Lesson 3

ESP Design Parameters and Their Effects on Collection Efficiency

Goal

To familiarize you with the variables used by vendors to optimally design ESP systems.

Objectives

At the end of this lesson, you will be able to do the following:

1. Define the term *migration velocity*
2. Explain the difference between the Deutsch-Anderson equation and the Matts-Ohnfeldt equation for estimating collection efficiency
3. Define the term *resistivity*
4. List three ways to reduce high resistivity and two ways to combat low resistivity
5. Explain how sectionalization and increasing corona power improves collection efficiency
6. Define aspect ratio and specific collection area and describe their importance for achieving collection efficiency
7. Calculate the aspect ratio and specific collection area of an ESP given a set of design information

Introduction

Because of legislation such as the Clean Air Act and the 1977 and 1990 Clean Air Act Amendments, ESPs have been carefully designed to collect more than 99.5% of particles in the flue gas from many industries. ESPs efficiently collect particles of various sizes: large particles of 3 to 10 μm in diameter, and smaller particles of less than 1 μm in diameter.

An ESP is designed for a particular industrial application. Building an ESP is a costly endeavor, so a great deal of time and effort is expended during the design stage. Manufacturers use various methods to design ESPs. They also consider a variety of operating parameters that affect collection efficiency including resistivity, electrical sectionalization, specific collection area, aspect ratio, gas flow distribution, and corona power. This lesson focuses on these methods and operating parameters.

Design Methods

Manufacturers use mathematical equations to estimate collection efficiency or collection area. In addition, they may build a pilot-plant to determine the parameters necessary to build the full-scale ESP. They may also use a mathematical model or computer program to test the design features and operating parameters in a simulation of the final design. Once the basis of the ESP design is completed, the vendor can design the unit using various individual parameters that are appropriate for each specific situation.

Using Estimates of Collection Efficiency

Collection efficiency is the primary consideration of ESP design. The collection efficiency and/or the collection area of an ESP can be estimated using several equations. These equations give a theoretical estimate of the overall collection efficiency of the unit operating under ideal conditions. Unfortunately, a number of operating parameters can adversely affect the collection efficiency of the precipitator. A discussion of collection-efficiency equations and operating parameters affecting collection-efficiency equations follows.

Particle-Migration Velocity

Before determining the collection area and the collection efficiency, the designer must estimate or measure (if possible) the **particle-migration velocity**. This is the speed at which a particle, once charged, migrates toward the grounded collection electrode. Variables affecting particle velocity are particle size, the strength of the electric field, and the viscosity of the gas. How readily the charged particles move to the collection electrode is denoted by the symbol, w, called the particle-migration velocity, or **drift velocity**. The migration-velocity parameter represents the collectability of the particle within the confines of a specific ESP. The migration velocity is expressed in Equation 3-1.

$$w = \frac{d_p E_o E_p}{4\pi\mu} \qquad (3\text{-}1)$$

Where: d_p = diameter of the particle, μm
E_o = strength of field in which particles are charged (represented by peak voltage), V/m (V/ft)
E_p = strength of field in which particles are collected (normally the field close to the collecting plates), V/m (V/ft)
μ = gas viscosity, Pa • s (cp)
π = 3.14

As shown in Equation 3-1, migration velocity depends on the voltage strength of both the charging and collection fields. Therefore, the precipitator must be designed using the maximum electric field voltage for maximum collection efficiency. The migration velocity also depends on particle size; larger particles are collected more easily than smaller ones.

Particle-migration velocity can also be determined by Equation 3-2.

$$w = \frac{qE_p}{6\pi\mu r} \tag{3-2}$$

Where: q = particle charge(s)
       E_p = strength of field in which particles are collected, V/m (V/ft)
       μ = gas viscosity, Pa • s (cp)
       r = radius of the particle, μm
       π = 3.14

The particle-migration velocity can be calculated using either Equations 3-1 or 3-2, depending on the information available on the particle size and electric field strength. However, most ESPs are designed using a particle-migration velocity based on field experience rather than theory. Typical particle migration velocity rates, such as those listed in Table 3-1, have been published by various ESP vendors.

Table 3-1. Typical effective particle-migration velocity rates for various applications		
Application	**Migration velocity**	
	(ft/sec)	**(cm/s)**
Utility fly ash	0.13-0.67	4.0-20.4
Pulverized coal fly ash	0.33-0.44	10.1-13.4
Pulp and paper mills	0.21-0.31	6.4-9.5
Sulfuric acid mist	0.19-0.25	5.8-7.62
Cement (wet process)	0.33-0.37	10.1-11.3
Cement (dry process)	0.19-0.23	6.4-7.0
Gypsum	0.52-0.64	15.8-19.5
Smelter	0.06	1.8
Open-hearth furnace	0.16-0.19	4.9-5.8
Blast furnace	0.20-0.46	6.1-14.0
Hot phosphorous	0.09	2.7
Flash roaster	0.25	7.6
Multiple-hearth roaster	0.26	7.9
Catalyst dust	0.25	7.6
Cupola	0.10-0.12	3.0-3.7

Sources: Theodore and Buonicore 1976; U.S. EPA 1979.

Deutsch-Anderson Equation

Probably the best way to gain insight into the process of electrostatic precipitation is to study the relationship known as the Deutsch-Anderson equation. This equation is used to determine the collection efficiency of the precipitator under ideal conditions. The simplest form of the equation is given below.

$$\eta = 1 - e^{-w(A/Q)} \tag{3-3}$$

Where: η = collection efficiency of the precipitator
e = base of natural logarithm = 2.718
w = migration velocity, cm/s (ft/sec)
A = the effective collecting plate area of the precipitator, m^2 (ft^2)
Q = gas flow through the precipitator, m^3/s (ft^3/sec)

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Source: Deutsch 1922; Anderson 1924.

This equation has been used extensively for many years to calculate theoretical collection efficiencies. Unfortunately, while the equation is scientifically valid, a number of operating parameters can cause the results to be in error by a factor of 2 or more. The Deutsch-Anderson equation neglects three significant process variables. First, it completely ignores the fact that dust reentrainment may occur during the rapping process. Second, it assumes that the particle size and, consequently, the migration velocity are uniform for all particles in the gas stream. As stated previously, this is not true; larger particles generally have higher migration velocity rates than smaller particles do. Third, it assumes that the gas flow rate is uniform everywhere across the precipitator and that **particle sneakage** (particles escape capture) through the hopper section does not occur. Particle sneakage can occur when the flue gas flows down through the hopper section instead of through the ESP chambers, thus preventing particles from being subjected to the electric field. Therefore, this equation should be used only for making preliminary estimates of precipitator collection efficiency.

