

Section 6

Particulate Matter Controls

Chapter 3

Electrostatic Precipitators

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September 1999

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3.1 Process Description

3.1.1 Introduction

An electrostatic precipitator (ESP) is a particle control device that uses electrical forces to move the particles out of the flowing gas stream and onto collector plates. The particles are given an electrical charge by forcing them to pass through a corona, a region in which gaseous ions flow. The electrical field that forces the charged particles to the walls comes from electrodes maintained at high voltage in the center of the flow lane. Figure 3.1 is an example of electrostatic precipitator components.

Once the particles are collected on the plates, they must be removed from the plates without reentraining them into the gas stream. This is usually accomplished by knocking them loose from the plates, allowing the collected layer of particles to slide down into a hopper from which they are evacuated. Some precipitators remove the particles by intermittent or continuous washing with water.

3.1.2 Types of ESPs

ESPs are configured in several ways. Some of these configurations have been developed for special control action, and others have evolved for economic reasons. The types that will be described here are (1) the plate-wire precipitator, the most common variety; (2) the flat plate precipitator, (3) the tubular precipitator; (4) the wet precipitator, which may have any of the previous mechanical configurations; and (5) the two-stage precipitator. See Figure 6.14 for examples of typical flate-plate and plate-wire ESP configurations.

3.1.2.1 Plate-Wire Precipitators

Plate-wire ESPs are used in a wide variety of industrial applications, including coal-fired boilers, cement kilns, solid waste incinerators, paper mill recovery boilers, petroleum refining catalytic cracking units, sinter plants, basic oxygen furnaces, open hearth furnaces, electric arc furnaces, coke oven batteries, and glass furnaces.

In a plate-wire ESP, gas flows between parallel plates of sheet metal and high-voltage electrodes. These electrodes are long wires weighted and hanging between the plates or are supported there by mast-like structures (rigid frames). Within each flow path, gas flow must pass each wire in sequence as flows through the unit.

The plate-wire ESP allows many flow lanes to operate in parallel, and each lane can be quite tall. As a result, this type of precipitator is well suited for handling large volumes of gas. The need for rapping the plates to dislodge the collected material has caused the plate to be divided

into sections, often three or four in series with one another, which can be rapped independently. The power supplies are often sectionalized in the same way to obtain higher operating voltages, and further electrical sectionalization may be used for increased reliability. Dust also deposits on the discharge electrode wires and must be periodically removed similarly to the collector plate.

The power supplies for the ESP convert the industrial ac voltage (220 to 480 V) to pulsating dc voltage in the range of 20,000 to 100,000 V as needed. The supply consists of a step-up transformer, high-voltage rectifiers, and sometimes filter capacitors. The unit may supply either half-wave or full-wave rectified dc voltage. There are auxiliary components and controls to allow the voltage to be adjusted to the highest level possible without excessive sparking and to protect the supply and electrodes in the event a heavy arc or short-circuit occurs.

The voltage applied to the electrodes causes the air between the electrodes to break down electrically, an action known as a “corona.” The electrodes usually are given a negative polarity because a negative corona supports a higher voltage than a positive corona before sparking occurs. The ions generated in the corona follow electric field lines from the wires to the collecting plates. Therefore, each wire establishes a charging zone through which the particles must pass.

Particles passing through the charging zone intercept some of the ions, which become attached. Small aerosol particles ($<1 \mu\text{m}$ diameter) can absorb tens of ions before their total charge becomes large enough to repel further ions, and large particles ($>10 \mu\text{m}$ diameter) can absorb tens of thousands. The electrical forces are therefore much stronger on the large particles.

As the particles pass each successive wire, they are driven closer and closer to the collecting walls. The turbulence in the gas, however, tends to keep them uniformly mixed with the gas. The collection process is therefore a competition between the electrical and dispersive forces. Eventually, the particles approach close enough to the walls so that the turbulence drops to low levels and the particles are collected.

If the collected particles could be dislodged into the hopper without losses, the ESP would be extremely efficient. The rapping that dislodges the accumulated layer also projects some of the particles (typically 12 percent for coal fly ash) back into the gas stream. These reentrained particles are then processed again by later sections, but the particles reentrained in the last section of the ESP have no chance to be recaptured and so escape the unit.

Practical considerations of passing the high voltage into the space between the lanes and allowing for some clearance above the hoppers to support and align electrodes leave room for part of the gas to flow around the charging zones. This is called “sneakage” and amounts to 5 to 10 percent of the total flow. Antisneakage baffles usually are placed to force the sneakage flow to mix with the main gas stream for collection in later sections. But, again, the sneakage flow around the last section has no opportunity to be collected.

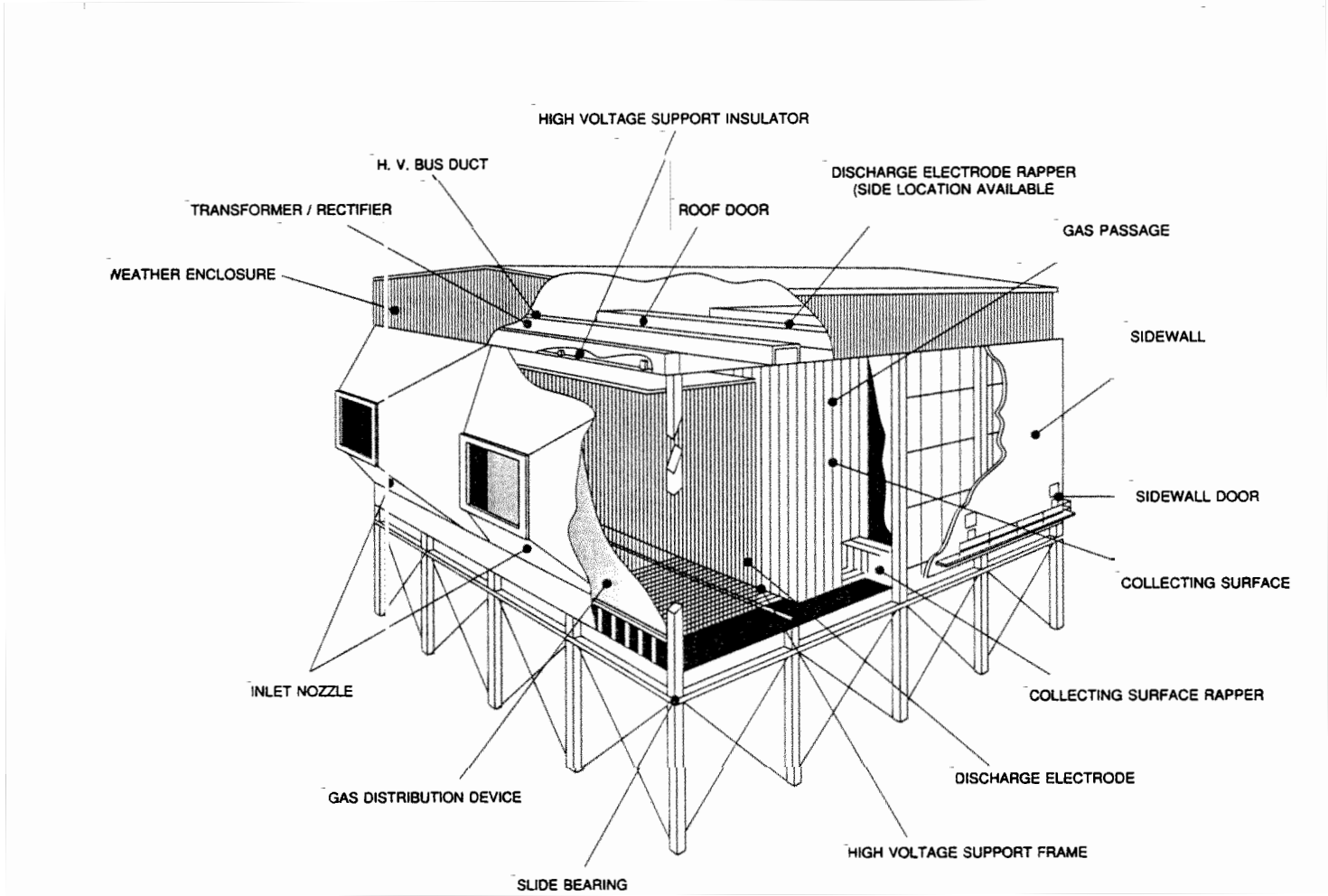


Figure 3.1: Electrostatic Precipitator Components
(Courtesy of the Institute for Clean Air Companies)

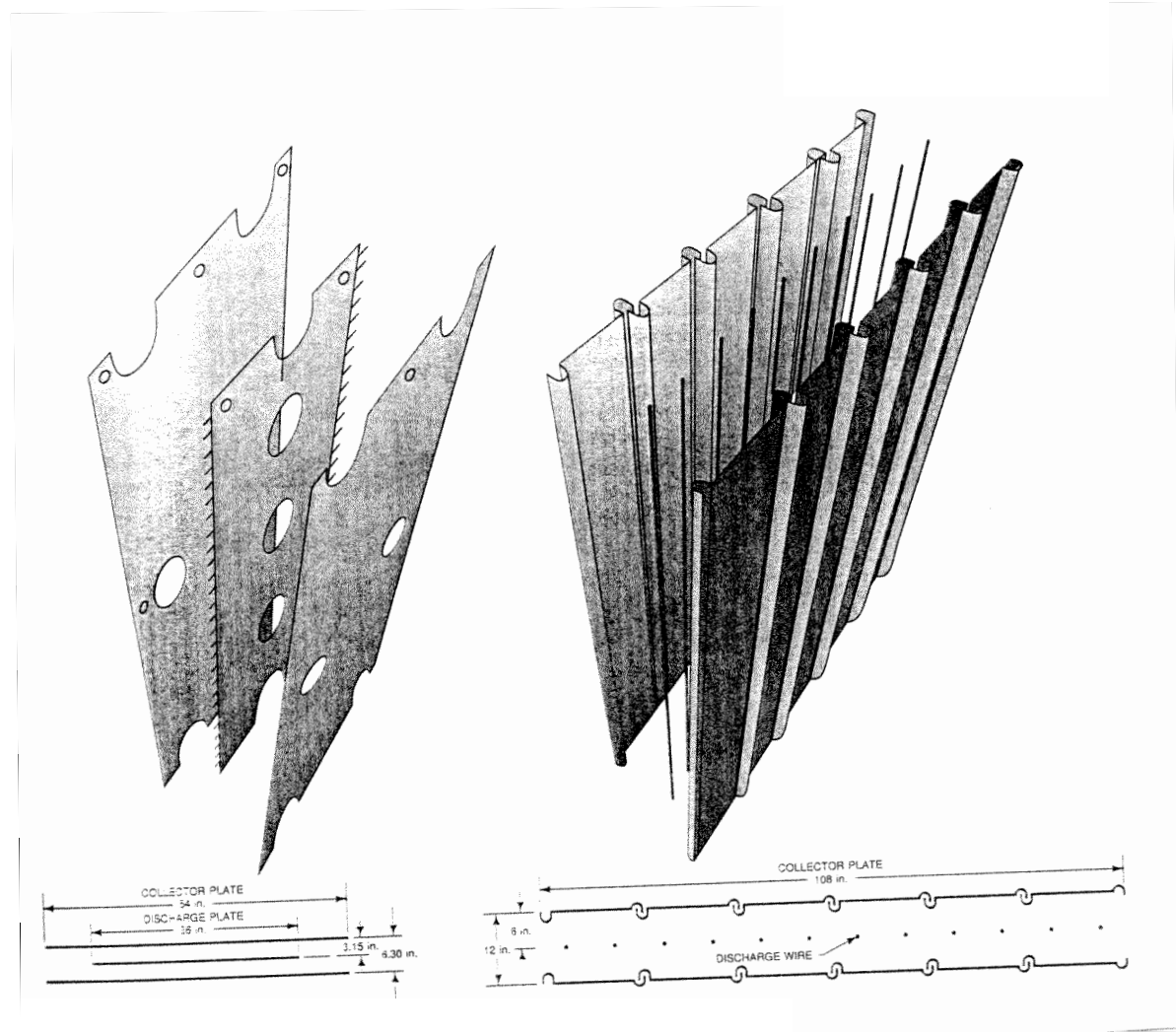


Figure 3.2: Flate-plate and Plate-wire ESP Configurations
(Courtesy of United McGill Corporation)

These losses play a significant role in the overall performance of an ESP. Another major factor is the resistivity of the collected material. Because the particles form a continuous layer on the ESP plates, all the ion current must pass through the layer to reach the ground-plates. This current creates an electric field in the layer, and it can become large enough to cause local electrical breakdown. When this occurs, new ions of the wrong polarity are injected into the wire-plate gap where they reduce the charge on the particles and may cause sparking. This breakdown condition is called “back corona.”

Back corona is prevalent when the resistivity of the layer is high, usually above 2×10^{11} ohm-cm. For lower resistivities, the operation of the ESP is not impaired by back coronas, but resistivities much higher than 2×10^{11} ohm-cm considerably reduce the collection ability of the unit because the severe back corona causes difficulties in charging the particles. At resistivities below 10^8 ohm-cm, the particles are held on the plates so loosely that rapping and nonrapping reentrainment become much more severe. Care must be taken in measuring or estimating resistivity because it is strongly affected by variables such as temperature, moisture, gas composition, particle composition, and surface characteristics.

3.1.2.2 Flat Plate Precipitators

A significant number of smaller precipitators (100,000 to 200,000 acfm) use flat plates instead of wires for the high-voltage electrodes. The flat plates (United McGill Corporation patents) increase the average electric field that can be used to collect the particles, and they provide an increased surface area for the collection of particles. Corona cannot be generated on flat plates by themselves, so corona-generating electrodes are placed ahead of and sometimes behind the flat plate collecting zones. These electrodes may be sharp-pointed needles attached to the edges of the plates or independent corona wires. Unlike plate-wire or tubular ESPs, this design operates equally well with either negative or positive polarity. The manufacturer has chosen to use positive polarity to reduce ozone generation.

A flat plate ESP operates with little or no corona current flowing through the collected dust, except directly under the corona needles or wires. This has two consequences. The first is that the unit is somewhat less susceptible to back corona than conventional units are because no back corona is generated in the collected dust, and particles charged with both polarities of ions have large collection surfaces available. The second consequence is that the lack of current in the collected layer causes an electrical force that tends to remove the layer from the collecting surface; this can lead to high rapping losses.

Flat plate ESPs seem to have wide application for high-resistivity particles with small (1 to 2 μm) mass median diameters (*MMDs*). These applications especially emphasize the strengths of the design because the electrical dislodging forces are weaker for small particles than for large ones. Fly ash has been successfully collected with this type of ESP, but low-flow velocity appears to be critical for avoiding high rapping losses.

