GLASS MANUFACTURING
AP-42 Section 8.13
Reference Number
8

FINE PARTICLE EMISSIONS FROM STATIONARY AND MISCELLANEOUS SOURCES IN THE SOUTH COAST AIR BASIN

FINAL REPORT

KVB 5806-783

PREPARED FOR:

CALIFORNIA AIR RESOURCES BOARD
SACRAMENTO, CALIFORNIA

PREPARED BY:

H. J. TABACK
A. R. BRIENZA
J. MACKO
N. BRUNETZ

KVB, INC.

FEBRUARY 1979

A Research-Cottrell Company

17332 IRVINE BLVD., TUSTIN, CALIFORNIA 92680 • (714) 832-9020
HOUSTON, TX (713) 780-8316 • MINNEAPOLIS, MN (612) 545-2142 • HARTSDALE, NY (914) 949-6300

4.3 PARTICULATE CONTROL EQUIPMENT EFFICIENCIES

Eleven simultaneous tests were done using the larger SASS train on the control equipment exit and the smaller train on the inlet, to evaluate the efficiency of the control equipment. Eight of these were baghouses, two were electrostatic precipitators, and one was a cyclone. The percentage efficiency for each of these was calculated from the following equation:

$$\text{efficiency} = \frac{wt_{in} - wt_{out}}{wt_{in}} \times 100$$

Table 4-87 summarizes the efficiency of the control equipment tested by KVB in this study. Two values are listed for the efficiency, one of which inclu[des] the weight from impinger catch in the calculation (SCAQMD method), and the other which ignores it (EPA method).

An interesting way to evaluate efficiency is to determine the efficiency as a function of particle size. Using the particle size distribut[ion] curves and the grain loading for the inlet and outlet for each test with cont[rol] equipment, the efficiency can be calculated at each particle size from the following equation:

$$\text{efficiency (size)} = \frac{[(\text{wt in})\ (\%\text{ of particle between size A and B}) - (\text{wt out})\ (\%\text{ of particle between size A and B})] \times 100}{(\text{wt in})\ (\%\text{ of particle between Size A and B})}$$

The results of this calculation for each of the control equipment tests are listed in Table 4-88. Figure 4-81 is a plot of the efficiency vs particle size for baghouses. Note that the efficiency increases as the size increase[s]. This is in agreement with the literature (Ref. 4-49 to 4-52). Figure 4-82 is a plot of the efficiency vs particle size for ESP and a cyclone. The efficiency of the cyclone decreases as particle size increase (Ref. 4-53 to 4-58). The efficiency of ESP's goes through a minimum between 0.1 and 2μm (Ref. 4-59).

TABLE 4-87. CONTROL EQUIPMENT EFFICIENCY

st #	Process Type	Control Type	Efficiency: Impinger Catch Included	Efficiency: Impinger Catch Not Included
30	Wood Sanding	Baghouse	86.9	96.3
29	Asphalt Batch	"	99.9	99.9
34	Abrasive Blasting	"	99.9	99.9
26	Sintering	"	77.6	97.8
19	Chemical Fertilizer	"	99.6	99.1
17	Boric Acid	"	96.1	98.7
14	Steel Heat Treating	"	95.2	90.0
8	Brick Grinding	"	99.5	99.8
20	Glass Mfg.	ESP	83.0	98.2
36	Steel Open Hearth Furn.	"	82.2	90.3
39	Wood Resawing	Cyclone	99.1	99.2

TABLE 4-88. SIZE EFFICIENCY CALCULATION RESULTS

Test	Percent of Particles 10-3µm	3-1µm	1-0.1µm	gr/DSCF	Control Type	Industrial Type
39J in	0.5	0.3	0.3	0.366	Cyclone	Wood Resaw
39S out	10	9	11.5	0.00317		
Efficiency	82.7	74	66.8			
30J	4	12	20	0.0168	Baghouse	Wood Sanding
30S	3	3	7	0,0022		
Efficiency	90.2	96.7	95.4			
29J	18	18	26	11.485	Baghouse	Asphalt Batc Plant
29S	6	4	7	0.00776		
Efficiency	99.98	99.98	99.98			
34J	3.5	1.7	1.6	1.922	Baghouse	Steel Sand-blasting
34S	6	6	12	0.00088		
Efficiency	99.92	99.8	99.7			
26J	1	1	2	0.205	Baghouse	Sinter Plant
26S	1.2	1.4	3	0.0459		
Efficiency	73.1	68.6	66.4			
20J	0.4	0.5	1.9	0.0364	ESP	Glass Mfg.
20S	0.6	1	2	0.00617		
Efficiency	74.6	66.1	82.2			
19J	0.2	0.01	0.2	0.7154	Baghouse	Chemical Fertilizer
19S	1	1	2	0.0028		
Efficiency	98	60.8	96.1			
17J	1	0.01	1	0.6105	Baghouse	Boric Acid Mfg.
17S	0.5	0.5	1	0.0237		
Efficiency	98.1	94.1	96.12	-		
14J	7	10	30	0.0593	Baghouse	Steel Heat Treating
14S	8	14	41	0.00283		
Efficiency	94.55	93.3	93.5			
8J	0.85	0.3	0.14	1.169	Baghouse	Brick Mfg.
8S	4	4	8	0.00641		
Efficiency	97.4	92.7	68.7			
36J	3	4	11	0.206	ESP	Steel Open Hearth F:
36S	3.8	7	23	0.0366		
Efficiency	77.5	68.9	64.1			

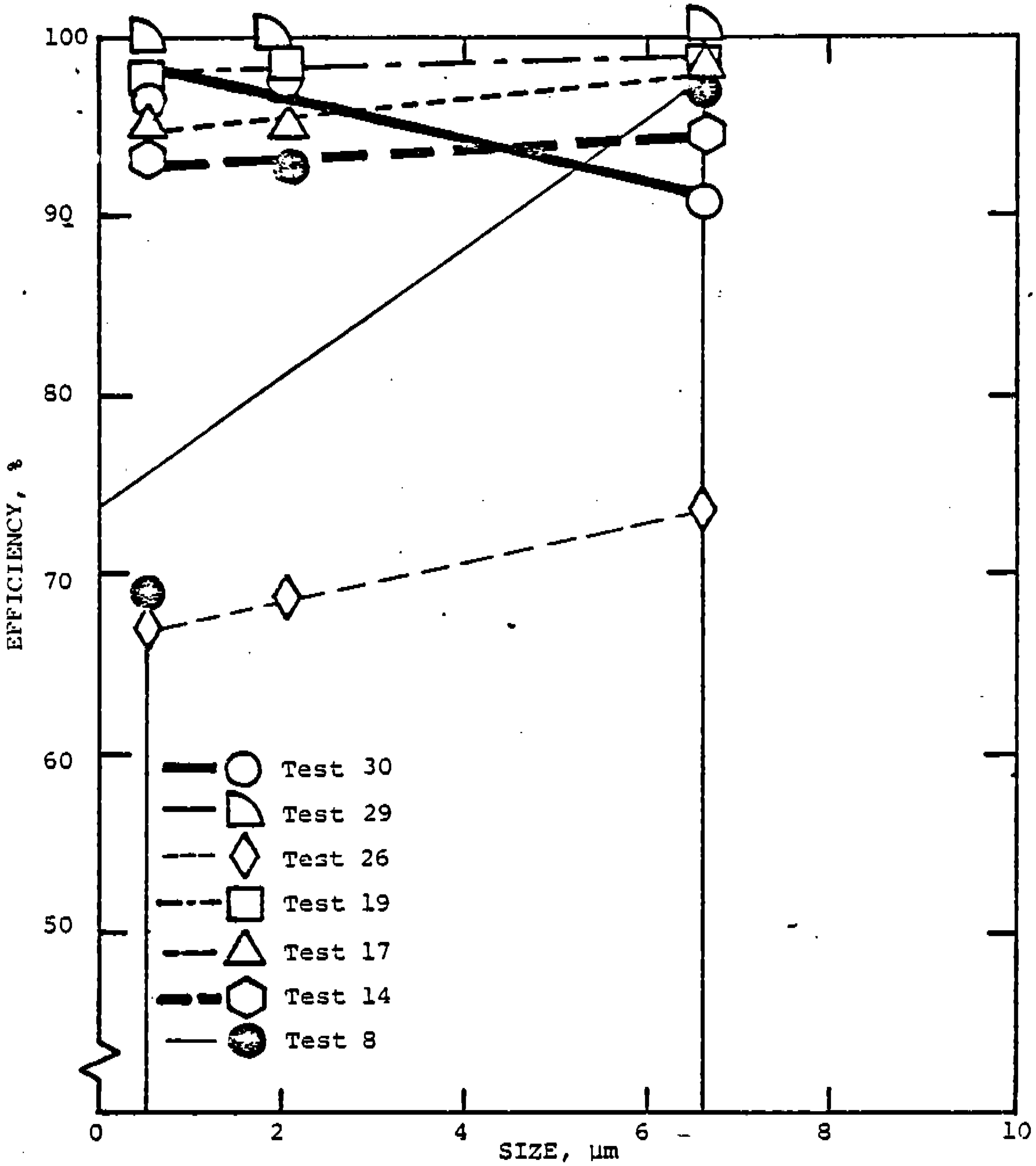

Figure 4-81. Baghouse size includes Impinger.

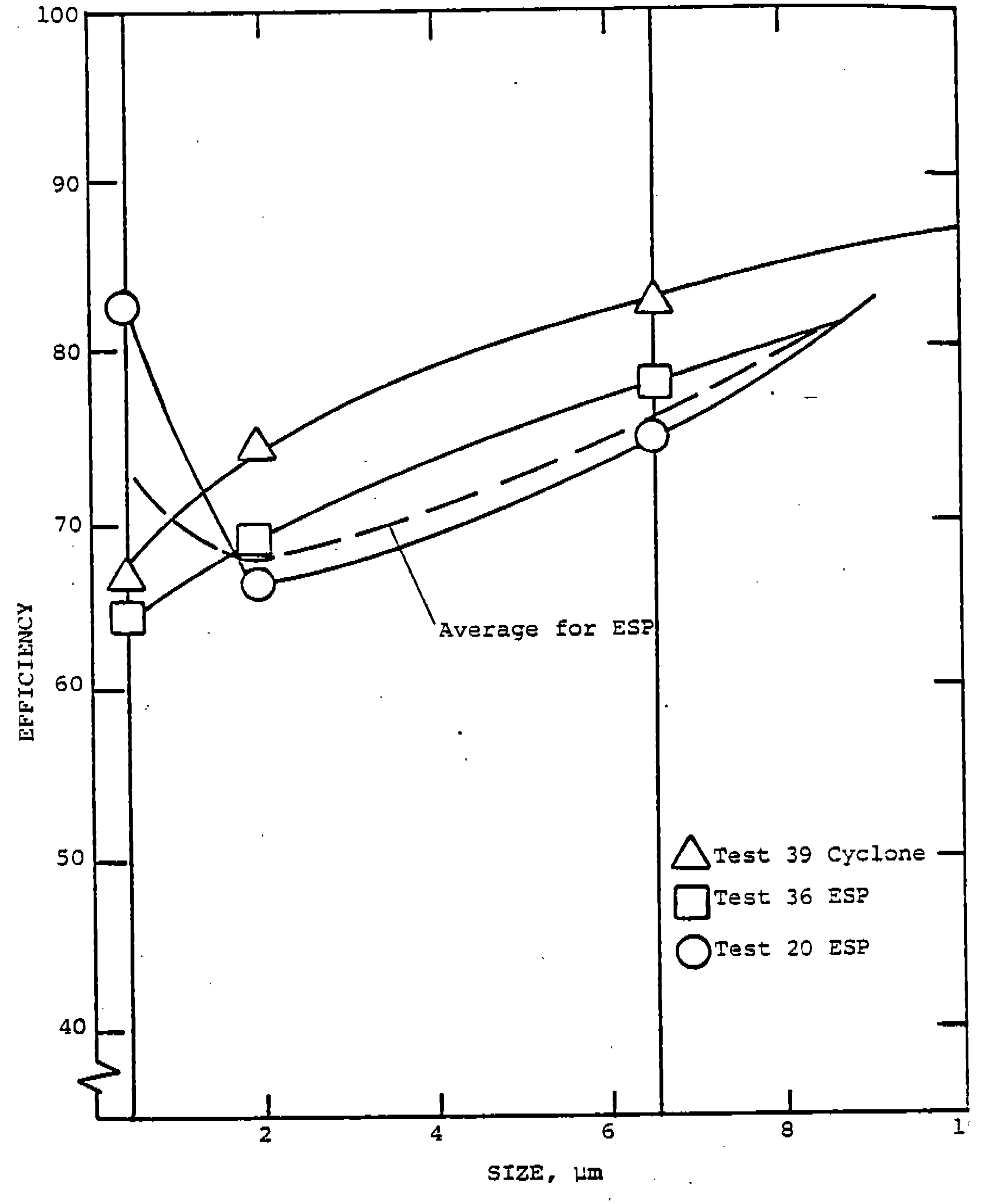

Figure 4-82. Cyclone and electrostatic precipitator efficiency curve.

SECTION 4.0

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SECTION 5.0

PARTICULATE EMISSION CONTROL TECHNOLOGY

INTRODUCTION

The removal of particulate matter from gas streams to reduce emissions to environmentally acceptable levels can be accomplished in a wide variety of ways. This section describes various types of particulate control equipment and includes suggested areas of applications as well as estimates of their performance and costs.

The selection of the most appropriate particulate control device is usually based on the size of the particulate matter which must be removed from the gas stream. Figure 5-1 illustrates the normal areas of application from a particle size standpoint, relative to particle size, for the following types of particulate control devices:

- Settling Chambers
- Momentum Separators
- Cyclones
- Spray Towers
- Tray and Packed Towers
- Venturi Scrubber
- Fabric Filters
- Electrostatic Precipitators

Table 5-1 is a generalized rating of these devices for various applications in the opinion of the authors.

An analysis of Figure 5-1 indicates that successful control of virtually all particulate emissions can be achieved by selecting the appropriate emission control device.

It is important to note that accurate information regarding the size distribution, grain loading, physical properties and removal requirements is essential to selecting the proper control device.

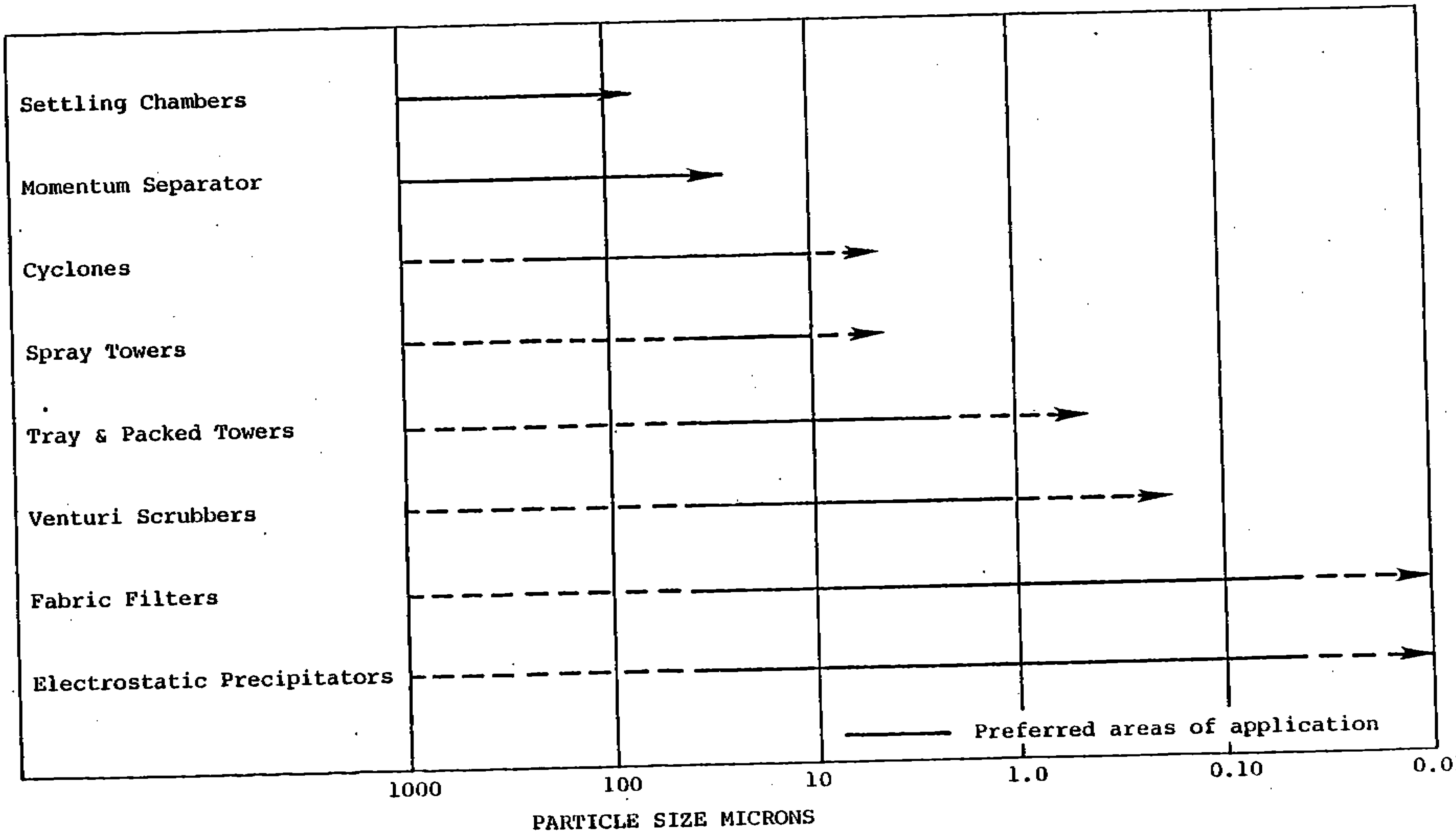

Figure 5-1. Areas of application for particulate control devices (Ref. 5-2).