More accurate estimates of collection efficiency can be obtained by modifying the Deutsch-Anderson equation. This is accomplished either by substituting **the effective precipitation rate**, w_e, in place of the migration velocity, w, or by decreasing the calculation of collection efficiency by a factor of k, which is constant (**Matts-Ohnfeldt equation**). These calculations are used in establishing preliminary design parameters of ESPs.

Modified Deutsch-Anderson Equation
Using the Effective-Precipitation Rate

To make the Deutsch-Anderson equation more accurate in cases where all particles are not uniform in size, a parameter called the effective precipitation rate (w_e) can be substituted for the migration velocity in the equation. Therefore, Dr. Harry White proposed modifying the Deutsch-Anderson equation by using the term w_e instead of w in the Deutsch-Anderson equation (White 1982).

$$\eta = 1 - e^{-w_e(A/Q)} \tag{3-4}$$

Where: η = collection efficiency of the precipitator
e = base of natural logarithm = 2.718
w_e = effective migration velocity, calculated from field experience
A = collecting area, m^2 (ft^2)
Q = gas flow rate, m^3/s (ft^3/sec)

In contrast to the migration velocity (w), which refers to the speed at which *an individual charged particle* migrates to the collection electrode, the effective precipitation rate (w_e) refers to the *average* speed at which all particles in the entire dust mass move toward the collection electrode. The variable, w_e, is calculated from field experience rather than from theory; values for w_e are usually determined using data banks accumulated from ESP installations in similar industries or from pilot-plant studies. In summary, the effective precipitation rate represents a semi-empirical parameter that can be used to determine the total collection area necessary for an ESP to achieve a specified collection efficiency required to meet an emission limit.

Using the Deutsch-Anderson equation in this manner could be particularly useful when trying to determine the amount of additional collection area needed to upgrade an existing ESP to meet more stringent regulations or to improve the performance of the unit. However, other operating parameters besides collection area play a major role in determining the efficiency of an ESP.

Matts-Ohnfeldt Equation

Another modification to the Deutsch-Anderson equation that accounts for non-ideal effects was devised by Sigvard Matts and Per-Olaf Ohnfeldt of Sweden (Svenska Flaktfabriken) in 1964. The Matts-Ohnfeldt equation is

$$\eta = 1 - e^{-w_k(A/Q)^k} \tag{3-5}$$

Where: η = collection efficiency of the precipitator
e = base of natural logarithm = 2.718
w_k = average migration velocity, cm/s (ft/sec)
k = a constant, usually 0.4 to 0.6
A = collection area, m^2 (ft^2)
Q = gas flow rate, m^3/s (ft^3/sec)

The term, w_k, the average migration velocity in equation 3-5, is determined from information obtained from similar installations. The terms w_k and w_e (in equations 3-5 and 3-4 respectively) are similar in that both are average migration velocities. The constant, k, in the equation is usually between 0.4 and 0.6, depending on the standard deviation of the particle size distribution and other dust properties affecting collection efficiency. However, most people who have used this equation report that a value of k equal to 0.5 gives satisfactory results (Gallaer 1983 and U.S. EPA 1985). In an Electric Power Research Institute (EPRI) study, a table was constructed to show the relationship of predicting collection efficiency using the Deutsch-Anderson and Matts-Ohnfeldt equations. This information is given in Table 3-2.

Table 3-2. Collection-efficiency estimations using the Deutsch-Anderson and Matts-Ohnfeldt equations				
Relative size of ESP (A/Q)	**Deutsch k = 1.0**	**Matts-Ohnfeldt**		
		k = 0.4	**k = 0.5**	**k = 0.6**
1	90	90	90	90
2	99	95.1	96.2	97.2
3	99.9	97.2	98.1	98.8
4	99.99	98.1	99	99.5
5	99.999	98.7	99.6	99.76

Source: Gallaer 1983.

When k = 1.0, the Matts-Ohnfeldt equation is the same as the Deutsch-Anderson equation. To predict the collection efficiency of an existing ESP when the collection area or gas flow rate is varied, using lower values for k gives more conservative results. From Table 3-2, you can see that the efficiency estimates calculated using the Matts-Ohnfeldt equation are more conservative than those estimated using the Deutsch-Anderson equation, and may more likely predict how efficiently the ESP will actually operate.

Using Pilot Plants

Probably the most reliable method for designing ESPs is to construct and operate a pilot plant. However, time limitations and the expense of construction may make this impossible; a pilot plant can easily cost one million dollars or more. A pilot ESP project can be constructed on an existing industrial process. In this case, a side stream of flue gas is sent to the small pilot ESP. Flue gas sampling gives valuable information such as gas temperature, moisture content, and dust resistivity. Relating these parameters to the measured collection efficiency of the pilot project will help the design engineers plan for scale-up to a full-sized ESP.

Using Computer Programs and Models

Engineers can also use mathematical models or computer programs to design precipitators. A mathematical model that relates collection efficiency to precipitator size and various operating parameters has been developed by Southern Research Institute (SoRI) for EPA. The (SoRI/EPA) model is used to do the following:

- Design a full-scale ESP from fundamental principles or in conjunction with a pilot-plant study·
- Evaluate ESP bids submitted by various manufacturers
- Troubleshoot and diagnose operating problems for existing ESPs
- Evaluate the effectiveness of new ESP developments and technology, such as flue gas conditioning and pulse energizing.

Details of this model are given in EPA publications *A Mathematical Model of Electrostatic Precipitation* (Revision 1), Volumes I and II.

Table 3-3 lists the input data used in the SoRI/EPA Model. Assuming that accurate input data are available for use, the model usually can estimate emissions within ± 20 percent of measured values (U.S. EPA 1985). The computer model goes through an iterative computational process to refine its predictions of emission levels for a particular ESP. First, the model uses secondary voltage and current levels (corona power) to predict emission levels leaving the ESP. Then, actual emission levels are measured and compared to the predicted emission levels. Empirical factors are then adjusted and the process repeats itself until the predicted emission levels of the model agree with the actual, measured levels. This model can be used to obtain reasonable estimates of emission levels for other ESP operating conditions (U.S. EPA 1985). For example, once you create a good, working computer model for a particular ESP design under one set of operating conditions, you can run the model for different scenarios by altering one or more of the parameters (precipitator length, number of fields, etc.) to obtain reasonably accurate emission level predictions.