3.1.2.3 Tubular Precipitators

The original ESPs were tubular like the smokestacks they were placed on, with the high-voltage electrode running along the axis of the tube. Tubular precipitators have typical applications in sulfuric acid plants, coke oven by-product gas cleaning (tar removal), and, recently, iron and steel sinter plants. Such tubular units are still used for some applications, with many tubes operating in parallel to handle increased gas flows. The tubes may be formed as a circular, square, or hexagonal honeycomb with gas flowing upwards or downwards. The length of the tubes can be selected to fit conditions. A tubular ESP can be tightly sealed to prevent leaks of material, especially valuable or hazardous material.

A tubular ESP is essentially a one-stage unit and is unique in having all the gas pass through the electrode region. The high-voltage electrode operates at one voltage for the entire length of the tube, and the current varies along the length as the particles are removed from the system. No sneakage paths are around the collecting region, but corona nonuniformities may allow some particles to avoid charging for a considerable fraction of the tube length.

Tubular ESPs comprise only a small portion of the ESP population and are most commonly applied where the particulate is either wet or sticky. These ESPs, usually cleaned with water, have reentrainment losses of a lower magnitude than do the dry particulate precipitators.

3.1.2.4 Wet Precipitators

Any of the precipitator configurations discussed above may be operated with wet walls instead of dry. The water flow may be applied intermittently or continuously to wash the collected particles into a sump for disposal. The advantage of the wet wall precipitator is that it has no problems with rapping reentrainment or with back coronas. The disadvantage is the increased complexity of the wash and the fact that the collected slurry must be handled more carefully than a dry product, adding to the expense of disposal.

3.1.2.5 Two-Stage Precipitators

The previously described precipitators are all parallel in nature, *i.e.*, the discharge and collecting electrodes are side by side. The two-stage precipitator invented by Penney is a series device with the discharge electrode, or ionizer, preceding the collector electrodes. For indoor applications, the unit is operated with positive polarity to limit ozone generation.

Advantages of this configuration include more time for particle charging, less propensity for back corona, and economical construction for small sizes. This type of precipitator is generally used for gas flow volumes of 50,000 acfm and less and is applied to submicrometer sources emitting oil mists, smokes, fumes, or other sticky particulates because there is little electrical force

to hold the collected particulates on the plates. Modules consisting of a mechanical prefilter, ionizer, collecting-plate cell, after-filter, and power pack may be placed in parallel or series-parallel arrangements. Preconditioning of gases is normally part of the system. Cleaning may be by water wash of modules removed from the system up to automatic, in-place detergent spraying of the collector followed by air-blow drying.

Two-stage precipitators are considered to be separate and distinct types of devices compared to large, high-gas-volume, single-stage ESPs. The smaller devices are usually sold as pre-engineered, package systems.

3.1.3 Auxiliary Equipment

Typical auxiliary equipment associated with an ESP system is shown schematically in Figure 3.3. Along with the ESP itself, a control system usually includes the following auxiliary equipment: a capture device (i.e., hood or direct exhaust connection); ductwork; dust removal equipment (screw conveyor, etc.); fans, motors, and starters; and a stack. In addition, spray coolers and mechanical collectors may be needed to precondition the gas before it reaches the ESP. Capture devices are usually hoods that exhaust pollutants into the ductwork or are direct exhaust couplings attached to a combustor or process equipment. These devices are usually refractory lined, water cooled, or simply fabricated from carbon steel, depending on the gas-stream temperatures. Refractory or water-cooled capture devices are used where the wall temperatures exceed 800°F; carbon steel is used for lower temperatures. The ducting, like the capture device, should be water cooled, refractory, or stainless steel for hot processes and carbon steel for gas temperatures below approximately 1150°F (duct wall temperatures <800°F). The ducts should be sized for a gas velocity of approximately 4,000 ft/min for the average case to prevent particle deposition in the ducts. Large or dense particles might require higher velocities, but rarely would lower velocities be used. Spray chambers may be required for processes where the addition of moisture, or decreased temperature or gas volume, will improve precipitation or protect the ESP from warpage. For combustion processes with exhaust gas temperatures below approximately 700°F, cooling would not be required, and the exhaust gases can be delivered directly to the precipitator.

When much of the pollutant loading consists of relatively large particles, mechanical collectors, such as cyclones, may be used to reduce the load on the ESP, especially at high inlet concentrations. The fans provide the motive power for air movement and can be mounted before or after the ESP. A stack, normally used, vents the cleaned stream to the atmosphere. Screw conveyors or pneumatic systems are often used to remove captured dust from the bottom of the hoppers.

Wet ESPs require a source of wash water to be injected or sprayed near the top of the collector plates either continuously or at timed intervals. The water flows with the collected particles

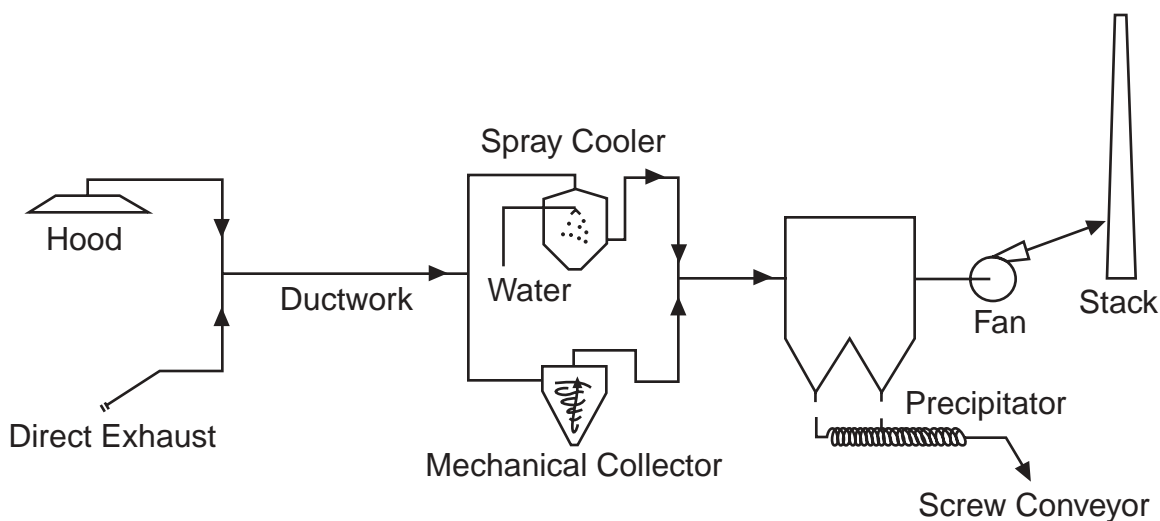


Figure 3.3: Control Device and Typical Auxiliary Equipment

into a sump from which the fluid is pumped. A portion of the fluid may be recycled to reduce the total amount of water required. The remainder is pumped directly to a settling pond or passed through a dewatering stage, with subsequent disposal of the sludge.

Gas conditioning equipment to improve ESP performance by changing dust resistivity is occasionally used as part of the original design, but more frequently it is used to upgrade existing ESPs. The equipment injects an agent into the gas stream ahead of the ESP. Usually, the agent mixes with the particles and alters their resistivity to promote higher migration velocity, and thus higher collection efficiency. However, electrical properties of the gas may change, rather than dust resistivity. For instance, cooling the gas will allow more voltage to be applied before sparking occurs. Significant conditioning agents that are used include SO_3 , H_2SO_4 , sodium compounds, ammonia, and water, but the major conditioning agent by usage is SO_3 . A typical dose rate for any of the gaseous agents is 10 to 30 ppm by volume.

The equipment required for conditioning depends on the agent being used. A typical SO_3 conditioner requires a supply of molten sulfur. It is stored in a heated vessel and supplied to a burner, where it is oxidized to SO_2 . The SO_2 gas is passed over a catalyst for further oxidation to SO_3 . The SO_3 gas is then injected into the flue gas stream through a multi-outlet set of probes that breach a duct. In place of a sulfur burner to provide SO_2 , liquid SO_2 may be vaporized from a storage tank. Although their total annual costs are higher, the liquid SO_2 systems have lower capital costs and are easier to operate than the molten sulfur based systems.

Water or ammonia injection requires a set of spray nozzles in the duct, along with pumping and control equipment.

Sodium conditioning is often done by coating the coal on a conveyor with a powder compound or a water solution of the desired compound. A hopper or storage tank is often positioned over the conveyor for this purpose.

3.1.4 Electrostatic Precipitation Theory

The theory of ESP operation requires many scientific disciplines to describe it thoroughly. The ESP is basically an electrical machine. The principal actions are the charging of particles and forcing them to the collector plates. The amount of charged particulate matter affects the electrical operating point of the ESP. The transport of the particles is affected by the level of turbulence in the gas. The losses mentioned earlier, sneackage and rapping reentrainment, are major influences on the total performance of the system. The particle properties also leave a major effect on the operation of the unit.

The following subsections will explain the theory behind (1) electrical operating points in the ESP, (2) particle charging, (3) particle collection, and (4) sneackage and rapping reentrainment. General references for these topics are White [1] or Lawless and Sparks [2].

3.1.4.1 Electrical Operating Point

The electrical operating point of an ESP section is the value of voltage and current at which the section operates. As will become apparent, the best collection occurs when the highest electric field is present, which roughly corresponds to the highest voltage on the electrodes. In this work, the term “section” represents one set of plates and electrodes in the direction of flow. This unit is commonly called a “field”, and a “section” or “bus section” represents a subdivision of a “field” perpendicular to the direction of flow. In an ESP model and in sizing applications, the two terms “section” and “field” are used equivalently because the subdivision into bus sections should have no effect on the model. This terminology has probably arisen because of the frequent use of the word “field” to refer to the electric field.

The lowest acceptable voltage is the voltage required for the formation of a corona, the electrical discharge that produces ions for charging particles. The (negative) corona is produced when an occasional free electron near the high-voltage electrode, produced by a cosmic ray, gains enough energy from the electric field to ionize the gas and produce more free electrons. The electric field for which this process is self-sustained has been determined experimentally. For round wires, the field at the surface of the wire is given by:

$$E_c = 3.126 \times 10^6 d_r \left[1 + 0.0301 \left(\frac{d_r}{r_w} \right)^{0.5} \right] \quad (3.1)$$

where

$$\begin{aligned} E_e &= \text{corona onset field at the wire surface (V/m)} \\ d_r &= \text{relative gas density, referred to 1 atm pressure and 20°C} \\ &\quad \text{(dimensionless)} \\ r_w &= \text{radius of the wire, meters (m)} \end{aligned}$$

This is the field required to produce “glow” corona, the form usually seen in the laboratory on smooth, clean wires. The glow appears as a uniform, rapidly moving diffuse light around the electrode. After a period of operation, the movement concentrates into small spots on the wire surface, and the corona assumes a tuft-like appearance. The field required to produce “tuft” corona, the form found in full-scale ESPs, is 0.6 times the value of E_c .

The voltage that must be applied to the wire to obtain this value of field, V_c , is found by integrating the electric field from the wire to the plate. The field follows a simple “ $1/r^2$ ” dependence in cylindrical geometry. This leads to a logarithmic dependence of voltage on electrode dimensions. In the plate-wire geometry, the field dependence is somewhat more complex, but the voltage still shows the logarithmic dependence. V_c is given by:

$$V_c = E_c r_w \ln \left(\frac{d}{r_w} \right) \quad (3.2)$$

where

$$\begin{aligned} V_c &= \text{corona onset voltage (V)} \\ d &= \text{outer cylinder radius for tubular ESP (m)} \\ &\quad 4/B \times \text{(wire-plate separation) for plate-wire ESP (m)} \end{aligned}$$

No current will flow until the voltage reaches this value, but the amount of current will increase steeply for voltages above this value. The maximum current density (amperes/square meter) on the plate or cylinder directly under the wire is given by:

$$j = \mu \epsilon \frac{V^2}{L^3} \quad (3.3)$$

where

j	=	maximum current density (A/m ²)
μ	=	ion mobility m ² /Vs) (meter ² /volt second)
ϵ	=	free space permittivity (8.845 x 10 ⁻¹² F/m)(Farad/meter)
V	=	applied voltage (V)
L	=	shortest distance from wire to collecting surface (m)

For tuft corona, the current density is zero until the corona onset voltage is reached, when it jumps almost to this value of j within a few hundred volts, directly under a tuft.

The region near the wire is strongly influenced by the presence of ions there, and the corona onset voltage magnitude shows strong spatial variations. Outside the corona region, it is quite uniform.

The electric field is strongest along the line from wire to plate and is approximated very well, except near the wire, by:

$$E_{\max} = \frac{V}{L} \quad (3.4)$$

where

E_{\max}	=	maximum field strength (V/m)
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When the electric field throughout the gap between the wire and the plate becomes strong enough, a spark will occur, and the voltage cannot be increased without severe sparking occurring. The field at which sparking occurs is not sharply defined, but a reasonable value is given by:

$$E_s = 6.3 \times 10^5 \left(\frac{273}{T} P \right)^{1.65} \quad (3.5)$$

where

E_s	=	sparking field strength (V/m)
T	=	absolute temperature (K)
P	=	gas pressure (atm)

This field would be reached at a voltage of, for example, 35,000 V for a plate-wire spacing of 11.4 cm (4.5 in.) at a temperature of 149°C (300°F). The ESP will generally operate near this voltage in the absence of back corona. E_{max} will be equal to or less than E_s .

Instead of sparking, back corona may occur if the electric field in the dust layer, resulting from the current flow in the layer, reaches a critical value of about 1×10^6 V/m. Depending on conditions, the back corona, may enhance sparking or may generate so much current that the voltage cannot be raised any higher. The field in the layer is given by:

$$E_l = j\rho \quad (3.6)$$

where

$$\begin{aligned} E_l &= \text{electric field in dust layer (V/m)} \\ \rho &= \text{resistivity of the collected material (ohm-m)} \end{aligned}$$

3.1.4.2 Particle Charging

Charging of particles takes place when ions bombard the surface of a particle. Once an ion is close to the particle, it is tightly bound because of the image charge within the particle. The “image charge” is a representation of the charge distortion that occurs when a real charge approaches a conducting surface. The distortion is equivalent to a charge of opposite magnitude to the real charge, located as far below the surface as the real charge is above it. The notion of the fictitious charge is similar to the notion of an image in a mirror, hence the name. As more ions accumulate on a particle, the total charge tends to prevent further ionic bombardment.

There are two principal charging mechanisms: diffusion charging and field charging. Diffusion charging results from the thermal kinetic energy of the ions overcoming the repulsion of the ions already on the particle. Field charging occurs when ions follow electric field lines until they terminate on a particle. In general, both mechanisms are operative for all sizes of particles. Field charging, however, adds a larger percentage of charge on particles greater than about $2\mu\text{m}$ in diameter, and diffusion charging adds a greater percentage on particles smaller than about $0.5\mu\text{m}$.

