CHAPTER 43

CONTROL OF INDUSTRIAL STACK EMISSIONS

*Engineering Staff**

George D. Clayton & Associates

INTRODUCTION

Simply defined, pollution is the wrong substance in the wrong place at the wrong time. Air pollution existed long before man discovered fire. Volcanic eruptions, dust storms, forest fires and other natural phenomena have released millions of tons of pollutants into the air since the beginning of time.

With the advent of the industrial revolution, continuous exposure to a variety of gaseous and particulate materials became commonplace. The synergistic effects of these chemicals on health has led to several air pollution disasters throughout the United States. The first recorded episode occurred in Donora, Pennsylvania in 1948, when 20 people died during a five-day atmospheric inversion.

In addition to health effects, pollutants in the air can cause extensive economic damage. The poisoning of livestock by lead and zinc, the destruction of crops by sulfur dioxide, ozone and fluorides, and the damage to neighborhoods by smoke, dust and gaseous pollutants combined carry an economic price tag ranging between 10 and 60 billion dollars per year. One estimate given for the personal cost to a resident living in a relatively polluted community is $84 per year. This figure includes only those costs resulting from the maintenance of the household itself.

The cost to industry of reducing emissions to the level required by the Clean Air Act will entail

*The following staff members participated in writing this chapter: George T. McCollough, Delno Malzahn, John E. Mutchler and George D. Clayton.

TABLE 43-1.
Stationary Sources
Estimates of Potential and Reduced Emission
Levels and Associated Costs
[298 Metropolitan Areas]

		Quantity of Emissions[1] (Thousands of Tons per Year)						Control Costs (Millions of Dollars)	
Source	Year	Part	SO_x	CO	HC	F	Pb	Investment	Annual
Solid Waste Disposal	1967	1,110	—	3,770	1,400	—	—		
	FY 76 W/O[2]	1,500	—	5,450	2,020	—	—		
	FY 76 W[3]	185	—	414	293	—	—	201	113
Stationary Fuel Combustion	1967	3,247	11,416	—	—	—	—		
	FY 76 W/O	3,867	14,447	—	—	—	—		
	FY 76 W	930	4,697	—	—	—	—	2,432	1,006
Industrial Processes	1967	4,601	5,156	7,520	1,412	53	20		
	FY 76 W/O	6,053	6,229	10,040	1,736	73	30		
	FY 76 W	453	1,720	539	849	9	10	3,877	1,095
TOTAL	1967	8,958	16,572	11,290	2,812	53	20		
	FY 76 W/O	11,420	20,676	15,490	3,756	73	30		
	FY 76 W	1,568	6,417	953	1,142	9	10	6,510	2,214

[1]Emission abbreviations are: particulates (Part), sulfur oxides (SO_x), carbon monoxide (CO), hydrocarbons (HC), fluorides (F), and lead (Pb). Blanks in the table indicate the emission levels meet the applicable regulation or that emissions are negligible or do not exist.

[2]Estimates without implementation of the Clean Air Act, for fiscal year 1976.

[3]Estimates with implementation of the Clean Air Act, for fiscal year 1976.

From "The Economics of Clean Air, Senate Document No. 92-67" annual report of the Administration of the EPA to Congress.

a total investment of $6.5 billion by 1976, according to one estimate. By that year the associated total annual control cost including depreciation, operating and maintenance costs will amount to an estimated $2.2 billion (Table 43-1).

LEGISLATION

Federal air pollution legislation was enacted because of the inconsistency of local air pollution control regulations and the increasing deterioration of the nation's air quality. The first Federal legislation concerning air pollution (Public Law 84-159) was enacted in 1955; it authorized a program of research and technical assistance to the states. This legislation was amended and strengthened in 1963, 1965 and again in 1966.

The Air Quality Act of 1967, more commonly called the "Clean Air Act" represented a major shift in the enforcement level of air pollution regulations. Introduced into this Act was the concept of "air quality control regions" within a single state or interstate area. The state or states having jurisdiction in a particular region were empowered to set standards of air quality, based on desired ambient air levels and guided by criteria published by the Department of Health, Education and Welfare. Initial and ongoing emission standards were also established so that compliance would insure the attainment and maintenance of desired air quality.

Within three years, the discrepancies arising in ambient standards among different air quality regions and the lack of national air quality standards led to the Clean Air Amendments of 1970. Under these amendments, states are required to adopt implementation plans (emission limitations) for the entire air region, with priority to be given to development of plans for areas where air pollution is most serious. National emission standards or limits have been established for certain new or newly-modified stationary sources for particulate, sulfur dioxide, sulfuric acid, nitrogen dioxide and plume opacity. In addition, national emission standards for hazardous chemicals such as beryllium, mercury and asbestos were set on existing sources.

CONTROL CONSIDERATIONS

The aggregate demands for improvement of air quality created by the existence of health hazards, economic damage, public pressure and legal requirements would seem to place industry in a position of "clean-up or shut-down." The degree of control necessary to fulfill these demands dictates the efficiency and sophistication of required abatement systems.

Once the required collection efficiency is determined for a single emission source, five basic factors of the source process must be characterized before proper design of an appropriate system can be undertaken:

1) The chemical and physical properties of the atmospheric effluent must be measured. These include size, density, shape, size-spectrum, chemical composition and corrosiveness.
2) The carrier exhaust gas must be characterized, including temperature, humidity, density and pressure.
3) Estimation of process factors such as volumetric flowrate, velocity and particulate gaseous concentrations must be made.
4) Construction factors including equipment size, layout, materials of construction and safety requirements must be determined.
5) Operational factors, such as maintenance, utility and disposal costs must be obtained.

Comparative cost data for collector designs is based on a variety of process variables. Emission abatement costs increase as the total volume of gas to be treated is increased. Careful analysis of the equipment included in the collector system, plus the installation and maintenance costs, must be made for an optimum design choice between alternative systems. Table 43-2 presents curves to obtain preliminary cost estimates. It is important to note that the installed cost may exceed the cost of the collection device as shipped by the manufacturer by a factor ranging between 100 and 400 percent.

Equipment modification and the substitution of process materials can often be the most effective means of solving air pollution problems. Substantial reduction of the loading in effluent air streams can be brought about by replacement of raw materials or fuel types used. For example, conversion from coal to natural gas as a combustion fuel dramatically reduces sulfur dioxide and particulate emissions.

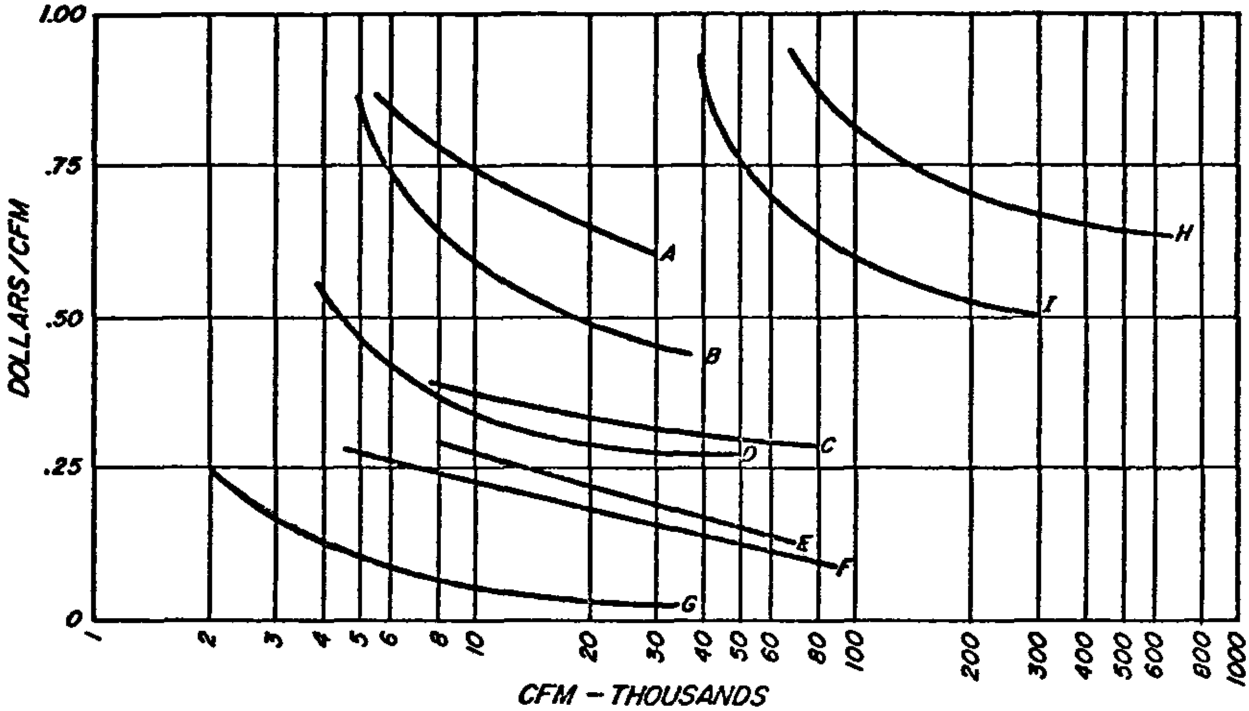
Modifications to the plant design which suppress contaminant formation at the source are, of course, the ideal solution. In addition, any design change which concentrates the contaminant loading to the collecting device into a smaller air volume, reduces the size and cost of the collector needed, since most collecting devices are designed on the volume rate of air to be handled and are relatively insensitive to changes in contaminant loading.

