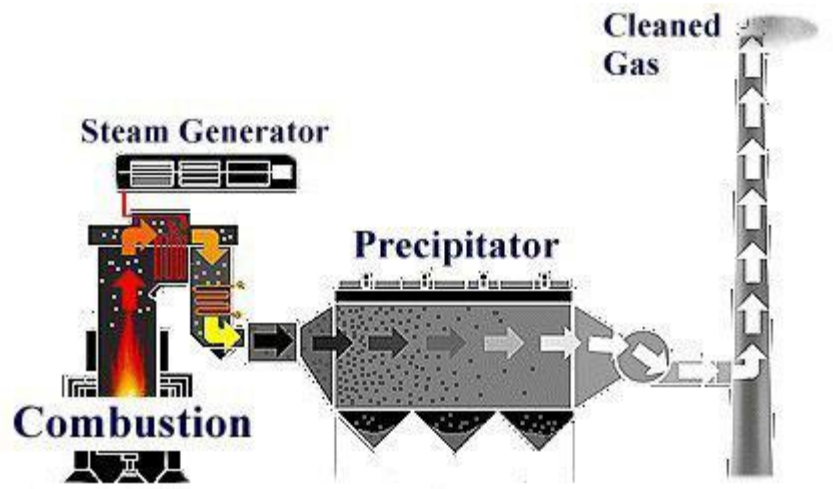
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Electrostatic Precipitators Fundamentals

Design and Operation



Electrostatic Precipitators Fundamentals

A White Paper

FOREWORD

One of the difficulties confronting many of the world's power stations is that they were designed with electrostatic precipitators at a time when emission limits were set at a level above those that are currently acceptable. In addition, the characteristics of coals that are presently being used may well be different to those of the coals for which the plant was originally designed. Means of overcoming these difficulties in order to comply with reduced emission limits have been addressed in a number of ways, including (in the event that the end-result must meet stringent today's or the future requirements) enlarging the precipitators, converting precipitators to the fabric filters/baghouses, or by employing different novel technologies. Alternatively, relatively simple, low cost flue gas additive (flue gas conditioning or FGC) to modify the characteristics of the fly ash and thus make it easier to collect have been adopted as a means of significantly improving the collection efficiency.

An electrostatic precipitator (ESP) is an air pollution control device that removes particles from a flowing gas with electric forces. In another words, an electrostatic precipitator 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. Once the particles are collected on the plates, they must be removed from the plates without re-entraining 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.

The electrical force acts for the most part on the particles and not the gas. Thus, the pressure drop is very low compared to other control options. ESPs are used in industry (for example, steel mills, pulp/paper plants, cement kilns, and waste incineration), coal-fired electric power plants, and indoors in homes and offices. The existence of electrostatic forces of attraction have been noted for centuries. However, it was not until 1907 that Dr. Frederick Cottrell designed the first ESP.

An ESP is designed for a particular industrial application. 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 document presents the electrostatic precipitator's fundamentals and is intended to assist a reader in understanding of the electrostatic precipitation technology and basic sizing procedures. It briefly discusses options related to improving existing electrostatic precipitators and address the novel technologies and developments.

Particle collection in the ESP is disrupted if back corona occurs in the collected material. With high resistivity particles, localized areas of high electric field (due to high current flow) in the collected dust layer can cause electrical breakdown. Ions with polarity opposite to that of the corona on the wires then move into the gas stream where they reduce the charge on particles and may cause sparking. Back corona is associated with low-sulfur coals, which have relatively high resistivities. For this reason, many utilities in the southwestern U.S. use baghouses.

Recent trends in the design of ESPs for electric utilities focus on improved collection of low-sulfur/high-resistivity coal and cost reductions gained from saving energy and structural materials. Innovations include wide plate spacing, intermittent energization, pulse energization, precharging, and microprocessor control of energization and rapping. In addition, several new novel technologies combining both electrostatic precipitator and baghouse in one common housing is under development.

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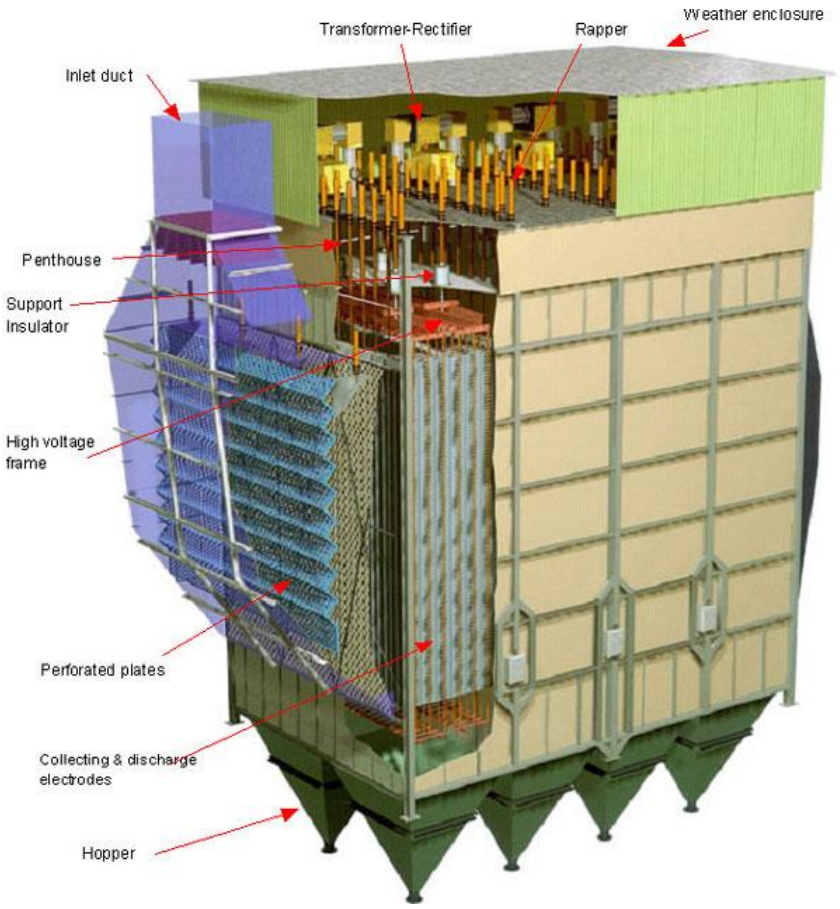
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3.0 EXECUTIVE SUMMARY

Nearly ninety percent of U.S. coal-fired utility boilers are equipped with electrostatic precipitators (ESP). In recent years there had been increasing interest and activity related to improving existing precipitators. The ESP technology is effective for capturing and controlling particulate emissions down to 2.5 μκ dia. The challenge is to capture very fin particulates below this diameter, which are small enough to penetrate deep into the lings and threaten human health.

Before "diving" into the ESP technology discussion and review the possible upgrade/retrofit technologies, it might help to take a brief trip into the electrostatic precipitation history. The first US Patent on electrostatic precipitation (No. 342,548) was issued to A. Q. Walker in 1886. Unfortunately, Mr. Walker's device was unsuccessful, mainly due to an inadequate power supply. The first successful ESP was patented by Dr. Frederic Cottrell (No. 895,729) in 1908. He used the then newly developed synchronous mechanical rectifier and a high voltage AC transformer to produce DC power of 10 to 15 kV. His initial commercial units were used for the collection of sulfuric acid mist at a powder works in Pinole, California and a nearby smelter at Selby.

Figure 1. Electrostatic Precipitator General Description



The success at Selby unit led Dr. Cottrell, in 1910, to install his third commercial ESP at the Balaklala smelter in Northern California to collect lead and zinc oxide fume. Application of the process was extended to the collection of cement kiln dust at Riverside, California in 1912 with the first unit installed on a PC fire utility boiler at Detroit Edison Co. in 1923.

Electrostatic precipitators use electrical fields to remove particulate from boiler flue gas. Because precipitators act only on the particulate to be removed, and only minimally hinder flue

gas flow, they have very low pressure drops, and thus low energy requirements and operating costs.