Diffusion charging, as derived by White [1], produces a logarithmically increasing level of charge on particles, given by:

$$q(t) = \left(\frac{rkT}{e} \right) \ln(1 + r) \quad (3.7)$$

where

$q(t)$	=	particle charge (C) as function of time, t, in seconds
r	=	particle radius (m)
k	=	Boltzmann's constant (j/K)
T	=	absolute temperature (K)
e	=	electron charge ($1.67 \times 10^{-19}C$)
τ	=	dimensionless time given by:

$$\tau = \frac{\pi r v N e^2 \theta}{kT} \quad (3.8)$$

where

v	=	mean thermal speed of the ions (m/s)
N	=	ion number concentration near the particle (No./m ³) 2 = real time (exposure)
θ	=	real time (exposure time in the charging zone) (s)

Diffusion charging never reaches a limit, but it becomes very slow after about three dimensionless time units. For fixed exposure times, the charge on a particle is proportional to its radius.

Field charging also exhibits a characteristic time-dependence, given by:

$$q(t) = \frac{q_s \theta}{\theta + \tau'} \quad (3.9)$$

where

q_s	=	saturation charge, charge at infinite time (C)
θ	=	real time (s)
τ'	=	another dimensionless time unit

The saturation charge is given by:

$$q_s = 12 \pi \epsilon r^2 E \quad (3.10)$$

where

ϵ	=	free space permittivity (F/m)
E	=	external electric field applied to the particle (V/m)

The saturation charge is proportional to the square of the radius, which explains why field charging is the dominant mechanism for larger particles. The field charging time constant is given by:

$$r' = \frac{4 \epsilon}{Ne\mu} \quad (3.11)$$

where

μ = ion mobility

Strictly speaking, both diffusion and field charging mechanisms operate at the same time on all particles, and neither mechanism is sufficient to explain the charges measured on the particles. It has been found empirically that a very good approximation to the measured charge is given by the sum of the charges predicted by Equations 3.7 and 3.9 independently of one another:

$$q_{tot} = q_d(t) + q_f(t) \quad (3.12)$$

where

$q_{tot}(t)$ = particle charge due to both mechanisms
 $q_d(t)$ = particle charge due to diffusion charging
 $q_f(t)$ = particle charge due to field charging

3.1.4.3 Particle Collection

The electric field in the collecting zone produces a force on a particle proportional to the magnitude of the field and to the charge:

$$F_e = qE \quad (3.13)$$

where

F_e = force due to electric field (N)
 q = charge on particle (C)
 E = electric field (V/m)

Because the field charging mechanism gives an ultimate charge proportional to the electric field, the force on large particles is proportional to the square of the field, which shows the advantage for maintaining as high a field as possible.

The motion of the particles under the influence of the electric field is opposed by the viscous drag of the gas. By equating the electric force and the drag force component due to the electric field (according to Stokes' law), we can obtain the particle velocity:

$$v(q, E, r) = \frac{q(E, r) E C(r)}{6\pi \eta r} \quad (3.14)$$

where

$v(q, E, r)$	=	particle velocity (m/s)
$q(E, r)$	=	particle charge (C)
$C(r)$	=	Cunningham correction to Stokes' law (dimensionless)
η	=	gas viscosity (kg/ms)

The particle velocity, is the rate at which the particle moves along the electric field lines, *i.e.*, toward the walls.

For a given electric field, this velocity is usually at a minimum for particles of about $0.5 \mu\text{m}$ diameter. Smaller particles move faster because the charge does not decrease very much, but the Cunningham factor increases rapidly as radius decreases. Larger particles have a charge increasing as r^2 and a viscous drag only increasing as r^1 ; the velocity then increases as r .

Equation 3.14 gives the particle velocity with respect to still air. In the ESP, the flow is usually very turbulent, with instantaneous gas velocities of the same magnitude as the particles velocities, but in random directions. The motion of particles toward the collecting plates is therefore a statistical process, with an average component imparted by the electric field and a fluctuating component from the gas turbulence.

This statistical motion leads to an exponential collection equation, given by:

$$N(r) = N_0(r) \exp\left(\frac{-vr}{v_0}\right) \quad (3.15)$$

where

- $N(r)$ = particle concentration of size r at the exit of the collecting zone (No./m³)
 $N_0(r)$ = particle concentration of size r at the entrance of the zone (No./m³)
 $v(r)$ = size-dependent particle velocity (m/s)
 v_o = characteristic velocity of the ESP (m/s), given by:

$$v_o = \frac{Q}{A} = \frac{1}{SCA} \quad (3.16)$$

where

- Q = volume flow rate of the gas (m³/s)
 A = plate area for the ESP collecting zone (m²)
 SCA = specific collection area (A/Q) (s/m)

When this collection equation is averaged over all the particle sizes and weighted according to the concentration of each size, the Deutsch equation results, with the penetration (fraction of particles escaping) given by:

$$p = \exp(-w_e SCA) \quad (3.17)$$

where

- p = penetration (fraction)
 w_e = effective migration velocity for the particle ensemble (m/s)

The collection efficiency is given by:

$$Eff (\%) = 100 (1 - p) \quad (3.18)$$

and is the number most often used to describe the performance of an ESP.

3.1.4.4 Sneakage and Rapping Reentrainment

Sneakage and rapping reentrainment are best considered on the basis of the sections within an ESP. Sneakage occurs when a part of the gas flow bypasses the collection zone of a section. Generally, the portion of gas that bypasses the zone is thoroughly mixed with the gas that passes through the zone before all the gas enters the next section. This mixing cannot always be

assumed, and when sneakage paths exist around several sections, the performance of the whole ESP is seriously elected. To describe the effects of sneakage and rapping reentrainment mathematically we first consider sneakage by itself and then consider the effects of rapping as an average over many rapping cycles.

On the assumption that the gas is well mixed between sections, the penetration for each section can be expressed as:

$$p_s = S_N + [(1 - S_N) \times p_c(Q')] \quad (3.19)$$

where

$$\begin{aligned} p_s &= \text{section's fractional penetration} \\ S_N &= \text{fraction of gas bypassing the section (sneakage)} \\ p_c(Q') &= \text{fraction of particles penetrating the collection zone, which is functionally dependent on } Q', \text{ the gas volume flow in the collection zone, reduced by the sneakage (m}^3\text{/s)} \end{aligned}$$

The penetration of the entire ESP is the product of the section penetrations. The sneakage sets a lower limit on the penetration of particles through the section.

To calculate the effects of rapping, we first calculate the amount of material captured on the plates of the section. The fraction of material that was caught is given by:

$$\frac{m}{m_0} = 1 - p_s = 1 - S_N - [(1 - S_N) \times p_c(Q')] \quad (3.20)$$

where

$$m/m_0 = \text{mass fraction collected from the gas stream}$$

This material accumulates until the plates are rapped, whereupon most of the material falls into the hopper for disposal, but a fraction of it is reentrained and leaves the section. Experimental measurements have been conducted on fly ash ESPs to evaluate the fraction reentrained, which averages about 12 percent.

The average penetration for a section including sneakage and rapping reentrainments, is:

$$p_s = S_N + [(1 - S_N) \times p_c(Q')] + RR (1 - S_N)[1 - p_c(Q')] \quad (3.21)$$

where

RR = fraction reentrained

This can be written in a more compact form as:

$$p_s = LF + [(1 - LF) \times p_c(Q')] \quad (3.22)$$

by substituting LF (loss factor) for $S_N + RR(1 - S_N)$. These formulas can allow for variable amounts of sneakage and rapping reentrainment for each section, but there is no experimental evidence to suggest that it is necessary.

Fly ash precipitators analyzed in this way have an average S_N of 0.07 and an RR of 0.12. These values are the best available at this time, but some wet ESPs, which presumably have no rapping losses, have shown S_N values of 0.05 or less. These values offer a means for estimating the performance of ESPs whose actual characteristics are not known, but about which general statements can be made. For instance, wet ESPs would be expected to have $RR = 0$, as would ESPs collecting wet or sticky particles. Particulate materials with a much smaller mass mean diameter, MMD , than fly ash would be expected to have a lower RR factor because they are held more tightly to the plates and each other. Sneakage factors are harder to account for; unless special efforts have been made in the design to control sneakage, the 0.07 value should be used.

3.2 ESP Design Procedure

3.2.1 Specific Collecting Area

Specific collecting area (SCA) is a parameter used to compare ESPs and roughly estimate their collection efficiency. SCA is the total collector plate, area divided by gas volume flow rate and has the units of s/m or s/ft . Since SCA is the ratio of A/Q , it is often expressed as $m^2/(m^3/s)$ or $ft^2/kacfm$, where $kacfm$ is thousand $acfm$. SCA is also one of the most important factors in determining the capital and several of the annual costs (for example, maintenance and dust disposal costs) of the ESP because it determines the size of the unit. Because of the various ways in which SCA can be expressed, Table 3.1 gives equivalent SCA s in the different units for what would be considered a small, medium, and large SCA .

The design procedure is based on the loss factor approach of Lawless and Sparks [2] and considers a number of process parameters. It can be calculated by hand, but it is most conveniently used with a spreadsheet program. For many uses, tables of effective migration velocities can be used to obtain the SCA required for a given efficiency. In the following subsection, tables have

Table 3.1: Small, Medium, and Large SCAs as Expressed by Various Units

Units	Small	Medium	Large
ft ² /kacfm ^a	100	400	900
s/m	19.7	78.8	177
s/ft	6	24	54

^a 5.080 ft²/kacfm = 1 (s/m)

been calculated using the design procedure for a number of different particle sources and for differing levels of efficiency. If a situation is encountered that is not covered in these tables, then the full procedure that appears in the subsequent subsection should be used.

3.2.1.1 SCA Procedure with Known Migration Velocity

If the migration velocity is known, then Equation 3.17 can be rearranged to give the SCA:

$$SCA = \frac{-\ln(p)}{w_e}$$

A graphical solution to Equation 3.23 is given in Figure 3.4. The migration velocities have been calculated for three main precipitator types: plate-wire, flat plate, and wet wall ESPs of the plate-wire type. The following three tables, keyed to design efficiency as an easily quantified variable, summarize the migration velocities under various conditions:

- In Table 3.2, the migration velocities are given for a plate-wire ESP with conditions of no back corona and severe back corona; temperatures appropriate for each process have been assumed.
- In Table 3.3, the migration velocities calculated for a wet wall ESP of the plate-wire type assume no back corona and no rapping reentrainment.
- In Table 3.4, the flat plate ESP migration velocities are given only for no back corona conditions because they appear to be less affected by high-resistivity dusts than the plate-wire types.

It is generally expected from experience that the migration velocity will decrease with increasing efficiency. In Tables 3.2 through 3.4, however, the migration velocities show some

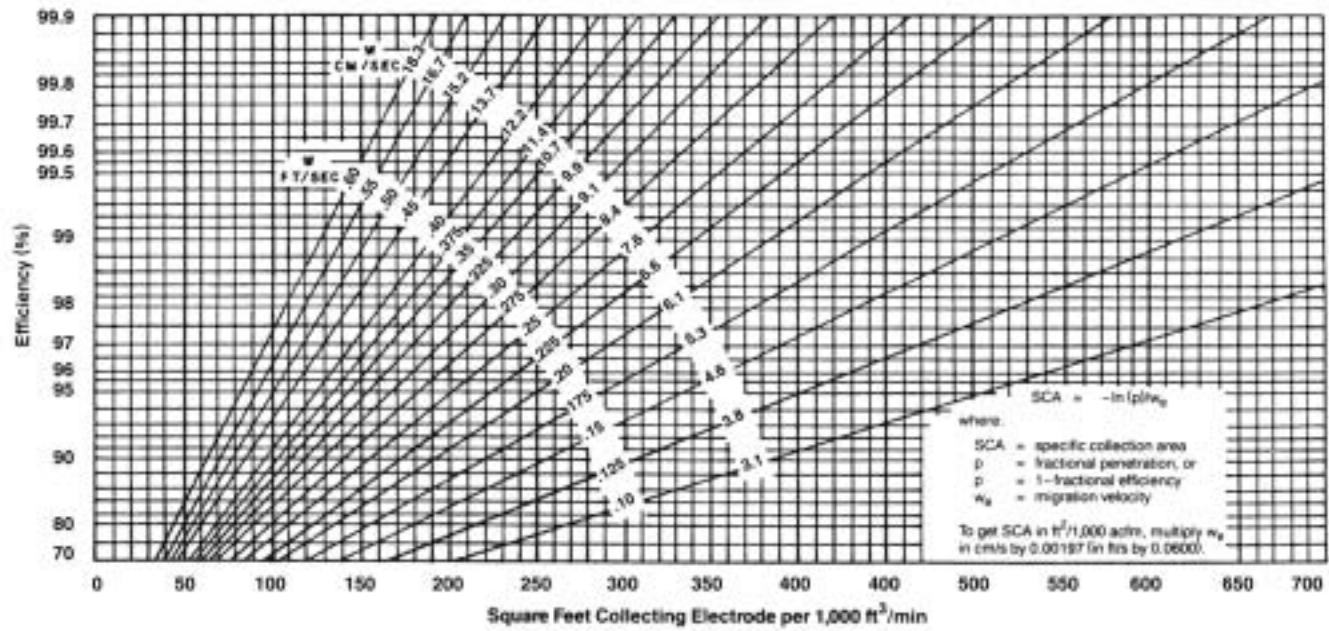


Figure 3.4: Chart for Finding SCA

Table 3.2: Plate-Wire ESP Migration Velocities (cm/s)^a

Particle Source		Design Efficiency, %			
		95	99	99.5	99.9
Bituminous coal fly ash ^b	(no BC)	12.6	10.1	9.3	8.2
	(BC)	3.1	2.5	2.4	2.1
Sub-bituminous coal fly ash in tangential-fired boiler ^b	(no BC)	17.0	11.8	10.3	8.8
	(BC)	4.9	3.1	2.6	2.2
Other coal ^b	(no BC)	9.7	7.9	7.9	7.2
	(BC)	2.9	2.2	2.1	1.9
Cement Kiln ^c	(no BC)	1.5	1.5	1.8	1.8
	(BC)	0.6	0.6	0.5	0.5
Glass plant ^d	(no BC)	1.6	1.6	1.5	1.5
	(BC)	0.5	0.5	0.5	0.5
Iron/steel sinter plant dust with mechanical precollector ^b	(no BC)	6.8	6.2	6.6	6.3
	(BC)	2.2	1.8	1.8	1.7
Kraft-paper recovery boiler ^b	(no BC)	2.6	2.5	3.1	2.9
Incinerator fly ash ^e	(no BC)	15.3	11.4	10.6	9.4
Copper reverberatory furnace ^f	(no BC)	6.2	4.2	3.7	2.9
Copper converter ^g	(no BC)	5.5	4.4	4.1	3.6
Copper roaster ^h	(no BC)	6.2	5.5	5.3	4.8
Coke plant combustion stack ⁱ	(no BC)	1.2 ^j	-	-	-

BC = Back Corona

^a To convert cm/s to fps, multiply cm/s by 0.0328m but computational procedures uses SI units. To convert cm/s to m/s, multiply by 0.01. Assumes same particle size as given in full computational procedure.^b At 300°F. Depending on individual furnace/boiler conditions, chemical nature of the fly ash, and availability of naturally occurring conditioning agents (e.g., moisture in the gas stream). Migration velocities may vary considerably from these values. Likely values are in the range from back corona to no back corona. BC = back corona.^c At 600°F.^d At 500°F.^e At 250°F.^f 450°F to 570°F^g 500°F to 700°F^h 600°F to 660°Fⁱ 360°F to 450°F^j Data available only for inlet concentrations in the range of 0.02 to 0.2 g/s m³ and for efficiencies less than 90%.

