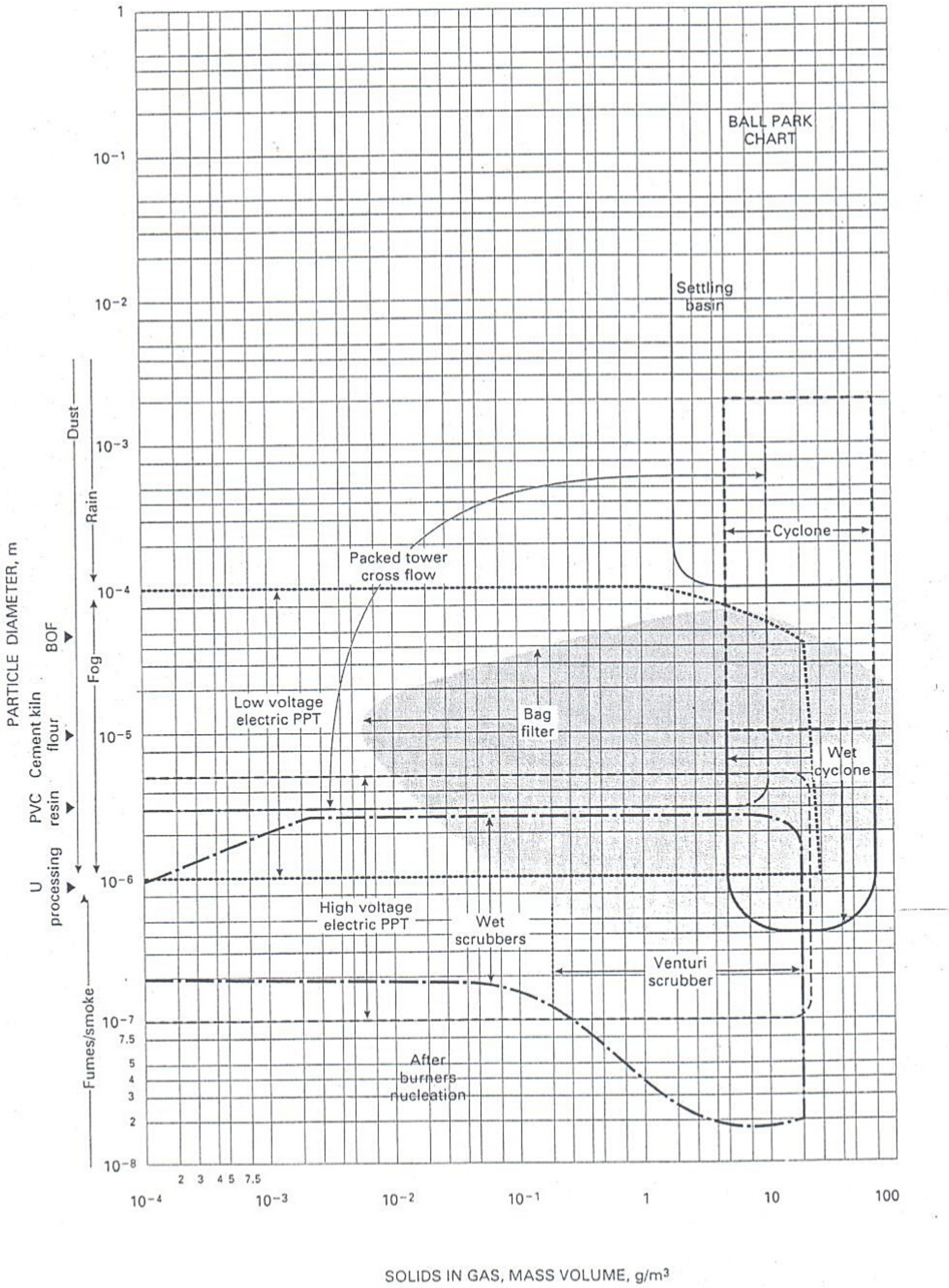


Figure 5–4 General Regions of Applicability for Gas-Solid Separations: Based on Particle Size and Concentration

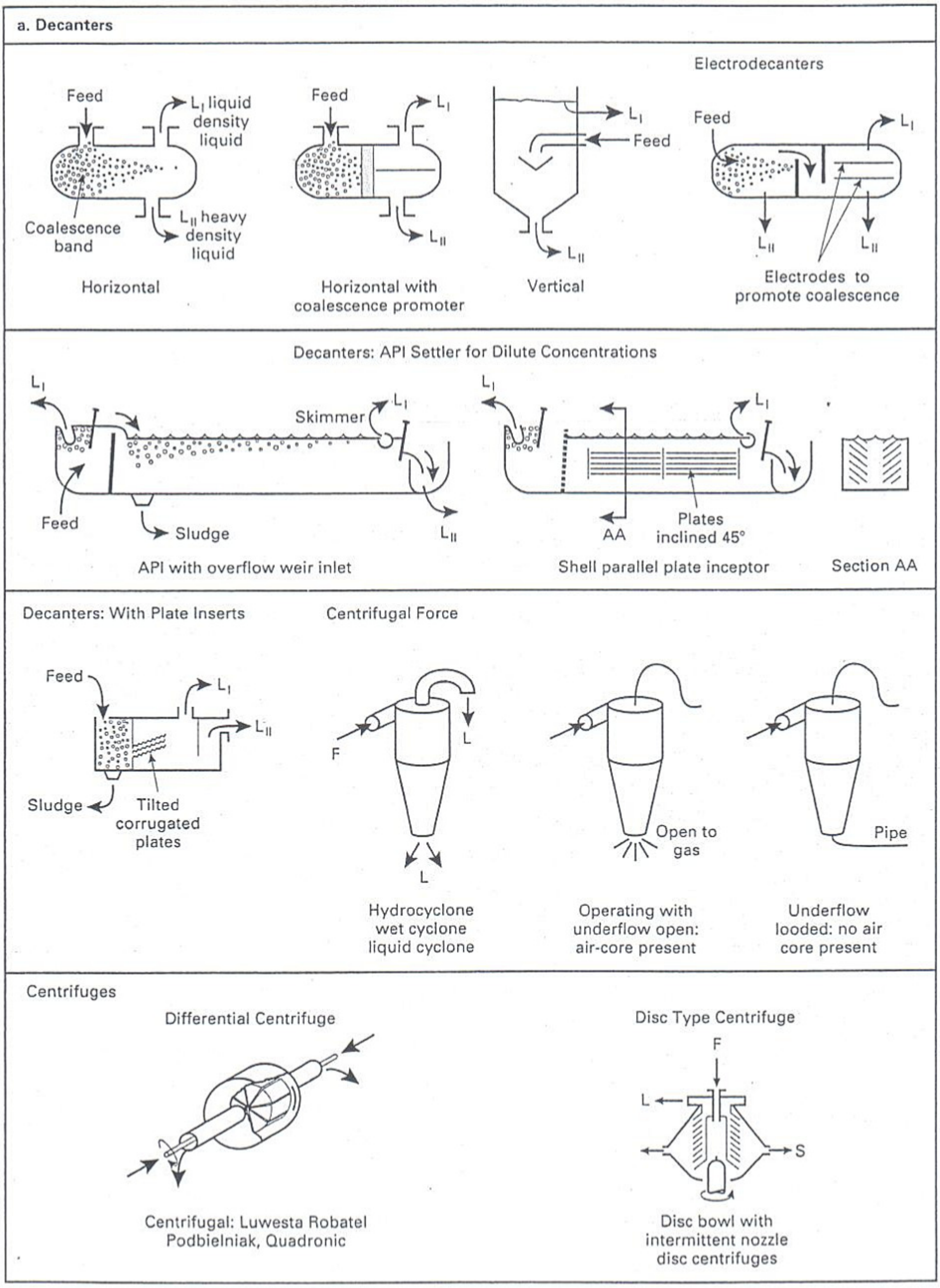


Figure 5–5 Equipment Options for Separating Liquid-Liquid Systems
a) Decanters
b) Deep Bed Filtration; Membrane
c) DAF; Coagulation; High Gradient Magnetic Separation

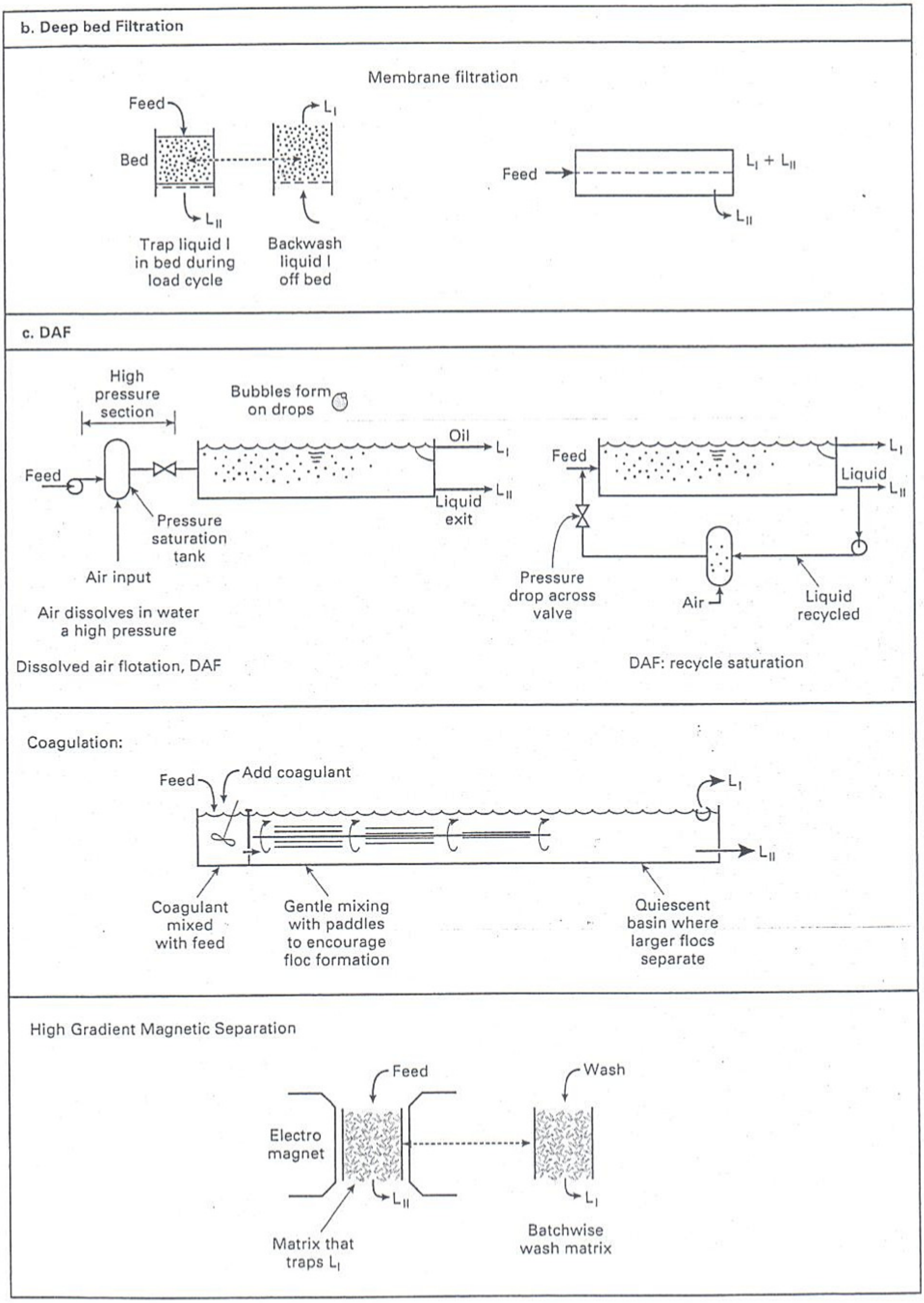


Figure 5–5 (Continued)

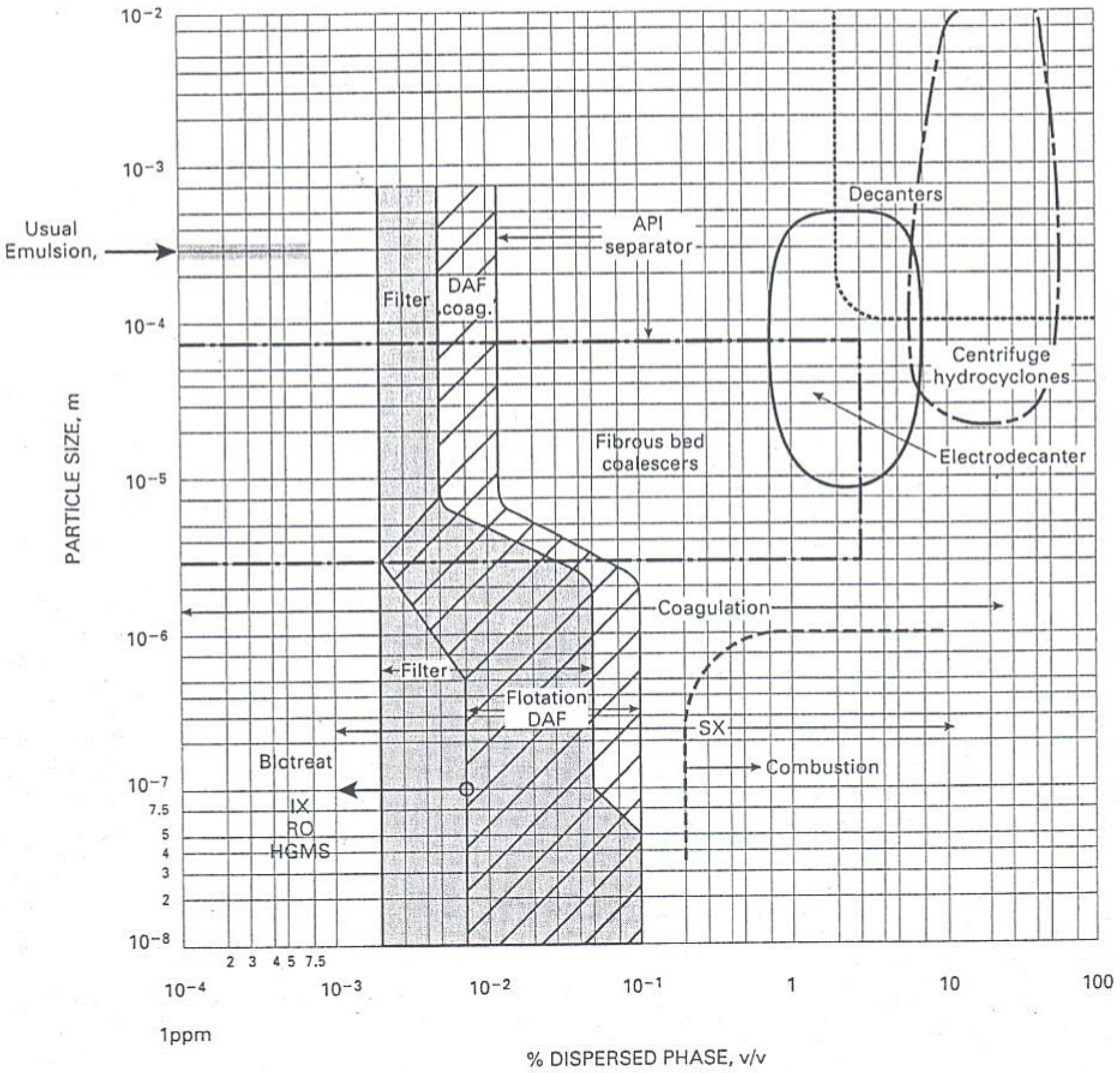


Figure 5–6 General Regions of Applicability for Liquid-Liquid Separations: Based on Particle Size and Concentration (reprinted from Woods and Diamadopoulos, 1988, p. 464, by courtesy of Marcel Dekker, Inc.)

D. Separating Liquid-Solid Systems. For liquid-solid separations, a very wide range of options exist: screens, dryers, leachers, expellers, filters, and settlers. These are illustrated in Figures 5–7, 5–8, and 5–9. Some options exploit differences in vapor pressure; Figure 5–7 shows dryers, evaporators, or devolatizers. Some options are based on differences in settling characteristics; Figure 5–8 illustrates these. Some options exploit the "size" of the particles relative to the size in a mesh. Figure 5–9 shows trommels screens and filters. If the size is very small, we often increase the size via flocculation or coagulation. Sometimes we add a bed of coarse particles or bubbles to try to capture the small particles. These latter options have been sketched in Figure 5–5. Now, however, the phase L_1 should be replaced by the "Solid" phase.

Figure 5–10 shows the general regions of application for these options.

For the settling devices illustrated in Figure 5–8, Figures 5–11 and 5–12 provide more detail about where slightly different types of settlers are best suited.

For screens and filters, the overall *class* of filter is selected based on the size of particle (screens versus filters versus filtering centrifuges); within a class, the concentration helps suggest the *type*. For example, Figure 5–12 shows the type of centrifugal filter to use. Figure 5–13 gives the type of filter or screen to use.

Larger-sized particles in liquid-solid systems may also be processed by "dewatering presses or expellers" or by leaching. This type of equipment is illustrated in Figures 5–14 and 5–15. Presses and expellers are like filters in the

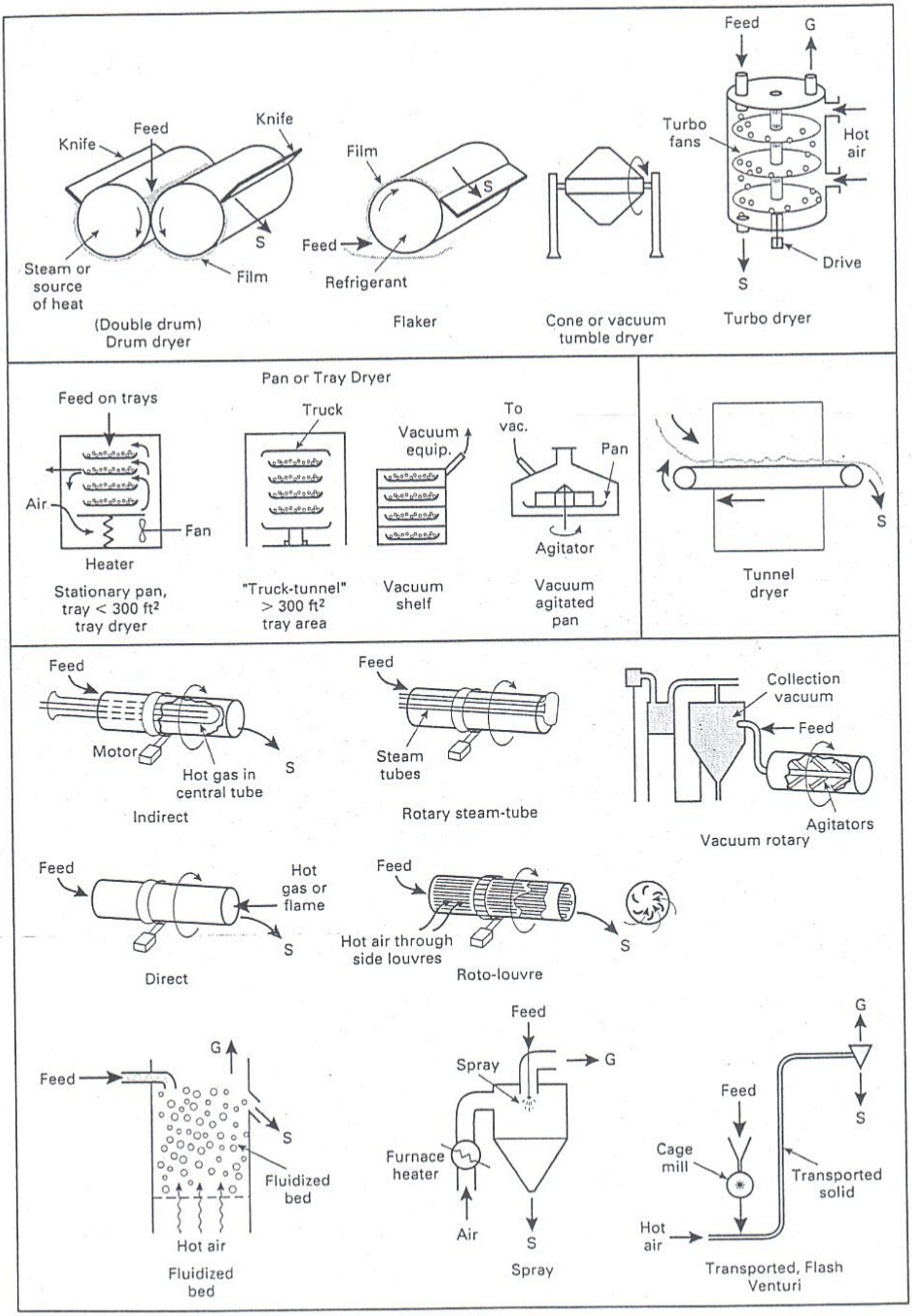


Figure 5–7 Equipment Options for Separating Liquid-Solid Systems: Dryers

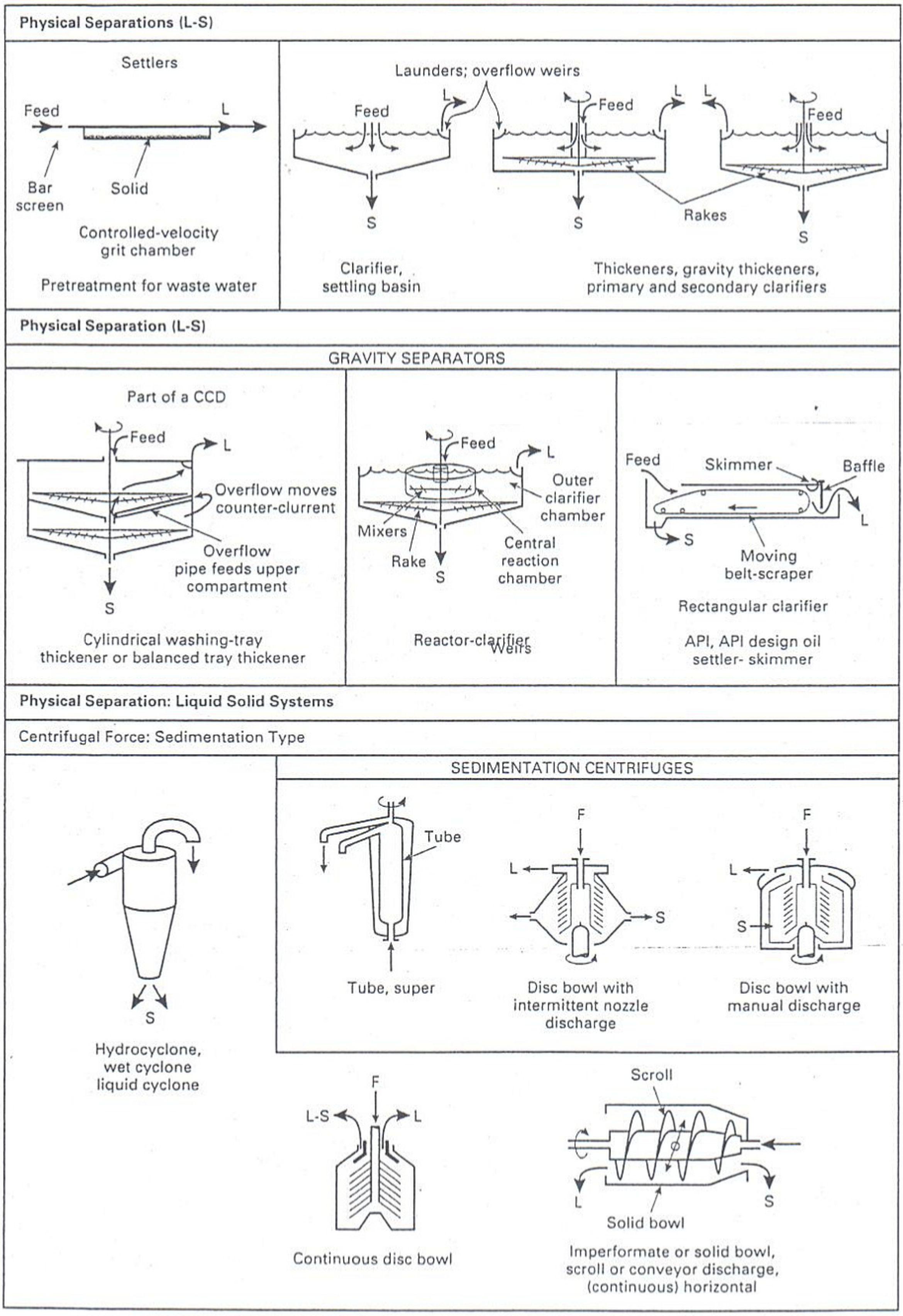


Figure 5–8 Equipment Options for Separating Liquid-Solid Systems: Settler, Thickeners, Hydrocyclones and Centrifuges

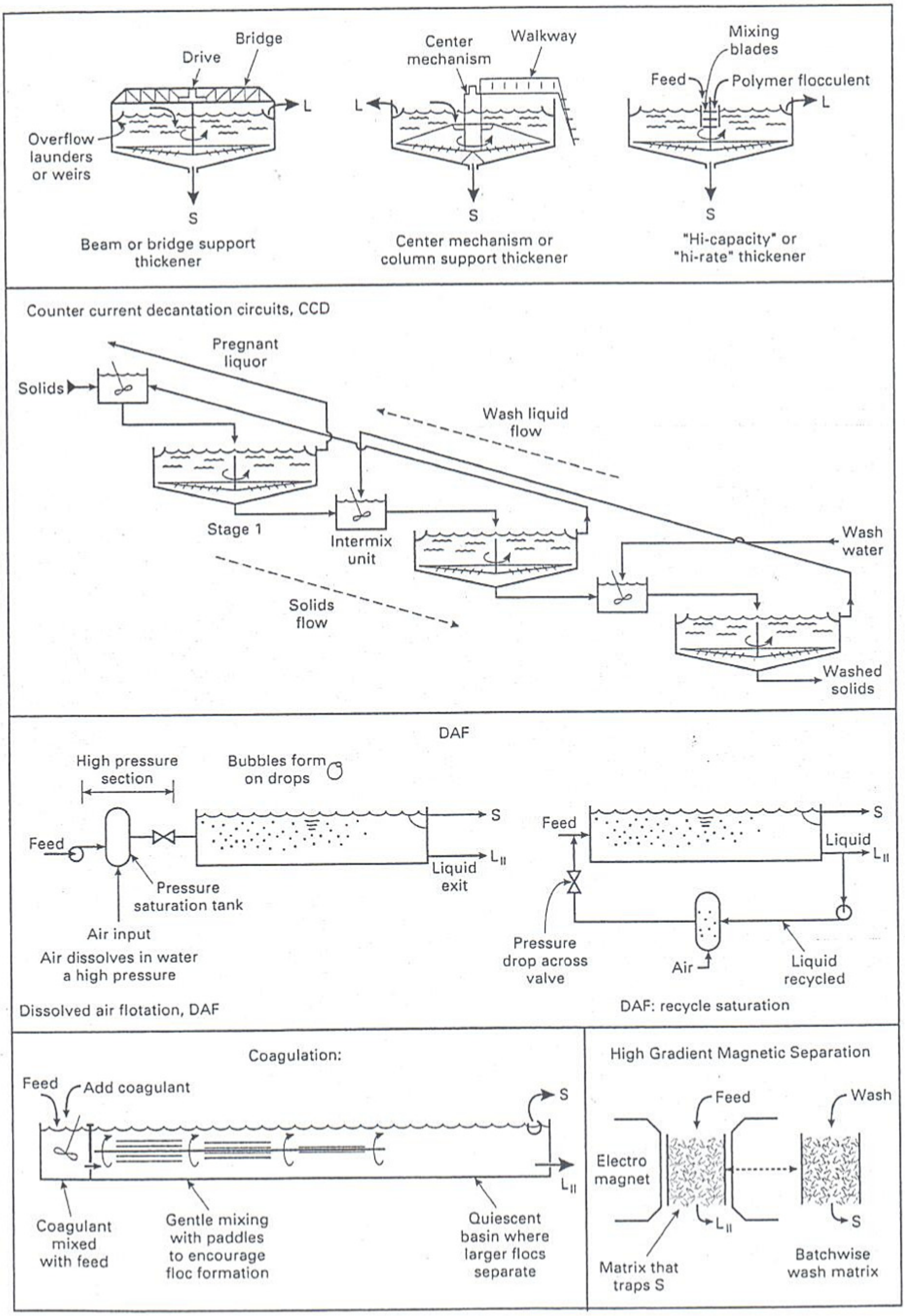


Figure 5–8 (Continued)

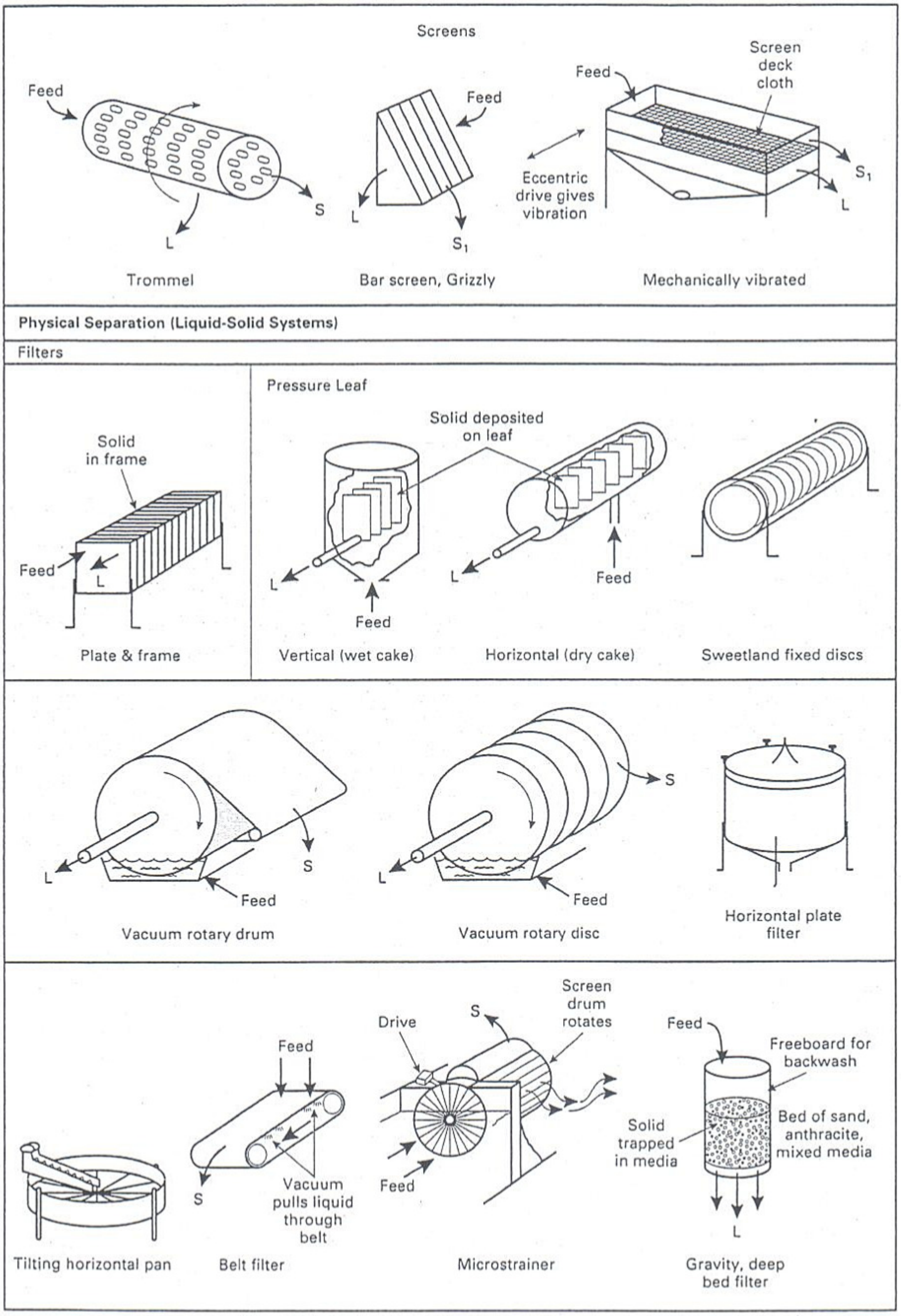
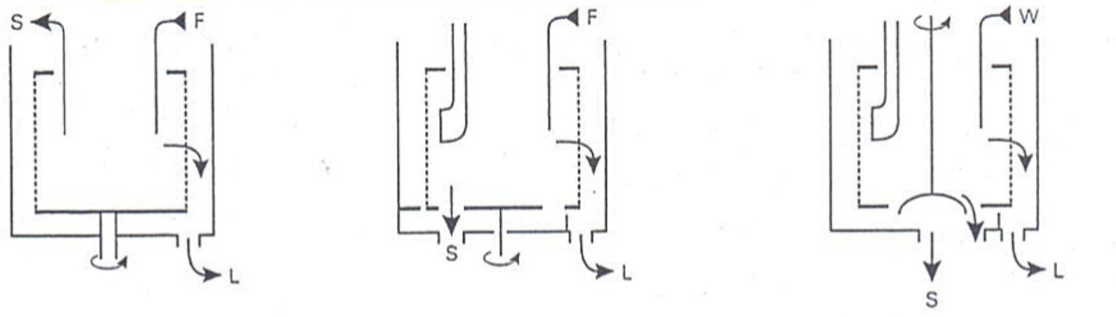


Figure 5–9 Equipment Options for Separating Liquid-Solid Systems: Screens and Trommels, Filters and Filtering Centrifuges

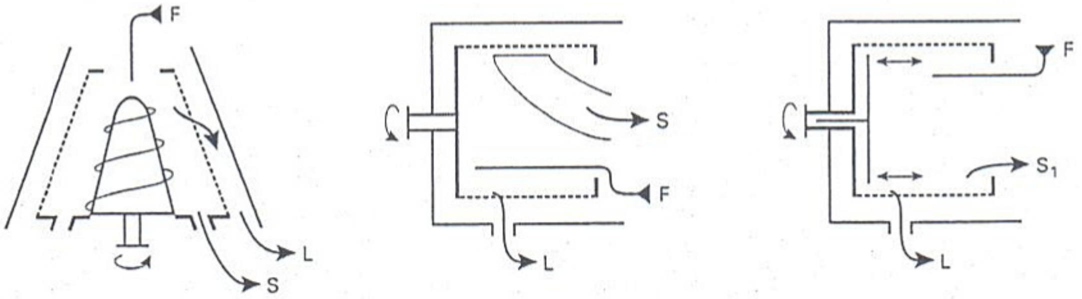
Sketches Of Different Types of Filtering Centrifuges Exploiting



A. Vertical underdrive basket, batch discharge

B. Vertical underdriven basket, bottom plough discharge

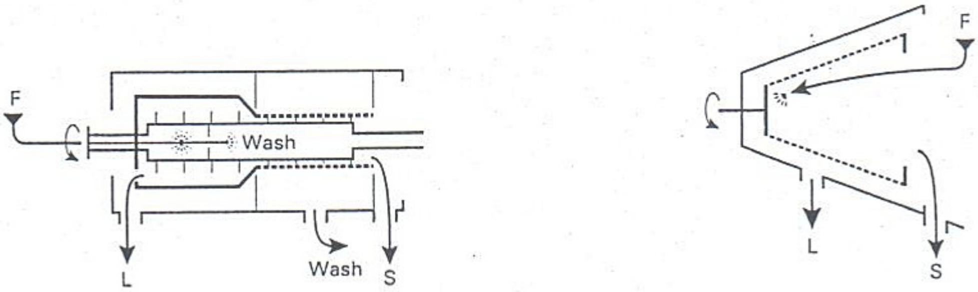
C. Vertical overdriven basket, bottom plough discharge



D. Vertical cone, scroll discharge

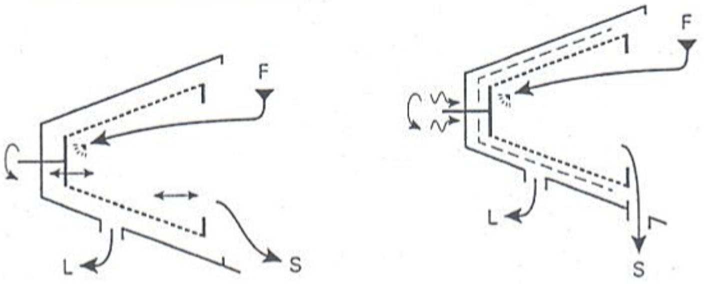
E. Automatic batch knife peeler, plough discharge horiz basket. Super D hyd.

