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Electrostatic Precipitation

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ELECTROSTATIC PRECIPITATION

BY

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of the Requirements for the Degree
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I. INTRODUCTION

Electrostatic attraction of rubbed amber for small particles and fibers was known to the Greeks as early as 600 B.C.. The quantitative character of the electrostatic force involved was investigated by Coulomb (1) and published during the period of 1785 through 1789. The first recorded reference to the electrical attraction of smoke particles appears in the famous work, DeMagnete, of the English court physician, William Gilbert, in the year 1600 (1). He described the phenomenon as,

> Everything rushes toward electricks excepting flame and flaming bodies and the thinnest air . . . . yet they (electricks) entice smoke sent out by an extinguished light . . . bodies are borne towards electricks in straight line towards the center of the electrick.

Hohfeld, in 1824 performed the experiment of clearing fog in a jar containing an electrified point and Nahrwold, in 1878, experimented with the discharge from a sewing needle point in a tin cylinder, noticing that the electric discharge greatly increased the rate of settling or collection of atmospheric dust (1).

The first attempt to apply electrostatic precipitation commercially was made by Walker and Hutchings at a lead-smelting works in North Wales in 1885. As illustrated in Figure 1, it consisted of a system of metallic points situated in the flue and was excited from two Wimhurst influence machines with glass plates five feet in diameter; and each machine was driven by a one-horsepower steam engine.

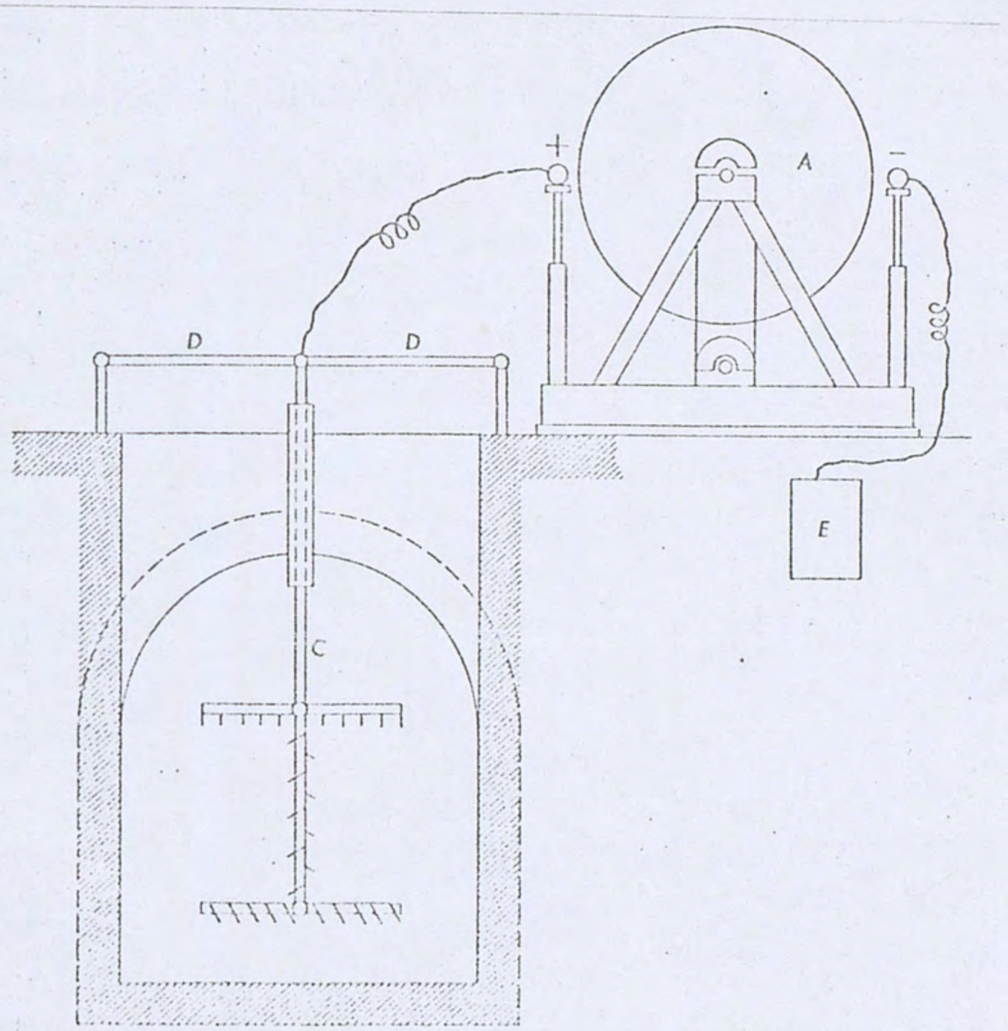


Figure 1.--Illustration from first U. S. patent on electrostatic precipitation (1886).