Table 3.3: Wet Wall Plate - Wire ESP Migration Velocities
(No back corona, cm/s)^a

Particle Source ^b	Design Efficiency, %			
	95	99	99.5	99.9
Bituminous coal fly ash	31.4	33.0	33.5	24.9
Sub-bituminous coal fly ash in tangential-fired boiler	40.0	42.7	44.1	31.4
Other coal	21.1	21.4	21.5	17.0
Cement kiln	6.4	5.6	5.0	5.7
Glass plant	4.6	4.5	4.3	3.8
Iron/steel snter plant dust with mechanical precollector	14.0	13.7	13.3	11.6

^a To convert cm/s to ft/s, multiply cm/s by 0.0328. Computational procedure uses SI units; to convert cm/s to m/s, multiply cm/s by 0.01. Assumes same particle size is given in full computational procedure.

^b All sources asumed at 200°F.

fluctuations. This is because the number of sections must be increased as the efficiency increases, and the changing sectionalization affects the overall migration velocity. This effect is particularly noticeable, for example, in Table 3.4 for glass plants. When the migration velocities in the tables are used to obtain SCAs for the different efficiencies in the tables, the SCAs will increase as the efficiency increases.

3.2.1.2 Full SCA Procedure

The full procedure for determining the SCA for large plate-wire, flat plate, and (with restrictions) tubular dry ESPs is given here. This procedure does not apply to the smaller, two-stage precipitators because these are packaged modules generally sized and sold on the basis of the waste gas volumetric flow rate. Nor does this procedure apply to determining the SCA for wet ESPs. The full procedure consists of the 15 steps given below:

Step 1 – Determine the design collection efficiency, Eff (%). Efficiency is the most commonly used term in the industry and is the reference value for guarantees. However, if it has not been specified, it can be computed as follows:

$$Eff (\%) = 100 \times \left(1 - \frac{\text{outlet load}}{\text{inlet load}} \right) \quad (3.18a)$$

Table 3.4: Flat Plate ESP Migratoin Velocities^a

Particle Source	Design Efficiency, %			
	95	99	99.5	99.9
Biguminous coal fly ash ^c	13.2	15.1	18.6	16.0
Sub-bituminous coal fly ash in tangential-fired boiler ^c	28.6	18.2	21.2	17.7
Other coal ^c	15.5	11.2	15.1	13.5
Cement kiln ^d	2.4	2.3	3.2	3.1
Glass plant ^e	1.8	1.9	2.6	2.6
Iron/steel sinter plant dust with mechanical precollector ^c	13.4	12.1	13.1	12.4
Kraft-paper recovery boiler ^c	5.0	4.7	6.1	5.3
Incinerator fly ash ^f	25.2	16.9	21.1	18.3

^a Assumes same particle size as given in full computational procedure. These values give the grounded collector plate SCA, from which the collector plate area is derived. In flat plate ESPs, the discharge or high-voltage plate area is typically 40% of the ground-plate area. The flat plate manufacturer usually counts all the plate area (collector plates plus discharge plates in meeting an SCA specification, which means that the velocities tabulated above must be divided by 1.4 to be used on the manufacturer's basis. BC = back corona.

^b To convert cm/s to ft/s, multiply cm/s by 0.0328. computational procedure uses SI units; to convert cm/s to m/s, multiply cm/s by 0.01.

^c At 300°F.

^d At 600°F.

^e At 500°F.

^f At 250°F.

Step 2 – Compute design penetration, p :

$$p = 1 - \left(\frac{Eff}{100} \right) \quad (3.17a)$$

Step 3 – Compute or obtain the operating temperature, T_k , °K. Temperature in Kelvin is required in the calculations which follow.

Step 4 – Determine whether severe back corona is present. Severe back corona usually occurs for dust resistivities above 2×10^{11} ohm-cm. Its presence will greatly increase the size of the ESP required to achieve a certain efficiency.

Step 5 – Determine the *MMD* of the inlet particle distribution MMD_i (μm). If this is not known, assume a value from the following table:

Table 3.5

Source	MMD_i (μm)
Bituminous coal	16
Sub-bituminous coal, tangential boiler	21
Sub-bituminous coal, other boiler types	10 to 15
Cement kiln	2 to 5
Glass plant	1
Wood burning boiler	5
Sinter plant,	50
with mechanical precollector	6
Kraft process recovery	2
Incinerators	15 to 30
Copper reverberatory furnace	1
Copper converter	1
Coke plant combustion stack	1
Unknown	1

Step 6 - Assume value for sneakage, S_N , and rapping reentrainment, RR , from the following tables:

Table 3.6

ESP Type	S_N
Plate-wire	0.07
Wet wall	0.05
Flat plate	0.10

Table 3.7

ESP/Ash Type	RR
Coal fly ash, or not known	0.14
Wet wall	0.0
Flat plate with gas velocity > 1.5 m/s (not glass or cement)	0.15
Glass or cement	0.10

Step 7 – Assume values for the most penetrating size, MMD_p , and rapping puff size, MMD_r :

$$MMD_p = 2 \mu\text{m} \quad (3.24)$$

$$MMD_r = 5 \text{ m for ash with } MMD_i > 5 \mu\text{m} \quad (3.25)$$

$$MMD_r = 3 \text{ m for ash with } MMD_i < 5 \mu\text{m} \quad (3.26)$$

where

MMD_p = MMD of the size distribution emerging from a very efficient collecting zone

MMD_r = MMD of the size distribution of rapped/reentrained material.

Step 8 – Use or compute the following factors for pure air:

$$\epsilon_0 = 8.845 \times 10^{-12} \text{ free space permittivity } \left(\frac{\text{F}}{\text{m}} \right) \quad (3.27)$$

$$\eta = 1.72 \times 10^{-5} \left(\frac{T_k}{273} \right)^{0.71} \text{ gas viscosity } \left(\frac{\text{kg}}{\text{m} \cdot \text{s}} \right) \quad (3.28)$$

$$E_{bd} = 630,000 \left(\frac{273}{T_k} \right)^{1.65} \text{ electric field at sparking } \left(\frac{\text{V}}{\text{m}} \right) \quad (3.29)$$

$$LF = S_N + RR (1 - S_N) \text{ loss factor (dimensionless)} \quad (3.30)$$

For plate-wire ESPs:

$$E_{avg} = \frac{E_{ba}}{1.75} \text{ average field with no back corona} \quad (3.31)$$

$$E_{avg} = 0.7 \times \frac{E_{ba}}{1.75} \text{ average field with severe back corona} \quad (3.32)$$

For flat plate ESPs:

$$E_{avg} = E_{bd} \times \frac{5}{6.3} \text{ average field, no back corona, positive polarity} \quad (3.33)$$

$$E_{avg} = 0.7 \times E_{bd} \times \frac{5}{6.3} \text{ average field, severe back corona, positive polarity} \quad (3.34)$$

Step 9 – Assume the smallest number of sections for the ESP, n , such that $LF^n < p$. Suggested values of n are:

These values are for an LF of 0.185, corresponding to a coal fly ash precipitator. The values are approximate, but the best results are for the smallest allowable n .

Table 3.8

Efficiency (%)	n
<96.5	2
<99	3
<99.8	4
<99.9	5
<99.9	6

Step 10 – Compute the average section penetration, p_s :

$$p_s = p^{\frac{1}{n}} \quad (3.35)$$

Step 11 – Compute the section collection penetration, p_c :

$$p_c = \frac{p_s - LF}{1 - LF} \quad (3.36)$$

If the value of n is too small, then this value will be negative and n must be increased.

Step 12 – Compute the particle size change factors, D and MMD_{rp} , which are constants used for computing the change of particle size from section to section:

$$\begin{aligned} D &= p_s = S_N + P_c (1 - S_N) + RR (1 - S_N) (1 - p_c) \\ &= MMD_{rp} = RR (1 - S_N) (1 - p_c) \frac{MMD_r}{D} \end{aligned} \quad (3.37)$$

Step 13 - Compute a table of particle sizes for sections 1 through n :

Table 3.9

Section MMDs	
1	MMD1 = MMDi
2	MMD2 = {MMD1 x S_N + [1 - p_c] x MMD _p + p_c x MMD1] x p_c }/D + MMD _{rp}
3	MMD3 = {MMD2 x S_N + [1 - p_c] x MMD _p + p_c x MMD2] x p_c }/D + MMD _{rp}
.	.
.	.
.	.
n	MMDn = {MMDn - 1 x S_N + [1 - p_c] x MMD _p + p_c x MMDn - 1] x p_c }/D + MMD _{rp}

Step 14 - Calculate the SCA for sections 1 through n , using MMD_n , η , ϵ , E_{avg} , and p_e :

$$SCA_1 = -\left(\frac{\eta}{\epsilon}\right) \times (1 - S_N) \times \frac{\ln(p_c)}{E_{avg}^2 \times MMD_1 \times 10^{-6}} \quad (3.38)$$

$$SCA_n = -\left(\frac{\eta}{\epsilon}\right) \times (1 - S_N) \times \frac{\ln(p_c)}{E_{avg}^2 \times MMD_n \times 10^{-6}} \quad (3.39)$$

where the factor 10^{-6} converts micrometers to meters. Note that the only quantity changing in these expressions is MMD_x ; therefore, the following relation can be used:

$$SCA_{n+1} = SCA_n \times \frac{MMD_n}{MMD_{n+1}} \quad (3.40)$$

Step 15 – Calculate the total *SCA* and the English *SCA*, *ESCA*:

$$SCA \left(\frac{s}{m} \right) = \sum_{i=1}^n SCA_i \quad (3.41)$$

$$ESCA \left(\frac{ft^2}{kacfm} \right) = 5.080 \times SCA \left(\frac{s}{m} \right) \quad (3.42)$$

This sizing procedure works best for p_c values less than the value of LF , which means the smallest value of n . Any ESP model is sensitive to the values of particle diameter and electric field. This one shows the same sensitivity, but the expressions for electric field are based on theoretical and experimental values. The *SCA* should not be strongly affected by the number of sections chosen; if more sections are used, the *SCA* of each section is reduced.

3.2.1.3 Specific Collecting Area for Tubular Precipitators

The procedure given above is suitable for large plate-wire or flat plate ESPs, but must be used with restrictions for tubular ESPs. Values of $S_N = 0.015$ and $RR = 0$ are assumed, and only one section is used.

Table 3.10 gives migration velocities that can be used with Equation 3.23 to calculate *SCAs* for several tubular ESP applications.

3.2.2 Flow Velocity

A precipitator collecting a dry particulate material runs a risk of nonrapping (continuous) reentrainment if the gas velocity becomes too large. This effect is independent of *SCA* and has

been learned through experience. For fly ash applications, the maximum acceptable velocity is about 1.5 m/s (5 ft/s) for plate-wire ESPs and about 1 m/s (3 ft/s) for flat plate ESPs. For low resistivity applications, design velocities of 3 ft/s or less are common to avoid nonrapping reentrainment. The frontal area of the ESP ($W \times H$), e.g., the area normal to the direction of gas flow, must be chosen to keep gas velocity low and to accommodate electrical requirements (e.g., wire-to-plate spacing) while also ensuring that total plate area requirements are met. This area can be configured in a variety of ways. The plates can be short in height, long in the direction of flow, with several in parallel (making the width narrow). Or, the plates can be tall in height, short in the

Table 3.10: Tubular ESP Migration Velocities
(cm/s)^b

Particle Source		Design Efficiency, %	
		90	95
Cement kiln	(no BC)	2.2-5.4	2.1-5.1
	(BC)	1.1-2.7	1.0-2.6
Glass plant	(no BC)	1.4	1.3
	(BC)	0.7	0.7
Kraft-paper recovery boiler	(no BC)	4.7	4.4
Incinerator 15 μ m MMD	(no BC)	40.8	39.
Wet, at 200°F MMD(μ m)			
	1	3.2	3.1
	2	6.4	6.2
	5	16.1	15.4
	10	32.2	30.8
	20	64.5	61.6

BC = Back corona

^a These rates were calculated on the basis of: $S_N = 0.015$, $RR = 0$, one section only. These are in agreement with operating tubular ESPs; extension of results to more than one section is not recommended.

^b To convert cm/s to ft/s, multiply cm/s by 0.0328.

direction of flow, with many in parallel making the width large). After selecting a configuration, the gas velocity can be obtained by dividing the volume flow rate, Q , by the frontal area of the ESP:

$$v_{gas} = \frac{Q}{WH} \quad (3.43)$$

where:

v_{gas}	=	gas velocity (m/s)
W	=	width of ESP entrance (m)
H	=	height of ESP entrance (m)

When meeting the above restrictions, this value of velocity also ensures that turbulence is not strongly developed, thereby assisting in the capture of particles.

3.2.3 Pressure Drop Calculations

The pressure drop in an ESP is due to four main factors:

- Diffuser plate (usually present)—(perforated plate at the inlet)
- Transitions at the ESP inlet and outlet
- Collection plate baffles (stiffeners) or corrugations
- Drag of the flat collection plate

The total pressure drop is the sum of the individual pressure drops, but any one of these sources may dominate all other contributions to the pressure drop. Usually, the pressure drop is not a design-driving factor, but it needs to be maintained at an acceptably low value. Table 3.11 gives typical pressure drops for the four factors. The ESP pressure drop, usually less than about 0.5 in. H₂O, is much lower than for the associated collection system and ductwork. With the conveying velocities used for dust collected in ESPs, generally 4,000 ft/min or greater, system pressure drops are usually in the range of 2 to 10 in H₂O, depending upon the ductwork length and configuration as well as the type(s) of preconditioning device(s) used upstream.

The four main factors contributing to pressure drop are described briefly below.