Table 3-3. Input data for EPA/SORI ESP computer model	
ESP Specifications	**Gas/particulate specifications**

Estimated efficiency
Precipitator length
Superficial gas velocity
Fraction of sneakage/reentrainment
Normalized standard deviation of gas velocity distribution
Number of stages for sneakage/reentrainment
Number of electrical sections in direction of gas flow
For each electrical section
    Length
    Area
    Applied voltage
    Current
    Corona wire radius
    Corona wire length
    Wire-to-wire spacing (1/2)
    Wire-to-plate spacing
    Number of wires per linear section
	Gas flow rate
	Gas pressure
	Gas temperature
	Gas viscosity
	Particulate concentration
	Particulate resistivity
	Particulate density
	Particle size distribution
	Dielectric constant
	Ion speed

Source: U.S. EPA 1985.

Another model, the EPA/RTI model, has been developed by the Research Triangle Institute (RTI) for EPA (Lawless 1992). The EPA/RTI model is based on the localized electric field strengths and current densities prevailing throughout the precipitator. These data can be input based on actual readings from operating units, or can be calculated based on electrode spacing and resistivity. The data are used to estimate the combined electrical charging on each particle size range due to field-dependent charging and diffusional charging. Particle size-dependent migration velocities are then used in a Deutsch-Anderson type equation to estimate particle collection in each field of the precipitator. This model takes into account a number of the site specific factors including gas flow maldistribution, particle size distribution, and rapping reentrainment.

These performance models require detailed information concerning the anticipated configuration of the precipitator and the gas stream characteristics. Information needed to operate the EPA/RTI model is provided below. It is readily apparent that all of these parameters are not needed in each case, since some can be calculated from the others. The following data is data utilized in the EPA/RTI computerized performance model for electrostatic precipitators.

ESP Design

- Specific collection area
- Collection plate area
- Collection height and length
- Gas velocity
- Number of fields in series
- Number of discharge electrodes
- Type of discharge electrodes
- Discharge electrode-to-collection plate spacing

Particulate Matter and Gas Stream Data

- Resistivity
- Particle size mass median diameter
- Particle size distribution standard deviation
- Gas flow rate distribution standard deviation
- Actual gas flow rate
- Gas stream temperature
- Gas stream pressure
- Gas stream composition

Design Parameters

Once the basis of the ESP design has been set, the vendor will complete the design by incorporating a number of parameters that can be adjusted for each specific industrial application. However, before starting this design phase, the vendor must take into account the effect that particle resistivity can have on the actual collection efficiency.

Resistivity

Resistivity, which is a characteristic of particles in an electric field, is a measure of a particle's resistance to transferring charge (both accepting and giving up charges). Resistivity is a function of a particle's chemical composition as well as flue gas operating conditions such as temperature and moisture. Particles can have high, moderate (normal), or low resistivity.

In an ESP, where particle charging and discharging are key functions, resistivity is an important factor that significantly affects collection efficiency. While resistivity is an important phenomenon in the inter-electrode region where most particle charging takes place, it has a particularly important effect on the dust layer at the collection electrode where discharging occurs. Particles that exhibit high resistivity are difficult to charge. But once charged, they do not readily give up their acquired charge on arrival at the collection electrode. On the other hand, particles with low resistivity easily become charged and readily release their charge to the grounded collection plate. Both extremes in resistivity impede the efficient functioning of ESPs. ESPs work best under normal resistivity conditions.

Resistivity is the electrical resistance of a dust sample 1.0 cm^2 in cross-sectional area, 1.0 cm thick, and is recorded in units of ohm-cm. A method for measuring resistivity will be described later in this lesson. Table 3-4 gives value ranges for low, normal, and high resistivity.

Table 3-4. Low, normal, and high resistivity	
Resistivity	**Range of measurement**
Low	between 10^4 and 10^7 ohm • cm
Normal	between 10^7 and 10^{10} ohm • cm
High	above 10^{10} ohm • cm (usually between 10^{10} and 10^{14} ohm • cm)

Dust Layer Resistivity

Let's take a closer look at the way resistivity affects electrical conditions in the dust layer. A potential electric field (voltage drop) is formed across the dust layer as negatively charged particles arrive at the dust layer surface and leak their electrical charges to the collection plate. At the metal surface of the electrically grounded collection plate, the voltage is zero. Whereas at the outer surface of the dust layer, where new particles and ions are arriving, the electrostatic voltage caused by the gas ions can be quite high. The strength of this electric field depends on the resistivity and thickness of the dust layer.

In high resistivity dust layers, the dust is not sufficiently conductive, so electrical charges have difficulty moving through the dust layer. Consequently, electrical charges accumulate on and beneath the dust layer surface, creating a strong electric field. Voltages can be greater than 10,000 volts. Dust particles with high resistivities are held too strongly to the plate, making them difficult to remove and causing rapping problems.

In low resistivity dust layers, the corona current is readily passed to the grounded collection electrode. Therefore, a relatively weak electric field, of several thousand volts, is maintained across the dust layer. Collected dust particles with low resistivity do not adhere strongly enough to the collection plate. They are easily dislodged and become reentrained in the gas stream.

The following discussion of normal, high, and low resistivity applies to ESPs operated in a dry state; resistivity is not a problem in the operation of wet ESPs because of the moisture concentration in the ESP. The relationship between moisture content and resistivity is explained later in this lesson.

Normal Resistivity

As stated above, ESPs work best under normal resistivity conditions. Particles with normal resistivity do not rapidly lose their charge on arrival at the collection electrode. These particles slowly leak their charge to grounded plates and are retained on the collection plates by intermolecular adhesive and cohesive forces. This allows a particulate layer to be built up and then dislodged from the plates by rapping. Within the range of normal dust resistivity (between 10^7 and 10^{10} ohm-cm), fly ash is collected more easily than dust having either low or high resistivity.

High Resistivity

If the voltage drop across the dust layer becomes too high, several adverse effects can occur. First, the high voltage drop reduces the voltage difference between the discharge electrode and collection electrode, and thereby reduces the electrostatic field strength used to drive the gas ion - charged particles over to the collected dust layer. As the dust layer builds up, and the electrical charges accumulate on the surface of the dust layer, the voltage difference between the discharge and collection electrodes decreases. The migration velocities of small particles are especially affected by the reduced electric field strength.

Another problem that occurs with high resistivity dust layers is called **back corona**. This occurs when the potential drop across the dust layer is so great that corona discharges begin to appear in the gas that is trapped within the dust layer. The dust layer breaks down electrically, producing small holes or craters from which back corona discharges occur. Positive gas ions are generated within the dust layer and are accelerated toward the "negatively charged" discharge electrode. The positive ions reduce some of the negative charges on the dust layer and neutralize some of the negative ions on the "charged particles" heading toward the collection electrode. Disruptions of the normal corona process greatly reduce the ESP's collection efficiency, which in severe cases, may fall below 50% (White 1974).

