ACHIEVING HIGH RELIABILITY FROM GRAVITY FLOW HOPPERS AND BINS AND PNEUMATIC CONVEYING SYSTEMS

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ABSTRACT

This paper will provide recommendations for proper engineering and design practices to enhance the reliability of gravity flow of bulk materials from storage hoppers and bins; to establish the proper design criteria for feeding bulk materials to the pneumatic conveying system; and to provide an insight into good engineering practices for the design of dilute phase pneumatic conveying.

INTRODUCTION.

Pneumatic conveying started in 1866 with the application of a fan and ducts to remove the dust and fine particles from woodworking operations. Since then, the field of pneumatic conveying has greatly expanded to include nearly all fine granular bulk materials in the chemical, cement, agricultural, pharmaceutical and food processing industries.

Unfortunately, the art of pneumatic conveying is still very empirical and can lead to many misapplications. Research is still being done by many universities around the world, but the theoretical solutions for "two-phase flow" are often too complex for the practicing engineer. Besides, many of these solutions require experimentally-derived coefficients, which are not readily available. Since practical "know-how" in this empirical field of engineering is so important, this paper will endeavor to provide important guidelines for establishing proper design criteria for dilute-phase pneumatic conveying systems.

This subject will cover:

A.   Storage of the bulk materials and discharge from hoppers and bins.
B.   Feeding these materials into the pneumatic conveying line.
C.   Conveying the material in an air stream through a pipeline.
D.   Separating the air from the solids and collecting the solids.

E.   Prime air movers.

Figure 1 and 2 show typical layouts of a total system, which can be either a negative pressure (vacuum) or a positive pressure system.

The proper interface between the storage bins, feeders and pneumatic conveying systems is often neglected or ignored. Quite often a feeder is selected strictly for its volumetric feed rate without concern for the potential gravity flow problems in the preceding feed bin.

Knowledge of material properties is extremely important. In many cases actual laboratory measurements are required.

A.   Storage of Surge Bin Design.

Most granular bulk solids are passing through silos, bins and hoppers prior to or after being conveyed. In some cases this process is repeated a few times. The basic requirement of a good storage bin is that it can store the required quantity of materials and that it can discharge this quantity safely and reliably by gravity.

As granular bulk solids have varying particle size distributions, chemical composition, bulk densities and moisture contents, the flowability characteristics can also vary over a wide range. In order to establish the proper dimensioning of the storage bins and hoppers, it is generally advisable to measure these flowability characteristics carefully before any design is contemplated.

A poorly flowing material may cause an arch or bridge over the hopper outlet or may cause a stable rathole within the bin (see Figure 3). A very flowable material (dry fine powder) may become aerated and subsequently fluidize, causing potential flooding problems.

There are basically three flow patterns in bins. These are known as mass-flow, funnel-flow, and expanded-flow (see Figure 4). Each of these flow patterns has its advantages and disadvantages.

Funnel-flow occurs when the material moves strictly within a confined channel above the hopper outlet. The material outside this flow channel is at rest, until such a time that the bin level drops and the materials slides into this channel. The diameter of this flow channel is established essentially by the hopper outlet dimensions.

When the cohesive strength of the material is high enough, it may be possible to empty out this flow channel without the upper layers in the bin sloughing off into this channel. Then an open channel will be formed right within the bin. This is referred to as a "stable rathole".

Mass-flow refers to a flow pattern where all the material in the bin is in a downward motion, whenever the feeder is discharging. In essence, the material column slides along the hopper walls. In order to attain this type of flow pattern, the hopper walls must be steep and smooth. Figure 5 shows a graph, where the hopper slope angle is plotted against the sliding friction of the hopper wall. There is a very specific combination of slope angle and sliding friction coefficient that will result in mass-flow, as identified by the hatched area.

The expanded-flow uses the mass-flow pattern in the lower hopper section up to the point where the "stable rathole" diameter is reached, and then the flow pattern continues as funnel-flow. The "stable rathole" diameter can be calculated when the flow properties are known.

The measurement of the flow properties is essential for the proper design of the storage bin and hopper. These properties can be measured by either a linear or rotational shear test apparatus. The influence of operational conditions, such as moisture changes, temperature, consolidating time, particle degradation, slideability, etc., can be accurately determined. A typical test result is shown for a milk powder product, see Figure 6.

Once these properties are known, the critical arching dimensions of the hopper outlet and the stable rathole diameter in the bin can be determined. For the milkpowder, shown in Figure 6, the following dimensions were determined:

Critical arching diameter:
      Instantaneous   - 18"
      3 days consolidation   - 70"
Stable rathole diameter:
      Instantaneous   - 5'
      3 days consolidation   - 20'
Mass-flow hopper angle (cone):
      For 304-2B stainless   - 70°

In addition to straight gravity flow, flow promoting devices are sometimes used with varying success.

A. Feeding into the Pneumatic Conveying Line.

The selection, design and operation of feeders for controlling the delivery of bulk solids into the pneumatic conveying line is critical. The feeder and hopper bottom should be designed as an integral unit.

There are a number of different feeders that can be considered for pneumatic conveying systems. The most common type of dilute phase systems is the rotary-vane feeder, sometimes called the rotary-air-lock feeder, as shown in Figure 7.

The rotary feeder is the heart of a dilute phase system where an airlock feeder is needed. In many cases, a system that was almost inoperable has been put back on its feet by simply removing an improperly sized or wrong style of feeder and installing the right unit for the job.

Many designers try to skimp on the rotary feeders, but it is generally penny-wise and pound-foolish to do so because of the troubles that can develop with reduced system capacity, frequent plug-ups, and especially with subsequent high maintenance of misapplied feeders.

Apart from conveying systems that utilize "blow pots" as a feeder, there is generally a pressure differential involved across the rotary vane feeder, either positive or negative. Under negative (vacuum) conditions the feed problems are usually minimal. However, under positive pressure conditions in the pipeline, a certain amount of the air will try to flow through the feeder in the opposite directions from the solids. This counter flow of air will generally impede the gravity flow from the hopper (see Figure 8).

The amount of air that escapes at each feeder location is directly proportional to the available air gap area. For rotary vane feeders this air leakage for powders amounts to approximately $17\,A\sqrt{\Delta P}$, where A is the cross-sectional area of the airgap in sq. in. and ΔP is the pressure differential in inches of water column.

Figure 9 shows a table of the approximate static leakage rates for various sizes of rotary vane feeders under various pressure conditions. The dynamic air loss must be added, which is based on rpm and rotary vane feeder volume. Rotary-air-lock feeders are usually sized for 50-60% of pocket-fill efficiency.

The air leakage rate is also dependent on the type of granular bulk material handled in the feeder. Figure 10 shows some typical leakage rates for different products.

The air pressure that builds up under the hopper outlet-opening due to the air leakage around the feeder, will affect the gravity flow from the hopper. For fine powders (with low permeability) this air pressure may even stop all flow. In order to avoid these problems, proper venting of the feeder is recommended, as shown in Figure 11.

As the vent line of the feeder may have to handle "dusty" air, the obvious solution would be to connect it to the supply bin or to a separate air filter. Because of the potential dust loading in the vented air stream, the diameter of the vent pipe should be at least 4" or, better still, 6". If any slope is required to the vent pipe, the minimum slope angle should be about 65°. Any material that drops out of the vent pipe must be picked up by the feeder.

The feeding of negative pressure systems is much easier, as there is no need to feed against an adverse pressure gradient. Simple rotary-vane feeders may be used, as long as they match the hopper outlet. A screw feeder may also be considered, if the hopper outlet dimensions are much larger than the required volumetric capacity of the rotary-vane feeder.

A. Conveying through a Pipline.

There are basically five classification categories for pneumatic conveying systems, as shown in our Figure 12, depending on range of velocities and pressures. "Dilute phase" are usually the high velocities and low pressure systems, while "dense phase" are the low velocities and high pressure systems. The air-activated gravity conveyor (sometimes referred to as "airslide") is a classification by itself.

For time's sake, we will confine our attention primarily to the dilute-phase conveying systems, as they are still the most commonly used in the industry. Dense-phase systems do not rely on keeping the bulk solids in suspension in the air stream during the conveyance, but are pushing the solids more as a plug through the pipeline; hence, the higher pressures.

Conveyance of solids, suspended in an air stream, through a pipeline is, in essence, similar to other hydraulic conveyances. The pressure drop along the conveying line is primarily dependent on transport velocity, pipe diameter, bends and elbows, system length, solids-to-air ratio and type of solids handled. There are a few theoretical equations available in the industry for computing the pressure drop of a pneumatic conveying system. These computations, however, are fairly complex and require generally the use of a computer.

For quick estimating purposes, a simpler method can be used, utilizing the "multiplier factor". The total pressure drop in a system can be resolved as follows:

$$\Delta P_{air + solids} = P_{air}(1 + kR)$$

where $(1 + kR)$ = multiplication factor

$$\Delta P \qquad = \text{ pressure drop in inches WC}$$
$$k \qquad = \text{ factor related to solids friction}$$
$$R \qquad = \text{ solids-to-sir ratio (lbs solids/lb air)}$$

Typical values for k are shown in Figure 13 for different values of R.

The pressure drop for air alone (ΔP air) is shown in Figure 14 for different air velocities and pipe diameters.

Some typical values of R are shown in Figures 15 and 16 for dilute phase pressure systems.

It is customary to establish the pipe diameter on the basis that the pressure drop for air alone does not initially exceed 10" WC per 100 ft.

An example of this quick estimating method is as follows: let's assume we have to convey granulated sugar over a distance of 400 ft with about 4 bends of 90°. The approximate average air velocity for granular sugar (58 lb/ft³ and 60 Mesh) is about 5000 fpm (see graph Figure 17).

The desirable R value would be about 6 (see Figure 15). For a 4"-11 GA tubing (3.75 ID), the pressure drop for air alone would be about 10"WC per 100 ft and the air volume Q = 386 scfm. This would result in a solids flow rate of about 175 lb/min or 5.25 TPH. The k-factor for R = 6 is 0.5 and the friction multiplier is about 4.

Therefore:

$$\Delta P_{400' \text{ line}} = (4 \times 10 \frac{"WC}{100ft}) \times 4.0 \quad = 160" \text{ WC}$$

miscellaneous loss in cyclone/filter,

$$\text{etc.} = 10" \text{ WC}$$

$$\text{Total} = 170" \text{ WC}$$

or $\quad \dfrac{170 \ ("WC)}{28 \ (\frac{"\ WC}{psig})} = 6.07$ psig.

Add 1 psig for safety reasons and:

$$\Delta P_{total} = 7.0 \text{ psig for this system.}$$

If we have available a blower rated for 12 psig, then we could increase the solids-to-air loading. Or, we could also increase the air flow velocity to 6000 fpm (ΔP air = 15" WC/100') or Q = 463 scfm. The solids-to-air ratio may then become about 8, or 280 lbs/min solids flow rate.