F. Horizontal basket, pusher discharge



G. Horizontal, solid screen bowl combination, scroll discharge

H. Horizontal cone slip discharge



I. Horizontal cone oscillatory discharge

J. Horizontal conc torsional vibration discharge

Figure 5–9 (Continued)

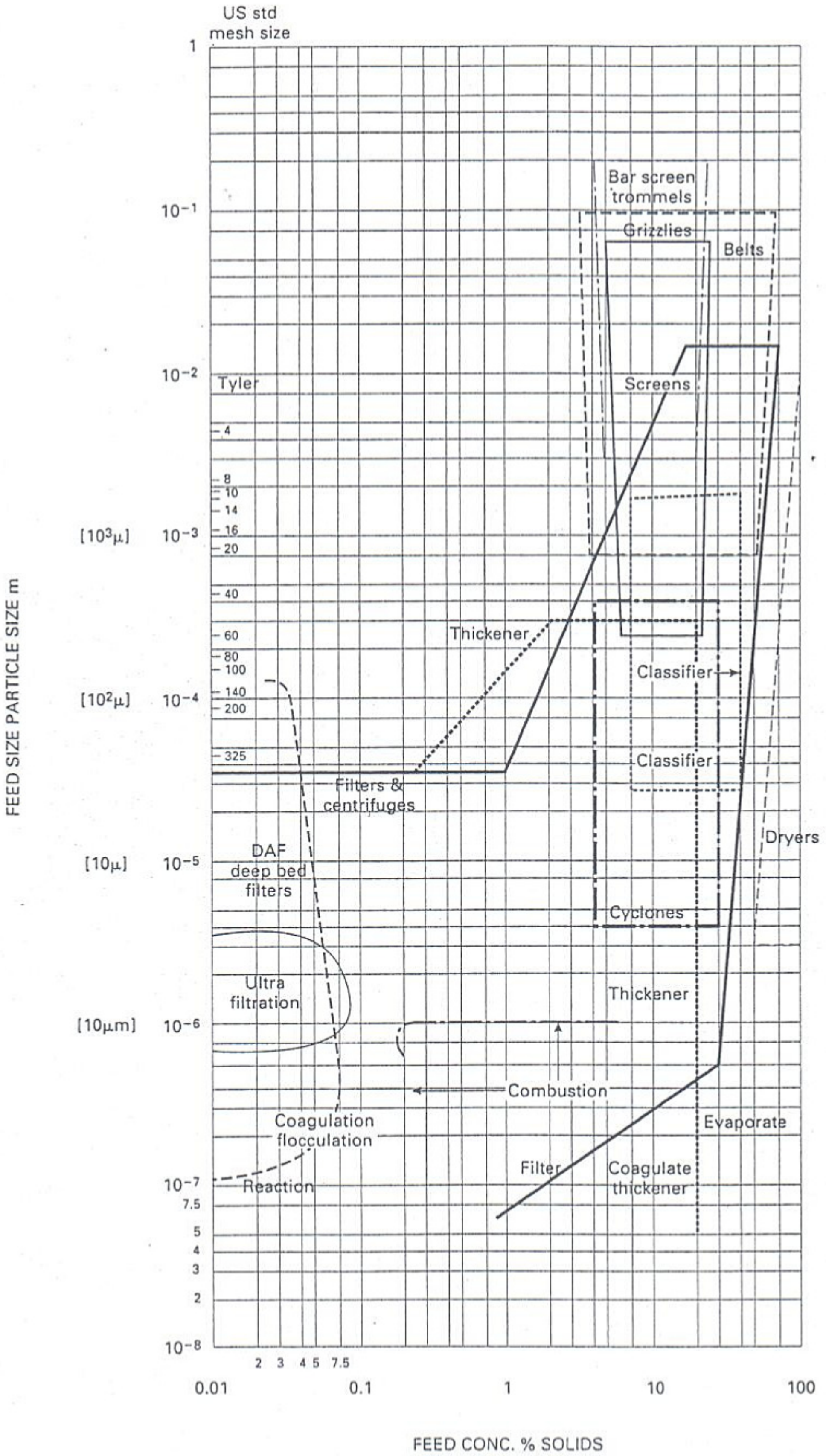


Figure 5–10 General Regions of Applicability for Liquid-Solid Separations: Based on Particle Size and Concentration (adapted from Dahlstrom and Cornell, 1971)

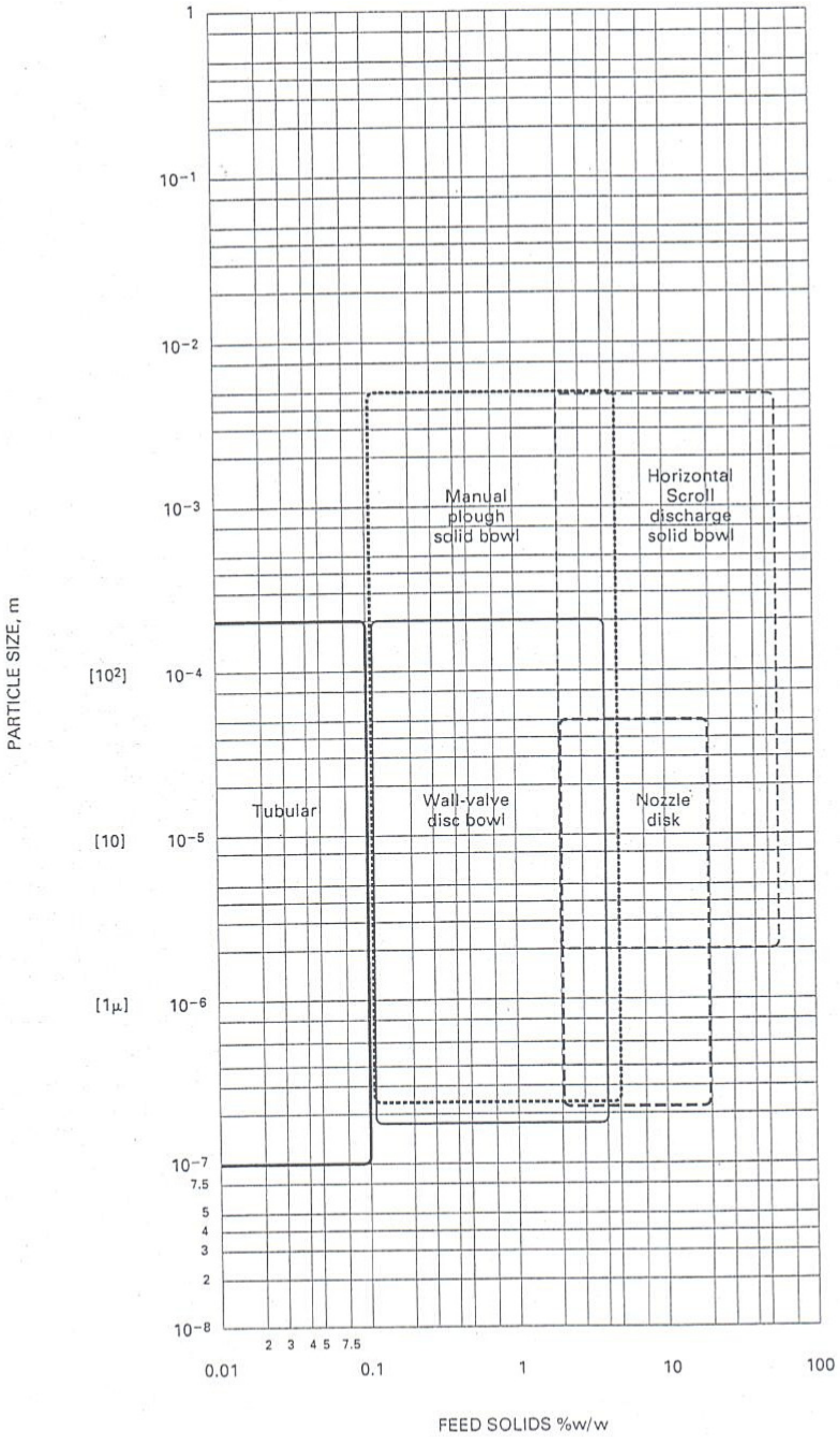


Figure 5–11 General Regions of Applicability for Liquid-Solid Separations: Based on Particle Size and Concentration for Sedimentation Centrifuges

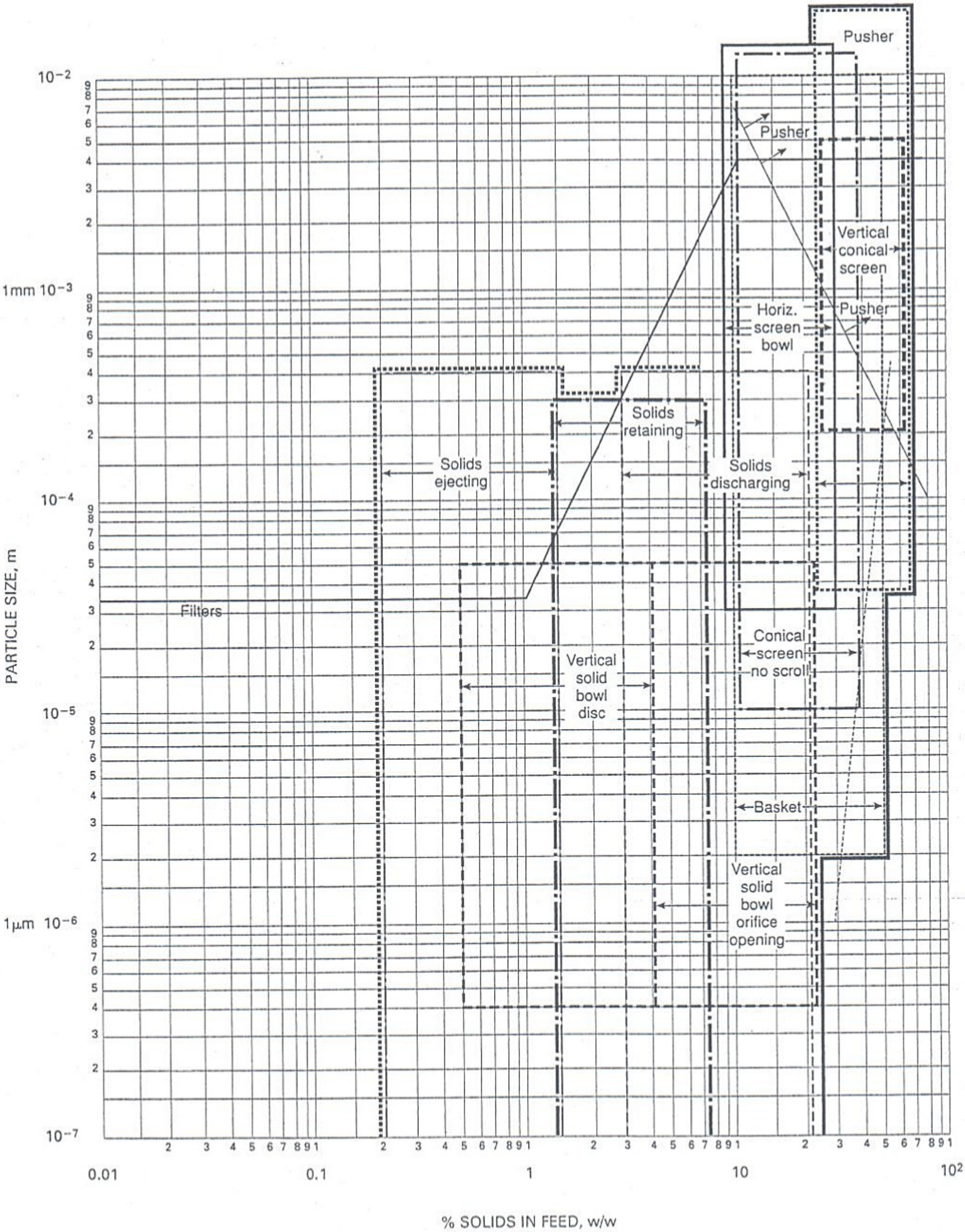


Figure 5–12 General Regions of Applicability for Liquid-Solid Separations:
Based on Particle Size and Concentration for Filtering (and Sedimentation) Centrifuges

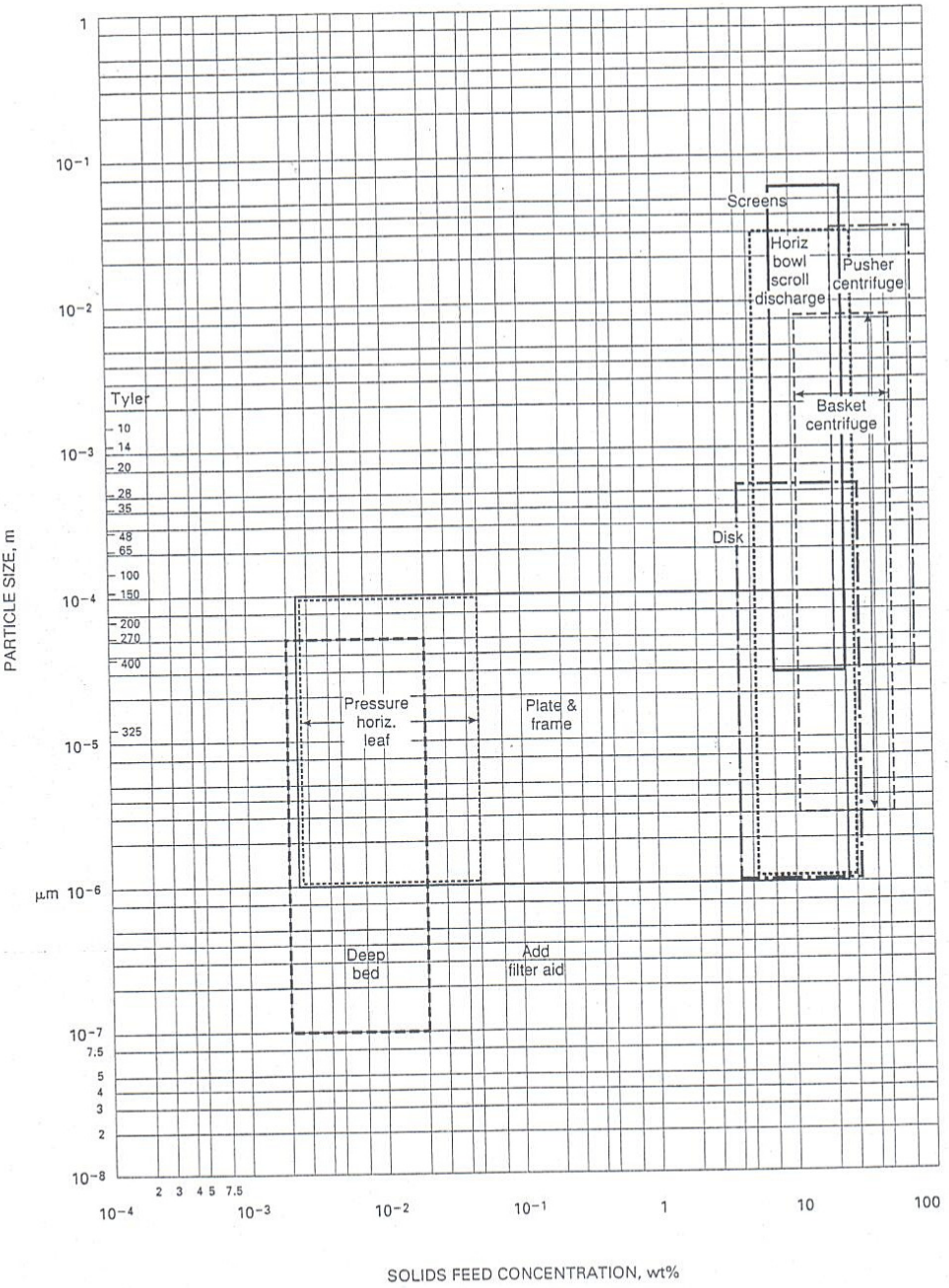


Figure 5–13 General Regions of Applicability for Liquid-Solid Separations: Based on Particle Size and Concentration for Filters and Centrifuges

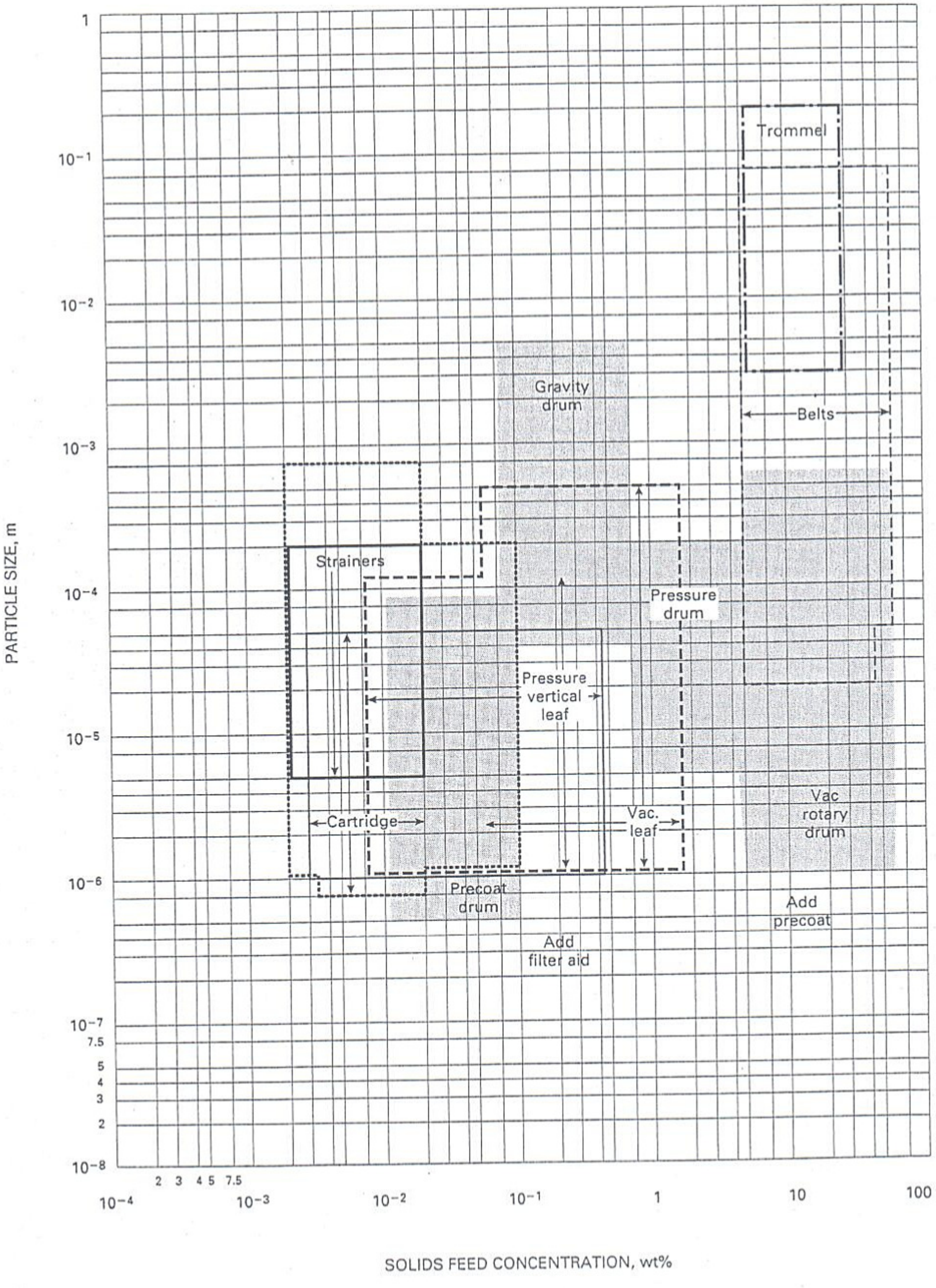


Figure 5–13 (Continued)

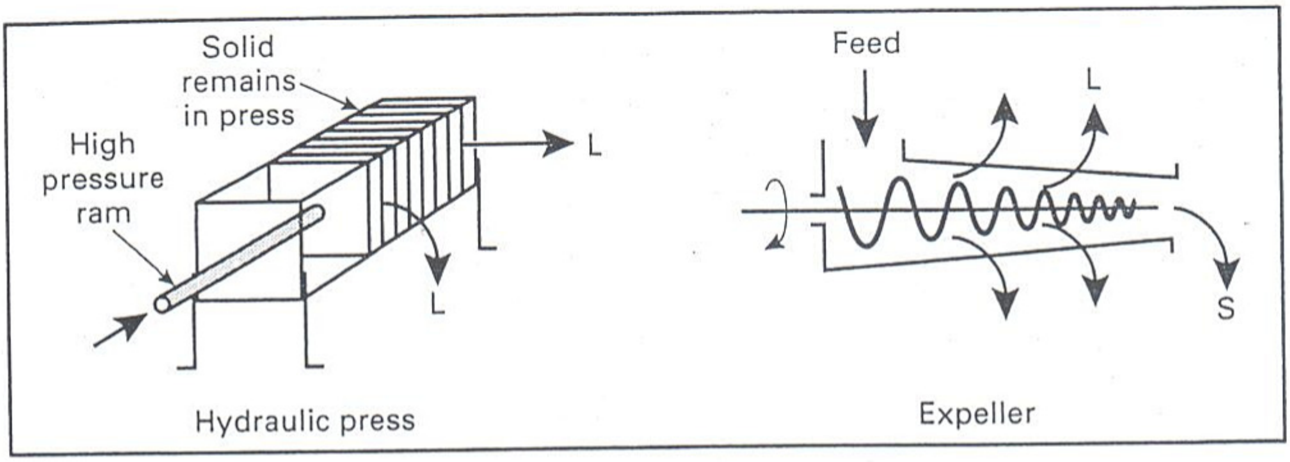


Figure 5–14 Equipment Options for Separating Liquid-Solid Systems: Presses and Expellers

sense that they use pressure to push the liquid out of the solid. In leaching, the solids contact a liquid solvent that extracts the liquid from the solid matrix. The applicability of this equipment can best be appreciated by using the *liquid* concentration on the abscissa (rather than the *solid* concentration as was done in Figure 5–10). Such a plot is shown in Figure 5–16.

E. Separating Solid-Solid Systems. For separating solids from solids, as with liquid-solid systems a wide variety of options are available. Some of the options use leaching (in which the desired component is *dissolved* away from an insoluble, undesired solid). This equipment is illustrated in Figure 5–15, "leachers." Other options require that the desired species is a particle that is to be *physically separated* from undesired particles. These physical separations are the options that are the focus of this section. These options require that particles must be ground fine enough so that the target solid species to be separated exist in different particles. For example, Figure 5–17 shows a rock made up of dark, valuable "mineral" that we want to separate from the white, useless "gangue." As shown, the two are bound together as one rock. Thus, we need to crush the rock until we have particles of just mineral and just gangue as illustrated ideally in Figure 5–17b. In practice, the mineral may be finely spread inhomogeneously throughout the gangue, or, if we are lucky, be concentrated in mineral grains embedded in the gangue. Unfortunately, when the rock is crushed, it doesn't break to produce the ideal situation shown in Figure 5–17b. Hence, to get particles that are predominantly mineral or predominantly gangue, we usually have to crush to about 1⁄100th the size of the mineral grain. Such a size is often referred to as the "liberation" size because the two species are now in separate particles. Even with this fine a particle, usually only about 60 to 70% of the mineral would be as a unique, uncontaminated particle.

Table 5–1 introduces some of the terminology used to help distinguish between the physical separation options: classifiers, concentrators, and "separators." Although some of the options exploit differences in density (or magnetic or electrostatic properties), we will initially use the particle size and concentration to identify regions where the equipment options are usually applied.

What does the equipment look like? Figure 5–18 illustrates different types of classifiers. Figure 5–18a shows classifiers that use air or gas as the conveying media. Here the media whooshes the particles through a series of baffles or twists and turns. The different density-size combinations for the particles means that they end up at different exits. Figure 5–18b shows hydrocyclones, and rake and spiral classifiers that use water or liquids as the conveying media. Figure 5–18c shows various types of screens that can be used as classifiers. The principle here is to use the size of the particle relative to the size in the screen as the method of separation. These can be operated dry or wet.

Figure 5–19 shows jigs, tables, and sluices that serve as concentrators. These concentrators exploit differences in settling velocities of the particles to achieve the separation. Figure 5–20 shows DMS or dense media separators that exploit differences in density between the target species and the rest.

Figure 5–21 illustrates the workhorse of solid-solid separations: the froth flotation unit. Here, the surface of the target species is conditioned so that the solid clings to gas bubbles that rise through the liquid. The gas bubbles or froth can then be skimmed off, bringing the clinging solid with it into the "float." Figure 5–21a shows single contacting stages or cells. Figure 5–21b illustrates how series of these cells are hooked together. The fundamental difference exploited here is the surface wettability of the target species.

Figure 5–22 illustrates electrostatic separators, which are effective because some particles will acquire an electrostatic charge; others will not. This difference can be exploited, as illustrated in Figure 5–22, to achieve separation.

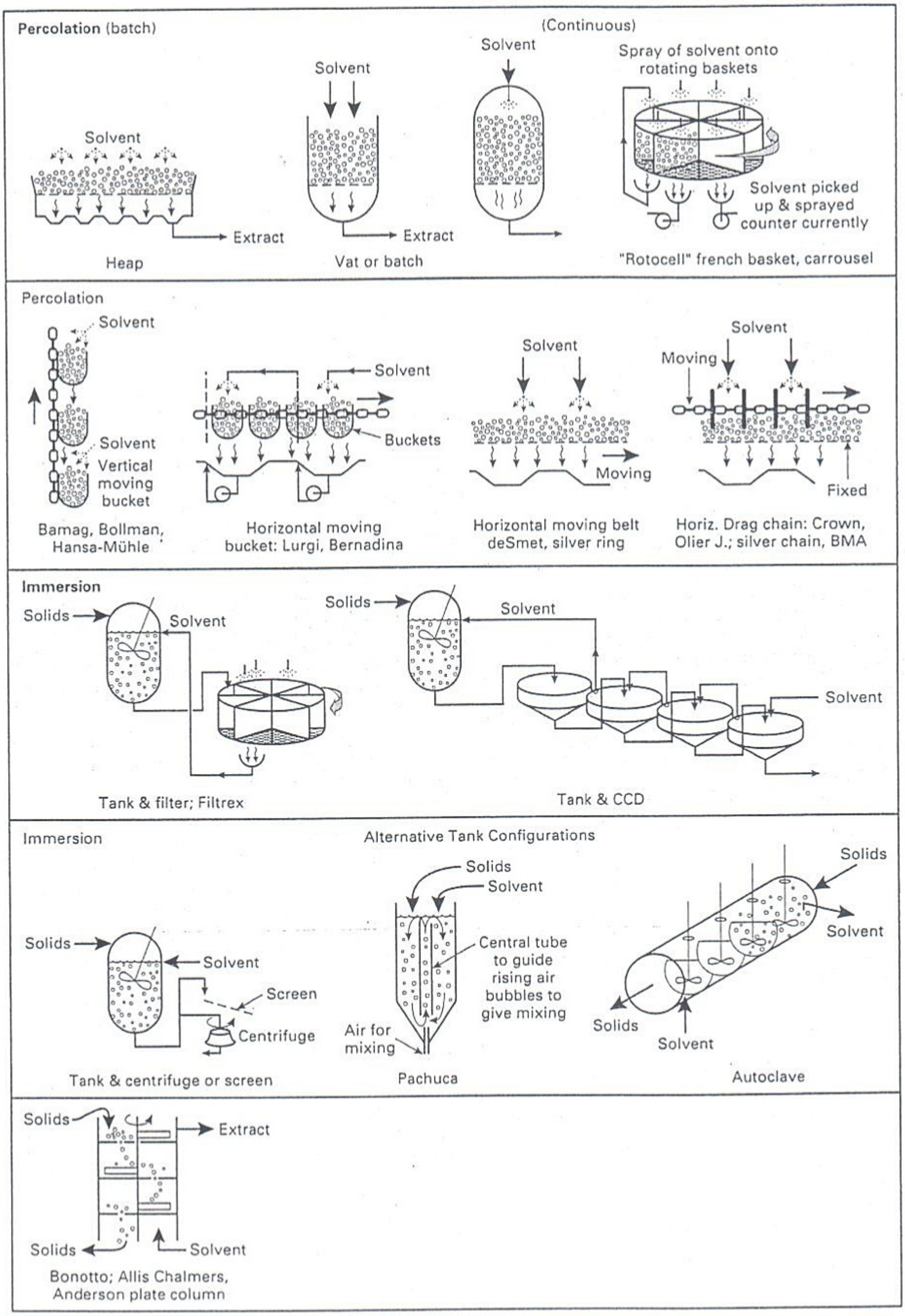


Figure 5–15 Equipment Options for Separating Liquid-Solid Systems: Leaching

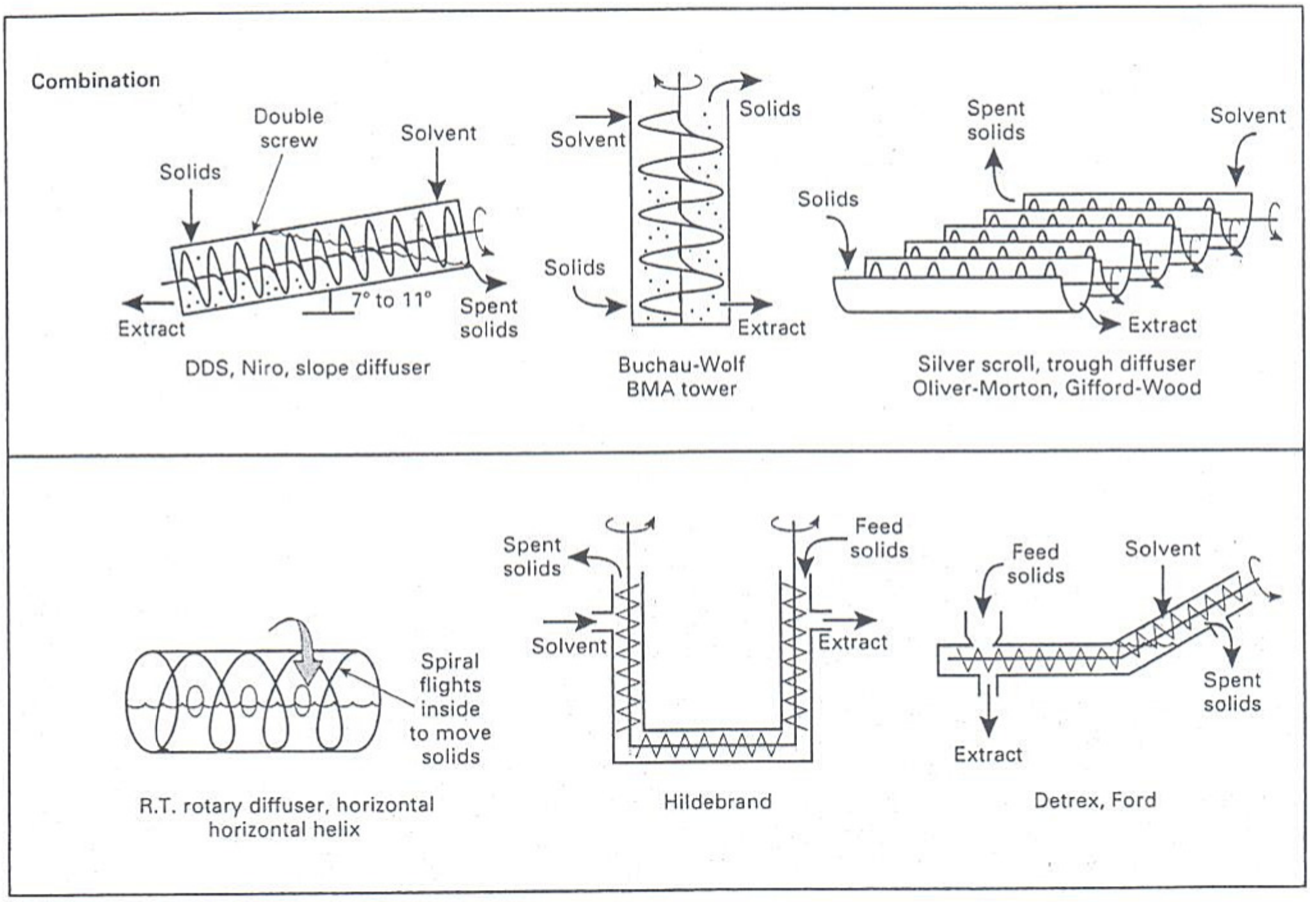


Figure 5–15 (Continued)

Figure 5–23 shows how materials with different conductivity can be separated via "eddy-current." Similarly, some target materials are sufficiently magnetic that a magnetic field can be used to obtain a separation. Equipment based on magnetic separation is illustrated in Figure 5–24.