The third, and generally most common problem with high resistivity dust is increased electrical sparking. When the sparking rate exceeds the "set spark rate limit," the automatic controllers limit the operating voltage of the field. This causes reduced particle charging and reduced migration velocities toward the collection electrode.

High resistivity can generally be reduced by doing the following:

- Adjusting the temperature
- Increasing moisture content
- Adding conditioning agents to the gas stream
- Increasing the collection surface area
- Using hot-side precipitators (occasionally)

Figure 3-1 shows the variation in resistivity with changing gas temperature for six different industrial dusts (U.S. EPA 1985). For most dusts, resistivity will decrease as the flue gas temperature increases. However, as can be seen from Figure 3-1, the resistivity also decreases for some dusts (cement and ZnO) at low flue gas temperatures.
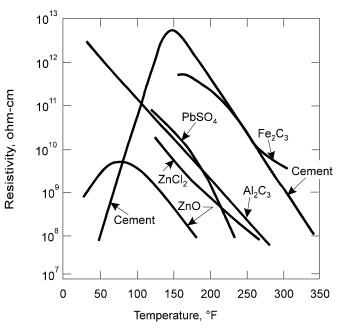

Figure 3-1.   Resistivity of six different dusts at various temperatures
Source: U.S. EPA 1985.

The moisture content of the flue gas stream also affects particle resistivity. Increasing the moisture content of the gas stream by spraying water or injecting steam into the duct work preceding the ESP lowers the resistivity. In both temperature adjustment and moisture conditioning, one must maintain gas conditions above the dew point to prevent corrosion problems in the ESP or downstream equipment. Figure 3-2 shows the effect of temperature and moisture on the resistivity of cement dust. As the percentage of moisture in the dust increases from 1 to 20%, the resistivity of the dust dramatically decreases. Also, raising or lowering the temperature can decrease cement dust resistivity for all the moisture percentages represented.
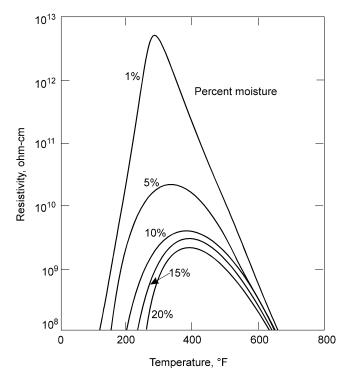

Figure 3-2. Effect of temperature and moisture on the resistivity of cement dust
Sources: Schmidt 1949, White 1977.

The presence of SO_3 in the gas stream has been shown to favor the electrostatic precipitation process when problems with high resistivity occur. Most of the sulfur content in the coal burned for combustion sources converts to SO_2. However, approximately 1% of the sulfur converts to SO_3. The amount of SO_3 in the flue gas normally increases with increasing sulfur content of the coal. The resistivity of the particles decreases as the sulfur content of the coal increases (Figure 3-3).
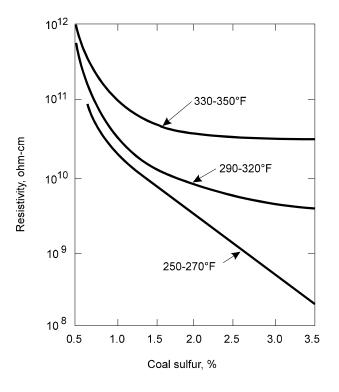
Figure 3-3. Fly ash resistivity versus coal sulfur content
for several flue gas temperature bands
Source: White 1977.

The use of low-sulfur western coal for boiler operations has caused fly ash resistivity problems for ESP operators. For coal fly ash dusts, the resistivity can be lowered below the critical level by the injection of as little as 10 to 30 ppm SO_3 into the gas stream. The SO_3 is injected into the duct work preceding the precipitator. Figure 3-4 shows the flow diagram of a sulfur-burning flue gas conditioning system used to lower resistivity at a coal-fired boiler.
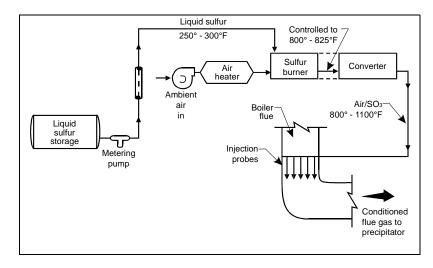

Figure 3-4. Flow diagram of sulfur-burning flue gas conditioning system
Courtesy of Wahlco, Inc.

Other conditioning agents, such as sulfuric acid, ammonia, sodium chloride, and soda ash, have also been used to reduce particle resistivity (White 1974). Therefore, the chemical composition of the flue gas stream is important with regard to the resistivity of the particles to be collected in the ESP. Table 3-5 lists various conditioning agents and their mechanisms of operation (U.S. EPA 1985).

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Table 3-5. Reaction mechanisms of major conditioning agents	
Conditioning agent	**Mechanism(s) of action**
Sulfur trioxide and sulfuric acid	Condensation and adsorption on fly ash surfaces; may also increase cohesiveness of fly ash. Reduces resistivity.
Ammonia	Mechanism is not clear; various ones proposed: Modifies resistivity Increases ash cohesiveness Enhances space charge effect
Ammonium sulfate[1]	Little is known about the actual mechanism; claims are made for the following: Modifies resistivity (depends upon injection temperature) Increases ash cohesiveness Enhances space charge effect Experimental data lacking to substantiate which of these is predominant
Triethylamine	Particle agglomeration claimed; no supporting data
Sodium compounds	Natural conditioner if added with coal. Resistivity modifier if injected into gas stream
Compounds of transition metals	Postulated that they catalyze oxidation of SO_2 to SO_3; no definitive tests with fly ash to verify this postulation
Potassium sulfate and sodium chloride	In cement and lime kiln ESPs: Resistivity modifiers in the gas stream NaCl - natural conditioner when mixed with coal

[1] If injection occurs at a temperature greater than about 600°F, dissociation into ammonia and sulfur trioxide results. Depending upon the ash, SO_2 may preferentially interact with fly ash as SO_3 conditioning. The remainder recombines with ammonia to add to the space charge as well as increase the cohesiveness of the ash.
Source: U.S. EPA 1985.