In an electrostatic precipitator, an intense electric field is maintained between high-voltage discharge electrodes, typically wires, or rigid frames, and grounded collecting electrodes, typically plates. A corona discharge from the discharge electrodes ionizes the gas passing through the precipitator, and gas ions subsequently ionize fly ash (or other) particles. The electric field drives the negatively charged particles to the collecting electrodes. Periodically, the collecting electrodes are rapped mechanically to dislodge collected particulate, which falls into hoppers for removal.

In a typical electrostatic precipitator, collecting plates are arranged parallel to the gas flow, normally 9-18 inches apart, with discharge electrodes between them. Most precipitators have 3-5 independent electrical sections, i.e., sets of discharge and collecting electrodes with independent power supplies, in series. Each independent section removes a fraction of the particulate in the gas stream. This arrangement allows the use of higher voltages in the first sections of the precipitator, where there is more particulate to be removed. Lower voltages must be used in the final, cleaner precipitator sections to avoid excessive sparking between the discharge and collecting electrodes. In a precipitator with only one electrical section, the power input would be limited to the input which would cause sparking at the precipitator exit, thus limiting the performance of the entire precipitator.

Precipitator sectionalization has the added advantage that particles re-entrained in the flue gas stream by rapping may be collected in downstream sections of the precipitator, thus minimizing net rapping reentrainment losses.

While several factors determine electrostatic precipitator removal efficiency, precipitator size is of paramount importance. Size determines treatment time: the longer a particle spends in the precipitator, the greater its chance of being collected, other things being equal.

Precipitator size also is related to the specific collection area (SCA), the ratio of the surface area of the collection electrodes to the gas flow. Higher collection areas lead to better removal efficiencies. Collection areas normally are in the range of 200-800 ft^2/1,000 acfm. In order to achieve collection efficiencies of 99+ %, specific collection areas of 350-400 ft^2/1000 acfm are typically used with some larger installations reaching SCA's of 600 and even up to 1,000 ft^2/1,000 acfm. On the other hand, some older precipitators on utility boilers are small, with specific collection areas below 200 ft^2/1,000 acfm and correspondingly short treatment times. Expansion of these precipitators, or their replacement with larger precipitators, can lead to greatly enhanced performance.

Maximizing electric field strength will maximize precipitator collection efficiency. Automatic voltage controllers are used to maintain an electric field strength as high as possible to ensure maximum particle charging and collection, consistent with preventing electrical breakdown of the gas and sparking between the discharge and collecting electrodes, which would extinguish the electric field. These controllers detect spark onset, and maintain voltages just below the level at which sparking would occur.

Factors limiting precipitator performance are flow non-uniformity and reentrainment. More uniform flow will ensure that there are no high gas velocity, short treatment time paths through the precipitator. Attaining flow uniformity also will minimize "sneakage," or gas flows

bypassing the electrical fields. Reentrainment of collected particles may occur during rapping. Proper rapper design and timing will minimize rapper reentrainment. Maintenance of appropriate hopper ash levels and of flow uniformity will minimize reentrainment of ash from the hoppers.

A key determinant of electrostatic precipitator collection efficiency is the resistivity of the particles to be collected. Resistivity is the resistance of particles to the flow of electric current. Particles with resistivities in the range of 10^7-10^{10} Ohm-cm are amenable to collection with precipitators: these particles are easy to charge, and only slowly lose their charge once deposited on a collecting electrode. Particles with low resistivities (less than 10^7 Ohm-cm), on the other hand, loose their charge to a collecting electrode so rapidly that they tend not to adhere to the electrode, with the result that there will be high rapping reentrainment losses. Carbon black is an example of a low resistivity material.

Particles with high resistivity (greater than 10^{10} Ohm-cm) can be difficult to remove with a precipitator: such particles are not easily charged, and thus are not easily collected. High-resistivity particles also form ash layers with very high voltage gradients on the collecting electrodes. Electrical breakdowns in these ash layers lead to injection of positively charged ions into the space between the discharge and collecting electrodes ("back corona"), thus reducing the charge on particles in this space and lowering collection efficiency. Fly ash from the combustion of low-sulfur coal typically has a high resistivity, and thus is difficult to collect.

Electrostatic precipitator overall (mass) collection efficiencies can exceed 99.9% for "normal" "well behaved" fly ash resistivity, and efficiencies in excess of 99.5% are common (although requiring quite large real state/footprint). Precipitators with high overall collection efficiencies will have high collection efficiencies for particles of all sizes, so that excellent control of PM_{10} may be achieved with well designed and operated electrostatic precipitators (again, assuming the resistivity of the dust collected is in the "normal, well behaved" region).

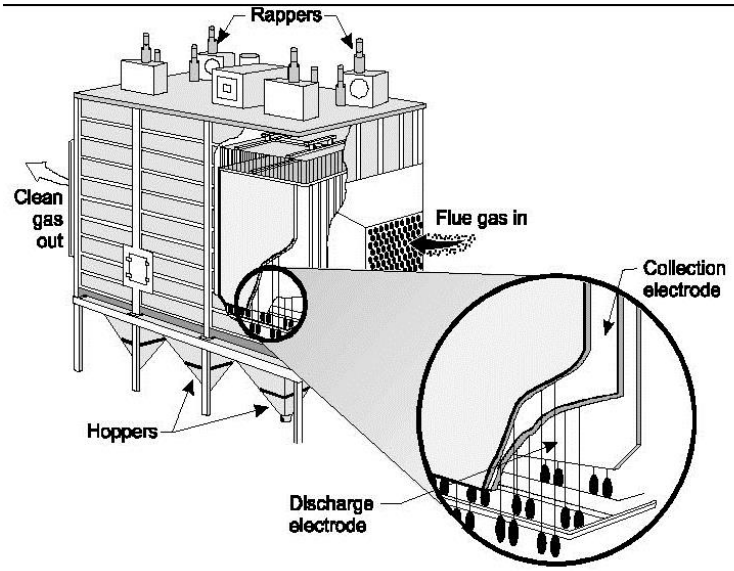


Figure 2. Typical Dry ESP

Precipitator collection efficiencies will be somewhat lower for particles with diameters near 0.3 microns ($PM_{2.5}$). The reason for a minimum in collection efficiency for 0.3-micron particles is that both particle charge and the resistance of the gas to particle motion both increase with particle size. Near 0.3 micron, the particle charge is low enough and the resistance to particle motion is high enough that particles are collected relatively poorly. In practice, however, this effect means only that a precipitator with a 99.9% overall mass collection efficiency will collect over 90% of 0.3-micron particles, and over 97-98% of all 0-5 micron particles.

Older electrostatic precipitators may show poor performance not only due to the particulate properties, but also to the fact that they were "grossly" undersized by today's standards. In addition to general deterioration of the precipitators, several design factors can lead to less-than-desired performance. These can include small size and consequent short treatment time and low specific collection area, non-uniform flow, and inadequate electrical control systems.

Options for improving the performance of existing precipitators begin with simple rebuilds. These normally include the replacement of electrodes, rappers, and other internal elements, and modernization of the precipitator power supply and control system. An upgraded control system allows for improved voltage control, so that the voltage in each field may be maintained at the highest level possible without sparking. Precipitator rebuilds also include improvements to the ductwork, casing, and flow devices to improve the flow distribution, seal leaks, etc.

Replacement of electrodes typically is accompanied by an increase in the spacing between collecting electrodes from nine to 12 or 18 inches. While using a wider plate spacing lowers specific collection area, the ability to use higher operating voltages without sparking increases collection efficiency enough to more than compensate for this change.

Further performance improvements can be obtained by increasing precipitator size and specific collection area. Some older utility units have specific collection areas as low as 150 ft^2/1000 acfm; increases to values near 400-600 ft^2/1,000 acfm may be necessary in order to meet the new source performance level of 0.03 lb/MBtu. Specific collection area and treatment time may be done by increasing plate height, which allows maximum use of the existing casing. On the other hand, there is a limit to the extent to which plate height can be increased, as precipitators should be longer than they are wide for maximum performance. Better options for increasing treatment time and collection area are adding one or more electrical fields and increasing the length of the fields. Because these options require additional construction outside of the existing casing, they are more expensive.