Figure 5–25 shows the usual regions of application for options to physically separate solids from solids. Figure 5–16 shows, for percolation and immersion leaching, the usual regions of application for separating solids from solids by chemical leaching. Figure 5–25 is a very busy diagram. Many options are available, and many overlap. Nevertheless, this is useful for a "first approximation" for reasonable options. On the left-hand ordinate is summarized the size of the particles expressed in terms of *mesh* size.

Another way to consider solid-solid separations is analogous to that given for homogeneous phase separation in Figure 4–1. This is shown in Figure 5–26, where now the separation factor is defined for solid-solid options in Table 5–2.

In summary, for each combination of phases, a convenient, initial choice of option can be made based on the size of the particles, drops, or bubbles and the concentration.

5.1-2 A More Detailed Consideration of Options: Exploit the Properties of the Phases and Consider the Product Requirements

So far we have considered a very sloppy method of selecting possible separation options based on only the feed concentration and the particle size. If more details are needed, then by successive approximation, we need to consider the differences in properties that can be exploited and the product requirements.

A. Exploiting the Property Differences. Despite what the screening charts given in the previous section suggest about the importance of particle size, the key fact is that for any separation *there must be a difference in physical or chemical properties that can be exploited.*

The options include:

1. a difference in **vapor pressure.** This is especially useful for a liquid-solid mixture. By adding heat or by pulling a high vacuum we can convert the liquid trapped in the pores between the solid particles into a gas that can be separated easily from the solid. This

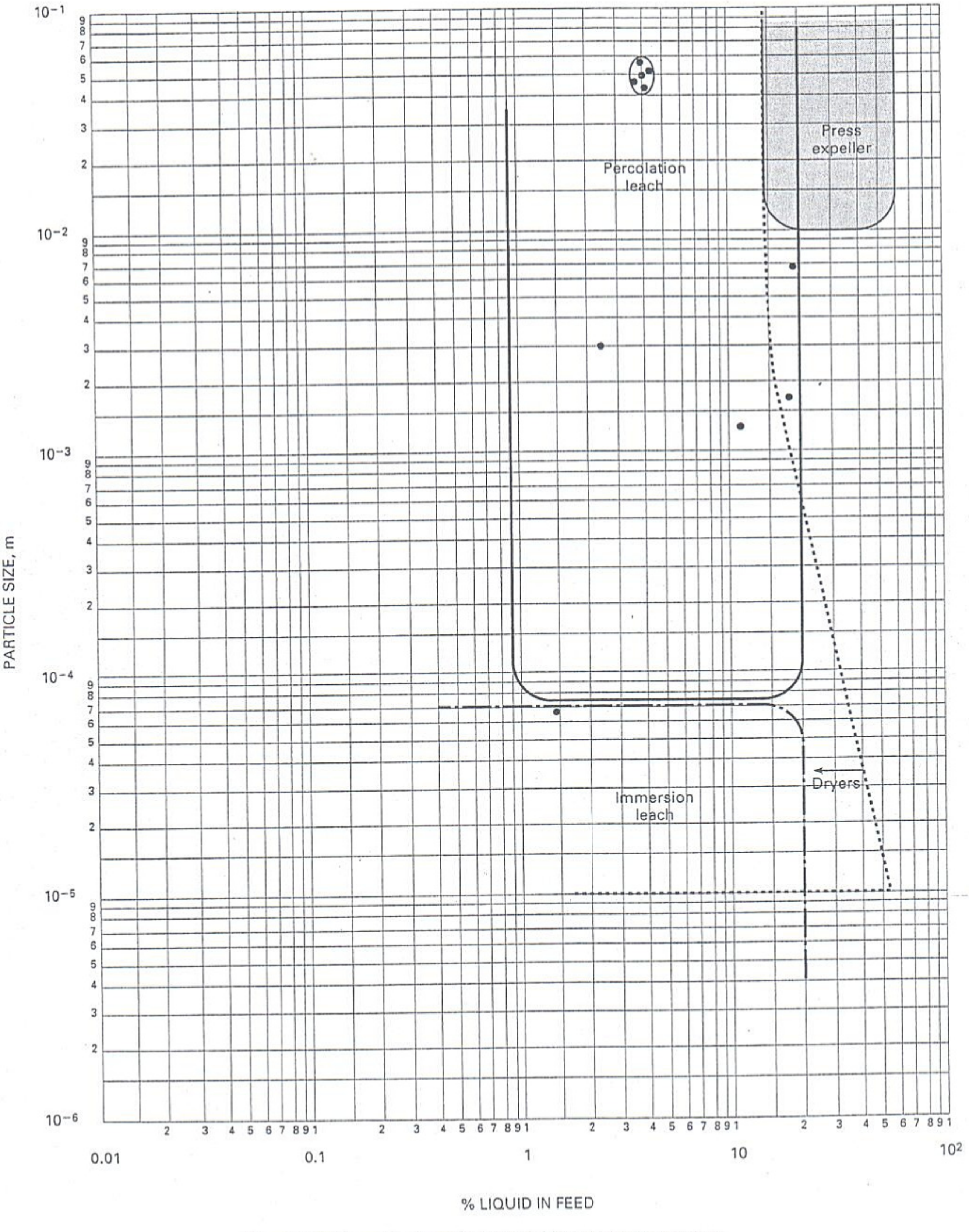


Figure 5–16 General Regions of Applicability for Liquid-Solid Separations: Based on Particle Size and Concentration for Presses, Expellers, and Leachers

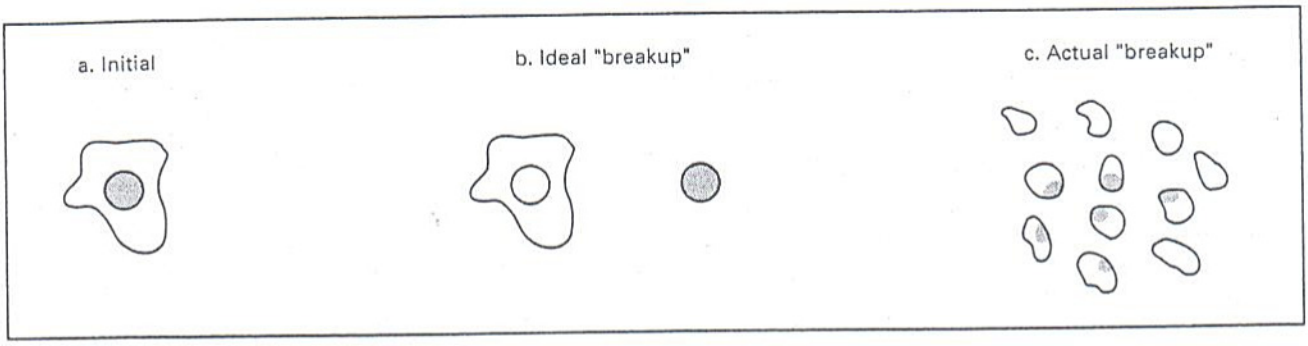


Figure 5–17 "Liberating" the Target Species for Solid-Solid Separation

interstitial phase is illustrated in Figure 5–27. More will be said about the importance of the interstitial volume in Section B.

2. a difference in **size.** This can be used for every type of combination of phases: gas-liquid, gas-solid, etc. The larger-sized particles can be separated by a physical barrier that either mechanically blocks the free movement of the particles or attracts them via van der Waals forces. Screens, grizzlies, bar screens, trommels, filtering centrifuges, and filters all are mechanical blocking devices. The principle is illustrated in Figure 5–28. Deep bed filters rely on van der Waals forces to cause the separation as illustrated in Figure 5–29.
3. a difference in **size and density.** We can exploit these differences in two ways.

   First, if the mixture of particles and fluid flows rapidly and suddenly is forced to change direction because of an obstruction, the heavier particles keep going and hit the obstruction, while the fluid bends and flows past it. This is illustrated in Figure 5–30. Now all we have to do is make the particulates "stick" to the obstruction. Sometimes we use water as the obstruction (to which particles will impact and remain enveloped). This is the principle of a wet scrubber. Another variation on the same theme is when large-diameter particles keep going and hit the obstacle, whereas small diameter particles follow the gas and miss the obstacle. This is the principle upon which some classifiers of sold-solid systems operate. Sometimes we use the "wettability" of the obstruction to effect the separation. Wettability refers to the behavior of two fluids in contact with a solid. That is, we always have a three-phase system: say water droplets in air flowing through wire mesh. In Figure 5–31 three possible conditions are shown. In case (a), the water droplets upon impact with the solid spread out and cover the wire. Here we say that the water "wets" the solid. In case (b), the water retains much of its spherical shape and, although it remains attached to the solid via van der Waals force, it is not strongly attached because the contact area is small. Here we say that the water does *not* wet the solid. In case (c), the water partially wets the solids. For good separation of a liquid-liquid or liquid-gas system, the target liquid must wet the solid mesh or obstacles.

   The second way that size and density difference can be exploited is in the settling velocity of the particles. We can use this to separate particles from liquids or we can use the *difference* in settling velocities to separate solids from solids. This is the principle used in centrifuges, cyclones, settling and thick-

TABLE 5-1. Solid-solid separations: classification of options

		Exploit Particle Size Difference	
		Narrow range	Wide range
Exploit Particle Density Difference	Narrow Range	"Separators" Froth flotation, Electrostatic Magnetic	"Classifiers" Air classifiers, Hydrocyclones, rake classifiers, spiral classifiers, screens, trommels
	Wide Range	"Concentrators" Jigs Tables Sluices Dense Media	Use concentrator then a classifier or vice versa

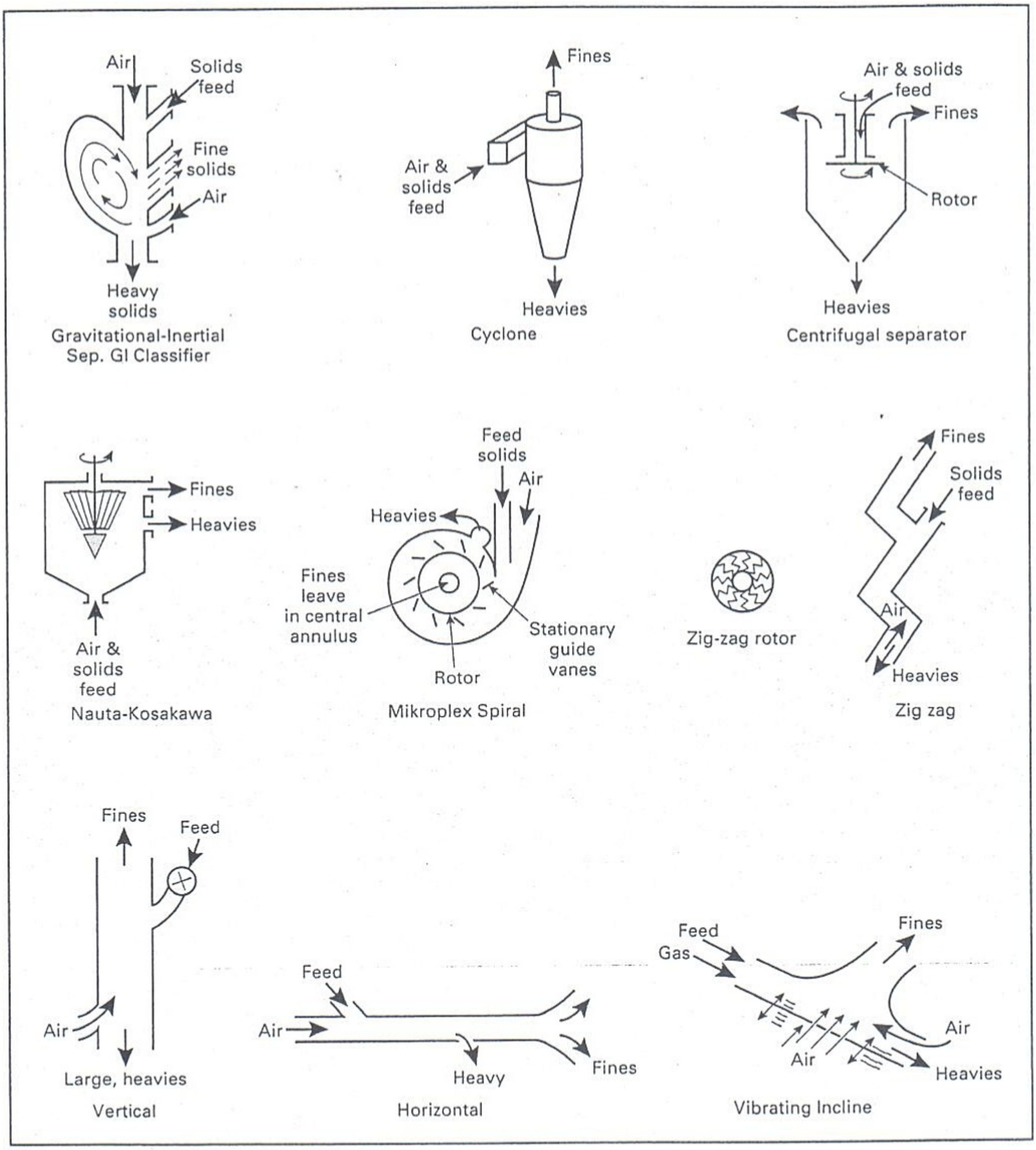


Figure 5–18 Equipment Options for Separating Solid-Solid Systems: Air and Liquid Classifiers, Screens and Trommels
a) Air or Gas Classifiers
b) Hydroclones and Rake and Spiral Liquid Classifiers
c) Screen Classifiers

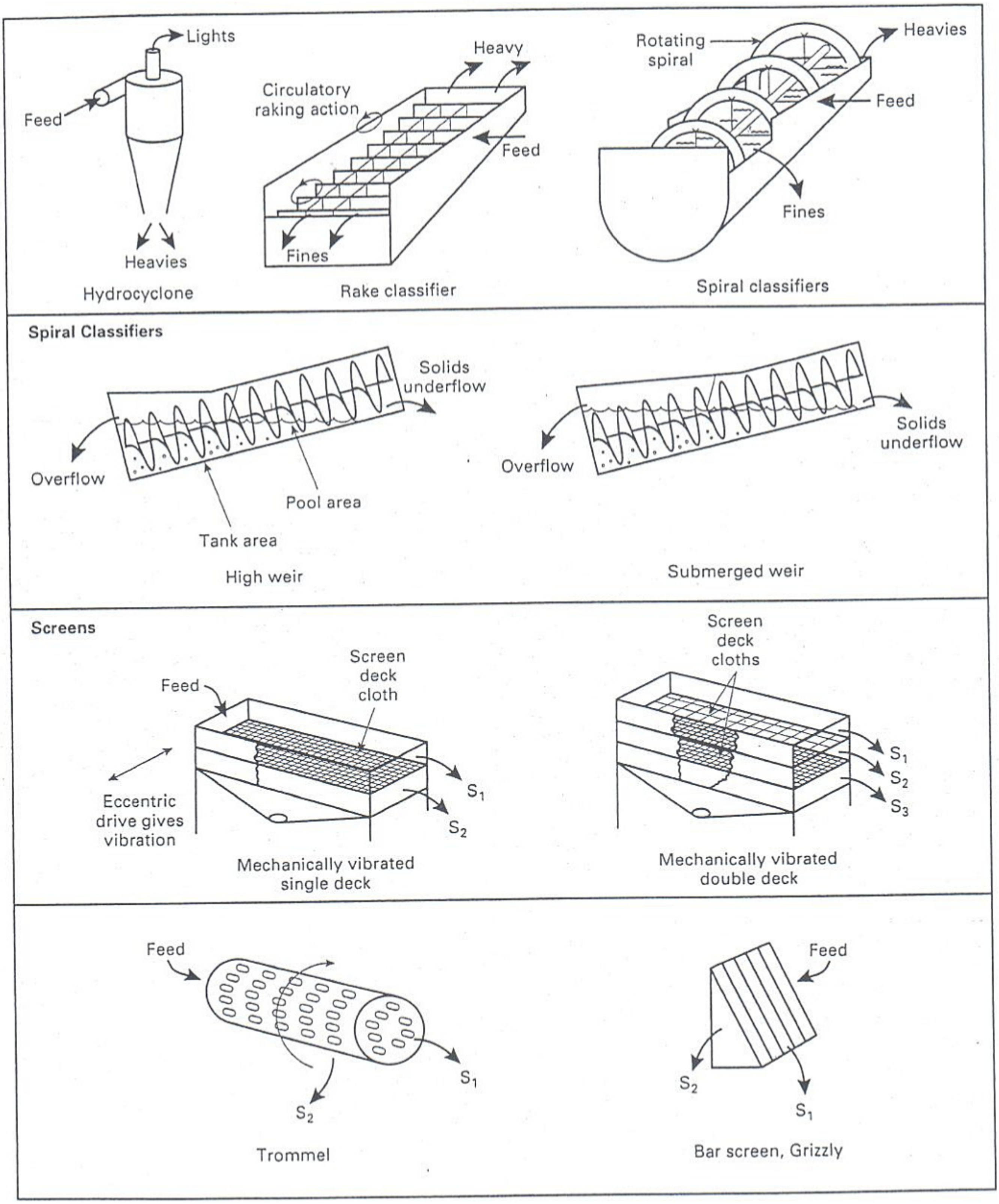


Figure 5–18 (Continued)

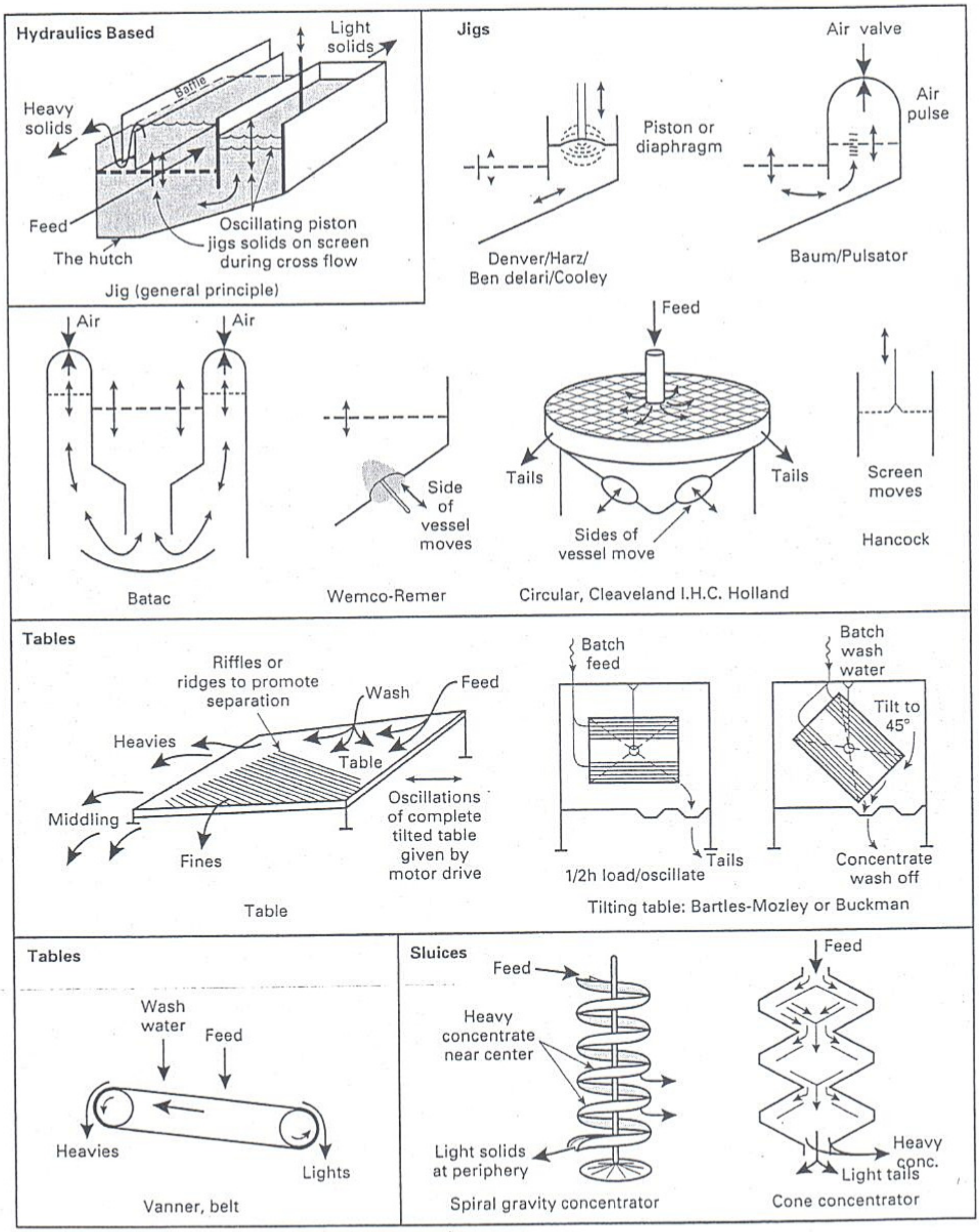


Figure 5–19 Equipment Options for Separating Solid-Solid Systems: Concentrators

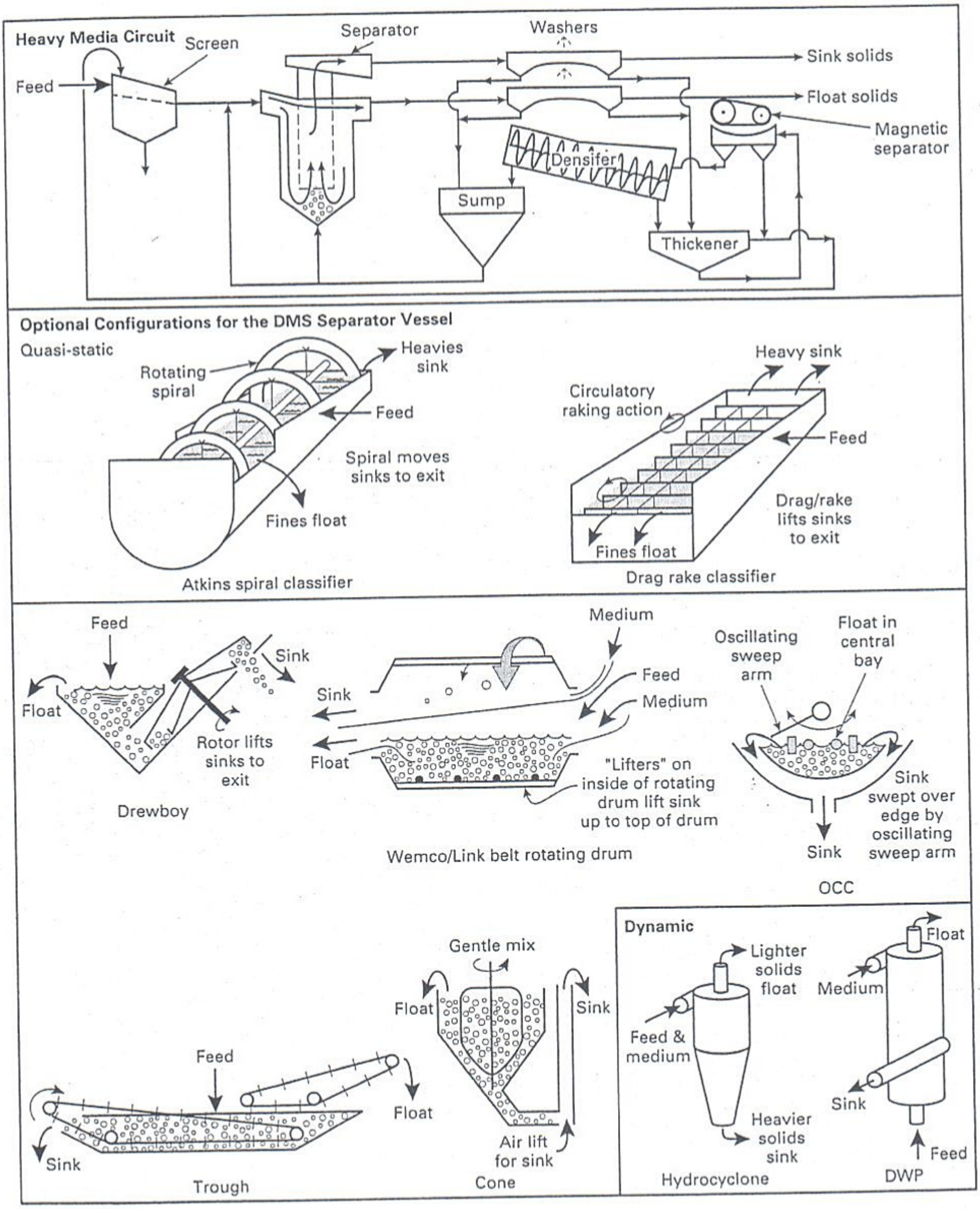


Figure 5–20 Equipment Options for Separating Solid-Solid Systems: Dense Media Separators

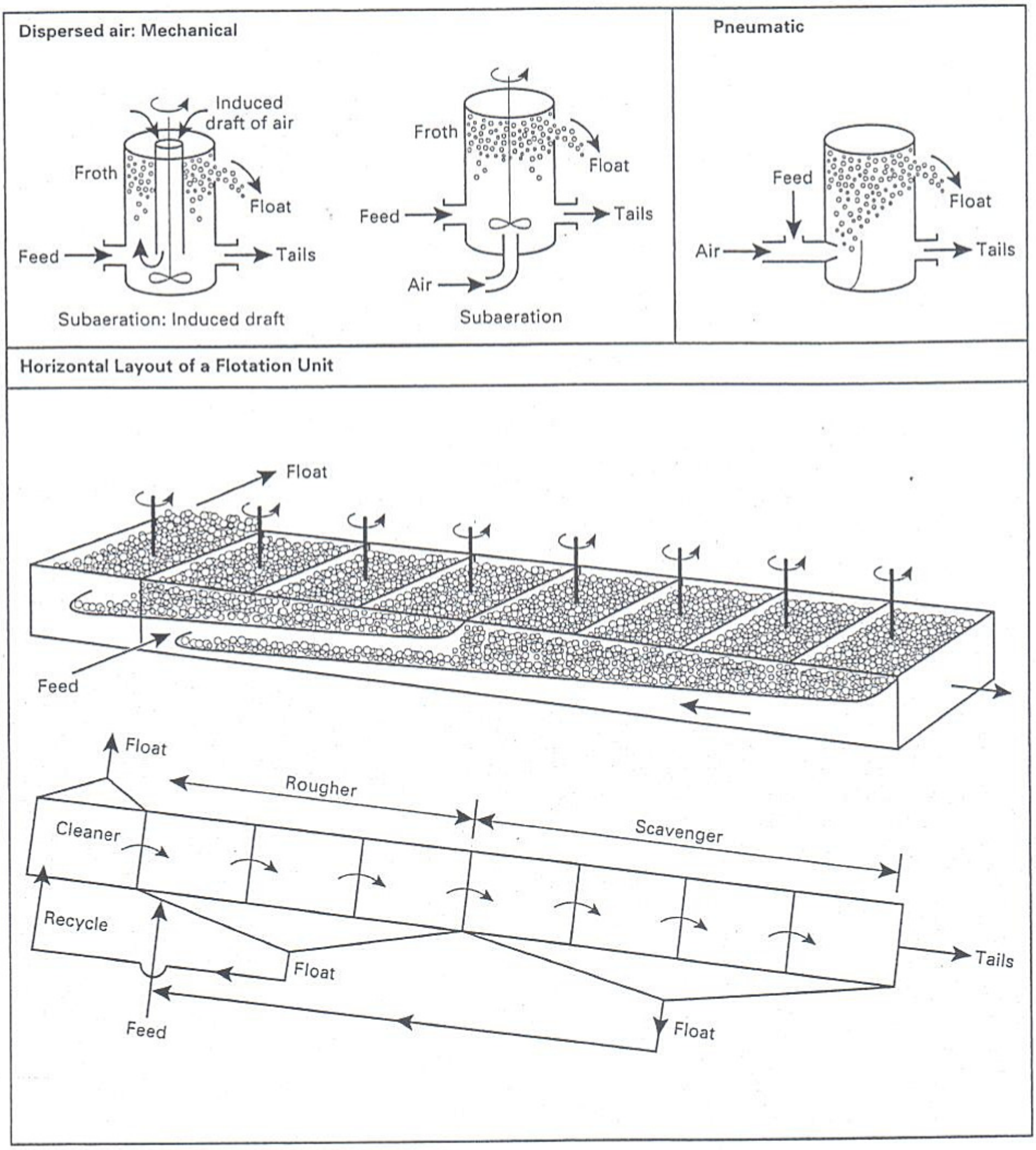
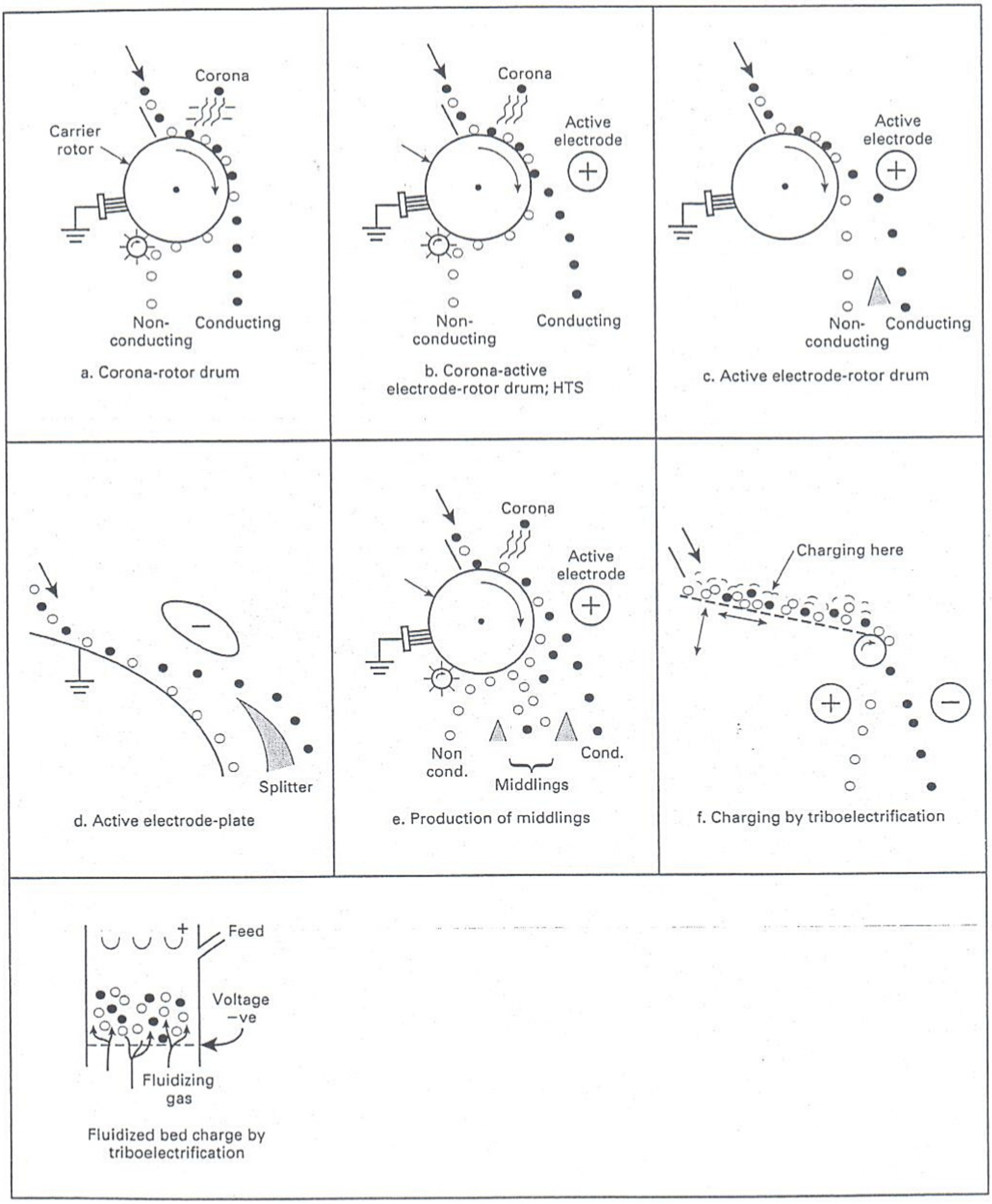


Figure 5–21 Equipment Options for Separating Solid-Solid Systems: Froth Flotation
a) Dispersed Air: Mechanical and Pneumatic
b) Horizontal Layout of a Flotation Unit

ening basins, hydrocyclones, decanters, jigs, rakes, tables, and spirals.