Two other methods that reduce particle resistivity include increasing the collection surface area and handling the flue gas at higher temperatures. Increasing the collection area of the precipitator will increase the overall cost of the ESP, which may not be desirable. Hot-side precipitators, which are usually located in front of the combustion air preheater section of the boiler, are also used to combat resistivity problems. However, the use of conditioning agents has been more successful and very few hot-side ESPs have been installed since the 1980s.

Low Resistivity

Particles that have low resistivity are difficult to collect because they are easily charged (very conductive) and rapidly lose their charge on arrival at the collection electrode. The particles take on the charge of the collection electrode, bounce off the plates, and become reentrained in the gas stream. Thus, attractive and repulsive electrical forces that are normally at work at higher resistivities are lacking, and the binding forces to the plate are considerably lessened. Examples of low-resistivity dusts are unburned carbon in fly ash and carbon black.

If these conductive particles are coarse, they can be removed upstream of the precipitator by using a device such as a cyclone. Baffles are often installed on the collection plates to help eliminate this precipitation-repulsion phenomenon.

The addition of liquid ammonia (NH_3) into the gas stream as a conditioning agent has found wide use in recent years. It is theorized that ammonia reacts with H_2SO_4 contained in the flue gas to form an ammonium sulfate compound that increases the resistivity of the dust. Ammonia vapor is injected into the duct leading to the precipitator at concentrations of 15 to 40 ppm by volume. The injection of NH_3 has improved the resistivity of fly ash from coal-fired boilers with low flue gas temperatures (Katz 1979).

Table 3-6 summarized the characteristics associated with low, normal and high resistivity dusts.

Measuring Resistivity

Particle resistivity is determined by measuring the leakage current through a dust layer to which a high voltage is applied using conductivity cells. A number of conductivity cells have been used in particle-resistivity measurements. For a good review of the different kinds of cells employed, see White (1974). Resistivity can be measured by a number of methods in either the laboratory or the field. In the lab method, dust samples are first extracted from the flue gas leaving the industrial process and collected on a filter as described in EPA Reference Method 5. The samples are then taken back to the laboratory and analyzed.

Resistivity measurements are made in the field using an in-situ resistivity probe. The probe is inserted into the duct leaving the industrial process and a dust sample is extracted into the probe. High voltage is applied across a point and plate electrode system inside the probe. Particles are charged and then collected on the plate. After a sufficiently thick layer of dust has collected on the plate, the power to the point is turned off and a disc is lowered onto the collected dust sample. The thickness of the dust layer is first measured. Increasing voltages are then applied to the disc, and the corresponding current is recorded until the dust layer breaks down and sparkover occurs. The resistivity is calculated from the last set of voltage and current readings obtained before sparkover occurs. Since these resistivity measurements are made at the industrial process conditions, these data are generally more useful than data obtained from the laboratory methods. A good review of in-situ resistivity measuring techniques is given by White (1974) and Gallaer (1983).

Table 3-6.	ESP characteristics associated with different levels of resistivity
Resistivity Level, ohm-cm	**ESP Characteristics**
Less than 10^7 (Low Resistivity)	1. Normal operating voltage and current levels unless dust layer is thick enough to reduce plate clearances and cause higher current levels 2. Reduced electrical force component retaining collected dust, vulnerable to high reentrainment losses 3. Negligible voltage drop across dust layer 4. Reduced collection performance due to (2)
10^7 to 10^{10} (Normal Resistivity)	1. Normal operating voltage and current levels 2. Negligible voltage drop across dust layer 3. Sufficient electrical force component retaining collected dust 4. High collection performance due to (1), (2), and (3)
10^{11}	1. Reduced operating voltage and current levels with high spark rates 2. Significant voltage loss across dust layer 3. Moderate electrical force component retaining collected dust 4. Reduced collection performance due to (1) and (2)
Greater than 10^{12} (High Resistivity)	1. Reduced operating voltage levels; high operating current levels if power supply controller is not operating properly 2. Very significant voltage loss across dust layer 3. High electrical force component retaining collected dust 4. Seriously reduced collection performance due to (1), (2), and probable back corona
Typical values	
Operating voltage: Operating current density: Dust layer thickness:	30 to 70 kV, dependent on design factors 5 to 50 nA/cm^2 1/4 to 1 inch

Source: Adapted from U.S. EPA 1985.

Electrical Sectionalization

Field Sectionalization

An electrostatic precipitator is divided into a series of independently energized **bus sections** or **fields** (also called stages) in the direction of the gas flow. Precipitator performance depends on the number of individual bus sections, or fields, installed. Figure 3-5 shows an ESP consisting of four fields, each of which acts as an independent precipitator.
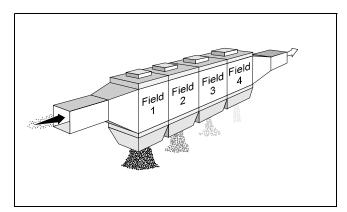
Figure 3-5.   Field sectionalization

Each field has individual transformer-rectifier sets, voltage-stabilization controls, and high-voltage conductors that energize the discharge electrodes within the field. This design feature, called field **electrical sectionalization**, allows greater flexibility for energizing individual fields to accommodate different conditions within the precipitator. This is an important factor in promoting higher precipitator collection efficiency. Most ESP vendors recommend that there be at least three or more fields in the precipitator. However, to attain a collection efficiency of more than 99%, some ESPs have been designed with as many as seven or more fields. Previous experience with a particular industry is the best factor for determining how many fields are necessary to meet the required emission limits.

The need for separate fields arises mainly because power input requirements differ at various locations within a precipitator. The maximum voltage at which a given field can be maintained depends on the properties of the gas and dust being collected. The particulate matter concentration is generally high at the inlet fields of the precipitator. High dust concentrations tend to suppress corona current, requiring a great deal of power to generate corona discharge for optimum particle charging. In the downstream fields of a precipitator, the dust loading is usually lighter, because most of the dust is collected in the inlet fields. Consequently, corona current flows more freely in downstream fields. Particle charging will more likely be limited by excessive sparking in the downstream than in the inlet fields. If the precipitator had only one power set, the excessive sparking would limit the power input to the entire precipitator, thus reducing the overall collection efficiency. The rating of each power set in the ESP will vary depending on the specific design of the ESP.