From this example it is apparent that there are quite a few combinations possible, between air velocity, solids flow rate, and pressure drop. Additional bends or elbows can often be simulated as "equivalent

lengths" distances. For 90° bends, having a bend radius to pipe diameter ratio of about 12, the "equivalent length" is typically about 15 – 20 ft for air only, allowing at least 15 – 20 ft distance between elbows.

For dilute phase systems it is generally recommended to allow for at least 20 ft horizontal run of pipeline before a bend or elbow is applied. This allows the particles in the airstream to accelerate to sufficient speed before they are slowed down again at the first bend or elbow.

Routing of conveying lines is a key ingredient in establishing a good plant layout. Short distances and a minimum number of bends are desirable. Dilute-phase conveying lines should, in general, comprise horizontal and vertical runs. Behavior of solids in upwardly <u>inclined</u> dilute-phase conveying runs is unpredictable and should be avoided in laying out the system.

Conveying lines do get plugged, so access for cleanout is a must. Careful routing can make cleanout much easier, as can support at key locations and careful placement of connectors for break-out.

After the total pressure drop has been established, the blower shaft horsepower can be computed. Assuming a leakage loss of about 25% for the rotary vane feeder, the horsepower would be about
$$0.006 \times 1.25 \times Q \times P,$$

where $\quad Q$ = scfm calculated for line transport,
ΔP = total pressure drop in psig.

Grounding of conveyor piping is a must, including jumpering across non-conducive insulators such as sight glasses, gaskets and most types of couplings.

A. Air-Solids Separation.

After material has been transported through the system, it is necessary to separate the solids from the air stream. There are many devices available to effect efficient solids recovery. The type of system selected will depend upon the degree of recovery required and also the harmful effects on the product being conveyed. It is also possible to achieve some form of sizing of the product.

The more common devices used for air-solids separation (receivers) in pneumatic conveying systems are (see Figure 18):

> Cyclones,
> Bag filters,
> Cyclone filter receivers.

Cyclones can be used to effect product sizing by utilizing a number of cyclones in series, each designed to separate out up to a certain size fraction. There are several types of cyclones available and relatively high separation efficiencies are possible, approximately 98% for particles above 10 microns (see Figure 19).

Bag filters are more commonly used for fine powder conveying systems and these, too, are available in many forms.   Perhaps the most common bag filter system used in pneumatic conveying are (see Figure 20, 21, and 22):

> Mechanical- or hand-shaking cleaning,
> Reverse jet cleaning,
> Reverse flow cleaning.

Bag filters essentially consist of filter bags made from various types of fabrics, depending upon the application. The dust-laden air is passed through the bags, the pores of which are sufficiently small as to collect the finest particle. Mechanical or air cleaning techniques are employed to remove the fines from the bags. As a guide, Figure 23 shows a table for some typical air-to-cloth ratios for filter receivers.

Air-solids separation is a vast subject. Being at the end of the conveying process, its importance is often overlooked, and yet, incorrect design can cause endless problems in the conveying system.
In dilute-phase systems, the selection of a suitable air-solids separation system must take into account two aspects. First, since it is important to conserve as much energy for the conveying of the material as possible, the system must operate at as low a pressure drop as possible (of the order of 8 – 9" WC). Second, by virtue of its characteristics, dilute-phase conveying is synonymous with a relatively high dust loading and the system must be designed accordingly.

Cyclones alone are used less and less in today's atmosphere of strict environmental protection, but are still acceptable for many applications.

Removal of dust from a collector hopper can be critical. Rotary valves or other discharge devices often must operate with a differential pressure across them. The dust is usually harder to handle than the parent solids stream. Flow aids are often required in dust collectors in which the dust is allowed to accumulate. Sometimes the dust can be accumulated in the collector until the conveying system can be shut down, then the batch of dust is discharged through a single shut-off valve. Many dust collectors, however, are set up to constantly discharge the dust through a rotary valve, with no accumulation.

A. Prime Air Movers.

Two basic forms of air supply systems are used in dilute-phase systems:
High pressure fans,
Roots-type blowers.

Fan Systems.

The use of centrifugal fans is generally confined to the granular type agricultural products, such as wheat, maize and derivatives, generally classed as non-abrasive products.

There are several examples of fan systems in which the product actually passes through the fan, thus eliminating the need for any feeding device. Such systems require robust fans an often economics justify the replacement of impellors, scroll cases, etc., rather than to employ rotary valves or other such feeders. Fan systems are also extremely well suited to the "suck and blow" conveying systems, in which material is vacuum-lifted and then pressure-conveyed over a long distance, utilizing only one fan.

When utilizing a conveying system which employs a fan, particular attention must be paid to the "fan characteristic" curve to ensure that the system requirements will be matched to the fan performance. Selection of a fan is important to avoid operating on the "wrong" side of the performance curve.

In general, since it is possible to pass product through the fan, air solids separation requirements can often be satisfied with cyclones, resulting in lower capital requirements.

For conveying systems the radial, backward inclined type of fan is most often used (see Figure 24). The fan blades are curved backwards to develop much of the energy as pressure. Small variations in system volume generally result in small variations of air pressure, which makes these fan units easy to control.

Roots-Type Blower Systems.

The roots-type blower (see Figure 25), because of its positive displacement characteristics, is extremely well suited to pneumatic conveying systems. Essentially, these prime movers have an almost linear P-V relationship, which facilitates higher solids loading than can be achieved with a fan system.

The use of roots-type blower systems extends over a wide range of products to include fine sub-micron powders as well as large (3 inch) lumps of coal and rock. Their popularity is largely attributable to their relatively low cost. They are normally restricted to maximum output pressures of 12 – 15 psig.

The nature of construction of a roots-type blower (with lobes rotating at high speeds with close tolerances) dictates that particular attention must be paid to preventing any material from entering the blower. As such, superior intake filters must be employed to ensure a long life. Further, it is good practice to protect the blower by means of non-return valves.

Roots-type blowers are normally classified as being very noisy and it is common to find a blower unit fitted with both inlet and discharge silencers. In recent years many manufacturers have devoted a lot of attention to this noise aspect and at least one supplier claims to have included internal design modifications which have reduced noise production considerably.

Blowers can be used to provide bother a positive and negative pressure head, but, as discussed above, adequate filters are necessary, especially on negative pressure applications. In addition, with a negative pressure system it is necessary to protect the blower with a vacuum relief valve.

Conclusion.

Although this subject is too extensive to be covered in one short paper, the main and significant items, influencing the reliability of the system, have been discussed. It may be well to emphasize again the importance of knowing the flow properties of the bulk solids to be handled prior to designing the system.
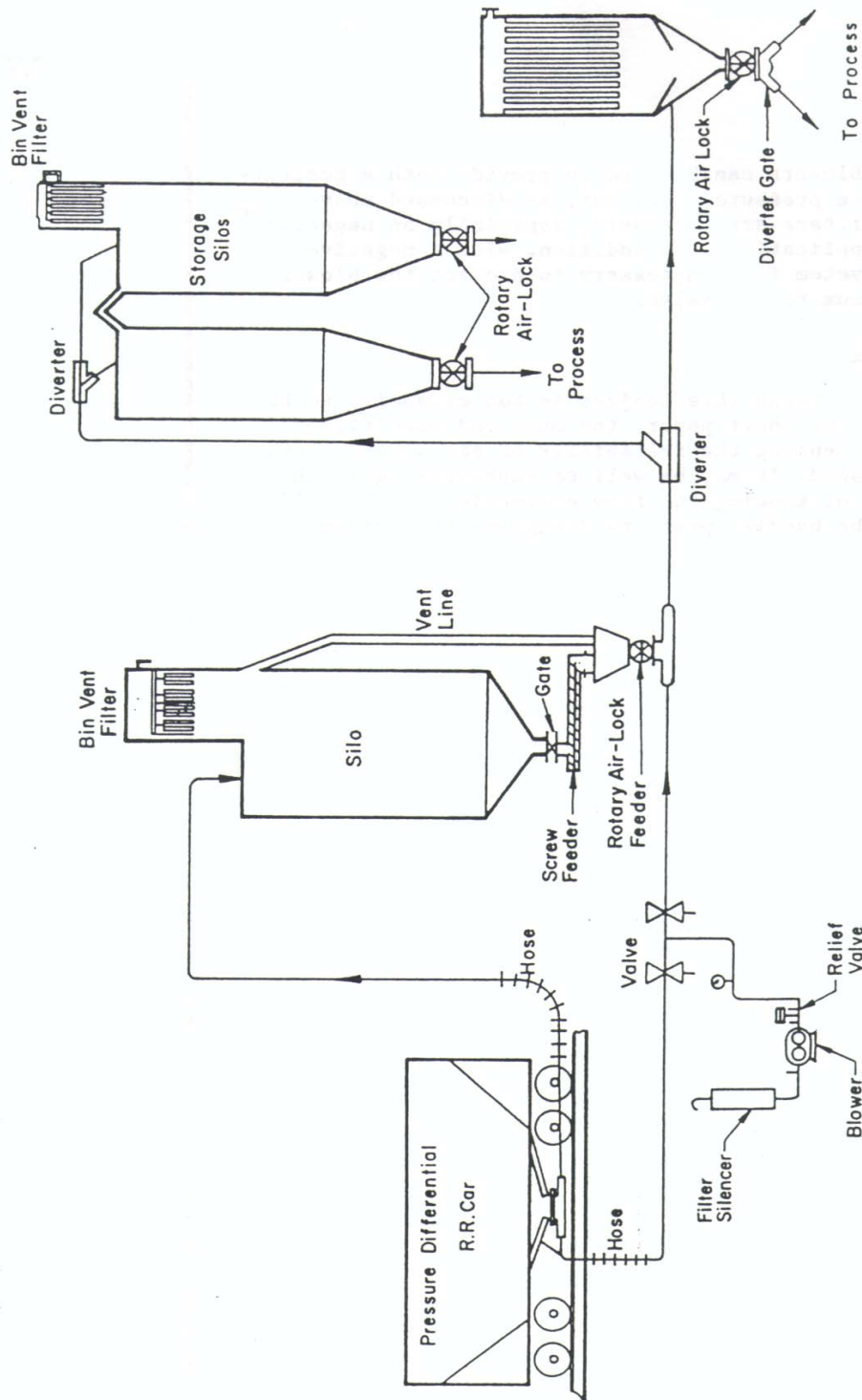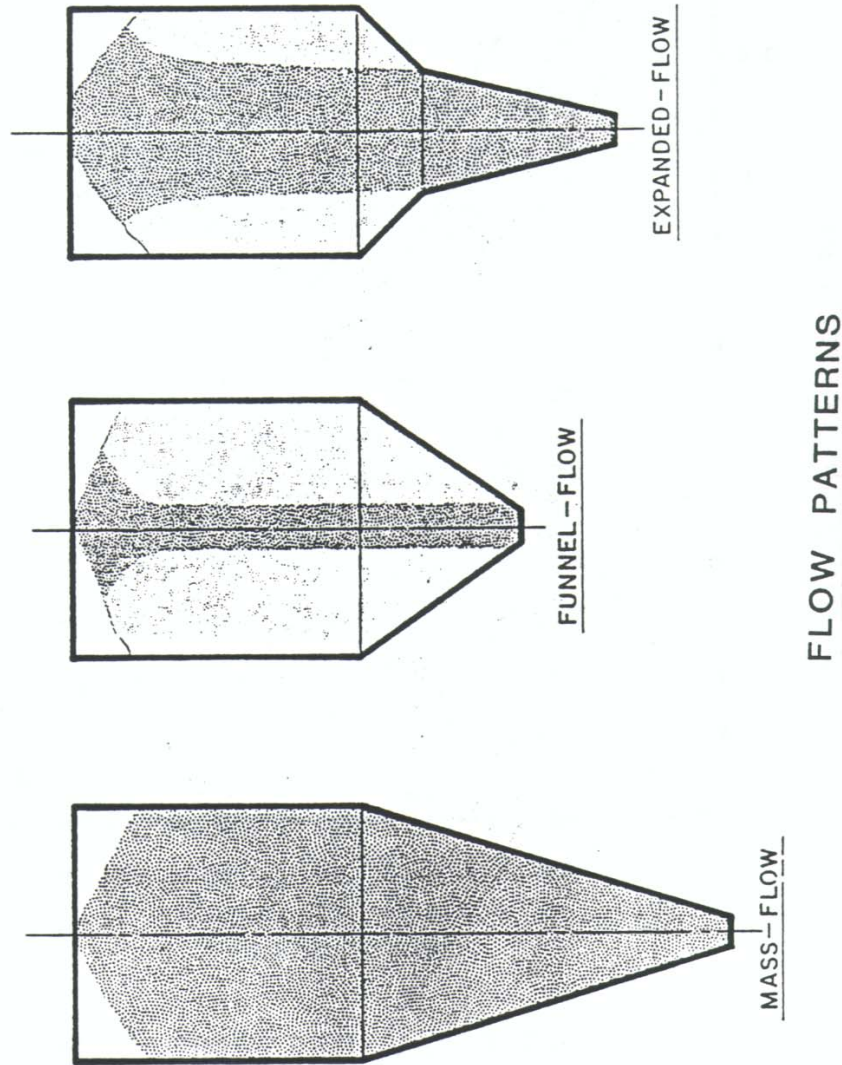
POSSITIVE PRESSURE SYSTEM