The diffuser plate is used to equalize the gas flow across the face of the ESP. It typically consists of a flat plate covered with round holes of 5 to 7 cm diameter (2 to 2.5 in.) having an open area of 50 to 65 percent of the total. Pressure drop is strongly dependent on the percent open area, but is almost independent of hole size.

Table 3.11: Components of ESP Pressure Drop

Component	Typical Pressure Drop (in. H ₂ O)	
	Low	High
Diffuser	0.010	0.09
Inlet transition	0.07	0.14
Outlet transition	0.007	0.015
Baffles	0.0006	0.123
Collection plates	0.0003	0.008
Total	0.09	0.38

The pressure drop due to gradual enlargement at the inlet is caused by the combined effects of flow separation and wall friction and is dependent on the shape of the enlargement. At the ESP exit, the pressure drop caused by a short, well-streamlined gradual contraction is small.

Baffles are installed on collection plates to shield the collected dust from the gas flow and to provide a stiffening effect to keep the plates aligned parallel to one another. The pressure drop due to the baffles depends on the number of baffles, their protrusion into the gas stream with respect to electrode-to-plate distance, and the gas velocity in the ESP.

The pressure drop of the flat collection plates is due to friction of the gas dragging along the flat surfaces and is so small compared to other factors that it may usually be neglected in engineering problems.

3.2.4 Particle Characteristics

Several particle characteristics are important for particle collection. It is generally assumed that the particles are spherical or spherical enough to be described by some equivalent spherical diameter. Highly irregular or elongated particles may not behave in ways that can be easily described.

The first important characteristic is the mass of particles in the gas stream, *i.e.*, the particle loading. This quantity usually is determined by placing a filter in the gas stream, collecting a known volume of gas, and determining the weight gain of the filter. Because the ESP operates over a wide range of loadings as a constant efficiency device, the inlet loading will determine the outlet loading directly. If the loading becomes too high, the operation of the ESP will be altered, usually for the worse.

The second characteristic is the size distribution of the particles, often expressed as the cumulative mass less than a given particle size. The size distribution describes how many particles of a given size there are, which is important because ESP efficiency varies with particle size. In practical terms, an ESP will collect all particles larger than 1.0 μm in diameter better than ones smaller than 10 μm . Only if most of the mass in the particles is concentrated above 10 μm would the actual size distribution above 10 μm be needed.

In lieu of cumulative mass distributions, the size distribution is often described by log-normal parameters. That is, the size distribution appears as a probabilistic normal curve if the logarithm of particle size used is the abscissa. The two parameters needed to describe a log-normal distribution are the mass median (or mean) diameter and the geometric standard deviation.

The *MMD* is the diameter for which one-half of the particulate mass consists of smaller particles and one-half is larger (see the Procedure, Step 5, of Subsection 3.2.1.2). If the *MMD* of a distribution is larger than about 3 μm , the ESP will collect all particles larger than the *MMD* at least as well as a 3 μm particle, representing one-half the mass in the inlet size distribution.

The geometric standard deviation is the equivalent of the standard deviation of the normal distribution: It describes how broad the size distribution is. The geometric standard deviation is computed as the ratio of the diameter corresponding to 84 percent of the total cumulative mass to the *MMD*; it is always a number greater than 1. A distribution with particles of all the same size (monodisperse) has a geometric standard deviation of 1. Geometric standard deviations less than 2 represent rather narrow distributions. For combustion sources, the geometric standard deviations range from 3 to 5 and are commonly in the 3.5 to 4.5 range.

A geometric standard deviation of 4 to 5, coupled with an *MMD* of less than 5 μm , means that there is a substantial amount of submicrometer material. This situation may change the electrical conditions in an ESP by the phenomenon known as “space charge quenching”, which results in high operating voltages but low currents. It is a sign of inadequate charging and reduces the theoretical efficiency of the ESP. This condition must be evaluated carefully to be sure of adequate design margins.

3.2.5 Gas Characteristics

The gas characteristics most needed for ESP design are the gas volume flow and the gas temperature. The volume flow, multiplied by the design *SCA*, gives the total plate area required for the ESP. If the volume flow is known at one temperature, it may be estimated at other temperatures by applying the ideal gas law. Temperature and volume uncertainties will outweigh inaccuracies of applying the ideal gas law.

The temperature of the gas directly affects the gas viscosity, which increases with temperature. Gas viscosity is affected to a lesser degree by the gas composition, particularly the water vapor content. In lieu of viscosity values for a particular gas composition, the viscosity for air may be used. Viscosity enters the calculation of *SCA* directly, as seen in Step 14 of the design procedure.

The gas temperature and composition can have a strong effect on the resistivity of the collected particulate material. Specifically, moisture and acid gas components may be chemisorbed on the particles in a sufficient amount to lower the intrinsic resistivity dramatically (orders of magnitude). For other types of materials, there is almost no effect. Although it is not possible to treat resistivity here, the designer should be aware of the potential sensitivity of the size of the ESP to resistivity and the factors influencing it.

The choice of the power supply size (current capacity and voltage) to be used with a particular application may be influenced by the gas characteristics. Certain applications produce gas whose density may vary significantly from typical combustion sources (density variation may result from temperature, pressure, and composition). Gas density affects corona starting voltages and voltages at which sparking will occur.

3.2.6 Cleaning

Cleaning the collected materials from the plates often is accomplished intermittently or continuously by rapping the plates severely with automatic hammers or pistons, usually along their top edges, except in the case of wet ESPs that use water. Rapping dislodges the material, which then falls down the length of the plate until it lands in a dust hopper. The dust characteristics, rapping intensity, and rapping frequency determine how much of the material is reentrained and how much reaches the hopper permanently.

For wet ESPs, consideration must be given to handling waste waters. For simple systems with innocuous dusts, water with particles collected by the ESP may be discharged from the ESP system to a solids-removing clarifier (either dedicated to the ESP or part of the plant wastewater treatment system) and then to final disposal. More complex systems may require skimming and sludge removal, clarification in dedicated equipment, pH adjustment, and/or treatment to remove dissolved-solids. Spray water from the ESP preconditioner may be treated separately from the water used to flood the ESP collecting plates, so that the cleaner of the two treated waters may be returned to the ESP. Recirculation of treated water to the ESP may approach 100 percent.

The hopper should be designed so that all the material in it slides to the very bottom, where it can be evacuated periodically, as the hopper becomes full. Dust is removed through a valve into a dust-handling system, such as a pneumatic conveyor. Hoppers often are supplied with auxiliary heat to prevent the formation of lumps or cakes and the subsequent blockage of the dust handling system.

3.2.7 Construction Features

The use of the term “plate-wire geometry” may be somewhat misleading. It could refer to three different types of discharge electrodes: weighted wires hung from a support structure at the top of the ESP, wire frames in which wires are strung tautly in a rigid support frame, or rigid electrodes constructed from a single piece of fabricated metal. In recent years, there has been a trend toward using wire frames or rigid discharge electrodes in place of weighted wire discharge electrodes (particularly in coal-fired boiler applications). This trend has been stimulated by the user’s desire for increased ESP reliability. The wire frames and rigid electrodes are less prone to failure by breakage and are readily cleaned by impulse-type cleaning equipment.

Other differences in construction result from the choice of the ratio of gas passage (flow lane) width or discharge electrode to collecting electrode spacing. Typically, discharge to collecting electrode spacing varies from 11 to 19 cm (4.3 to 7.5 in.). Having a large spacing between discharge and collecting electrodes allows higher electric fields to be used, which tends to improve dust collection. To generate larger electric fields, however, power supplies must produce higher operating voltages. Therefore, it is necessary to balance the cost savings achieved with larger electrode spacing against the higher cost of power supplies that produce higher operating voltages.

Most ESPs are constructed of mild steel. ESP shells are constructed typically of 3/16 or 1/4 in. mild steel, plate. Collecting electrodes are generally fabricated from lighter gauge mild steel. A thickness of 18 gauge is common, but it will vary with size and severity of application.

Wire discharge electrodes come in varied shapes from round to square or barbed. A diameter of 2.5 mm (0.1 in.) is common for weighted wires, but other shapes used have much larger effective diameters, e.g., 64 mm (0.25 in.) square electrodes.

Stainless steel may be used for corrosive applications, but it is uncommon except in wet ESPs. Stainless steel discharge electrodes have been found to be prone to fatigue failure in dry ESPs with impact-type electrode cleaning systems.[3]

Precipitators used to collect sulfuric acid mist in sulfuric acid plants are constructed of steel, but the surfaces in contact with the acid mist are lead-lined. Precipitators used on paper mill black liquor recovery boilers are steam-jacketed. Of these two, recovery boilers have by far the larger number of ESP applications.

3.3 Estimating Total Capital Investment

Total capital investment (TCI) for an ESP system includes costs for the ESP structure, the internals, rappers, power supply, auxiliary equipment, and the usual direct and indirect costs associated with

installing or erecting new control equipment. These costs, in **second-quarter 1987** dollars, are described in the following subsections.⁸

3.3.1 Equipment Cost

3.3.1.1 ESP Costs

Five types of ESPs are considered: plate-wire, flat plate, wet, tubular, and two-stage. Basic costs for the first two are taken from Figure 3.5, which gives the flange-to-flange, field-erected price based on required plate area and a rigid electrode design. This plate area is calculated from the sizing information given previously for the four types. Adjustments are made for standard options listed in Table 3.12. Costs for wet/tubular ESPs are discussed under Recent Trends, below, and costs for two-stage precipitators are given in a later subsection.

The costs are based on a number of actual quotes. Least squares lines have been fitted to the quotes, one for sizes between 50,000 and 1,000,000 ft² and a second for sizes between 10,000 and 50,000 ft². An equation is given for each line. Extrapolation below 10,000 or above 1,000,000 ft² should not be used. The reader should not be surprised if quotes are obtained that differ from these curves by as much as ± 25 percent. Significant savings can be had by soliciting multiple quotes. All Units include the ESP casing, pyramidal hoppers, rigid electrodes and internal collecting plates, transformer rectifier (TR) sets and microprocessor controls, rappers, and stub supports (legs) for 4 feet clearance below the hopper discharges. The lower curve is the basic unit without the standard options. The upper curve includes all of the standard options (see Table 3.12) that are normally utilized in a modern system. These options add approximately 45 percent to the basic cost of the flange-to-flange hardware. Insulation costs are for 3 in. of field-installed glass fiber encased in a metal skin and applied on the outside of all areas in contact with the exhaust gas stream. Insulation for ductwork, fan casings, and stacks must be calculated separately.

Impact of alternative electrode designs All three designs—rigid electrode, weighted wire, and rigid frame—can be employed in most applications. Any cost differential between designs will depend on the combination of vendor experience and site-specific factors that dictate equipment size factors. The rigid frame design will cost up to 25 percent more if the mast or plate height is restricted to the same used in other designs. Several vendors can now provide rigid frame collectors with longer plates, and thus the cost differential can approach zero.

The weighted wire design uses narrower plate spacings and more internal discharge electrodes. This design is being employed less; therefore, its cost is increasing and currently is

⁸ For information on escalating these prices to more current dollars, refer to the EPA report *Escalation Indexes for Air Pollution Control Costs* and updates thereto, all of which are installed on the OAQPS Technology Transfer Network (CTC Bulletin Board).

approximately the same as that for the rigid electrode collector. Below about 15,000 ft² of plate area, ESPs are of different design and are not normally field erected, and the costs will be significantly different from values extrapolated from Figure 3.5.

Impact of materials of construction: metal thickness and stainless steel Corrosive or other adverse operating conditions may suggest the specification of thicker metal sections in the precipitator. Reasonable increases in metal sections result in minimal cost increases. For example, collecting plates are typically constructed of 18 gauge mild steel. Most ESP manufacturers can increase the section thickness by 25 percent without significant design changes or increases in manufacturing costs of more than a few percent.

Changes in type of material can increase purchase cost of the ESP from about 30 to 50 percent for type 304 stainless steel collector plates and precipitator walls, and up to several hundred percent for more expensive materials used for all elements of the ESP. Based on the type 304 stainless steel cost, the approximate factors given in Table 3.13 can be used for other materials. Appendix A provides more detail on the effects of material thickness and type.

Lower limits for condensable stack emissions (MACT and Risk Assessment), have resulted in increased demand for Wet ESTs.[7]

Recent trends As of 1987, most of the market was in the 50,000 to 200,000 ft² plate area size range. ESP selling prices had increased very little over the previous 10 years because of more effective designs, increased competition from European suppliers, and a shrinking utility market.

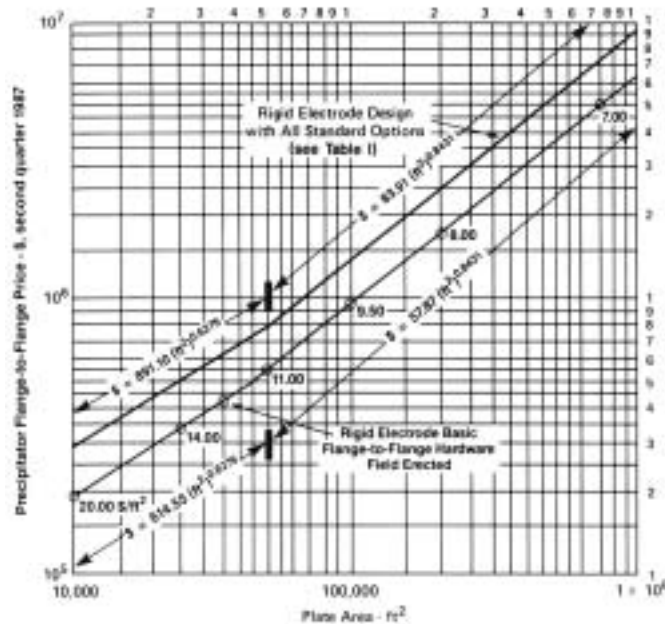


Figure 3.5: Dry-type ESP flange-to-flange purchase price vs. plate area.

Table 3.12: Standard Options for Basic Equipment

Option		Cost adder (%)
1	Inlet and outlet nozzles and diffuser plates	8 to 10
2	Hopper auxiliaries/heaters, level detectors	8 to 10
3	Weather enclosures and stair access	8 to 10
4	Structural supports	5
5	Insulation	8 to 10
Total options 1 to 5		1.37 to 1.45 x Base

Table 3.13

Material	Factor	Reference(s)
Stainless steel, 316	1.3	[4,5,6]
Carpenter 20CB-3	1.9	[6]
Monel-400	2.3	[4,6]
Nickel-200	3.2	[6]
Titanium	4.5	[6]

Industry sources report that ESP costs (1999) have not changed significantly since 1987. [8][9] Design improvements have allowed wider plate spacings that reduce the number of internal components and higher plates and masts that provide additional plate area at a low cost. Wider plate spacing has reduced overall material and installation costs, easily compensating for any increases in material and labor costs.[7] Downflow tubular Wet ESPs use gravity to remove water and entrained particulate which has been collected onto the tubes, resulting in low operational costs. These units can be designed to intermittently wash the tubes while on line. Tubular units are typically delivered as “shop assembled” modules because the tubes are welded together in bundles. The size of the modules is limited by shipping considerations. Plate type units are usually shipped “knocked down”. These units do have the same size limitations as tubular Wet ESPs, but do not require comparatively more labor for field installation. Use of high-grade alloys for corrosive applications (e.g., incinerators) increases material costs.[7] Microprocessor controls and energy management systems have lowered operating costs.