Modern precipitators have voltage control devices that automatically limit precipitator power input. A well-designed automatic control system keeps the voltage level at approximately the value needed for optimum particle charging by the discharge electrodes. The voltage control device increases the primary voltage applied to the T-R set to the maximum level. As the primary voltage applied to the transformer increases, the secondary voltage applied to the discharge electrodes increases. As the secondary voltage is increased, the intensity and number of corona discharges increase. The voltage is increased until any of the set limits (primary voltage, primary current, secondary voltage, secondary current, or spark rate limits) is reached. Occurrence of a spark counteracts high ESP performance because it causes an immediate, short-term collapse of the precipitator electric field. Consequently, power that is applied to capture

particles is used less efficiently. There is, however, an optimum sparking rate where the gains in particle charging are just offset by corona-current losses from sparkover.

Measurements on commercial precipitators have determined that the optimum sparking rate is between 50 and 150 sparks per minute per electrical section. The objective in power control is to maintain corona power input at this optimum sparking rate by momentarily reducing precipitator power whenever excessive sparking occurs.

Besides allowing for independent voltage control, another major reason for having a number of fields in an ESP is that electrical failure may occur in one or more fields. Electrical failure may occur as a result of a number of events, such as over-filling hoppers, discharge-wire breakage, or power supply failure. These failures are discussed in more detail later in this course. ESPs having a greater number of fields are less dependent on the operation of all fields to achieve a high collection efficiency.

Parallel Sectionalization

In field sectionalization, the precipitator is designed with a single series of independent fields following one another consecutively. In **parallel sectionalization**, the series of fields is electrically divided into two or more sections so that each field has parallel components. Such divisions are referred to as **chambers** and each individual unit is called a **cell**. A precipitator such as the one shown in Figure 3-6 has two parallel sections (chambers), four fields, and eight cells. Each cell can be independently energized by a bus line from its own separate transformer-rectifier set.
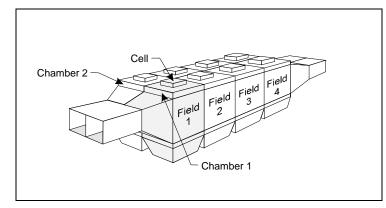

Figure 3-6.   Parallel sectionalization (with two parallel sections, eight cells, and four fields)

One important reason for providing sectionalization across the width of the ESP is to provide a means of handling varying levels of flue gas temperature, dust concentration, and problems with gas flow distribution. When treating flue gas from a boiler, an ESP may experience gas temperatures that vary from one side of the ESP to the other, especially if a rotary air preheater is used in the system. Since fly ash resistivity is a function of the flue gas temperature, this temperature gradient may cause variations in the electrical characteristics of the dust from one side of the ESP to the other. The gas flow into the ESP may also be stratified, causing varying gas velocities and dust concentrations that can also affect the electrical characteristics of the dust. Building numerous fields and cells into an ESP design can provide a means of coping with vari-

ations in the flue gas. In addition, the more cells provided in an ESP, the greater the chance that the unit will operate at its designed collection efficiency.

Specific Collection Area

The **specific collection area (SCA)** is defined as the ratio of collection surface area to the gas flow rate into the collector. This ratio represents the A/Q relationship in the Deutsch-Anderson equation and consequently is an important determinant of collection efficiency. The SCA is given in Equation 3-6.

$$\text{SCA} = \frac{\text{total collection surface}}{\text{gas flow rate}} \quad\quad\quad (3\text{-}6)$$

Expressed in metric units,

$$\text{SCA} = \frac{\text{total collection surface in m}^2}{1000 \text{ m}^3/\text{h}}$$

Expressed in English units,

$$\text{SCA} = \frac{\text{total collection surface in ft}^2}{1000 \text{ ft}^3/\text{min}}$$

For example, if the total collection area of an ESP is 600,000 ft^2 and the gas flow rate through the ESP is 1,000,000 ft^3/min (acfm), the SCA is 600 ft^2 per 1000 acfm as calculated below.

$$\text{SCA} = \frac{600,000 \text{ ft}^2}{1000 \text{ (1000 acfm)}}$$

$$= \frac{600 \text{ ft}^2}{1000 \text{ acfm}}$$

Increases in the SCA of a precipitator design will, in most cases, increase the collection efficiency of the precipitator. Most conservative designs call for an SCA of 20 to 25 m^2 per 1000 m^3/h (350 to 400 ft^2 per 1000 acfm) to achieve collection efficiency of more than 99.5%. The general range of SCA is between 11 and 45 m^2 per 1000 m^3/hr (200 and 800 ft^2 per 1000 acfm), depending on precipitator design conditions and desired collection efficiency.

Aspect Ratio

The **aspect ratio**, which relates the length of an ESP to its height, is an important factor in reducing rapping loss (dust reentrainment). When particles are rapped from the electrodes, the gas flow carries the collected dust forward through the ESP until the dust reaches the hopper. Although the amount of time it takes for rapped particles to settle in the hoppers is short (a matter of seconds), a large amount of "collected dust" can be reentrained in the gas flow and carried out of the ESP if the total effective length of the plates in the ESP is small compared to their effective height. For example, the time required for dust to fall from the top of a 9.1-m plate (30-ft plate) is several seconds. Effective plate lengths must be at least 10.7 to 12.2 m (35 to 40 ft) to prevent a large amount of "collected dust" from being carried out of the ESP before reaching the hopper.

The aspect ratio is the ratio of the effective length to the effective height of the collector surface. The aspect ratio can be calculated using Equation 3-7.

$$AR = \frac{\text{effective length, m (ft)}}{\text{effective height, m (ft)}} \qquad (3-7)$$

The effective length of the collection surface is the sum of the plate lengths in each consecutive field and the effective height is the height of the plates. For example, if an ESP has four fields, each containing plates that are 10 feet long, the effective length is 40 feet. If the height of each plate is 30 feet, the aspect ratio is 1.33 as shown below:

$$AR = \frac{10 \text{ ft} + 10 \text{ ft} + 10 \text{ ft} + 10 \text{ ft}}{30 \text{ ft}}$$

$$= \frac{40 \text{ ft}}{30 \text{ ft}}$$

$$= 1.33$$

Aspect ratios for ESPs range from 0.5 to 2.0. However, for high-efficiency ESPs (those having collection efficiencies of > 99%), the aspect ratio should be greater than 1.0 (usually 1.0 to 1.5) and in some installations may approach 2.0.