FIGURE 1

EXPANDED - FLOW

FUNNEL - FLOW

MASS - FLOW

FLOW PATTERNS

FIGURE 4

Nominal Feeder Size	6"	8"	10"	12"	14"	16"	18"
Volume Capacity ft³/rev.	0.125	0.25	0.50	1.0	2.0	3.0	4.0
Pressure — Inch Water 28 / PSIG 1	11	15	20	26	32	36	39
56 / 2	16	22	28	36	44	48	54
112 / 4	17	31	40	51	62	68	76
168 / 6	27	38	48	62	76	81	96
252 / 9	33	46	59	76	92	96	116
336 / 12	38	53	68	87	106	112	130
420 / 15	42	59	76	97	118	122	144

Air Leakage $\approx 17 \times A$ in.^{2} $\times \sqrt{\Delta P}$" WC
Product: Light Powder

Static Air Leakage in CFM of Rotary Vane Feeder
(Clearance=0.006")

FIGURE 9
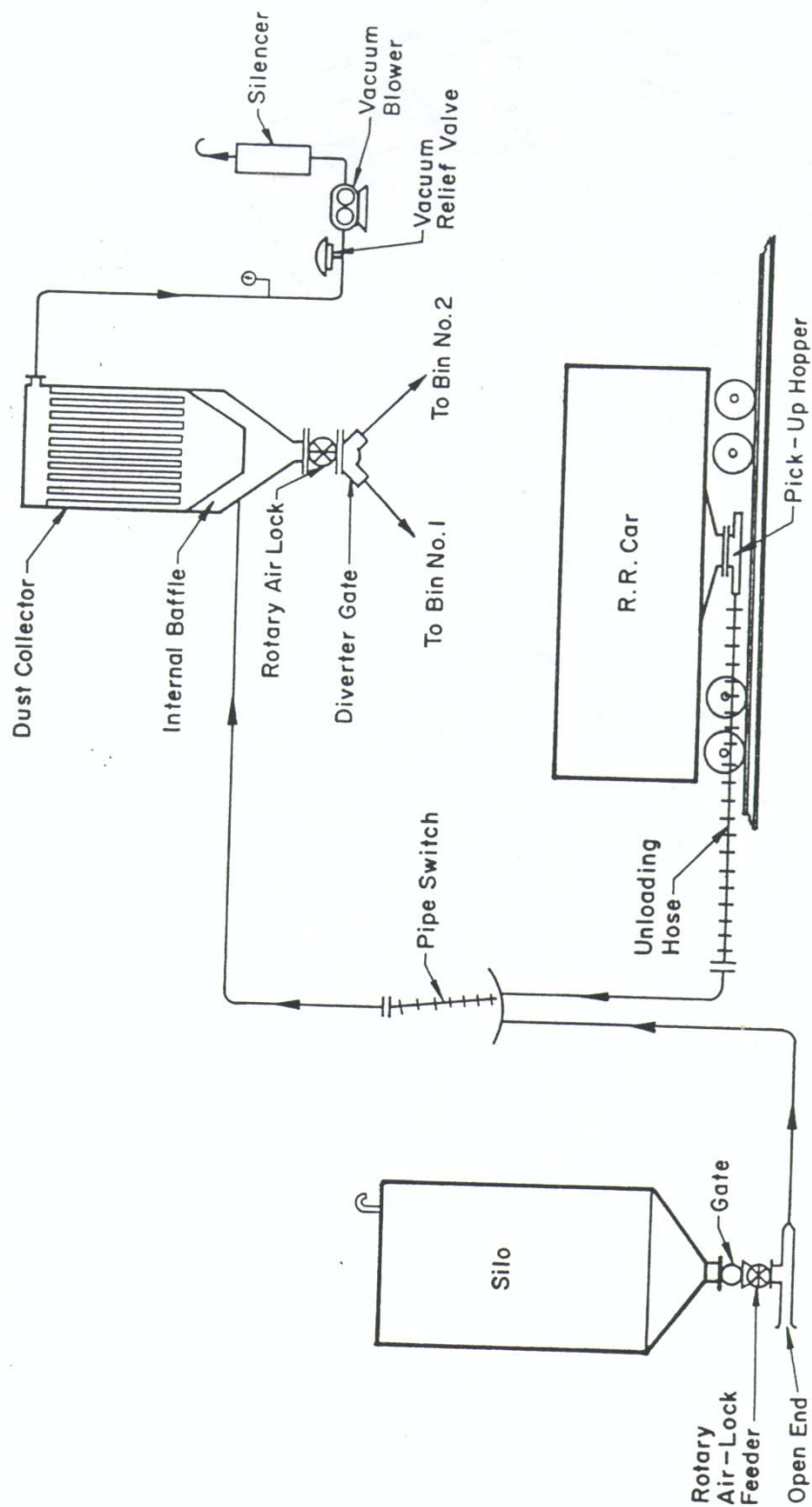
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NEGATIVE PRESSURE SYSTEM

Silencer

Vacuum Blower

Vacuum Relief Valve

To Bin No. 2

To Bin No. 1

Dust Collector

Internal Baffle

Rotary Air Lock

Diverter Gate

Pipe Switch

Unloading Hose

R.R. Car

Pick-Up Hopper

Silo

Gate

Rotary Air-Lock Feeder

Open End

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ROTARY AIR-LOCK FEEDERS
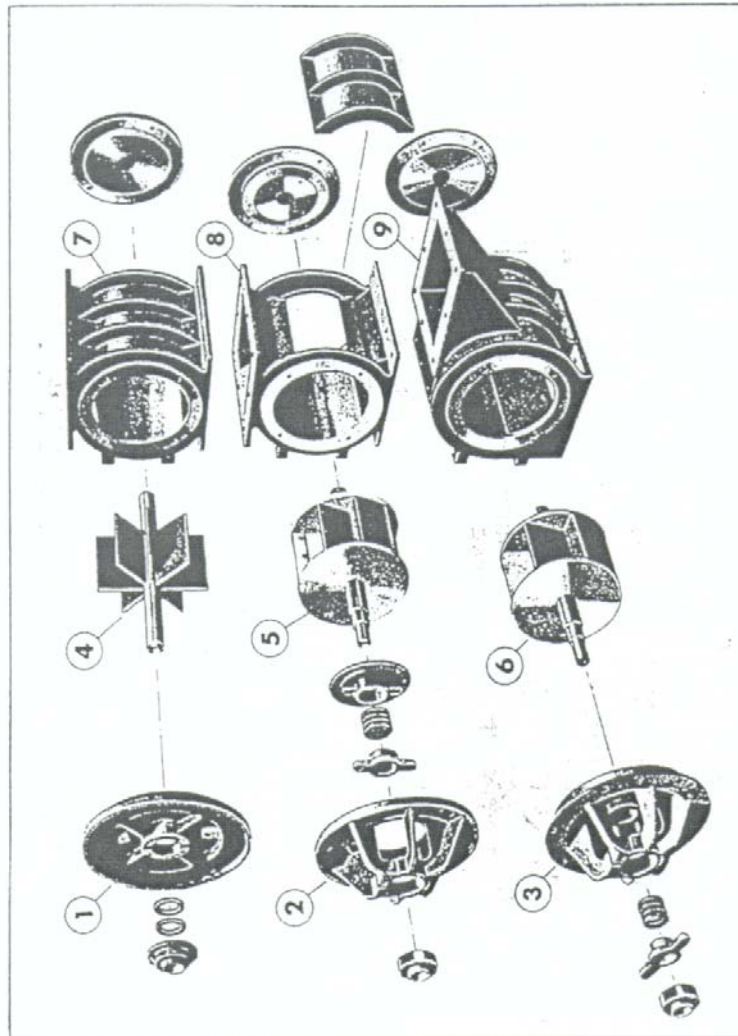
End Plates

1. Flange bearing and lip seals.
2. Packing gland, separate stuffing box and cartridge bearing.
3. Packing gland, integral stuffing box and cartridge bearing.