Good plant layout, construction and housekeeping can be an effective system for contaminant suppression. The prevention of leaks, periodic vacuuming and "hosing down" procedures and the elimination of open piles of chemicals are a few of the many possible methods for lowering emissions within the plant area.

The engineer, after carefully studying the costs related to such factors as: 1) the need for controls; 2) the degree of control required; and 3) potential process changes, has available to him a variety of types, designs and manufacturers of control devices. Proper selection of the optimum system requires a thorough understanding of the characteristics of process factors, along with a fundamental knowledge of the principles associated with each type of control equipment.

Table 43-3 includes a summary of the characteristics of particles and the effective range of certain collection devices. Table 43-4 includes the operating mechanisms and minimum size data for 90% collection efficiency. For a more detailed discussion, the equipment types are divided into

TABLE 43-2.
Cost Estimates of Dust Collecting Equipment



A—High temperature fabric collector (continuous duty)
B—Reverse jet fabric collector (continuous duty)
C—Wet collector (maximum cost range)
D—Intermittent duty fabric collector
E—High efficiency centrifugal collector
F—Wet collector (minimum cost range)
G—Low pressure drop cyclone (maximum cost range)
H—High voltage precipitators
I—High voltage precipitators (minimum cost range)

Note 1: Cost based on collector section only. Cost does not include ducting, water requirement, power requirement or exhausters (unless exhaust is integral part of secondary air circuit.)

"Industrial Ventilation — A manual of Recommended Practice" 12th Edition, Committee on Industrial Ventilation, American Conference of Governmental Industrial Hygienists, Lansing, Michigan.

six broad, general categories: 1) mechanical separators; 2) filtration devices; 3) wet collectors; 4) electrostatic precipitators; 5) gas adsorbers; and 6) combustion incinerators.

Mechanical Separators

These devices impart either inertial or gravitational forces on the particle to remove it from the carrier stream. The range of particle sizes consistent with effective collection efficiencies is 15 to 40 microns in diameter; a sharp dropoff of collection efficiency occurs with particles smaller than 15 microns in diameter. Industrial use is limited to applications where the particulate is very coarse or the separator is used in series with other devices.

The many varieties of mechanical separators can be divided into three broad categories: gravity chambers, cyclone collectors and impingement separators.

Gravity Chambers. These chambers are the oldest and least efficient method of dust collection. They consist of a low-velocity enclosure where the larger contaminant particles are removed by the force of gravity. Particles smaller than 40μ in diameter usually pass through, uncollected.

Collection efficiency is related to the terminal settling velocity, U_t, and is expressed in the following equation:

$$\eta = \frac{100\, U_t\, A_h}{Q}$$

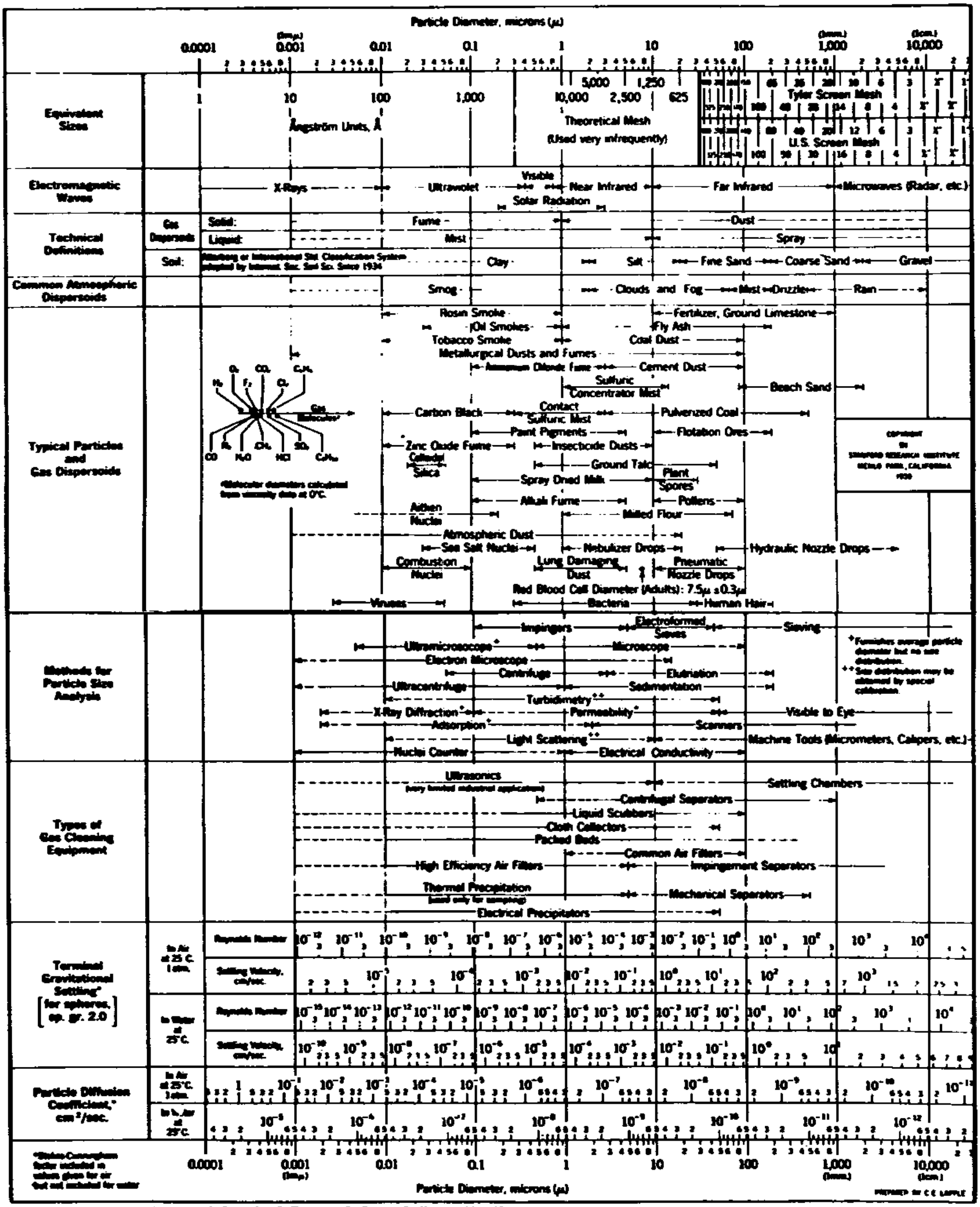
where: η = % collection efficiency by weight
U_t = particle terminal settling velocity, ft./min.
A_h = horizontal area of chamber, ft^2
Q = volumetric flowrate of gas, ft^3/min.

An increase in the effective horizontal area, A_h, through the use of horizontal baffles, or a decrease in volumetric flowrate and velocity profile, favorably affects collection efficiency.

Advantages of gravity settlers include: low initial cost (between 5¢ and 25¢ per cfm), simple construction and a slight pressure drop. These advantages are offset by an inability to remove particles smaller than 40 microns in diameter and large space requirements.

Gravity chambers are most useful as a precleaning stage before treatment by a higher collection efficiency device. The removal of large-

TABLE 43-3.
Properties of Aerosols



Reprinted by permission of *Stanford Research Inst. J.* 5, 95 (1961).

Characteristics of particles and particle dispersions. Courtesy Stanford Research Institute.

Source: "Air Pollution Manual". Part II, p. 13, American Industrial Hygiene Association, Akron, Ohio.

TABLE 43-4.
General Classification of Particulate Collectors

Control Device	Class	Force	Particle Diameter for 90% Removal in Microns
Settling Chamber	Mechanical	Gravity	50
Impingement Separator	Mechanical	Inertial Impingement	25
Cyclone (Small Diameter)	Mechanical	Centrifugal	>5
Cyclone (Large Diameter)	Mechanical	Centrifugal	25
Baghouse	Filtration	Inertial Impingement + Electrostatic + Diffusional	>1
Panel Filters	Filtration	Inertial Impingement + Electrostatic + Diffusional	>1
Mat Filters	Filtration	Inertial Impingement + Electrostatic + Diffusional	10
Deep Filter Beds	Filtration	Inertial Impingement + Electrostatic + Diffusional	1
Spray Chamber	Scrubber	Inertial Impingement	25
Packed Tower	Scrubber	Inertial Impingement	5
Cyclone Scrubbers	Scrubber	Inertial Impingement + Centrifugal	5
Venturi	Scrubber	Inertial Impingement + Centrifugal	>1
Wet Inertial (Mechanical)	Scrubber	Inertial Impingement + Centrifugal	5
Orifice	Scrubber	Inertial Impingement + Centrifugal	5
Single-Stage High Voltage	Electrostatic Precipitators	Electrostatic Attraction	>1
Two-Stage Low Voltage	Electrostatic Precipitators	Electrostatic Attraction	>1

Source: "Air Pollution Manual". Part II, p. 13, American Industrial Hygiene Association, Akron, Ohio.

size particulates which may prove erosive to a second-stage cleaner optimizes the system by increasing the efficiency and life of the second collector.

Impingement Separators. Impingement separators encompass a large, heterogeneous group of collection devices, all of which are based on the inertial force of a particle to accomplish its removal from the carrier gas stream.

The separator utilizes a network of baffles to collect or concentrate the particulates, as depicted in Figure 43-1. As the particles moving in the gas stream approach a stationary target, the air will deflect around the impingement target, carrying with it the lighter particles. The inertial force of the heavier particles causes them to cross the fluid streamlines, strike the target, and be removed, as shown in Figure 43-2.