4. a difference in **density.** We may be able to separate solid-solid systems by carefully selecting the density of the continuous phase, or the surrounding media. This is called "dense media separation."
5. a difference in **wettability.** The concepts of wettability are illustrated in Figure 5–31. Here a liquid spreads out over or wets a solid, or the liquid may retain a spherical shape and *not* wet the solid, or it may partially wet it. We can use this to "capture" liquids on solid wires or surfaces.

Displacement or "solvent drying" is based on wettability. For a solid bed of particles or for capillaries or cracks in rocks that are filled with liquid, we can use wettability to displace the liquid. A displacing solvent is pushed into the system. The solvent preferentially wets the solid and displaces the previ-



a. Corona-rotor drum

b. Corona-active electrode-rotor drum; HTS

c. Active electrode-rotor drum

d. Active electrode-plate

e. Production of middlings

f. Charging by triboelectrification

Fluidized bed charge by triboelectrification

Figure 5–22 Equipment Options for Separating Solid-Solid Systems: Electrostatic Separators

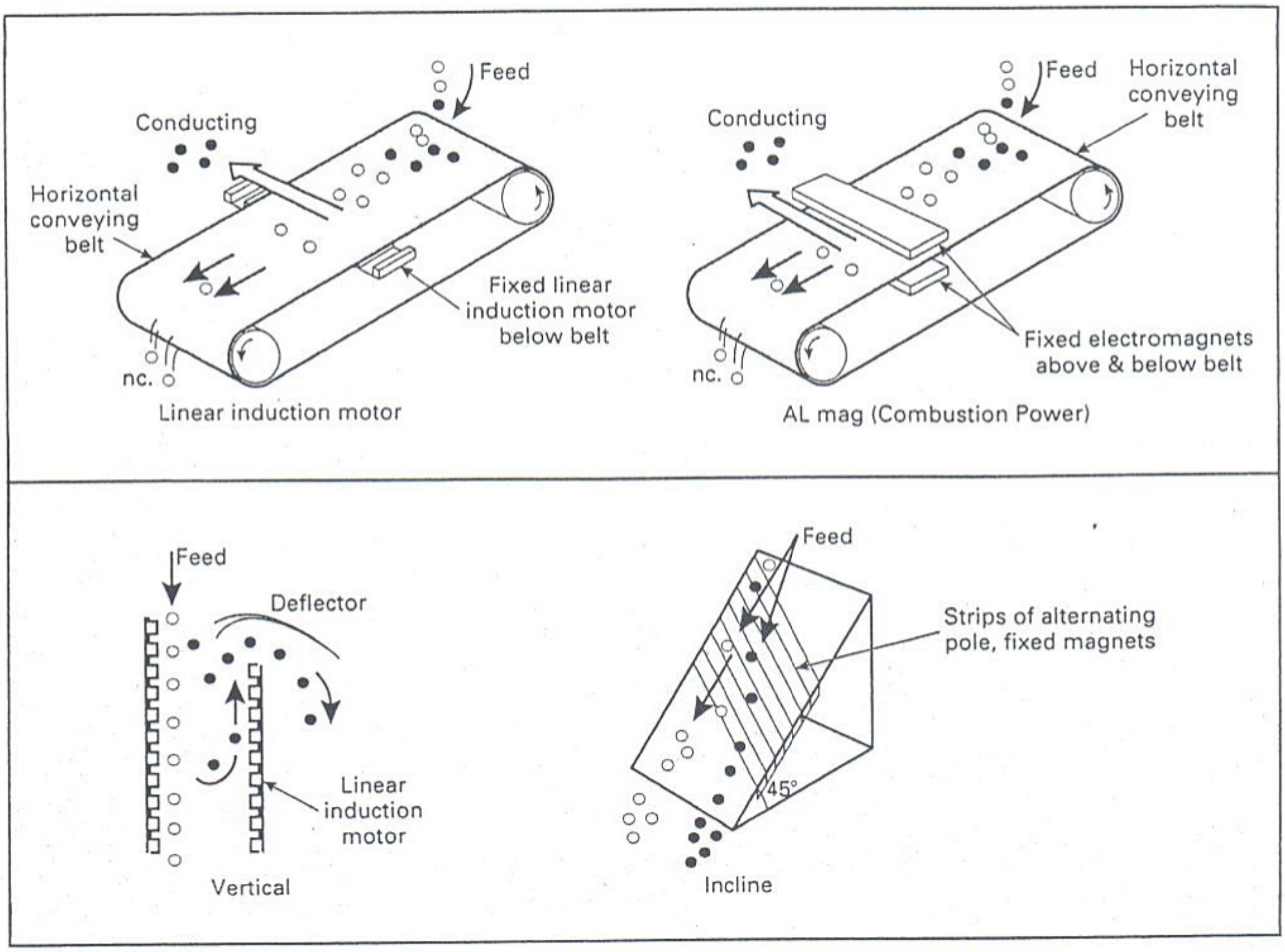


Figure 5–23 Equipment Options for Separating Solid-Solid Systems: Eddy-Current Separation

ous liquid that "peels away from the solid" as drops. Solvent "drying" is an analogous process in which water is *displaced* (not dissolved) by a solvent.

In *froth flotation*, air bubbles are introduced into a liquid pool that contains two different types of solids. One of the solids is *not* wet by the liquid; it prefers to attach to the bubble and leave the liquid with the bubble. Thus, one type of solid is separated from another.

In *dissolved air flotation*, liquid supersaturated with gas is added to the pool of liquid containing the suspended solids. The gas nucleates to form bubbles on the solid particles present in a pool of liquid. The bubbles rise and lift the solids free from the liquid. Thus all of the solid particles are separated from the liquid.

6. a difference in **solubility.** In leaching, a solvent is added to which the liquid component (of a liquid-solid mixture) is preferentially absorbed. For example, hexane is added to ground-up peanuts to extract the peanut oil from the fibrous protein peanut cake.

   In *dissolution*, a solvent or heat is added to convert one solid in a solid-solid mixture into a liquid. For example, sodium hydroxide is used to dissolve solid alumina from solid (but insoluble) silicates in bauxite ore.

   Alternately, we can dissolve one of the phases in a two-phase system and thus create a homogeneous phase. Techniques introduced in Chapter 4 could then be used for the separation.
7. a difference in **electrical conductivity.** Particles with electrical conductivities different from those of the surrounding media can acquire a charge that can, in turn, be used to cause the particles to migrate in a DC field. This is the principle of electrodecantation, precipitators, and electrostatic separators.
8. a difference in **magnetic permeability.** This can be used to separate two solids by placing them in a magnetic field. For example, magnets can be used to keep metals from getting into boxes of breakfast cereal or to prevent metals from getting into crushing machines in cattle-food processing.

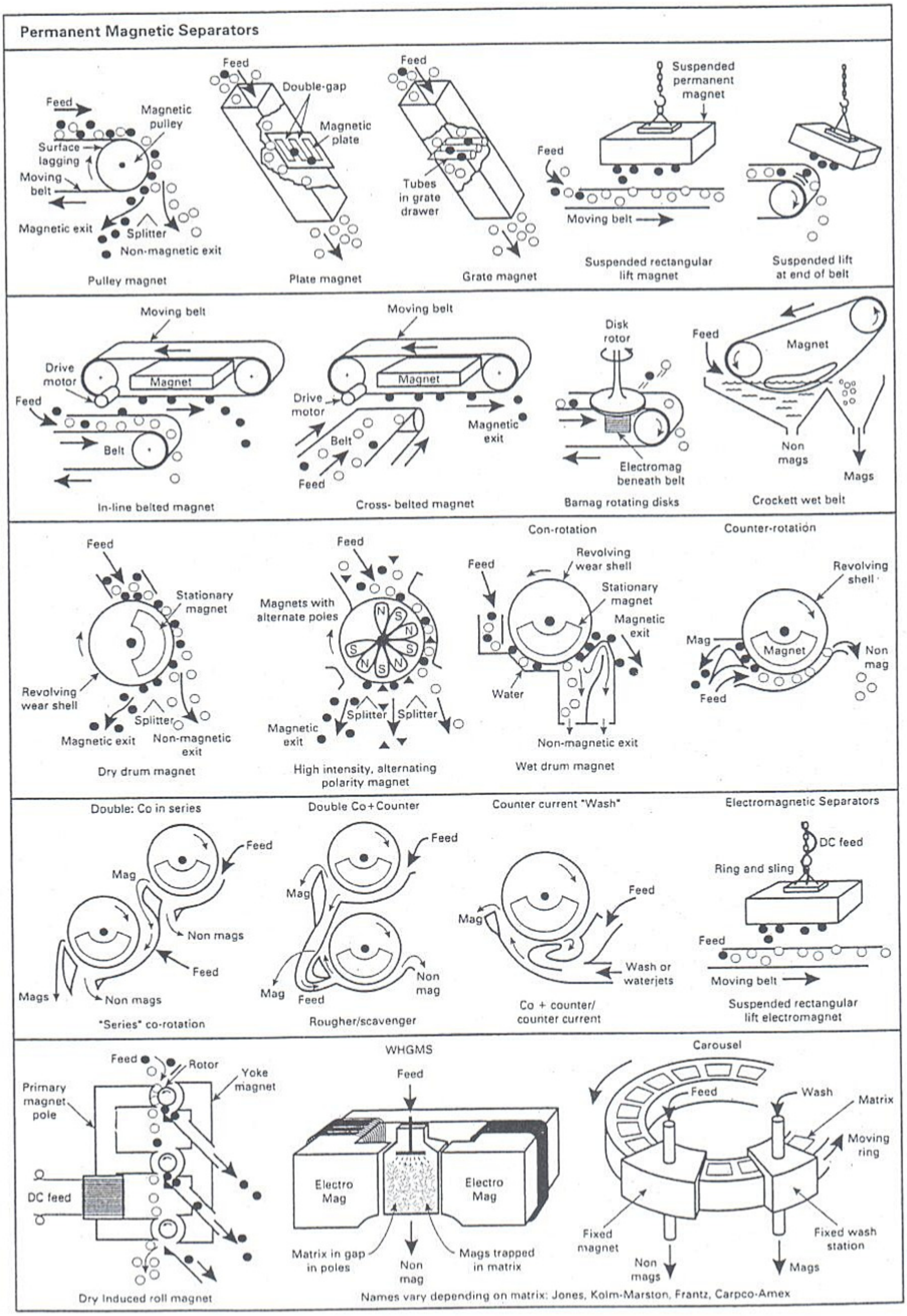


Figure 5–24 Equipment Options for Separating Solid-Solid Systems: Magnetic Separators

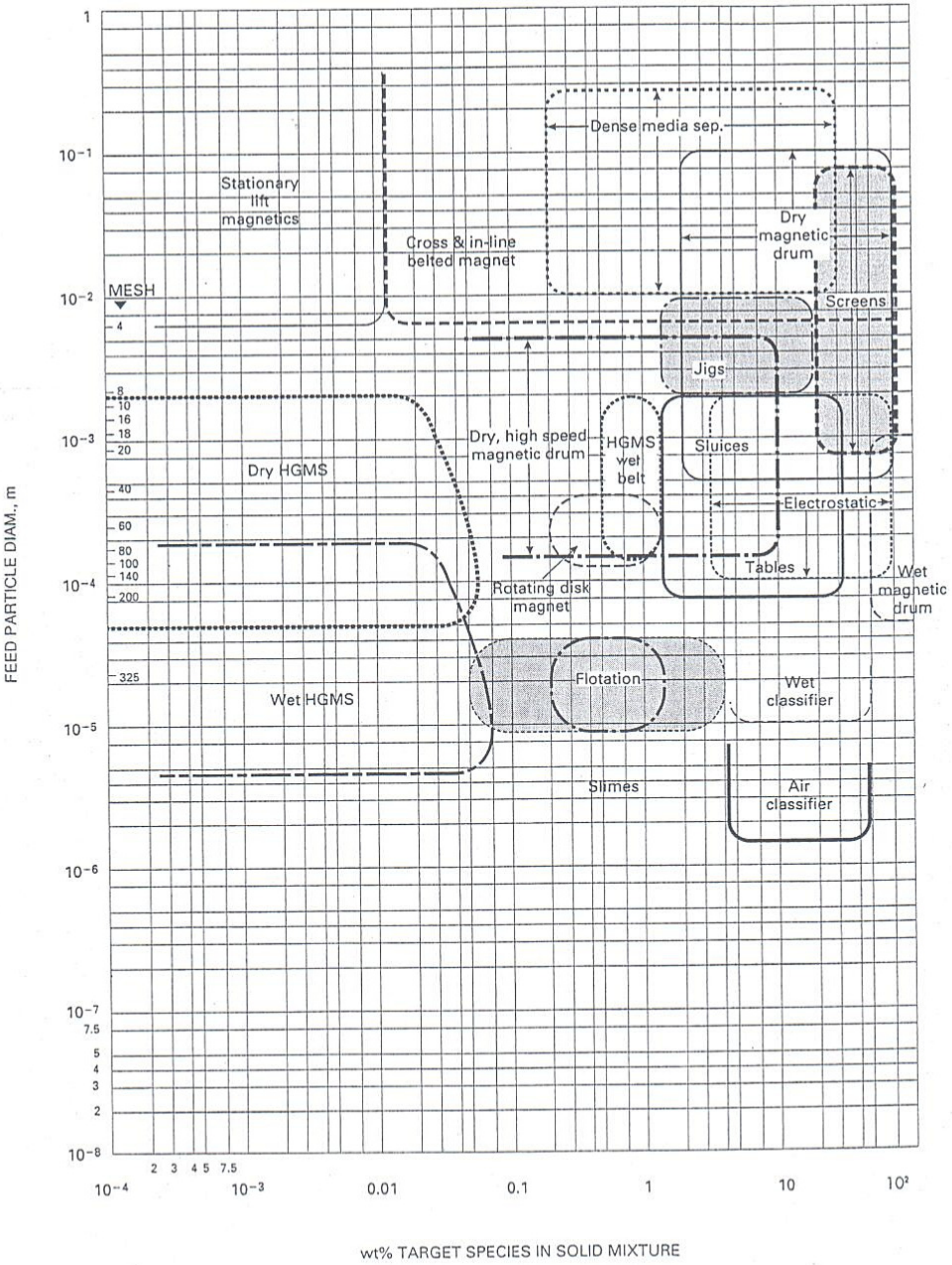


Figure 5–25 General Regions of Applicability for Solid-Solid Separations: Based on Particle Size and Concentration

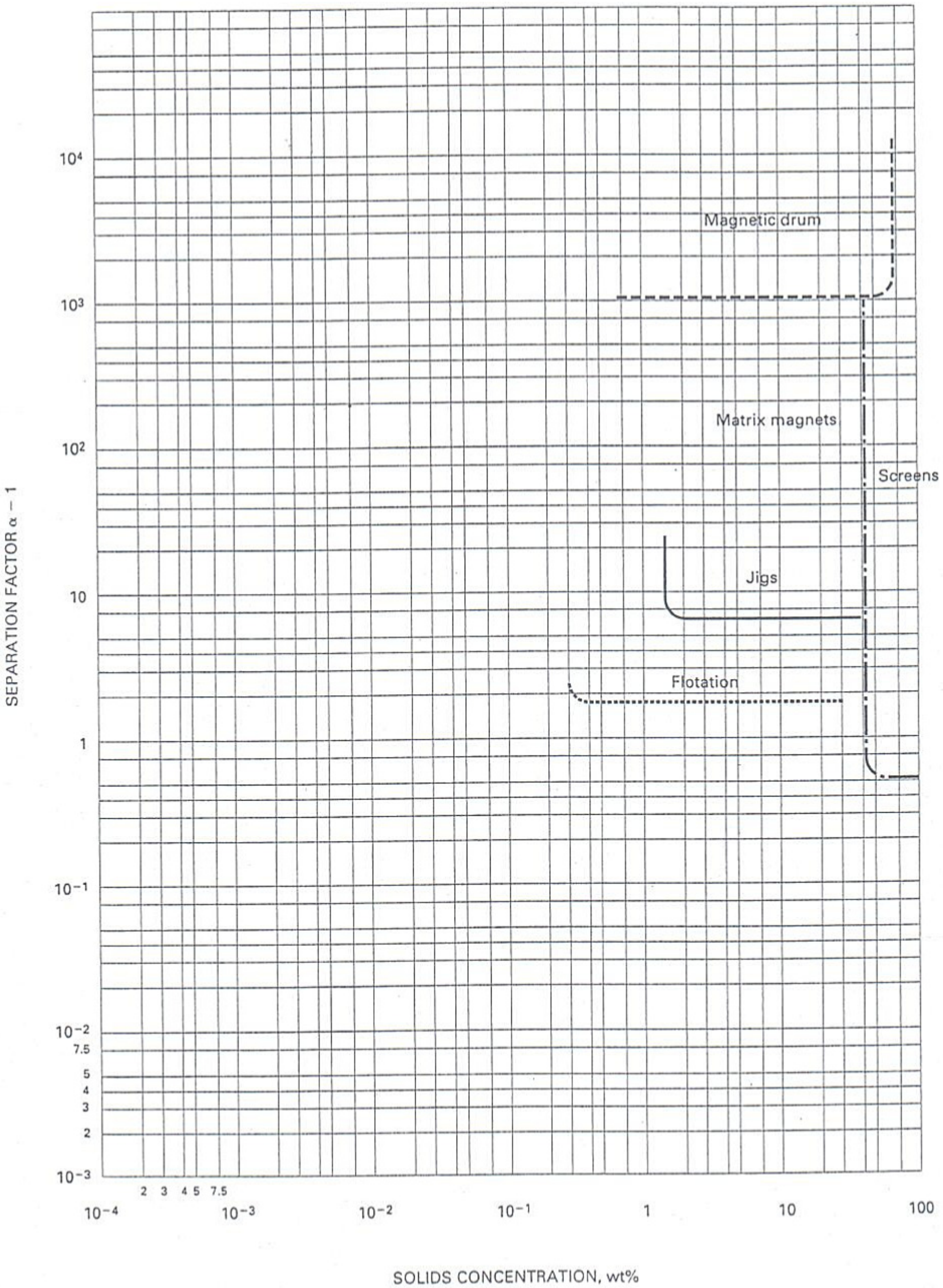


Figure 5–26 General Regions of Applicability for Solid-Solid Separations: Based on Separation Factor

TABLE 5-2. Definitions of separation factor a for solid-solid separations

Exploiting Difference in . . .	α	Definition and Example
Size	$\alpha = \frac{D_{p1}}{D_{p2}}$	D_p = diameter Screens, trommels, grizzlies
Size and density	$\alpha = \frac{v_1}{v_2}$	v = settling velocity rakes, tables, jigs, spirals
Electrical conductivity	$\alpha = \frac{\varepsilon_{r1}}{\varepsilon_{r2}}$	ε_r relative permittivity electrostatic separators
Wettability	$\alpha = \frac{S_{e1} - S_{e2}}{-\gamma}$	θ = contact angle induced draft flotation S_e = spreading coefft. γ = surface tension liquid
Solubility	$\alpha = \frac{K_1}{K_2}$	K = solubility in phase
Density	$\alpha = \frac{(\rho_1 - 1)}{(\rho_2 - 1)}$ or Bird no.	ρ = density
Magnetic permeability	$\alpha = \frac{\kappa_1}{\kappa_2}$	κ = magnetic susceptibility

9. a difference in **electrical charge at the surface of the particle.** Whenever two *neutral* phases are mixed, a small charge usually develops at the surface separating the phases. This can be because ions preferentially adsorb at the surface or are preferentially soluble in one of the phases. The overall system is neutrally charged; it must be! Therefore to provide this neutrality, locally near the surface will be an equal and opposite countercharge. Usually these charges go unnoticed because they are so small. However, if the size of the particles is below 1000 μm, then the charge can indeed dominate. An example of this occurs when we mix clay with water. The fine clay particles usually acquire negative charges because of the adsorption of OH^- ions. Because all the particles have similar charges, the clay particles remain suspended and do not clump together and settle out.

   The presence of the charges can be exploited by placing the charged particles in a DC field. Electroosmosis, electrophorésis, and electrodialysis are centered around this principle.

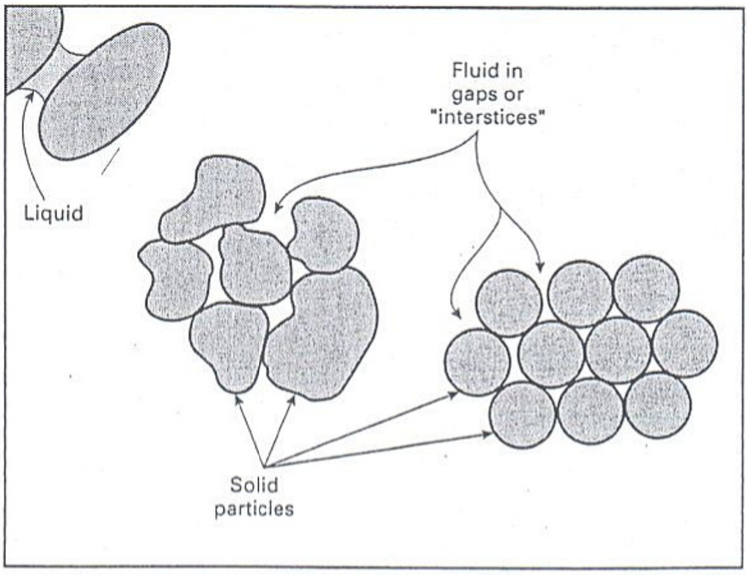


Figure 5–27 Fluids Fill Gaps Between Solid Particles

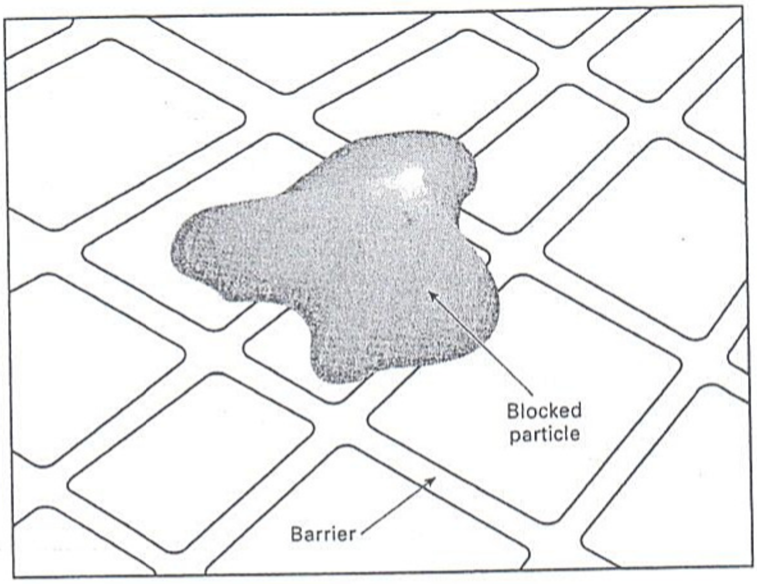


Figure 5–28 Physical Barrier Prevents Large Particles from Moving Through

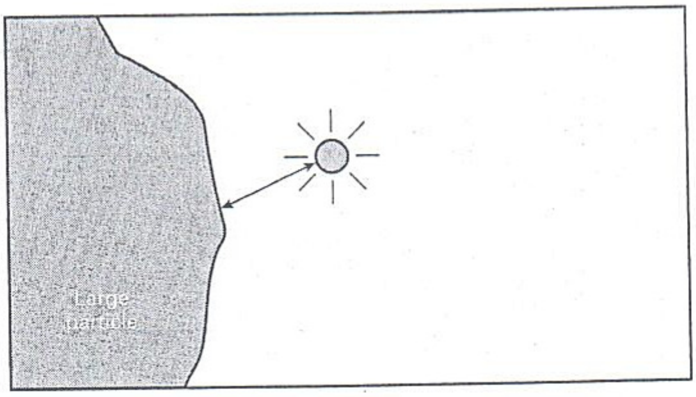


Figure 5–29 Large "Filter" Particle Attracts (Via van der Waals Force) Small Particle

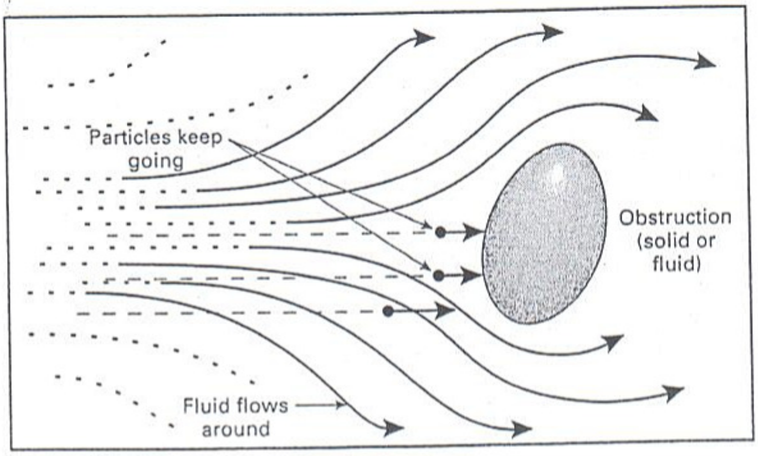


Figure 5–30 Particles Hit Obstacle

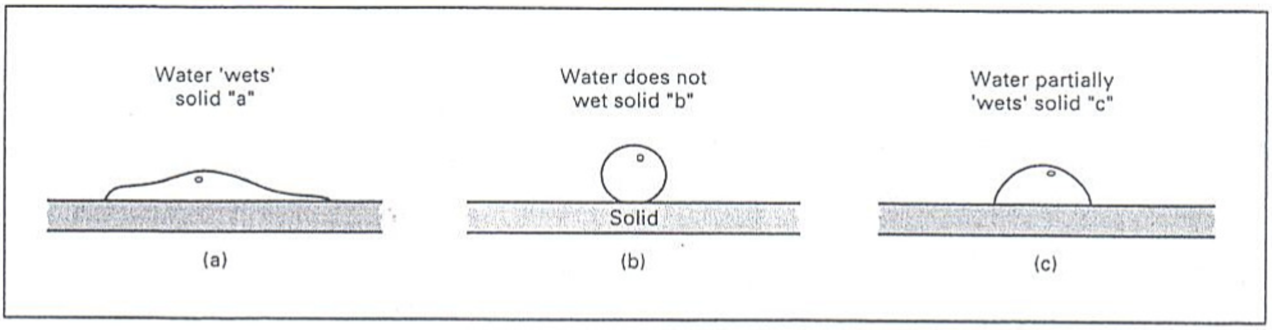


Figure 5–31 Water "Wets" Different Solids Differently

We can also recognize that this surface charge is the reason that particles might not separate out on a filter or by gravity. Hence, some of the other differences may not be able to be exploited until the surface charge has been controlled. This is the basis for coagulation and flocculation as a precursor to sedimentation or filtration.

10. a difference in **reactivity.** We can react one component to create new properties to be exploited; so we can react a two-phase system to create a homogeneous phase system. Then the principles of Chapter 4 can be exploited.

These then are the property differences that can be exploited. Tables 5–3 through 5–7 relate the names of the options to the property to be exploited for each of the different phase combinations. Actually, for many of the phase systems only a few options are available, and they may all exploit the same property difference.

B. Consider the Desired Characteristics of the Product. Another important distinguishing feature among options is based on the desired characteristics of the product. Three different classes of product specifications are common. For example, if we have a liquid-solid system we might have a goal:

1. to separate the solids from the liquid to create a "solid-free" liquid; this is illustrated in Figure 5–32a.
2. to separate the liquid from the solid to create a "liquid-free" solid; this is shown in Figure 5–32b.
3. to do **both** of the above. Figure 5–32c illustrates this.

The difficulty in easily getting both phases separated sharply occurs because the spaces or interstices between a bed of particles is filled with the other phase, as was illustrated in Figure 5–27. Because we are dealing with particles often we must appreciate three complications:

1. Not all of the particles may be the same size or shape. We account for this by identifying an average size, or a critical size pertinent for the separation. A "distribution" of particles is usually represented graphically as the number (or mass) of particles of a size less than a given size. This is called a cumulative plot. We can characterize the distribution by stating the mean or average and the standard deviation. The standard deviation represents the spread of the particles' sizes about the mean and is related to the "slope" of the cumulative plot. This is illustrated in Figure 5–33, where at the top is shown a *frequency* plot showing the "number" of particles of each size, where all the particles are the same size and where they are different. Below is shown the corresponding cumulative plot. The key point is that the larger the differences in particle size, the larger will be the standard deviation.
2. All beds of particles contain void volume, ε, between the particles. Even in the most tightly packed "bed" of particles, about 30 to 40% of the total bed volume consists of the interstitial volume, $\varepsilon = 0.3$ to 0.4. Figure 5–34 illustrates pictorially the void volume of liquid in a gas-liquid-solid system. Also shown are the typical product conditions for liquid-solid separations performed by different types of separators. Thus, gravity thickening will give a liquid porosity of between 0.8 to 0.9.

   The interstitial or void volume for a bed of particles depends on the degree of packing, the shape of the particles, and the size distribution, as represented by the standard deviation. Figure 5–35 illustrates this variation. Thus, a bed of tightly packed spheres with a standard deviation of 2 would have a porosity or interstitial volume of about 0.19.

   The key point is that with particulates, we do not easily get complete separation of the two phases. The "continuous" phase occupies the interstices. Some separation options can expel this fluid relatively easily; others, with difficulty.
3. Because of the porosity of beds of particles, the "density" of particles may be ambiguous. We can report the "solid" density of the pure solid (coal is 1.4 Mg/m^3); we can report the "bulk density" in air of the bed of particles (coal is 0.6 to 0.8 Mg/m^3).