TABLE 5-1. APPLICATION TABLE

Industry Type	Settling Chamber *	Cyclones *	Multiclones	Packed Columns	Spray Towers	Venturi Scrubbers	Filters (Baghouses)	ESP	Other
COMBUSTION OF FUELS									
Utility Boilers	P	NU*	G	NU	G	NB/B	NB	B	
Industrial Boilers	P	NU*	G	NU	G	NB	NB/B	B/NB	
Waste Incinerators	P	NU	G	NU	G	NG/B	NU	B	
MINERALS									
Cement Plant	P	G	G	NU	G	NU	B/NB	B	
Gypsum	P	-	-	-	-	-	B/NB	B	
Brick Grinder	P	G	G	-	-	G	B	-	
Glass Plants	NU	NU	-	-	-	N/B	B	B	
Asphalt	P	P	G	-	-	NB	B	NB	
FOOD & AGR.									
Cotton Gin	-	-	B	-	-	-	B		
Alfalfa Dehydrator	-	-	G	-	-	-	B	B	Incinerator
Rice Dryer	-	-	G	-	-	-	B	-	
METALLURGICAL									
Steel	P	NU	G	NU	NU	G	B/NB	NB/B	
Aluminum	-	NU	-	-	-	G	B/NB	B	
Lead	P	NU	G	NU	NU	G	B	NB	
CHEMICAL									
Fertilizer	-	-	-	-	G	B	NB	-	
Soap	-	-	-	-	-	-	B	-	
ORGANIC SOLVENT USE									
Spray Booth	NU	NU	NU	B	NB	G	NU	NU	Incineration
Wood Processing	NU	NU	NU	B	NB	G	NU	NU	
PETROLEUM									
FCC Unit	P	G	G	NU	NU	G	NU	G	
Heaters	-	-	-	-	-	-	B/NB	B	

* - Not used as primary pollutant removal devices
NU - No data available
B - Best
NB - Next to best
G - Good
P - Poor

This section has been prepared as a guide to introduce users to various types of control devices, to aid in understanding their capabilities and to serve as a general reference regarding their application.

There are many variables like disposal methods, potential for recycle, and variability of particulate characteristics to name but a few, which influence the selection of particulate removal devices that are beyond the scope of this report. Users must consider each application on an individual basis in order to select the most appropriate particulate control device.

5.1 METHODS OF CONTROL

5.1.1 Settling Chambers and Momentum Separators

A. Settling Chambers--

1. Settling chambers represent the simplest device available for particulate collection. They normally include nothing more than a low velocity region in the gas handling system where gravitional forces cause larger particles to settle out from the moving gas stream.

In these devices gravitational forces are sometimes augmented by directing the gas stream to impart a downward momentum to the particles to improve particulate collection. Figure 5-2 illustrates a typical settling chamber.

2. Settling chambers rely on gravitational forces for particulate separation. Since these forces are proportional to the weight of the particle, larger high density particles will be acted on by the large separating forces. The major force inhibiting collection is aerodynamics drag. This force is proportional to the cross sectional area of the particle and its velocity relative to the gas stream. With the exception of large particles which are readily collected, most particles quickly attain terminal velocity in the settling chamber. This velocity is reached when the gravitational forces are just balanced by the drag forces. It is this velocity which determines whether a particle will be collected. If the particle falls quickly enough while in the settling chamber to reach the hopper before it reaches the chamber outlet it will be collected, if it does not, it will pass through the chamber uncollected.

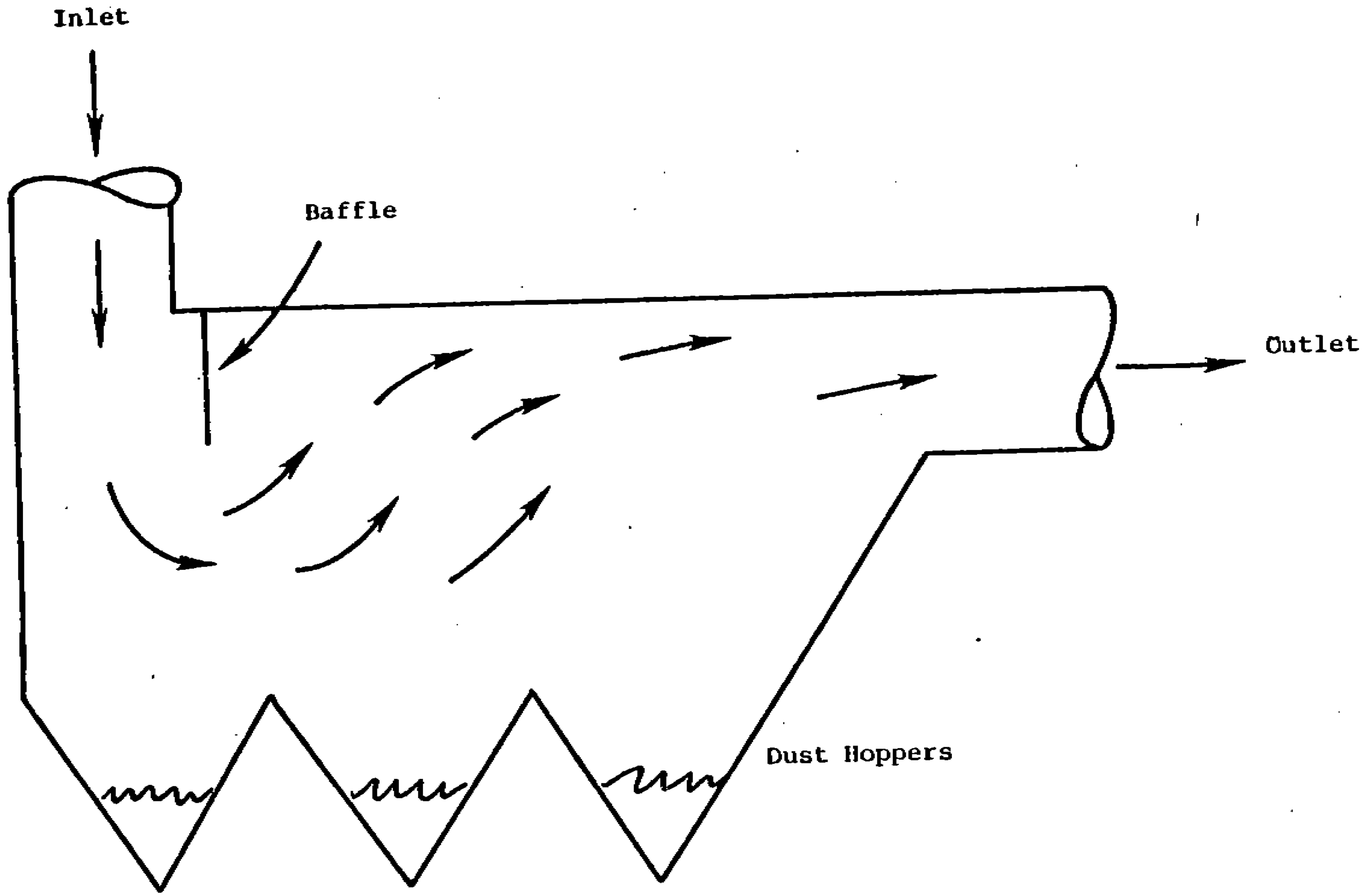

Figure 5-2. Settling chamber. (Ref. 5-1)

In theory particles as small as 5 microns, the size where suspension by Brownian motion takes on significance, could be collected in settling chambers. However, economic and space considerations limit efficient collection in settling chamber sizes to particles above 80 microns.

3. Other factors which also influence separation in settling chambers include chamber dimensions, gas density and gas viscosity.

The most important factors are gas velocity and chamber dimensions since these can be selected for a given application whereas all of the others are essentially fixed.

Figure 5-3 illustrates typical settling chamber collection efficiency and shows the effect of particle density on collection.

Maintaining a uniform velocity is critical to achieving good collection efficiency since eddies or areas of high velocity cause poor settling and result in unnecessary carryover of particles.

In addition, overall and local velocities must be maintained below the reentrainment velocity for the particular dust being collected to prevent pickup from the hopper. The reentrainment velocity is a function of the particle size and density as well as the tendency of collected particles to agglomerate.

4. The main problems associated with the operation of settling chambers are maintaining uniform gas velocity and avoiding plugging in the hoppers. The first problem can be virtually eliminated by proper settling chamber design coupled with good upstream and downstream duct layouts. The second problem can be controlled by designing hoppers with adequate slope, adding insulation and heat tracing to prevent condensation and adding hopper vibrators to aid in discharging collected dust. Where agglomeration and bridging are severe, the hopper should be discharged continuously.

B. Momentum Separators

1. Separators relying solely on momentum in which the gas stream impinges on the surface of a collector operate at substantially higher efficiencies than settling chambers. There are numerous configurations using this principle; one is illustrated in Figure 5-4.

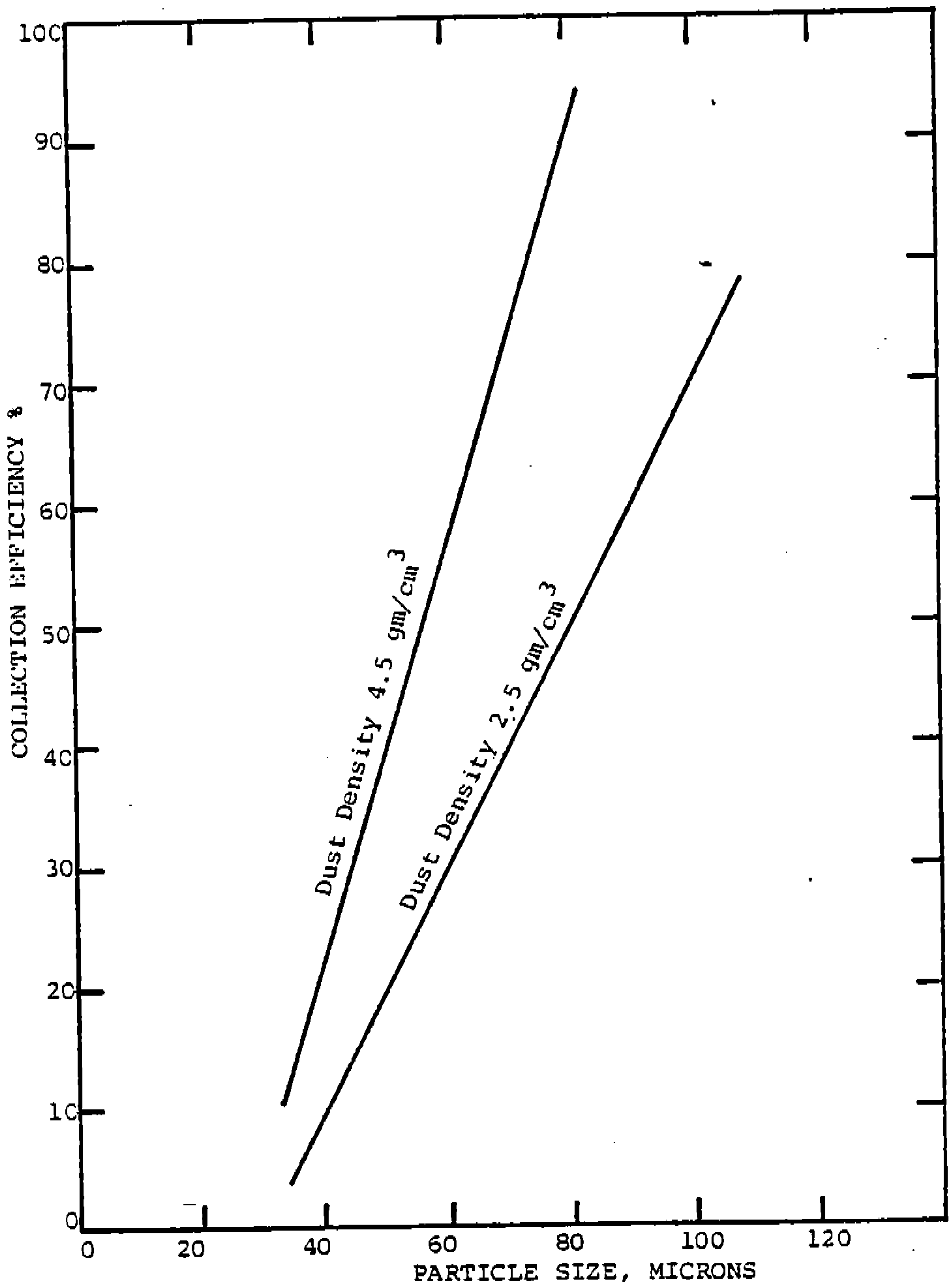

Figure 5-3. Typical settling chamber collection efficiency. (Ref. 5-1)

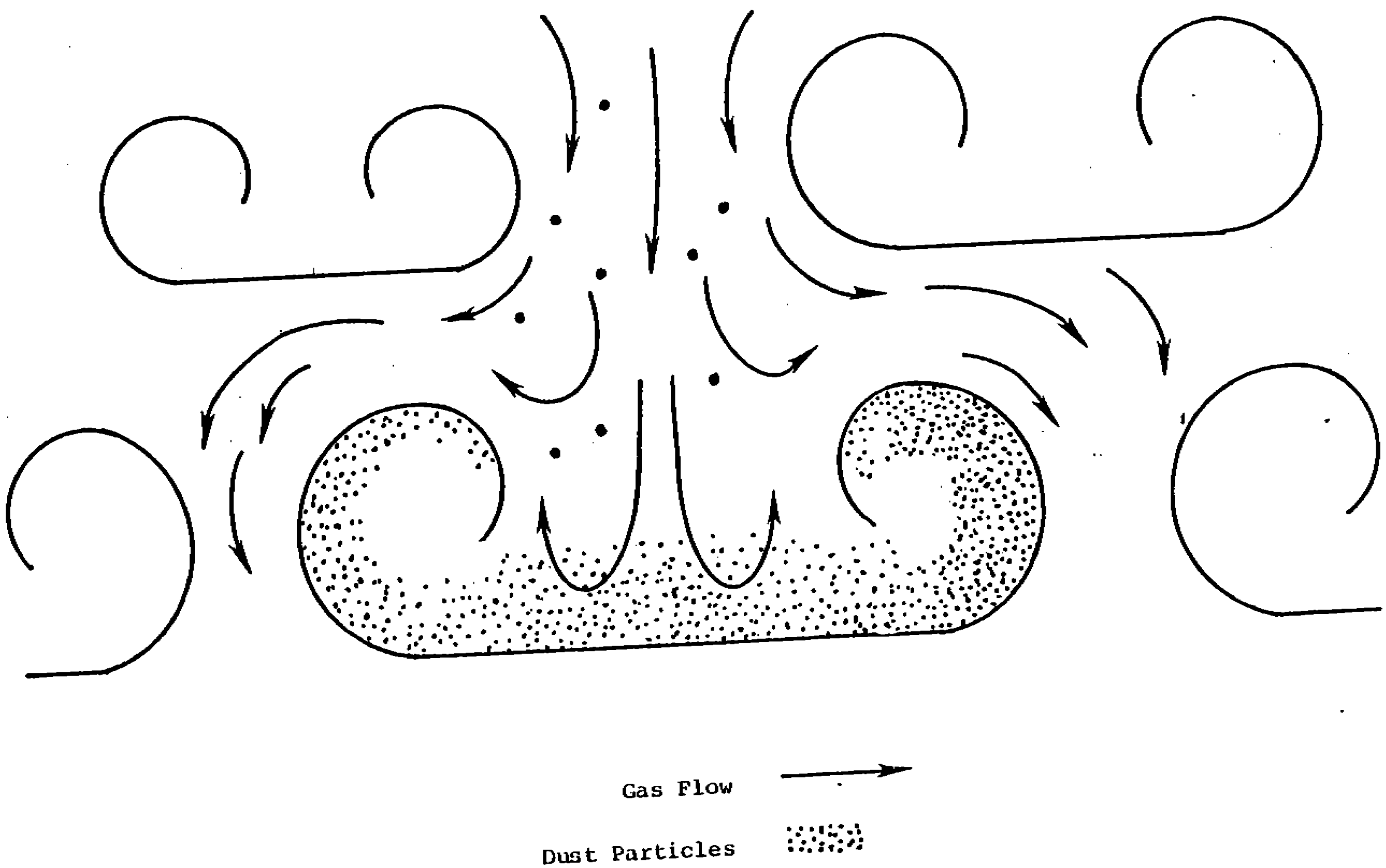

Figure 5-4. Momentum separator (Ref. 5-1).