The target efficiency of impingement is the percentage of particles which collide with the stationary object. This value can be obtained graphically from the separation number, N_s, which is a dimensionless value obtained from classical hydrodynamics and reported graphically in Figure 43-3.

$$N_s = \frac{D_p^2 \, V \, \rho_p}{18 \mu \, D_b}$$

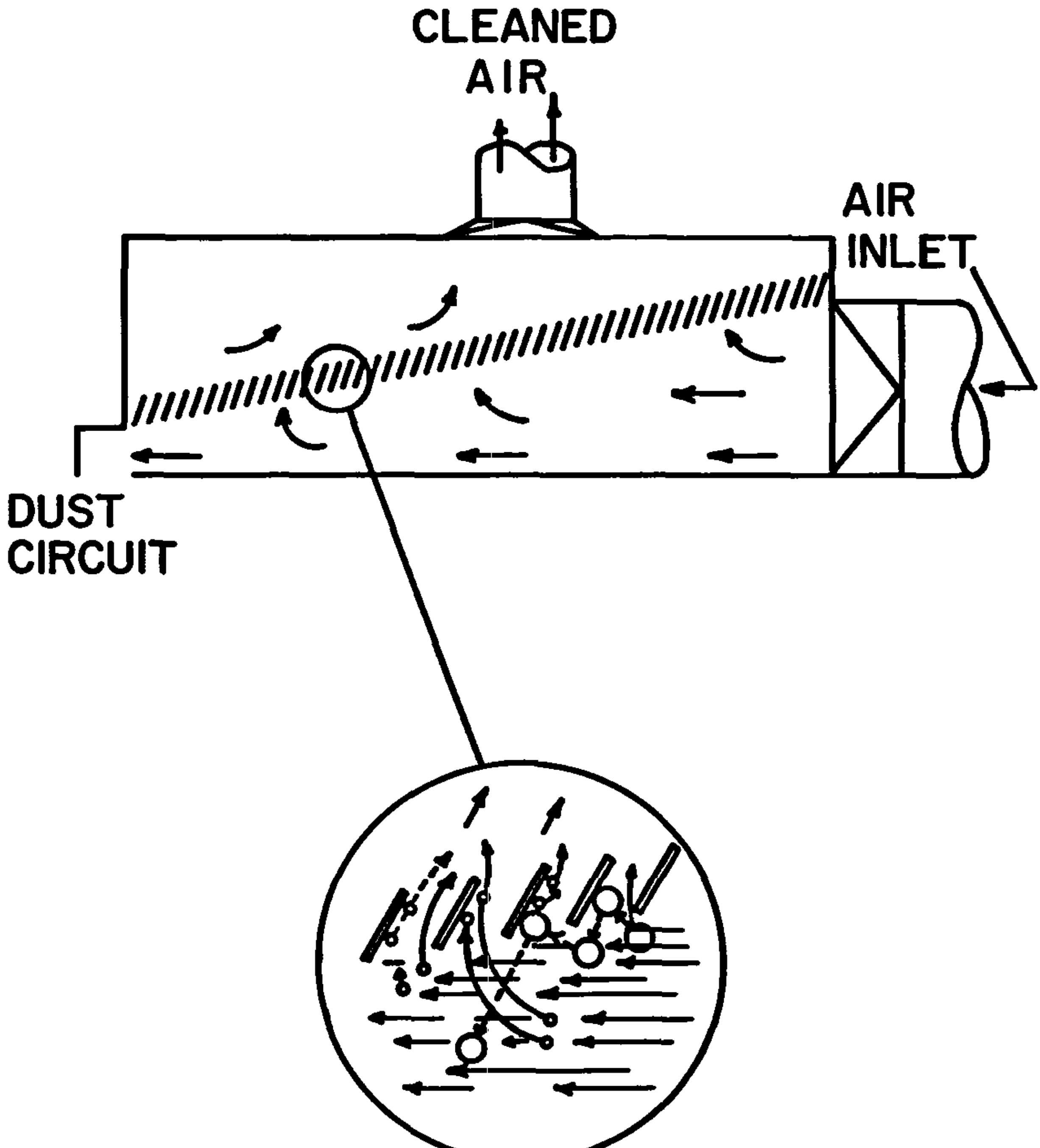
where: N_s = Separation number, dimensionless
D_p = particle diameter, feet
V = relative velocity gas to target, ft./sec.
ρ_p = particle density, lb./ft.^{3}
μ = gas viscosity, lb./ft.-sec.
D_b = target diameter, ft.

The collection efficiency increases with increasing particle size, gas velocity and particle density; but overall efficiency is quite low, in the range of 50-80%, with particles smaller than 20 microns uncollected. Optimum designs, therefore, utilize small openings between baffles and high gas velocities.

Advantages of impingement separators include: low cost (from 15¢ to 30¢ per cfm), simple construction and trouble-free operation. Disadvantages include low overall efficiency, erosion of baffles and corrosion.

Impingement collectors find use throughout industry as: precleaners for more elaborate devices, collection devices where large particles are involved and devices that concentrate the particulates, in a smaller percentage of the gas stream.

Cyclone Collectors. The most prevalent type of mechanical collector in use today is the cyclone. It operates on the principle of creating a vortex from the inlet gas stream velocity.



American Industrial Hygiene Association: Air Pollution Manual. Akron, Ohio, 1968, part II, p. 34.

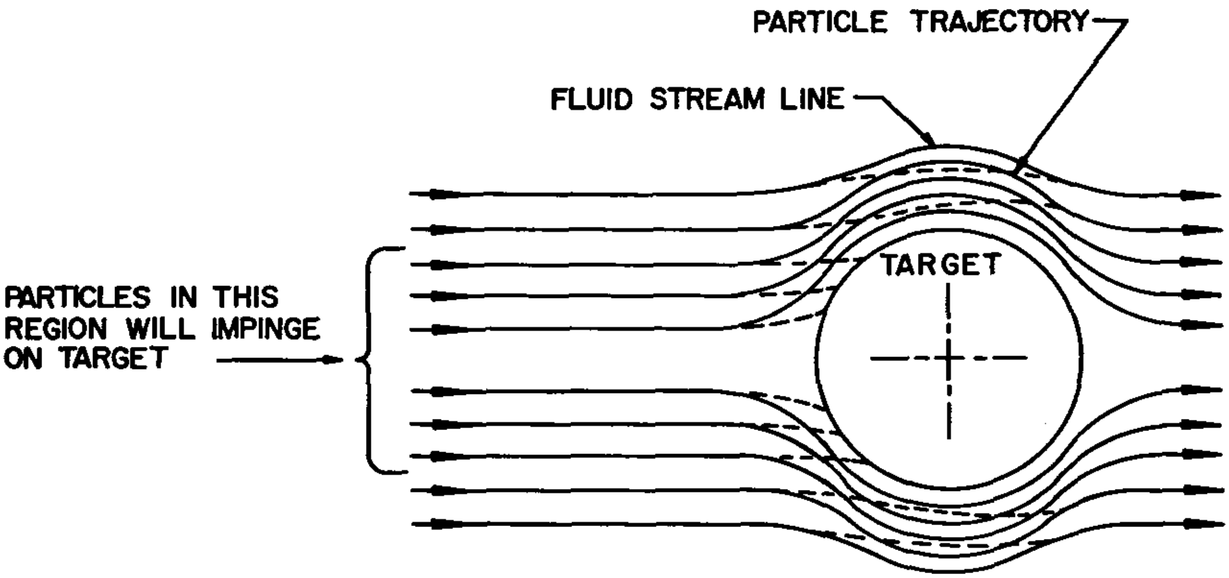
Figure 43-1. Flat Lower Impingement Separator.

The entrained particles are drawn outward by centrifugal force, where they impinge on the wall surface and are removed by gravity to a collection point. The air flows in a double vortex, spiraling downward at the outside periphery and returning upward through the inside regions as shown in Figure 43-4.

During cyclonic separation, the gas stream velocity may increase several times over the inlet conditions. The separation mechanism is similar to gravitational settling except that the force acts centrifugally instead of gravitationally, resulting in an increased force on the particle. In small-diameter cyclones, this value may reach upwards of 2500 times the force of gravity.