Rotors

4. Type I open end.
5. Type II closed end with adjustable tips.
6. Type I closed end.

Casing

7. Without inspection panel.
8. With inspection panel.
9. Side inlet.

FIGURE 7

CLASSIFICATION OF PNEUMATIC CONVEYOR SYSTEMS

SYSTEM	DILUTED PHASE	DILUTED PHASE	MEDIUM DENSE PHASE	DENSE PHASE	AIR ACTIVATED GRAVITY CONVEYOR
	FAN	BLOWER	PUMP	BLOW TANK	AIRSLIDE
PRESSURE RANGE	± 20" H₂O	± 7 PSI	15 – 35 PSI	30 – 125 PSI	FAN TYPE 0.5 – 1 PSI (CLOSED) 4 – 5 PSI (OPEN)
SATURATION CU. FT. AIR/ LB. MATL.	VAC. 10 – 30 PRES. 4.5 – 13	VAC. 3 – 5 PRES. 1 – 3.5	0.35 – 0.75	0.1 – 0.35	3 – 5 CFM/SQ. FT.
MATL. LOADING LB. MATL./LB. AIR	VAC. 1.3 – .45 PRES. 3 – 1	VAC. 4.5 – 2.5 PRES. 13 – 3.8	45 – 18	135 – 45	
AIR VELOCITY FPM	6000	4000 – 8000	1500 – 3000	200 – 2000	10 THRU DIAPHRAM
MAX. CAPACITY TPH	50	100	300	400	500
PRACTICAL DISTANCE LIMITS IN FT.	VAC. 100 PRES. 200	VAC. 200 PRES. 500	3000	8000	100 FT. 6 FT. DROP/LENGTH 3° TO 10° SLOPE

FIGURE 12

FRICTION MULTIPLIER CHART

The chart shows Friction Multiplier (vertical axis, 0 to 11) plotted against Material Loading lb. Solid/lb. Air (R) (horizontal axis, 0 to 17).

$$\Delta P_{Air+Solids} = \Delta P_{Air} \underbrace{(1+kR)}_{F.M.}$$

(90° Elbow/100 FT.) Included

Curves labeled: Powders, Granular, Pellets

k=0.7, k=0.6, k=0.5, k=0.4, k=0.3

FIGURE 13

Material: Milk Powder
Moisture: 1.0%; temp 90°F

Wall fx. coeff = 0.40 (ϕ' = 22°)
For Type 304 − 2B Stainless Steel
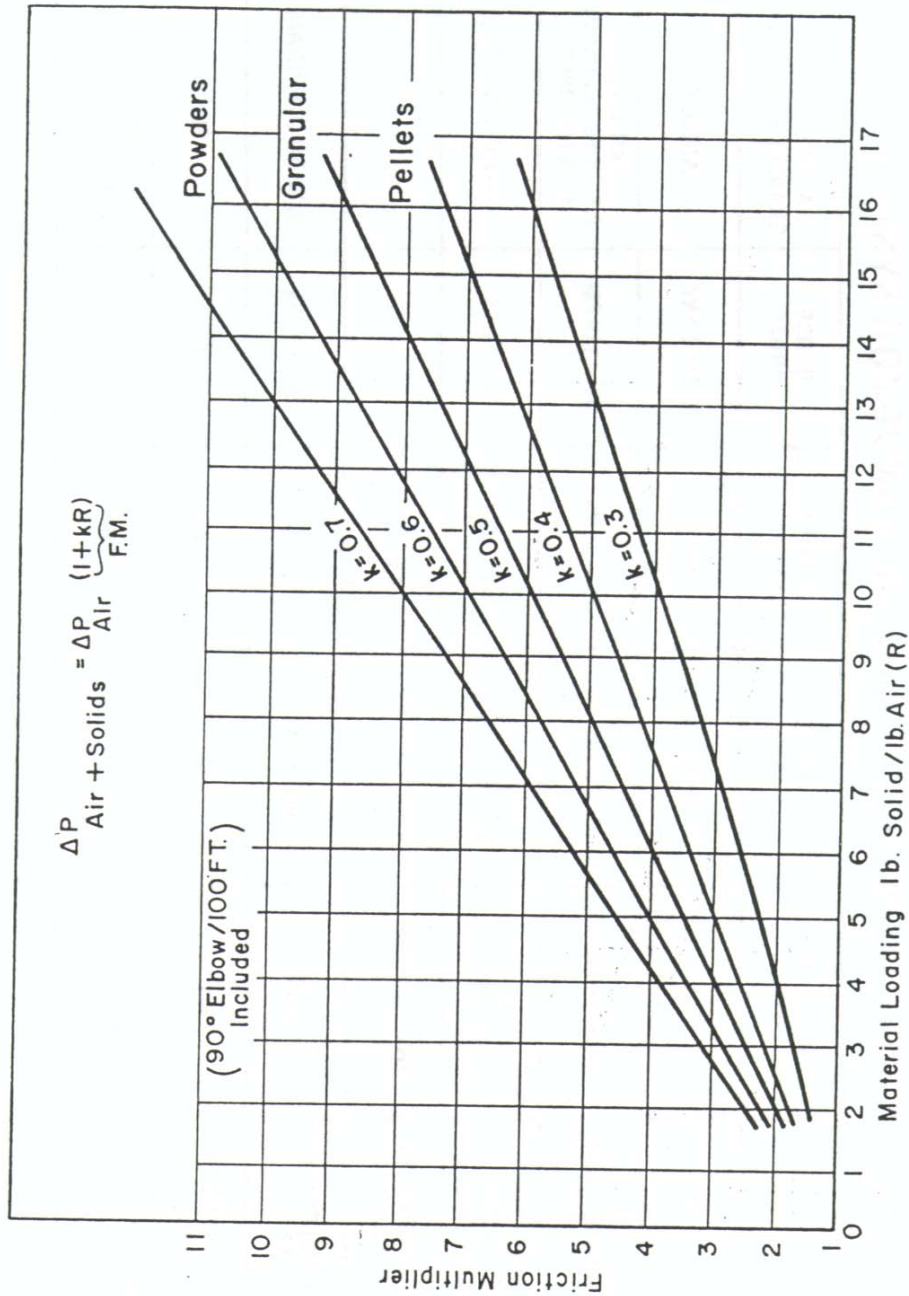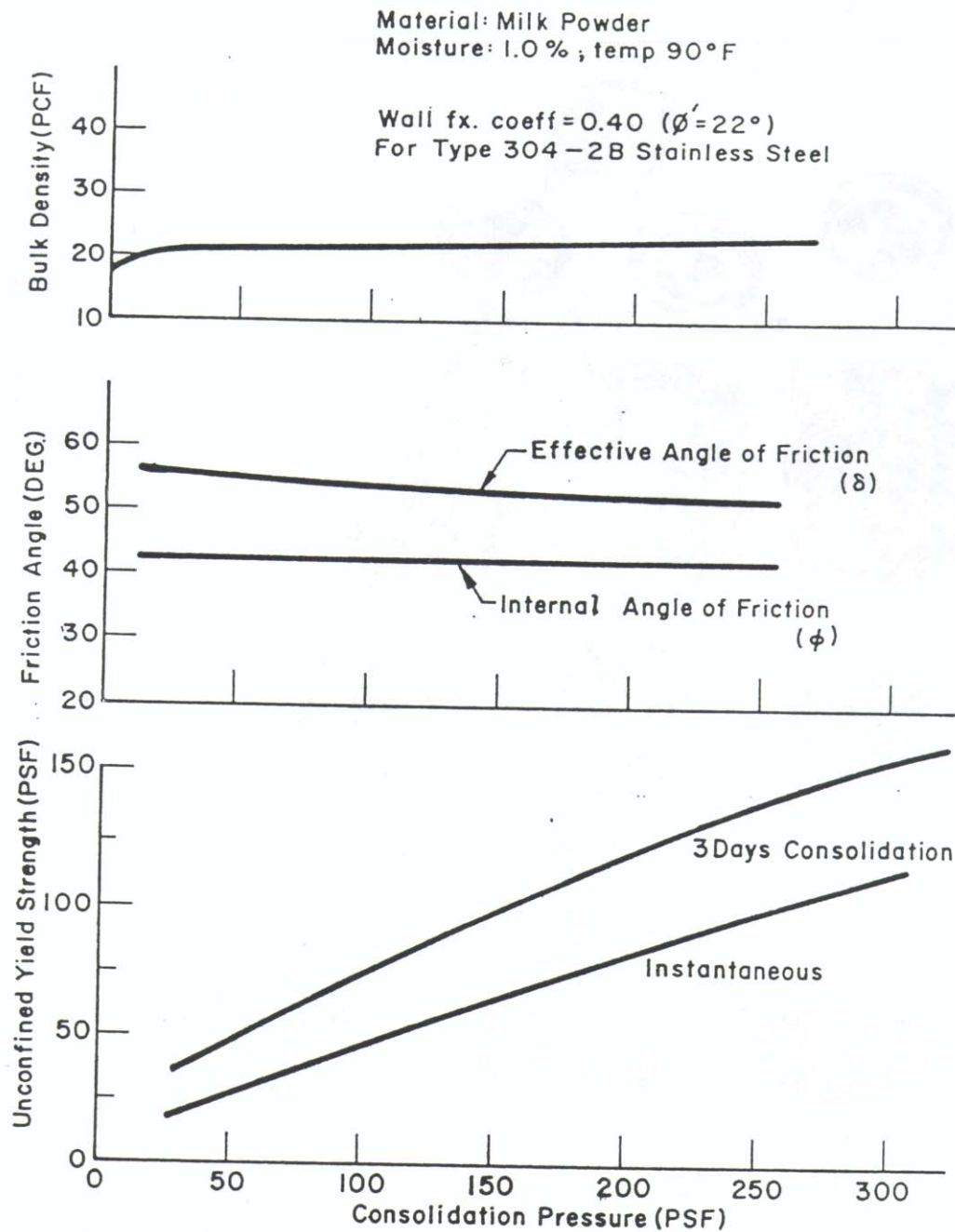
FLOW PROPERTIES