Table 3.14 lists costs (total and per acfm) for various gas volumes and removal efficiencies for Wet ESPs. For larger gas volumes, multiple modules may be used. The pricing is based on “shop assembled” modules.[7]

Table 3.14: Air Pollution Wet Electrostatic Precipitator

Saturated Volume (acfm)	80% Efficiency		85% Efficiency		90% Efficiency		95% Efficiency	
	Price (\$x1000)	Price (\$/acfm)	Price (\$x1000)	Price (\$/acfm)	Price (\$x1000)	Price (\$/acfm)	Price (\$x1000)	Price (\$/acfm)
10,000	315	31.5	327	32.7	339	33.9	365	36.5
15,000	342	22.8	355	23.7	378	25.5	408	27.2
20,000	369	18.5	385	19.3	412	20.6	451	22.6
25,000	398	16.0	423	17.0	448	18.0	---	---
30,000	427	14.3	441	14.7	---	---	---	---
35,000	442	12.7	---	---	---	---	---	---

Few, if any, hot-side ESPs (those used upstream from an air preheater on a combustion source) are being specified for purchase. Recognition that low sodium coals tend to build resistive ash layers on the collection plates, thus reducing ESP efficiency, has almost eliminated sales of these units. Of about 150 existing units, about 75 are candidates for conversion to cold-side units over the next 10 years.

Specific industry application has little impact on either ESP design or cost, with three exceptions: paper mills and sulfuric acid manufacturing plants, and coke by-product plants. Paper mill ESPs use drag conveyor hoppers that add approximately 10 percent to the base flange-to-flange equipment cost. For emissions control in sulfuric acid plants and coke byproduct ovens, wet ESPs are used. In sulfuric acid manufacture, wet ESPs are used to collect acid mist. These precipitators usually are small, and they use lead for all interior surfaces; hence, they normally cost \$65 to \$95/ft² of collecting area installed (mid-1987 dollars) and up to \$120/ft² in special situations. In addition, a wet circular ESP is used to control emissions from a coke oven off-gas detarring operation. These precipitators are made using high-alloy stainless steels and typically cost \$90 to \$120/ft², installed. Because of the small number of sales, small size of units sold, and dependency on site-specific factors, more definitive costs are not available.

3.3.1.2 Retrofit Cost Factor

Retrofit installations increase the costs of an ESP because of the common need to remove something to make way for the new ESP. Also, the ducting usually is much more expensive. The ducting path is often constrained by existing structures, additional supports are required, and the confined areas make erection more labor intensive and lengthy. Costs are site-specific; however, for estimating purposes, a retrofit multiplier of 1.3 to 1.5 applied to the total capital investment can be used. The multiplier should be selected within this range based on the relative difficulty of the installation.

A special case is conversion of hot-to-cold side ESPs for coal-fired boiler applications. The magnitude of the conversion is very site-specific, but most projects will contain the following elements:

- Relocating the air preheater and the ducting to it
- Resizing the ESP inlet and outlet duct to the new air volume and rerouting it
- Upgrading the ID (induced draft) fan size or motor to accommodate the higher static pressure and horsepower requirements
- Adding or modifying foundations for fan and duct supports
- Assessing the required SCA and either increasing the collecting area or installing an SO₃ gas-conditioning system
- Adding hopper heaters
- Upgrading the analog electrical controls to microprocessor-type controls
- Increasing the number of collecting plate rappers and perhaps the location of rapping

In some installations, it may be cost-effective to gut the existing collector totally, utilize only the existing casing and hoppers, and upgrade to modern internals.

The cost of conversion is a multimillion dollar project typically running at least 25 to 35 percent of the total capital investment of a new unit.

3.3.1.3 Auxiliary Equipment

The auxiliary equipment depicted in Figure 3.2 is discussed elsewhere in the Manual. Because dust-removal equipment (e.g., screw conveyers), hoods, precoolers, cyclones, fans, motors, and stacks are common to many pollution control systems, they are (or will be) given extended treatment in separate sections.

3.3.1.4 Costs for Two-Stage Precipitators

Purchase costs for two-stage precipitators, which should be considered separately from large-scale, single-stage ESPs, are given in Figure 3.6.[10] To be consistent with industry practice, costs are given as a function of flow rate through the system. The lower cost curve is for a two-cell unit without precooler, an installed cell washer, or a fan. The upper curve is for an engineered, package system with the following components: inlet diffuser plenum, prefilter, cooling coils with coating, coil plenums with access, water flow controls, triple pass configuration, system exhaust fan with accessories, outlet plenum, and in-place foam cleaning system with semiautomatic controls and programmable controller. All equipment is fully assembled mechanically and electrically, and it is mounted on a steel structural skid.

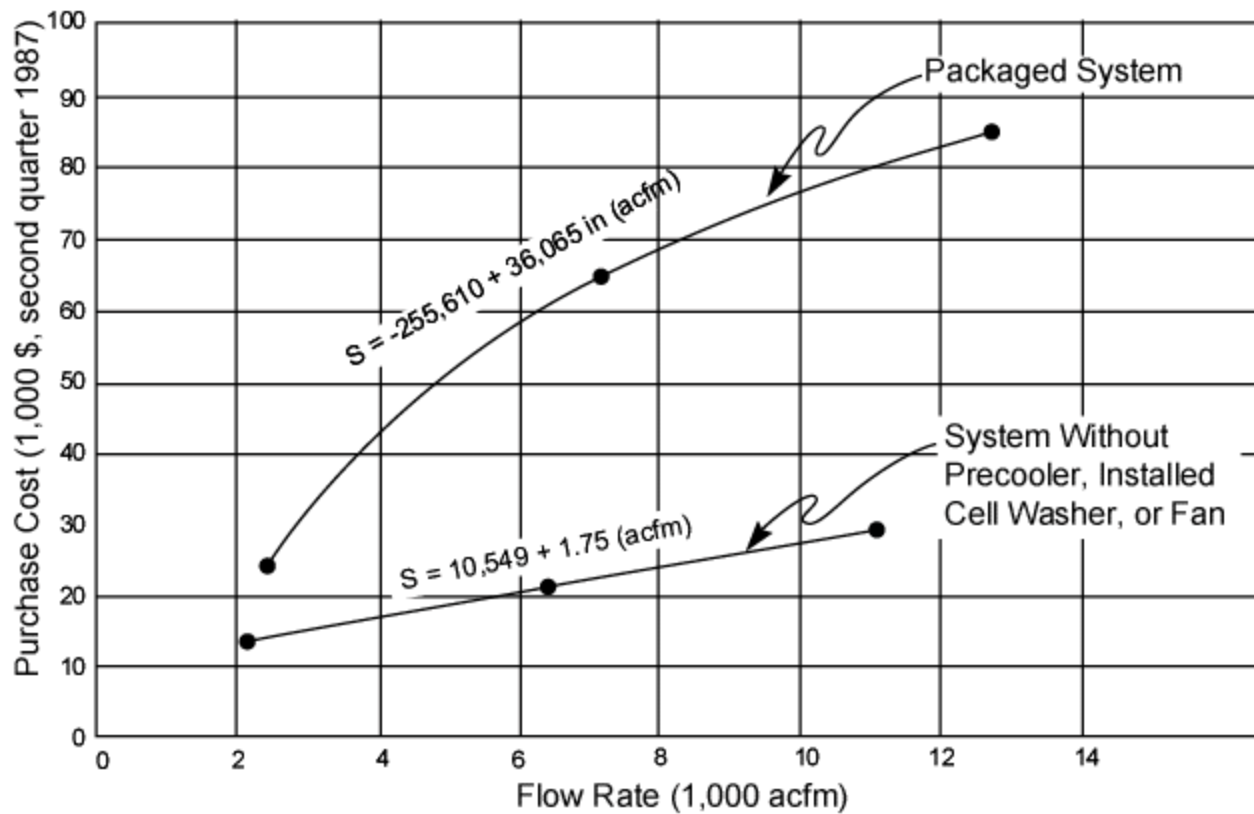


Figure 3.6: Purchase Costs for Two-stage, Two-cell Precipitators [40]

3.3.2 Total Purchased Cost

The total purchased cost of an ESP system is the sum of the costs of the ESP, options, auxiliary equipment, instruments and controls, taxes, and freight. The last three items generally are taken as percentages of the estimated total cost of the first three items. Typical values, from Section 1 of the Manual, are 10 percent for instruments and controls, 3 percent for taxes, and 5 percent for freight.

Costs of standard and other options can vary from 0 to more than 150 percent of bare ESP cost, depending on site and application requirements. Other factors that can increase ESP costs are given in Table 3.15.

Table 3.15: Items That Increase ESP Costs

Item	Factor	Applied
Rigid frame electrode with restricted plate height	1.0 to 1.25	ESP base coat
Type 304 stainless steel collector plates and precipitator walls	1.3 to 1.5	ESP base coat
All stainless steel construction	2 to 3	ESP base coat
ESP with drag conveyor hoppers (paper mill)	1.1	ESP base coat
Retrofit installations	1.3 to 1.5	ESP total capital investment (new facility installation)
Wet ESP		
Sulfuric acid mist	See 3.3.1.1	---
Sulfuric acid mist (special installation)	See 3.3.1.1	---
Coke oven off gas	See 3.3.1.1	---

3.3.3 Total Capital Investment (TCI)

Using the Section 1.2 methodology, TCI is estimated from a series of factors applied to the purchased equipment cost to obtain direct and indirect costs for installation. The TCI is the sum of these three costs. The required factors are given in Table 3.16. Because ESPs may vary from small units attached to existing buildings to large, separate structures, specific factors for site preparation or for buildings are not given. However, costs for buildings may be obtained from such references as Means Square Foot Costs 1987 [11]. Land, working capital, and off-site facilities are excluded from the table because they are not normally required. For very large installations, however, they may be needed and could be estimated on an as-needed basis.

Note that the factors given in Table 3.16 are for average installation conditions, e.g., no unusual problems with site earthwork, access, shipping, or interfering structures. Considerable variation may be seen with other-than-average installation circumstances. For two-stage precipitators purchased as packaged systems, several of the costs in Table 3.16 would be greatly reduced or eliminated. These include instruments and controls, foundations and supports, erection and handling, painting, and model studies. An installation factor of 0.20 B to 0.25 B would be more nearly appropriate for the two-stage ESPs.

3.4 Estimating Total Annual Costs

3.4.1 Direct Annual Costs

Direct annual costs include operating and supervisory labor, operating materials, replacement rappers and electrodes, maintenance (labor and materials), utilities, dust disposal, and wastewater treatment for wet ESPs. Most of these costs are discussed individually below. They vary considerably with location and time and, for this reason, should be obtained to suit the specific ESP system being costed. For example, current labor rates may be found in such publications as the Monthly Labor Review, published by the U.S. Department of Labor, Bureau of Labor Statistics.

3.4.1.1 Operating and Supervisory Labor

Proper operation of the ESP is necessary both to meet applicable particulate emission regulations and to ensure minimum costs. An ESP is an expensive piece of equipment. Even well-designed equipment will deteriorate rapidly if improperly maintained and will have to be replaced long before it should be necessary. Not only can proper operation and maintenance save the operator money, such an operation and maintenance program can also contribute to good relations with the governing pollution control agency by showing good faith in efforts to comply with air regulations.

Although each plant has its own methods for conducting an operation and maintenance program, experience has shown that plants that assign one individual the responsibility of coordinating all the pieces of the program operate better than those where different departments look after only a certain portion of the program. The separate departments have little knowledge of how their portion impacts the overall program. In other words, a plant needs one individual to coordinate the operation, maintenance, and troubleshooting components of its ESP program if it expects to have a relatively trouble-free operation. The coordinator typically is an engineer who reports to plant management and interfaces with the maintenance and plant process supervisors, the laboratory, and the purchasing department. For companies with more than one plant, he would be responsible for all ESPs. The portion of his total time that this individual spends on the ESP then becomes an operating expense for the ESP. This can be expressed as:

Table 3.16: Capital Cost Factors for ESPs^a [26]

Cost Item	Factor
<u>Direct Costs</u>	
Purchased equipment costs	
ESP + auxiliary equipment	As estimated, A
Instrumentation	0.10 A
Sales taxes	0.03 A
Freight	0.05 A
Purchased equipment cost, PEC	B = 1.18 A
Direct installation costs	
Foundations & supports	0.04 B
Handling & erection	0.50 B
Electrical	0.08 B
Piping	0.01 B
Insulation for ductwork ^a	0.02 B
Painting	0.02 B
Direct installation costs	0.67 B
Site preparation	As required, SP
Buildings	As required, Bldg.
Total Direct Costs, DC ^b	1.67 B + SP + Bldg.
<u>Indirect Costs (installation)</u>	
Engineering	0.20 B
Construction and field expenses	0.20 B
Contractor fees	0.10 B
Start-up	0.01 B
Performance test	0.01 B
Model study	0.02 B
Contingencies	0.03 B
Total Indirect Costs, IC	0.57 B
Total Capital Investment = DC + IC	2.24 B + SP + Bldg.

^a If ductwork dimensions have been established, cost may be estimated based on \$10 to \$12/ft² of surface for field application. (Alternatively, refer to Section 2 of this Manual.) Fan housing and stacks may also be insulated. [42]

^b For two stage precipitators, total installation direct costs are more nearly 0.20 to 0.25 + SP + Bldg.

$$AC = X (LCC) \quad (3.44)$$

where

AC	=	annual coordination cost (\$/yr)
X	=	fraction of total time spent on ESP
LCC	=	individual annual labor cost for ESP coordinator (\$/yr)

In addition to coordination costs, typical operating labor requirements are 1/2 to 2 hours per shift for a wide range of ESP sizes.[8] Small or well-performing units may require less time, and very large or troublesome units may require more time. Supervisory labor is taken as 15 percent of operating labor.

3.4.1.2 Operating Materials

Operating materials are generally not required for ESPs. An exception is the use of gas-preconditioning agents for dust resistivity control.