The installation failed its purpose due in part to the primitive method of producing high-voltage electricity and in part to the unfortunate choice of lead fume for the first commercial test. Lead fume is one of the most difficult dispersoids to precipitate because of its highly insulating character and very finely divided state (1).

Few articles and patents appeared in the years following until the start of the Twentieth Century. In 1906 Frederick G. Cottrell, being interested in electrostatic precipitation, realized the need for a better source of high-potential electrical energy and turned to a newly developed, synchronous-mechanical rectifier and the high-voltage transformer. His application led to the installation of commercial equipment, first at a powder works at Pinole, California and then at the nearby Selby smelter which was at the time embroiled in acute air pollution difficulties. Particulate removal efficiencies of these units were around 80 to 90% (1).

Electrostatic precipitators grew in quantity and quality through the years following these initial efforts. Application of electrostatic precipitation to the Portland Cement, steel and other common metals, precious metals, chemical, electric power generating and a host of other industries has played a large role in keeping air pollution within existing limits.

Electrostatic precipitation is one of many techniques for removing particulate emissions from industrial gas streams. Table 1

TABLE 1

VARIOUS COLLECTION EQUIPMENTS WITH CORRESPONDING CHARACTERISTICS

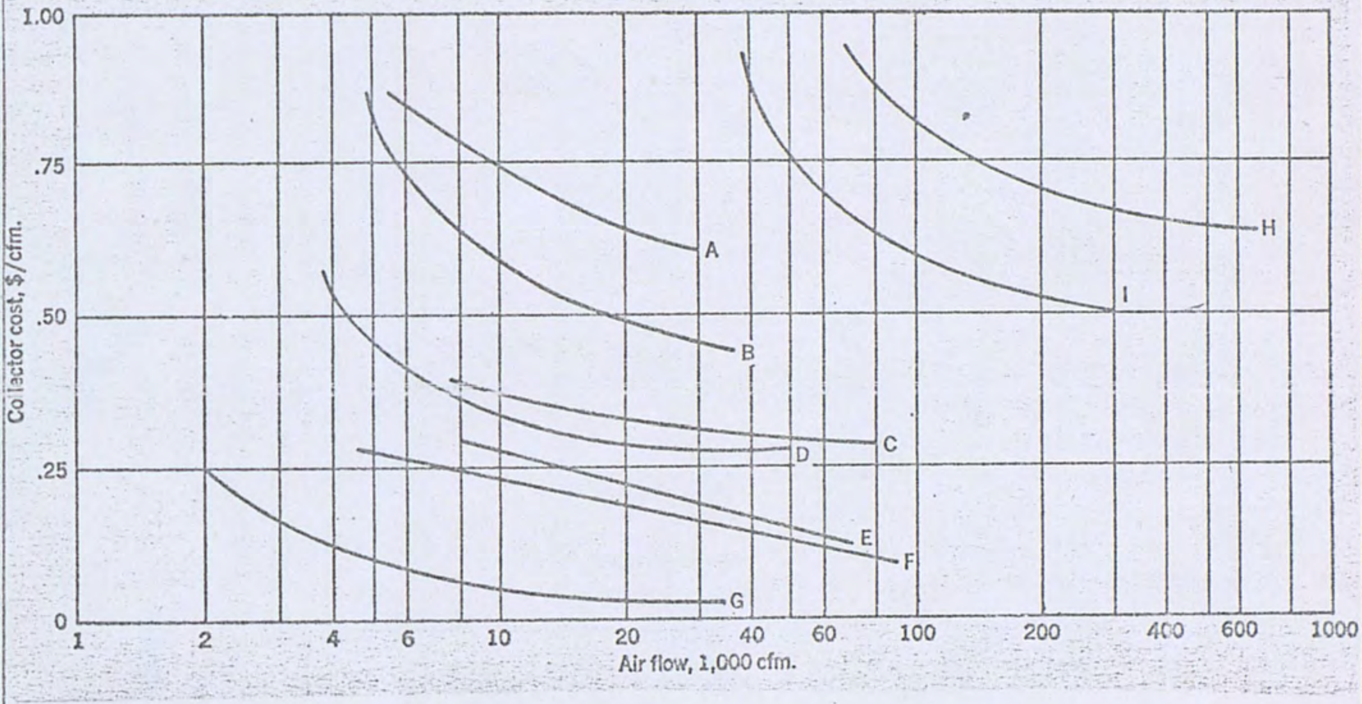
Types of Dust Collecting Equipment	Particle Size Microns	Loading Grains/ Cu. Ft.	Collection Efficiency Weight %	Pressure Loss Gas, In. W.G.	Pressure Loss Liquid Psi.
Dry inertial collectors					
Settling chamber	>50	>5	<50	<0.2	---
Baffle chamber	>50	>5	<50	0.1-0.5	---
Skimming chamber	>20	>1	<70	<1	---
Louver	>20	>1	<80	0.5-2	---
Cyclone	>10	>1	<85	0.5-3	---
Multiple cyclone	>5	>1	<95	2-6	---
Impingement	>10	>1	<90	1-2	---
Dynamic	>10	>1	<90	Provides head	
Wet scrubbers					
Gravity spray	>10	>1	<70	<1	20-100
Centrifugal	>5	>1	<90	2-6	20-100
Impingement	>5	>1	<95	2-8	20-100
Packed bed	>5	>0.1	<90	1-10	5-30
Dynamic	>1	>1	<95	Provides head	5-30
Submerged nozzle	>2	>0.1	<90	2-6	None
Jet	0.5-5	>0.1	<90	Provides head	50-100
Venturi	>0.5	>0.1	<99	10-30	5-30
Fabric filters	>0.2	>0.1	<99	2-6	---
Electrostatic precipitators	<2	>0.1	<99	0.2-1	---