New and emerging technologies may offer a simpler and better solutions, while maintaining the available system footprint and reducing the environmental risk.

4.0 PHYSICS AND PRINCIPLES OF OPERATION

A typical ESP as shown in Figure 1 and Figure 2**Error! Reference source not found.** as thin wires called discharge electrodes, which are evenly spaced between large plates called collection electrodes, which are grounded. A negative, high-voltage, pulsating, direct current is applied to the discharge electrode creating a negative electric field. The inter-electrode electric field can be divided into three regions (Figure 3). The field is strongest right next to the discharge electrode, weaker in the areas between the discharge and collection electrodes called the inter-electrode region, and weakest near the collection electrode. The region around the discharge electrode is where the particle charging process begins.

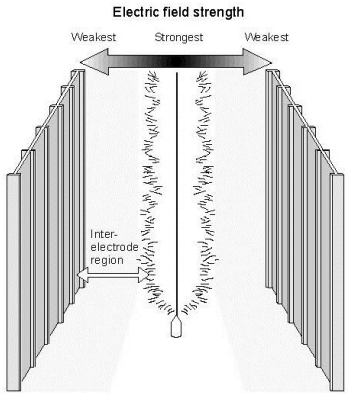


Figure 3. Electric Field in the ESP

4.1 CORONA DISCHARGE: FREE ELECTRON GENERATION

Several things happen very rapidly (in a matter of a millisecond) in the small area around the discharge electrode. The applied voltage is increased until it produces a corona discharge, which can be seen as a luminous blue glow around the discharge electrode.

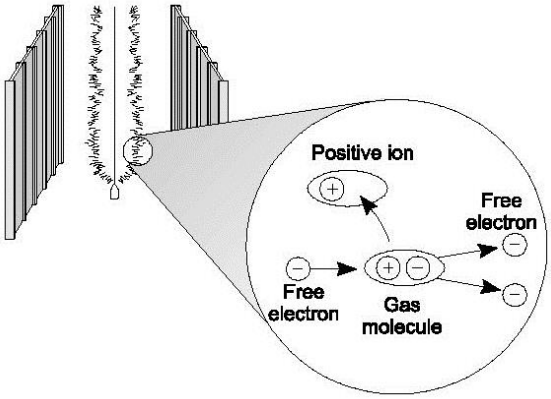


Figure 4. Corona Generation

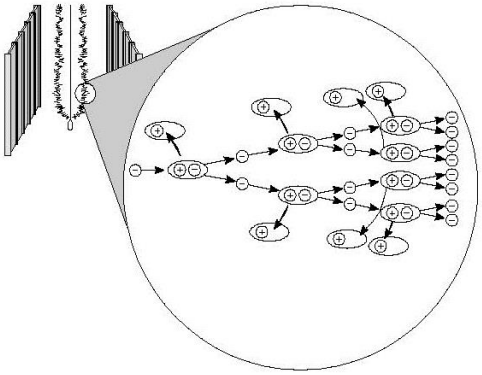


Figure 5. Avalanche Multiplication of Gas Molecules

The free electrons created by the corona are rapidly fleeing the negative electric field, which repulses them. They move faster and faster away from the discharge electrode. This acceleration causes them to literally crash into gas molecules, bumping off electrons in the molecules. Because of losing an electron (which is negative), the gas molecules become positively charged, that is, they become positive ions(Figure 4). Therefore, the gas molecules become ionized, and electrons are liberated. All this activity takes place in an immediate vicinity of the discharge electrode.

This process continues, creating more and more free electrons and more positive ions. The name for all this electron generation activity is avalanche multiplication (Figure 5). The electrons bump into gas molecules and create additional ionized molecules. The positive ions, on the other hand, are drawn back toward the negative discharge electrode. The molecules are hundreds of times bigger than the tiny electrons and move slowly, but they do pick up speed. In fact, many of them collide right into the metal discharge electrode or the gas space around the wire causing additional electrons to be knocked off. This is called secondary emission.

4.2 IONIZATION OF GAS MOLECULES

As the electrons leave the strong electrical field area around the discharge electrode, they start slowing down. Now they're in the inter-electrode area where they are still repulsed by the discharge electrode but to a lesser extent. There are also gas molecules in the inter-electrode region, but instead of violently colliding with them, the electrons kind of bump up to them and are captured (Figure 6).

Figure 6. Negative Gas Ions Formation

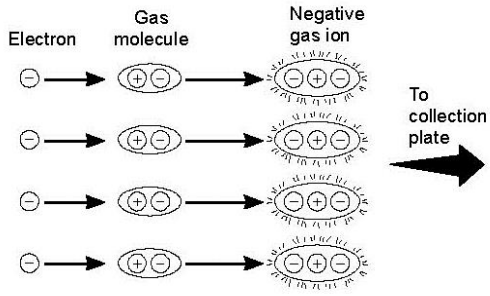
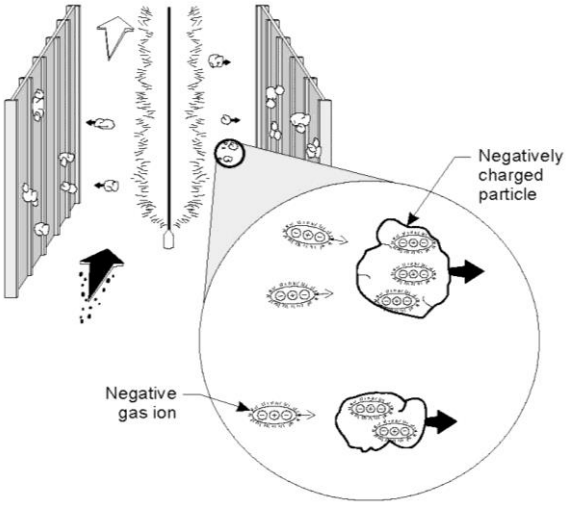


Figure 7. Particle Charging



This imparts a negative charge to the gas molecules, creating negative gas ions. This time, because the ions are negative, they too want to move in the direction opposite the strong negative field. Now we have ionization of gas molecules happening near the discharge electrode and in the inter-electrode area, but with a big difference. The ions near the discharge electrode are positive and remain in that area. The ions in the middle area are negative and move away, along the path of invisible electric field lines, toward the collection electrode.

4.3 CHARGING OF PARTICLES

These negative gas ions play a key role in capturing dust particles. Before the dust particles can be captured, they must first acquire a negative charge. This is when and where it happens. The particles are traveling along in the gas stream and encounter negative ions moving across their path. Actually, what really happens is that the particles get in the way of the negatively charged gas ions. The gas ions stick to the particles, imparting a negative charge to them

(Figure 7). At first the charge is fairly insignificant as most particles are huge compared to a gas molecule. But many gas ions can fit on a particle, and they do. Small particles (less than 1 μm diameter) can absorb "tens" of ions. Large particles (greater than 10 μm) can absorb "tens of thousands" of ions. Eventually, there are so many ions stuck to the particles, the particles emit their own negative electrical field. When this happens, the negative field around the particle repulses the negative gas ions and no additional ions are acquired. This is called the **saturation charge**.

Now the negatively-charged particles are feeling the inescapable pull of electrostatic attraction. Bigger particles have a higher saturation charge (more molecules fit) and consequently are pulled more strongly to the collection plate. In other words, they move faster than smaller particles. Regardless of size, the particles encounter the plate and stick, because of adhesive and cohesive forces.

4.4 PARTICLE COLLECTION

When a charged particle reaches the grounded collection electrode, the charge on the particle is only partially discharged. The charge is slowly leaked to the grounded collection plate. A portion of the charge is retained and contributes to the inter-molecular adhesive and cohesive forces that hold the particles onto the plates (Figure 8). Adhesive forces cause the particles to physically hold on to each other because of their dissimilar surfaces.

Newly arrived particles are held to the collected particles by cohesive forces; particles are attracted and held to each other molecularly. The dust layer is allowed to build up on the plate to a desired thickness and then the particle removal cycle is initiated.