3.4.1.3 Maintenance

The reader should obtain Publication No. EPA/625/1-85/017, Operating and Maintenance Manual for ESPs,[13] for suggested maintenance practices. Routine ESP maintenance labor costs can be estimated using data provided by manufacturers. If such data are unavailable, the following procedure can be used. Based on data for a 100,000 ft² collector, maintenance labor is estimated to require 15 h/wk, 44 wk/yr. At a direct labor cost of \$12.50/h (mid-1987 costs), an estimated annual maintenance labor cost of \$8,250 or \$0.0825/ft² of collector area is established. This relationship can be assumed to be linear above a 50,000 ft² collector-size and constant at \$4,125 below this size. To the maintenance labor cost must be added the cost of maintenance materials. Based on an analysis of vendor information, annual maintenance materials are estimated as 1 percent of the flange-to-flange precipitator purchase cost:

$$MC = 0.01 (FCC) + labor\ cost \quad (3.45)$$

where

MC	=	annual maintenance cost (\$/yr)
FCC	=	ESP flange-to-flange purchase cost (\$)
$labor\ cost$	=	\$4,125 if $A < 50,000\ ft^2$ 0.825 A if $> 50,000ft^2$

and

A	=	ESP plate area (ft ²)
-----	---	-----------------------------------

3.4.1.4 Electricity

Power is required to operate system fans, transformer-rectifier (TR) sets, and cleaning equipment. Fan power for primary gas movement can be calculated as described in Section 2 of the Manual. After substituting into this equation a combined fan-motor efficiency of 0.65 and a specific gravity of 1.0, we obtain:

$$FP = 0.000181 (Q) (\Delta P) (\theta') \quad (3.46)$$

where

FP	=	fan power requirement (kWh/yr)
Q	=	system flow rate (acfm)
ΔP	=	system pressure drop (in. H ₂ O)
θ'	=	annual operating time (h/yr)

Pump power for wet ESPs can be calculated from:

$$PP = \frac{0.746 Q_i Z S_g \theta'}{3,960 \eta} \quad (3.47)$$

where

PP	=	pump power requirement (kWh/yr)
Q	=	water flow rate (gal/min)
Z	=	fluid head (ft)
S_g	=	specific gravity of water being pumped compared to water at 70°F and 29.92 in. Hg
θ'	=	annual operating time (h/yr)
η	=	pump-motor efficiency (fractional)

Energy for TR sets and motor-driven or electromagnetic rapper systems is the sum of the energy consumption for operating both items. Manufacturers' averaged data indicate that the following relationship can be used:

$$OP = 1.94 \times 10^{-3} A \theta' \quad (3.48)$$

where

OP	=	annual ESP operating power (kWh/yr)
A	=	ESP plate area (ft ²)
θ'	=	annual operating time (h/yr)

For installations requiring hopper heaters, hopper heater power can be similarly estimated:

$$HH = 2 (HN) \theta' \quad (3.49)$$

where

HH	=	annual hopper heater power consumption (kWh/yr)
HN	=	number of hoppers
θ'	=	annual operating time (h/yr)

For two-stage precipitators, power consumption ranges from 25 to 100 W/kacfm, with 40 W/kacfm being typical.

3.4.1.5 Fuel

If the ESP or associated ductwork is heated to prevent condensation, fuel costs should be calculated as required. These costs can be significant, but they may be difficult to predict. For methods of calculating heat transfer requirements, see Perry. [14]

3.4.1.6 Water

Cooling process gases for preconditioning can be done by dilution with air, evaporation with water, or heat exchange with normal equipment. Spray cooling requires consumption of plant water (heat exchangers may also require water), although costs are not usually significant. Section 1 of the Manual provides information on estimating cooling water costs. Water consumption in wet ESPs is estimated at 5 gal/min kacfm [15] for large single-stage units and 16 gal/min-kacfm for two-stage precipitators.[16]

3.4.1.7 Compressed Air

ESPs may use compressed air at pressures of about 60 to 100 psig for operating rappers. Equivalent power cost is included in Equation 3.9 for operating power.

3.4.1.8 Dust Disposal

If collected dust cannot be recycled or sold, it must be landfilled or disposed of in some other manner. Costs may typically run \$20/ton or \$30/ton for nonhazardous wastes exclusive of transportation (see Section 1 of the Manual). Landfilling of hazardous wastes may cost 10 times as much. The disposal costs are highly site-specific and depend on transportation distance to the landfill, handling rates, and disposal unloading (tipping) fees. If these factors are known, they lead to the relationship:

$$DD = 4.29 \times 10^{-6} G \theta' Q [T + (TM) D] \quad (3.50)$$

where

DD	=	annual dust disposal cost (\$/yr)
G	=	ESP inlet grain loading or dust concentration (gr /ft ³)
θ'	=	annual operating time (h/yr)
Q	=	gas flow rate through ESP (acfm)
T	=	tipping fee (\$/ton)
TM	=	mileage rate (\$/ton-mile)
D	=	dust hauling distance (miles)

3.4.1.9 Wastewater Treatment

As indicated above, the water usage for wet ESPs is about 5 gal/min kacfm.[15] Treatment cost of the resulting wastewater may vary from about \$1.30 to \$2.15/1,000 gal [16] depending on the complexity of the treatment system. More precise costs can be obtained from Gumerman *et al.*[18]

3.4.1.10 Conditioning Costs

Adaptation of information on utility boilers [19] suggests that SO₃ conditioning for a large ESP (2.6 x 10⁶ acfm) costs from about \$1.60/10⁶ ft³ of gas processed for a sulfur burner providing 5 ppm SO₃ to about \$2.30/10⁶ ft³ (in first-quarter 1987 dollars) for a liquid SO₂ system providing 20 ppm of SO₃.

3.4.2 Indirect Annual Costs

Capital recovery, property taxes, insurance, administrative costs (“G&A”), and overhead are examples of indirect annual costs. The capital recovery cost is based on the equipment lifetime and the annual interest rate employed. (See Section 1 for a thorough discussion of the capital recovery cost and the variables that determine it.) For ESPs, the system lifetime varies from 5 to 40 years, with 20 years being typical. Therefore, as Section 1 of the Manual suggests, when figuring the system capital recovery cost, one should base it on the total capital investment. In other words:

$$CRC_s = TCI \times CRF_s \quad (3.51)$$

where

- CRC_s = capital recovery cost for ESP system (\$/yr)
- TCI = total capital investment (\$)
- CRF_s = capital recovery factor for ESP system (defined in Section 1.2)

For example, for a 20-year system life and a 7 percent annual interest rate, the CRF_s s would be 0.09439.

The suggested factor to use for property taxes, insurance, and administrative charges is 4 percent of the TCI. Overhead is calculated as 60 percent of the sum of operating, supervisory, coordination, and maintenance labor, as well as maintenance materials.

3.4.3 Recovery Credits

For processes that can reuse the dust collected in the ESP or that can sell the dust in a local market, such as fly ash sold as an extender for paving mixes, a credit should be taken. As used below, this credit (RC) appears as a negative cost.

3.4.4 Total Annual Cost

Total annual cost for owning and operating an ESP system is the sum of the components listed in Subsections 3.4.1 through 3.4.3, i.e.:

$$TAC = DC + IC - RC \quad (3.52)$$

where

- TAC = total annual cost (\$)
- DC = direct annual cost (\$)
- IC = indirect annual cost (\$)
- RC = recovery credits (annual) (\$)

3.4.5 Example Problem

Assume an ESP is required for controlling fly ash emissions from a coal-fired boiler burning bituminous coal. The flue gas stream is 50 kacf_m at 325°F and has an inlet ash loading of 4 gr/ft³. Analysis of the ash shows of 7 μ_m and a resistivity of less than 2 x 10¹¹ ohm-cm. Assume that the ESP operates for 8,640 h/yr (360 d) and that an efficiency of 99.9 percent is required.

3.4.5.1 Design SCA

The SCA can be calculated from Equation 3.23. Assuming that a flat plate ESP design is chosen, the fly ash migration velocity is 16.0 cm/s (see Table 3.3). Then:

$$SCA = \frac{-\ln(1 - 0.999)}{16.0} = 0.432 \frac{\text{s}}{\text{cm}} = 43.2 \frac{\text{s}}{\text{m}}$$

Converting to English units (see Step 15 in the procedure):

$$ESCA = 5.080 \times 43.2 = 219 \frac{\text{ft}^2}{\text{kacfm}}$$

Total collector plate area is then:

$$219 \frac{\text{ft}^2}{\text{kacfm}} \times 50 \text{ kacfm} = 10,950 \text{ ft}^2$$

To obtain a more rigorous answer, we can follow the steps of the procedure given in Subsection 3.2.1:

Step 1 – Design efficiency is required as 99.9.

Step 2 – Design penetration:

$$1 - \frac{99.9}{100} = 0.001$$

Step 3 – Operating temperature in Kelvin:

$$(325^\circ \text{F} - 32^\circ \text{F}) \times \frac{5}{9} + 273^\circ \text{C} = 436^\circ \text{K}$$

Step 4 – Because dust resistivity is less than 2×10^{11} ohm-cm (see Step 4), no severe back corona is expected and back corona = 0.

Step 5 – The *MMD* of the fly ash is given as 7 μm .

Step 6 – Values for sneakage and rapping reentrainment (from table 3.1) are:

$$\begin{aligned}SN &= 0.10 \\RR &= 0.124 \text{ (assuming gas velocity } < 1\text{-}5 \text{ m/s)}\end{aligned}$$

Step 7 – The most penetrating particle size, from Step 7 of the procedure is:

$$MMD_p = 2 \mu\text{m}$$

The rapping puff size is:

$$MMD_r = 5 \mu\text{m}$$

Step 8 – From the procedure (Subsection 3.2.1):

$$\begin{aligned}\epsilon_{\omega} &= 8.845 \times 10^{-12} \\ \eta &= 1.72 \times 10^{-5} (436/273)^{0.71} = 2.40 \times 10^{-5} \\ E_{bd} &= 6.3 \times 10^5 (273/436)^{1.65} = 2.91 \times 10^5 \text{ V/m} \\ E_{avg} &= E_{bd} \times 5/6.3 = 2.31 \times 10^5 \\ LF &= S_N + RR(1 - S_N) = 0.1 + 0.124(1 - 0.1) = 0.212\end{aligned}$$

Step 9 – Choose the number of sections for $LF^n < p$, $p = 0.001$. Try four sections:

$$LF^n = 0.212^4 = 0.002$$

This value is larger than p . Try five sections:

$$LF^n = 0.212^5 = 0.000428$$

This value is smaller than p and is acceptable.

Step 10 – Average section penetration is:

$$p_s = p^{\frac{1}{n}} = 0.001^{\frac{1}{5}} = 0.251$$

Step 11 – Section collection penetration is:

$$p_c = \frac{p_s - LF}{1 - LF} = \frac{0.251 - 0.212}{1 - 0.212} = 0.0495$$

Step 12 – Particle size change factors are:

$$\begin{aligned} D &= p_s + S_N + p_c (1 - S_N) + RR (1 - S_N) (1 - p_c) \\ &= 0.10 + 0.0495 (1 - 0.1) + 0.214 (1 - 0.1) (1 - 0.0495) \\ &= 0.251 \end{aligned}$$

$$\begin{aligned} MMD_{rp} &= \frac{RR (1 - S_N) (1 - p_c) MMD_r}{D} \\ &= \frac{0.124 (1 - 0.1) (1 - 0.0495) (5)}{0.251} \\ &= 2.11 \end{aligned}$$

Step 13 - Particle sizes for each section are:

Table 3.17: Mass Median Diameter

Section	MMD (μm)
1	$MMD_1 = MMD_i = 7$
2	$MMD_2 = \frac{\{MMD_1 \times S_N + [(1 - p_c) \times MMD_p + p_c \times MMD_1] \times p_c\}}{D + MMD_{rp}}$ $= \frac{\{7 \times 0.1 + [(1 - 0.0495) \times 2 + 0.0495 \times 7] \times 0.0495\}}{0.251 + 2.11} = 5.34$
3	$MMD_3 = \frac{\{5.34 \times 0.1 + [(1 - 0.0495) \times 2 + 0.0495 \times 5.34] \times 0.0495\}}{0.251 + 2.11} = 4.67$
4	$MMD_4 = \frac{\{4.67 \times 0.1 + [(1 - 0.0495) \times 2 + 0.0495 \times 4.67] \times 0.0495\}}{0.251 + 2.11} = 4.39$
5	$MMD_5 = \frac{\{4.39 \times 0.1 + [(1 - 0.0495) \times 2 + 0.0495 \times 4.39] \times 0.0495\}}{0.251 + 2.11} = 4.28$

Step 14 – SCAs for each section are:

Table 3.18: Specific Collection Area

Section	SCA (s/m)
1	$SCA_1 = -(\zeta/\dot{a}_0) \times (1 - S_N) \times \ln(p_c) / (E_{avg}^2 \times MMD_1 \times 10^{-6}) = 8.86$
2	$SCA_2 = SCA_1 \times MMD_1/MMD_2 = 8.86 (7 / 5.34) = 11.61$
3	$SCA_3 = SCA_2 \times MMD_2/MMD_3 = 11.61 (5.34 / 4.67) = 13.28$
4	$SCA_4 = SCA_3 \times MMD_3/MMD_4 = 13.28 (4.67 / 4.39) = 14.13$
5	$SCA_5 = SCA_4 \times MMD_4/MMD_5 = 14.13 (4.39 / 4.28) = 14.49$

Step 15 – Calculate the total SCA.

$$\text{Total SCA} = 19.65 + 25.76 + 29.46 + 31.34 + 32.15 = 138.36 \frac{\text{s}}{\text{m}}$$

$$\text{English SCA} = 5.080 \times 138.36 = 702.87 \frac{\text{ft}^2}{\text{kacfm}}$$

Note that the more rigorous procedure calls for an SCA that is considerably higher than the value found by using Equation 3.23. This discrepancy is caused by the considerably smaller particle size used in the example problem than is assumed for Table 3.3. In this case, the shorter method would lead to an unacceptably low cost estimate.

Total collector plate area is:

$$702.87 \frac{\text{ft}^2}{\text{kacfm}} \times 50 \text{ kacfm} = 35,144 \text{ ft}^2$$

3.4.5.2 ESP Cost

From Figure 3.5, the basic flange-to-flange cost of the rigid electrode ESP is \$438,060 (mid-1987 dollars). Assuming all standard options are purchased. The ESP cost rises to \$635,189 (mid-1987 dollars).

3.4.5.3 Costs of Auxiliaries

Assume the following auxiliary costs have been estimated from data in other parts of the Manual:

Table 3.19: Auxiliary Equipment Costs

Ductwork	\$16,000
Fan	16,000
Motor	7,500
Starter	4,000
Dampers	7,200
Pneumatic conveyer	4,000
Stack	8,000
Total	\$62,700

3.4.5.4 Total Capital Investment

Direct costs for the ESP system, based on the factors in Table 3.16, are given in Table 3.20. (Again, we assume site preparation and building costs to be negligible.) TCI is \$1,840,000 (rounded, mid-1987 dollars).