Note: The terms expressing concentration, or loading, can be defined as light = ½-2, moderate = 2-5, and heavy = 5+ grains/cu. ft. Particle size: fine, 50% in ½-7 micron size range; medium 50% in 7-15 micron size range; coarse 50% over 15 microns.

TABLE 1--Continued

Utilities Per 1,000 Cfm.	Gas, Velocity Fpm.	Size Range Limits 1,000 Cfm.	Space Required (Relative)
---	300-600	None	Large
---	1,000-2,000	None	Medium
---	2,000-4,000	50	Small
---	2,000-4,000	30	Medium
---	2,000-4,000	50	Medium
---	2,000-4,000	200	Small
---	3,000-6,000	None	Small
1-2hp.	---	50	
0.5-2 gpm.	100-200	100	Medium
1-10 gpm.	2,000-4,000	100	Medium
1-5 gpm.	3,000-6,000	100	Medium
5-15 gpm.	100-300	50	Medium
1-5 gpm. 3-20 hp.	3,000-4,000	50	Small
No pumping	3,000	50	Medium
50-100 gpm.	2,000-20,000	100	Small
3-10 gpm.	12,000-42,000	100	Small
---	1-20	200	Large
0.1-0.6 kw.	100-600	10-2,000	Large

lists several techniques with their operating characteristics (2). As indicated in Table 1, the electrostatic precipitator is suitable for large flows of gas, however, at a large relative initial cost as indicated in Figure 2 (3). The costs shown here do not reflect the precipitator's low operating and maintenance costs.



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 (fly ash installations)
I - High voltage precipitators (minimum cost range)

Figure 2.--Initial cost of various dust collectors versus flow

One of the reasons that the electrostatic precipitator is heavily used in large industry is because of its low-pressure-drop characteristics. It can operate at temperatures to over 1,000°F and can collect dry dust and fume as well as mists and fogs. In most cases, it can be designed for very high efficiencies by installing several units in series.

In general, the precipitator with its high initial cost relative to other collectors offsets this disadvantage with low cost superior operation. Because of the low treatment velocities and large cross sectional area, it is sometimes difficult to fit precipitators into an existing plant. However, these problems can usually be solved by placing the precipitator in an open available area (near the stack base, suspended from the ceiling or on the roof with proper shelter) and connected with the appropriate ductwork.