FIGURE 6

Air Velocity X 1000 FPM

$$\frac{\Delta P}{100'} = 0.0056\,\frac{V^2 fpm}{3600 \times D}\ (in.WC)$$

in.WC/100ft

Cross Sectional Area

Pressure Drop for Air Flow
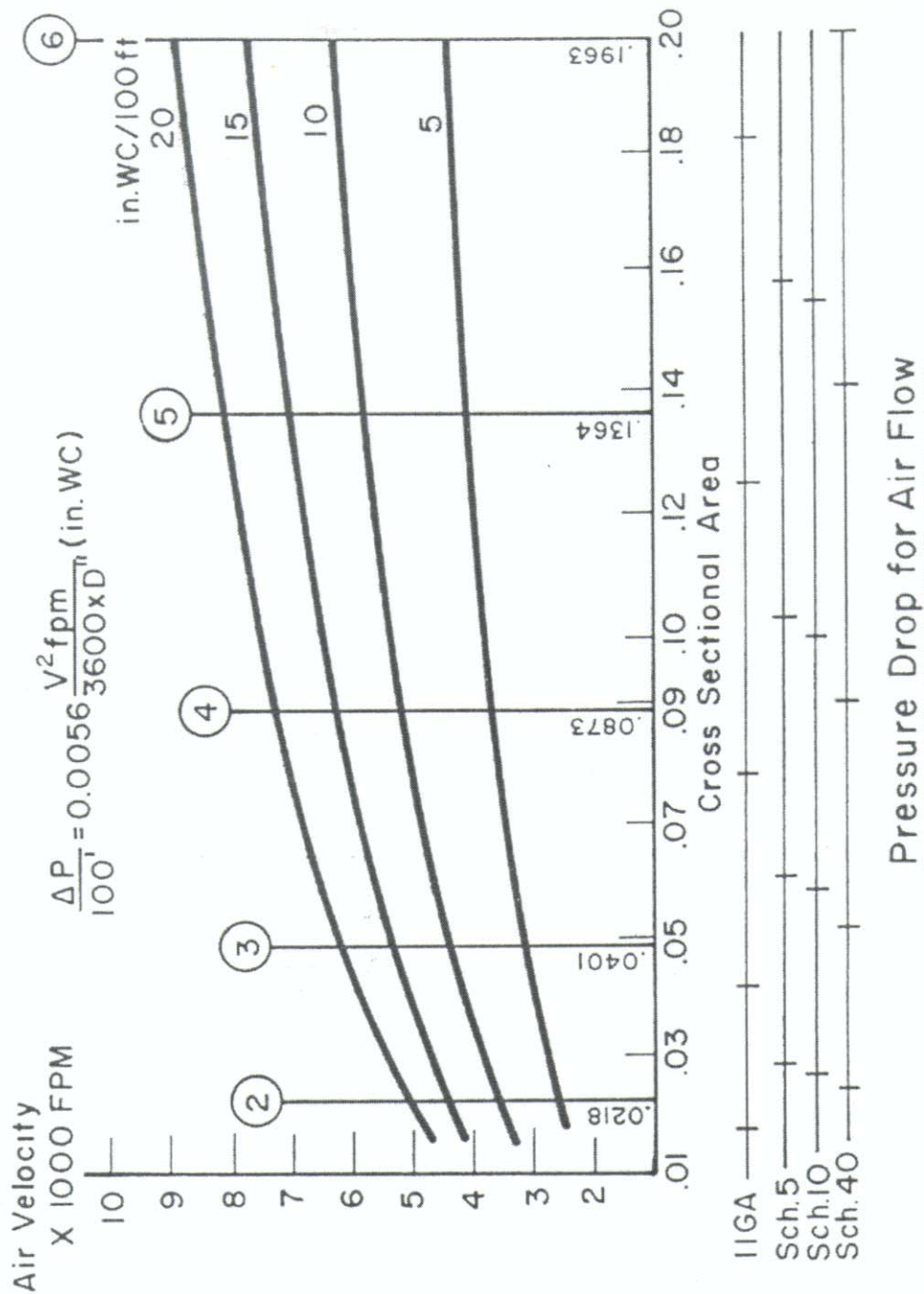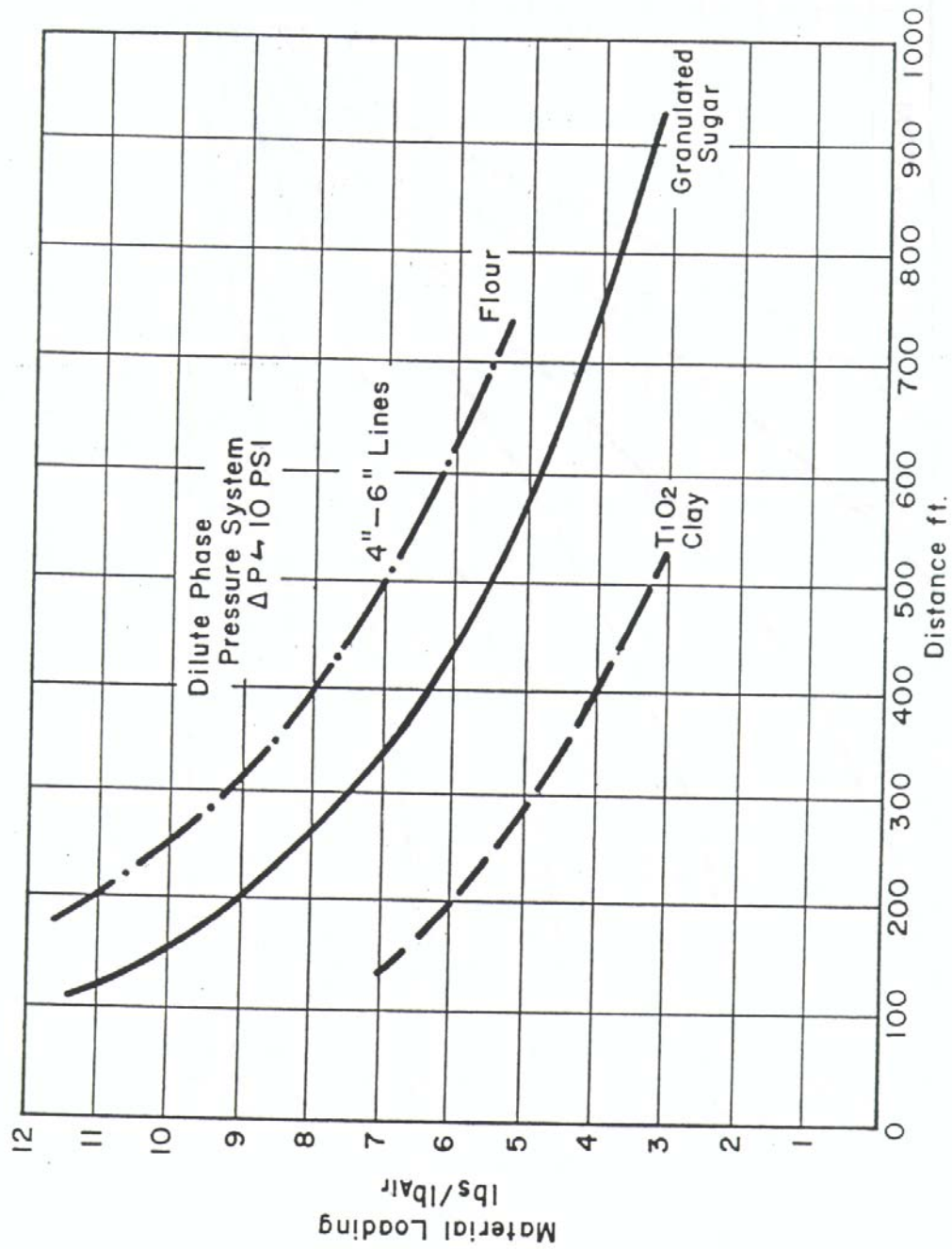
FIGURE 14