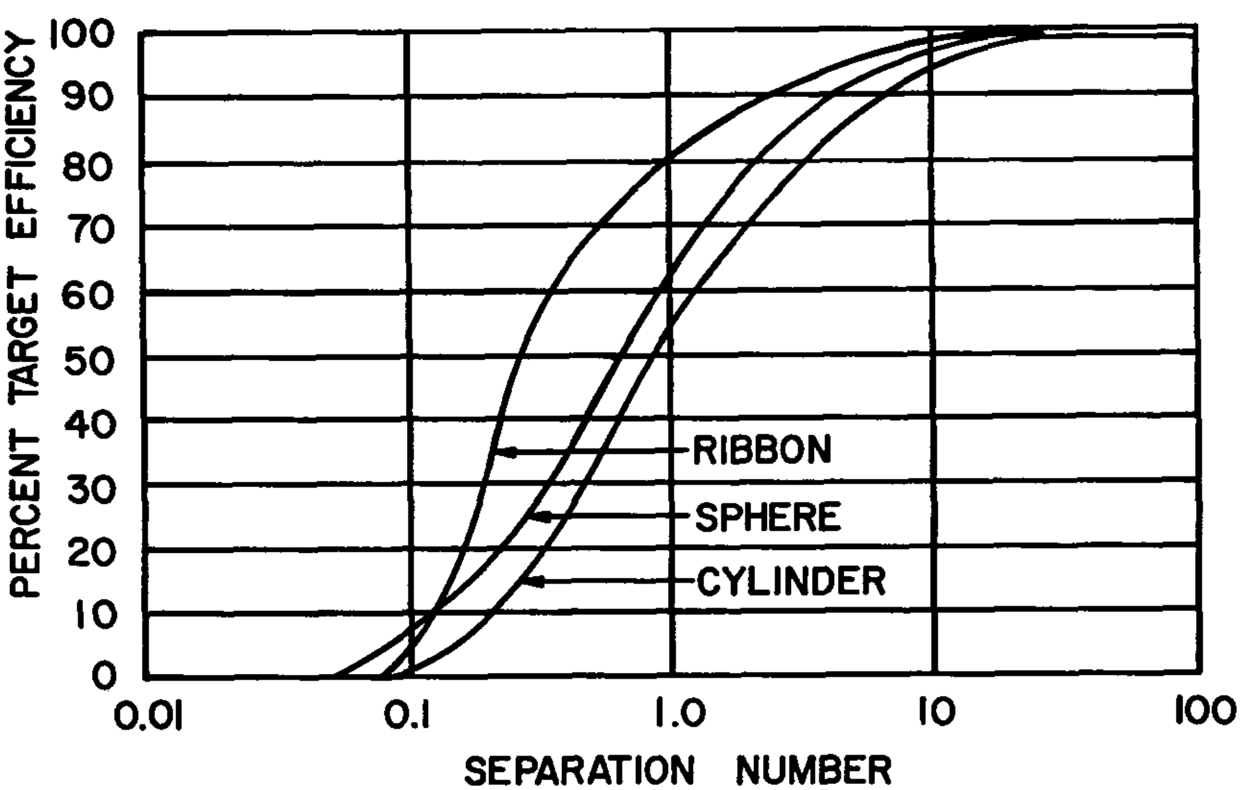
One typical equation for calculation of the size of particles collected is listed below:

$$D_{pc} = \sqrt{\frac{9 \mu b}{2\pi N_e V_i (\rho_p - \rho_g)}}$$



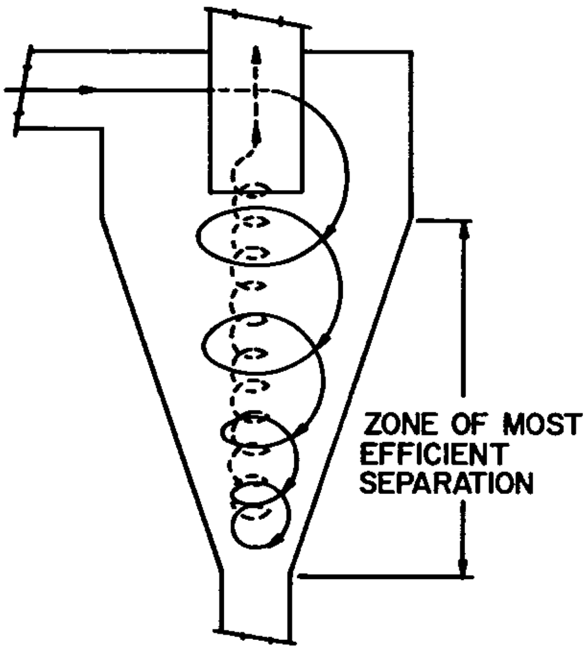
Stern: Air Pollution, 2nd Edition. Academic Press, p. 401.

Figure 43.2. Physics of Impingement.



Stern: Air Pollution, 2nd Edition. Academic Press, p. 401.

Figure 43-3. Target Efficiency of Impingement.



Air Pollution Engineering Manual, Department of Health, Education and Welfare, 1967, p. 93.

Figure 43-4. A Simplified Cyclone Collector.

where: D_{pc} = diameter of particle collected at 50% efficiency

μ = gas viscosity, lbs./sec.-ft.

b = cyclone inlet, ft.

N_e = number of turns within the cyclone (approximately 5)

V_i = inlet gas velocity, ft./sec.

ρ_p = particle density, lb./ft.^{3}

ρ_g = gas density, lb./ft.^{3}.

Caution is recommended in applying this equation to a design problem since the cyclone may be a poor classifier by particle size due to the variation of factors such as radius of rotation, distance from the wall and tangential velocity.

In design consideration, the factor of primary importance is the cyclone's radius. Collection efficiency increases as the radius is reduced. This is due to the increased centrifugal force created on the particle. Pressure drop increases with efficiency.

Small diameter or high efficiency cyclones have seen increased application in the last few years. Often, an arrangement of cyclones in parallel is used to handle high-volumetric flowrates rather than one large-diameter cyclone.

Cyclones have widespread use due to several inherent advantages: low initial cost (from 10¢ to 50¢/cfm) for simple construction, moderate pressure drop and low maintenance requirements. Disadvantages include: low collection efficiencies for particles below 5 microns and erosion from impingement of particulate matter.

Filtration Devices

Filtration is an effective technique for controlling emissions in the form of dust or fume from a carrier stream. Collection efficiencies of over 99.9% have been recorded in some applications. Three classes of filters exist: mat filters, ultrafilters and fabric filters. Of the three, the latter is the most important for industrial applications of air pollution control.

Mat filters are extremely porous, containing 97-99% void space. They have limited life and are usually used as process air cleaners. Ultrafiltration involves deep filter beds used for high efficiency removal requirements such as radio-active wastes. Baghouses or panel filters utilize fabrics to effect separation and are common throughout industry for a multitude of applications.

Fabric filters are employed in two basic designs, panel filters and baghouses. Panel filters are composed of individual filters, one or two inches thick. These panels filter out the particulate, as the gas flows through the medium. Baghouses are composed of long sleeves of fabric, up to 45 feet in length. These bags filter the air as it passes through the cloth. Periodic cleaning is important to both types to prevent excessive pressure drops from developing. Some mechanisms used for reducing the filter buildup of particulates are mechanical shaking, reverse air jet and low-frequency sound generation. A typical baghouse is shown in Figure 43-5.

The fabric weave often has interstices on the order of 100 microns, yet collection efficiencies of over 90% are reached on particles of one micron in diameter. Obviously, the filtering mechanism cannot be simple sieving. The theory of fabric filtration is not well developed. Empirically, the cloth openings quickly fill, as large-diameter particles "bridge over" the openings. Forces of electrostatic attraction appear to exert the greatest influence, but other forces, such as Brownian diffusion, impingement and gravitational settling may contribute to the overall process.

The cake of particles that develops becomes the filtering medium. As this cake grows thicker, increasingly smaller particles are collected and the pressure drop increases. Periodic cleaning must be performed to limit the pressure drop to design levels.

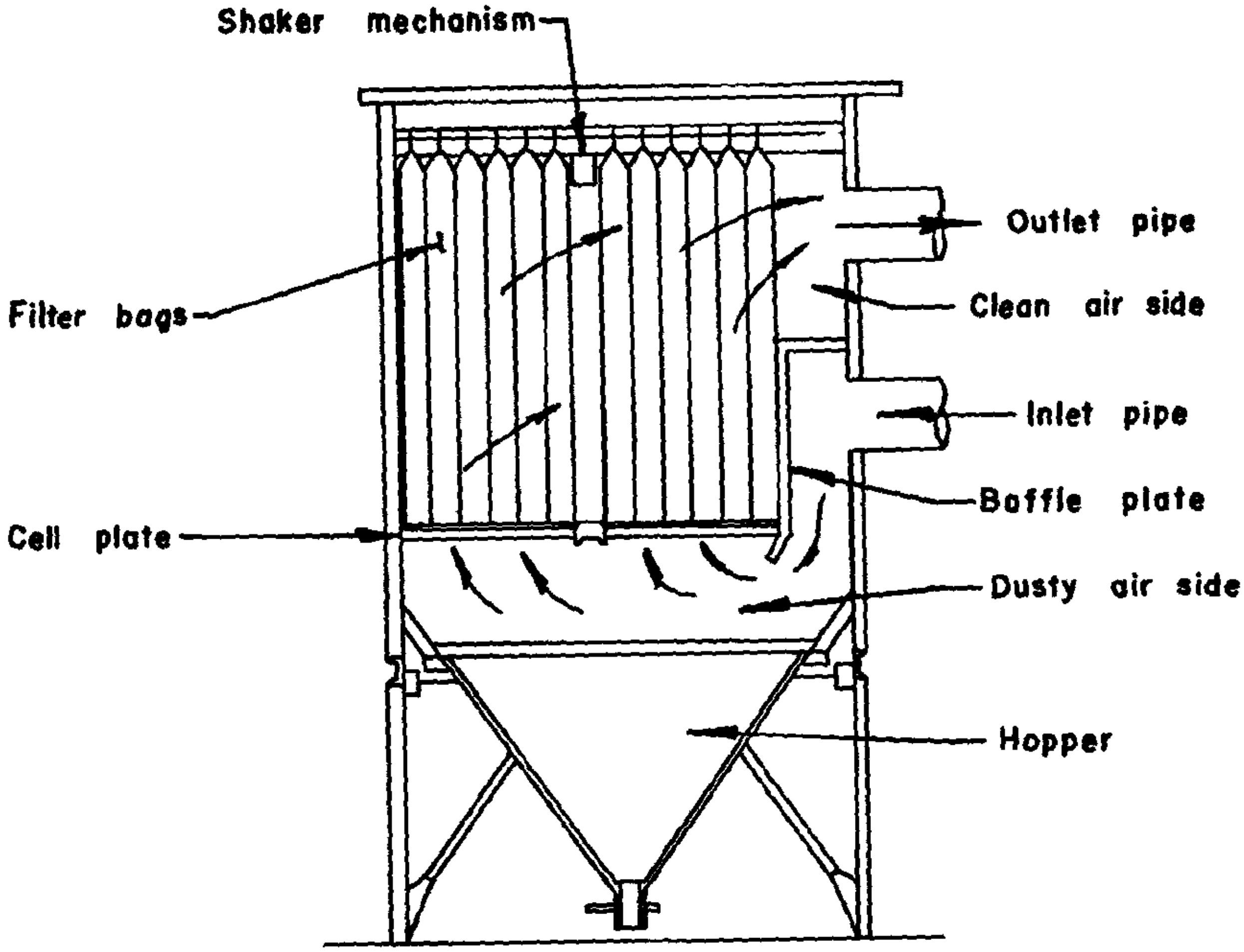
The pressure drop through a fabric filter and the cost of the device are the two most important factors in the design of a collection system for fabric filters. Generally, an increase in cloth area will enhance efficiency, lower the pressure drop and lengthen the fabric life through a reduced cleaning interval, but it also increases the cost of the device.