TABLE 5-3a. Gas-liquid separations: Exploiting properties

Properties	Gravity	Centrifugal Field		+ Filter Media	+ Agent	± Heat	± Power or Mech. Agitation
		via Mechanical	via Pressure				
Vapor Pressure							
Size							
Size and density	knock out pots		cyclones		wet scrubbers		
Density							
Wettability					demisters		
Solubility							
Electrical conductivity							
Magnetic permeability							
Electric charge							
Reactivity					Combustion		

TABLE 5-3b. Gas-liquid separations: Effect of product recovery requirements

Recover Gas	Combustion, wet scrubbers
Recover both	Knock out pots, cyclones, demisters
Recover Liquid	

TABLE 5-4a. Gas-solid separations: Exploiting properties

Properties	By Gravity	Centrifugal Field		+ Filter Media	+ Agent	± Heat	± Power or Mech. Agitation
		via Mechanical	via Pressure				
Vapor Pressure							
Size				filters			
Size and density	knock out pots		cyclones		wet scrubbers		
Density							
Wettability							
Solubility							
Electrical conductivity							Electrostatic precipitator
Magnetic permeability							
Electric charge							
Reactivity					Combustion		

TABLE 5-4b. Gas-solid separations: Effect of Product recovery requirements

Recover Gas	Combustion, wet scrubbers
Recover both	Cyclones, precipitators, filters
Recover Solids	Wet scrubbers with subsequent L-S separation

TABLE 5-5a. Liquid-liquid separations: Exploiting properties

Properties	By Gravity	Centrifugal Field		+ Filter Media	+ Agent	± Heat	± Power or Mech. Agitation
		via Mechanical	via Pressure				
Vapor Pressure							
Size				Deep bed filters			
Size and density	decanters	centrifuges sedimentation type	hydrocyclones				
Density							
Wettability	dissolved air flotation				Fibrous bed coalescers Dissolved air flot.		
Solubility							Solvent extraction
Electrical conductivity							
Magnetic permeability							
Electric charge							
Reactivity							

TABLE 5-5b. Liquid-liquid separations: Effect of product recovery requirements

	No coalescence occurs	Complete coalescence occurs
Recover the dispersed phase	Solvent extraction	
Recover both phases	decanters, hydrocyclones, centrifuges (but there is interstitial cross contamination)	decanters, solvent extraction, with no interstitial cross contamination
Recover continuous phase	Dissolved air flotation, deep bed filters, solvent extraction, fibrous bed coalescers	dissolved air flotation, deep bed filters, hydrocyclones, centrifuges and fibrous beds

TABLE 5-6. Liquid-solid separations: Exploiting properties

Properties	By Gravity	Centrifugal Field		+ Filter Media	+ Agent	± Heat	± Power or Mech. Agitation
		via Mechanical	via Pressure				
Vapor Pressure						drying freeze drying	
Size	deep bed filter	filtering centrifuge		expeller, hydraulic press filter			screens, grizzlies, bar screens trommels
Size and density	settling basin thickener elec.	sedimentation centrifuge	hydrocyclones				
Density							
Wettability	dissolved air flotation				dissolved air flotation		
Solubility					leaching		
Electrical conductivity							
Magnetic permeability							
Electric charge							electroosmosis
Reactivity							

TABLE 5-7. Solid-solid separations

Properties	By Gravity	Centrifugal Field		+ Filter Media	+ Agent	± Heat	± Power or Mech. Agitation
		via Mechanical	via Pressure				
Vapor Pressure							
Size				screens, trommels, grizzlies			screens, trommels, grizzlies classifiers
Size and density							rakes, jigs, tables, sprials
Density					dense media separation		
Wettability					induced draft flotation		
Solubility					leaching	dissolution	leaching
Electrical conductivity							electrostatic eddy current
Magnetic permeability							magnetic
Electric charge							
Reactivity							

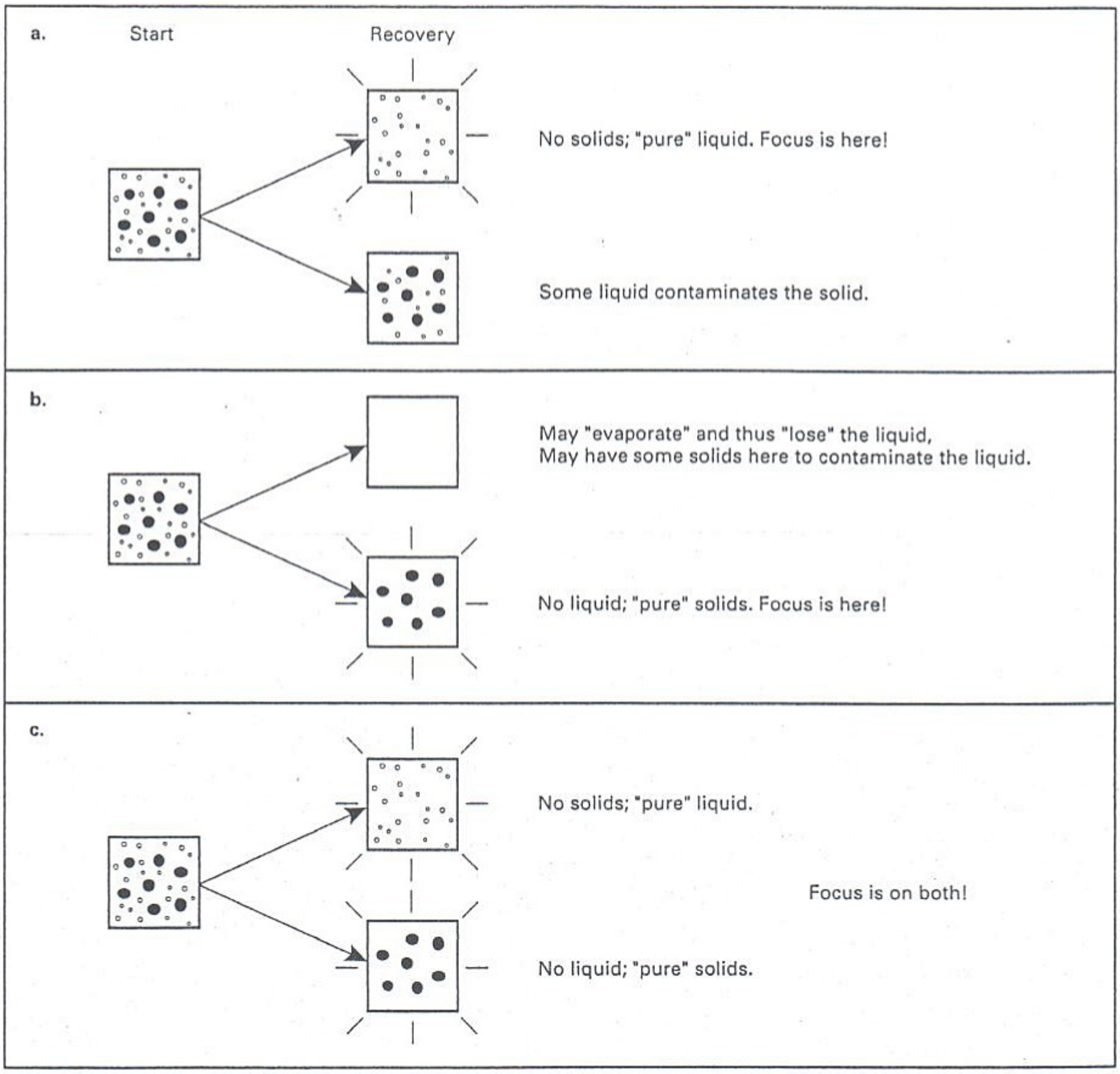


Figure 5–32 Different Targets for Recovery
a) Creating a "Solid-Free" Liquid
b) Creating a "Liquid-Free" Solid
c) Creating Both a "Solid-Free" Liquid and a "Liquid-Free" Solid

Thus, for particulate systems we must clearly identify what products we are trying to obtain: recover "pure" solids, recover "pure" liquids, or recover both. Different equipment options are suited for different specifications. This is qualitatively illustrated for liquid-solid systems in Figure 5–34, where the target solid concentration possible from different options is presented. In the next section, the effect of product specifications is outlined for each type of phase combination, where appropriate.

C. Putting It All Together: Exploiting the Property Difference and the Product Specifications. Now that the principles have been introduced in sections *A* and *B*, we consider the application of these principles to the selection of separation options. We consider each combination of phases in turn.

1. Gas-Liquid. For **gas-liquid** systems, the options are predominantly based on size-density differences as illustrated in Table 5–3a. Table 5–3b illustrates that many of the options recover both the liquid and the gas. Combustion and wet scrubbers would recover the gas but would destroy the liquid in the process. Hence if we wanted to recover the liquid, neither of these two options would be attractive. No method is designed to recover only the liquid. Essentially Figure 5–2 is an acceptable basis for selection.

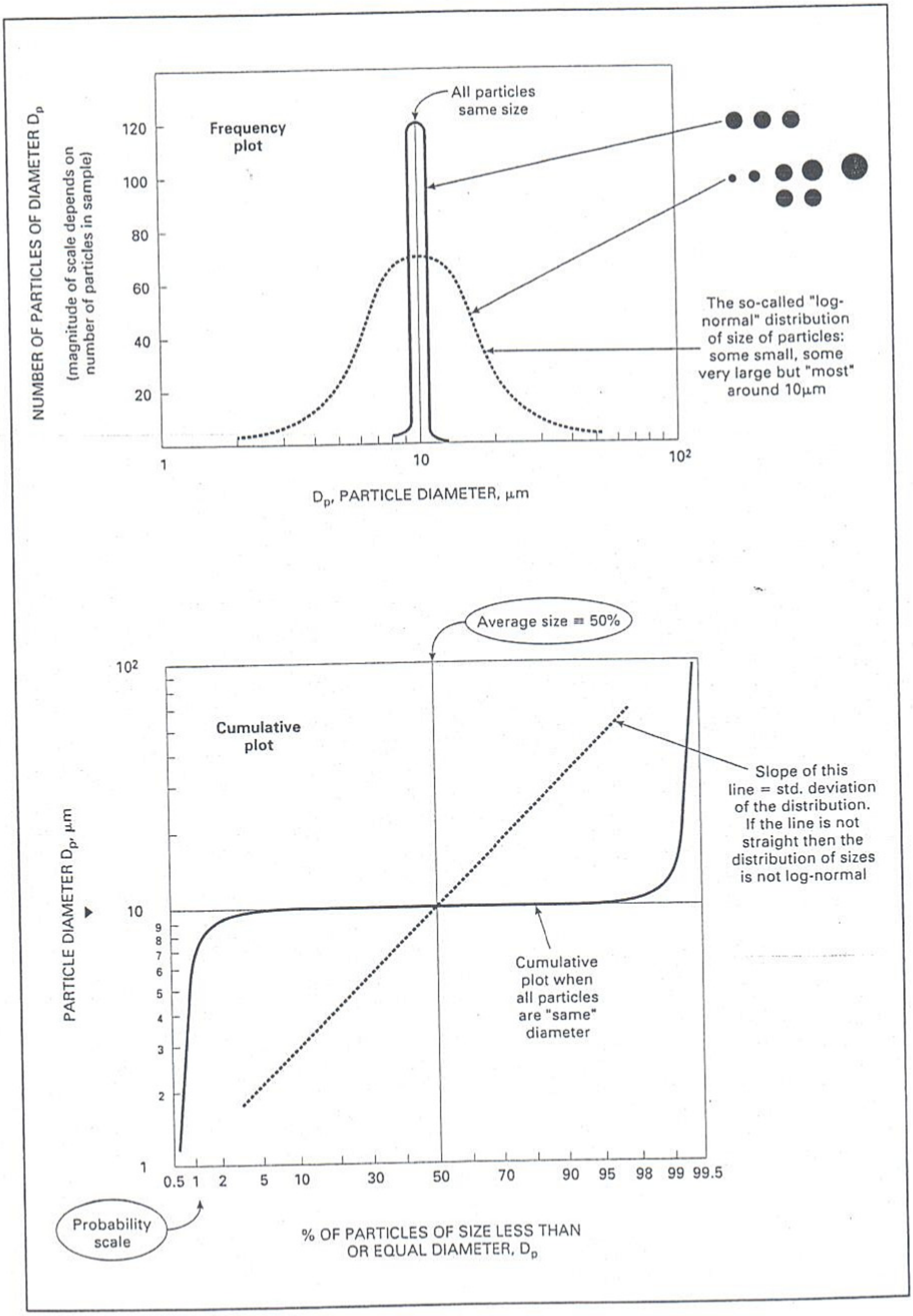


Figure 5–33 Reporting Particle Size Characteristics When There Is More Than One "Size"

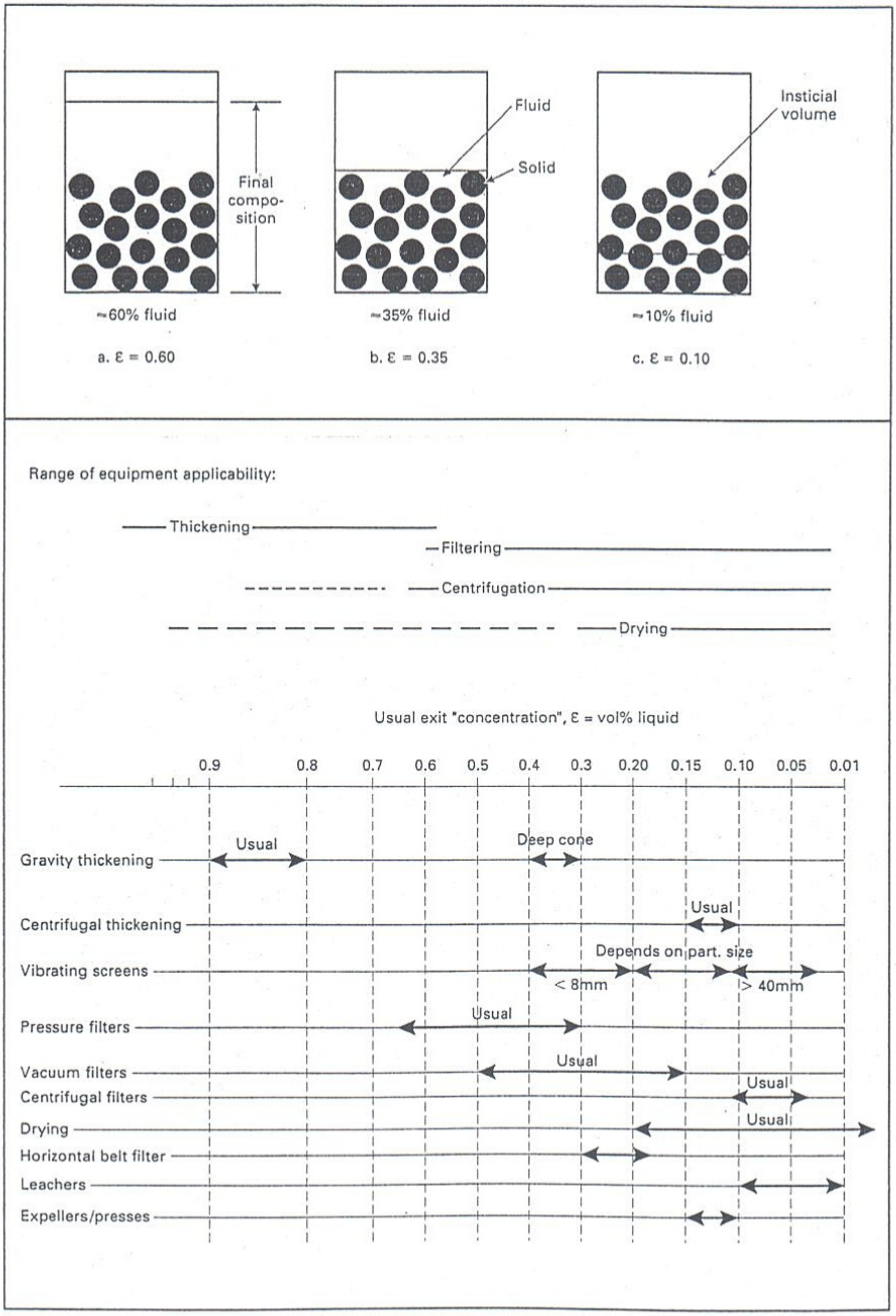


Figure 5–34 Relating Solid, Fluid, and Interstitial Volumes to the "Usual" Exit Concentrations for Different Equipment Alternatives

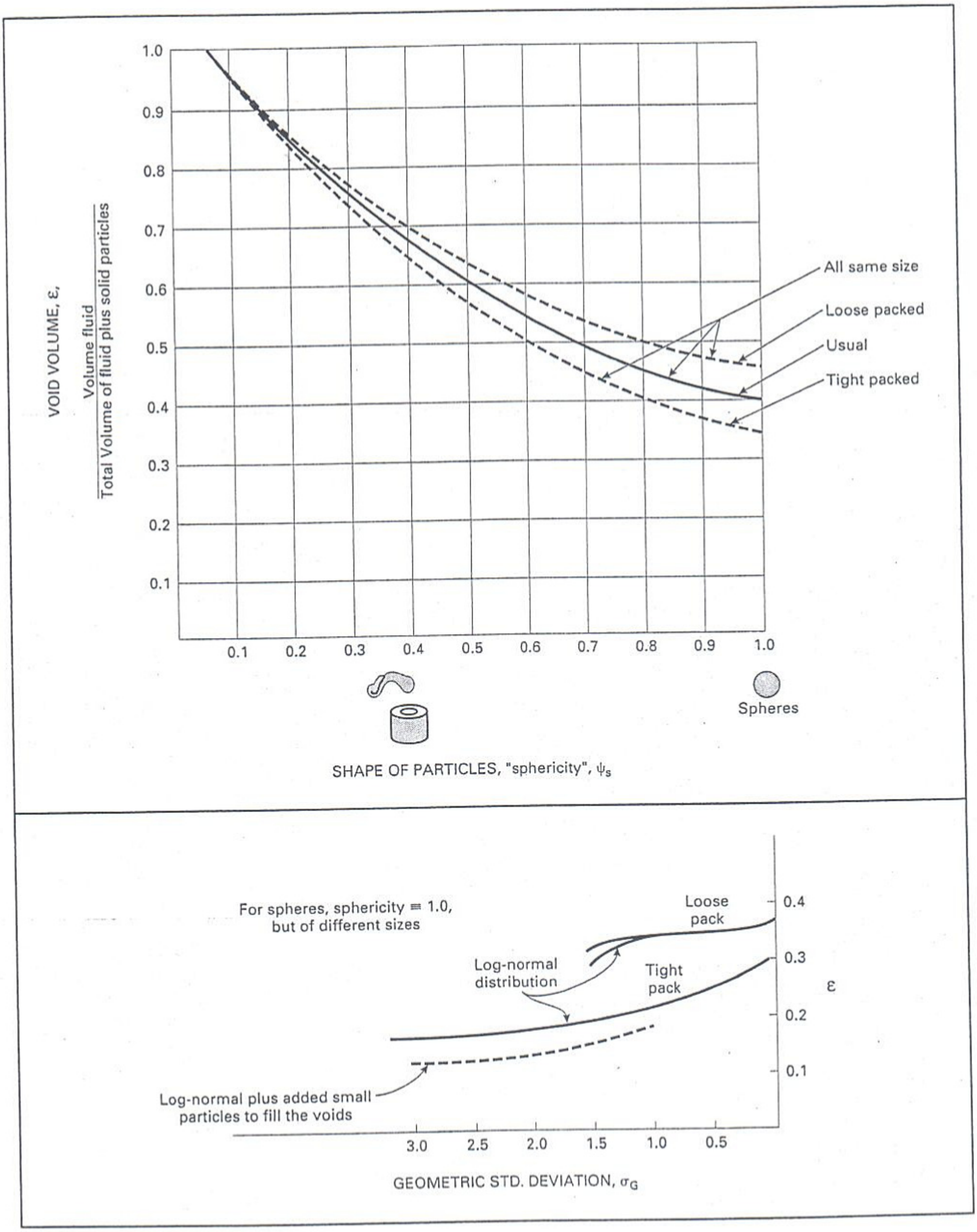


Figure 5–35 Porosity of Particulate Beds

2. Gas-Solid. For **gas-solid** systems, size-density differences offer the major basis as shown in Table 5–4a. However, size or electrical conductivity offer other choices. For electrical conductivity to be attractive, the conductivity of the solid particulates should be greater than 10^{-10}/ohm-cm. Thus, damp ferrous oxide or damp aluminum oxide meet this criterion, but these same particulates *dry* do not.

Table 5–4b shows the effect of recovery expectations; wet scrubbers and combustion make it difficult, if not impossible, to recover the solids (although they can remove the solids from the gas). Some options provide a separate gas and a recovered solid stream. (For the solids, the interstices would likely be contaminated by the gas). This information, together with Figure 5–4, provides an acceptable basis for initial selection.

3. Liquid-Liquid. **Liquid-liquid** systems are challenging. A variety of options are available as illustrated in Table 5–5. What can have a great impact on the recovery of the two separate phases are:

- the mutual solubility of the liquids for each other. This can place constraints on the purity of the products before we even consider separation options;
- whether the dispersed phase "coalesces" into one large layer or whether the drops remain as drops and thus we are limited by the concentrations illustrated in Figure 5–34 and by interstitial cross-contamination.

The property being exploited in Table 5–5 assumes that *coalescence* is not important. Table 5–5b shows that if coalescence is made to occur, a different set of options is available. Consider this table in more detail. When negligible coalescence occurs, only solvent extraction can yield a relatively pure recovered phase from the dispersed liquid. Decanters, hydrocyclones, and centrifuges can give a relatively pure continuous phase and can separate the uncoalesced "band of drops." However, the band of drops will be cross-contaminated with the continuous phase in the interstices. Hence, we cannot get a recovered "dispersed phase" that is very pure. On the other hand, dissolved air flotation, deep bed filtration, and coalescers will produce a "clean" recovered continuous phase; however, it is extremely difficult to recover the dispersed phase.

When complete coalescence does occur or is required, both decantation and solvent extraction will yield relatively pure streams of both recovered fluids. However, hydrocyclones and centrifuges usually have such short residence times that coalescence is unlikely to occur even in rapidly coalescing systems. Furthermore, for liquid-liquid systems, care is needed in selecting centrifugal devices because the forces acting on the dispersed drops might *break up* the drops and more intimately disperse the phases rather than achieve the goal of separating the phases. (A brief word about coalescence. Although the coalescence between isolated drops may take only milliseconds, the coalescence of groups and clusters of drops usually takes on the order of 2 to 5 min. Furthermore, coalescence is extremely sensitive to the presence of trace quantities of contamination and to surface charge. Thus, for screening studies it is more conservative to assume the coalescence *does not* occur. On the other hand, when the target recoveries require that coalescence occur, procedures are available to size options based on coalescence as the controlling mechanism. [For details see Woods, 1993] The approach at the "selection" stage is to select options where complete coalescence is possible. This is more likely to be achieved in gravity devices than in centrifugal devices.) Electrodecantation facilitates drop migration and perhaps coalescence.

The dominant characteristic to be exploited for liquid-liquid separation is the *size-density* that affects the velocity of the droplets. Figure 5–36 shows the settling or rising velocity of drops, bubbles, or particulates as a function of size and density. This is based on Stokes's law for single droplets rising through water at 20°C. (This figure is analogous to Figure 3–26 which showed Stokes's law for particles in air.) The "usual" drop size for emulsions is for liquid-liquid surface tensions of about 30 mN/m and where the liquid mixture has not been subjected to pumping or excessive shear. The drop size decreases with a decrease in surface tension and increase in shear. Figure 5–37 shows the regions where different types of devices are used depending on the settling velocity of the dispersed phase and the flowrate of the continuous phase. Thus, if the droplets are very small we might add coalescence promoters; if the density difference is very small, then centrifugal devices should be considered. The overall result of this analysis yields information that is similar to that given on the size-concentration chart in Figure 5–6. Thus, for screening, Figure 5–6, combined with the product recovery expectations in Table 5–5b, is the prime basis for selection. The choices are sensitive to the need for coalescence to occur.

Example 5–3: We have a hexane-water mixture that is 43% v/v water. The temperature is 60°C and the density difference is 0.33 Mg/m^3. The feed flowrate is 0.3 L/s. Our goal is to recover the "pure" hexane so that it can be reused in the process. The recycled hexane should not be cross-contaminated with anything other than the mutually soluble water because this is a food-processing operation. We also want "pure" water so that we can dispose of it through our waste treatment facilities. Assume that hexane is the dispersed phase. What options might we select? The feed flows from a condenser.

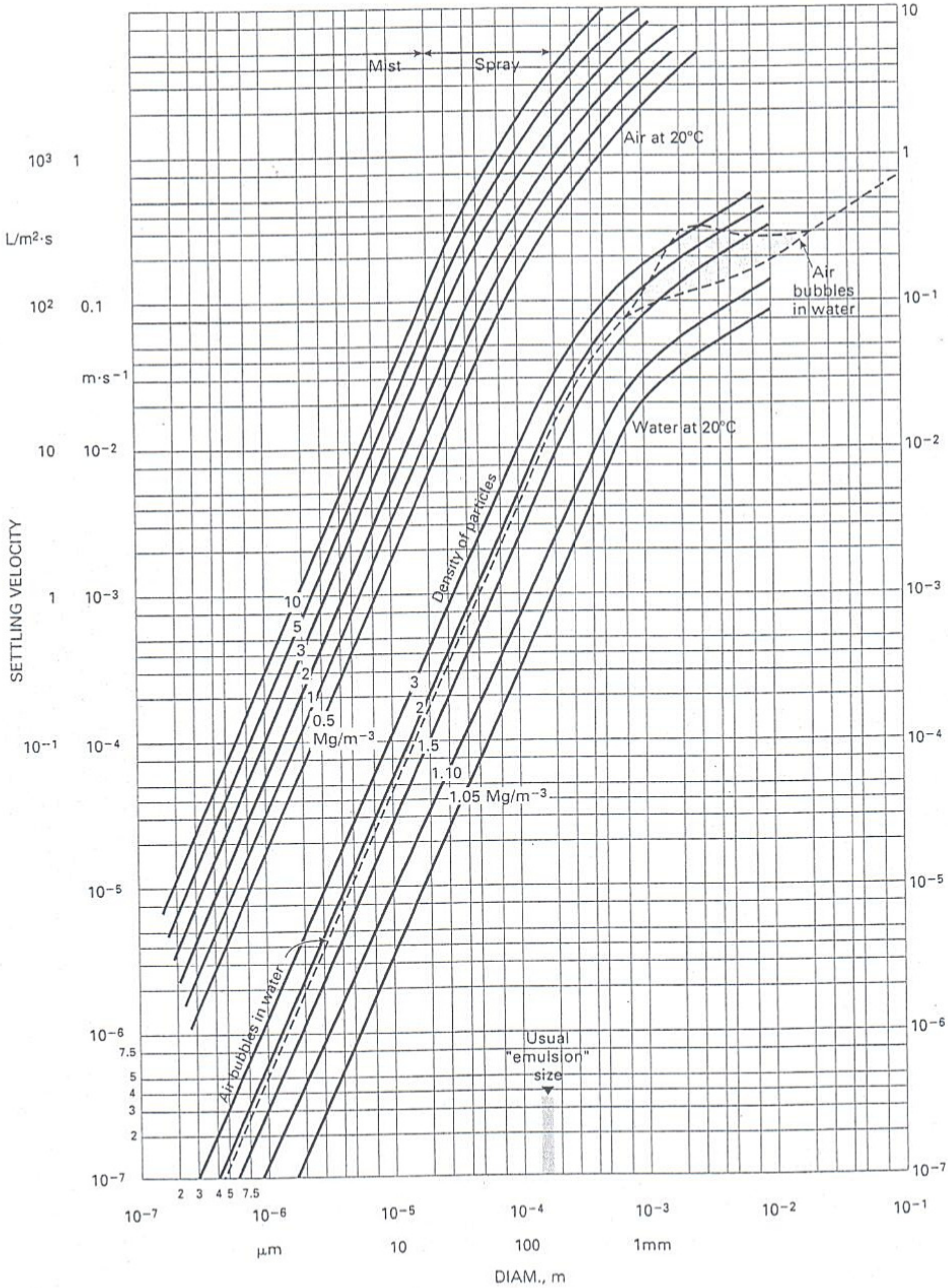


Figure 5–36 Settling Velocity of Single Particles in Air or Water

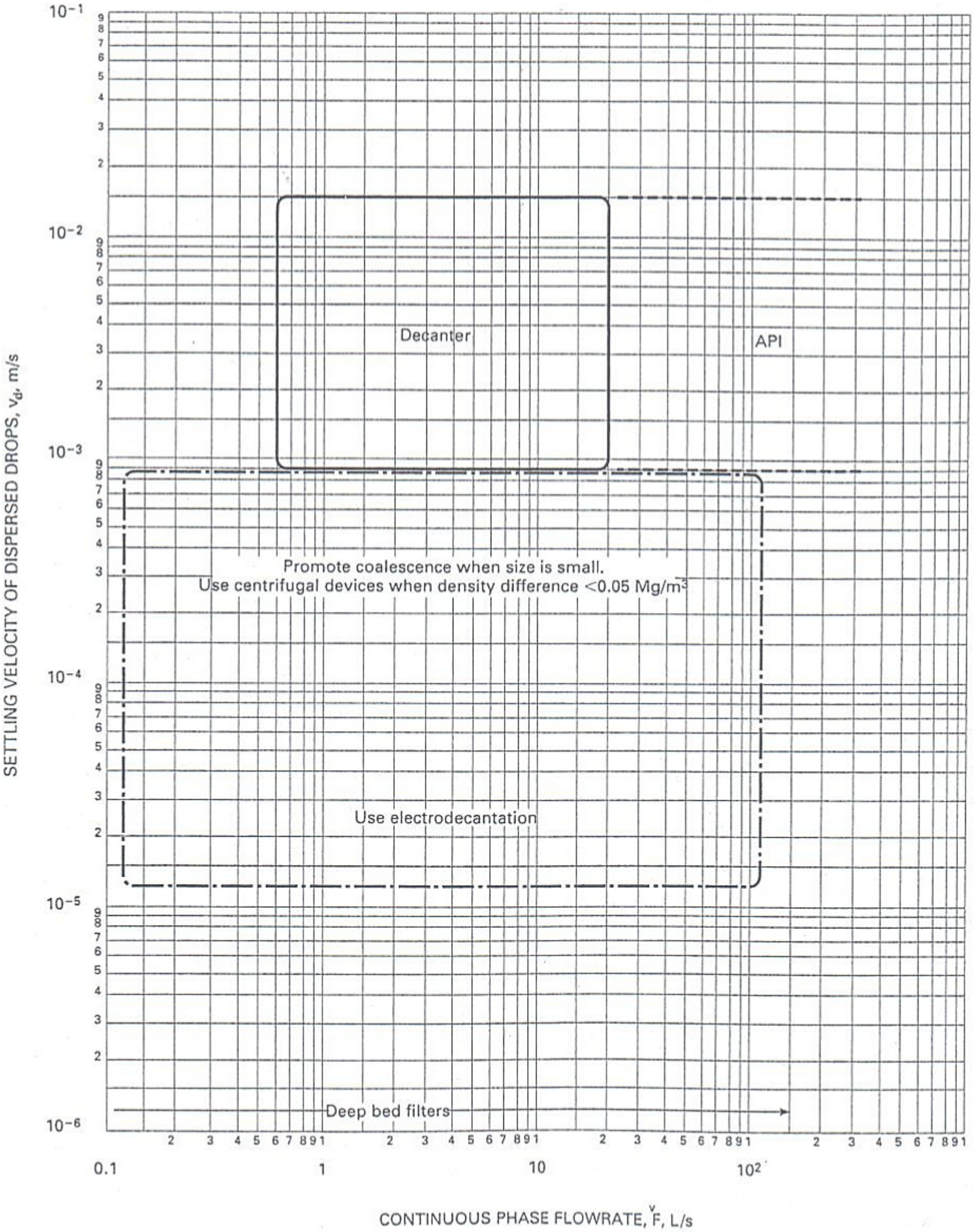


Figure 5–37 General Regions of Applicability for Liquid-Liquid Separations: Based on Settling Velocities and Flowrates

An Answer: First, we need to estimate reasonable values for the drop size. We do not know the diameter of the drops. The source of the drops is condensation and the hexane-water mixture flows by gravity into the proposed device. Hence, the liquid should not have been subjected to excessive shear and the drop size is probably "the usual" size of about 100 to 200 μm, as shown on Figure 5–36 and Figure 5–6.

Next, consider the implications of the recoveries. Here, we expect to recover both phases as "pure" phases (apart from cross-contamination by mutual solubility). This means that all the dispersed phase must coalesce. At this stage we do not know enough about the contamination or about the coalescing characteristics of this system. Hence, the best we can do is to try to select options where there is the potential for coalescence. Usually this means that centrifugal devices would not be options. Fortunately, the density difference is relatively large, at 0.33 Mg/m^3, and, from Figure 5–37, gravity options seem viable. From Table 5–5b, decanters and solvent extraction are possible. The requirement of no new contamination for the hexane rules out solvent extraction.

Consider now the size-concentration and settling velocity-flowrate implications. From Figures 5–6 and 5–37, decanters seem applicable.

Comment: More on predicting drop size from flowrate conditions is given by Woods and Diamadopoulos (1988). A decanter was used for this option in industry.

Example 5–4: In the alkylation plant light hydrocarbon is scrubbed with caustic solution to remove the acidity. The resultant liquid-liquid mixture needs to be separated. The caustic is being recirculated and may be a mixture of caustic drops in hydrocarbon. The continuous phase, the hydrocarbon, must be recovered as a "pure" phase. The total feed flowrate is 7.6 L/s and is 22% caustic. Assume caustic is the dispersed phase. What options might we consider? The density difference is about 0.58 Mg/m^3. The viscosity of the continuous phase is 0.1 mPa.s.

An Answer: First, we need to estimate reasonable values for the drop size. The source is from a contactor but we do not know if the mixture is pumped after the contactor. Assume that it is not. Hence, the liquid should not have been subjected to excessive shear and the drop size is probably "the usual" size of about 100 to 200 μm, as shown on Figure 5–36 and Figure 5–6.

Next, consider the implications of the recoveries. Here, we expect to recover only the continuous phase. From Table 5–5b, just about all the options are available. The density difference is large, at 0.58 Mg/m^3, and, from Figure 5–37, gravity options seem viable.

Consider now the size-concentration and settling velocity-flowrate implications. From Figure 5–6, decanters, hydrocyclones, and centrifuges are options.

Comment: Hydrocyclones are viable options for non-coalescing requirements provided the surface tension between the liquids is higher than 10 mN/m. This is true for caustic and the hydrocarbon system.