SUGGESTED SOLIDS –TO – AIR RATIOS

FIGURE 16

FIGURE 17

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CYCLONE

CYCLONE – FILTER

BIN VENT FILTER
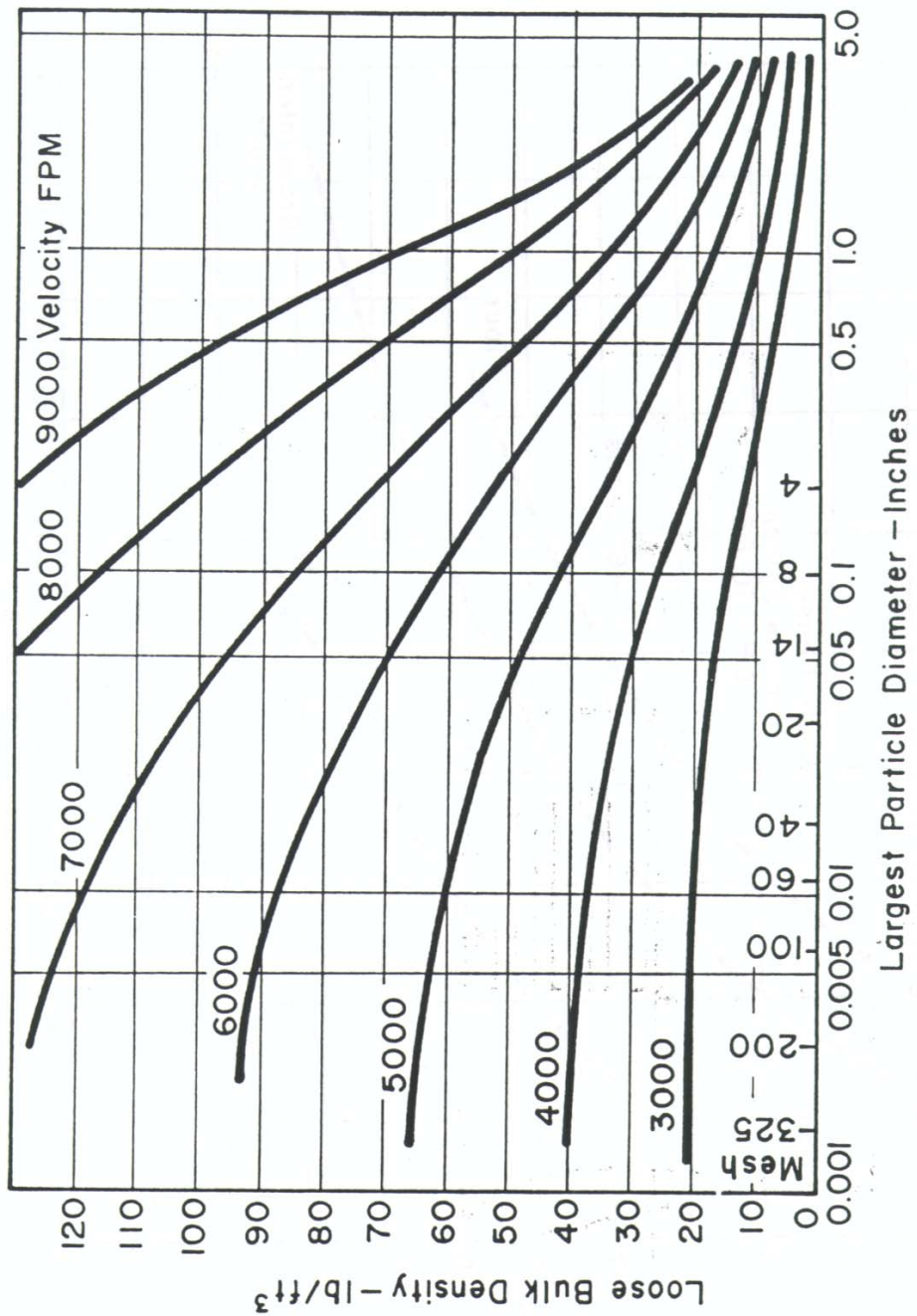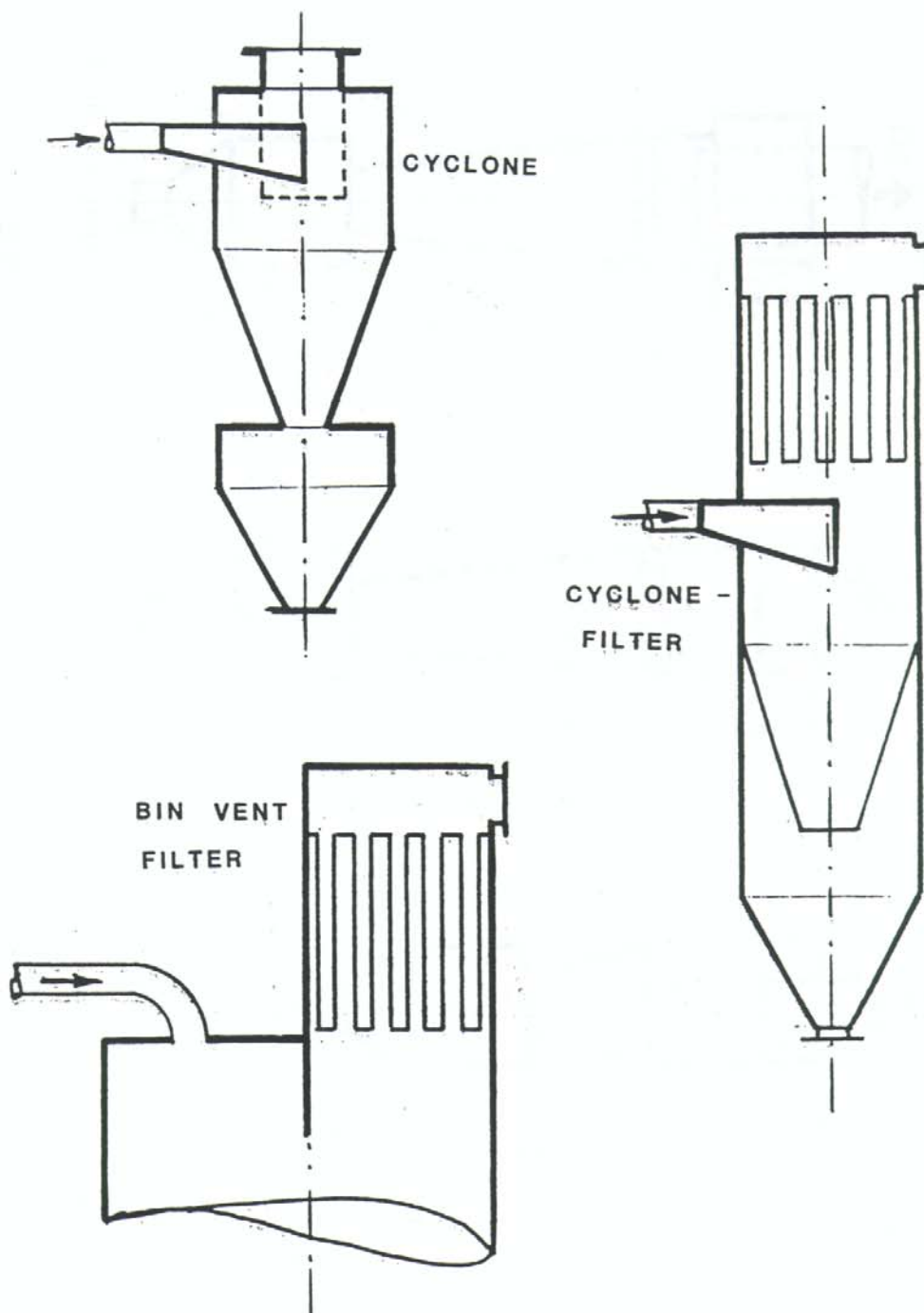
VARIOUS TYPES OF RECEIVERS

FIGURE 18
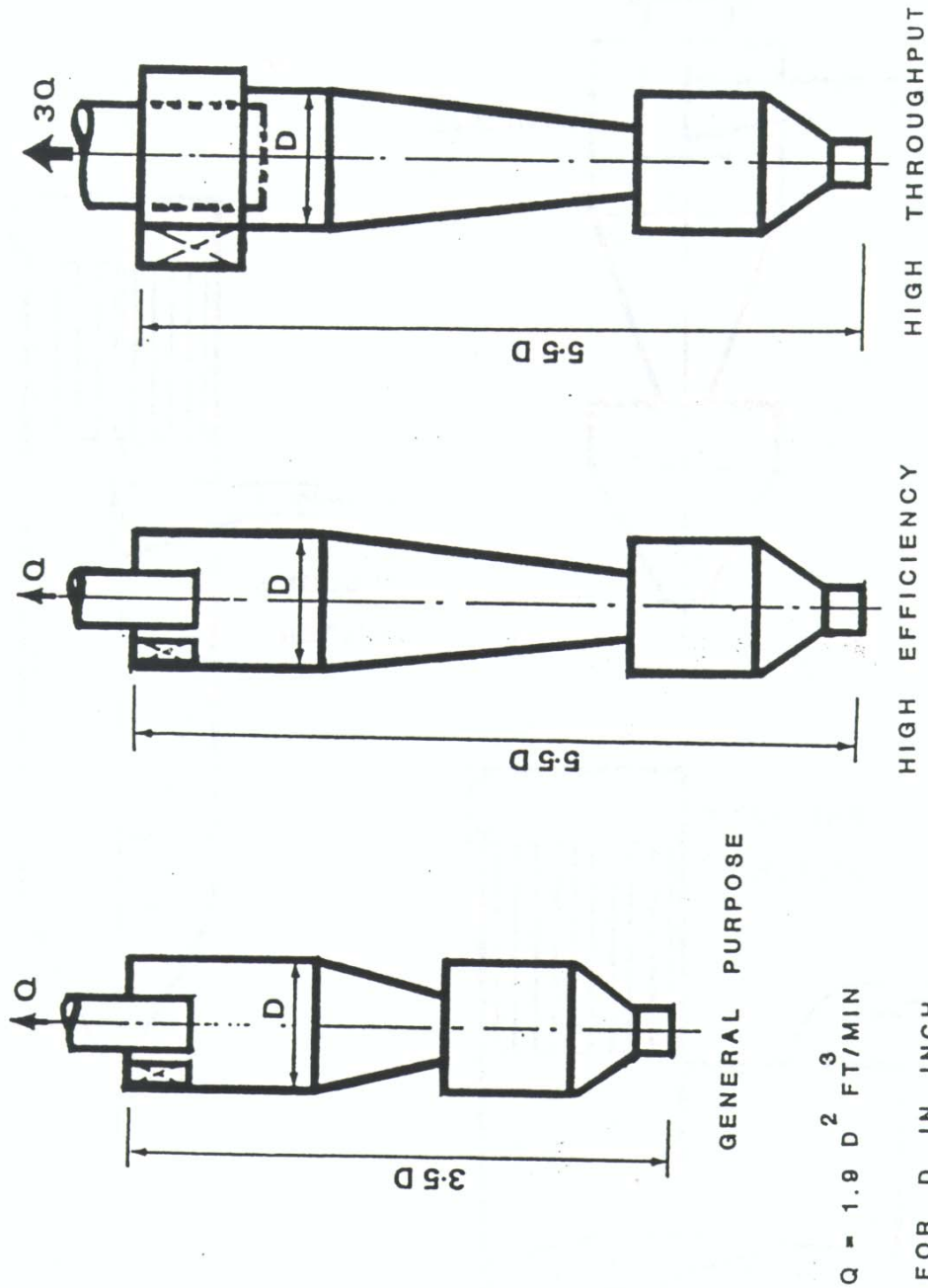
VARIOUS TYPES OF CYCLONES

HIGH THROUGHPUT

HIGH EFFICIENCY

GENERAL PURPOSE

$Q = 1.8 \, D^2 \, FT^3/MIN$

FOR D IN INCH

FIGURE 19

NYLON FILTER
TUBES, AIR-
CLEANED AND
AUTOMATICALLY
SHAKEN EVERY
TWO MINUTES

(Shaking.
mechanism
not shown)

AIR
(To
exhauster)

FLOW
(From carrier
or storage)

SOLIDS
(To storage
or processing)
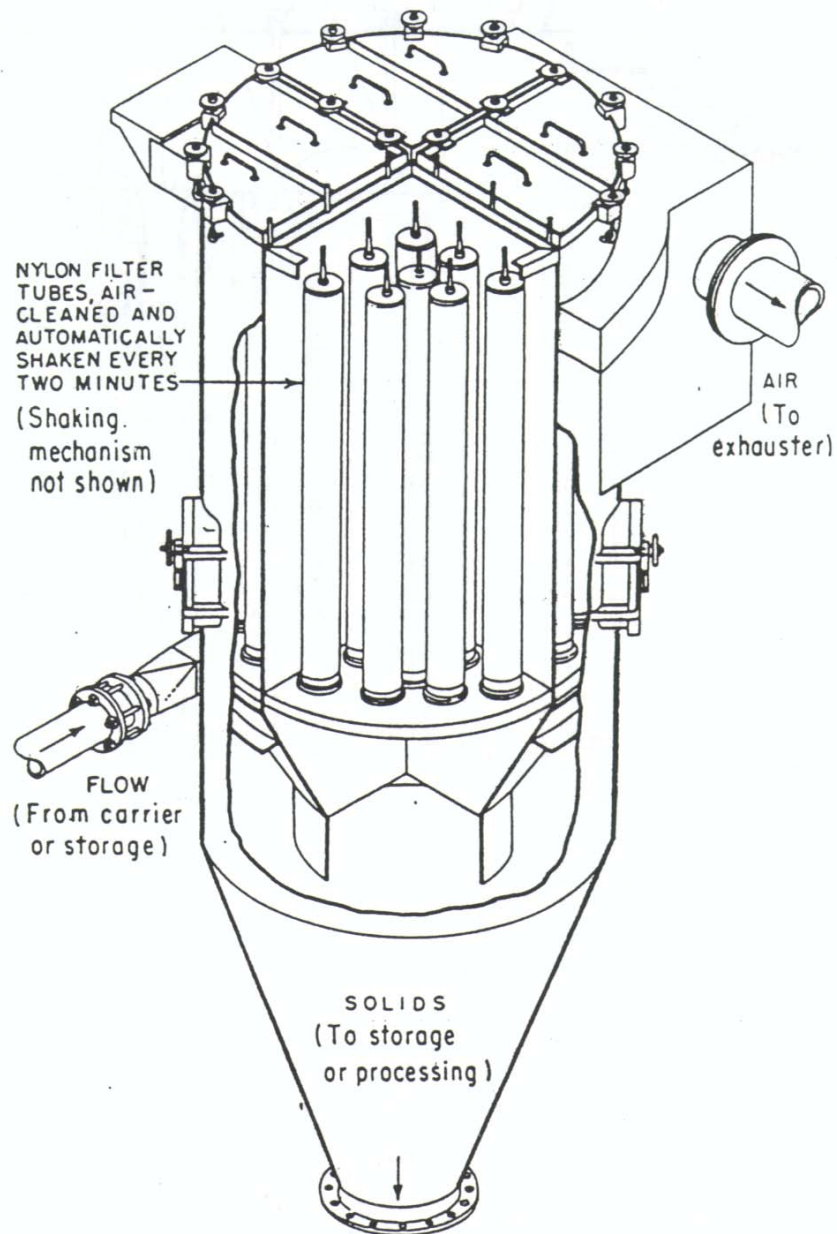
MECHANICAL SHAKER FILTER RECEIVER