There are two basic types of precipitators, plate and pipe. This report will deal mainly with the more common of the two, the plate type. This type is primarily for removal of dry dust. The grounded collecting electrodes are a series of parallel plates encased in a shell, with the discharge electrodes constructed of round steel, steel alloy, square or coated wire, depending upon the application, suspended between the plates and connected to the high voltage source.

The pipe type of precipitator is mainly for removal of liquid or sludge particles and volatilized fumes. In this type, a number of pipes are contained in a cylindrical shell under a header plate. The pipes are the collecting electrodes, and the discharge electrodes are suspended within them.

In either design the great difference in voltage between the discharge electrode and the collecting electrode sets up a strong electrical field between them. The gas, containing the suspended particles to be collected, passes through this field. Ions and electrons from a corona discharge are attached to these particles, giving them a negative charge. Then the particles are attracted to the positively charged collecting electrode where their charge is dissipated and they become electrically inert (1, 3, 4).

Next the particles must be removed from the electrode. In the pipe precipitator, if the collected material is a liquid, it will flow down and off the electrode by itself. If it's a solid, it is washed down with water or another liquid. In the plate precipitator, material is removed by rapping (a mechanical or electro-mechanical plate cleaning process explained in Part III) or sometimes by washing. After removal from the electrodes, the material is deposited in a hopper at the chamber bottom from which it can easily be taken for use or disposal when required.

One basic advantage of the precipitator is that its energy is applied only to the particles to be collected permitting large volumes of gas to be handled with almost no pressure drop and relatively little power requirement (1, 2, 3, 4).

Also, a precipitator can handle gases at high temperatures under pressure or suction. For handling corrosives, it can be made of stainless steel or other resistant material (1).

There are some cases in which a precipitator will not work well. These include separating dusts with high resistivity, where the particles retain their charge after being collected, thus decreasing the effective potential difference between the two electrodes and in turn decreasing the field to an ineffective strength, and dusts that tend to build up and form hard substances impossible to remove from the collecting electrodes. These dusts can usually be collected effectively by changing the gas temperature or moisture content to a more favorable level that lowers resistivity or adhesiveness (3).

There are other cases where a mist will pass through a precipitator at high temperature and condense later upon contact with the ambient air, forming an objectionable vapor plume. Prior to precipitation the temperature of the gas should be reduced to approximately the ambient temperature thru water injection and/or heat exchangers so that the precipitator could collect all the material in mist form (1).

II. THEORY

Corona Discharge

The vital role of corona discharge in electrical separation of particles from gases has been recognized from the earliest experiments of Hohlfeld, in 1824, to the present day broad scale use of the process. Although electrostatic precipitation is physically possible using other means such as radioactivity, flame ionization, etc., no other method has proved technically feasible or economically competitive with corona for performing this basic function.

Corona is usually established between a fine wire, or active electrode, maintained at high voltage and a smooth cylinder or plate electrode at ground potential. Under these conditions corona is manifested by a highly active visible glow in the strong electric-field region near the wire's surface. In the case of negative corona used exclusively for precipitation, large numbers of both positive ions and electrons are formed in this active region (1, 4)

Particle Charging and Collection

Ordinarily, gases at near standard conditions are good electrical insulators, even though natural processes generate approximately 10 ions per cubic centimeter per second (5) . It is these free carriers that provide the initiating electrons for the corona process. If an electric field is applied to a gas, the free electrons and the remaining positive ions will be driven by the electrical force. The electrons will move at a significantly greater velocity than will the relatively sluggish positive ions. When the applied electric field reaches some critical value (approximately 90 kv/cm), the free electrons will acquire sufficient energy between collisions to remove a valance electron from some of the neutral gas molecules. This process, termed avalanche multiplication, will continue as long as the localized electric field exceeds the critical value for electron avalanche (4). In the above process it is the large number of free electrons which eventually contribute to the charging of the particles in the gas stream. The free electrons entering the low-field regions of the corona combine with molecules of the gas to form negative ions via electron attachment to these gas molecules. These ions next attach to the gas particles which become charged negatively and are then attracted toward the collecting electrode.

During the period of 1910 through 1930 Peek's work stands out as a classic. His investigations included determination of the critical corona-voltage gradient as a function of wire diameter, effect of air temperature and pressure, effect of coating the corona wire with oil, water and dirt films, effect of wire conduction material and the effect of electrode geometry. These can be located in Peek, Jr., F. W., Dielectric Phenomena in High Voltage Engineering, 3rd. edition, McGraw-Hill, New York, 1929.