Example 5–5: Solvent extraction is a stagewise contacting of the liquid with a solvent. Assume that we are contacting water containing penicillin F with amyl acetate. The density difference is about 0.11 Mg/m^3; the surface tension is 9.2 mN/m. Solvent to water ratio is about 1:1. How might we separate the two phases after the mass transfer in one stage is finished? We want both phases recovered with the minimum of cross-contamination from one stage to the next in the processing.

An Answer: This is an interesting situation. Usually we do not consider the phase separation in isolation from the solvent extraction, as considered in Chapter 4. Nevertheless, let's explore just the separation aspect.

First, we need to estimate reasonable values for the drop size. We do not know the diameter of the drops. The source of the drops depends on the type of contactor used. For the usual mixer settler or for pulsed systems the drop size is about 1 to 2 mm. In other words, these are usually about 10 times larger than shown in Figure 5–6. However, for this system the surface tension is 9.2 mN/m, whereas for most systems it is between 20 and 30 mN/m. Thus, the drop size will be much smaller than 1 to 2 mm. Let's assume that they are about 100 µm.

Next consider the implications of the recoveries. Here, we expect to recover both phases as "pure" phases (apart from cross-contamination by mutual solubility). This means that all the dispersed phase must coalesce. At this stage we do not know enough about the contamination or about the coalescing characteristics of this system. Hence, the best we can do is try to select options where there is the potential for coalescence. Usually this means that centrifugal devices would not be options. Unfortunately, the density difference is relatively small, at 0.11 Mg/m^3, and, from Figure 5–37, perhaps centrifugal devices may be required.

Consider now the size-concentration and settling velocity-flowrate implications. From Figures 5–6 and 5–37, centrifuges and decanters seem applicable. Perhaps because of the low density differences we might have to go to a centrifugal device despite the challenges of getting complete coalescence.

Comment: The product of the surface tension and the density difference is about 1 Mg/m^3. mN/m. From Section 4.2-9, this suggests that a centrifugal device is appropriate for solvent extraction.

Example 5–6: A waste water stream from an API separator contains 130 ppm of immiscible oil. We wish to recover the water only. What might we do? The flowrate is 4 L/s. Assume the density difference is 0.20 Mg/m^3 and that the surface tension is about 30 mN/m.

An Answer: First, we need to estimate reasonable values for the drop size. We do not know the diameter of the drops. The source and pumping history of the stream are not given. Assume that the drop size is probably "the usual" size of about 100 to 200 µm, as shown on Figures 5–36 and 5–6.

Next consider the implications of the recoveries. Here, we expect to recover only the water of continuous phase. Hence, from Table 5–5b most of the options are available. Consider now the size-concentration and settling velocity-flowrate implications. From Figures 5–6 and 5–37, deep bed filters or dissolved air flotation may be feasible options.

Comment: For more on the separation of dilute oil-water mixtures and the surface phenomena that affect these separations see Woods and Diamadopoulos (1988). From Figure 5–41, given later in this section under liquid-solid separations, we might expect about 80% removal for dissolved air flotation. The data for deep bed filtration suggest that this concentration, at 100 ppm or mg/L, is higher than is often used in deep bed filters. However, data summarized by Woods and Diamadopoulos (1988; p. 512) suggest that for this concentration about 60 to 70% oil is removed by deep bed filtration.

4. Liquid-Solid. For **liquid-solid** systems we have a wide range of choice. Table 5–6 illustrates the type of property difference that can be exploited. From Figures 5–7 through 5–16 we note that there is a wide range of equipment—even within the same class—and a lot of apparent overlap on the size-concentration diagrams of Figures 5–10 and 5–16. Consider the properties that we wish to exploit in the same sequence as given in Table 5–6.

- For *vapor pressure* differences, drying is the option. This is appealing when we wish to recover the *solid.* Usually the liquid, which has been vaporized, is not recovered.

The specific type of dryer is chosen based on the condition of the feed, the expected form of the final product, and the temperature sensitivity of the solid. Table 5–8 illustrates how the type of feed material affects the choice. (The descriptions may be a little misleading because, for example, "thin liquids" sounds as though there are no solids present when indeed solids are or will be present.) Table 5–9 shows how the form of the product affects the choice. Table 5–10 illustrates qualitatively that the temperature sensitivity of the solid also affects the choice of configuration. Especially for temperature sensitive solids, leaching and expellers may be appropriate, as given by the general regions shown in Figure 5–16. Thus, Figures 5–10 and 5–16 can be used to identify the general region when drying might be appropriate; Tables 5–8 through 5–10 guide us in selecting the special type of dryer. Dryers recover the solids.

- For *size* differences, basically a screen or filter is the choice. However, the particles also might have a density different from the liquid and so will have a difference in settling velocity. Let's focus first on exploiting size difference. Options are basically "filters." However, the terminology can be confusing. For large-size particles, the term *filter* is replaced with such terms as *trommel* (a rotating filter), *screen* (a filter cloth on a frame), and *grizzly* (a filter cloth made up of rods and bars). We can also place a screen in a centrifugal field to obtain a "filtering" centrifuge. These are distinct from "sedimentation" centrifuges

TABLE 5-8. How feed condition affects choice of dryer

Type of Feed Material	Indirect Contact		Direct Contact	Vacuum	
	Conduction	Convection	Convection	Conduction	Convection
Thin liquids	single drum, pan, dielectric	spray	spray	freeze, pan	
Thick liquids (slurries)	double drum, pan, dielectric	spray	spray	freeze, pan	
Soft, paste-like	double drum, pan, dielectric			freeze, pan	
Stiff, paste-like	double drum, pan, dielectric		tunnel, disk, screen, belt, trough	shelf, belt, conveyor, freeze, pan	belt, conveyor, shelf
Moist, crumb-like	pan, screw, vibrating tray, steam rotary, dielectric	steam rotary, vibrating tray	agitated, paddle, rotating drum, tunnel, disk, fluid bed, pneumatic	kneader, shelf, freeze, pan	
Powdery, grained, grit-like <150 µm	pan, screw, vibrating tray, steam rotary, dielectric	steam rotary, vibrating tray	agitated, paddle, rotary, tunnel, disk, fluid bed, pneumatic	shelf, freeze, pan	
Granular lumps >150 µm	pan, screw, vibrating tray, steam rotary, dielectric	steam rotary, vibrating tray	shelf, tunnel, belt	shelf, freeze, pan, steam rotary	steam rotary
Coherent sheets	cylinder			freeze	
Discontinuous sheets		shelf, belt, tunnel	shelf, belt, tunnel	shelf, freeze	shelf
Shaped pieces lumber, pottery	dielectric	shelf, belt, tunnel	shelf, belt, tunnel		

TABLE 5-9. Effect of product temperature sensitivity on options

Temperature Sensitivity	Temperature Difference °C	Some Examples	Options	
			Dryers:[*] Classes	Other Options
Extremely sensitive	<5	Pharmaceuticals, antibiotics, penicillin, some foods	Indirect vacuum conduction, vacuum conduction, freeze dry	Expellers, leachers, "solvent extraction"
Very sensitive	5 to 10		Most drying options possible except direct convection	Expellers, leachers, "solvent extraction"
Sensitive	10 to 40		Direct or indirect convection plus indirect conduction	
Moderately insensitive	40 to 100	Polymers, dyes, organic pigments, general organics	Direct and/or indirect convection	
Insensitive	100 to 150	General inorganics	Direct convection	

[*] For examples of devices in each class, see Table 5-8

that do not have a filter cloth or screen inside. Often the term *imperforate* or *solid* bowl will be used to describe sedimentation centrifuges. The pictures in Figure 5–8 for sedimentation centrifuges should be contrasted with those in Figure 5–9 for "filtering" centrifuges. In this section, we focus on filtering centrifuges.

For screens and filters, select the class of screening device based on the size of particles; then within a class, select the type based on the concentration. For example, Figure 5–13 shows the type of filter to use; Figure 5–12 shows the type of "filtering" centrifugal filter to use. (Precaution: only the centrifuges in Figure 5–12 operating at concentrations greater than about 10% are filtering centrifuges. They are described by the terms *basket, conical screen, pusher, horizontal screen bowl,* and *vertical conical screen.* Figure 5–11 is for sedimentation centrifuges.)

If the size of the particle is too small for any of the options, we can add a filtering aid or use a precoat. One approach is to add a filtering aid to the feed. A filtering aid is a coagulant or flocculant (such as starch, added to increase the size of the species in the feed) or diatomous earth or perlite particles (which are bigger particles that collect on the filter cloth together with the target species). Filter aids adjust the "permeability" of the filter media to be equivalent to filtering particles of about 1 to 8 μm. Figure 5–38 illustrates how the particle size is related to the "permeability" of a cake of such particles and to different filtering conditions and cake conditions. Filter aids can be used with almost any type of filter.

Another approach is to leave the feed alone and to alter the filter cloth with a precoat. Such a precoat deposits, on the filter cloth, a "mini-deep bed" of larger-sized particles, say about 1 to 10 μm. Usually a precoat is added to a drum or rotary filter so that as filtration proceeds, a thin layer of the product plus the precoat can be shaved off each revolution with a "doctor knife." We refer to this as precoat filtration.

Recovery considerations for "filters" (excluding screens, trommels, and bar screens) are summarized in Table 5–11. Depending on how the filter is backwashed and run, the solids may be reasonably dry. Figure 5–34

TABLE 5-10. How product specifications affect dryer choice

Product Expectations	Type of Dryer
Powder	Spray
Flakes	Drum
Solid cake	Pan

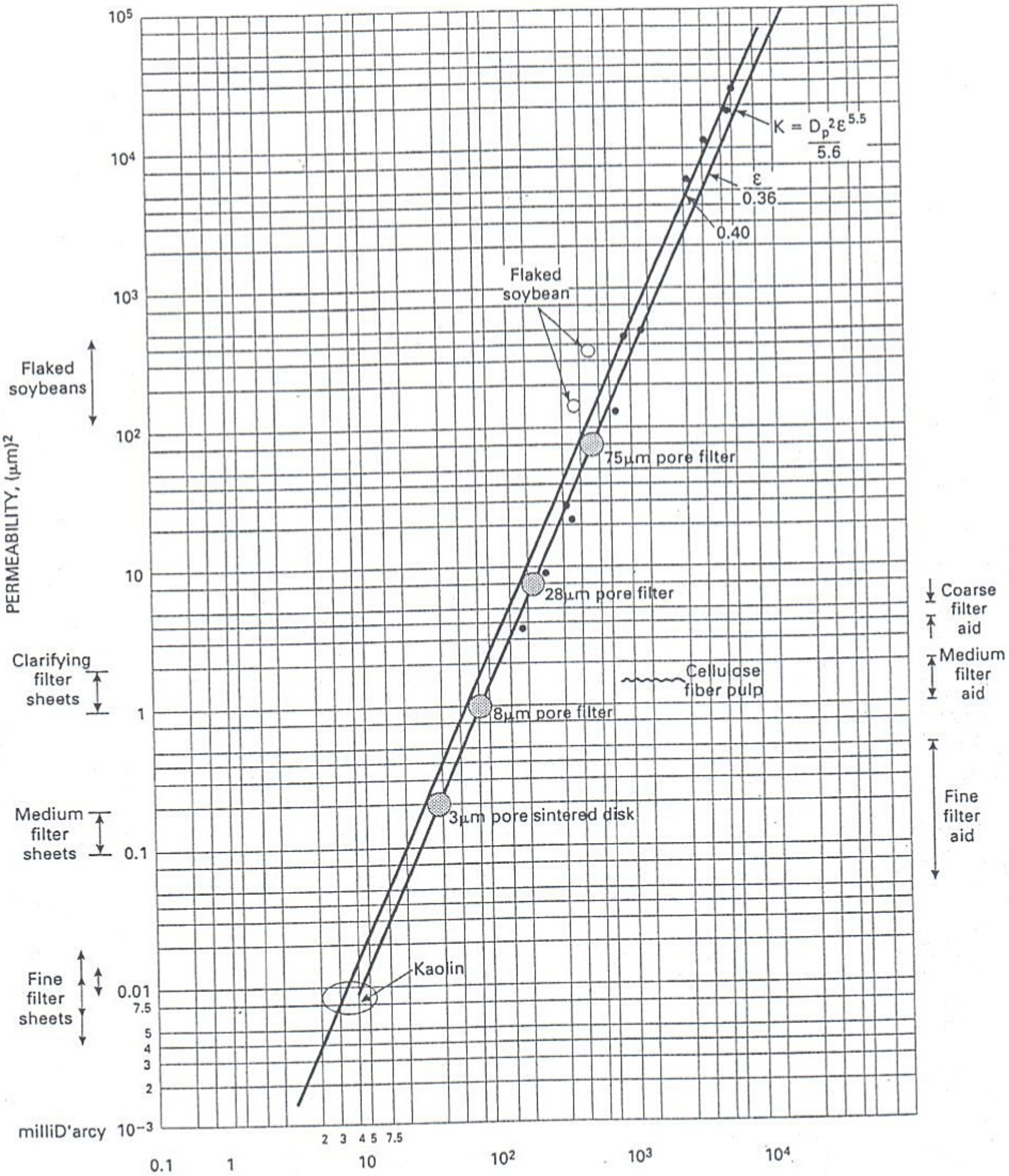


Figure 5–38 Permeability of Porous Media

TABLE 5-11. Effect of recovery on choice of filters

	Gravity or Pressure	Centrifugal
Recover Liquid	1. Deep bed, horizontal vacuum, pressure leaf, gravity flat table. 2. Gravity flat table 3. Cartidge 4. Precoat drum 5. Plate and Frame	Vertical basket (A,B)*
And high liquid viscosity	1. Plate and frame	Horizontal (H)
Recover Solid	For large sized particles: Expellers and presses (drying?)	Usually the solids are "dry." Basket centrifuge Batch automatic, auto vertical basket (const. speed) horizontal basket (var. speed) Continuous: conical screen, scroll conveyor; conical screen, oscillating cylindrical screen with pusher conveyor Horizontal solid screen scroll conveyor
With good washing	1. Pressure, vacuum, gravity table/pan 2. Horizontal pressure or vacuum 3. Horizontal belt 4. Vacuum drum 5. - - - - - - - - - - - - - - - -> 6. Plate and frame	Vertical basket overdriven (C)* Vertical basket underdriven (A,B) Horizontal batch (E) Cylindrical screen scroll discharge (F)
And crystals break easily	1. Gravity, vacuum table/pan 2. Vacuum, pressure, gravity drum 3. Plate and frame	
And cake compressible	1. Low pressure rotary vacuum drum	

*(Letters refer to the filtering centrifuge type shown in Figure 5-9)

provides guidelines. In Table 5–11, priority is shown, where appropriate, by the numerical sequence listed with the options. Thus, to recover solids and provide good washing, the first choice is usually a pressure, vacuum, gravity table, pan filter, or an overdriven vertical basket centrifuge. Beside some of the descriptions of filtering centrifuges is a code letter that refers to the sketches shown in Figure 5–9. Expellers and presses apply to large-size particles where the main function is to recover either solid or liquid. The range of application is given in Figure 5–16.

To sum up, the initial selection of filters depends on the size/concentration (as given in Figures 5–12 and 5–13), the expected recovery and complicating conditions (as given in Table 5–11), and the target concentration or "dryness" of the solids (as given in Figure 5–34).

- For *size and density* differences (or settling velocities), Figures 5–11 and 5–12 show the general regions of applicability for centrifugal devices, based again on particle size and concentration. Figure 5–36, analogous to Figure 3–26, shows the settling velocity of different size and density of particles in water. This is based on Stokes's law, which considers only single particles. Figure 5–39 is more specific in exploiting the settling velocity in a simple gravitational field versus the flowrate of recovered, clarified liquid. This helps us to distinguish between different types of gravity and centrifugal devices. Table 5–12 summarizes how the different expected recoveries affect the choice. Figure 5–40 is a rework of Figure 5–39 in terms of solids throughput for those situations where the emphasis is on recovering the solid.

When the size of the particles is too small, coagulation and flocculation can often be used to increase the size. Dissolved air flotation is an option to remove the solids from the liquid; usually little concern is for the recovery of the solids.

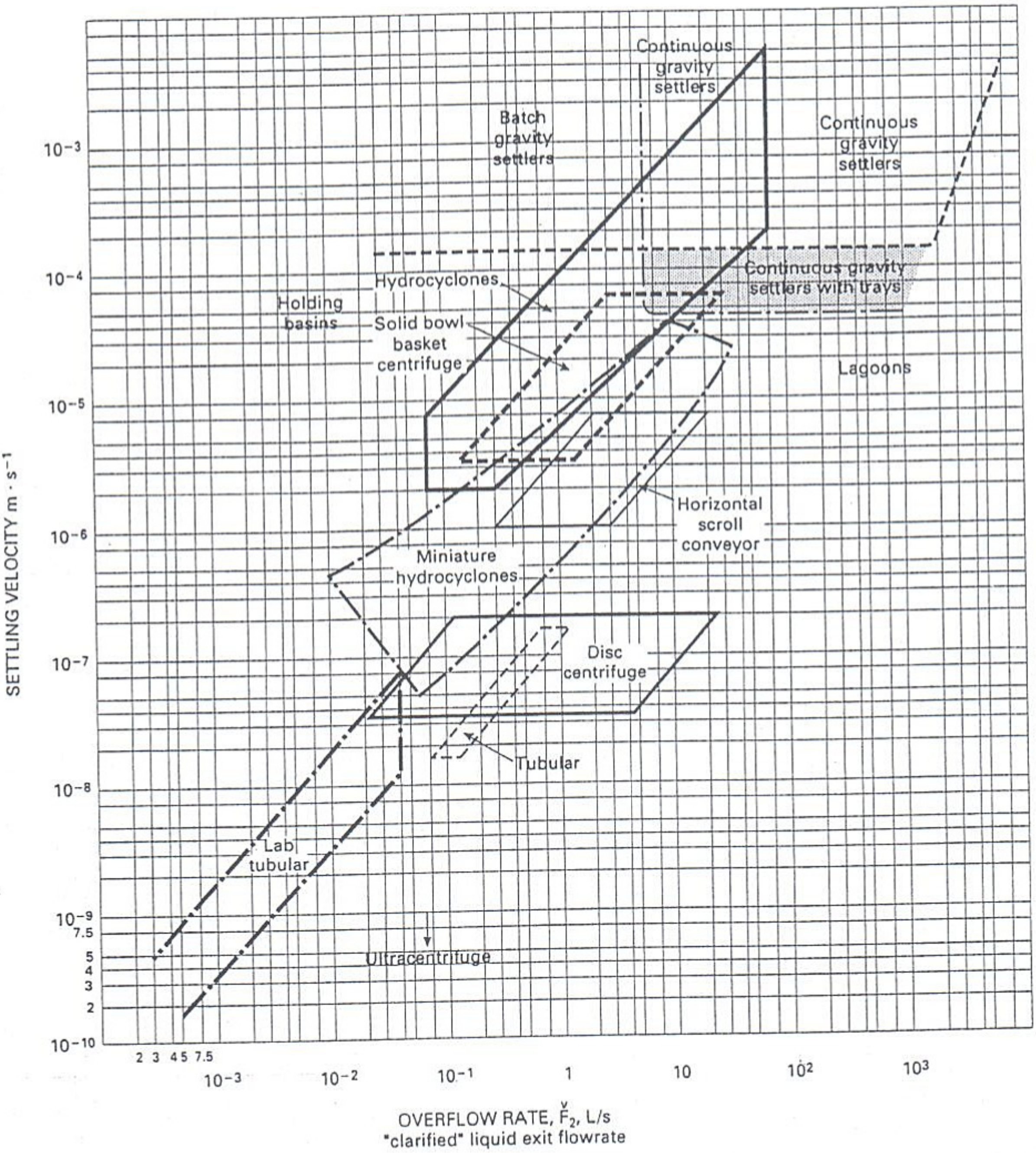


Figure 5–39 General Regions of Applicability for Liquid-Solid Separations: Based on Clarified Liquid Recovery

- For *solubility*, the "liquid" phase should preferentially dissolve in a solvent or be "washed out" by the solvent. Which mechanism applies depends on how the liquid is "bound" to the solid. If the liquid is intimately mixed within the solid (like soya oil inside the soya bean) then the oil needs to be dissolved out. On the other hand, the liquid might just occupy the interstitial spaces between the particles and need to be washed out. Table 5–13 illustrates how the size and condition of the solid and the condition of the liquid affect the configuration of the leacher. Figure 5–15 illustrates the configurations.

In summary, the initial screening charts of Figures 5–10 and 5–16 are but starting guidelines. Usually many overlapping options are possible. To resolve these, we can systematically work through the tables and charts described here to narrow the selection. Figure 5–41 gives some guidance as to the effectiveness in removing the solids from the liquid.

TABLE 5-12. Effect of recovery on choice of "settlers"

Purpose	Gravity Force	Centrifugal Force
To recover liquid	Clarifier, settler, washing tray thickener reactor-clarifier	Hydrocyclone, Batch, tubular bowl centrifuge Batch automatic: horizontal or vertical bowl, disc with intermittent nozzle discharge Continuous disc bowl centrifuge with nozzle discharge with/without recycle
To recover both	Continuous countercurrent decanter circuit, CCD	Horizontal, solid bowl centrifuge with scroll discharge
To recover solid	Thickener, Deep thickener Rake thickener Tray thickener	Hydrocyclone Batch automatic imperforate bowl centrifuge Continuous conical bowl centrifuge Continuous contour bowl vertical or horizontal centrifuge

Example 5–7: We want to dewater a coal slurry that has a particle size "B." This slurry is being conveyed in a pipeline. The density of the particles is 1.4 Mg/m^3 and the concentration is 50% wt. We are only interested in recovering the coal. We do not want water left in the interstices if it can be helped.

An Answer: First, the size of the particles is, from Figure 2–40, between about 200 µm and 4 mm. Thus, from Figure 5–36 the settling velocity is in the range of 0.01 to 0.3 m/s.

Consider next the size-concentration diagrams, Figures 5–10 and 5–16. This suggests that belt filters are appropriate. The size is a bit too large for hydrocyclones; the concentration of solids a little too large for a stationary screen.

The goal of having little water left in the interstices may be achieved if vibration or vacuum can be applied to the last portion of the belt filter.

Example 5–8: We want to separate the antibiotic erythromycin from the broth used to make this product. The feed concentration is 15 g dry product per L. The target is to recover the solid. What might we do?

An Answer: First, the size of the particles is, from Figure 4–4, about 1 nm. This is extremely small. We could add a filtering aid or use a precoat filter. These might alter the "diameter" of the solids to be about 1 to 5 µm.

Consider next the size-concentration diagrams, Figures 5–10 and 5–16. The feed concentration is about 1.5%. This suggests that a plate and frame or pressure leaf filter might be effective if a filter aid is used.

Table 5–10 adds little new information to aid in the selection.

Comment: Belter et al. (1989) describe the filtration of this system in their example 2.3-1, p. 25.

Example 5–9: We wish to create powdered milk. We wish to remove the water from milk. The feed concentration is about 87% water, 3.5% protein, 3.7% fat, and the rest milk sugar. The fat globules are about 0.1 to 20 µm. What options do we have?

An Answer: First, the size of the particles: proteins are, from Figure 4–4, about 10 nm; the sugars are also small. We are given the size of the fat globules. This is a wide range. This also is interesting because with this small size of particle we could treat this as a solid-liquid separation or a homogeneous phase separation. It really comes down to how small something must be before we cease to call it a particle. For continuity, let's consider these as particles. For powdered milk we would want to have everything except the water.

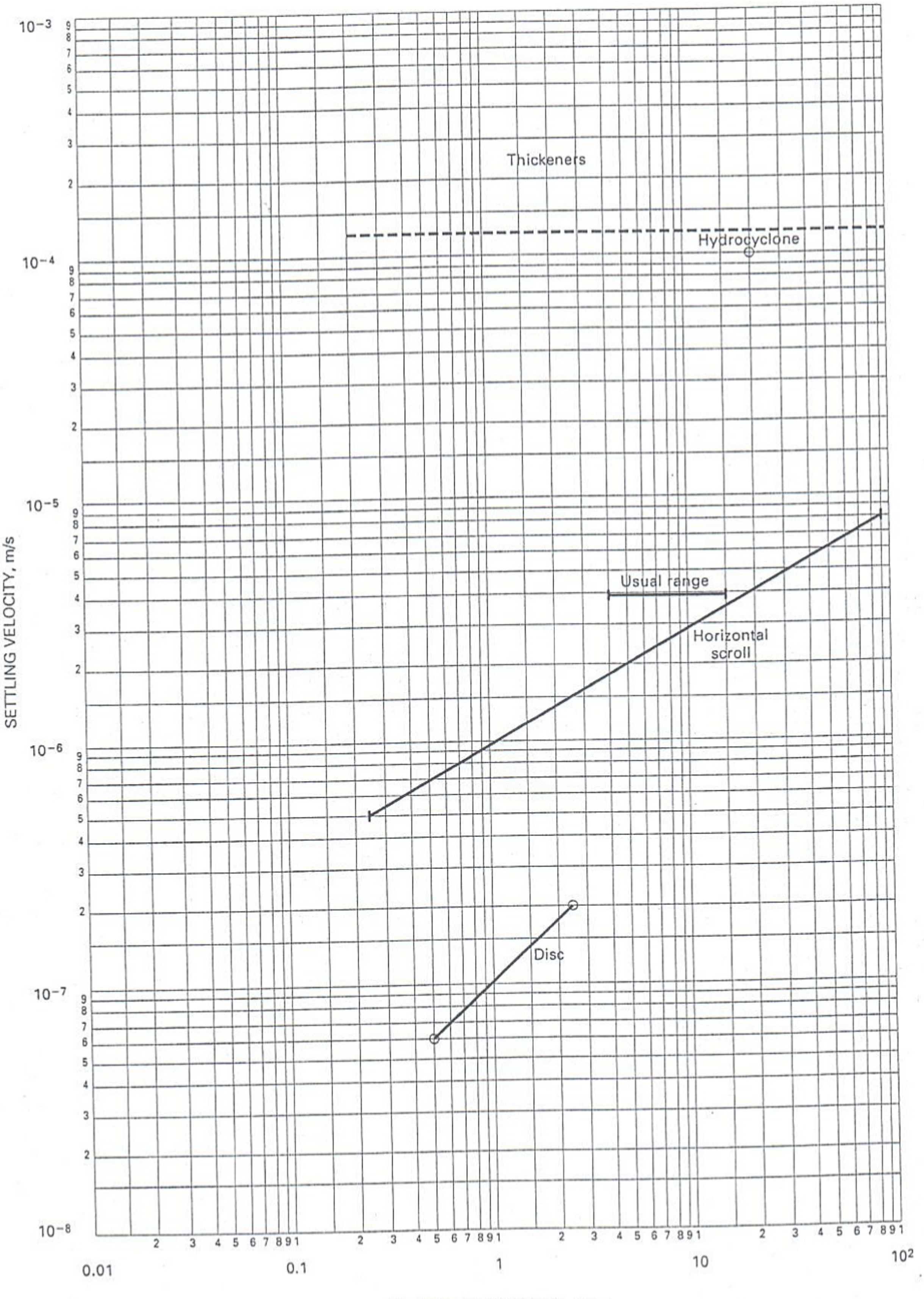
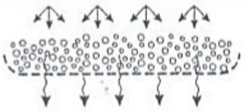
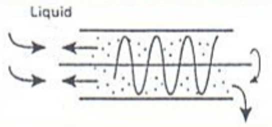


Figure 5–40 General Regions of Applicability for Liquid-Solid Separations: Based on Dry Solids Recovery

TABLE 5-13. Three types of contact for leachers

	Percolation or vat leach or heap leach or insitu leach	Immersion or stirred tank	Combination
			
Size of inert solid	large, coarse: try for uniform size (so that fines don't plug the interstices)	fine, <0.07 mm easy to suspend; or have broad size range that yield low bed porosity	
Strength of solid	relatively fragile	relatively strong; does not break up into fines because of mixing	should be strong so that it doesn't break up into fines and plug the leacher
Initial solute concentration	low and very low concentrations can be processed		high concentrations needed
For "bound" or soluble species	high rates of diffusion are needed if contact times are to be minimized	OK for low rates of diffusion because long contact times are easy to achieve	
For "unbound," washing conditions e.g. inorganics	often used for "washing" or pull a vacuum to draw liquid free of bed	usually not used	usually not used

Consider next the size-concentration diagrams, Figures 5–10 and 5–16. The feed concentration of solids is about 13%. This corresponds with filter-aid filtration and coagulation-thickening.

However, filtration would only capture the larger-sized molecules unless a precoat were used. Here we want to recover the solids and the precoat would contaminate the solids. Similarly, the particle size is so small that coagulation would have to be used to increase the size of even the fat globules. This would contaminate the product. Thus, the route would be to evaporate some of the liquid to preconcentrate the milk until an appropriate drying option can be used.

Consider Tables 5–8, 5–9, and 5–10.

5. Solid-Solid. For **solid-solid** systems, the general classes of separating devices depend on the particle size and density and how much each vary. This is illustrated in Table 5–1. The terms *classifiers, concentrators,* and *separators* help us to focus on the fundamental principle being exploited in the separation.

Classifiers exploit differences in size. Thus, an important consideration is the "cut" size of the particles that represents the boundary between the two different products. Screens, trommels, and grizzlies are related to the solid size range and to the concentration in Figures 5–10, 5–25, and 5–26. The "cut" size of interest must be in the size range. Usually these operate dry. Other classifiers that operate dry (or in a gas or air) are shown in Figure 5–18a. The general region of application for the different types depends on the "cut" size and on the mass of solid mixture to be processed, as illustrated in Figure 5–42.

Classifiers can also be operated "wet" or using a liquid to convey the solid mixture. These "liquid" classifiers are given in Figure 5–18b and the general region of applications of these are given in Figure 5–43.

Concentrators exploit the differences in the densities of the particles about a given "cut" density that separates the lower-density particles from the higher-density particles. We can express this two ways: the Bird Number (that is, the mass of solids that is within ± 0.1 Mg/m^3 density variation from the cut density) or the density ratio between one phase and the other. Table 5–14 uses the Bird number as a criterion; Figure 5–44 uses the density ratio. Sketches of the options of rakes, jigs, tables, spirals, and dense media separators are given in Figures 5–19 and 5–20. Some general regions of applicability are also given in Figure 5–25.