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2. In momentum separators particles which are carried along by the gas stream are separated when the gas stream is forced to make sharp change in direction. Factors which control separation are: (1) the weight and size of the particles, (2) velocity of the particles, (3) geometry of the separator, (4) gas density and velocity, and (5) the drag forces acting on the particles as the gas stream abruptly changes direction. High gas velocities and relatively high density particles favor separation, small lower density particles which tend to follow changes in gas flow patterns are not readily collected.

3. Collection in momentum separators is controlled by particle size and density, the geometry of the separating device and gas density and viscosity.

Figure 5-5 illustrates typical momentum separators collection efficiency as a function of particle size.

4. In momentum separators high velocities can cause excessive wear if the dust is abrasive and reentrainment can occur if dust removal is not adequate. The same precautions outlined above should be taken to avoid plugging problems.

5.1.2 Cyclones

A. Cyclones or centrifugal separators are devices which use centrifugal forces to separate particles from gas streams.

All cyclones consist of a device to induce a spinning motion to the gas and a means of removing the particles separated from the gas stream.

One of the most common configurations is the reverse flow cyclone illustrated in Figure 5-6. In this configuration gas which enters the cyclone tangentially is spun through several revolutions as it flows down the outer wall of the cyclone where the dust is separated before reversing its flow path and traveling up the center of the cyclone and out the top. The dust which was spun out to the wall, drops to the bottom of the cyclone where it is withdrawn.

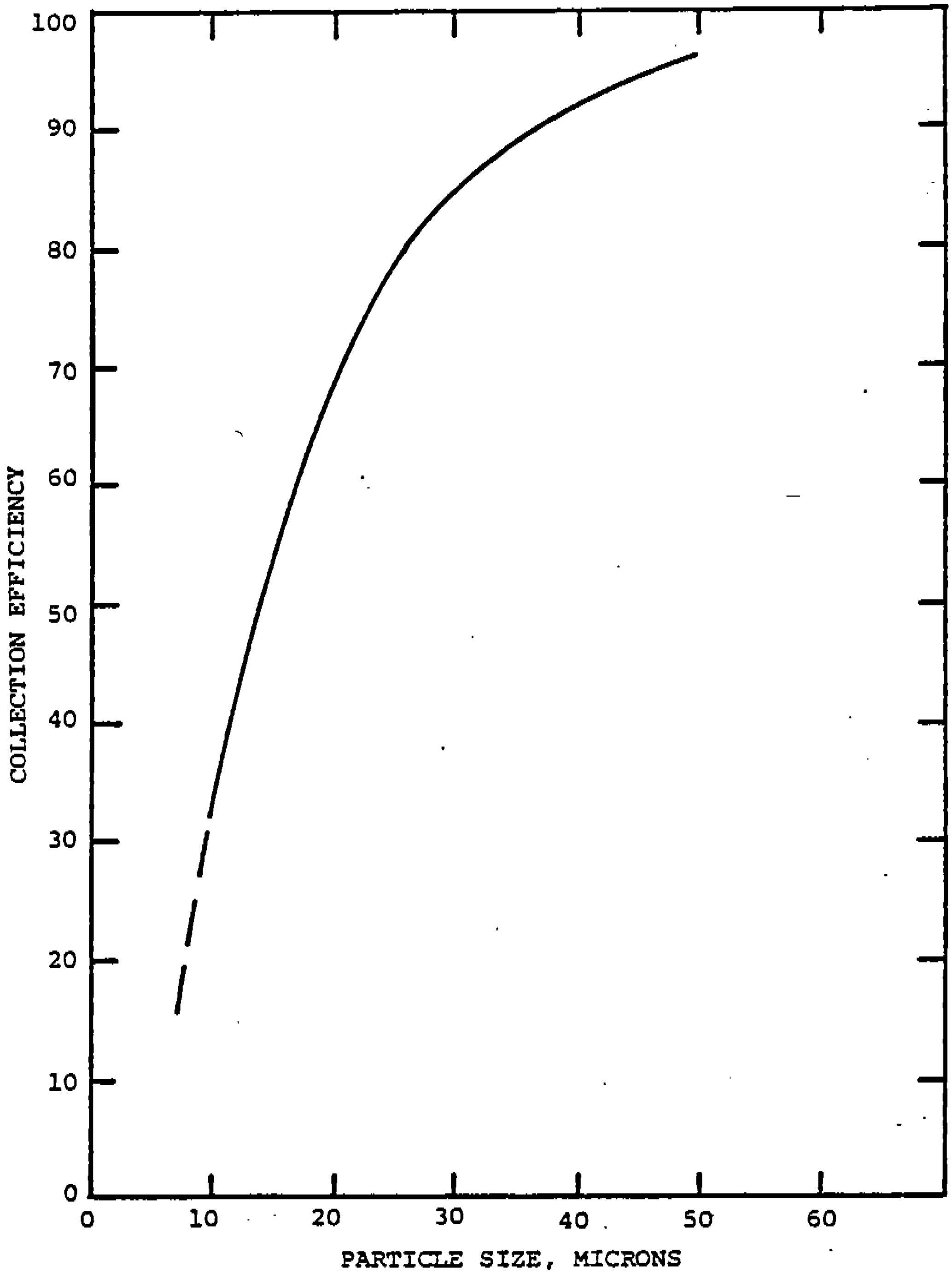

Figure 5-5. Typical momentum separator collection efficiency. (Ref. 5-1)

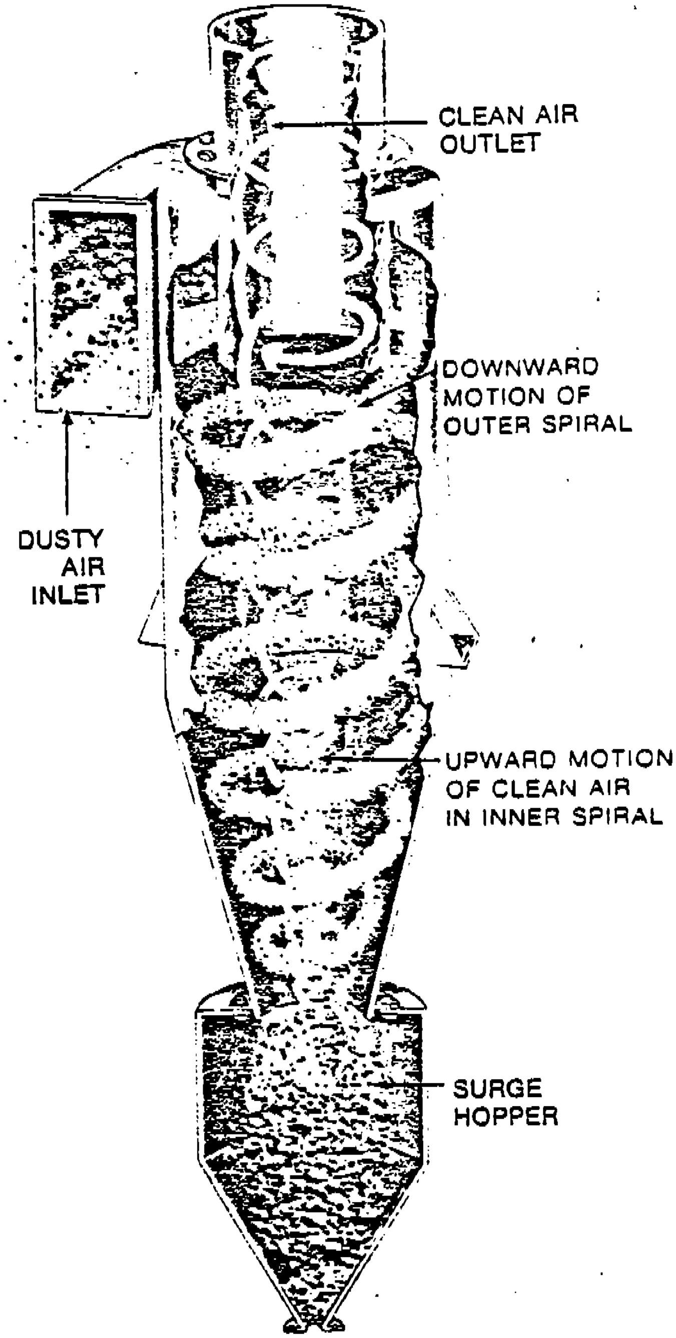

Figure 5-6. Reverse flow cyclone (Research-Cottrell).

B. The centrifugal forces created by spinning the gas stream in cyclones are often many times greater than the gravitational forces acting in settling chambers, therefore, cyclones can separate smaller particles than settling chambers in much smaller sized equipment. There is a substantial price in the form of pressure drop which must be paid for in the improvement in particle collection. Most cyclones require a pressure drop of 1 to 5 in w.c. for efficient operation.

The centrifugal force acting on a particle in the gas stream is proportional to the square of the velocity of the spinning gas and inversely proportional to the diameter of the cyclone.

$$F \approx \frac{V^2}{D} \qquad (1)$$

As in the other types of collectors, aerodynamic drag forces acting on the particles counteract the separating forces and limit collection.

C. An examination of Equation (1) above reveals that high velocities and small diameters increase separating forces thereby improving particle collection.

High efficiency collectors operate at high velocities and therefore higher pressure drops. They include a multiplicity of small diameter cyclones mounted in a common housing.

D. As in other collectors, particles which exhibit low aerodynamic drag relative to their size are collected more easily.

Figure 5-7 illustrates collection efficiency for a typical multi-cyclone operating at approximately 2-3 in w.c. pressure drop. As indicated in Figure 5-7, particles as small as 5 microns in diameter can be collected efficiently in this type of cyclone.

E. The problems most often associated with cyclones are erosion and reentrainment of dust due to high velocities and plugging of the hoppers where collected dust accumulates. The same precautions to overcome plugging, outlined previously for settling chambers, can be applied to cyclones. The

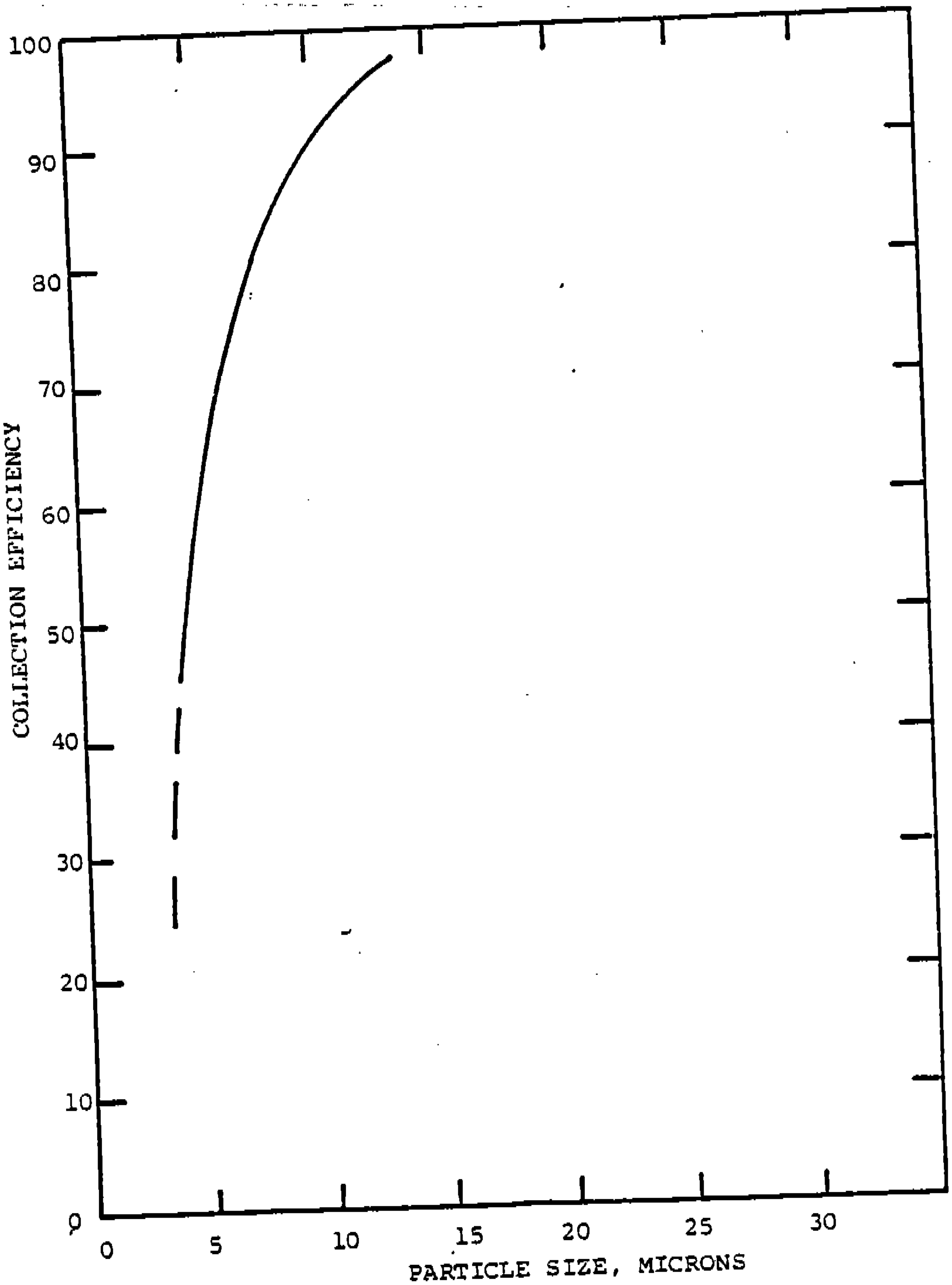

Figure 5-7. Typical multi-cyclone collection efficiency. (Ref. 5-1)

abrasion associated with high velocities and abrasive dust can be overcome by employing wear resistant materials and by using a precollector to remove coarse particles upstream from the cyclones.

5.1.3 Wet Scrubbers

Wet scrubbers can be divided into two basic categories: those designed for gas absorption and those designed for particulate removal. As convenient as these categories might be, they do not adequately depict actual scrubber behavior since all scrubbers remove some particulate matter while simultaneously absorbing constituents from the gas stream. When gas absorption is the primary objective, chemical reagents are often added to the scrubbing liquor.