Three variables of design are used to determine the ultimate pressure drop in the system:

1. Filter ratio, which is the ratio of carrier gas volumetric flowrate to filter area;
2. Type of cloth and weave selected;
3. Time period of cleaning and method utilized.

The pressure drop is the sum of the resistances of the cloth and the filter cake and can be calculated from the following formula:

$$\Delta P_t = \Delta P_f - \Delta P_i = K_2 L_t V^2$$



American Industrial Hygiene Association: Air Pollution Manual. Akron, Ohio, 1968, part II, p. 48.

Figure 43-5. Single Compartment Baghouse Filter.

where: ΔP_t = Pressure drop at time t due to dust cake, $lb._f/ft.^2$

ΔP_f = total filter resistance at time t, $lb._f/ft.^2$

ΔP_i = initial filter resistance of cleaned filter, $lb._f/ft.^2$

K_2 = proportionality constant, $\frac{lb._f\ sec.^2}{lb._m\ ft.}$

L_t = dust concentration in carrier gas, $lb._m/ft.^3$

t = time since cleaning

V = superficial filtering velocity, ft./sec.

The filter ratio affects the pressure drop by determining the loading rate on the filter. A ratio of three cubic feet per minute per square foot of cloth area is an average value for common dusts. Excessive loading leads to rapid filter buildup. This, in turn, requires a shorter cleaning interval and lowers the life of the cloth. The resistance of the cleaned cloth is determined by material and weave pattern.

The selection of cloth type depends on the temperature of the gas stream and the abrasive characteristics of the particulate. Table 43-5 illustrates some of the more common fabric materials.

Advantages of fabric filters include:

1) Upwards of 99% collection efficiency for virtually all particle sizes;
2) Moderate power requirements; and
3) Dry disposal of collection efficiency.

Disadvantages include:

1) High cost (between 30¢ and $2.50/cfm);
2) Large space requirements;
3) High maintenance and replacement costs;
4) Control of moisture in the dusts; and
5) Cooling for high temperature gas streams.

Wet Collectors

Wet collectors or scrubbers effect separation of both particulate and gaseous phase contaminants. Particle removal is accomplished by mechanisms similar to those operating in mechanical separators. In a wet collector the particles first impinge upon discrete droplets or sheets of liquid, and then subsequent separation of the liquid removes the particulates from the gas stream. Removal of gaseous components takes place by the

TABLE 43-5
Properties of Fiber Materials Used as Filters

Fiber	Physical characteristics: Relative strength	Specific gravity	Normal moisture content (%)	Maximum usable temperature (°F)	Relative resistance to attack by: Acid	Base	Organic solvent	Other attribute
Cotton	Strong	1.6	7	180	Poor	Medium	Good	Low cost
Wool	Medium	1.3	15	210	Medium	Poor	Good	—
Paper	Weak	1.5	10	180	Poor	Medium	Good	Low cost
Polyamide (nylon)	Strong	1.1	5	220	Medium	Good	Good[a]	Easy to clean
Polyester (Dacron)	Strong	1.4	0.4	280	Good	Medium	Good[b]	—
Acrylonitrile (Orlon)	Medium	1.2	1	250	Good	Medium	Good[c]	—
Vinylidene chloride	Medium	1.7	10	210	Good	Medium	Good	—
Polyethylene	Strong	1.0	0	250	Medium	Medium	Medium	—
Tetrafluoroethylene	Medium	2.3	0	500	Good	Good	Good	Expensive
Polyvinyl acetate	Strong	1.3	5	250	Medium	Good	Poor	—
Glass	Strong	2.5	0	550	Medium	Medium	Good	Poor resistance to abrasion
Graphitized fiber	Weak	2.0	10	500	Medium	Good	Good	Expensive
Asbestos	Weak	3.0	1	500	Medium[d]	Medium	Good	—
"Nomex" nylon	Strong	1.4	5	450	Good	Medium	Good	Poor resistance to moisture

"Air Pollution" 2nd Edition, Stern, A. C. ed., Academic Press, New York, N. Y., 1968.
[a]Except phenol and formic acid.
[b]Except phenol.
[c]Except heated acetone.
[d]Except SO_2

principle of absorption. This process proceeds through diffusional movement of the gas component towards the liquid upon which it absorbs by a concentration gradient across the interface region.

Wet collectors find industrial applications where one or more of the following conditions exist:

1) Polluting gaseous components need to be controlled;
2) Combustible situations would occur if dry collection were used;
3) A humid gas effluent is encountered; and
4) Cooling of the effluent is desired.

Gas Absorption. Gas absorption occurs either through a chemical reaction with the contacting liquid or by simple physical equilibrium of solubility. In a system where a reaction occurs, equilibrium between the gas and liquid phases for a component is impossible, since in the liquid phase a reaction removes the component from solution. This allows for separation of the component in excess of equilibrium values.

In a system involving simple gas solubility in water, Henry's Law can be used to calculate the equilibrium mole fractions in the liquid and vapor phases.

$$P_A = H\ X_A$$

where: P_A = partial pressure of gas A
H = Henry's Law constant
X_A = mole fraction of gas A dissolved in the liquid.

Mass transfer of the gas to the liquid controls the rate at which this equilibrium is approached. A concentration profile exists across both the liquid and gas interface (Figure 43-6). This driving force causes the molecules of the absorbent gas to diffuse from an area of higher gas concentration to an area of lower concentration, the interface.

Since the gas phase diffusion is usually the rate-determining step, the flux at the interface can be determined by the following equation:

$$N_A = K_G\ A\ P\ \Delta Y$$

where: N_A = moles transferred per hour, m/hr.
K_G = mass transfer coefficient, hr./lb.$_f$^{2}
P = total pressure, lb.$_f$/ft.^{2}
A = interface area, ft.^{2}
ΔY = driving force, lb.$_f$.

Gas Absorption Equipment. Absorption equipment operates on the principles of gaseous or liquid dispersion. Packed towers, venturi scrubbers and spray towers operate by liquid dispersion. Tray towers and sparging equipment operate by

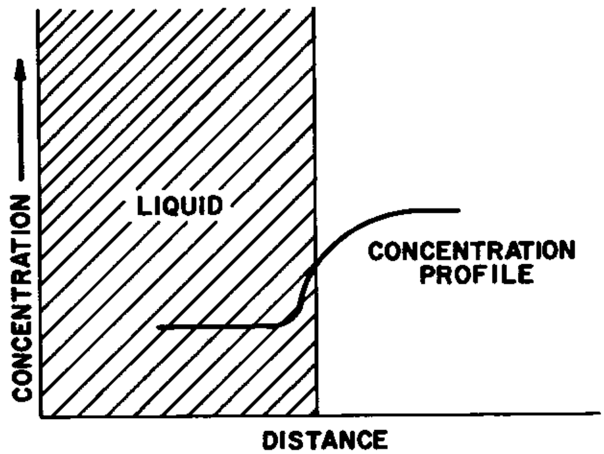


Figure 43-6. Concentration vs. Position in Liquid and Gas.

gas dispersion.

Particle Collection. Particle collection proceeds by a two-step process. First, the particle is contacted by a liquid droplet and is "wetted"; then the wetted particles are removed from the carrier gas. In some collectors, the liquid serves only to clean the impingement surfaces. Mechanisms for wetting the particle include:

1) Impingement upon liquid droplets;
2) Brownian diffusion;
3) Condensation of water around a particle as the gas dips below its dewpoint; and
4) Electrostatic attraction between the droplet and the particle.

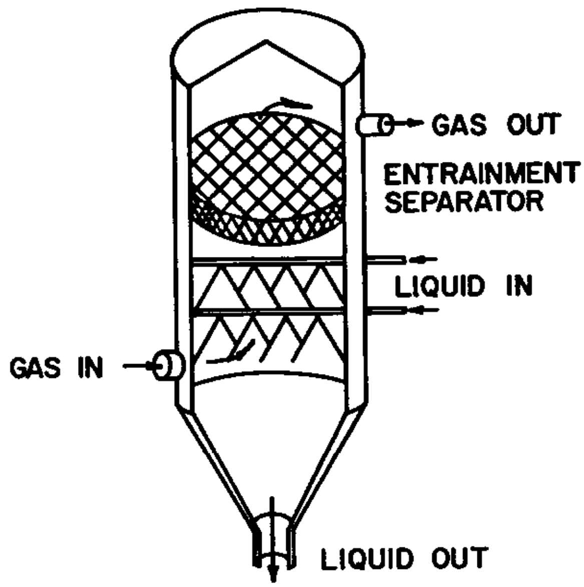
The wetted particles are removed through impingement and/or centrifugal force, depending on the type of device. The wetting of the particle increases its mass, allowing it to be readily removed by inertial force. Overall design and collection efficiency equations are not well developed and depend on the type of equipment. Decreasing water droplet size and increasing relative gas velocities will improve collection efficiency.