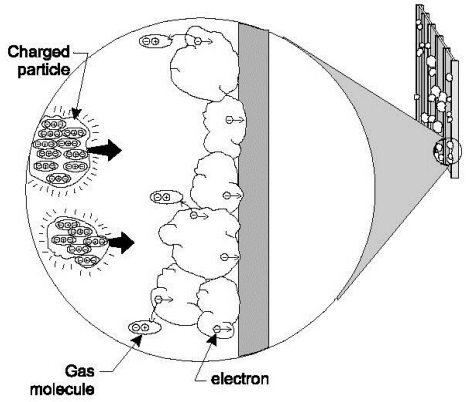


Figure 8. Particle Collection at Collecting Electrode

4.5 PARTICLE REMOVAL

Dust that has accumulated to a certain thickness on the collection electrode is removed by one of two processes, depending on the type of collection electrode. Collection electrodes in precipitators can be either plates or tubes, with plates being more common. Tubes are usually cleaned by water sprays, while plates can be cleaned either by water sprays or a process called rapping.

Rapping is a process whereby deposited, dry particles are dislodged from the collection plates by sending mechanical impulses, or vibrations, to the plates. Precipitator plates are rapped periodically while maintaining the continuous flue-gas cleaning process. In other words, the plates are rapped while the ESP is on-line; the gas flow continues through the precipitator and the applied voltage remains constant. Plates are rapped when the accumulated dust layer is relatively thick (0.08 to 1.27 cm or 0.03 to 0.5 in.). This allows the dust layer to fall off the plates as large aggregate sheets and helps eliminate dust reentrainment.

Most precipitators have adjustable rappers so that rapper intensity and frequency can be changed according to the dust concentration in the flue gas. Installations where the dust concen-

tration is heavy require more frequent rapping. Dislodged dust falls from the plates into the hopper. The hopper is a single collection bin with sides sloping approximately 50 to 70° to allow dust to flow freely from the top of the hopper to the discharge opening. Dust should be removed as soon as possible to avoid (dust) packing. Packed dust is very difficult to remove. Most hoppers are emptied by some type of discharge device and then transported by a conveyor.

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5.0 TYPES OF ELECTROSTATIC PRECIPITATORS

ESPs can be grouped, or classified, according to a number of distinguishing features in their design. These features include the following:

- The structural design and operation of the discharge electrodes (rigid-frame, wires or plate) and collection electrodes (tubular or plate)
- The method of charging (single-stage or two-stage)
- The temperature of operation (cold-side or hot-side)
- The method of particle removal from collection surfaces (wet or dry).

5.1 PRECIPITATOR COMPONENTS

All electrostatic precipitators, regardless of their particular designs, contain the following essential components:

- Discharge electrodes
- Collection electrodes
- High voltage electrical systems
- Rappers
- Hoppers
- Shell

Discharge electrodes are either small-diameter metal wires that hang vertically (in the electrostatic precipitator), a number of wires attached together in rigid frames, or a rigid electrode made from a single piece of fabricated metal. Discharge electrodes create a strong electrical field that ionizes flue gas, and this ionization charges particles in the gas.

Collection electrodes collect charged particles. Collection electrodes are either flat plates or tubes with a charge opposite that of the discharge electrodes.

High voltage equipment provides the electric field between the discharge and collection electrodes used to charge particles in the ESP.

Rappers impart a vibration, or shock, to the electrodes, removing the collected dust. Rappers remove dust that has accumulated on both collection electrodes and discharge electrodes. Occasionally, water sprays are used to remove dust from collection electrodes.

Hoppers are located at the bottom of the precipitator. Hoppers are used to collect and temporarily store the dust removed during the rapping process.

The *shell* provides the base to support the ESP components and to enclose the unit.

Figure 9 shows a typical ESP with wires for discharge electrodes and plates for collection electrodes. This ESP is used to control particulate emissions in many different industries.

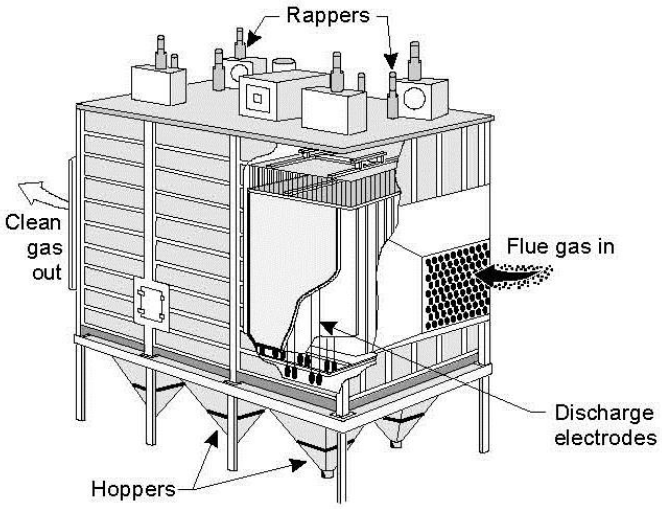


Figure 9. Typical Dry Electrostatic Precipitator

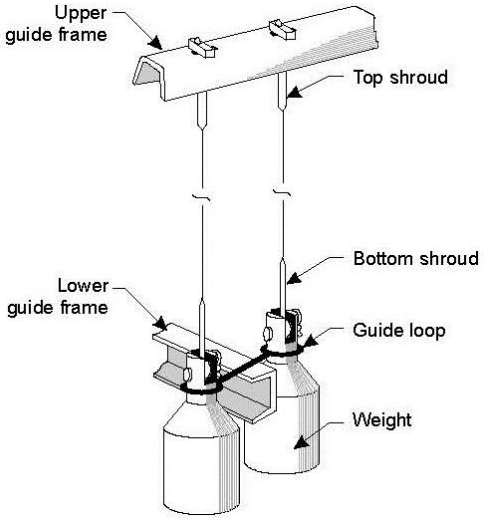


Figure 10. Weighted Wire Discharge Electrodes

5.1.1 Discharge Electrodes

The discharge electrodes in most U.S. precipitator designs (prior to the 1980s) are thin, round wires varying from 0.13 to 0.38 cm (0.05 to 0.15 in.) in diameter. The most common size diameter for wires is approximately 0.25 cm (0.1 in.). The discharge electrodes are hung vertically, supported at the top by a frame and held taut and plumb by a weight at the bottom. The wires are usually made from high-carbon steel, but have also been constructed of stainless steel, copper, titanium alloy, and aluminum. The weights are made of cast iron and are generally 11.4 kg (25 lb) or more. Discharge wires are supported to help eliminate breakage from mechanical fatigue. The wires move under the influence of aerodynamic and electrical forces and are subject to mechanical stress. The weights at the bottom of the wire are attached to guide frames to help maintain wire alignment and to prevent them from falling into the hopper in the event that the wire breaks (Figure 10).

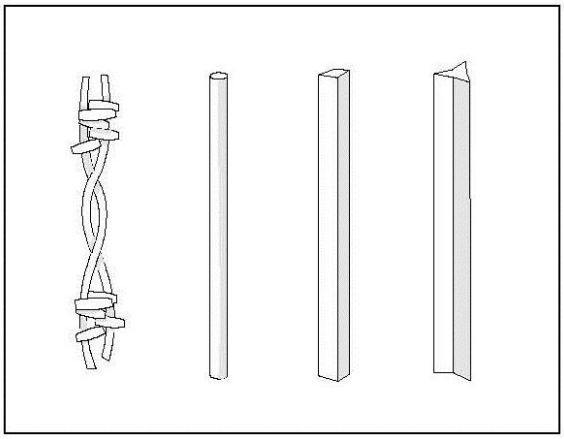


Figure 11. Typical Wire Discharge Electrodes

The size and shape of the electrodes are governed by the mechanical requirements for the system, such as the industrial process on which ESPs are installed and the amount and properties of the flue gas being treated. Most U.S. designs have traditionally used thin, round wires for co-

rona generation. Some designers have also used twisted wire, square wire, barbed wire, or other configurations, as illustrated in Figure 11.