A. Spray Towers--

Spray towers are the simplest type of wet scrubber; their primary function is coarse particulate collection. Since these scrubbers operate at relatively low gas velocities, some particulate settling will occur. In addition, in many scrubbers there is a sufficient difference in velocity between gas and scrubbing liquor droplets to collect some particles by interception and inertial impaction.* Finally, even submicron particles which move about in the gas stream via Brownian diffusion are collected when they contact droplets of scrubbing liquor.

1. A typical spray tower as illustrated in Figure 5-8 includes a gas inlet area where the wet-dry tower occurs, a quenching zone where gas cooling begins, the main gas-scrubber liquor contacting zone, the liquor spray manifold or manifolds and a mist elimination zone.

Gas containing dust particles enters the bottom portion of the scrubber where it makes contact with scrubbing liquor coming from the spray nozzles. The gas then passes through the mist eliminator on to the gas outlet.

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*These concepts are discussed in more detail in Section 5.1.3(C) Venturi Scrubbers.

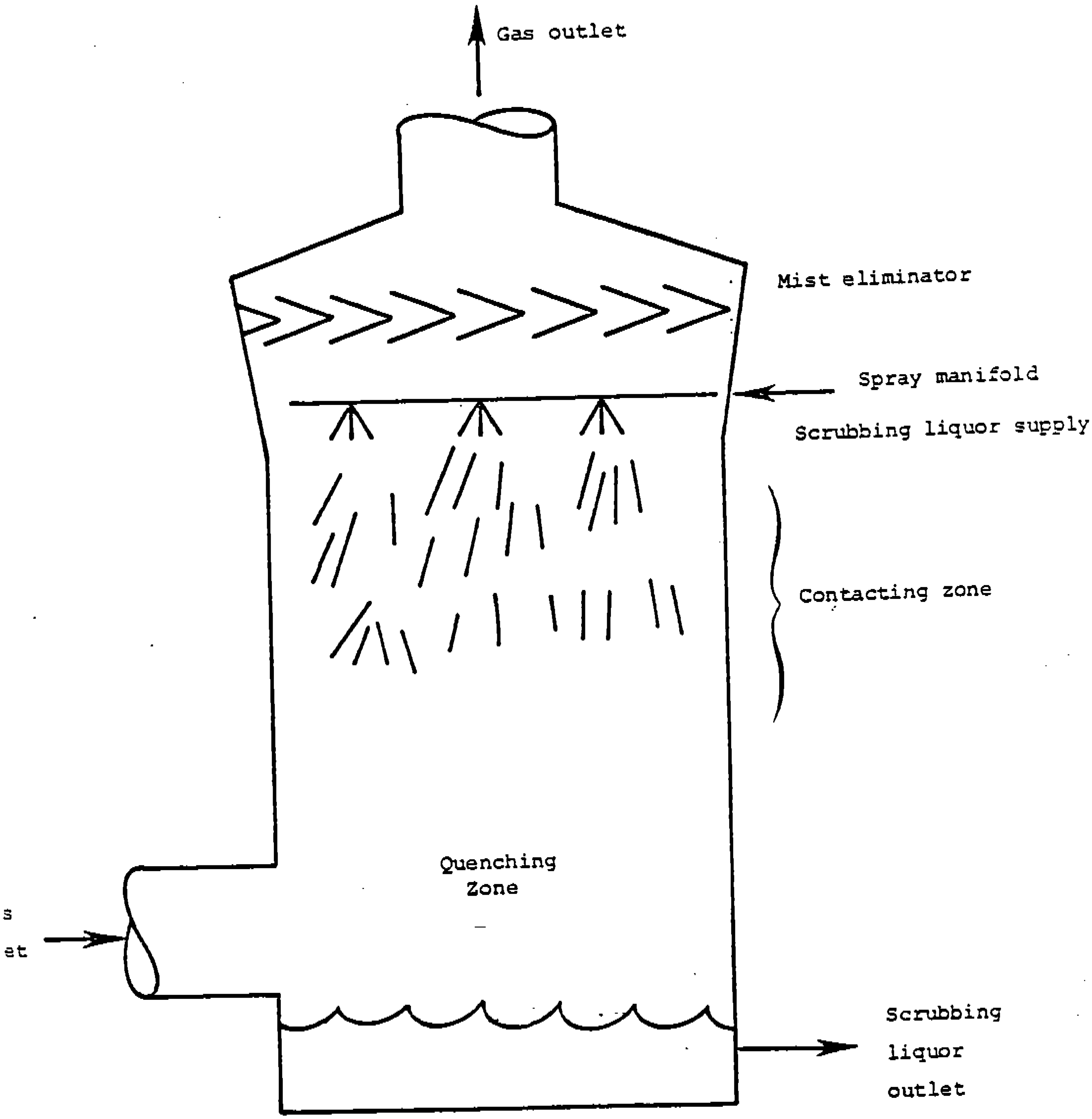

Figure 5-8. Typical spray tower.

The use of spray nozzles with appropriate manifolds is the most common method of creating droplets of scrubbing liquor in spray towers. The selection of spray nozzles is critical to successful operation. The scrubbing liquor must be uniformly distributed throughout the scrubber and the droplets which are produced must be large enough for gravitational forces to prevent aerodynamic drag forces from carrying them along with the gas.

Since all spray nozzles produce a range of different sized droplets, there are always some small droplets which will be swept along with the gas stream. It is usually necessary to prevent these droplets from leaving the scrubber, therefore, a mist eliminator is required.

There are many types of mist eliminators used in spray towers. The most common types use the principles of momentum separation described earlier. Figure 5-9 illustrates a typical Chevron type mist eliminator. Once the mist droplets are collected in the mist eliminator, they coalesce and drop off the lower edges in droplets large enough to fall down through the gas stream.

2. Investigations of particulate collection in spray towers has shown that there is an optimum droplet size for collecting particles from gas streams via inertial impaction and interception. These investigations have also shown that this droplet size is essentially independent of the size of the dust particles to be collected. For droplets composed mainly of water in gases similar to air the optimum droplet is approximately 800 microns in diameter.

An 800 micron water droplet has a terminal velocity in the air of approximately 10 ft/sec. However, spray nozzles designed to produce a mean droplet size of 800 microns produce substantial numbers of smaller droplets, therefore a maximum velocity of 4 to 5 ft/sec is usually selected. The use of larger droplets permits higher gas velocities, but the loss in collection efficiency, at least above 10 microns, can be offset by increasing scrubber liquor flow rates.

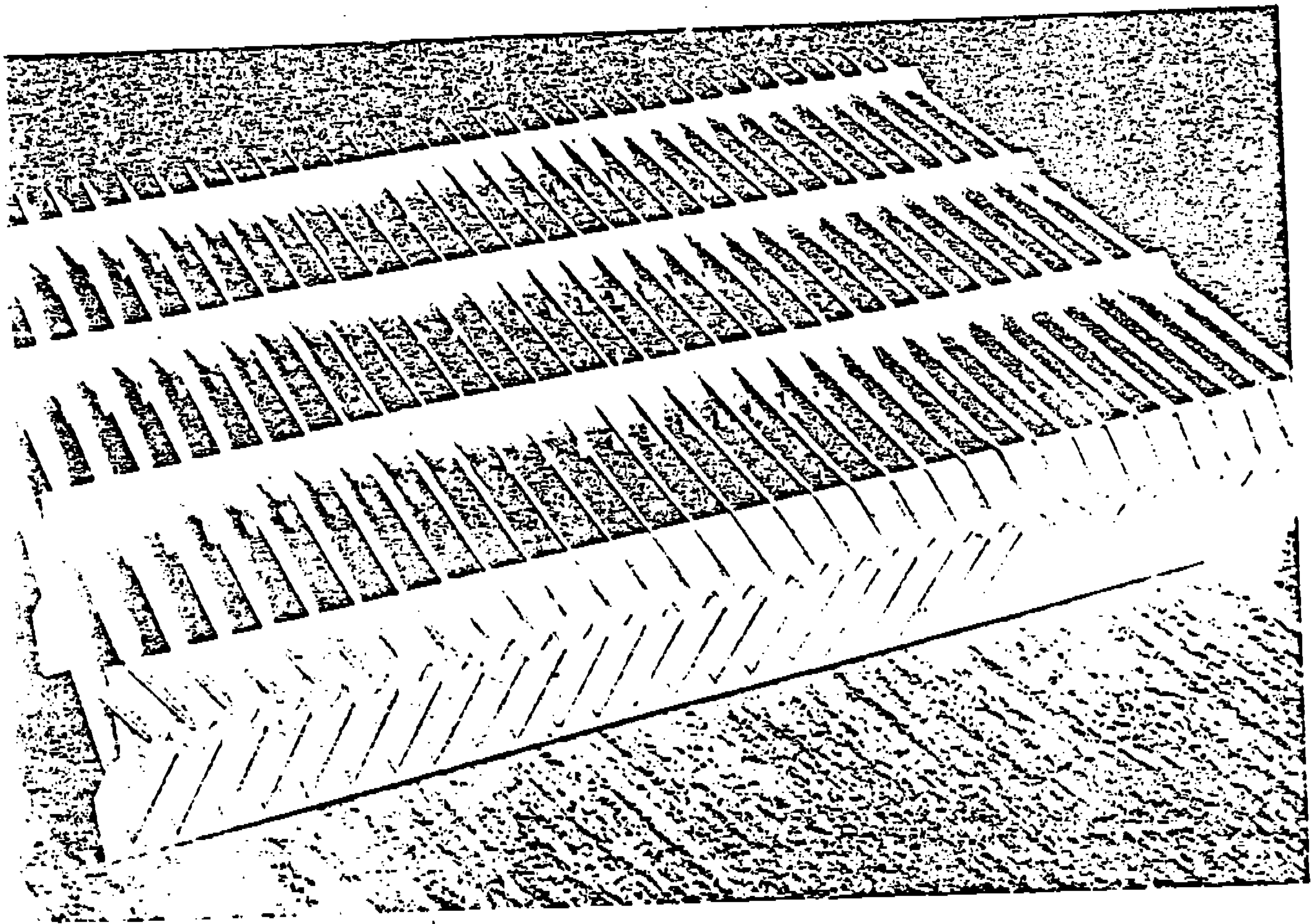

Figure 5-9. Chevron type mist eliminator (Munters Corp.).

3. The main factors which affect the particulate collection efficiency of spray towers are particle size distribution, scrubber liquor droplet size distribution and scrubber liquor to gas ratio. Figure 5-10 illustrates the theoretical collection efficiency of different sized particles for single droplets falling through air. Curves for 800 and 2000 micron droplets are presented.

The overall collection efficiency in a spray tower is essentially the aggregate of the collection of each of the droplets. Since this is so, increasing the number of droplets relative to the gas volume treated will increase the overall collection. Figure 5-11 illustrates the effect of increasing liquid rates on particulate removal in a typical spray tower.

4. The most common types of problems associated with spray towers are droplet carryover, wet-dry line solids buildup and corrosion, and spray nozzle erosion and plugging.

Droplet carryover can be controlled by the proper selection of scrubber gas velocity, spray nozzles and mist eliminator. Selecting the proper gas velocity and spray nozzle will minimize the amount of droplets carried upward by the gas stream and proper selection of the mist eliminator will result in a virtually droplet-free gas stream leaving the spray tower.

All scrubbers handling hot gas streams have a common potential source of problems in the area where the hot gas first contacts the scrubbing liquor.

The problems in this area are almost universally associated with inadequate irrigation of the scrubber shell in this area causing alternate wetting and drying and resulting in accumulation of particulate matter and corrosion of the scrubber shell. Usually supplemental spray nozzles to irrigate this area and the selection of adequate materials of construction will prevent difficulties.

In most spray towers scrubbing liquor is recirculated. This often results in the recirculation of substantial quantities of solids through the spray nozzles. If the particles are large or tend to agglomerate, spray nozzles can become plugged.

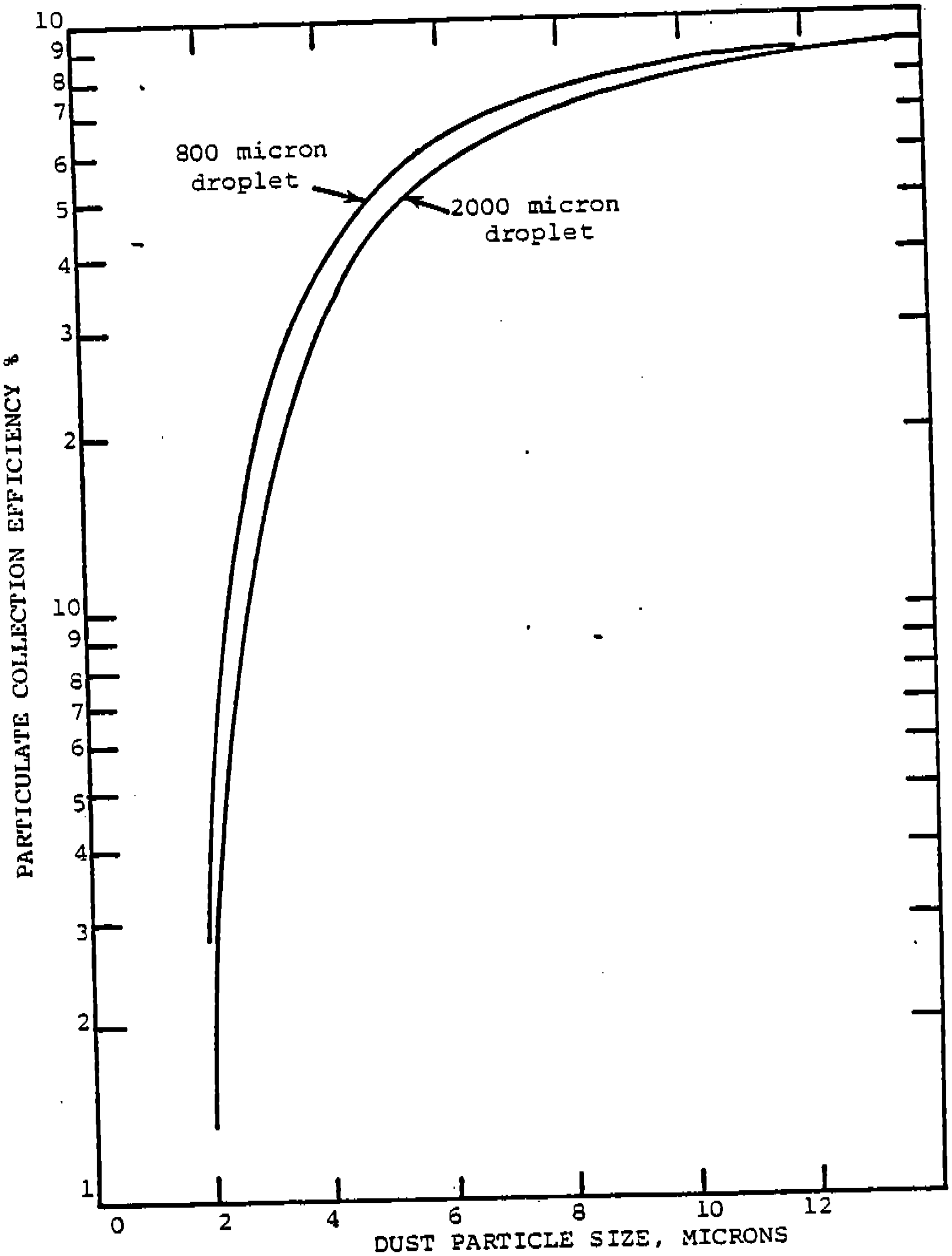

Figure 5-10. Theoretical collection efficiency for various sized droplets in a spray tower. (Ref. 5-1)