The charging process requires up to 0.1 seconds which means that the particles receive essentially their full charge in the first few inches of travel in the precipitator. On the other hand collection of the charged particles is basically a slower process so that the particles may be carried for many feet in the precipitation field before capture occurs. Therefore, the precipitation space is populated not only by gas ions but also by charged suspended particles of the same polarity. It is evident then that the electric-space charge of the particles adds to the space charge of the ions with the net result that the electric field near the corona wire is further weakened and the corona current is reduced by the presence of the charged particles. Quenching of the corona current obviously increases with the particle space charge and in practice it is quite possible to almost entirely extinguish the corona current. To combat these quenching effects, the corona voltage is then raised enough to offset the space charge effects. This control will be manual or automatic via the monitoring of the corona current (1).

Particle layers on the collecting surfaces of a precipitator influence the corona in either of two ways. First, if the particles have relatively high resistance, the voltage drop through the dust layer becomes abnormally high; and either excessive sparking at relatively low voltage or high-current back corona will occur. Particles of this type are represented, for example, by lime or lead oxide in hot, dry gases. Second, relatively coarse, high conductive particles such as carbon grit tend to be reentrained into the gas stream by the pith ball effect (discharge between the dust layer and collector electrode), and in the process may induce excessive sparking. High resistance particles occur more frequently in practice and usually are more serious in their effects (1). These problems are usually found in the metal and cement processing industries and can be minimized by more frequent cleaning of the collecting surfaces or certain compounds could be added to the combustion chamber or moisture could be added to the gas to alter the resistance characteristics of the particulate matter.

Particles deposited on the discharge wires can affect the corona discharge in two separate ways. First, small deposits may produce localized high-field regions which tend to emit corona simular to a point-plane corona. The effect is to reduce the corona-starting voltage and to shift the whole corona-current curve to a lower voltage region. When this occurs, the corona current will be higher and corona-starting voltage lower than normal. Second, heavy deposits on the discharge wires tend to suppress corona current by effectively increasing the wire diameter and thus reducing the corona voltage gradient by causing a voltage drop due to current flowing through a resistive dust layer and by effectively increasing the diameter of the discharge wire. Also, such heavy discharge-electrode deposits are usually nonuniform over the wire length so that the corona current which does flow may be correspondingly uneven. The net result is then a great reduction in precipitation efficiency (1).

Discharge-electrode deposits are usually most pronounced with fine particles such as fume. The presence of coarse particles tends to keep the discharge electrodes clean probably because of the scouring action of the larger particles. For example, fly ash (a generic term used to designate the particular matter carried in suspension by the effluent or waste gases from furnaces burning fossil fuels) precipitators frequently do not require high-tension electrode rapping, but a fly ash precipitator preceded by a cyclone collector (a collector which separates those particles with a greater specific gravity than the mean gas molecules through centrifugal action) requires such rapping. The removal of the coarse particles in the cyclone permits the fine particles in the precipitator to build up on the discharge wires (1).

III. DESIGN (1)

The fundamental design considerations for an electrostatic precipitator are covered in this section.

Basic Gas and Particle Properties

The basic gas and particle properties which must be known are:

1. Source of gas (type of fuel being burned).
2. Total gas flow, pressure, temperature and composition.
3. Particle size distribution and chemical composition.

All of these properties may be measured by known techniques and with available equipment. In general the properties will vary due to normal variations in processes, raw materials, and operating levels; therefore, ranges should be stated.

Basic Design Parameters for Precipitator

The basic design parameters will be determined from the properties of the gas and particles to be separated. The prime parameters are listed below:

1. Precipitation rate - is the migration velocity in ft./sec. of the particles in the electric field of the precipitator. This rate may be calculated from theory or determined empirically from

a pilot model.

2. Collection surface - is the required collecting surface area required for a given flow in sq. ft./cfm.

3. Duct width - is the actual physical clearance or spacing between collector plate surfaces.

4. Gas velocity - is the calculated average gas velocity through the precipitation zones and is a function of total gas flow and cross-sectional area.

5. Corona power density - is the corona power which can be absorbed per unit area in watts/sq. ft. and is limited by the properties of the gas, electrical quality of the precipitator and the stability of the power supplies.