European precipitator manufacturers and most of the newer systems (since the early 1980s) made by U.S. manufacturers use rigid support frames for discharge electrodes. The frames may consist of coiled-spring wires, serrated strips, or needle points mounted on a supporting strip. A typical rigid-frame discharge electrode is shown in Figure 2-4. The purpose of the rigid frame is to eliminate the possible swinging of the discharge wires. Another type of discharge electrode is a rigid electrode that is constructed from a single piece of fabricated metal and is shown in Figure 13. Both designs are occasionally referred to as rigid-frame electrodes. They have been used as successfully as the older U.S. wire designs. One major disadvantage of the rigid-frame design is that a broken wire cannot be replaced without removing the whole frame.

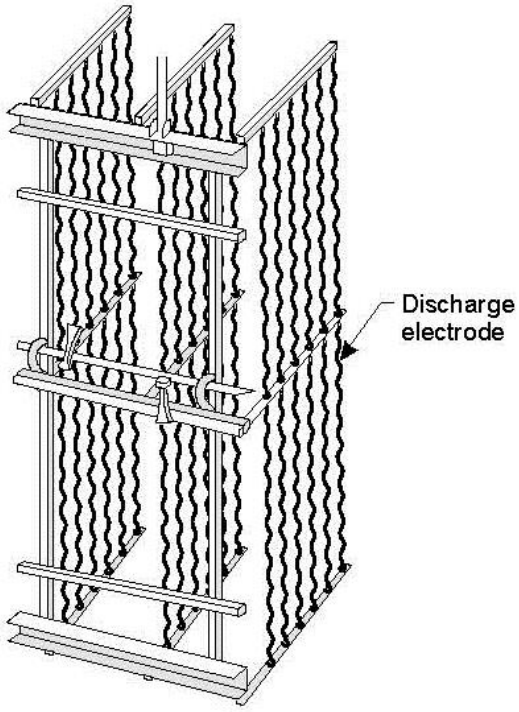


Figure 12. Rigid Frame Discharge Electrode Design

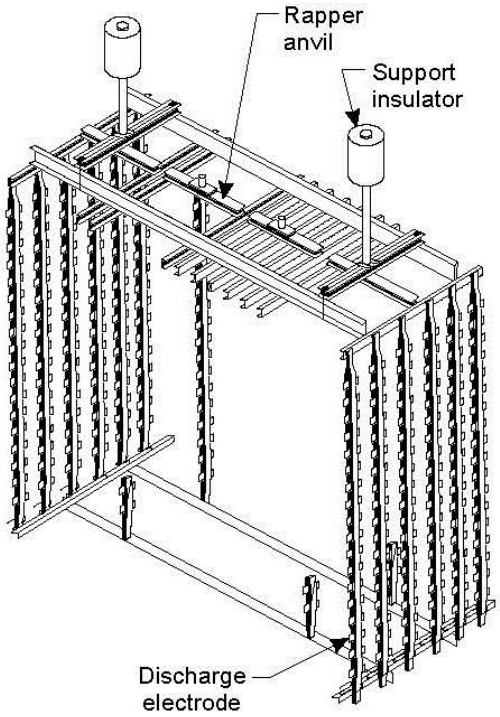


Figure 13. Typical Rigid Discharge Electrode (RDE)

5.1.2 Collection Electrodes

Most U.S. precipitators use **plate** collection electrodes because these units treat large gas volumes and are designed to achieve high collection efficiency. The plates are generally made of carbon steel. However, plates are occasionally made of stainless steel or an alloy steel for special flue-gas stream conditions where corrosion of carbon steel plates would occur. The plates range from 0.05 to 0.2 cm (0.02 to 0.08 in.) in thickness. For ESPs with wire discharge electrodes, plates are spaced from 15 to 30 cm apart (6 to 12 in.). Normal spacing for high-efficiency ESPs (using wires) is 20 to 23 cm (8 to 9 in.). For ESPs using rigid-frame or plate

discharge electrodes, collection plates are typically spaced 30 to 38 cm (12 to 15 inches) apart. Plates are usually between 6 and 12 m (20 to 40 ft) high.

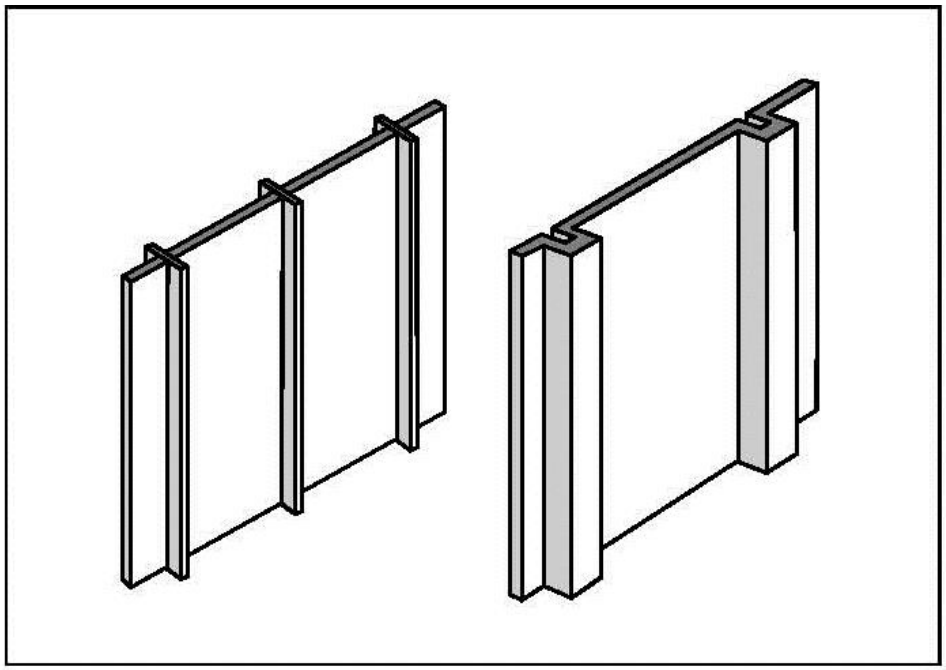


Figure 14. Typical Collecting Electrode Plate Shapes

Collecting plates are constructed in various shapes, as shown in Figure 14. These plates are solid sheets that are sometimes reinforced with structural stiffeners to increase plate strength. In some cases, the stiffeners act as baffles to help reduce particle reentrainment losses. This design minimizes the amount of excess rapping energy required to dislodge the dust from the collection plates, because the energy is distributed evenly throughout the plate. The baffles also provide a "quiet zone" for the dislodged dust to fall while minimizing dust reentrainment.

5.1.3 High-Voltage Equipment

High-voltage equipment determines and controls the strength of the electric field generated between the discharge and collection electrodes. This is accomplished by using power supply sets consisting of three components: a step-up transformer, a high-voltage rectifier, and control metering and protection circuitry (automatic circuitry). The power system maintains voltage at the highest level without causing excess sparkover between the discharge electrode and collection plate. These power sets are also commonly called **transformer-rectifier (T-R) sets**.

In a T-R set, the transformer steps up the voltage from 400 volts to approximately 50,000 volts. This high voltage ionizes gas molecules that charge particles in the flue gas. The rectifier converts alternating current to direct current. Direct (or unidirectional current) is required for electrical precipitation. Most modern precipitators use solid-state silicon rectifiers and oil-filled, high-voltage transformers. The control circuitry in a modern precipitator is usually a Silicon-controlled Rectifier (SCR) automatic voltage controller with a linear reactor in the primary side of the transformer. Meters, also included in the control circuitry, monitor the variations in the electrical power input. A simplified drawing of the circuitry from the primary control cabinet to the precipitator field is shown in Figure 15.