3.4.5.5 Annual Costs-Pressure Drop

Table 3.21 gives the direct and indirect annual costs, as calculated from the factors given in Section 3.4. Pressure drop (for energy costs) can be taken from Table 3.11 in Subsection 3.2.2. Using the higher values from the table, pressure drop for the inlet diffuser plate, inlet and outlet transitions, baffles, and plates is:

$$\Delta P = 0.09 + 0.14 + 0.015 + 0.123 + 0.008 = 0.38 \text{ in. H}_2\text{O}$$

Assume the ductwork contributes an additional 4.1 in. H₂O.⁹ The total pressure drop is, therefore, 4.48 in. H₂O. As is typical, the ductwork pressure drop overwhelms the ESP pressure drop.

⁹ For ductwork pressure drop data, refer to Section 2.1 (“Hoods, Ductwork, and Stacks”) of the *Manual*.

Table 3.20: Capital Cost Factors for ESP System Example Problem

Cost Item	Cost, \$
<u>Direct Costs</u>	
Purchased equipment costs	
Adsorber vessels and carbon	\$635,189
Auxiliary equipment	---
Sum = A	\$635,189
Instrumentation, 0.1 A	69,789
Sales taxes, 0.03 A	20,937
Freight, 0.05 A	34,894
Purchased equipment cost, B	\$823,509
Direct installation costs	
Foundations & supports, 0.04 B	32,940
Handling & erection, 0.50 B	411,755
Electrical, 0.08 B	65,881
Piping, 0.01 B	8,235
Insulation for ductwork, 0.02 B	16,470
Painting, 0.02 B	16,470
Direct installation costs	\$551,751
Site preparation	---
Facilities and Buildings	---
Total Direct Costs, DC	\$1,375,260
<u>Indirect Costs (installation)</u>	
Engineering, 0.20 B	164,702
Construction and field expenses, 0.20 B	164,702
Contractor fees, 0.10 B	82,351
Start-up, 0.01 B	8,235
Performance test, 0.01 B	8,235
Model study, 0.02 B	16,470
Contingencies, 0.03 B	24,705
Total Indirect Costs, IC	\$469,400
Total Capital Investment (rounded)	\$1,840,000

3.4.5.6 Total Annual Cost

The total annual cost, calculated in Table 3.21, is \$511,000 (rounded). Had the particle sizes being captured been larger, the ESP cost would have been considerably less. Also, for a much larger gas flow rate, the \$/acfm treated cost would have been more favorable. Reviewing components of the TAC, dust disposal is the largest single item. Care should be taken in determining this cost and the unit disposal cost (\$/ton). Finding a market for the dust, for example, as an extender in asphalt or a dressing for fields, even at giveaway prices, would reduce TAC dramatically.

Table 3.21: Annual Costs for Carbon Absorber System Example Problem

Cost Item	Calculations	Cost
Direct Annual Costs, DC		
Operating Labor		
Operator	3 hr/day x 360 days/yr x \$12/hr	\$12,960
Supervisor	15% of operator = 0.15 x 7,820	1,944
Coordinator	1/3 of operator = 1/3 x 12,960	4,320
Operating materials		
Maintenance		
Labor	\$4,125 for collector area < 50,000 ft ³	4,125
Material	1% of purchase equipment costs = 0.01 x 823,509	8,235
Utilities		
Electricity-fan	0.000181 x 50,000 acfm x 4.48 in. H ₂ O x 8,640 hr/yr x \$0.06 kWh	21,018
Electricity-operating	1.94 x 10 ⁻³ x 35,144 ft ² x 8,640 hr x \$0.06/kWh	35,344
Waste Disposal	at \$20/ton tipping fee at 2 miles and \$0.50/ton-mile for essentially 100% collection efficiency: 4.29 x 10 ⁻⁶ x 4 gr/ft ³ x 8,640 hr/yr x 50,000 acfm x (20 + 0.50 x 2) \$/ton	155,676
Total DC		\$243,622
Indirect Annual Costs, IC		
Overhead	60% of sum of operating labor, maintenance labor, & maintenance materials : = 0.6(12,960 + 1,944 + 4,320 + 4,125 + 8,235)	18,950
Administrative charges	2% of Total Capital Investment = 0.02(\$1,844,660)	36,893
Property tax	1% of Total Capital Investment = 0.01(\$1,844,660)	18,447
Insurance	1% of Total Capital Investment = 0.01(\$1,844,660)	18,447
Capital recovery ^a	0.1175 (\$1,844,660)	216,748
Total IC		\$309,485
Total Annual Cost (rounded)		\$553,000

^a The capital recovery cost factor, CRF, is a function of the fabric filter or equipment life and the opportunity cost of the capital (i.e., interest rate). For this example, for a 20 year equipment life and a 10% interest rate, CRF = 0.1175.

3.5 Acknowledgments

We gratefully acknowledge C. G. Noll, United McGill Corp. (Columbus, OH), for extensive review and the following companies for contributing data to this chapter:

- Research-Cottrell
- Joy Industrial Equipment Co., Western Precipitation Division (Los Angeles, CA)
- Environmental Elements Corp. (Baltimore, MD)

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Appendix A

Effects of Material Thickness and Type on ESP Costs

The impact of material thickness and composition of collecting plates and the ESP casing can be estimated using the following equations and Figure 6.17:

Plates:

$$I = \frac{\left[\left(\frac{W_t}{2} \times FS \right) - 0.90 \right] M + SP}{SP} \quad (3.54)$$

Casing:

$$I = \frac{\left[\left(\frac{W_t}{10} \times FS \right) - 0.58 \right] M + SP}{SP} \quad (3.55)$$

where

- I = incremental increase of flange-to-flange selling price (\$/ft²)
- W_t = weight of steel (lb/ft²)
- FS = fabricated steel selling price (\$/lb) (normally assume approximately 2 times material cost)
- M = manufacturer's markup factor of fabricated cost (direct labor, wages, and material cost before general and administrative expense and profit) to selling price (normally 2 to 3)
- SP = flange-to-flange selling price from Figure 6.17 (\$/ft²)

Most vendors can produce ESPs with collecting plate material thicknesses from 16 to 20 gauge and casing material thicknesses from 1/8 through 1/4 in. without affecting the 2 times material cost = fabricated cost relationship. Thus, the impact of increasing the collecting plates from 18 to 16 gauge and the casing from 3/16 to 1/4 in. plate on a 72,000 ft² collector having a selling price of \$10/ft² and assuming a markup factor of 2 is as follows:

Plates:

$$I = \frac{\left[\left(\frac{2.5}{2} \times 0.90 \right) - 0.90 \right] 2 + 10}{10} \quad (3.55)$$

$$= 1.045 = 4.5 \text{ percent increase}$$

Casing:

$$I = \frac{\left[\left(\frac{10.21}{10} \times 0.76 \right) - 0.58 \right] 2 + 10}{10} \quad (3.56)$$

$$= 1.039 = 3.9 \text{ percent increase}$$

Equations 3.53 and 3.54 were developed using the following assumptions:

$$I = \frac{\text{Material selling price increase} + \text{Standard ESP selling price}}{\text{Standard ESP selling price}}$$

Because Figure 3.5 identifies the standard ESP selling price /ft² of collecting area, the material selling price increase = (New material cost - Standard material cost)M. Then it follows that:

$$\text{Material selling price} = \frac{\text{lb steel}}{\text{ft}^2 \text{ collecting area}} \times \text{Fabricated cost in } \frac{\$}{\text{lb}} \times M \quad (3.57)$$

The ESP dimensions given in Figure 3.7 include:

- Casing area = 30 ft 30 ft x 8 = 7,200 ft² (assume 4 walls, 1 top, 2 hopper sides, 2 triangular hopper ends π 8 equivalent sides)
- Collecting plate area =

$$30 \text{ ft} \times 30 \text{ ft} \times 2 \frac{\text{sides}}{\text{plate}} \times \frac{30 \text{ ft}}{s} \text{ plates} = \frac{54,000}{s} \text{ ft}^2 = 72,000 \text{ ft}^2 \text{ for } s = 0.75 \text{ ft} \quad (3.59)$$

where s = plate spacing (ft)

Thus, there are:

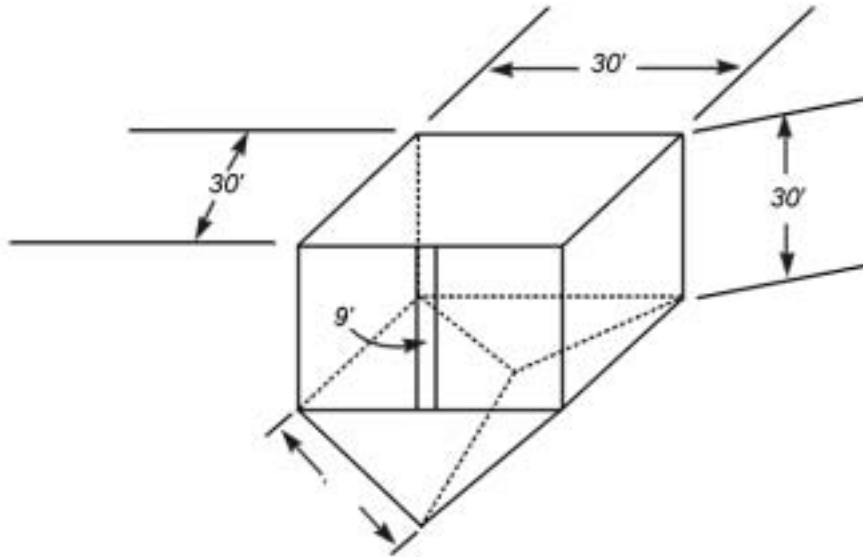


Figure 6.19: ESP Dimensions

- 7.50/s ft² of collecting area per 1 ft² of casing and
- 2 ft² of collecting area per 1 ft² of collecting plate

Material cost per ft² collecting area is:

$$\text{Plates} = \frac{\text{lb steel}}{2 \text{ ft}^2} \times \frac{\$}{\text{lb}} \quad (3.60)$$

$$\text{Casing} = \frac{\frac{\text{lb steel}}{\text{ft}^2}}{\frac{7.50}{s}} \times \frac{\$}{\text{lb}} \quad (3.61)$$

For a standard ESP with 18 gauge collecting plates and 3/16 in. plate casing. Assuming:

Material cost for 18 gauge mild steel	=	\$0.45/lb
Material cost for 3/16 in. plate mild steel	=	\$0.38/lb
Material cost to fabricated cost factor	=	2

These costs yield fabricated material costs of:

Plates:

$$\frac{2 \text{ lb}}{2 \text{ ft}^2} \times \frac{\$0.45}{\text{lb}} \times 2 = \frac{\$0.90}{\text{ft}^2} \text{ of collecting area} \quad (3.62)$$

Casing:

$$\frac{\frac{7.66 \text{ lb}}{\text{ft}^2}}{\frac{7.50}{s}} \times \frac{\$0.38}{\text{lb}} \times 2 = \$0.78 \frac{s}{\text{ft}^2} \text{ of collecting area} \quad (3.63)$$

At a typical 9 in. plate spacing the casing cost would be \$0.58/ft² of collecting area.

which gives us Equations 3.53 and 3.54. Note that the value 0.58 will change significantly if a plate spacing other than 9 in. is chosen.

$$\text{Selling price impact} = \frac{\left(\text{Cost of new material} - \text{Cost of old material} \right) M + \text{Original overall selling price}}{\text{Original overall selling price}} \quad (3.64)$$

Thus, for a less than 5 percent increase in flange-to-flange cost, all the precipitator exposed wall sections can be increased by more than 25 percent to provide increased life under corrosive conditions. Section thickness increases that are greater than those just discussed would probably result in significant cost increases because of both increased material costs and necessary engineering design changes.

The impact of changing from mild steel to 304 stainless steel assuming material costs of \$1.63/lb for 18 gauge collecting plates, \$1.38/lb for the 3/16 in. casing, and a markup factor of 3 is as follows:

Plates:

$$I = \frac{\left[\left(\frac{2}{2} \times 1.63 \right) - 0.9 \right] 3 + 10}{10} \quad (3.65)$$

= 21.9 percent increase

Casing:

$$I = \frac{\left[\left(\frac{7.66}{10} \times 1.38 \right) - 0.58 \right] 3 + 10}{10} \quad (3.66)$$

= 14.3 percent increase

To these material costs must be added extra fabrication labor and procurement costs that will increase the ESP flange-to-flange cost by a factor of 2 to 3. Note that a totally stainless steel collector would be much more expensive because the discharge electrodes, rappers, hangers, etc., would be also converted to stainless. The preceding equations can be used for other grades of stainless steel or other materials of construction by inserting material costs obtained from local vendors on a \$/lb basis.

TECHNICAL REPORT DATA

(Please read Instructions on reverse before completing)

1. REPORT NO. 452/B-02-001	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE The EPA Air Pollution Control Cost Manual	5. REPORT DATE January, 2002	
	6. PERFORMING ORGANIZATION CODE	
7. AUTHOR(S) Daniel Charles Mussatti	8. PERFORMING ORGANIZATION REPORT NO.	
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Environmental Protection Agency Office of Air Quality Planning and Standards Air Quality Standards and Strategies Division Innovative Strategies and Economics Group Research Triangle Park, NC 27711	10. PROGRAM ELEMENT NO.	
	11. CONTRACT/GRANT NO.	
12. SPONSORING AGENCY NAME AND ADDRESS Director Office of Air Quality Planning and Standards Office of Air and Radiation U.S. Environmental Protection Agency Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED Final	
	14. SPONSORING AGENCY CODE EPA/200/04	
15. SUPPLEMENTARY NOTES Updates and revises EPA 453/b-96-001, OAQPS Control Cost Manual, fifth edition (in English only)		
16. ABSTRACT In Spanish, this document provides a detailed methodology for the proper sizing and costing of numerous air pollution control devices for planning and permitting purposes. Includes costing for volatile organic compounds (VOCs); particulate matter (PM); oxides of nitrogen (NOx); SO₂, SO₃, and other acid gasses; and hazardous air pollutants (HAPs).		
17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Economics Cost Engineering cost Sizing Estimation Design	Air Pollution control Incinerators Absorbers Adsorbers Filters Condensers Electrostatic Precipitators Scrubbers	
18. DISTRIBUTION STATEMENT Release Unlimited	19. SECURITY CLASS (<i>Report</i>) Unclassified	21. NO. OF PAGES 1,400
	20. SECURITY CLASS (<i>Page</i>) Unclassified	22. PRICE