6. Corona power - is the corona power necessary in watts/cfm for a given precipitation efficiency.

7. High-tension sectionalization - is the number of high-tension sections per unit volume of gas treated. This parameter is a yardstick of the ability of a precipitator to usefully absorb corona power available from the high voltage power supplies. The amount of corona power absorbed increases with the degree of sectionalization (due to any given perturbation effecting less of the overall precipitator), and this in turn is reflected in a higher precipitator efficiency.

High Voltage Equipment

The function of high voltage equipment in electrical precipitation is to provide a high level of useful corona power with a high degree of reliability and stability. Fulfillment of this function implies proper voltage waveform stability against precipitator sparking, proper voltage and current output ratings, and sturdy electrical and mechanical design. In addition automatic control is essential for some applications. In general half-wave voltage is preferred to full-wave voltage for all applications where precipitator sparking is an important factor, because it provides a longer time for sparks to extinguish between current pulses. Stability against spark transients is provided not only by the use of half-wave voltage but also by ample series impedance. Power supplies having relatively small current ratings are inherently more stable than high-current supplies because of the higher internal impedance of the former.

Electrical supplies for any conceivable voltage and current output ratings needed for precipitators are easily designed and are readily available. In practice ratings usually range from about 30 kv to 100 kv peak voltage and 50 ma to 600 ma average current, although both higher and lower values are sometimes used. Supplies for indoor and outdoor locations are in common use. Various systems of key and other type interlocks are used for safety reasons.

Corona and collecting electrodes

Although numerous types of corona or emitting electrodes are described in the literature and tried in practice, ordinary round, straight wires have received widest acceptance and are the best choice for the majority of applications.

Collecting electrodes probably have received even more attention from inventors than corona electrodes. Fundamentally there are four basic technical requirements for effective collecting electrode design: 1. high sparkover voltage characteristics; 2. aerodynamic shielding of collection surfaces to prevent particle reentrainment; 3. good rapping characteristics; 4. high mechanical strength coupled with light weight construction.

Accurate centering of corona electrodes in pipe precipitators and accurate alignment of wires and plates in duct precipitators is of major importance for good performance. Off-center and misaligned electrodes of 5% may easily result in a loss of 10% to 15% in operating voltage and thus a loss of overall efficiency of a precipitator if the voltage is automatically controlled with a spark rate monitor. If the voltage is not automatically controlled and the electrodes are not aligned symmetrically, the side of the discharge wire which is farthest from a collecting plate will suffer in corona discharge and again, overall efficiency will fall. Electrode alignment is one of the major checks made by operators during equipment outage and overhaul periods.

Electrode rappers

An essential feature of efficient electrical precipitation is the removal of accumulated dust deposits from the electrodes (dust build-up on the collecting electrodes of ½ to 1 inch/minute is not uncommon). This is necessary not only to remove the collected material from the precipitator but also to maintain optimum electrical conditions in the precipitation zones. The deposits are usually dislodged by mechanical jarring or vibration of the electrodes, a process generally referred to as rapping. In some precipitator applications particles tend to build up on the discharge electrodes as well as on the collecting electrodes due to back corona or very fine fume, and this may occur to such an extent that the corona discharge is choked off and precipitation efficiency falls. In these cases it is necessary to provide effective rapping means for both the discharge and collecting electrodes.

Far from being a minor adjunct in electrical precipitation, rapping is of the utmost importance in determining overall performance and has been one of the difficult problems. One may understand this by considering the possibilities which exist for reentrainment of the collected particles from the plates and from major disturbances and dust-clouding effects in the hoppers. Many schemes have been devised for easing or avoiding the rapping problem. These include various types of pocket or hollow collecting electrodes, closing flue dampers during rapping, and many others. In general such schemes have only limited application and have been only partially effective in preventing extra loss during the cleaning operation. A satisfactory rapping system is characterized by a high degree of reliability, by ability to maintain uniform and closely controlled raps over long periods of time without attention, and by flexible and easily controlled rapping intensity.

Modern practice tends to favor the use of impact rappers for plates and vibrator rappers for corona wires. Pneumatic and mechanical rappers are traditional, but electric rappers have been widely and successfully used since about 1950. In general, mechanical rappers have required much more maintenance than electrical rappers. Rapping puffs, which are unsightly dark emissions caused by large volume reentrainment, have been eliminated by the use of systems that rap continuously at a particular frequency (1, 2, 3, etc. cycles/minute) depending on the application.