Particle Collection Equipment. All types of wet scrubbers including those that are used for gas absorption remove particulates to some degree. Generally, those devices that utilize high energy contact between the gas stream and small spray droplets achieve the greatest particle collection efficiency. A list of wet collecting devices is included below:

1. spray chambers
2. cyclone-type scrubbers
3. orifice-type scrubbers
4. mechanical scrubbers
5. mechanical-centrifugal collectors
6. venturi scrubbers
7. packed towers
8. wet filters.

Simplified drawings of several of the devices are depicted in Figures 43-7 through 43-10.

Discussion of Wet Collectors. Water pollution problems are always associated with wet scrubbers



Stern: Air Pollution, 2nd Edition. Academic Press, p. 474.

Figure 43-7. Spray Tower.

and should be considered when evaluating possible systems. It is often necessary to settle out the particulate sludge with flocculants and to adjust the pH before the water can be returned on-stream. Other problems include: freezing of process water, corrosion and increased opacity of the plume due to condensing liquid. Advantages of a wet collector include:

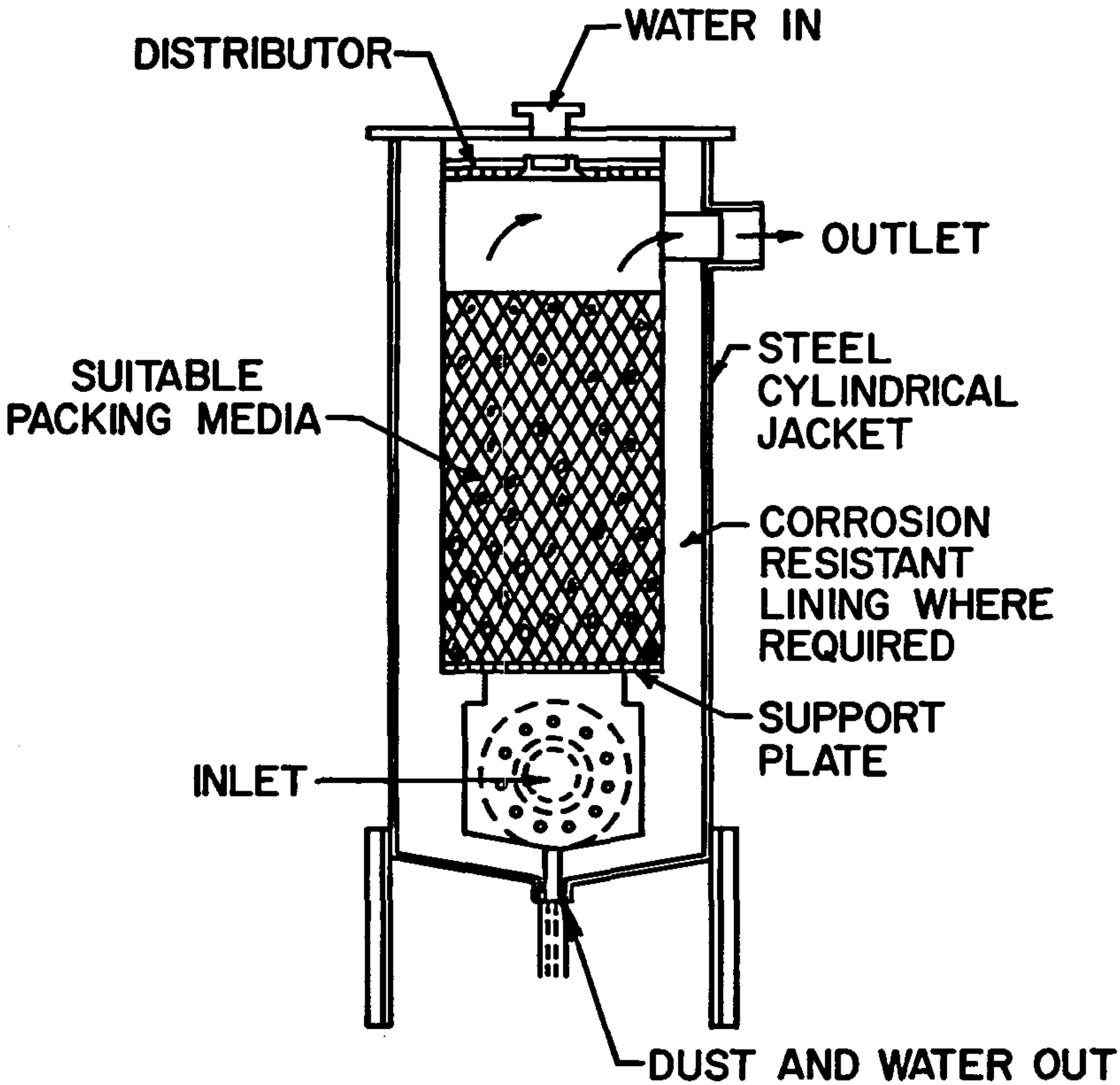
1. constant pressure drop
2. dust removal problems eliminated
3. treatment of high temperature and humid gases
4. compact design
5. moderate costs (between 25¢ and 75¢/cfm).

Electrostatic Precipitators

Electrostatic precipitation is a collection process that utilizes a field of charged gas ions to charge the particle followed by attraction to a collection electrode. This device is sometimes called the Cottrell Process, after Frederick Gardner Cottrell, who invented and designed the first electrostatic precipitator.

Three processes are involved in the operation of all electrostatic precipitators: particle charging, particle collection and removal of collected material. If particle charging and collection are separated, a two-stage precipitator results; otherwise, the unit is a single-stage precipitator. Most industrial use is of the latter design, as shown in Figure 43-11.

Particle charging occurs through the formation of a highly-charged region of unipolar gas ions called the corona field. The corona field forms from the electrical voltage potential between the electrodes. If this voltage potential becomes too large, sparking will occur and the corona field will



American Conference of Governmental Industrial Hygienists — Committee on Industrial Ventilation: Industrial Ventilation — A Manual of Recommended Practice, 12th Edition. Lansing, Michigan, 1972, p. 474.

Figure 43-8. Packed Scrubber.

be disturbed. The particles flowing through the corona field charge themselves by collision with charged gas ions and move towards the oppositely charged electrode where collection occurs. Removal from the electrode is effected by a mechanical shaker.

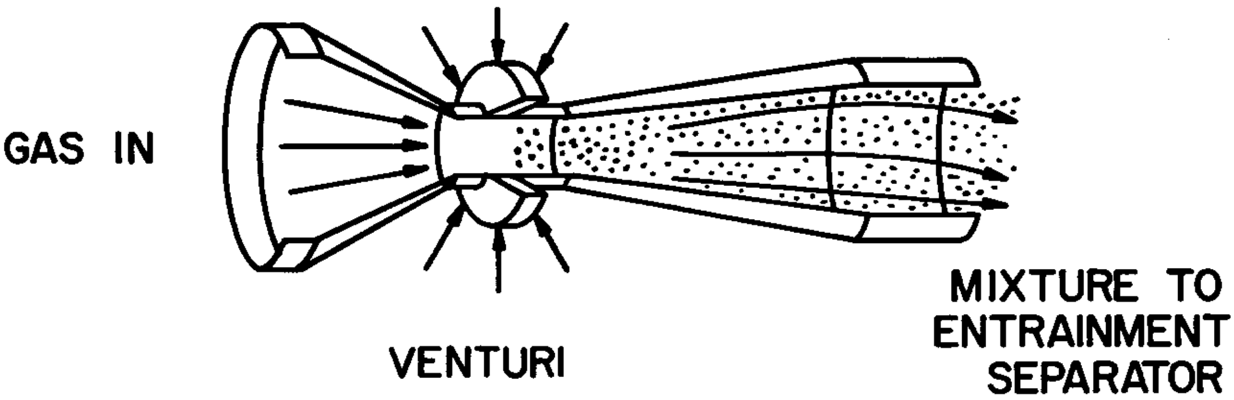
There is no theoretical limit to the size of the particles that can be collected. Collection efficiencies are related to the size of the equipment, with efficiencies of over 99% obtainable. The following equation can be used to calculate the efficiency of collection:

$$Ef = 100 - 100 \left[\exp \frac{-A\, E_o\, E_p\, a}{V\, 2\pi\eta} \right]$$

where: Ef = percent efficiency
A = surface area of collecting electrodes, ft^2
V = volumetric flowrate, $ft.^3/min.$
E_o = charging field, volts/ft.
E_p = collecting field, volts/ft.
a = particle radius, ft.
η = gas viscosity, lb./hr. ft.

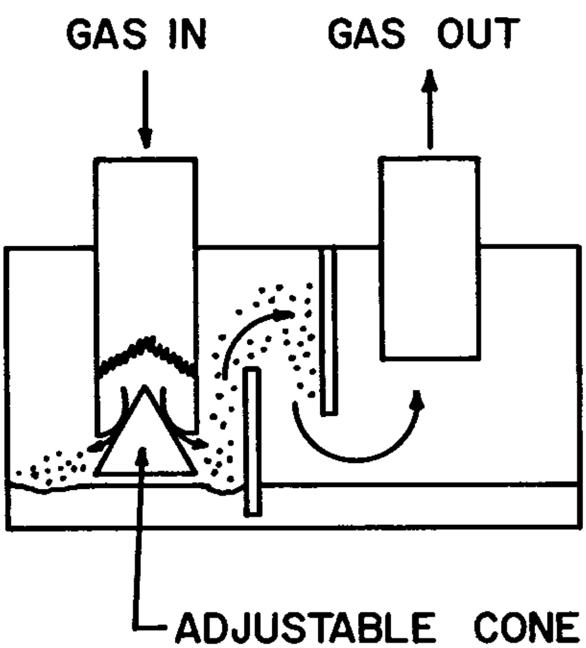
From the equation, it can be seen that an increase in voltage and surface area coupled with a decrease in volumetric flowrate gives optimum operating conditions.