Solid-solid *separators* exploit features other than the size or the density. The options include flotation, dissolution/leaching, electrostatic or magnetic separators. Sketches of the options are given in Figure 5–15 (for leachers/dissolution), Figure 5–21 for flotation, Figure 5–22 for electrostatic separations, Figure 5–23 for eddy-current separators to remove aluminum, and Figure 5–24 for magnetic

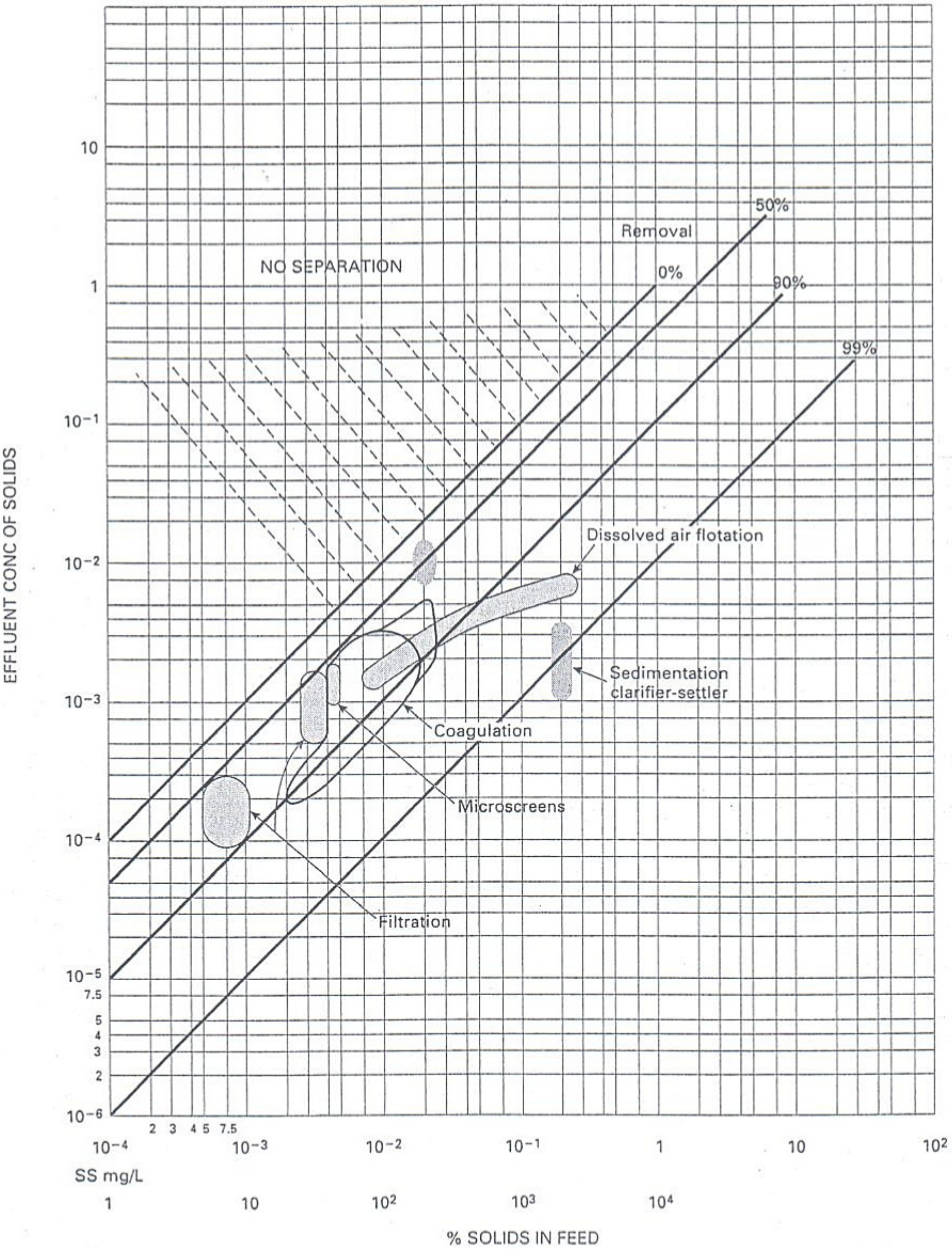


Figure 5–41 General Regions of Applicability for Liquid-Solid Separations: Based on Effluent Concentration (with Removal Efficiencies) Based on EPA 1975

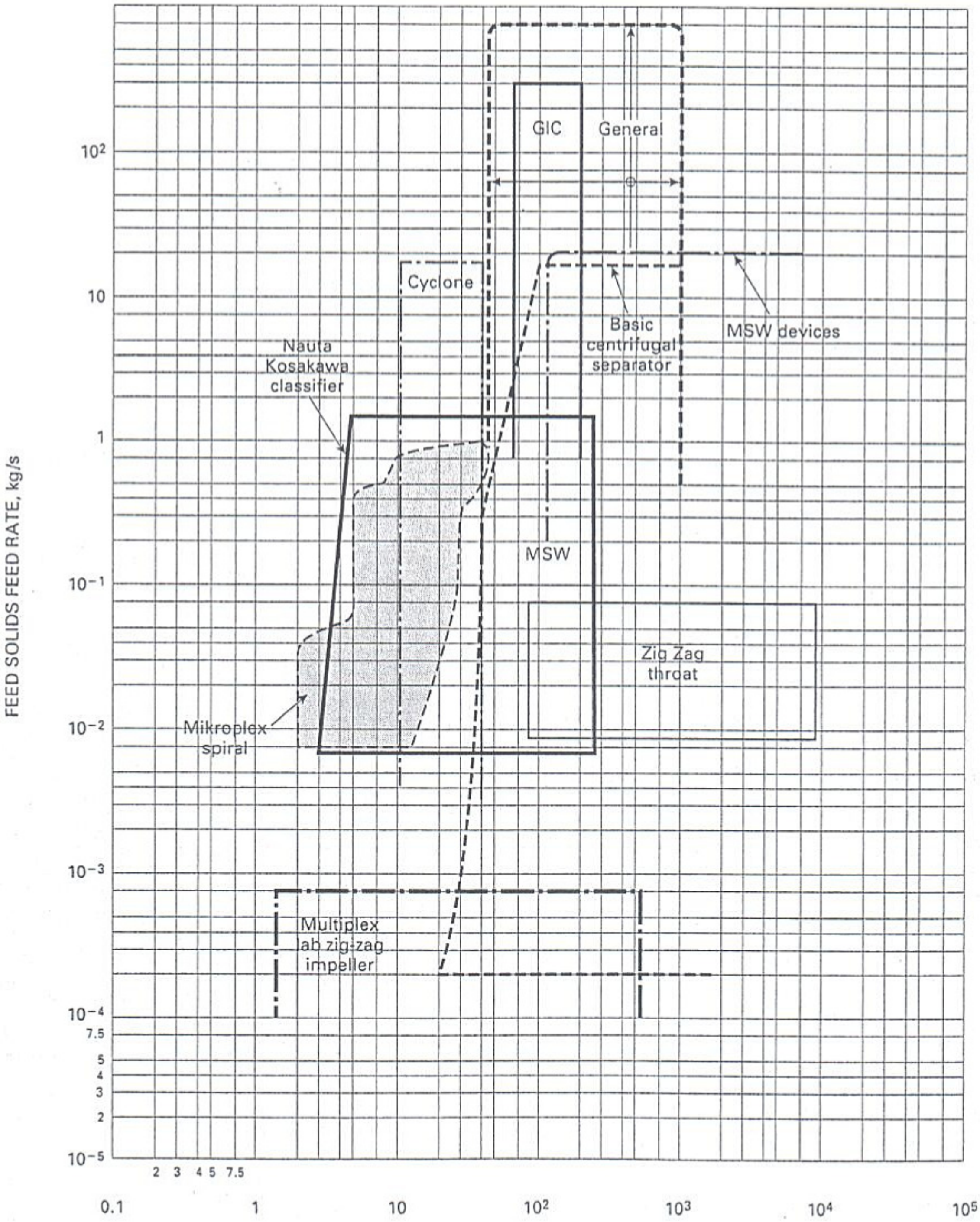


Figure 5–42 General Regions of Applicability for Solid-Solid Separations: Based on Feedrate and Cut Diameter for Air Classifiers (from Maier, 1982)

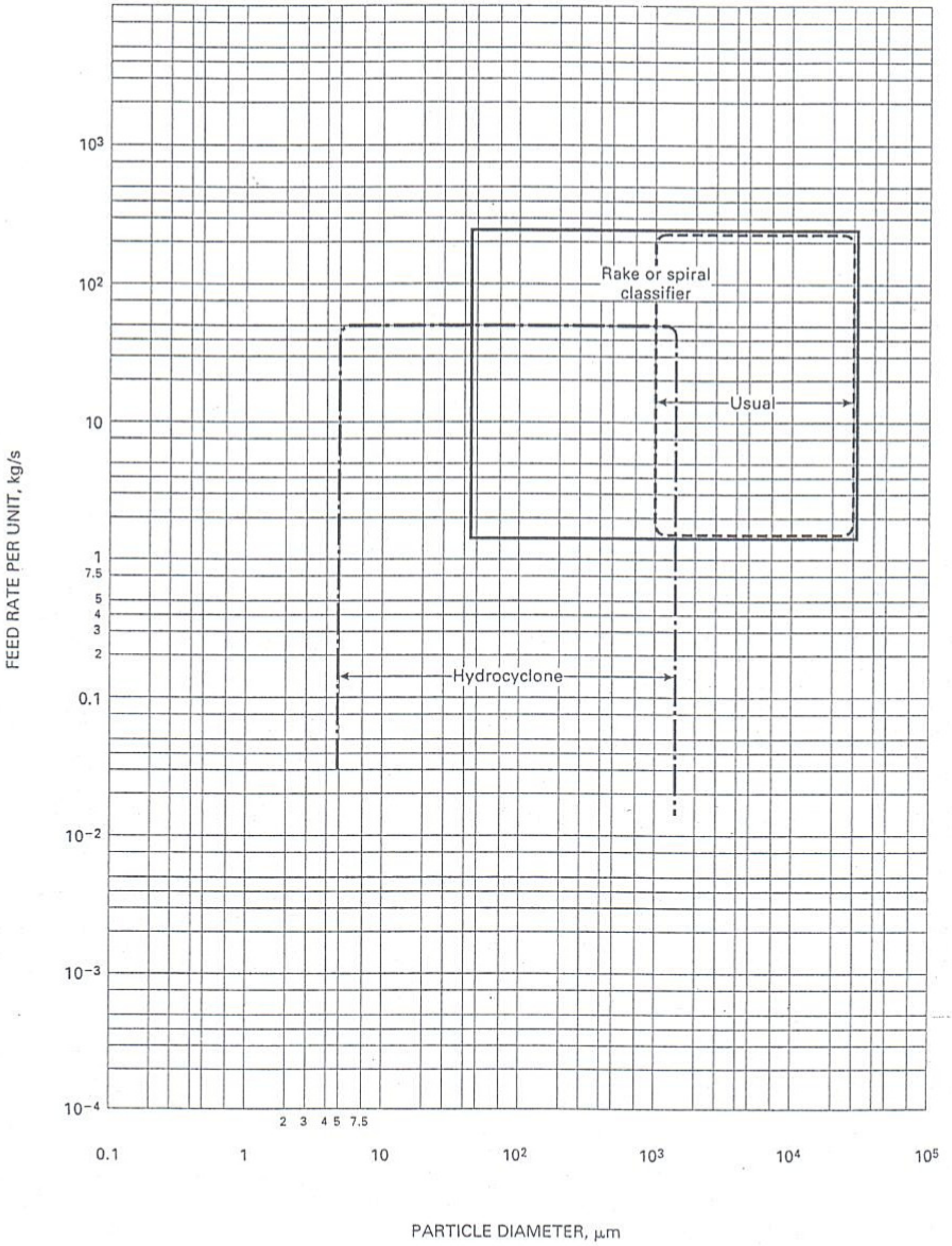


Figure 5–43 General Regions of Applicability for Solid-Solid Separations: Based on Feedrate and Cut Diameter for Liquid Classifiers

TABLE 5-14. Criteria for selecting concentrators

Bird Number	Ease of Concentration	Type of Device
0 to 7	easy	jigs, tables,
7 to 10	moderate	sluices
10 to 15	difficult	
15 to 20	very difficult	
20 to 25	exceedingly difficult	DMS
>25		

separators. Figure 5–25 (and to some extent Figure 5–26) illustrates the general regions of applicability.

Exploiting the solubility of the target species is done via leaching/dissolution. Table 5–13 is applicable except that "unbound" washing operations are not pertinent. Here for a solid-solid separation, one of the species is soluble. Usually the solids are ground very fine to liberate the desired species, to provide surface area for the mass transfer, and to minimize the distance through which the species must diffuse. Figure 5–45 illustrates that the size of the feed varies greatly and depends on the liberation size of the target species.

The workhorse for solid-solid separation using a wet medium is flotation, which exploits the difference in wettability of the species. Flotation has a relatively narrow range of particle size over which it is applicable. Basically, to exploit flotation, the solids need to be ground to this size range. The general regions are shown in Figure 5–25 and reproduced in Figure 5–45. We note from Figure 5–40 that only a small difference in properties can produce an effective separation. Sketches of a flotation unit and individual "cells" are given in Figure 5–21. In this section, the details of which method of introducing the air are not distinguished. Such details are given by Woods (1993).

Differences in particle electrical conductivity can be exploited by electrostatic "concentrators," which operate in a non-liquid or gaseous medium. Particles with relative permittivities greater than 10 are usually classed as conducting; those with less than 10, as nonconducting. Some example values for different solids are illustrated in Figure 5–46. The general region where electrostatics are applied is given in Figure 5–25, which shows that, in general, the species concentration and the particle size are usually larger than those expected for flotation. The size, however, should be relatively uniform and less than 1 mm. Although Figure 5–46 emphasizes a difference in electrical permittivity, electrostatic separation can be effective if two species have similar conductivities but have different threshold voltages at which they become charged or if they respond with different signs when they encounter an active electrode. Details about these properties are given in **Data** Part C.

The three basic charging options are by corona, by active electrode, or by bouncing and rubbing together or "triboelectrification." These are illustrated in Figure 5–22. An illustrative guide for the applicability of different types of electrostatic separators is given in Table 5–15.

To separate aluminum from other solids, eddy current separators, illustrated in Figure 5–23, can be used.

Differences in magnetic properties can be exploited using some of the configurations illustrated in Figure 5–24. The general regions of applicability are given in Figure 5–25 (and to some extent in Figure 5–26). In general, solids can be ferromagnetic, ferrimagnetic, paramagnetic, nonmagnetic, and diamagnetic to represent very strong attraction, strong attraction, weak attraction, no attraction, and weak repulsion when the solid encounters a magnetic field. These are measured as rationalized magnetic susceptibilities or by comparing their behavior relative to iron that has been assigned a value of 100. The data on Figure 5–47 are expressed on the relative basis; the data in Figure 5–48 and in **Data** Part C are expressed in terms of the rationalized mass susceptibilities. The periodic table, in **Data** Part C, gives magnetic characteristics of elements. Figure 5–49 illustrates the regions of applicability of different options based on the magnetic characteristics.

5.1-3 Sequencing Heuristics for Separating Multiphase, Multicomponent Systems

The focus so far has been on the separation of one phase from another. Sometimes, even for that situation, a sequence of options might be used simply because no one single option is possible. For example, we might separate a liquid from a solid by preconcentrating via sedimentation and then finishing with filtration. Sometimes, size reduction is included between some of the options. At other times, more than two target species are the expected products.

Few heuristics have been developed specifically for heterogeneous separations. We might start by using the same general heuristics about the sequence of options that were developed in Chapter 4 for homogeneous separations. These are:

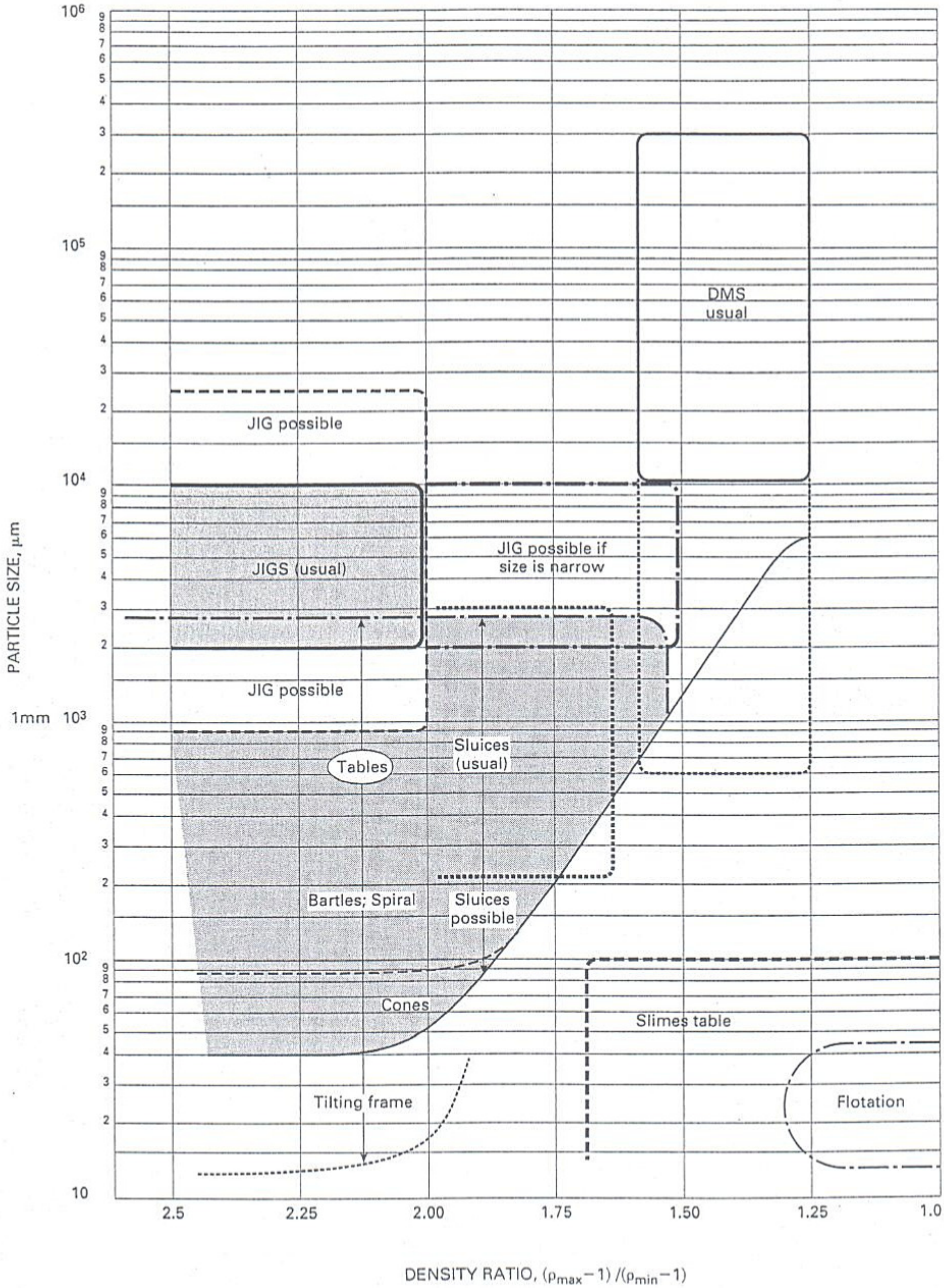


Figure 5–44 General Regions of Applicability for Solid-Solid Separations: Based on Particle Size and Density Ratio for Concentrators

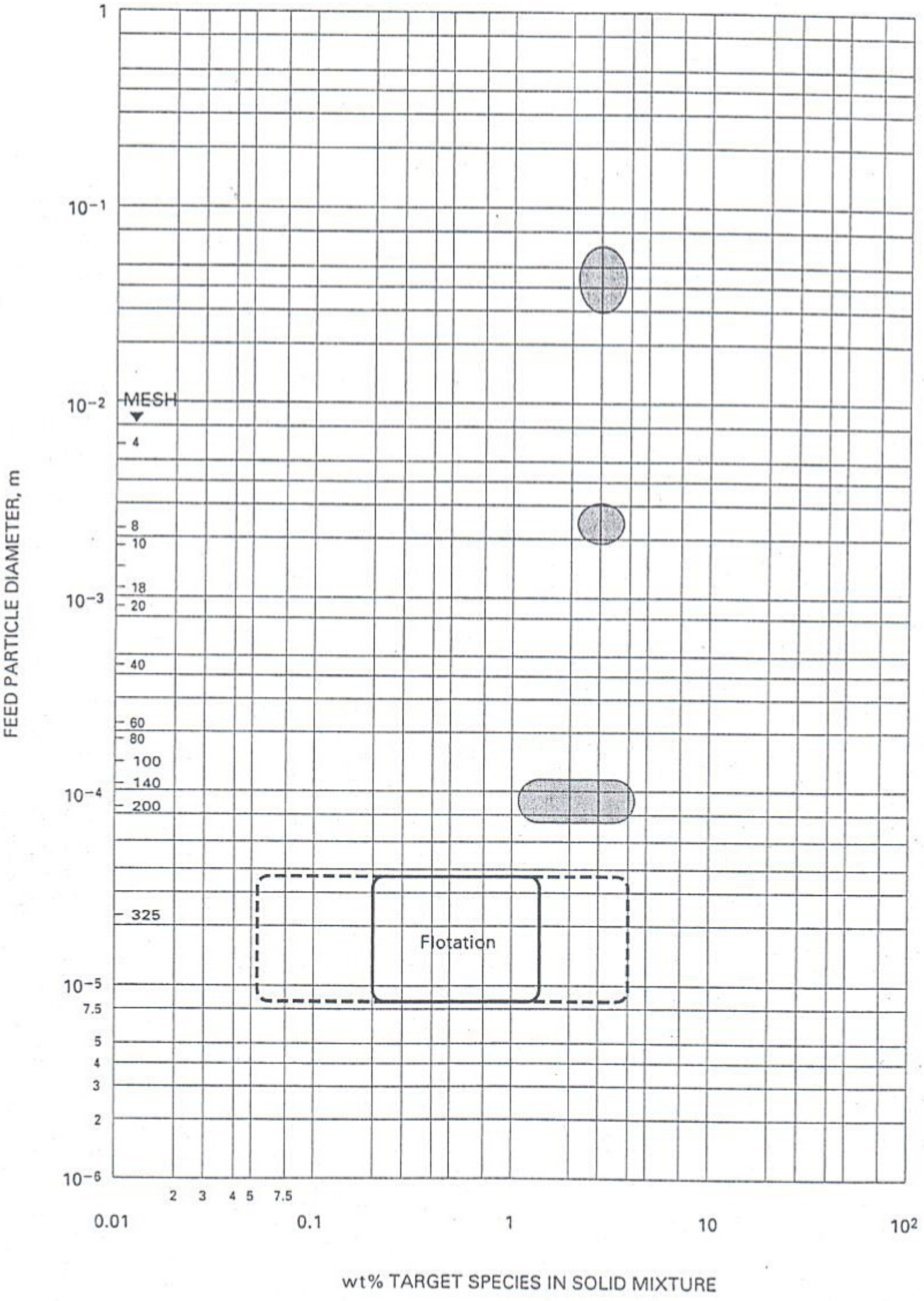
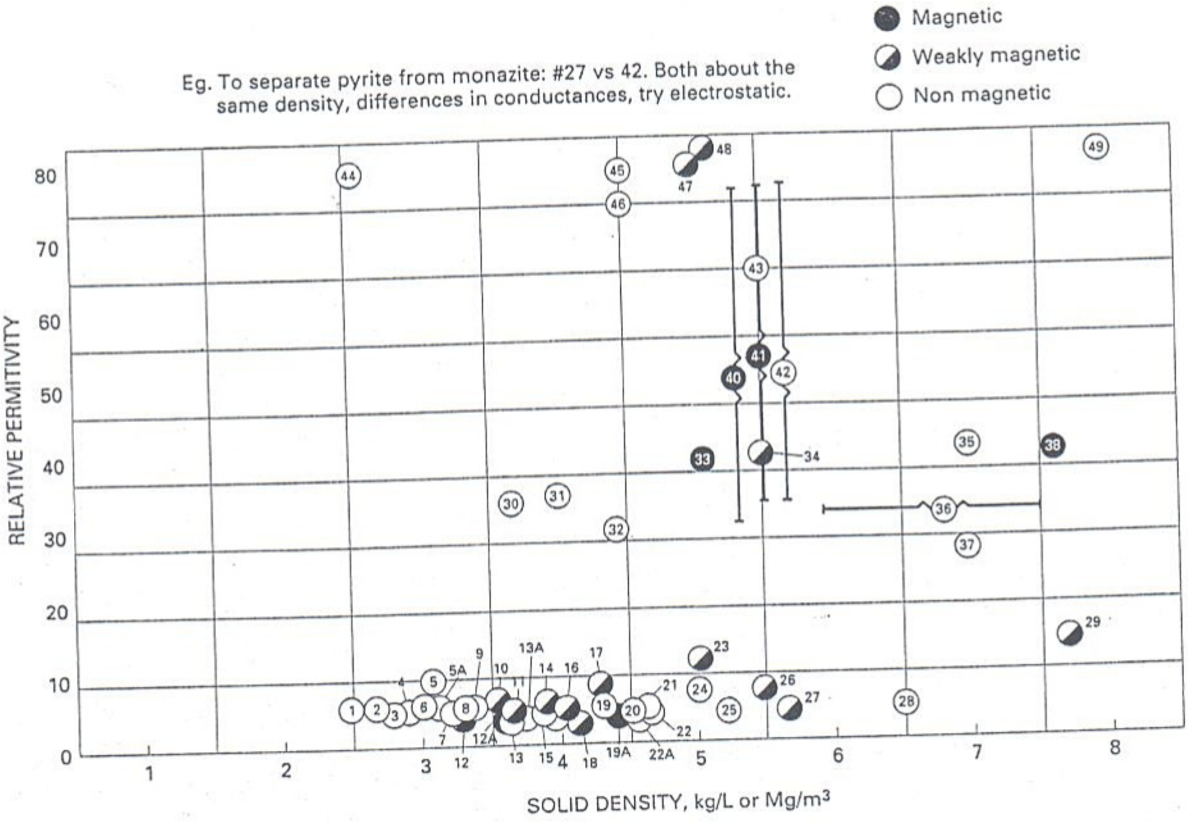


Figure 5–45 General Regions of Applicability for Solid-Solid Separations: Based on Particle Size and Concentration for Leaching and Flotation



Eg. To separate pyrite from monazite: #27 vs 42. Both about the same density, differences in conductances, try electrostatic.

8 Anhydrite
11 Apatite
24 Barite
26 Bastnasite
5A Beryl
32 Brookite
7 Calcite
37 Cassiterite
45 Chalcopyrite
23 Chromite
20 Celestite
30 Chrysolite
36 Columbite
22A Corundum

31 Diamond
33 Davidite
16 Epidote
34 Euxenite
2 Feldspar
38 Ferberite
13A Fluorite
49 Galena
17 Garnet
44 Graphite
3 Gypsum
47 Hematite
10 Hornblende
40 Ilmenite

Kyanite
19 Limonite
41 Magnetite
5 Mica (biotite)
6 (muscovite)
48 Molybdenite
27 Monazite
14 Olivine
4 Quartz
22 Perovskite
42 Pyrite
46 Rutile
43 Samarskite

28 Scheelite
18A Siderite
12A Sillimanite
15 Sphene
18 Staurolite
1 Sulphur
35 Tantalite
13 Topaz
12 Tourmaline
29 Wolframite
25 Zircon

Figure 5–46 Electrical Conductivity, Density (and Magnetic Properties) for Solids

TABLE 5-15. Electrostatic separations

	Exploit Difference in		
	electrical conductivity or permittivity	threshold voltage kV/cm	response to active electrode
Corona-active electrode-drum; HTS	separate good from poor conductors		
Active electrode-drum	separate good conductors from poor conductors	select voltage so that one conducts and other doesn't	if both respond the same, then the polarity of active electrode is important
Triboelectrification	both have similar conductances but different permittivities		adjust sign of active electrode

1. Remove the most hazardous, unstable, and corrosive species early. (Use the data in **Data** Parts C and D to get an idea of the hazard and corrosive rating of the species.)
2. Save the most difficult separations until the last (or do the easy ones first).
3. Separate the most plentiful components early.
4. Leave the high, specific recoveries until last.
5. Avoid extremes in operating conditions (especially pH, since many of the separations involve water).
6. If possible, separate the gas first, then the liquid, and then the solid-solid (except where the liquid is purposefully added for classification concentration to separate solids from solids).

Solid-solid separations seem to have received the most attention and Table 5–16 summarizes these. Since flotation is the workhorse for solid-solid separations, many of the heuristics have been developed for flotation.

5.2 Summary

A starting approach in selecting an option to separate heterogeneous phases is to classify the system according to the **type** of phases: gas-liquid, gas-solid, liquid-liquid, liquid-solid, and solid-solid. Then for each system, use the size-concentration values to make an initial choice.

If more discrimination in options is desired, consider whether:

- clean separation between both phases is required,
- the property difference we ought to exploit is different from "size."

If such factors pertain, then use the details of Section 5.1-2 to make the selection.

When a sequence of options is required, some heuristics are available to guide the sequencing. Most of these have been developed in the context of solid-solid separations. Overviews of the issues for each type of physical separation are given in Figures 5–49 to 5–53.

This minichapter has explored the selection of the equipment for the separation of heterogeneous systems. Details about the sizing and costing are given elsewhere (Woods, 1993a and b). Related to this topic are the selection and sizing of equipment to alter the size of dispersed phases: atomization, sprays, grinding, coagulation, crystallization. These are given in detail by Woods (1993c).

5.3 REFERENCES

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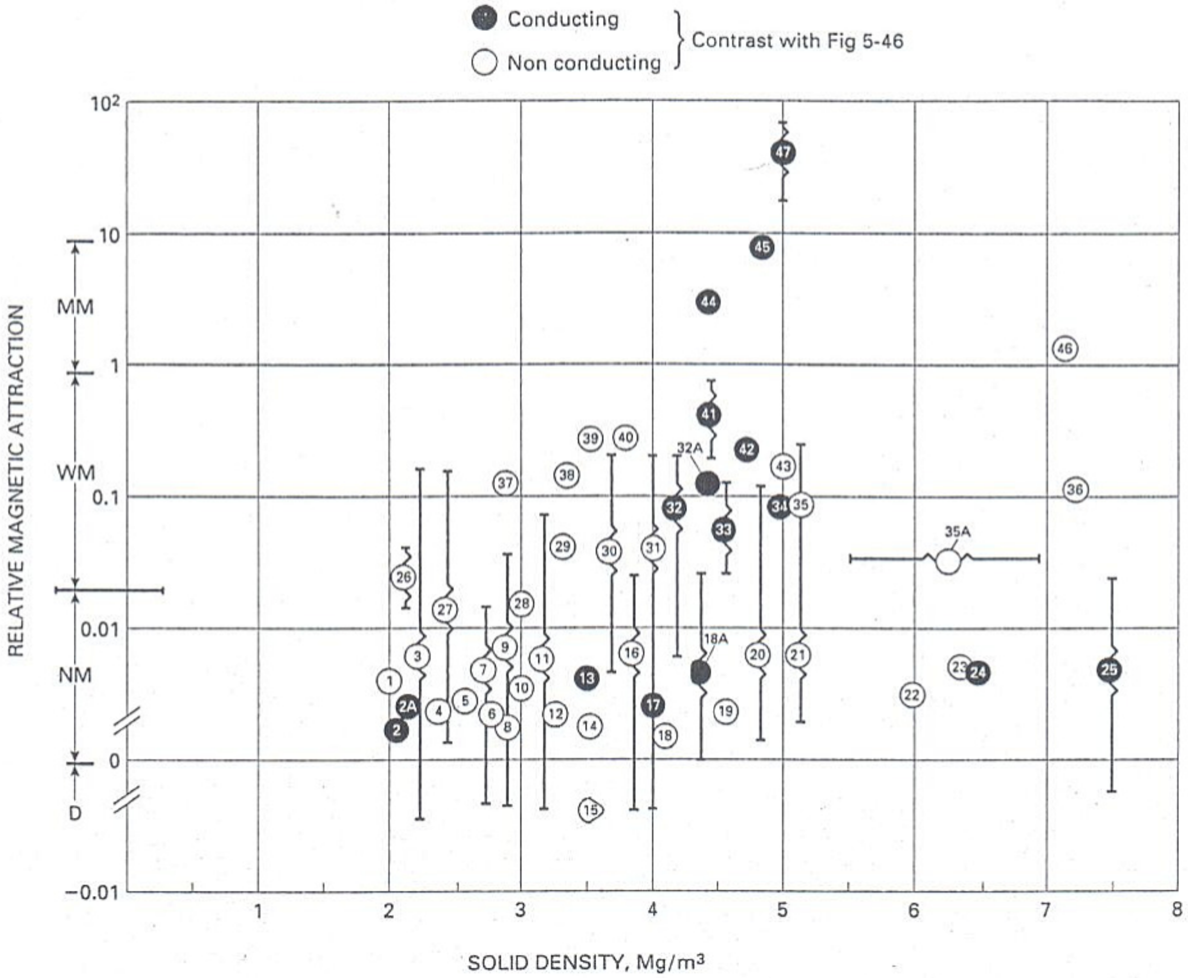

7 Anhydrite
11 Apatite
19 Barite
43 Bastnasite
8 Beryl
17 Brookite
5 Calcite
24 Cassiterite
16 Celestite
18A Chalcopyrite
32A Chromite
2A Chrysolite
35A Columbite
31 Corundum

13 Diamond
44 Davidite
38 Epidote
44 Euxenite
4 Feldspar
46 Ferberite
9 Fluorite
25 Galena
40 Garnet
2 Graphite
26 Gypsum
41 Hematite
Hornblende
45 Ilmenite

14 Kyanite
30 Limonite
47 Magnetite
27 Mica (biotite)
6 (Muscovite)
33 Molybdenite
35 Monazite
29 Olivine
3 Quartz
18 Perovskite
21 Pyrite
32 Rutile
34 Samarskite
22 Scheelite

Siderite
10 Sillimanite
Sphene
39 Staurolite
1 Sulphur
23 Tantalite
15 Topaz
37 Tourmaline
36 Wolframite
20 Zircon

Figure 5–47 Magnetic Conductivity, Density (and Electrical Properties) for Solids

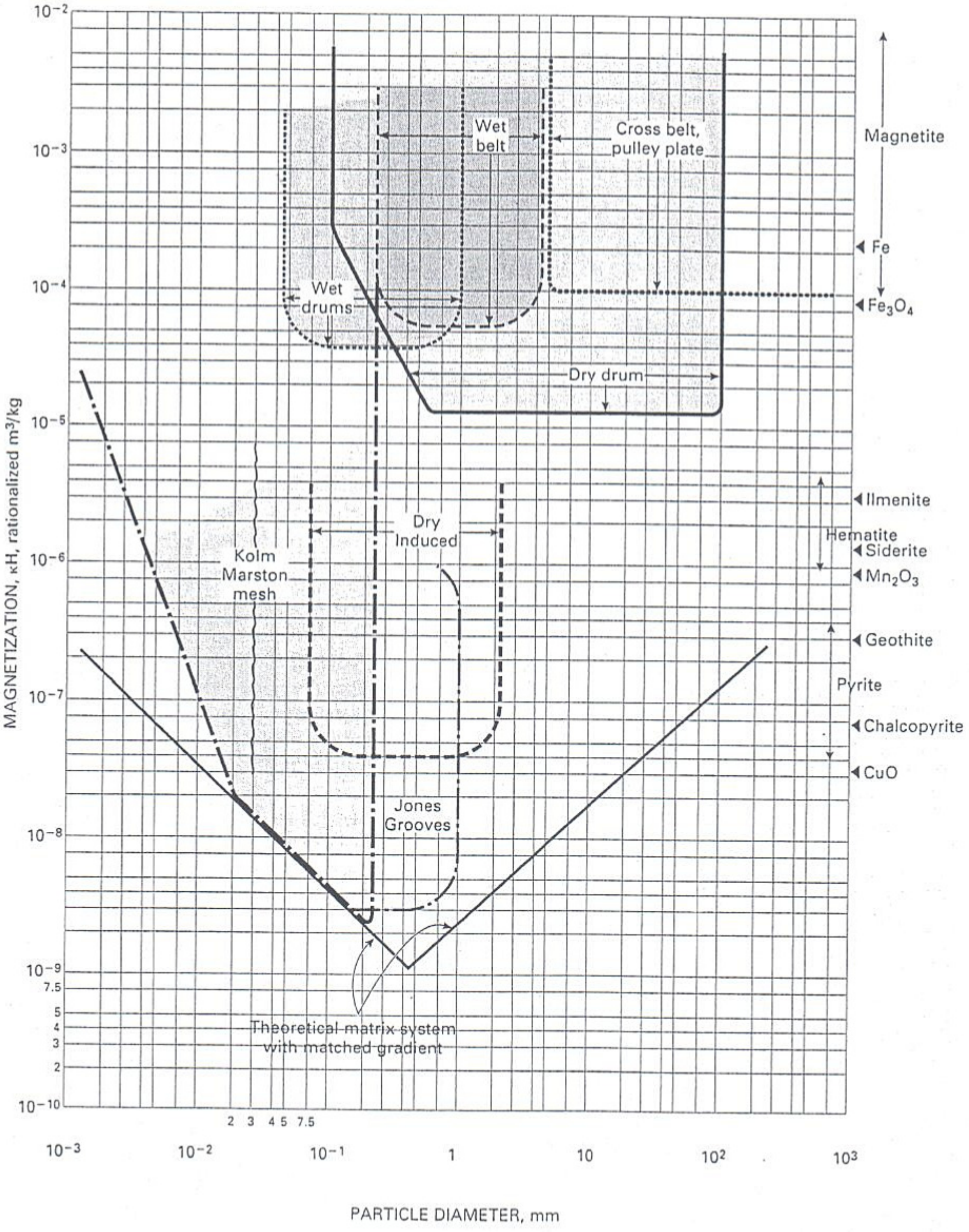

Figure 5–48 General Regions of Applicability for Solid-Solid Separations: Based on Particle Size and Magnetization for Magnetic Separators (adapted from Oberteuffer, 1974 Transactions on Magnetics © 1974 IEEE)