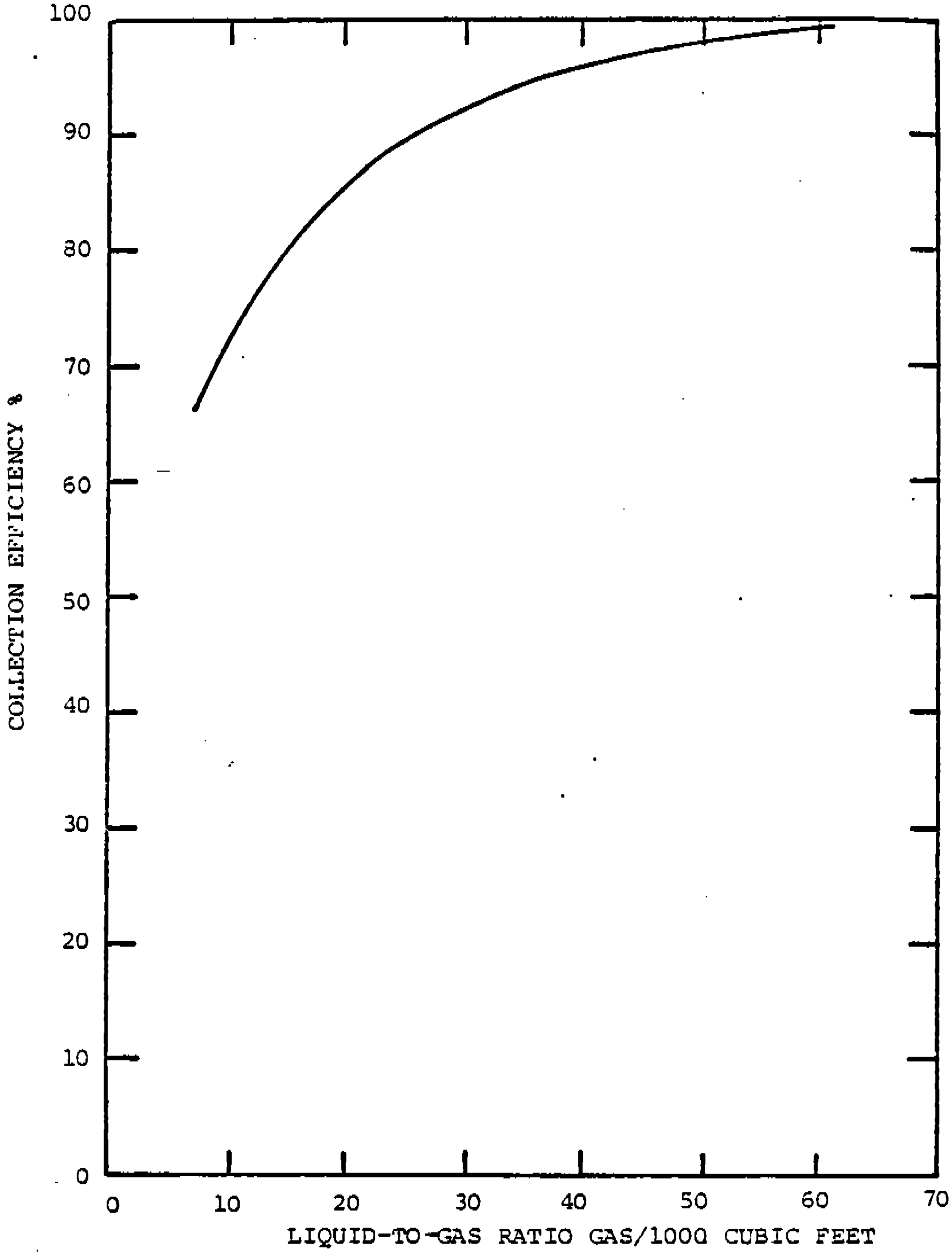

Figure 5-11. The effect of liquid-to-gas ratio on particulate collection in a spray tower. (Ref. 5-1)

The selection of nozzles with sufficiently large orifices to avoid plugging is usually not possible due to the fact that large nozzles produce large drops which may not produce adequate particulate collection or gas cooling. In this situation, some type of coarse screening device must be installed in the scrubber liquor recirculation loop or a precollector to remove these particles must be installed upstream of the scrubber.

The presence of solids in the recirculated liquor causes another problem, i.e., erosion of the nozzles. In time this results in enlarged nozzles, orifices and larger liquor droplets which cause scrubber performance to deteriorate. Using impingent or swirl type spray nozzles made of an abrasion and corrosion resistant material will usually result in a satisfactory service life. However, where excessively abrasive solids are present, nozzles should be operated at low pressure drops (15 psig maximum) even if there is some scrubber efficiency penalty to minimize downtime and costs for replacement of worn nozzles.

B. Tray and Packed Towers--

This class of equipment includes towers with a gas/liquid contacting medium which is continuous, i.e., packing or is comprised of discrete contacting units, i.e., trays.

This equipment is usually designed for gas/liquid mass transfer. In general these designs operate at relatively high gas velocities and are resistant to plugging.

1. The different types of tray and packed tower scrubbers used successfully for particulate removal are: (1) the floating bed scrubber (a packed device), (2) impingent plate, (3) valve tray, and (4) sieve tray scrubbers.

The floating bed scrubber illustrated in Figure 5-12 uses a bed of lightweight spheres retained between two grids for particulate collection. This bed is suspended by the gas flow and particulate collection occurs via inertial impaction, interception, momentum separators, gravity and diffusion. Scrubbing liquor which is sprayed in coarse droplets uniformly across the top of the suspended spheres to irrigate the bed washes out the collected solids thereby avoiding plugging in the bed.

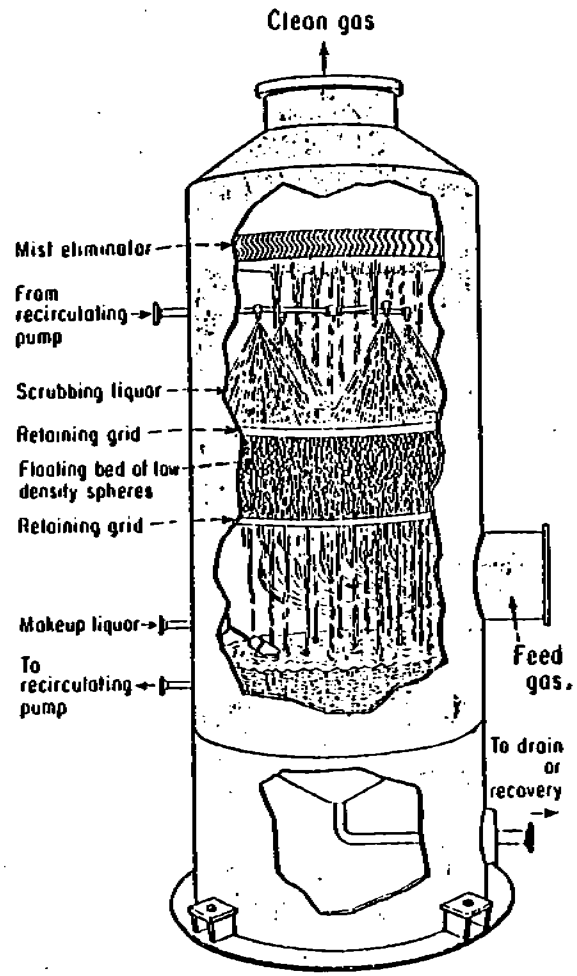

Figure 5-12. Floating-bed scrubber (Ref. 5-1).

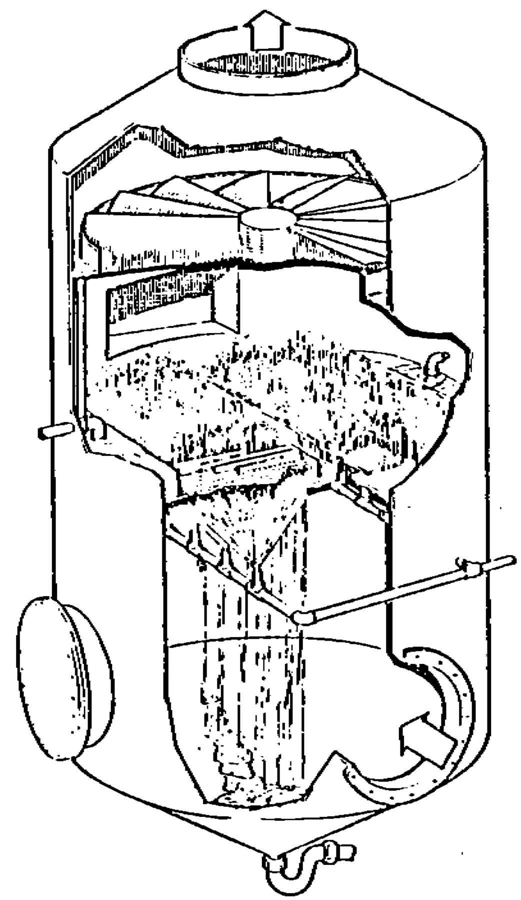

Figure 5-13. Impingement plate scrubber (Impinjet) (Ref. 5-1).

This type of scrubber normally operates at about 7 inches w.c. pressure drop and has been used successfully in fly ash and other applications.

Impingement, valve and sieve tray towers illustrated in Figure 5-13 all rely on the creation of high velocity jets in the openings of the trays to promote particulate collection. Each tray operates at a pressure drop of approximately 2 inches w.c.; they are often used in groups of two or more to increase overall collection efficiency. The hydraulic design of these devices is critical to minimize the possibility of plugging. Adequate irrigation of the plates is essential.

2. In essence, all of the packed and tray towers used for particulate collection rely primarily on inertial impaction and interception which are described in Section 5.1.3(C) for particulate collection. However, other mechanisms make significant contributions to overall particulate removal. Diffusion contributes substantially to collection of particles less than 0.5 microns in diameter and condensation effects, which increase the actual size of particles prior to collection, are often very important factors in these scrubbing processes. The differences among these scrubbers lie in: (1) the methods used to create droplets of scrubbing liquor, (2) the relative velocity between these droplets and the dust particles in gas streams, and (3) the means employed to handle solids in the scrubbing liquor to prevent plugging or excessive wear.

Since there are many types of packed and tray scrubbers, further details regarding their principles of operation are beyond the scope of this survey.

3. Since these scrubbers are designed primarily on the basis of collection by inertial impaction, their performance is controlled by the gas velocity through the various spaces, holes, slots, etc. in the scrubber. As a general rule, the higher the gas velocities, the higher the pressure drop and the higher the overall collection efficiency.

4. In addition to the types of problems outlined in Section 5.1.3(A)(4) above on spray towers, these scrubbers, with the exception of the floating bed device, must contend with the problem of solids settling in poorly agitated areas on the trays. Here again the use of a screening device or a precollector will substantially reduce the likelihood of settling problems due to large particles. The trays must be leveld and liquor distribution must be designed and controlled to maintain adequately high liquor velocities over the entire tray with and without gas flow.

C. Venturi Scrubbers--

1. This category of scrubbers includes a wide variety of devices which are often used to absorb gaseous pollutants and cool gas streams in addition to removing particulate matter.

The major components of a venturi scrubber include a venturi with a converging section, a high velocity throat and a diverging section, a means of introducing scrubbing liquor into the throat area and a device (usually a cyclonic mist eliminator) to collect the droplets of scrubbing liquor and collected particles from the gas stream. These components are illustrated in Figure 5-14.

A venturi throat cross sectional area is usually adjustable to compensate for gas flow variations or changes in particle size distribution. This is necessary since a venturi relies almost totally on gas stream pressure drop for atomization of scrubbing liquor and the pressure drop is dependent upon gas velocity in the throat.

2. Inertial impaction is the predominant mechanism for particulate collection in venturi scrubbers.

In this mechanism collection occurs when dust particles which are carried along by the gas stream impact on a droplet of scrubbing liquor. This impact occurs when the dust particles, because of their mass, have too much momentum to follow the gas stream as it diverges to flow around the droplets of scrubbing liquor. Figure 5-15 illustrates the path of the dust particles and the gas around a droplet of scrubbing liquor.

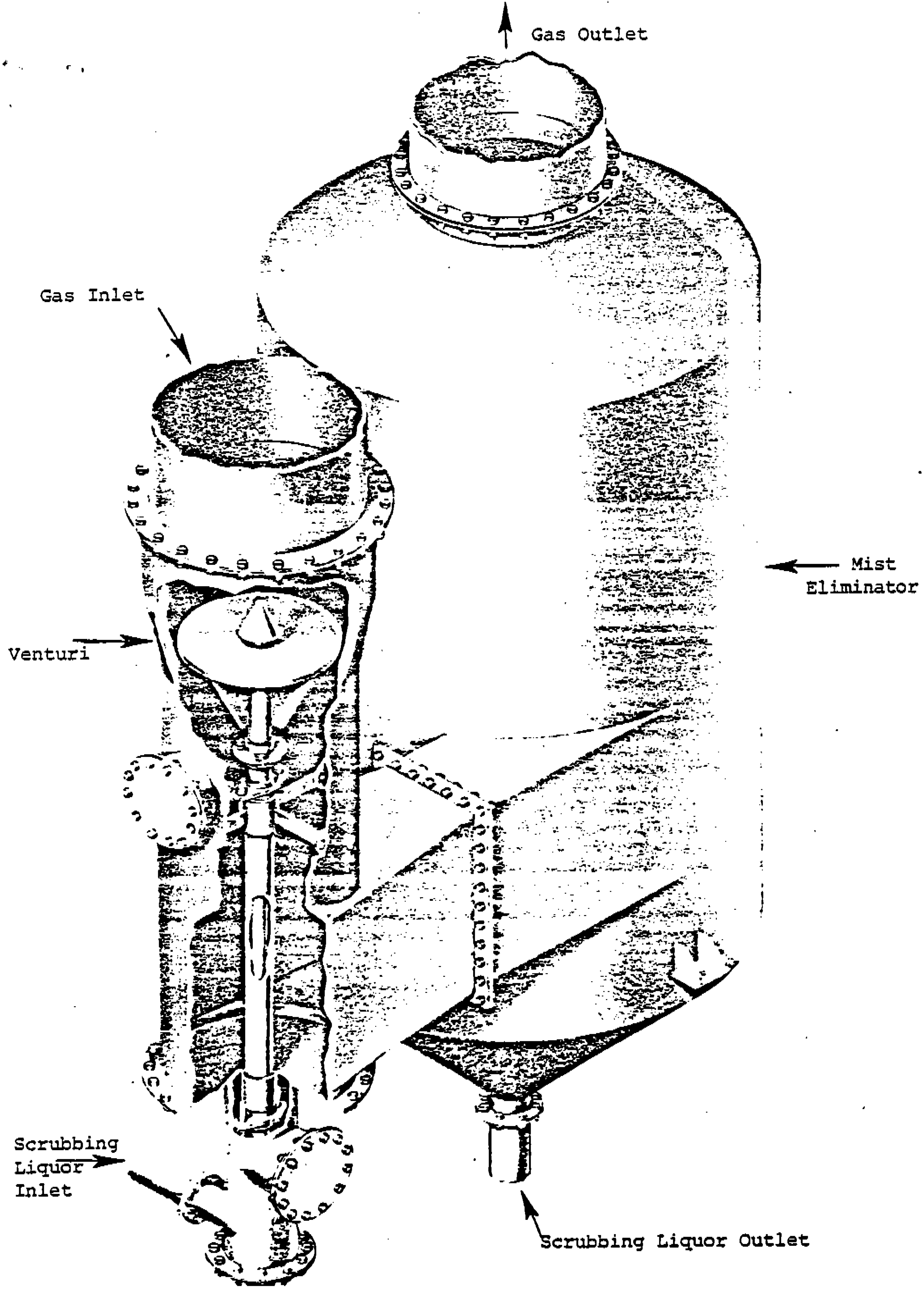

Figure 5-14. Venturi scrubber and mist eliminator (Research-Cottrell).