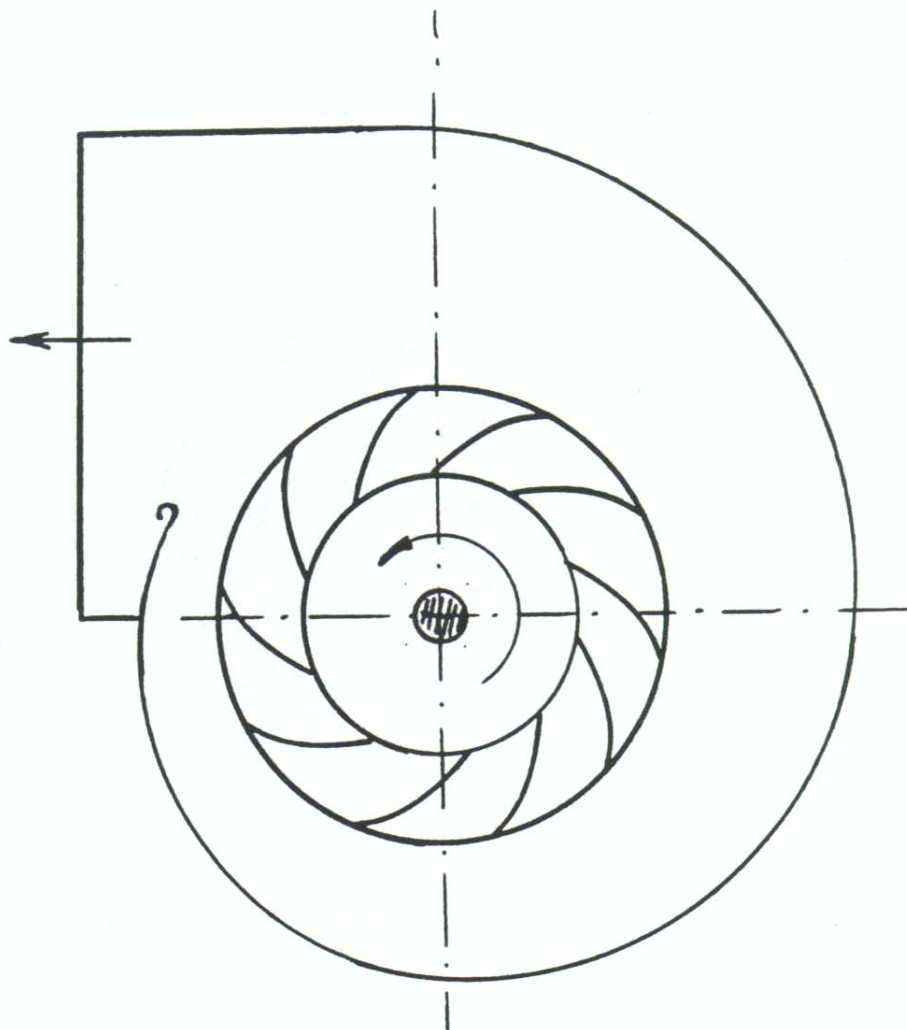FIGURE 20
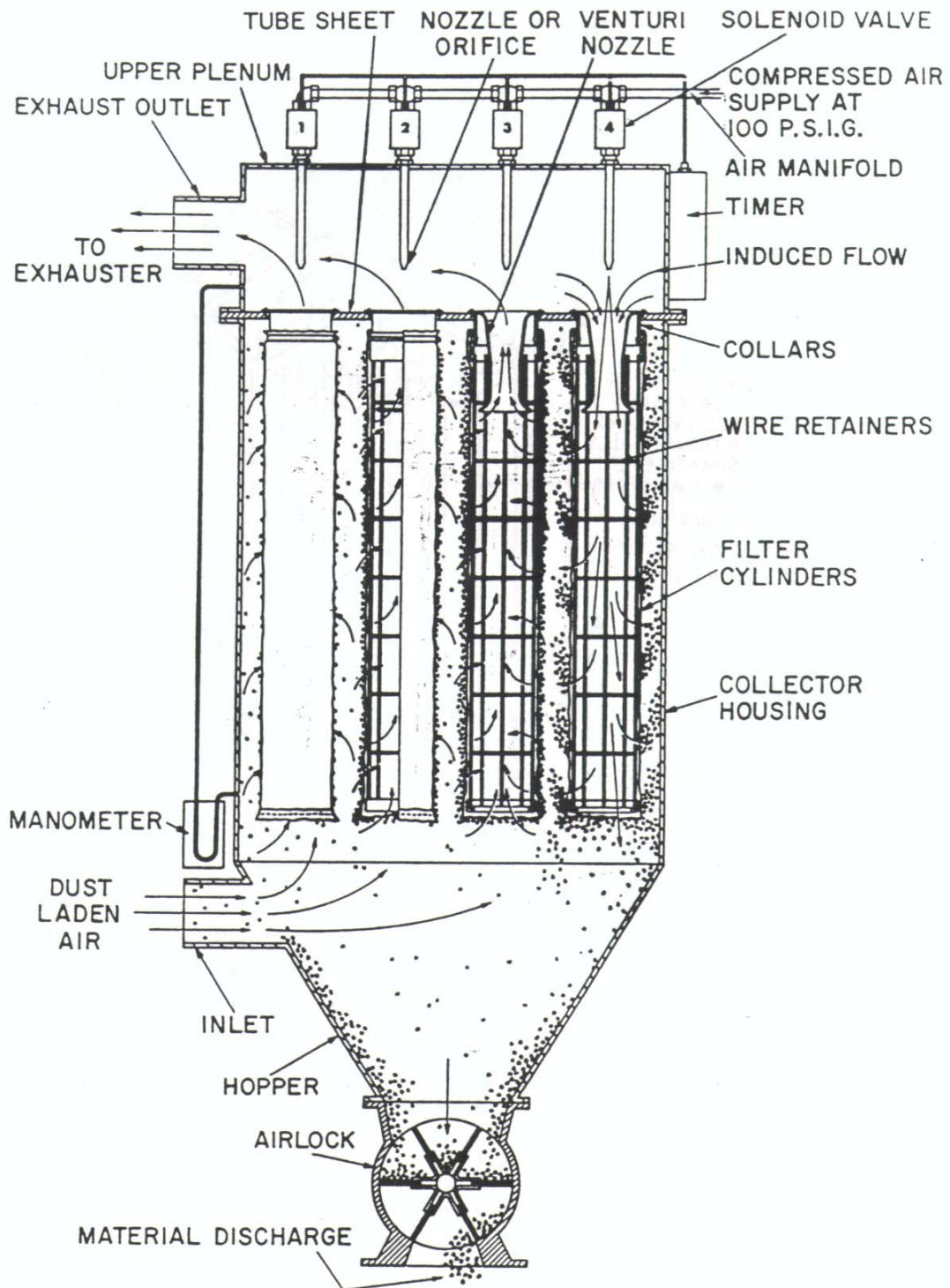
REVERSE JET FILTER RECEIVER