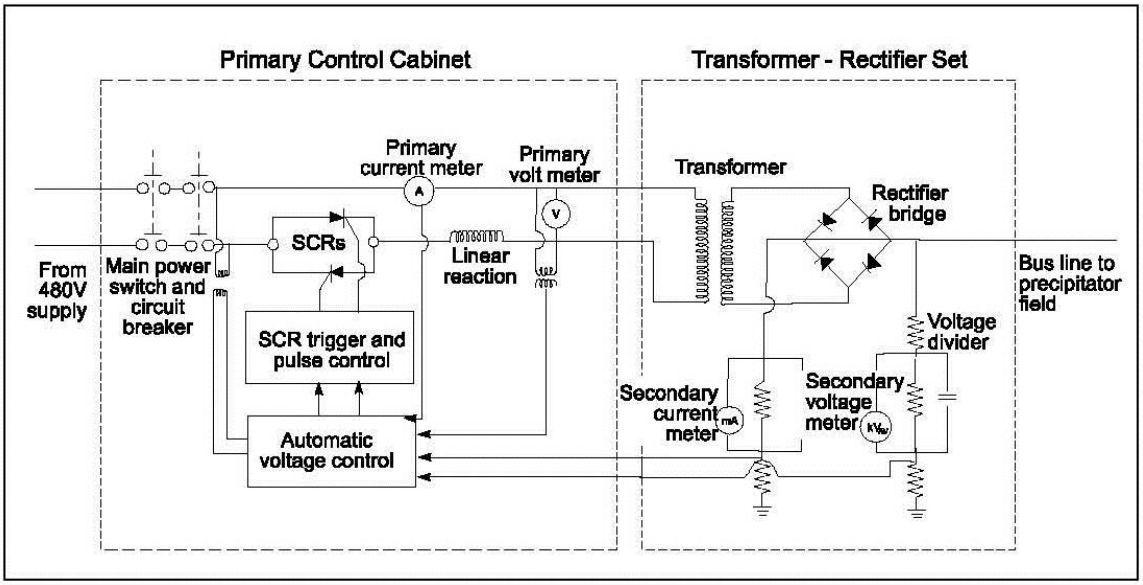


Figure 15. Schematic Diagram of the Transformer Rectifier Set

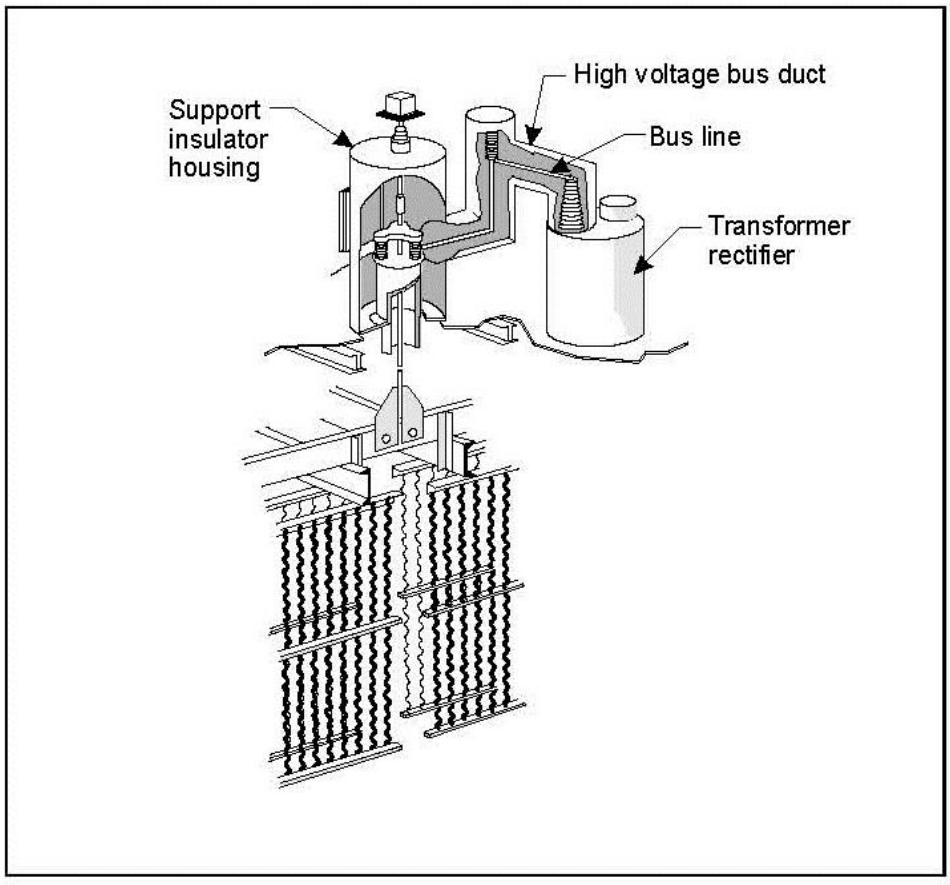


Figure 16. Schematic Representation of the High Voltage System

The transformer-rectifier set is connected to the discharge electrodes by a **bus line**. A bus line is electric cable that carries high voltage from the transformer-rectifier to the discharge

electrodes (Figure 16). The bus line is encased in a pipe, or bus duct, to protect the high-voltage line from the environment and to prevent the line from becoming a potential hazard to humans. The high-voltage bus lines are separated, or isolated, from the ESP frame and shells by insulators. The insulators are made of non-conducting plastic or ceramic material.

5.1.4 Rappers

Dust that has accumulated on collection and discharge electrodes is removed by rapping. Dust deposits are generally dislodged by mechanical impulses, or vibrations, imparted to the electrodes. A rapping system is designed so that rapping intensity and frequency can be adjusted for varying operational conditions. Once the operating conditions are set, the system must be capable of maintaining uniform rapping for a long time. Collection electrodes are rapped by **hammer/anvil** or **magnetic impulse** systems. Rigid frame discharge electrodes are rapped by **tumbling hammers** and wires are rapped by **vibrators**. As stated previously, liquid sprays are also used (instead of rapping) to remove collected particles form both tubes and plates.

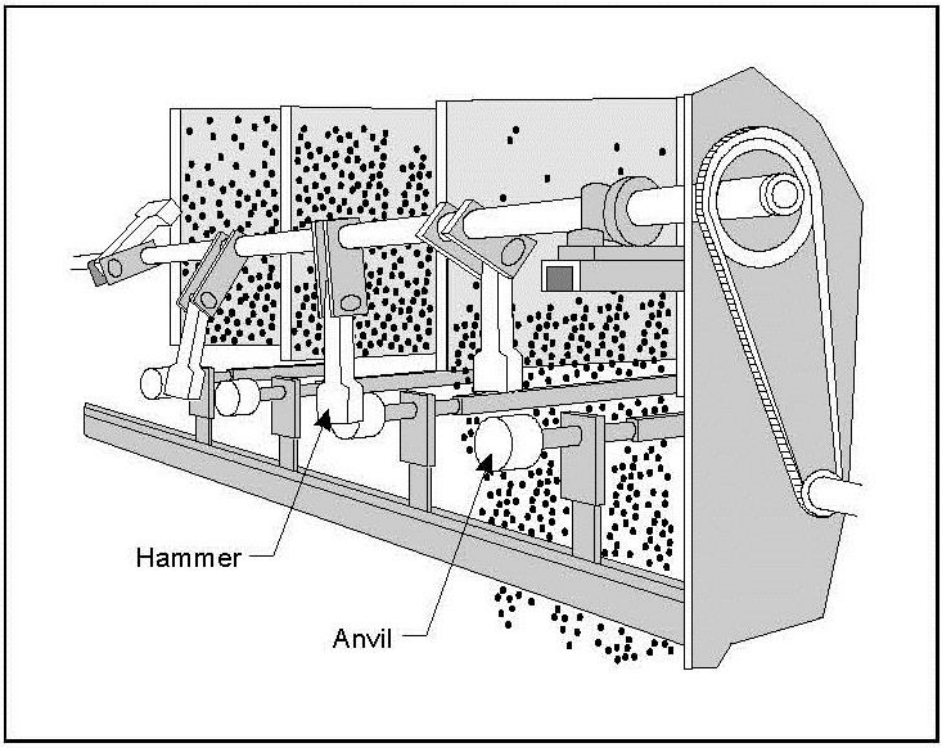


Figure 17. Typical Flail (Tumbling) Hammer Rapping Mechnism Design

5.1.5 Hammer Hammer/Anvil

Collection plates are rapped by a number of methods. One rapper system uses hammers mounted on a rotating shaft, as shown in Figure 17. As the shaft rotates, the hammers drop (by gravity) and strike anvils that are attached to the collection plates. Rappers can be mounted on the top or on the side of collection plates. European precipitator manufacturers use hammer and anvil rappers for removing particles from collection plates.