Initial cost for an electrostatic collector runs



Stern: Air Pollution, 2nd Edition. Academic Press, p. 474 (9, 10) and p. 440 (11).

Figure 43-9. Venturi Scrubber.



Stern: Air Pollution, 2nd Edition. Academic Press, p. 474 (9, 10) and p. 440 (11).

Figure 43-10. Doyle Impingement Scrubber.

from 80¢ to $2.50/cfm, with erected cost approximately 1.7 times the initial cost. Power costs are quite low, since energy is required only to separate the particle without having to do work on the carrier gas.

Electrostatic precipitators have many advantages, including:

1. high efficiency
2. dry collection of dusts
3. low pressure drop
4. ability to collect mists and corrosive acids
5. low maintenance costs
6. low operating costs
7. collection efficiency can be adjusted by unit size
8. ability to handle gases up to 1500°F.

Disadvantages include:

1. high initial cost (between 80¢ and $2.50/cfm)
2. frequent need for a precleaner
3. large space requirements
4. difficulty in collecting materials with extremely high or low electrical resistivity.

Gas Adsorbers

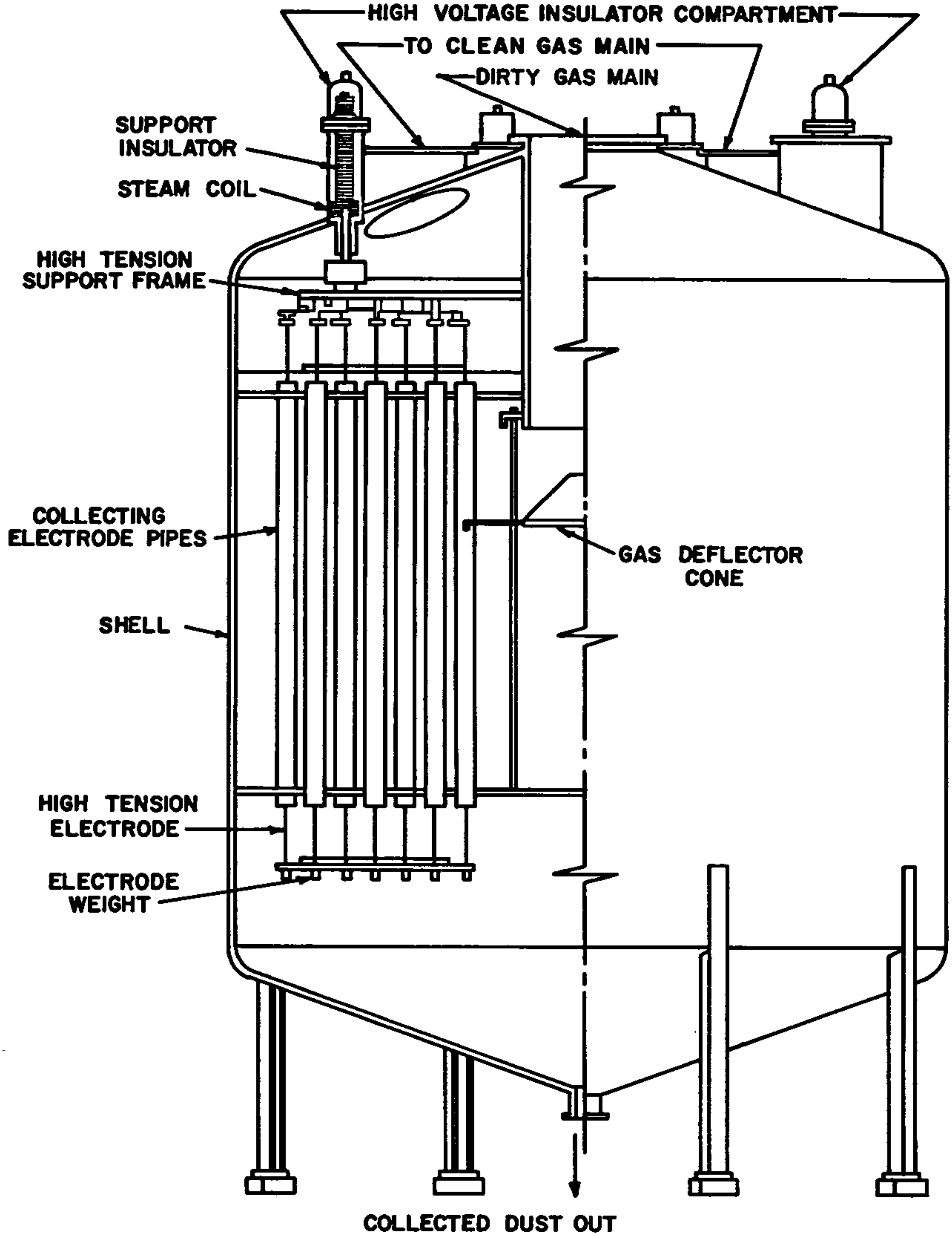
Adsorption is a useful process for controlling highly odorous, radioactive or toxic gases. This process involves retention of molecules from the gas phase onto a solid surface. Van Der Waals' forces, ionic attraction, secondary chemical bonds and capillary condensation — all have a role in the adsorption of the gas onto the solid surface.

Two general types of adsorbers exist: fixed bed and regenerative. In addition, recirculation may be utilized to increase the effectiveness of the device. Fixed bed adsorbers are economical only when the average contaminant concentration is less than a few parts per million. Regenerative adsorbers are designed to handle much heavier loadings with the additional advantage of recovery of the contaminant solvent which may have a high economic value. A typical fixed bed adsorber is shown in Figure 43-12.

The mechanism of adsorption progresses in three distinct steps:

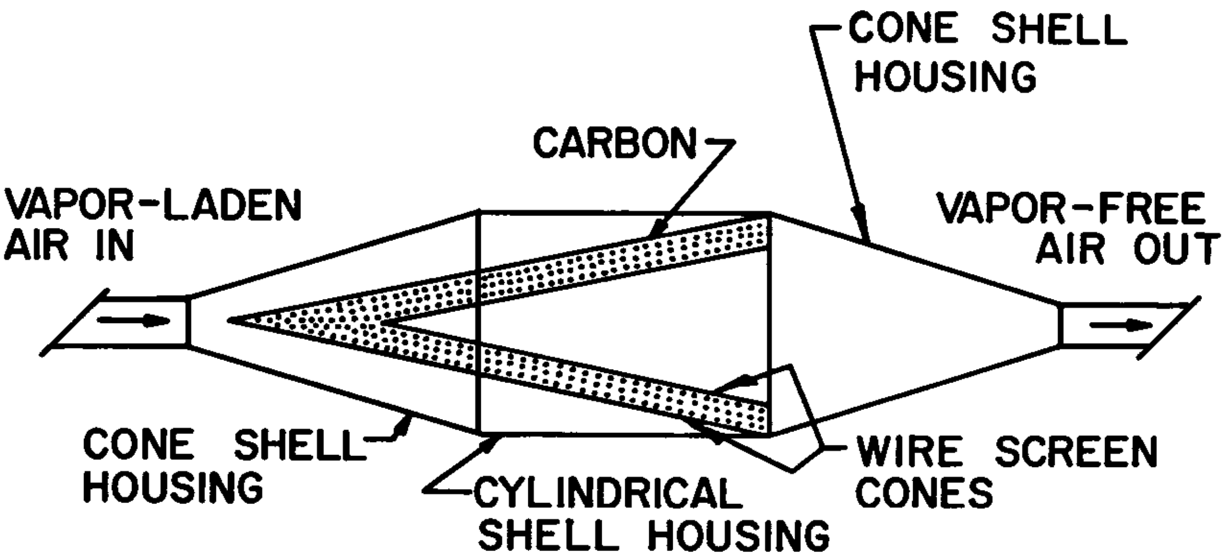
1) The adsorbent moves to the solid surface;
2) Physical bonding occurs; and
3) Adsorbent is removed through treatment with steam, hot brines or other methods.

In design of adsorbent systems, increased removal efficiency is often obtained if conditions of high pressure and low temperature are maintained. The high efficiency of adsorbers is offset by the many associated problems. Equipment costs may run as high as $35.00 per pound of vapor removed with operating costs running about five dollars per pound of vapor removed. Other prob-



Stern: Air Pollution, 2nd Edition. Academic Press, p. 474 (9, 10) and p. 440 (11).

Figure 43-11. Tube-Type Electrostatic Precipitator.



Air Pollution Engineering Manual, Department of Health, Education and Welfare, 1967, p. 197 and p. 172.

Figure 43-12. Fixed Bed Adsorber.

lems include corrosion and particulate contamination of the device.

Combustion Incinerators

Combustion incineration is a process that utilizes oxidation reactions for emission control. Combustion afterburners find numerous industrial applications and can be used for any of the following situations:

1. odor control
2. reduction in opacity of the plume
3. conversion of carbon monoxide to carbon dioxide
4. reduction of organic vapors and particulate emissions.