Gas Flow Distribution

Gas flow through the ESP chamber should be slow and evenly distributed through the unit. Gas velocity is reduced by the expansion, or diverging, section of the inlet plenum (Figure 3-7). The gas velocities in the duct leading into the ESP are generally between 12 and 24 m/s (40 and 80 ft/sec). The gas velocity into the ESP must be reduced to 0.6-2.4 m/s (2-8 ft/sec) for adequate particle collection. With aspect ratios of 1.5, the optimum gas velocity is generally between 1.5 and 1.8 m/s (5 and 6 ft/sec).
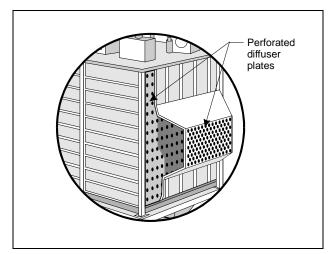

Figure 3-7.   Gas inlet with perforated diffuser plates

In order to use all of the discharge and collection electrodes across the entire width of the ESP, the flue gas must be evenly distributed. The inlet plenum contains perforated openings, called **diffuser plate openings** to evenly distribute the gas flow into the chambers formed by the plates in the precipitator.

Corona Power

As stated previously, a strong electric field is needed for achieving high collection efficiency of dust particles. The strength of the field is based on the rating of the T-R set. The **corona power** is the power that energizes the discharge electrodes and thus creates the strong electric field. The corona power used for precipitation is calculated by multiplying the secondary current by the secondary voltage and is expressed in units of watts. In ESP design specifications, the corona power is usually given in units of watts per 1000 m^3/h (watts per 1000 acfm). Corona power expressed in units of watts/1000 acfm is also called the **specific corona power**. Corona power for any bus section of an ESP can be calculated by the following approximate relation:

$$P_c = 1/2(V_p + V_m)I_c \tag{3-8}$$

Where: P_c = corona power, watts
V_p = peak voltage, volts
V_m = minimum voltage, volts
I_c = average corona current, amperes

As you can see, corona power increases as the voltage and/or current increases. The total corona power of the ESP is the sum of the corona power for all of the individual T-R sets. In an ESP, the collection efficiency is proportional to the amount of corona power supplied to the unit, assuming the corona power is applied effectively (maintains a good sparking rate).

$$\eta \propto 1 - e^{-kP_c/Q} \tag{3-9}$$

Where: η = collection efficiency
e = base of natural logarithm = 2.718
k = a constant, usually between 0.5 and 0.7
P_c/Q = corona power density in units of watts per 1000 m^3/hr
(watts per 1000 acfm)

From equation 3-9, you can see that for a given exhaust flow rate, the collection efficiency will increase as the corona power is increased. This efficiency will depend on the operating conditions of the ESP and on whether the amount of power has been applied effectively. For high collection efficiency, corona power is usually between 59 and 295 watts per 1000 m^3/h (100 and 500 watts per 1000 acfm). Recent ESP installations have been designed to use as much as 470 to 530 watts per 1000 m^3/h (800 to 900 watts per 1000 acfm).

The terms current density and power density are also used to characterize the design of the ESP. **Current density** is the secondary current supplied by the T-R set for the given plate area and expressed in units of mA/ft^2 of plate area. **Power density** is the corona power supplied to the plate area and is expressed in units of watts per ft^2 of plate area.

The size of the individual power sets (T-R sets) in the ESP will vary depending on their specific location and the conditions of the flue gas such as particle size, dust concentration, dust resistivity, and flue gas temperature. In an ESP, the T-R sets are selected to provide lower current density at the inlet sections, where the dust concentration will tend to suppress the corona current, and to provide higher current density at the outlet sections, where there is a greater percentage of fine particles.

Summary

ESPs can be designed using a number of techniques including mathematical equations, pilot plant studies, and computer modeling programs. The use of pilot plant studies is very effective but is not often used because of time limitations and the expense of construction. Use of computer models is therefore becoming more common for both the initial design and for troubleshooting of existing ESPs.

During this lesson we covered a number of equations. The equation for particle migration velocity depends on the voltage strength of both the charging and collection fields and on the particle size. The Deutsch-Anderson and Matts-Ohnfeldt equations can be used to estimate collection efficiency in an ESP. The Deutsch-Anderson equation assumes that all particles in the flue gas have the same migration velocity, and that particles do not become reentrained or do not sneak through the hopper sections. The Deutsch-Anderson equation can be modified by using field data to determine the effective migration velocity.

The Matts-Ohnfeldt equation also uses information obtained from similar ESP field installations. Use of both the modified Deutsch-Anderson and the Matts-Ohnfeldt equations will typically yield more accurate estimates for collection efficiency.

We also covered operating parameters that affect the collection efficiency of the ESP including the following:

- Resistivity
- Sectionalization
- Corona power
- Aspect ratio
- Specific collection area (SCA)

These parameters will be discussed in more detail in Lessons 4 and 6.

Careful design of the ESP involves consideration of the important operating parameters to keep the unit operating efficiently and effectively. Not only will this help an industry comply with air pollution regulations, but a good design up-front will also reduce plant downtime and keep maintenance problems to a minimum.
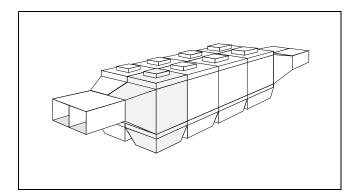
Review Exercise

1. A charged particle will migrate toward an oppositely charged collection electrode. The velocity at which the charged particle moves toward the collection electrode is called the _____ _____ and is denoted by the symbol w.

2. What is the name of the equation given below?

$$\eta = 1 - e^{-w(A/Q)}$$

   a. Johnstone equation
   b. Matts-Ohnfeldt equation
   c. Deutsch-Anderson equation
   d. Beachler-Joseph equation

3. The symbol η in the Deutsch-Anderson equation is the:

   a. Collection area
   b. Migration velocity
   c. Gas flow rate
   d. Collection efficiency

4. The Deutsch-Anderson equation does not account for:

   a. Dust reentrainment that may occur as a result of rapping
   b. Varying migration velocities due to various-sized particles in the flue gas
   c. Uneven gas flow through the precipitator
   d. All of the above

5. True or False? Using the Matts-Ohnfeldt equation to estimate the collection efficiency of an ESP will give less conservative results than using the Deutsch-Anderson equation.