Rapping intensity is controlled by the weight of the hammers and the length of the hammer mounting arm. The frequency of rapping can be changed by adjusting the speed of the rotat-

ing shafts. Thus, rapping intensity and frequency can be adjusted for the varying dust concentration of the flue gas.

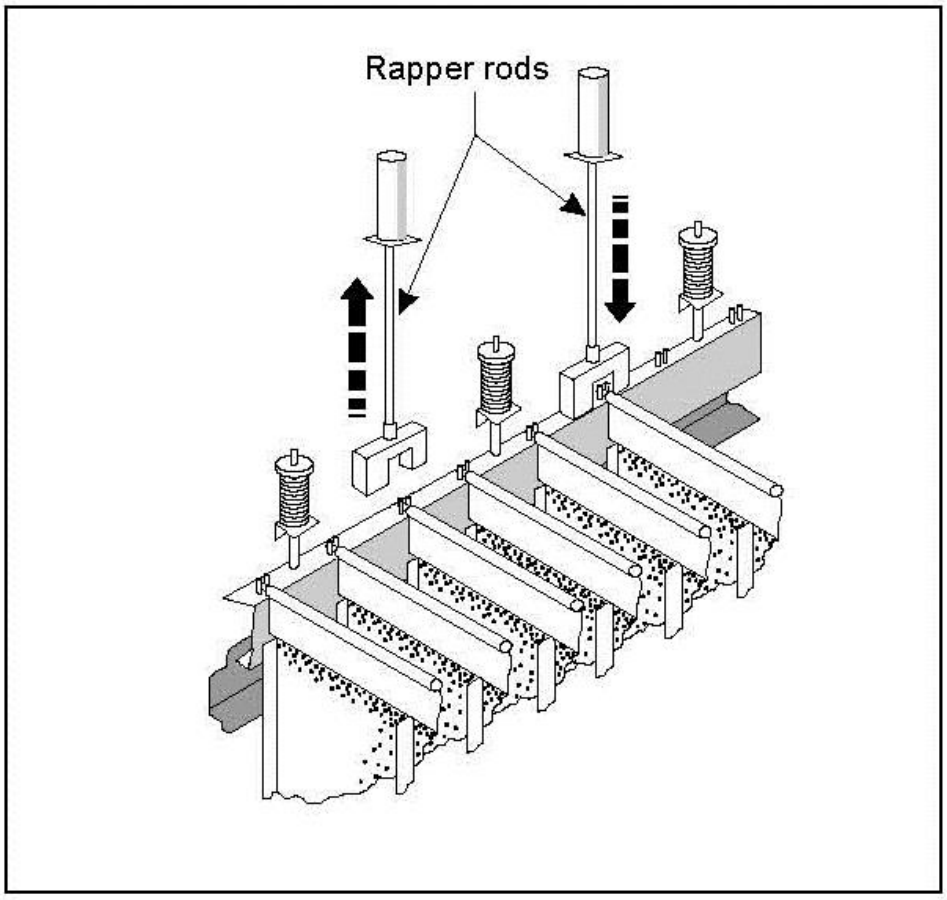


Figure 18. Typical Magnetic Impulse Rappers for Collecting Electrodes

5.1.6 Magnetic Impulse

Another rapping system used for many U.S. designs consists of magnetic-impulse rappers to remove accumulated dust layers from collection plates. A magnetic-impulse rapper has a steel plunger that is raised by a current pulse in a coil. The raised plunger then drops back, due to gravity, striking a rod connected to a number of plates within the precipitator as shown in Figure 18. Rapper frequency and intensity are easily regulated by an electrical control system. he frequency could be one rap every five minutes or one rap an hour with an intensity of 10 to 24 g's. Magnetic impulse rappers usually operate more frequently, but with less intensity, than rotating hammer and anvil rappers.

5.1.6.1 Tumbling Hammers for Rigid Frame Discharge Electrodes

Rigid frame discharge electrodes are rapped by tumbling hammers. The tumbling hammers operate similarly to the hammers used to remove dust from collection electrodes. The hammers are arranged on a horizontal shaft. As the shaft rotates, the hammers hit an impact beam which transfers the shock, or vibration, to the center tubes on the discharge system, causing the dust to fall (Figure 19).

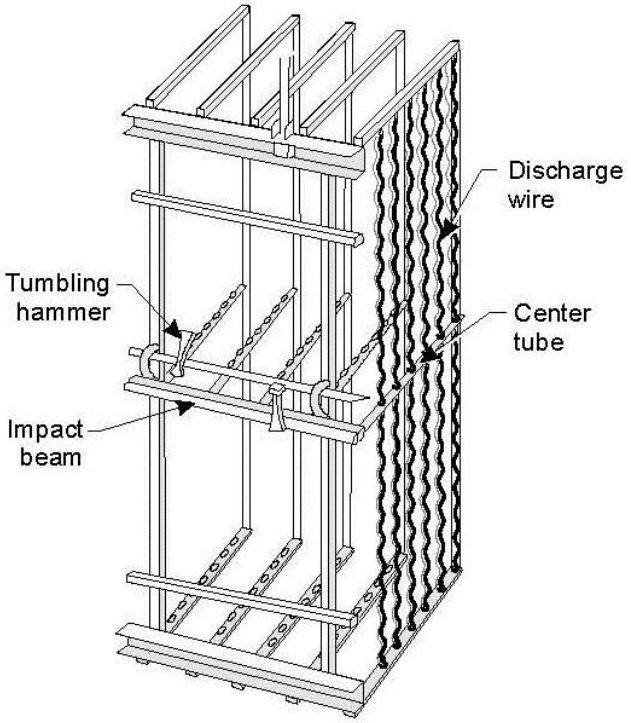


Figure 19. Tumbling Hummers for Rigid Frame Discharge Electrode System

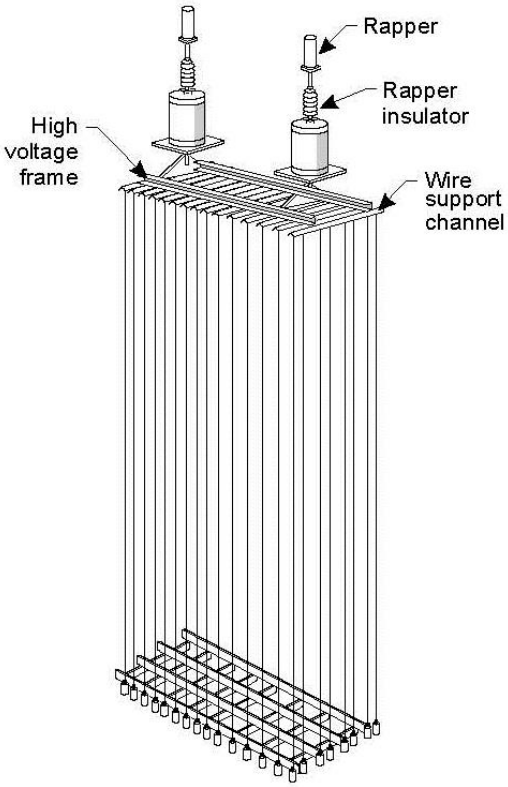


Figure 20. Typical Electro-Vibrator Rapper System for Wire Discharge Electrodes

5.1.6.2 Electric Vibrator

Wire discharge (or corona) electrodes must also be rapped to prevent excessive dust deposit buildup that will interfere with corona generation. This is usually accomplished by the use of air or electric vibrators that gently vibrate the discharge wires. Vibrators are usually mounted externally on precipitator roofs and are connected by rods to the high-tension frames that support the corona electrodes (Figure 20). An insulator, located above the rod, electrically insulates the rapper while mechanically transmitting the rapping force.