Combustion devices come in two types, direct flame and catalytic combustion. Direct flame incineration involves the burning of additional fuel to reach temperatures high enough for destruction of the gas or aerosol mixtures. Complete combustion yields H_2O and CO_2, whereas incomplete combustion may produce even more offensive compounds than originally found. A typical direct flame incinerator is shown in Figure 43-13.

Catalytic combustion utilizes a catalyst, normally a noble metal, to lower the activation energy of the oxidizing reactions to reduce the temperature and fuel costs required for oxidation. Combustion may even become self-sustaining if the concentration of combustibles in the gas stream is sufficiently high.

In designing or operating a flame combustion device, care should be taken to see that the temperature, residence time and turbulent mixing are sufficient for complete oxidation. One satisfactory method of achieving this goal is to admit the contaminant gases into a throat where the burner is located. High velocities can be obtained for thorough mixing of the gases in the region of highest temperature. A retention time of 0.3 to 0.5 second and operating temperature ranges between 850°F-1500°F have been found to be satisfactory for most applications. Efficiencies of 98% or higher can often be obtained in a well-designed incinerator.

The decision of whether to use flame or catalytic combustion is based on economic considerations and operational characteristics. Costs for flame and catalytic combustion vary widely, depending on the amount, types and concentration of pollutants to be burned. Some of the operational differences are listed below:

1) Generation of nitrogen oxides is reduced using catalytic combustion;
2) Catalysts require periodic cleaning and regeneration;
3) Integration of catalysts into the design of equipment permitting heat recovery is much easier.

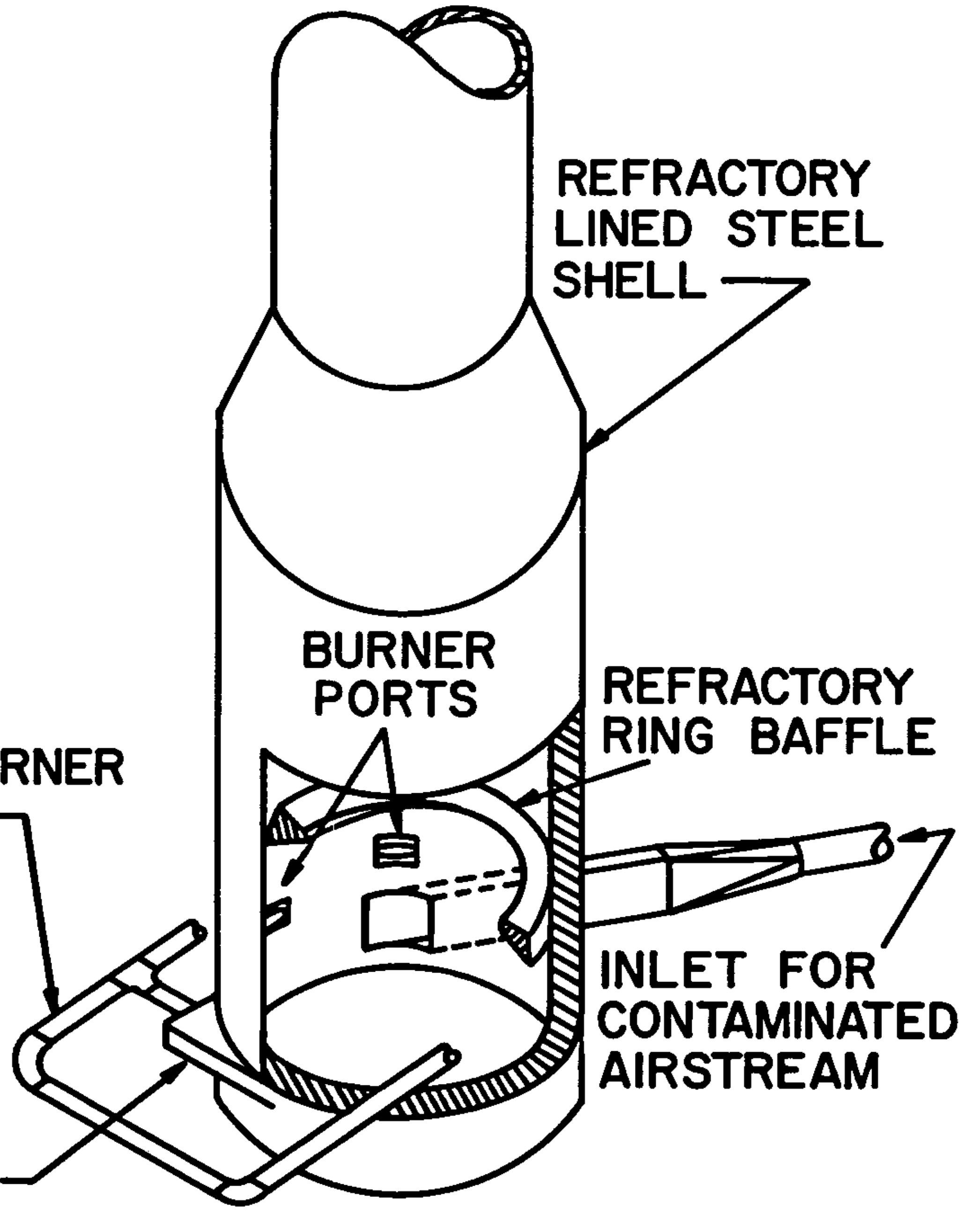
SUMMARY

This chapter has stressed the standard pollution control equipment in existence today: mechanical separators, filtration devices, wet collectors, electrostatic precipitators, gas adsorbers and combustion incinerators. These devices are listed and evaluated for comparison in Table 43-6.

One area which has been neglected is the water pollution and solid waste potential of air pollution control devices. Obviously, devices which reduce atmospheric emissions must eventually accumulate materials that must be disposed of by other means. A frequent argument against the use of wet collectors is the resulting liquid waste.

In many cases the collected materials can be used productively. They may be recycled back into the process stream, put to use in another plant application or (rarely) sold. All too frequently, however, the liquid wastes are simply discharged to city waste treatment systems, or directly into the waterways, while solid wastes are hauled away to landfills or incinerators.

The design of any air pollution control system must include consideration for potential pollution effects. A control system for one specific



Air Pollution Engineering Manual, Department of Health, Education and Welfare, 1967, p. 197 and p. 172.

Figure 43-13. Direct-Fired Afterburner.

airborne contaminant may involve more than just the design of an air pollution control device. An evaluation of the overall waste disposal system for the total operation may result in numerous additional modifications before all potential pollution sources are adequately controlled.

Preferred Reading

1. STRAUSS, W. *Industrial Gas Cleaning,* International Series of Monographs in Chemical Engineering, Volume 8, Pergamon Press, New York (1966).
2. STERN, A. C. *Air Pollution, Volume III — Sources of Air Pollution and Their Control,* Environmental Science Monograph Series, Academic Press, New York (1968).
3. DANIELSON, J. A. *Air Pollution Engineering Manual,* U. S. Department of Health, Education and Welfare, Public Health Service, Cincinnati, Ohio (1967).
4. LUND, H. F. *Industrial Pollution Control Handbook,* McGraw-Hill Book Company, New York (1971).
5. *Air Pollution Manual, Part II: Control Equipment,* American Industrial Hygiene Association, 66 South Miller Road, Akron, Ohio 44313 (1968).
6. *Journal of the Air Pollution Control Association,* Pittsburgh, Pennsylvania.

TABLE 43-6.
Comparison of Pollution Control Equipment

Device	To Control	Advantages	Disadvantages	Costs	Examples
Mechanical Separators	Medium to large diameter particles	1) Low initial cost 2) Simple construction 3) Ease of operation 4) Use as precleaners	1) Low efficiency 2) Erosion of components 3) Cannot remove small particles 4) Large space requirements	Low initial cost (5¢-25¢ per cfm)	1) Gravity Chambers 2) Impingement Separators 3) Cyclone Collectors
Filtration Devices	Dusts, fumes	1) High collection efficiency on small particles 2) Moderate power requirements 3) Dry disposal	1) High costs 2) Large space requirements 3) Must control moisture and temperature of gas stream	High costs (30¢-$2.50 per cfm)	1) Fabric Filters 2) Mat Filters 3) Ultrafilters
Wet Collectors	High-temperature, moisture-laden gases	1) Constant pressure drop 2) Elimination of dust removal problems 3) Compact design	1) Disposal of waste water may be expensive and troublesome	Moderate (between 25¢ and 75¢ per cfm)	1) Spray Chambers 2) Cyclone, Orifice, Venturi Scrubbers 3) Mechanical Scrubbers 4) Mechanical-Centrifugal Collectors
Electrostatic Precipitators	All sizes of particles—even very small mists which form free-running liquids	1) High efficiency 2) Dry dust collection 3) Low pressure drop 4) Can collect mists and corrosive acids	1) Often requires precleaner 2) Large space requirements 3) Cannot collect some high/low resistivity materials 4) High initial cost	High initial costs—low operating costs & low maintenance costs	1) Single-stage Precipitators 2) Two-stage Precipitators
Gas Adsorbers	Highly odorous, radioactive or toxic gases	1) Contaminant solvent may be recovered	1) High equipment & operating costs 2) Corrosion 3) Contamination	High equipment and operatingcosts	1) Fixed Bed 2) Regenerative
Combustion Incinerators	Odors, plume opacity, carbon monoxide, organic vapors	1) Capable of reaching high efficiency operation 2) Catalytic combustion reduces NO_x pollutants	1) Must burn additional fuel or add catalyst 2) Incomplete combustion can further complicate original problem 3) Catalysts require periodic cleaning & regeneration	Vary widely depending upon application	1) Direct Flame 2) Catalytic Combustion