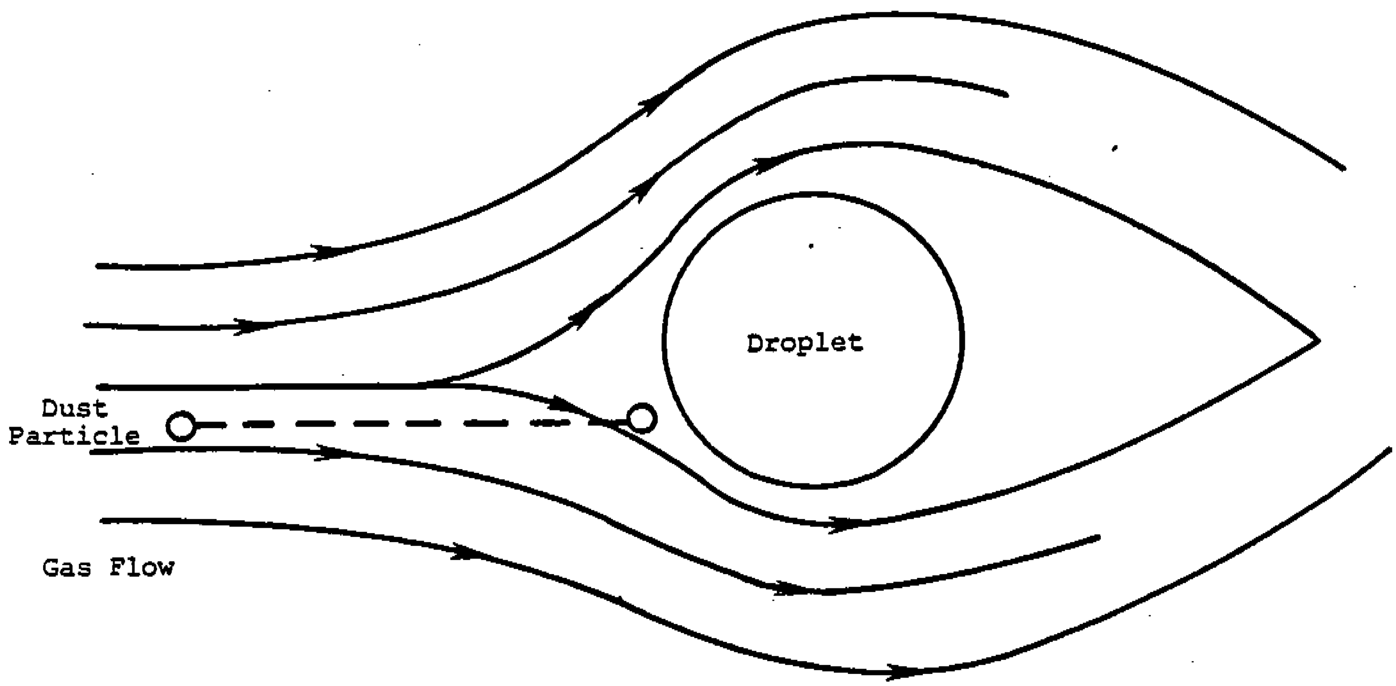

Figure 5-15. Path of dust particles (Ref. 5-1).

The collection efficiency of a venturi scrubber for a given sized particle is often estimated by using a model with the following form:

$$\text{Efficiency} = 1 - \exp\left[-K(L/G)(\Psi)^{1/2}\right] \quad (2)$$

where K is a system related parameter

L/G is the scrubbing liquor-to-gas ratio in gallons per 100 ACF of gas

$$\Psi = \frac{C\, d_p\, D_p^{\,2}\, V^2}{18\mu\ D_L} \quad (3)$$

where C is the Cunningham correction factor

D_p is the particle density

d_p is the particle diameter

V is the throat velocity

μ is the gas viscosity

D_L is the scrubbing liquor droplet diameter

The overall efficiency is estimated by summing up the efficiencies for each particle size in the inlet particle size distribution.

The normal range of liquid-to-gas ratios is 2 to 15 gallons per 1000 ACF; throat velocities are generally 200 to 400 ft per second.

3. The factors that effect particulate collection efficiency in venturi scrubbers include liquid-to-gas ratio, venturi throat velocity, particle size distribution and particle density.

In general, increasing the liquid-to-gas ratio increases collection efficiency up to ratios of 10 to 12. However, the venturi pressure drop increases somewhat as this ratio is increased.

Gas velocity in the venturi throat is the most important factor influencing collection efficiency. Even submicron particles can be collected at sufficiently high throat velocities. However, this ability to collect submicron particles comes at a high price since the pressure drop and therefore the power requirement increases as the square of the gas velocity.

The effect of particle size distribution on performance is simply this: efficient collection of small particles requires high throat velocities. If there are substantial amounts of submicron material which must be collected, very high throat velocities are required and pressure drops well over 50 in. w.c. may be required. The application of venturi scrubbers to remove particulate below 0.4 to 0.5 microns is generally not economical if the removal efficiencies required for these small particles are above 90%.

The density of the particles, i.e., the effect of density or the aerodynamic behavior of the particles has a significant effect on collection efficiency. High density, solid particles are relatively easy to collect while low density or fluffy particles like soot require very high throat velocities for efficient collection.

The collection efficiency for both moderate and high energy venturi scrubbers is illustrated in Figure 5-16.

4. The main problems associated with venturi scrubbers include erosion in the venturi throat and diffuser, plugging of the scrubbing liquor supply liner and carryover from the mist eliminator.

Since the throat velocity in a venturi scrubber is several hundred feet per second and scrubbing liquors often contain abrasive solids, erosion is a common problem. In applications where very high pressure drops are required, the throat and diffuser are often lined with a highly abrasion resistant material like alumina or silicon carbide. In addition, coarse particles can be removed from the scrubber liquor prior to recirculating it to the venturi throat to reduce erosion. This will also reduce the possibility of plugging the scrubber liquor supply liner. Maintaining the solids content of the scrubber liquor below 10 to 15% and maintaining uniform line velocities will also help to avoid plugging problems.

Proper design of the mist eliminator downstream from the venturi scrubber is essential to achieving high particulate collection efficiency. If the small droplets of scrubbing liquor from the venturi are not completely removed in the mist eliminator, unacceptable particulate emissions will occur because these droplets contain the particulate matter collected in the venturi.

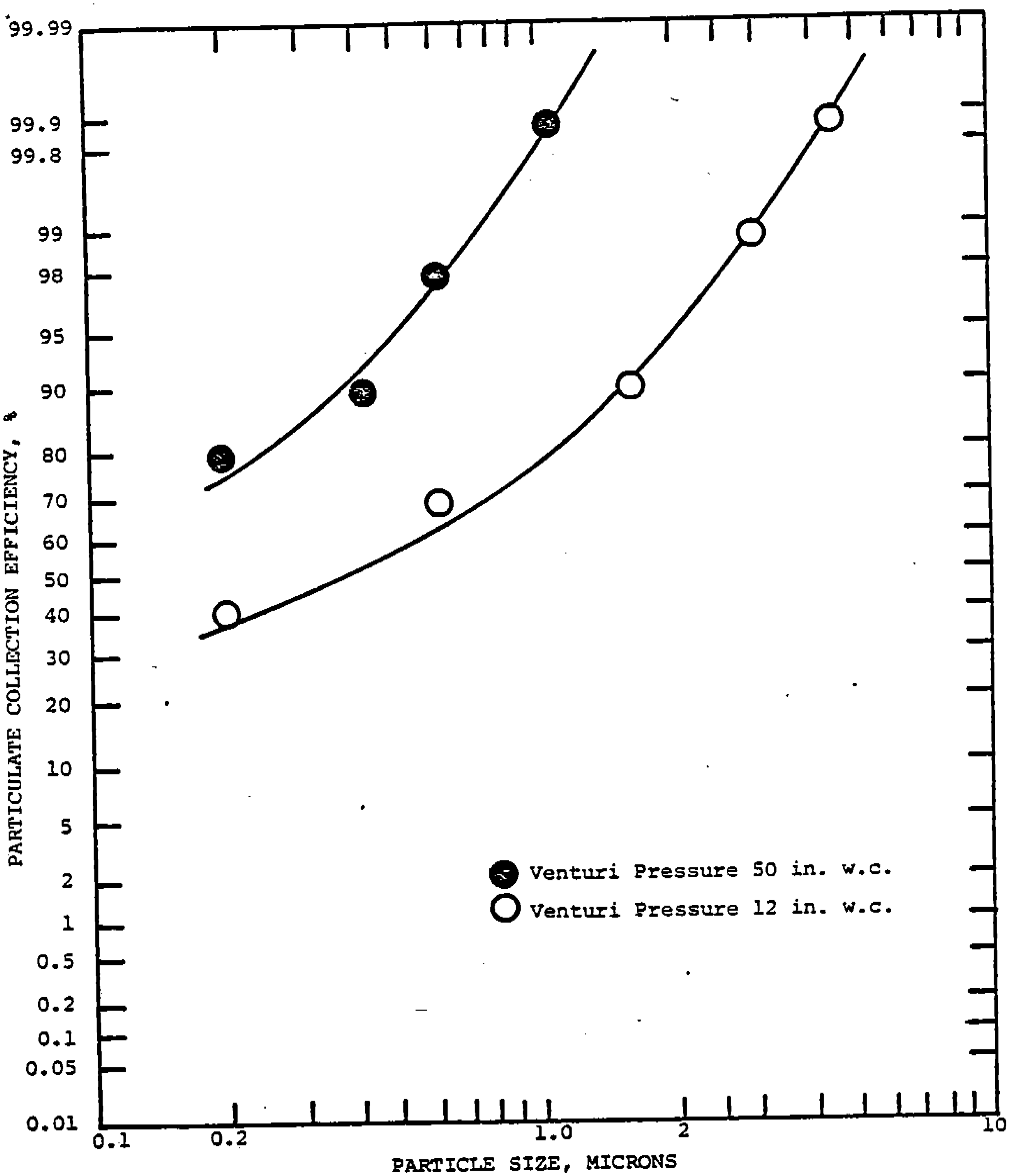

Figure 5-16. Typical venturi scrubber particulate collection efficiency (Research-Cottrell).

Since there are many different mist eliminators used, a detailed discussion is beyond the scope of this report. However, a cyclonic mist eliminator is the most common used in combination with venturi scrubbers. In these mist eliminators good performance can be assured by using conservative spin velocities (70 ft/sec max.) or conservative spin height, superficial gas velocities under 9 ft/sec and adequate sample level controls to prevent scrubber liquor from rising into the gas inlet.

5.1.4 Fabric Filters

Although fabric filters have been used for many years in a wide range of industrial applications, they were rarely used in large installations solely for control of emissions. With increasingly tighter emission limitations and the availability of fabric media with good life at relatively high temperatures, fabric filters are being used in areas once dominated by electrostatic precipitators. Today, if gas temperatures are below 500 °F and 99+% particulate removal is needed, fabric filters should be considered.

A. The basic components of a fabric filter or baghouse, as they are often called, include a suitable filter medium usually in the form of cylindrical bags, a gas tight enclosure for the bags, a mechanisms for cleaning accumulated dust from the bags, and a means for removing the accumulated dust from the device. A typical fabric filter is illustrated in Figure 5-17.

A gas stream containing particulate matter enters the fabric filter housing and enters either the inside or outside of the filter bags. As the gas stream passes through the filter bag and the dust layer accumulating on its surface, the dust particles are removed. A combination of collecting methods including inertial impaction, settling diffusion and electrostatic attraction contribute to particulate removal.

There are two modes of collection possible in a fabric filter, i.e., collection on the inside or outside of the bag. When collection occurs inside the bag, a woven fabric is normally used at relatively low gas rates, i.e., 1.5 to 3.5 $ft^3/min\ ft^2$. Woven fabrics are available in a wide range of materials and operation at temperatures up to 500 °F are possible.

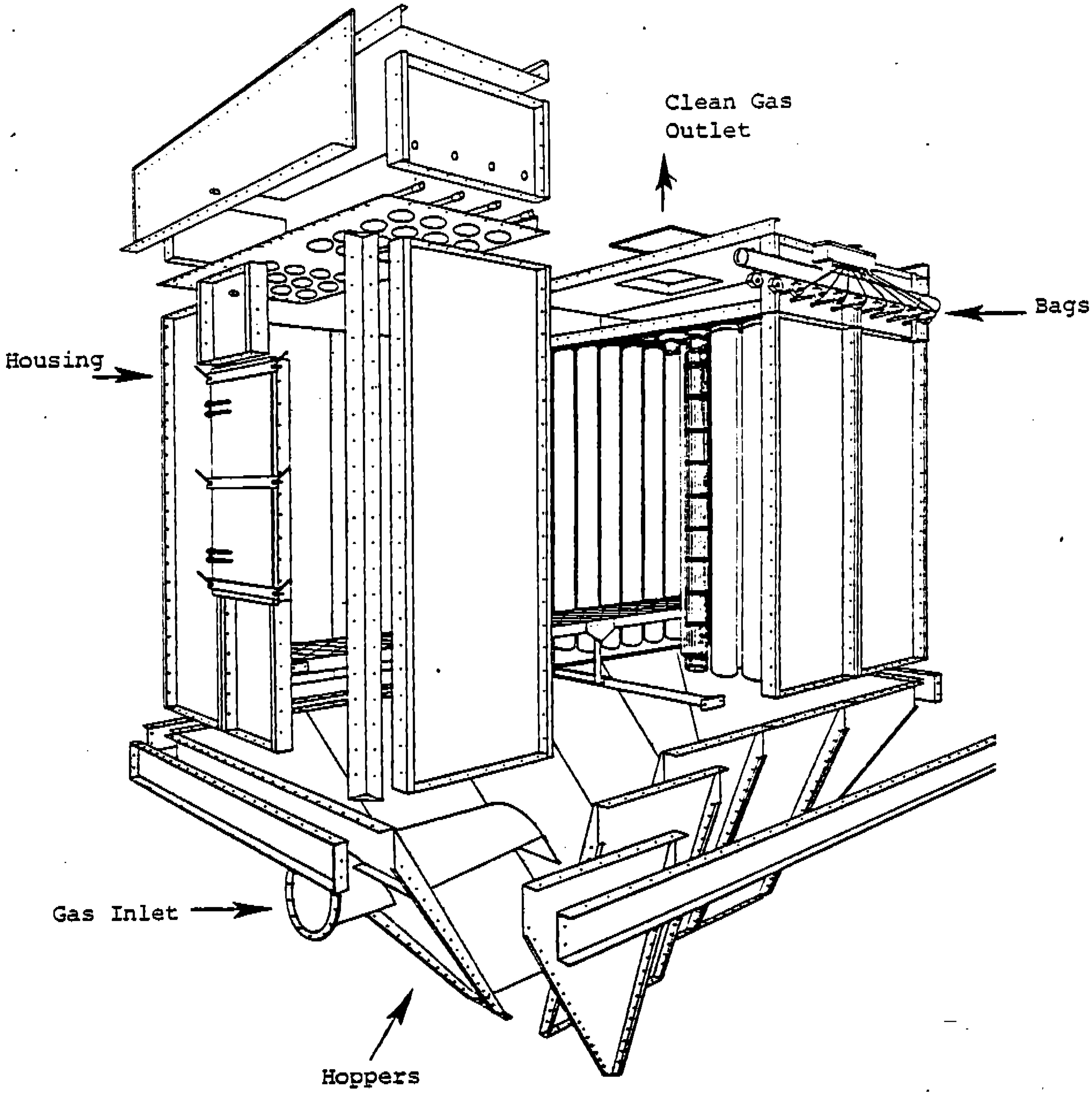

Figure 5-17. Typical pulse jet fabric filter (Research-Cottrell).

Felt fabrics are generally used when collection occurs on the outside of the bag. Since the pressure outside the bag is greater than that inside in this mode of operation, a support is necessary to prevent the bag from collapsing. Gas rates between 5 and 15 cfm/ft^2 are normal for outside collection applications.

Maximum gas temperatures are generally limited to 375 °F due to the types of felt materials available. In addition to the above, the choice between inside and outside collection affects housing and hopper design as well as the method chosen for cleaning. Mechanical shaking is suitable for either inside or outside collection. Reverse air cleaning, where a part of the clean gas is recycled backwards through the bags, is used for inside collection. Pulse jet cleaning, where a burst of high pressure clean gas is sent through the bags is used for outside collection. Cleaning cycles are initiated as needed to maintain the pressure drop across the bags at an acceptable level, usually in the range of 2 to 6 in. w.c. This minimization of cleaning cycles helps to maximize bag life.

The dust dislodged from the bags during the cleaning cycle collects in a hopper before removal via a rotary valve screw conveyor or other suitable device.

B. The selection of the best fabric filter medium for a given application is governed by the temperature of the gas stream and the nature of the dust.

Exotic materials like metal or ceramic cloth which can operate at temperatures above 550 °F are prohibitively expensive. Therefore as a matter of practicality fabric filters have an upper temperature limit of 550 °F.