6. Resistivity is a measure of a particle's resistance to _____ and _____ charge.

7. Dust resistivity is a characteristic of the particle in the flue gas that can alter the _____ of an ESP.

   a. Gas flow rate
   b. Collection efficiency
   c. Gas velocity

8. Dust particles with _____ resistivity are difficult to remove from collection plates, causing rapping problems.

   a. Low
   b. Normal
   c. High

9. High dust resistivity can be reduced by:

    a. Adjusting the flue gas temperature
    b. Increasing the moisture content of the flue gas
    c. Injecting SO_3 into the flue gas
    d. All of the above

10. True or False? Fly ash that results from burning high-sulfur coal generally has high resistivity.

11. A precipitator is divided into a series of independently energized bus sections called:

    a. Hoppers
    b. Fields
    c. Stages
    d. b and c, above

12. In the following figure there are _____ fields and _____
    cells.

    a. Two, four
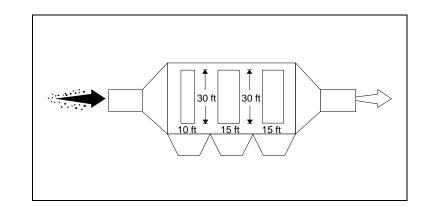   b. Four, eight
    c. Eight, two
    d. Eight, four

13. A precipitator should be designed with at least _____ field(s) to attain a high
    collection efficiency.

    a. One
    b. Two
    c. Three or four
    d. Ten

14. Electrical sectionalization improves collection efficiency by:

    a. Improving resistivity conditions
    b. Allowing for independent voltage control of different fields
    c. Allowing continued ESP operation in the event of electrical failure in one of the fields
    d. b and c, above

15. If the design of the precipitator states that 500,000 ft^2 of plate area is used to remove particles from flue gas flowing at 750,000 ft^3/min, what is the SCA of the unit?

    a. 0.667 ft^2/1000 acfm
    b. 667 ft^2/1000 acfm
    c. 667 acfm/1000 ft^2
    d. 1.5 acfm/ft^2

16. To achieve a collection efficiency greater than 99.5%, most ESPs have a SCA:

    a. Less than 250 ft^2/1000 acfm
    b. Between 350 and 400 ft^2/1000 acfm
    c. Always greater than 800 ft^2/1000 acfm

17. To improve the aspect ratio of an ESP design, the _____ of the collection surface should be increased relative to the _____ of the plate.

    a. Height; length
    b. Length; height

18. Given an ESP having a configuration as shown below, what is the aspect ratio of this unit?

    a. 0.33
    b. 1.5
    c. 0.75
    d. 1.33

19. What should the aspect ratio be for high-efficiency ESPs?

    a. Less than 0.8
    b. Greater than 1.0
    c. Always greater than 1.5

20. In a properly designed ESP, the gas velocity through the ESP chamber will be:

    a. Between 2 and 8 ft/sec
    b. Greater than 20 ft/sec
    c. Approximately between 20 and 80 ft/sec
    d. At least 400 ft^2/1000 acfm

21. In an ESP, the collection efficiency is proportional to the amount of _____
_____ supplied to the unit.

Review Exercise Answers

1. **Migration velocity (or drift velocity)**
   The velocity at which the charged particle moves toward the collection electrode is called the migration velocity (or drift velocity) and is denoted by the symbol w.

2. **c. Deutsch-Anderson equation**

   The following equation, $\eta = 1 - e^{-w(A/Q)}$, is the Deutsch-Anderson equation.

3. **d. Collection efficiency**
   The symbol η in the Deutsch-Anderson equation is the collection efficiency.

4. **d. All of the above**
   The Deutsch-Anderson equation does not account for the following:

   • Dust reentrainment that may occur as a result of rapping
   • Varying migration velocities due to various-sized particles in the flue gas
   • Uneven gas flow through the precipitator

5. **False**
   Using the Matts-Ohnfeldt equation to estimate the collection efficiency of an ESP will give more conservative results than using the Deutsch-Anderson equation because the Matts-Ohnfeldt equation accounts for non-ideal effects.

6. **Accepting**
   Releasing
   Resistivity is a measure of a particle's resistance to accepting and releasing charge.

7. **b. Collection efficiency**
   Dust resistivity is a characteristic of the particle in the flue gas that can alter the collection efficiency of an ESP.

8. **c. High**
   Dust particles with high resistivity are difficult to remove from collection plates, causing rapping problems.

9. **d. All of the above**
   High dust resistivity can be reduced by the following:

   • Adjusting the flue gas temperature
   • Increasing the moisture content of the flue gas
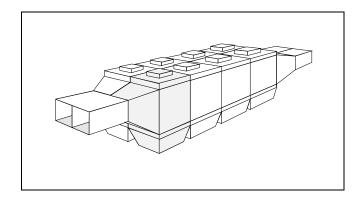   • Injecting SO_3 into the flue gas

10. **False**
    Fly ash that results from burning high-sulfur coal generally has low resistivity. SO_3, which lowers the resistivity of fly-ash, normally increases as the sulfur content of the coal increases.

11. **d.   b and c, above**

A precipitator is divided into a series of independently energized bus sections called fields or stages.

12. **b.   Four, eight**

In the above figure there are four fields and eight cells.

13. **c.   Three or four**

A precipitator should be designed with at least three or four fields to attain a high collection efficiency.

14. **d.   b and c, above**

Electrical sectionalization improves collection efficiency by allowing the following:

- Independent voltage control of different fields
- Continued ESP operation in the event of electrical failure in one of the fields

15. **b.   667 ft^2/1000 acfm**

If the design of the precipitator states that 500,000 ft^2 of plate area is used to remove particles from flue gas flowing at 750,000 ft^3/min, the SCA of the unit is as follows:

$$SCA = \frac{500,000 \ (\text{ft}^2)}{750 \ (1000 \ \text{acfm})}$$

$$= 667 \ \text{ft}^2 / 1000 \ \text{acfm}$$
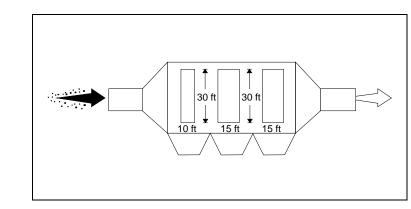
16. **b.   Between 350 and 400 ft^2/1000 acfm**

To achieve a collection efficiency greater than 99.5%, most ESPs have a SCA between 350 and 400 ft^2/1000 acfm.

17. **b.   Length; height**

To improve the aspect ratio of an ESP design, the length of the collection surface should be increased relative to the height of the plate.

18. **d. 1.33**

An ESP with the above configuration has the following aspect ratio:

$$AR = \frac{10 + 15 + 15}{30}$$

$$= \frac{40}{30}$$

$$= 1.33$$

19. **b. Greater than 1.0**
The aspect ratio for high-efficiency ESPs should be greater than 1.0.

20. **a. Between 2 and 8 ft/sec**
In a properly designed ESP, the gas velocity through the ESP chamber will be between 2 and 8 ft/sec, and most often between 4 and 6 ft/sec.

21. **Corona power**
In an ESP, the collection efficiency is proportional to the amount of corona power supplied to the unit.

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