FIGURE 21

CLEAN AIR

MATERIAL INLET
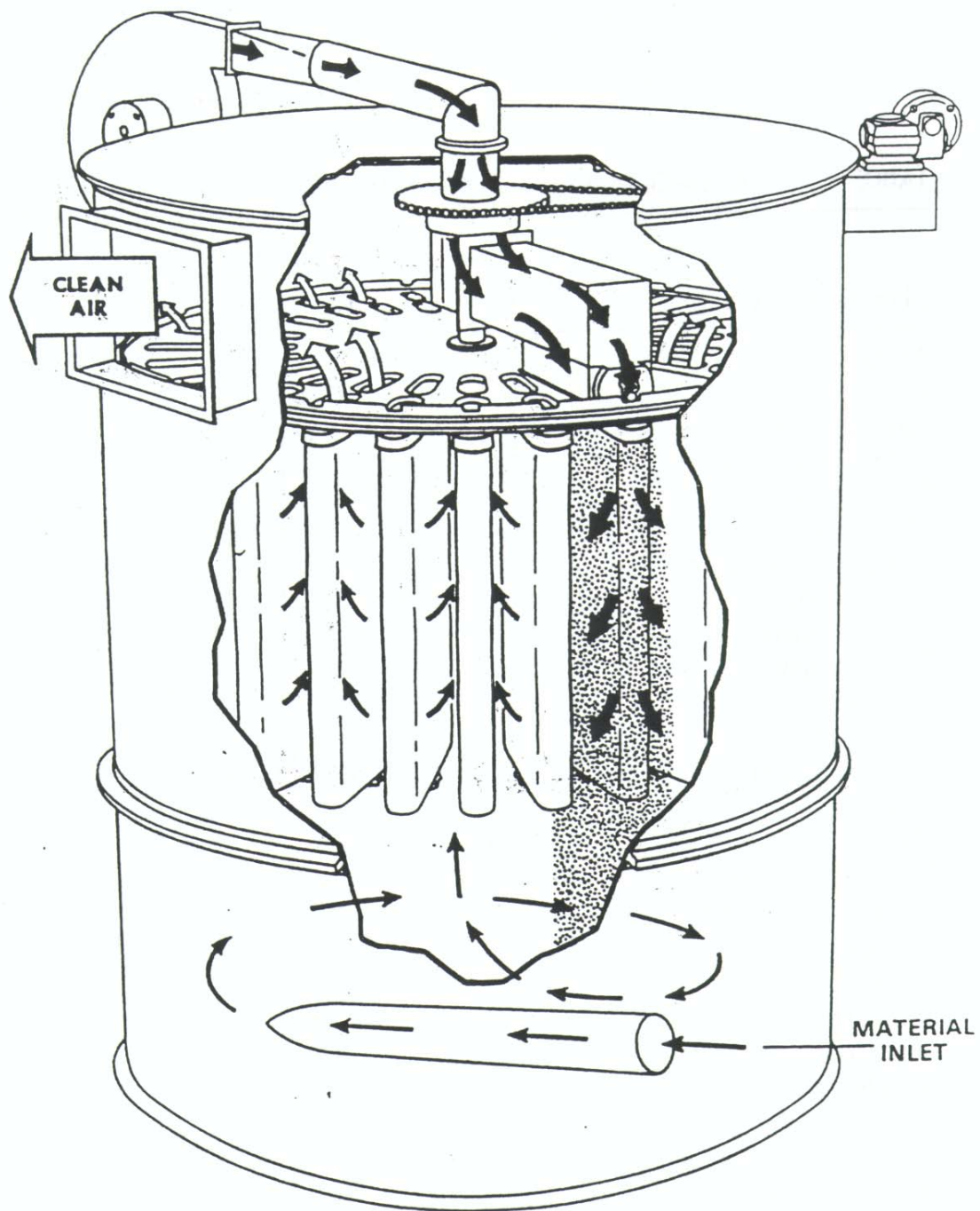
REVERSE-AIR FILTER RECEIVER

FIGURE 22

TABLE   Air-to-Cloth Ratios, Filter-Receivers

Material Conveyed	Filter Media	
	Woven	Felted
Alum	5–1	8–1
Alumina	3–1	5–1
Carbonate, calcium	4–1	6–1
Cellulose acetate	5–1	8–1
Clay, air floated	4–1	6–1
Clay, spray dried	4–1	6–1
Clay, water washed	4–1	6–1
Coffee beans	5.5–1	10–1
Corn, shelled	6–1	10–1
Flour, wheat	4.5–1	9–1
Grits, corn	5–1	8–1
Lime, pebble	5–1	8–1
Lime, hydrated	4–1	6–1
Malt	6–1	10–1
Oats	5.5–1	9–1
Phosphate, trisodium	3–1	5–1
Polyethylene pellets	6–1	10–1
Rubber pellets	3–1	5–1
Salt cake	3–1	5–1
Soda ash, light	4–1	6–1
Soft feeds	5–1	8–1
Starch, pulverized	4–1	6–1
Sugar granulated	4–1	6–1
Wheat	6–1	10–1
Wood flour	4–1	6–1

FIGURE 23

RADIAL TYPE, BACKWARD INCLINED FAN

FIGURE 24
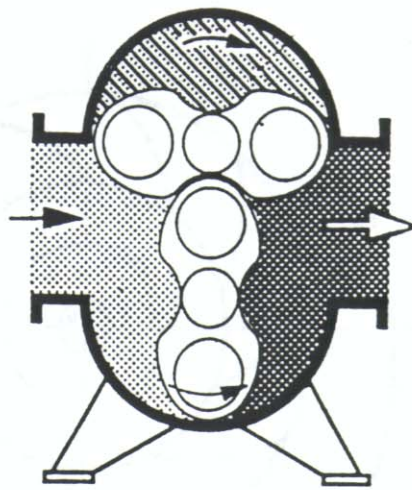
ROOTS TYPE BLOWER

FIGURE 25

Displaced Air Expanding
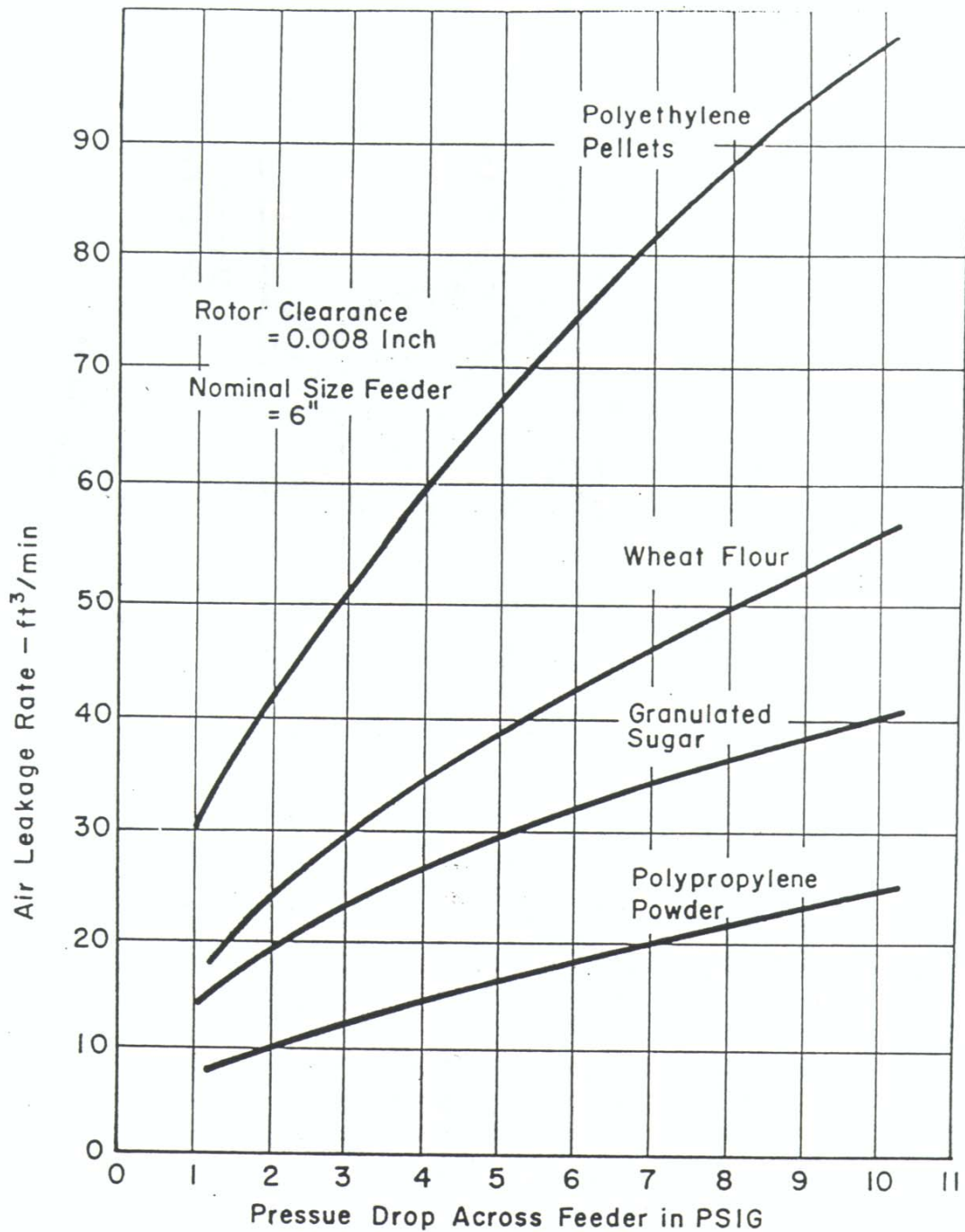
Product Feed

Driving Shaft

Pressure Gradient and Leakage Flow
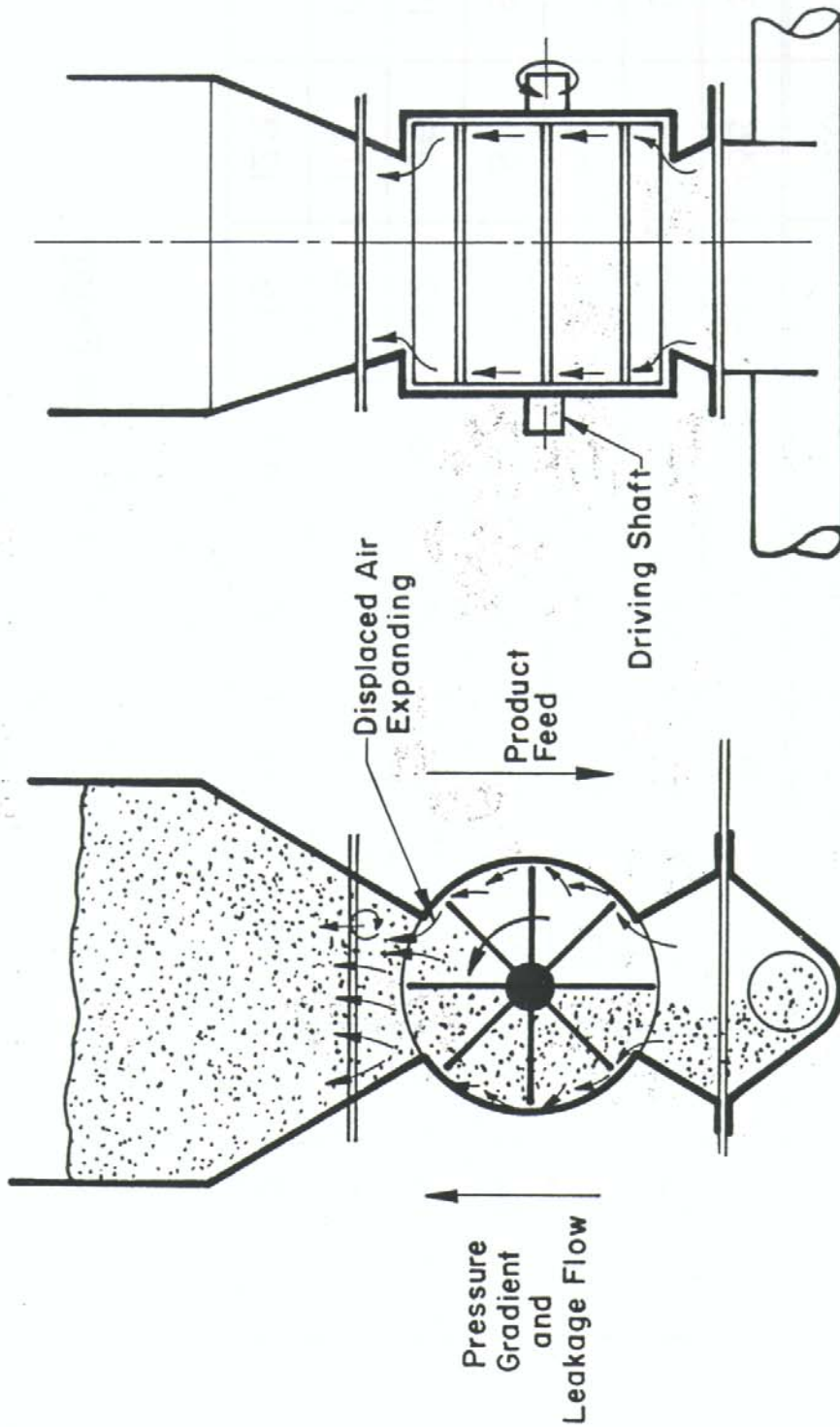
Leakage Paths When Feeding Positive Pressure Systems

ROTARY AIR-LOCK LEAKAGE

FIGURE 8

Influence of Pressure Drop and
Product on Feeder Leakage Rate