It is important to note that gas temperatures above 550 °F do not automatically preclude use of fabric filters. If the gas stream can be cooled below this temperature by heat exchange, evaporative cooling or dilution with cool air, a fabric filter can be used.

The other major factor influencing fabric selection is the abrasive qualities of the dust.

Certain materials which are hard and have sharp angular shapes tend to produce rapid wear of the fabric. This tendency can be minimized by lowering filtration rates and minimizing the number of cleaning cycles. It is also important to remember that coarse dusts tend to be more abrasive than fine ones. The selection of cloth is usually left to the supplier as is the filtration rate. The manufacturer selection can be checked by comparing it with the normal fabric and filtration rate used in similar applications.

Table 5-2 lists common fabrics and some of their relevant characteristics. Many of these fabrics can be knitted into seamless bags. This eliminates leaking and breakage which often occurs along the long seam in the bag.

C. Fabric filters are basically simple devices which take advantage of a number of particulate collection mechanisms. Particles are removed as the gas flows through the fabric filter medium by one or more of the following mechanisms:

1. Inertial impaction
2. Diffusion to the surface of an obstacle because of Brownian diffusion
3. Direct interception because of finite particle size
4. Sedimentation
5. Electrostatic phenomena

D. Parameters that are important in fabric filtration system design include air-to-cloth ratio and pressure drop. Each of these factors is discussed briefly below.

A major factor in the design and operation of a fabric filter, the air-to-cloth (A/C) ratio is the ratio of the quantity of gas entering the filter (cfm) to the surface area of the fabric (ft^2). The ratio is therefore expressed as cfm/ft^2 or sometimes also as filtering velocity (ft/min). In general, a lower ratio is used for filtering of gases containing small particles or particles that may otherwise be difficult to capture. Selection of the ratio is generally based on industry practice or the recommendation of the filter manufacturer.

TABLE 5-2. FABRIC CHARACTERISTICS

Material	Temperature Limits		Fabric Type Woven = W Felt = F	Abrasion Resistance	Resistance to Chemicals			Relative Fabric Cost
	Normal	Maximum			Acids	Alkali	Organic Acids	
Cotton	180	225	W	Good	Poor	Good	Good	1
Wool	200	250	W	Good	Fair	Poor	Fair	2
Nylon (Polyamide)	200	250	F	Excellent	Poor	Good	Fair	2.1
Orlon Polyacrylonitride	240	275	W	Good	Good	Fair	Good	2.1
Polyester	275	325	W/F	Excellent	Good	Good	Good	2.7
Polypropylene	200	250	F	Excellent	Excellent	Excellent	Excellent	2.7
Nomex (Polyamide)	425	500	F	Excellent	Fair	Good	Excellent	6.9
Fiberglass	550	600	W	Poor-Fair	Excellent	Poor	Excellent	2.3
Teflon	450	500	W/F	Fair	Excellent	Excellent	Excellent	4.0

(Ref. 5-3)

Pressure drop in a fabric filter is caused by the combined resistances of the fabric and the accumulated dust layer. The resistance of the fabric alone is affected by the type of cloth and the weave; it varies directly with the air flow. The permeability of various fabrics to clean air is usually specified by the manufacturer as the air flow rate (cfm) through 1 ft^2 of fabric when the pressure differential is 0.5 in. H_2O in accordance with the American Society for Testing and Materials (ASTM). At normal filtering velocities the resistance of the clean fabric is usually less than 10 percent of the total resistance. The spaces between the fibers are usually larger than the particles that are collected. Thus the efficiency and the pressure drop of a new filter are initially low. After a coating of particles is formed on the surface, the collection efficiency improves and the pressure drop also increases. Even after the first cleaning and subsequent cleaning cycles, collection efficiency remains high because the accumulated dust is not entirely removed.

The pressure drop through the accumulated dust layer has been found to be directly proportional to the thickness of the layer. Resistance also increases with decreasing particle size. Maximum pressure drop on existing utility fabric filters is 5 to 6 in. w.c.

Particulate collection in fabric filters even for submicron particles is very good. Overall efficiencies well over 99% are possible for a wide variety of particles. Figure 5-18 illustrates fabric filter collection efficiency as a function of particle size.

E. Various cleaning methods are used to remove collected dust from fabric filters to maintain a nominal pressure drop of 2 to 6 in. w.c. Mechanical shaking or reversed air flow are generally used to force the collected dust off the cloth.

Many mechanical shaking methods are in use. High-frequency agitation can be very effective, especially with deposits of medium to large particles adhering rather loosely. In such cases, high filtering velocities can be used and higher pressure drops can be tolerated without danger of blinding (blocking or clogging) the cloth.

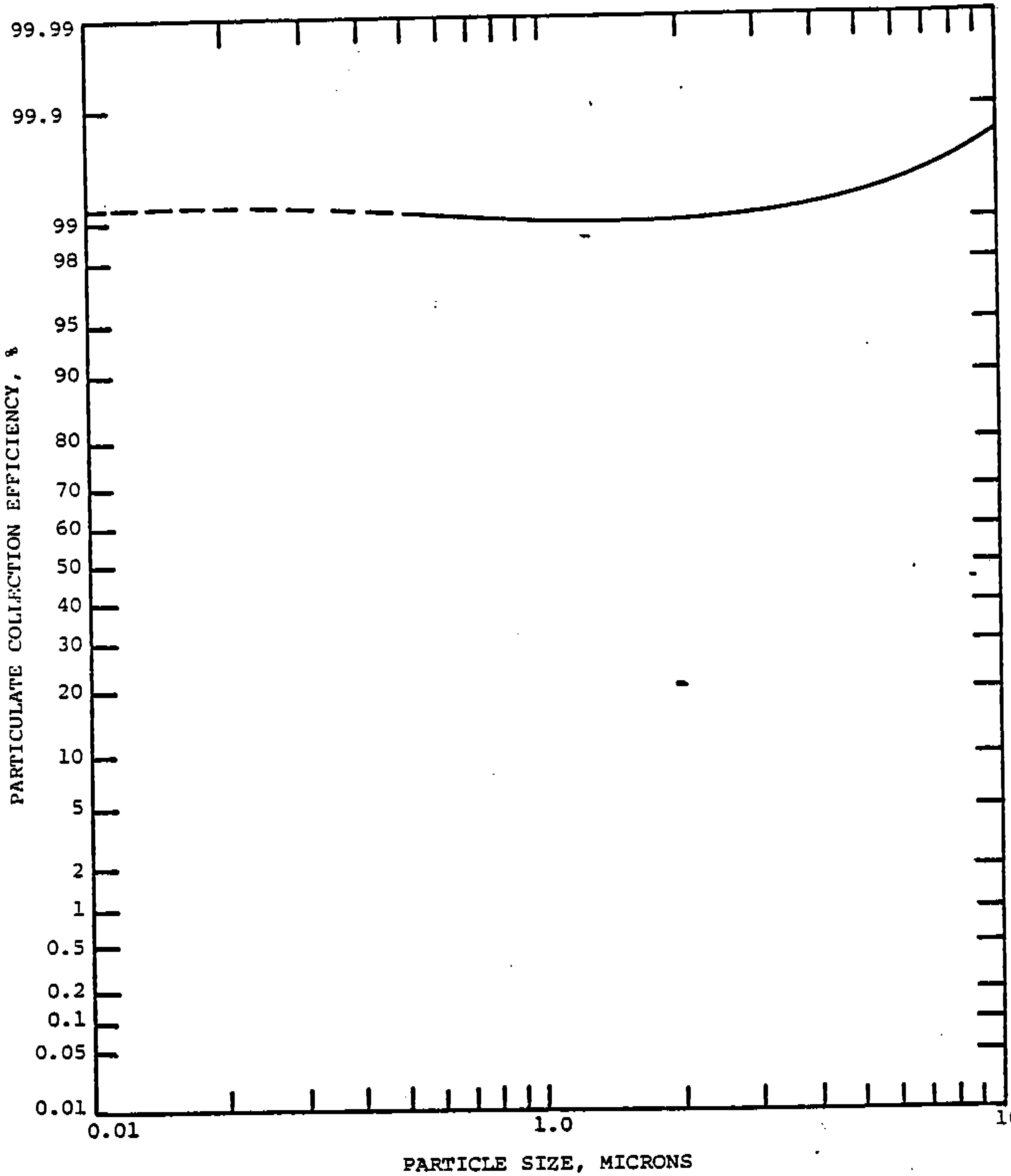

Figure 5-18. Fabric filter particulate collection efficiency (Ref. 5-4).

In an alternative cleaning method, an intermittent pulse jet of high-pressure air (100 psi) is directed downward into the bag to remove the collected dust. In some designs the air is introduced at lower pressures, but these systems may require a greater quantity of cleaning air. Felted fabrics are used in conjunction with the pulse-jet cleaning method. A qualitative comparison of cleaning methods is given in Table 5-3.

A normal cleaning cycle is actuated by a pressure transducer near the inlet to the induced-draft fan when the pressure drop across the bags exceeds about 4 in. w.c. The use of compartments, i.e., groups of bags with individual sets of cleaning controls, permits continuous operation and particulate removal.

During operation each compartment is cleaned in the following manner:

1. The gas inlet damper to the compartment closes, shutting off the flow of "dirty" flue gas to this compartment.

2. The collapse damper opens, allowing a reverse flow of "clean" flue gas from the outlet flue to be pulled through the bags, partially collapsing and thus cleaning the bags.

3. The collapse damper closes.

4. The gas inlet damper opens, returning the compartment to the filtering mode.

So that no sizable portion of the total fabric will be out of service for cleaning at any given time, the time required for cleaning should be a small fraction of the time required for dust deposition. With shake cleaning equipment, for example, a common cleaning-to-filtration time ratio is 0.1 or less. With a ratio of 0.1, 10 percent of the compartments in the baghouse are out of service at all times during operation. Therefore, the frequency of cleaning should be designed to minimize this ratio.

TABLE 5-3. COMPARISON OF FABRIC FILTER CLEANING METHODS

Cleaning Method	Uniformity of Cleaning	Bag Attrition	Equipment Ruggedness	Type Fabric	Filter Velocity	Apparatus Cost	Power Cost	Dust Loading
Shake	Average	Average	Average	Woven	Average	Average	Low	Average
Rev. Air	Good	Low	Good	Woven	Average	Average	Med. Low	Good
Pulse-jet	Average	Average	Good	Felt, Woven	High	High	High	V. high
Vibrating, rapping	Good	Average	Low	Woven	Average	Average	Med. Low	Average

(Ref. 5-3)

F. The normal problems associated with fabric filters include poor control of gas temperature resulting in overheated bags which fail prematurely, impingent of coarse particles on the bags which causes perforation, inadequate clearance between bags which results in excessive wear at contact points, condensation on bags during startup, or operation which results in a sticky cake which cannot be removed from the bags.

The selection of a fabric which is chemically attacked by constituents in the gas or in the particles, excessive pressure during the cleaning cycle which can cause the bags to tear or burst, and cleaning the bags too frequently which substantially reduces bag life.

In addition to the above, the problems of handling the dust collected in the hoppers must be considered.

5.1.5 Electrostatic Precipitators

A. Electrostatic precipitators (ESPs) are one of the simplest, most reliable and economical devices available for particulate removal. These devices operate at very low pressure drops and require minimal amounts of power for charging, rapping and dust removal.

A typical ESP incorporates an electrode arrangement consisting of positive grounded collecting plates and thin section negative discharge wires spaced approximately 5-6 inches apart. A high voltage (approximately 30 KV) DC charge is imposed on the negative element and an electrical field is set up between the two electrodes. The dust particles pass between the elements and are charged and transported to the electrode of opposite polarity. Periodically, the precipitated material must be removed from the electrodes; this is accomplished by vibrating or rapping the plate to dislodge the dust. Figure 5-19 shows the basic components involved and Figure 5-20 gives an idea of the arrangement of a typical full size precipitator.

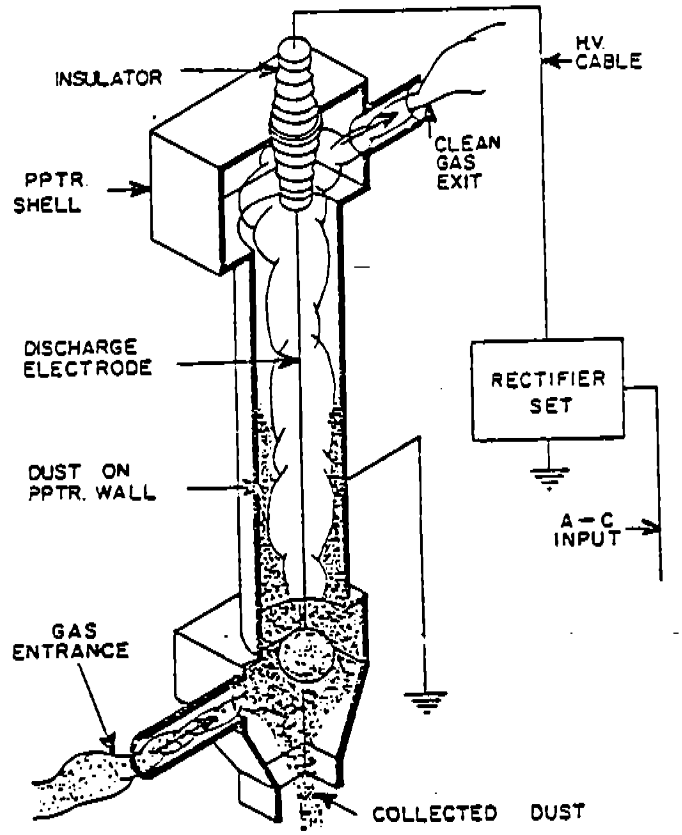

Figure 5-19. Typical precipitation process (courtesy of Research-Cottrell).

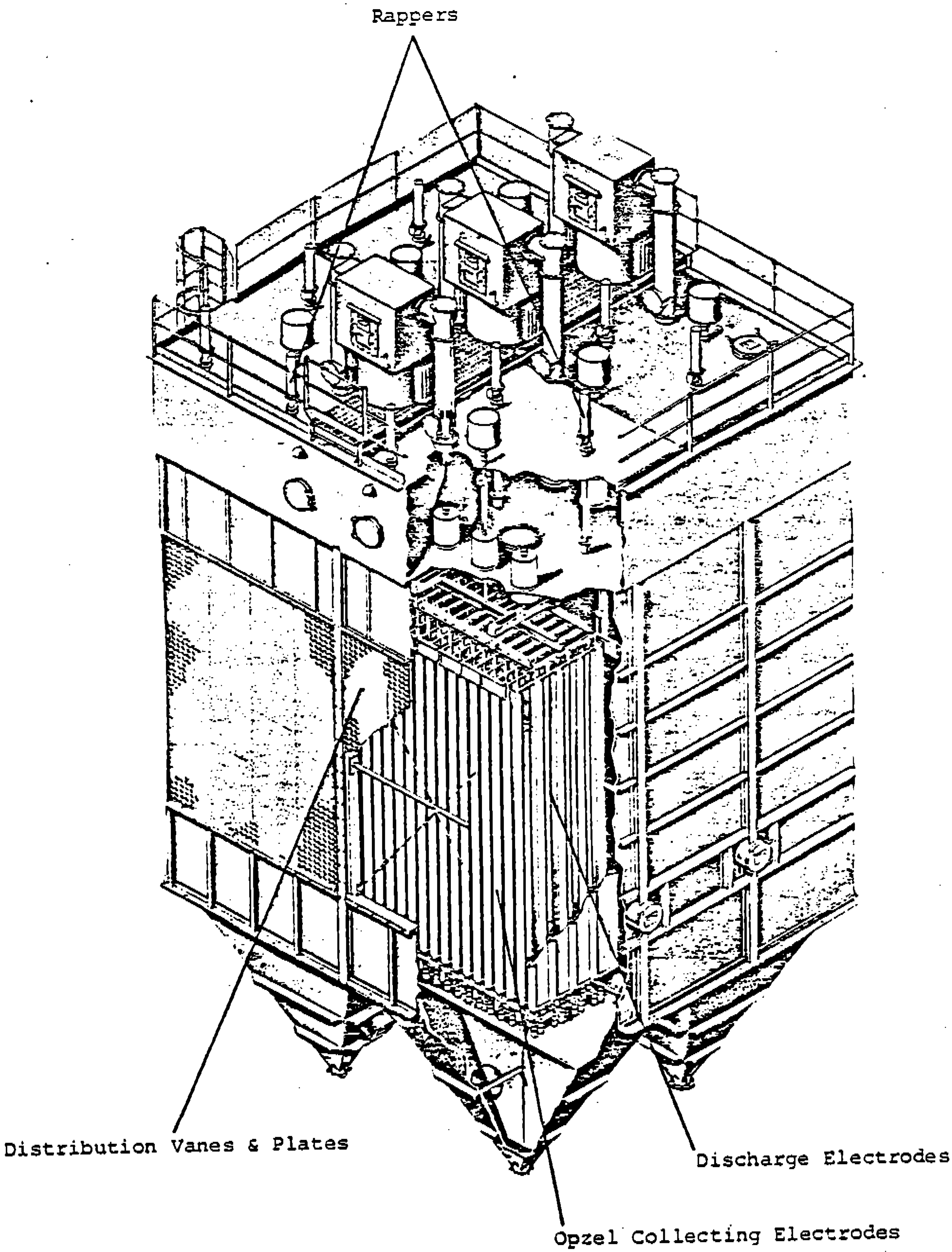

Figure 5-20. Typical full-size electrostatic precipitator (Research-Cottrell)

B. Historically, precipitator sizing has been based on use of the Deutsch equation where

$$\text{Efficiency} = 1 - \exp\left(-\frac{A}{V}w\right) \qquad (4)$$

e = Base of Natural Logarithms

A = Collecting Electrode Area (square feet)

V = Gas Flow Rate (cubic feet/second)

w = Migration Velocity (feet/second)

The designer must solve for "A". The parameter "w", migration velocity, is derived from an equation which takes into account the electrical field strength at the collecting surface and the discharge electrode, particle size of the dust, and gas viscosity. Basically, selection of this value reflects the expertise of the designer and the company's experience in the particular application. In essence, the following three values have been those considered of primary importance in sizing a precipitator:

Face Velocity - expressed in feet per second (the speed at which the gas travels through the precipitator). This determines the frontal area of the box.