IV. COSTS (6)

The Federal Power Commission (FPC), in cooperation with the National Air Pollution Control Administration in 1970, conducted a cost study survey on air pollution control of the steam-electric power generating industry. The questionnaire was designed to obtain cost and engineering information for collector systems installed since January 1, 1958. It was mailed to 18 utility companies that operate 131 plants. Cost information was obtained for 106 collector systems installed in 60 plants since 1958. The reported data show a definite trend in recent years toward the use of electrostatic precipitators rather than mechanical collectors or mechanical electrostatic collectors In addition, it was found that the installed cost per kilowatt for electrostatic precipitators was significantly lower for units installed in the last half of the period covered than that in the first half. A regression equation was developed by the FPC to be used for estimating the total installed cost for future installations. The equation may be used to predict the installed cost of precipitators as a function of the associated installed generating capacity of the boiler.

A 600 megawatt model plant was developed to show the relative contribution of particulate control expenditures to production expenditures of a power plant. The total annual cost of control ranges from .7 to 2.0% of the total annual power cost. The method used for calculating the total power cost is illustrated in Table 2. The model plant is presented in Table 3. Table 2 indicates the installation investment cost in $/kw and total power cost and breakdown in mills/kwhr. The values used were obtained statistically from the survey data. The first section of Table 3 is derived from Table 2 data and the second section is high and low costs from survey data. It is assumed by the FPC that the cost of air pollution control is included in the calculated total power costs.

The operating and maintenance costs, along with fly ash disposal cost, showed a large variation. These variations can be attributed in part to the differences in maintenance procedures and the disposal methods practiced by the various companies. For example, some companies sold the collected fly ash for as much as $5.87/ton while others paid to have it hauled away because of no market.

The air pollution control costs are presented as ranges that represent the extremes for data obtained from plants of a size similar to the model plant. The fixed charges for the pollution control equipment were assumed by the FPC to be 12%.

The cost of producing power at steam-electric plants accounts for approximately 50% of the total cost of electric power; the remainder being generated in hydroelectric and nuclear plants. Thus

TABLE 2

BREAKDOWN OF TOTAL POWER COSTS

Investment, $/kw		110
Fixed charges, mills/kwhr[a] (12% F. C., 80% capacity factor)		1.89
Operation and maintenance, mills/kwhr		0.25
Fuel cost, burn-up mills/kwhr (8800 Btu/kwhr, 25¢M Btu)	2.20	
Fuel cost, inventory, mills/kwhr (90 days inventory at 10%)	0.07	
Total fuel component, mills/kwhr		2.27
Total power costs, mills/kwhr		4.41

[a] In order to translate plant investment into a power cost component, the fixed charge rate on investment and the capacity factor at which the plant operates must be considered. Fixed charge rates range from 10 to 15%/yr., depending on the type of financing; i.e., the proportion of bonds, preferred stock, and common stock, earnings permitted by the regulating commissións; rate of depreciation; and state and local taxes.

TABLE 3

MODEL PLANT COST DATA

Installed capacity	600 Mw
Number of generating units	2
Size of units	300 Mw
Net generation	4204.8 million kwhr/yr
Plant factor	80
Steam production plant investment	$66,000,000 ($110/kw)
Annual cost	
Fixed charges	$ 7,950,000
Operation and maintenance	1,051,000
Fuel	9,545,000
Total annual power cost	18,546,000
Rate	4.41 mills/kwhr

TABLE 3--Continued

	Low	High
Cost of two electrostatic precipitators at 98% efficiency or greater	\$620,000	\$1,850,000
Fly ash disposal investment	\$180,000	\$ 600,000
Fixed Charges	\$ 96,000	\$ 294,000
Operation and maintenance	\$ 7,800	\$ 33,000
Annual fly ash disposal cost	\$ 27,000	\$ 52,500
Total annual cost of air pollution control	\$130,000	\$ 379,500
Rate	0.3 mills/kwhr	0.09 mills/kwhr
Total annual cost of air pollution control as a percent of total power cost	0.7%	2.0%

carrying the analysis a step further the cost for pollution control is 0.35-1.0% of the total cost of power to the consumed, including transmission and distribution costs as well as the production costs.

This means that, for the average annual U. S. residential electric bill of $120.00 from a utility with particulate control of 98% or greater, approximately $0.42-$1.20 may be accounted for by the costs related to the particulate control equipment.

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