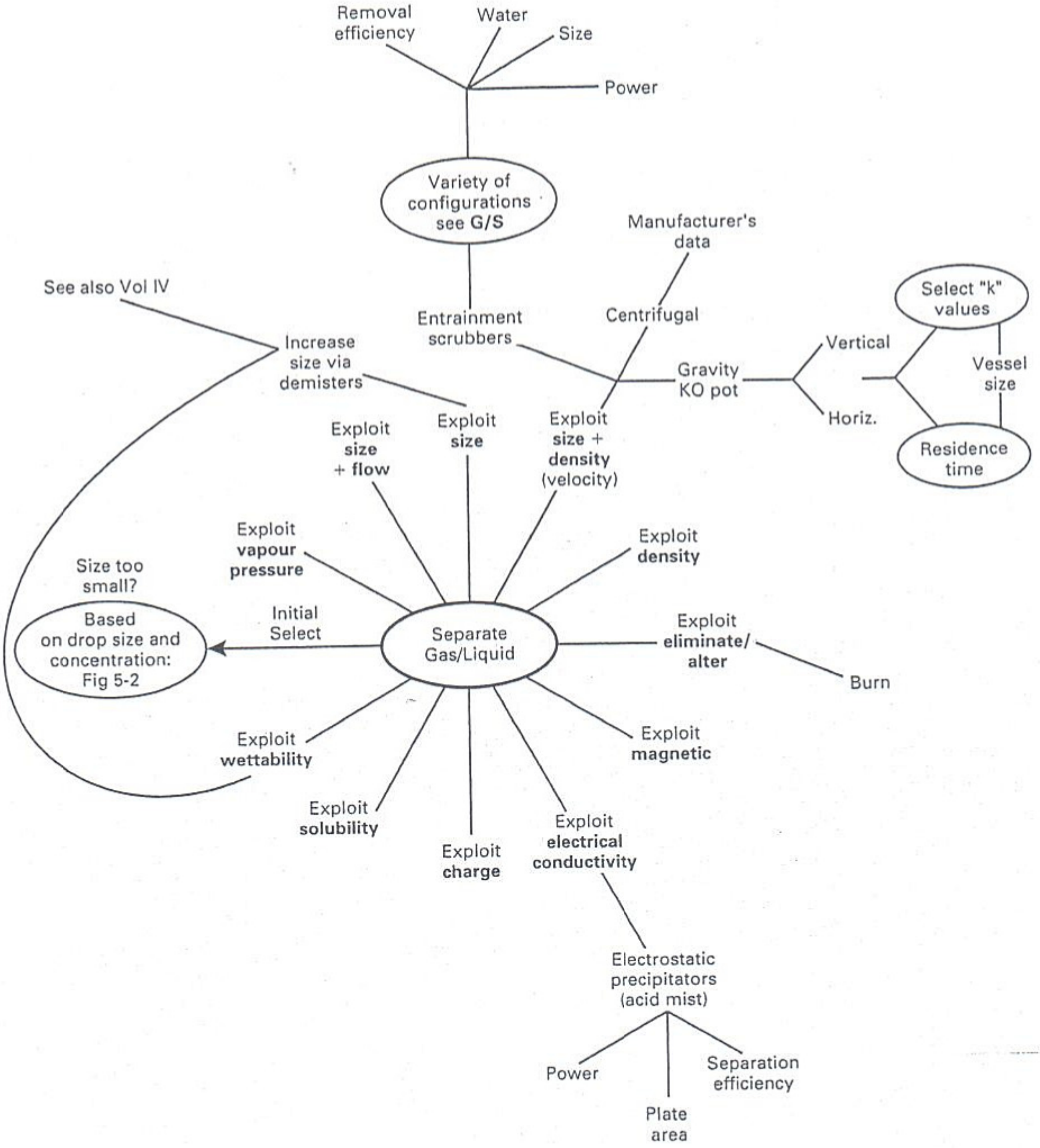

Figure 5–49 An Overview of Gas/Liquid Separations

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TABLE 5-16a. General suggestions about the selection of solid-solid separators

Consider using DMS to preconcentrate before grinding to final liberation size.
Preconcentrate before flotation if the grain size is large and coarse minerals can be removed via density difference before grinding further.
Above 44 μm use gravity concentration/separation techniques instead of flotation.
For feed ore assay <0.3% use a combination of gravity concentration and then flotation.
For feed ore assay 0.5 to 0.7% try flotation (with possible downstream concentration).
For particle sizes <20 μm, neither flotation nor gravity concentration are very effective.
Use flotation only and bypass a preconcentration if the gangue is dense or if the minerals are flaky.
If either "concentration" or "flotation" are possible, then select flotation because it is easier, usually cheaper and gives improved recovery/greater capacity.

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5.4 EXERCISES

5-1 We wish to process 2000 kg/h of inert soybean meal that has associated with it 800 kg of soy oil and 50 kg of hexane. The solvent is 1310 kg/h of hexane that contains initially 20 kg of oil. Our target is to have 120 kg of soy oil in the exit solids. Estimate what we might do.

5-2 Sugar beets are cut into "cossettes" that are 3 to 7 mm wide and about 5 to 8 cm long. The inlet concentration of sugar is 16.5% w/w. The desired exit concentration of sugar in the beet (or marc) is 0.2 to 0.3%. The operating temperature is 75°C. The desired exit solvent concentration is 12% w/w. What might we do to process about 15 kg/s?

5-3 An ore containing 0.6 to 1.2% cobalt arsenides is to be concentrated from its gangue that is primarily quartz, serpentine, and calcite. The density of the mineral is 5.7 to 6.8 Mg/m^3. The ore is available at –8 mm size. What might we do? The density/mass distribution has a Bird number of about 12. The feedrate is 24 Mg/h of ore.

5-4 A serpentine/iron ore contains about 19 to 20% iron. The

TABLE 5-16b. Rules-of-Thumb for Selecting/Developing Units & Networks

General:

- try to float at as coarse a grind as possible (if necessary regrind the concentrate).
- take products (whether they are tails or minerals) out of the main circuit coarse and early; in other words, try a bulk float as first option.
- try to separate early the material making up the majority of the ore (eg. tails).
- for mixed sulfide/oxide ores, float the sulfides first (to prevent depression of the sulfides downstream when sodium sulfide is added to depress quartz for oxide flotation).
- try to work at pH > 7 to minimize corrosion.
- for any recycle stream, try to match the mineral and - chemical composition of the recycle with the steam it joins.
- try to avoid surges to each stage; include buffer storage.
- in any recycle, ensure that all species can escape.

Bulk versus sequential use bulk when:	Flotation Sequencing use selective/sequential differential when:
— all valuable minerals are combined and are coarsely aggregated with respect to the ore as a whole (e.g. sulfide ores),	— all valuable minerals are individual, separately liberated at <200 μm (65 mesh) (eg: lead/zinc; lead/zinc/iron),
— if the concentration of Cu, Pb, Ag in soluble salt forms is high,	— more difficult; the differences in flotability may be less sharp; very careful choice of reagents needed; more delicate.
— it is relatively easy,	
— if depression of one species requires long contact and high reagent concentration.	

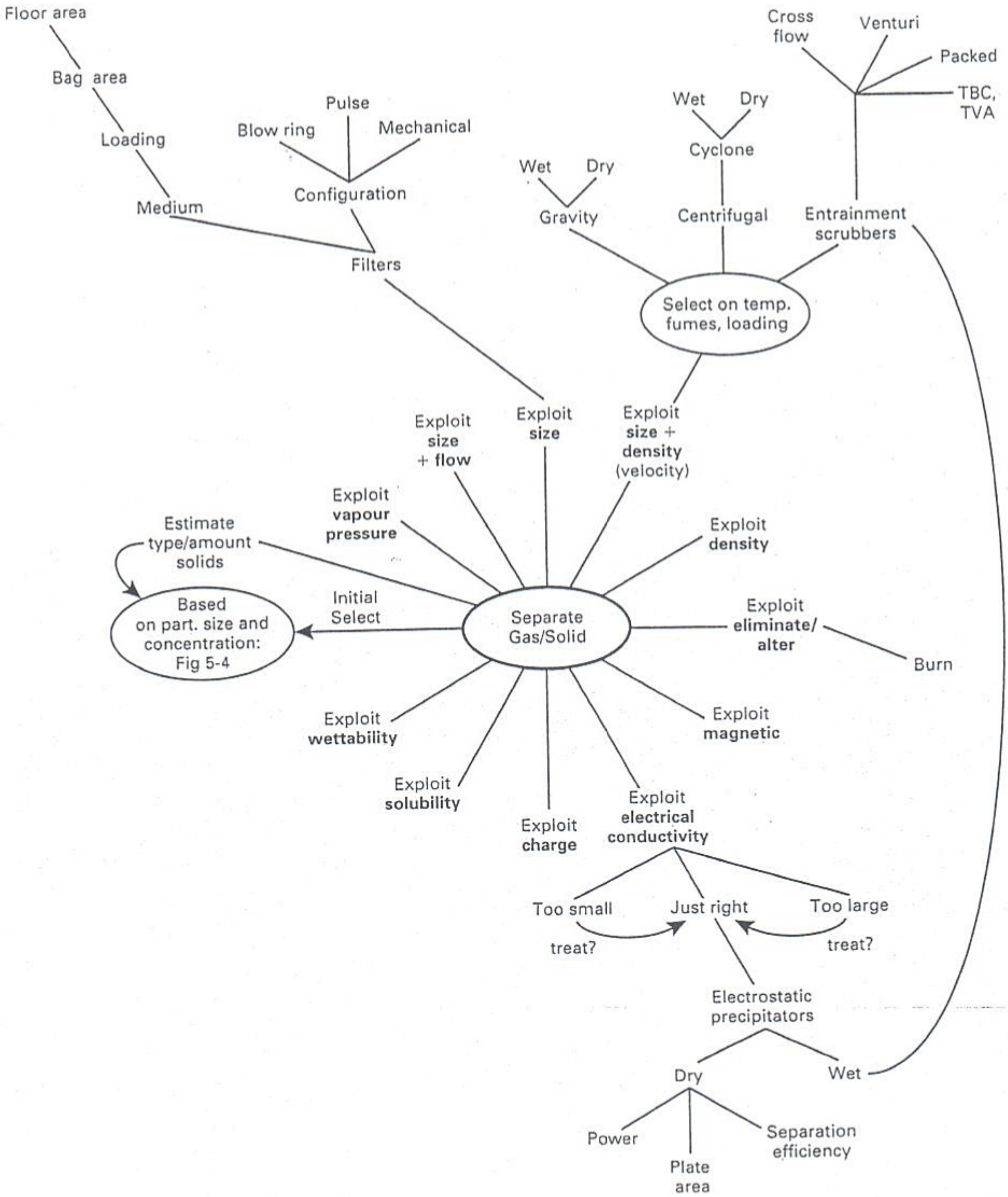


Figure 5–50 An Overview of Gas/Solid Separations

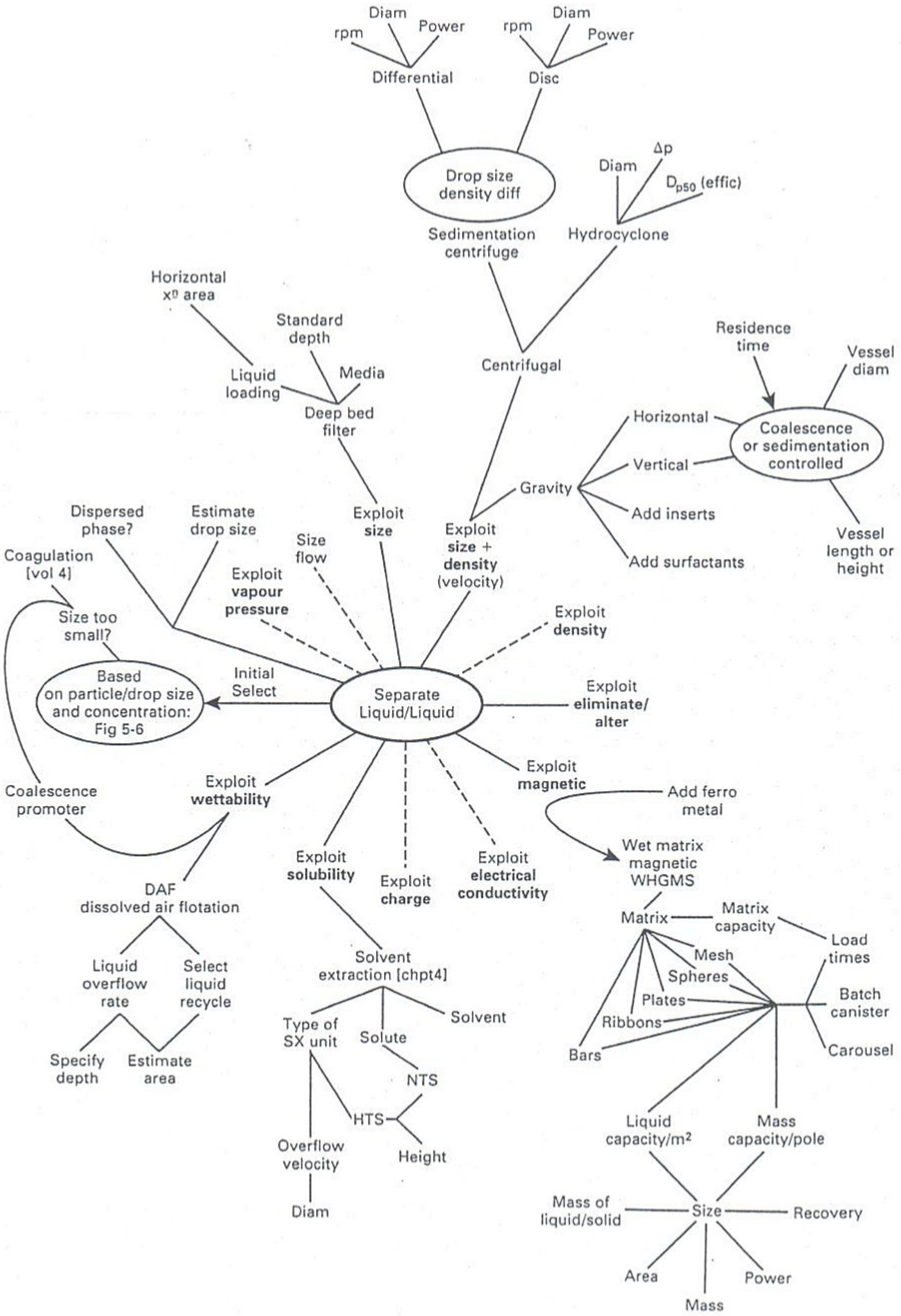


Figure 5–51 An Overview of Liquid/Liquid Separations

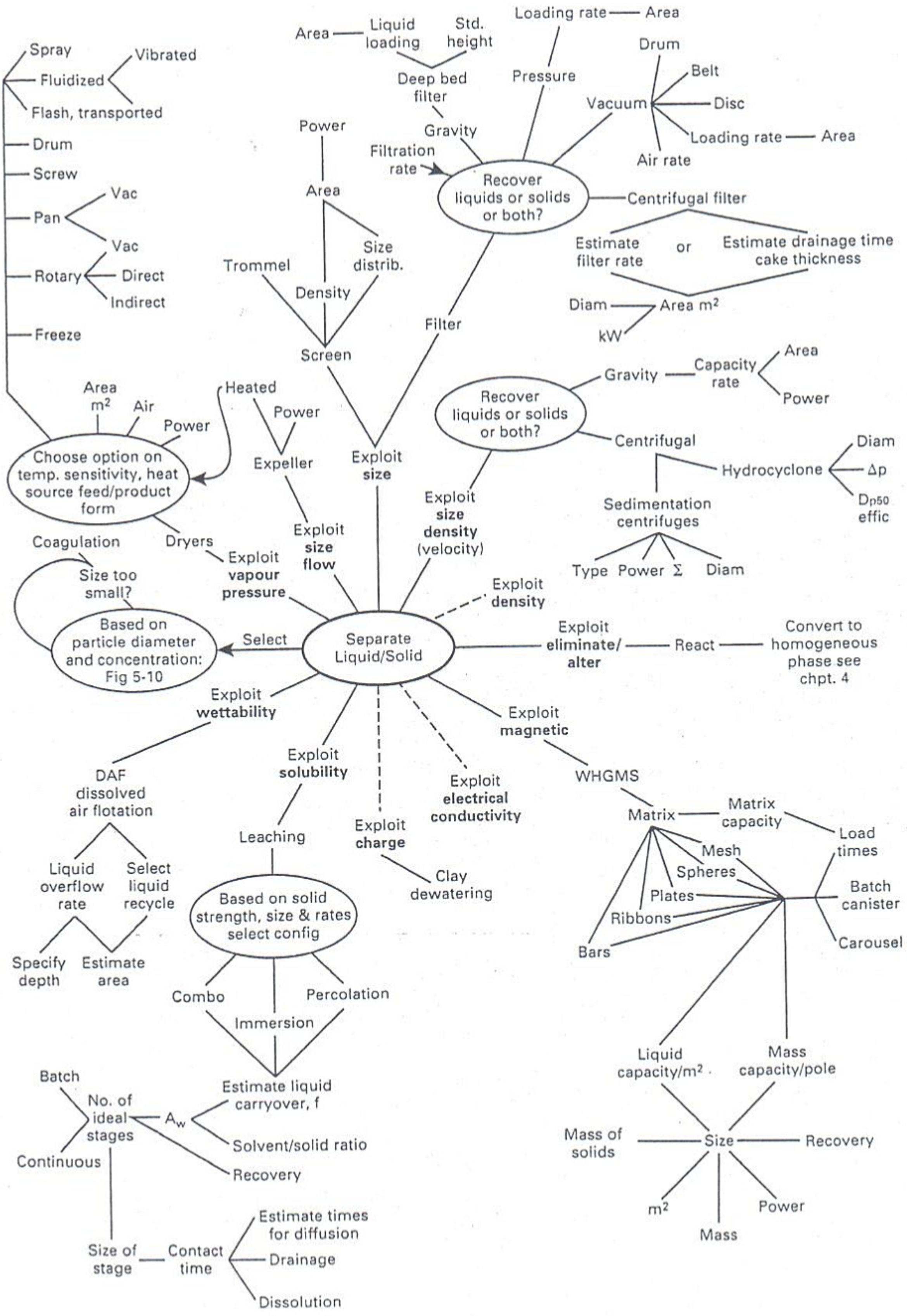


Figure 5–52 An Overview of Liquid/Solid Separations

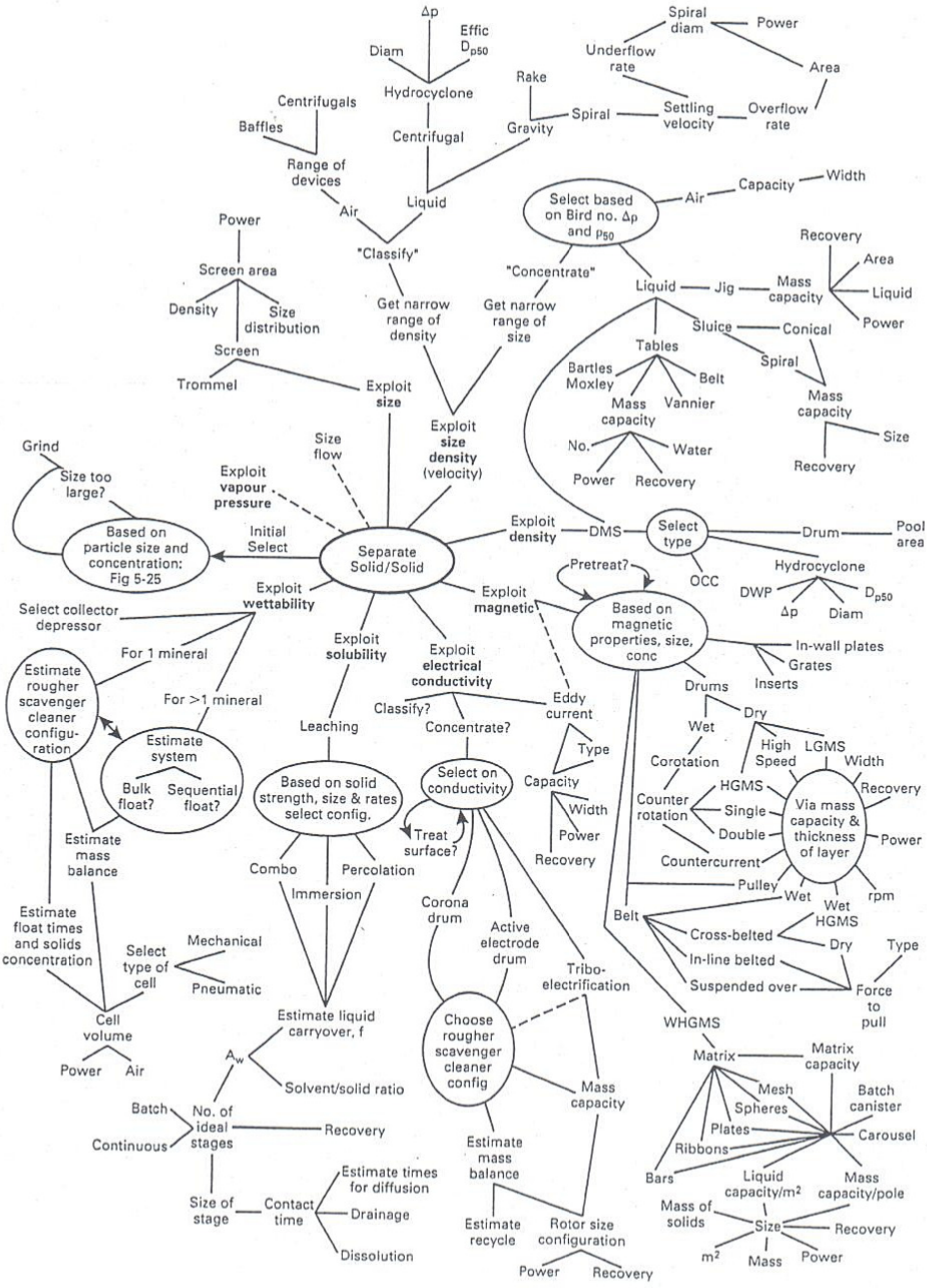


Figure 5–53 An Overview of Solid/Solid Separations

density/mass distribution has a Bird number of about 5. The gangue is silica. To liberate the mineral the ore has been crushed to yield a 0.030 to 0.6 mm size range. The ore has been deslimed to remove all of the particles less than 0.030 mm. What might we do?

5-5 We want to recover the solids from a stream that is 10% w/w solids. The solids are 5 mm diameter, density 1500 kg/m^3, and are fairly robust (as opposed to fragile). The density of the liquid phase is 800 kg/m^3 and is relatively toxic. The total slurry flowrate is 100 L/s. The desired exit liquid content is to be less than 1%. The liquid is to be recovered and recycled. What would you recommend?

5-6 Solids have been ground in a wet ball mill. The product is to be leached. However, before it is, we want to alter the solids concentration from 35% w/w to 75% w/w. The solids density is 2.7 Mg/m^3 and the liquid density is about 1 Mg/m^3.

a. Why would we do this?

b. If the particle size is 40% w/w −200 mesh and 100% w/w −28 mesh and the distribution is log normal, sketch the distribution and estimate the geometric mass average diameter and the geometric standard deviation.

c. Why do we not densify to 0% water?

d. Recommend some options.

5-7 We wish to separate vermiculite from kyanite and pyroxene. The feed is ground to 6 to 28 mesh and we want to keep the material dry. The capacity is 24 Mg/h. The feed is 32% vermiculite. What might we do?

5-8 We wish to separate phosphate from quartz. The feed is 71.7% phosphate and we would like to remove some of the quartz from this. The material is to be kept dry. The feedrate is 34 Mg/h. The particles are all less than 35 mesh. What might we do?

5-9 A feed stream of 15% water in Solvent 99 is to be separated. The density difference is 200 kg/m^3, the interfacial tension is 38.5 mN/m. The feed flowrate is 2 L/s. What might we select?

5-10 A frit smelter produces a waste gas containing 2.8 g/m^3 of particulates. The geometric mass median particle size is about 3 µm. The range is from 0.6 µm to about 8 µm. The gas flowrate is about 52,000 dm^3/s and contains about 0.5 g/m^3 of NO_2 and 0.3 g/m^3 of HF. The gas temperature is 200°C to 870°C. What might we do?

5-11 A refractory lined furnace incinerates 490 Mg/d of Municipal Solid Waste. This produces 111,400 dm^3/s of gas at 980°C. What alternatives are available if the dust loading is 3.5 kg/1000 kg gas?

5-12 The exhaust gas from a fluidized bed coal dryer flows at 69,000 dm^3/s at 90°C. The particles are classified as "ultra-fine"; the loading is about 6.4 g/m^3. Some SO_2 is present. What might you do?

5-13 A flow of 43,000 dm^3/s of hot gas exits from a cupola producing 14.5 Mg/h of iron using 140 kg of coke per Mg of iron. The gas temperature is 1150°C. The particle size and loadings are typical of cupola operation. What might you do to produce a waste gas at less than 110°C and containing less than 0.4 kg of particulates per Mg of exhaust gases?

5-14 A mixture of oil/sulfuric acid is to be separated. The temperature is 33°C. The oil is 23% v/v LIX 64N in Escaid 100. The oil/acid ratio is between 1:1 and 1:5. The total flowrate is 6.3 L/s. How might this separation be done?

5.5 PROCESS & INSTRUMENTATION DIAGRAM FOR WASTE WATER TREATMENT ILLUSTRATES APPLICATIONS

Processes to treat waste water must remove both the particulate and the dissolved contaminants. We must dispose of the solids involved in this process. Thus, this process illustrates the application of principles outlined in Chapter 5, with additional application of the separation for homogeneous phases.

PID-5: Waste Water Treatment

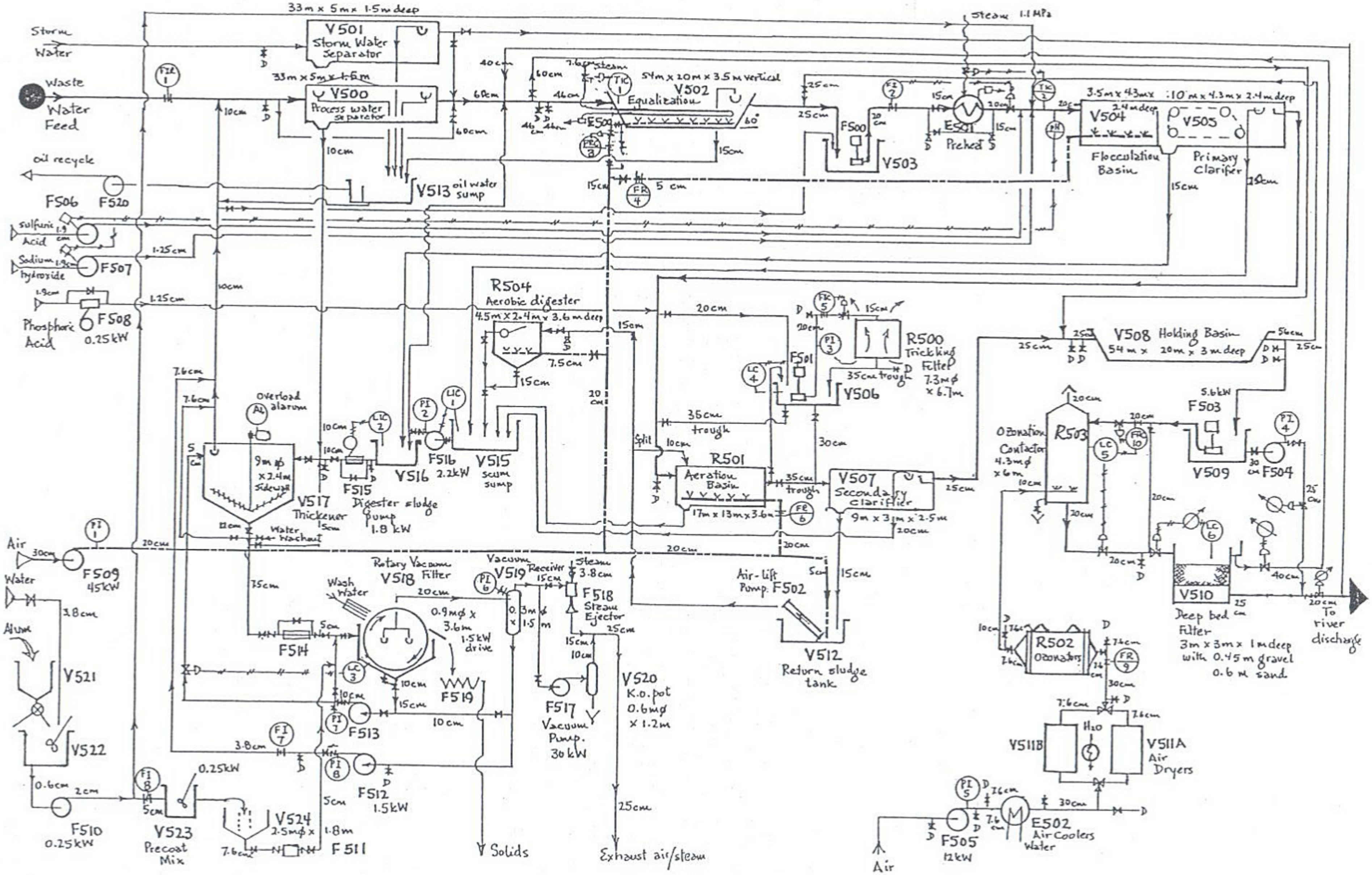
Industrial waste waters are contaminated with dissolved organics, solid particulate sludges, and immiscible oils. These combine to provide a liquid that is cloudy and dirty-looking, smelly, and toxic. The water may be a mixture of process water and rain water. The amount of water varies hourly, daily, and monthly.

An illustrative process to treat this industrial waste is shown in PID-5. The process is characterized by:

- duplication of much of the equipment as "standby" so that a working process is "always" available. (The standby equipment is not always shown explicitly in PID-5. Rather it is shown as Duplicate or Triplicate.) See, for example, **D** for just about every pump and major piece of equipment, **V500**, **V501**, and **T** for the equalization and holding basins **V502** and **V508**.
- flexibility: with piping to allow us to bypass and adjust the sequence of equipment.
- a lot of storage to handle the hourly and daily fluctuations in flow and concentration. This prevents surges and upsets. This is done mainly through the equalization and holding basins **V502** and **V508**. These former are designed for one-day capacity.

The feed to this example plant is about 30 L/s ± 30% with a variable amount of storm water. The process water is characterized by:

temperature	33°C
pH	10
immiscible light oil	2000 to 3000 ppm
heavy oils and sludges	130 ppm (parts per million)
suspended solids	130 ppm
phenol	50 ppb (parts per billion)
ammonia	8.8 ppm
nitrate	0.1 ppm
sulfides as H_2S	15.7 ppm



PID–5 Industrial Waste Water Treatment

TABLE 5A-1. Waste water treatment facility: cost contributions to the cost per litre of waste water treated

Contribution from	Approximate Unit Cost breakdown, %
Raw material	0.
Utilities	19
Catalyst and chemicals	1
Labor	29
Credit for byproducts: recycled oil	-31
Maintenance	11
Supervision	3
Depreciation	36
Indirectly attributable costs	32
General expense	0
Total	100