Migration Velocity - expressed in cm/second or feet/second. This is the speed at which the dust particle travels toward the plate under the influence of the electrical field. As mentioned, selection of this value has been based on experience.

Aspect Ratio - the ratio of the length of the precipitator to its height. (A unit with 30 foot high fields and 36 feet of treatment has an aspect ratio of 1.2). For high (99+%) efficiency, a minimum aspect ratio of 1 is considered necessary.

C. There are many factors which affect ESP efficiency. The following are the more important ones: gas distribution, rapping electrical sectionalization, gas sneakage, dust removal and the stability of the high voltage sytem.

Gas Distribution - Careful attention must be given to the flue arrangement conveying gases to and from the precipitator as well as to the design of the transitions. Nothing will downgrade the performance of a unit as effectively as maldistribution.

Rapping - Cleanliness of precipitator collecting surfaces and discharge electrodes is essential to proper performance. The manufacturer must provide adequate rapping equipment to keep the system clean. As a general rule, at lease one rapper per 2000 square feet of collecting surface and per 3000 lineal feet of discharge wire should be provided.

Electrical Sectionalization - Theoretically, the most efficient precipitator would be one in which each individual discharge electrode has its own power supply in order to maximize power input. This is obviously impractical. However, it is practical and advisable to have the precipitator divided into a number of separately energized electrical sections which can be individually isolated. This practice not only allows, to some extent for variations and stratification in temperature, dust loadings, etc., but it renders a smaller section of the precipitator vulneralbe to external malfunctions such as dust removal problems.

Gas Sneakage - Loss of efficiency can result from gas by-passing the electrostatic zone in a precipitator. This can occur between the end plates and the shell, over the top of the electrical fields, or in the hoppers. On high efficiency units, design provisions are made to provide such potential problems areas with proper sealing and baffling.

Dust Removal - Inadequately designed or under-sized dust removal systems can cause precipitator damage and loss of efficiency. Dust build-up in hoppers can cause damage to precipitator internals by distorting the lower high tension framework, bowing discharge electrodes and causing accelerated failure. Moreover, ash build-up in the hoppers increases possibility of dust re-entrainment and loss of efficiency.

Stability of High Voltage System - The efficiency of a precipitator is a direct function of the power input. Any condition which affects power input adversely should be avoided in the basic design of the precipitator. Proper alignment and stability of the high voltage system is essential.

Todays high efficiency ESPs are very effective collection devices for fine particles. Figure 5-21 illustrates typical collection efficiency as a function of particle size.

D. Rappers--

Removal of particulate matter collected on the plates in ESPs is accomplished by rapping the plates to dislodge the dust. The wires can also be cleaned in this manner.

There are three types of rapping devices in general use today: drop hammers, magnetic or pneumatic impulse rappers, and electromagnetic vibrators. Impulse rappers are used most often on the collecting electrodes or plates because the frequency and intensity of rapping can be adjusted to optimize performance. Charging electrodes are most often cleaned with vibrators.

Plate rapping is performed in either of two modes, i.e., in line with the plate or across the plate. In general, rapping across the plate produces higher levels of accelerations in the plates for a given energy input and results in more thorough cleaning of the plates. The interval between rapping operations is also an important factor in ESP performance. Rapping too often results in unnecessary reentrainment and a decrease in particulate collection efficiency, while overly long rapping cycles result in the buildup of excessively thick layers of insulating dust which also reduces particulate collection.

The optimum rapping cycle in a given ESP installation must be established for each field in the precipitator; fine tuning after startup is almost always required to maximize particulate collection efficiency.

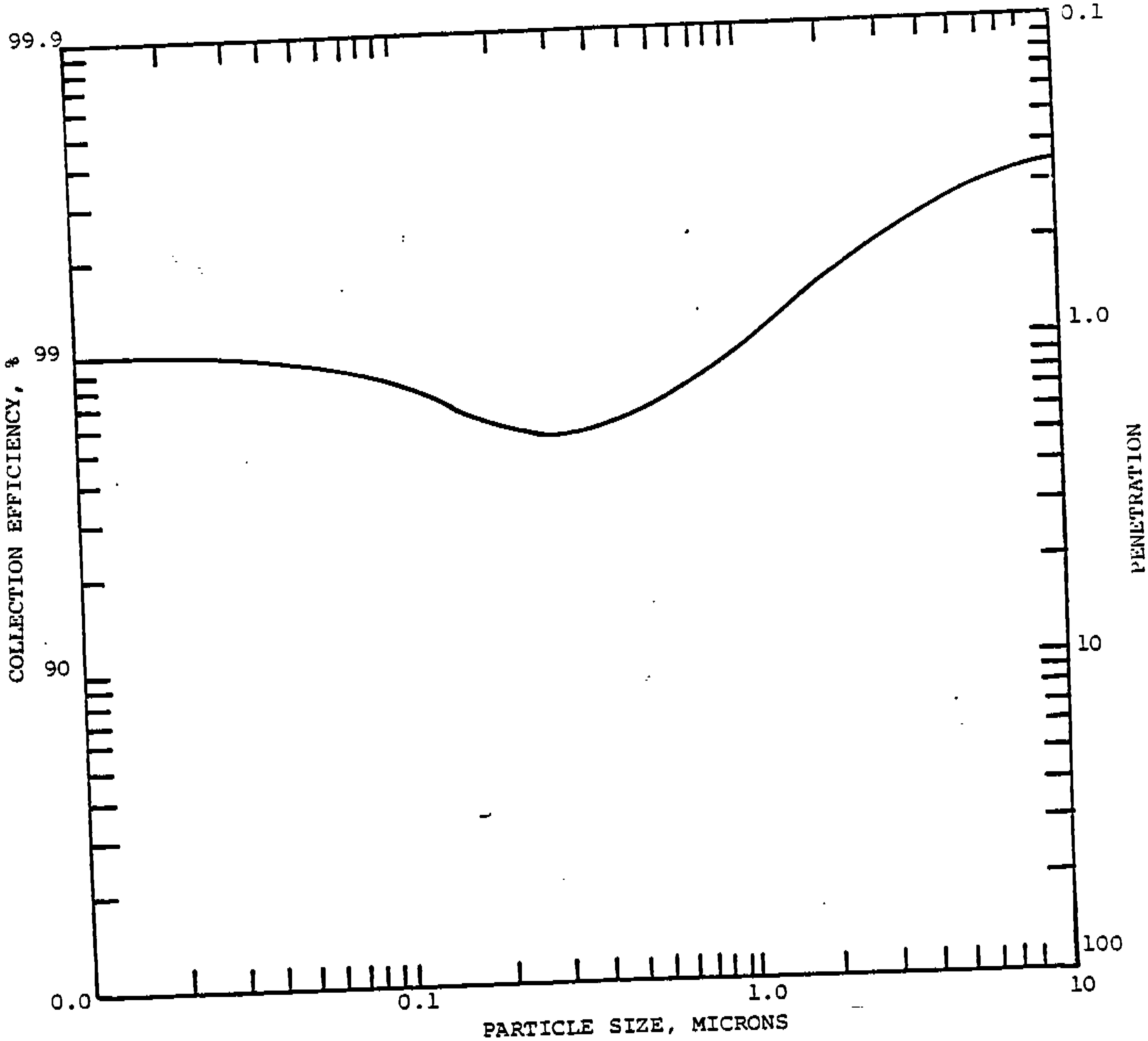

Figure 5-21. ESP collection efficiency (Research-Cottrell).

E. There are several problems that can arise which will substantially reduce ESP performance. The following are the most common encountered with fuel burning equipment:

Gas Volume - A precipitator is a volumetric device. Any increase in boiler load which results in excessive flow through the precipitator will cause a loss of efficiency. For example, a precipitator designed for 3 feet/second face velocity and an efficiency of 99% will drop to 96.5% if the the velocity increases to 4 feet/second (0.33% increase in load).

Temperature - A change in operating temperature may also have an effect on precipitator efficiency. The resistivity of fly ash (ability of the dust particle to be charged) varies greatly in the temperature range 200-400 °F. Ignoring the effects of temperature on gas volume the impact of temperature on efficiency would be (assuming 99% guarantee at 325 °F):

200 °F	99.9+%
325 °F	99%
400 °F	99.5%

Figure 5-22 is a typical fly ash temperature vs. resistivity curve. Bearing in mind that as resistivity increases efficiency decreases it can be seen that there is benefit to be derived in operating below or above the 300-350°F level.

Fuel - Any significant change in the type of fuel being fired will have an effect on the performance of a precipitator. For example, a change from a 2% sulfur bituminous coal to a 0.5% sulfur subbituminous western coal can result in a design efficiency of 99.5% dropping to 90% (or less). It has also been demonstrated that other chemical constituents (such as sodium oxide) in the ash can have an effect on performance by reducing bulk resistivity. It is, therefore, advisable that adequate attention be paid to the fuel as related to its impact on precipitator performance. Ash analysis should be submitted to the manufacturer, if it is available and the unit designed for the worst expected fuel.

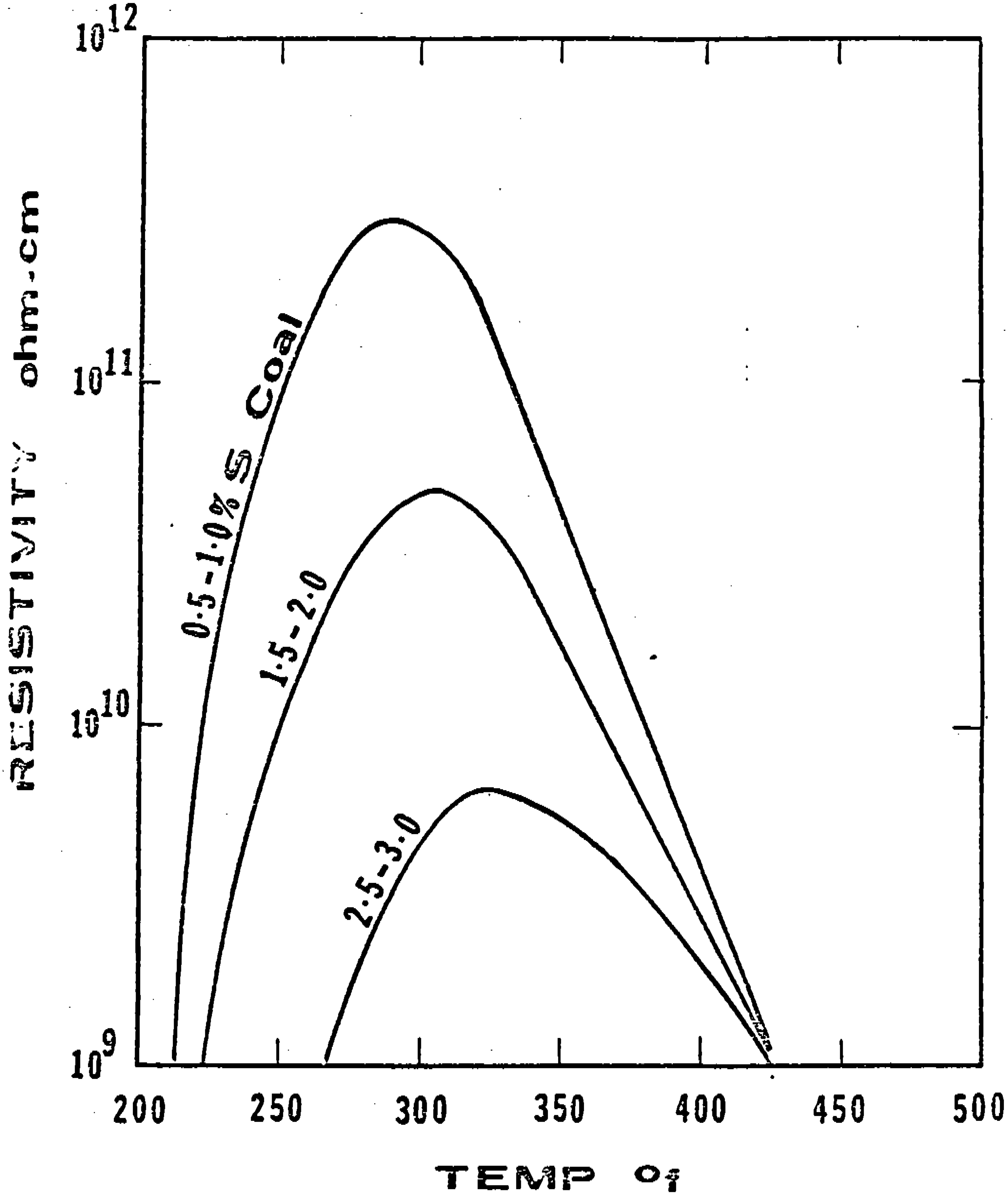

Figure 5-22. Typical fly ash temperature vs. resistivity curve. (Research-Cottrell)

Inlet Loading - The effect of increased dust loading is somewhat obvious. Since a precipitator is designed to remove a certain percentage by weight of the entering material, all things being equal, an increase of 50% at the inlet will result in the same increase at the outlet. Therefore, if a fuel change involves an increase in percentage ash one can expect a corresponding increase at the outlet with greater opacity resulting.

Carbon - Variations in firing practice or coal pulverization which affect the quantity of combustible materials in the fly ash also have an impact on precipitator performance. Carbonaceous materials are readily charged in a precipitator, but lose their charge quickly and are readily reentrained. Not only is the carbon particle very conductive, it is large and light compared to the other constituents making up fly ash. Precipitators on stoker fired boilers, where combustible content may be 25 to 50 percent, are more conservatively sized and employ lower face velocity than a P.C. fired unit firing the same fuel.

The above are the major variables which impact precipitator performance and should be considered if a deterioration in performance is to be avoided.

5.2 COST OF PARTICULATE CONTROL

The cost of particulate control equipment is governed primarily by the volume of gas to be treated, the size distribution of the particles to be removed, and the overall removal efficiency required.

In addition, the chemical and physical characteristics of the gas stream and the particulate matter may require special design features and use of special corrosion, abrasion, or temperature resistant materials.

Where applicable the necessity for considering these extraordinary measures will be noted and their impact on system cost will be indicated.

The particle size indicated on the following cost curves is the size that is collected at the 90% efficiency level. Exceptions to this are noted on the figure.