5.1.7 Hoppers

When the electrodes are rapped, the dust falls into hoppers and is stored temporarily before it is disposed in a landfill or reused in the process. Dust should be removed as soon as possible to avoid packing, which would make removal very difficult. Hoppers are usually designed with a 50 to 70° (60° is common) slope to allow dust to flow freely from the top of the hopper to the bottom discharge opening. Some manufacturers add devices to the hopper to promote easy and quick discharge. These devices include **strike plates, poke holes, vibrators,** and **rappers**. Strike plates are simply pieces of flat steel that are bolted or welded to the center of the hopper wall. If dust becomes stuck in the hopper, rapping the strike plate several times with a mallet will free this material. Hopper designs also usually include access doors, or ports. Access ports allow easier access for cleaning, inspection, and maintenance of the hopper (Figure 21).

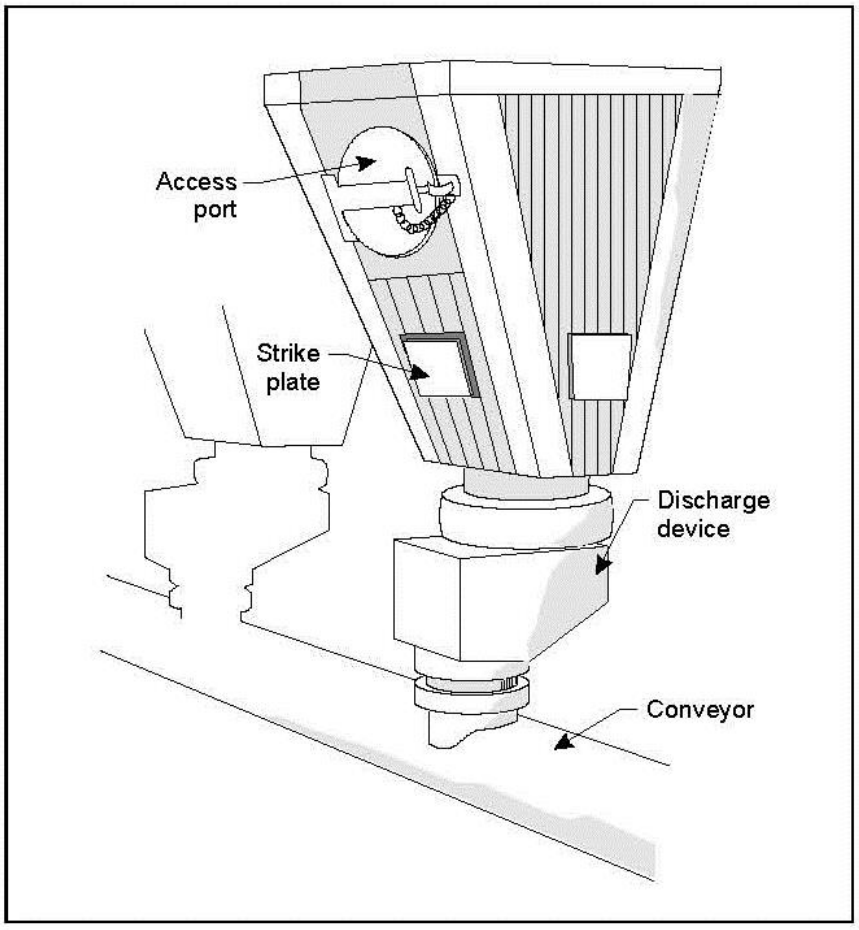


Figure 21. Hopper

Hopper vibrators are occasionally used to help remove dust from the hopper walls. Hopper vibrators are electrically operated devices that cause the side walls of the hopper to vibrate, thereby removing the dust from the hopper walls. These devices must be carefully designed and chosen so that they do not cause dust to be firmly packed against the hopper walls, and thereby plug the hopper. Before installing vibrators to reduce hopper plugging, make sure they have been successfully used in other, similar industrial applications.

5.1.8 Shell

The **shell** structure encloses the electrodes and supports the precipitator components in a rigid frame to maintain proper electrode alignment and configuration (Figure 22). The support structure is especially critical for hot-side precipitators because precipitator components can expand and contract when the temperature differences between the ESP (400°C or 752°F) and the ambient atmosphere (20°C or 68°F) are large. Excessive temperature stresses can literally tear the shell and hopper joints and welds apart. The outer sheet or casing wall is usually made of low-carbon or mild-grade steel that is 0.5 to 0.6 cm (3/16 to 1/4 in.) thick.

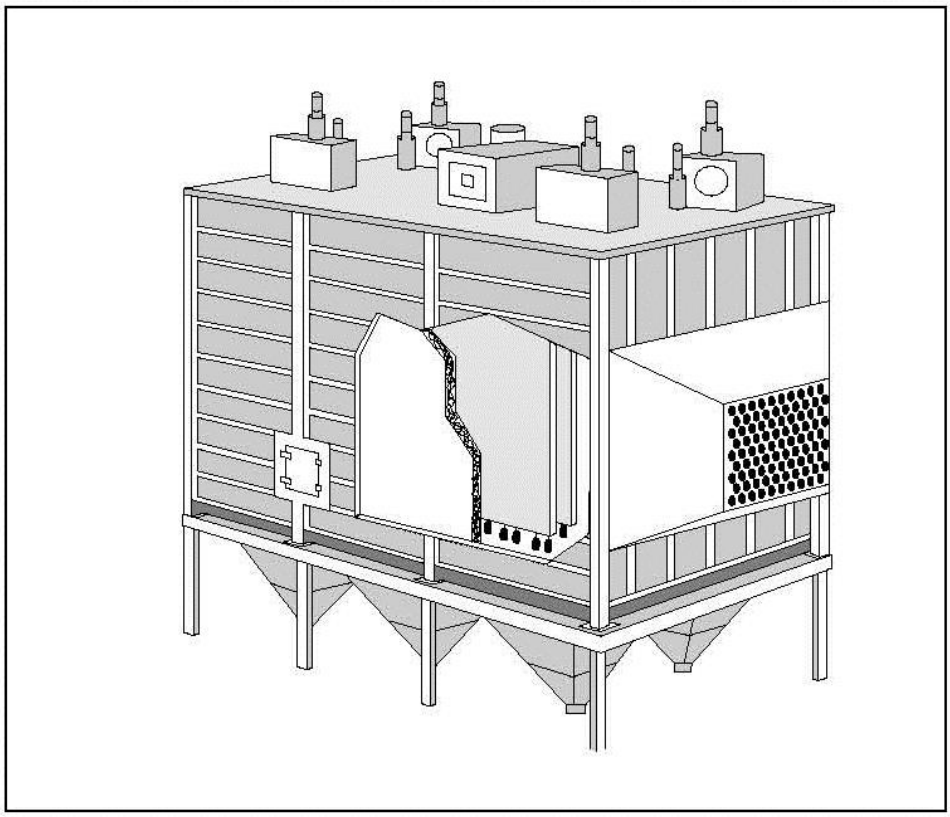


Figure 22. Electrostatic Precipitator Shell

6.0 ESP DESIGN PARAMETERS AND THEIR EFFECTS ON COLLECTION EFFICIENCY

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.

The design of an electrostatic precipitator for a particulate installation involves many parameters that can influence both cost and performance. The more significant variables involved in the design are:

i. Total area and type of collecting electrodes;
ii. Dimensions of the precipitator (available footprint);
iii. Size, spacing, and type of discharge electrodes;
iv. Size and type of power supply units;
v. Degree of sectionalization;
vi. Layout of the precipitators in accordance with physical space limitations;
vii. Design of the gas handling and distribution system;
viii. Size and shape of hoppers;
ix. Type and number of electrode rappers, and
x. Type of dust removal system.

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.

Before determining the collection area and the collection efficiency, the designer must estimate or measure (if possible) the **particle migration or drift velocity**. This is the speed at which a particle, once charged, moves (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, ω, 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.

Mathematically, the migration velocity could be expressed as follows:

$$\omega = \frac{d_p E_0 E_p}{4\mu\eta} \qquad \textbf{Equation 1}$$

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

In short, 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.

The above equation was further simplified by Dr. Harry White as:

$$\omega = \frac{qE_p}{6\mu\eta r}$$ **Equation 2**

Where: q - particle charge(s)
Ep - 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 equation, 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.

There are several methods used for the selection of suitable values for these variables and each manufacturer may utilize slightly different methods in arriving at a particulate design.

(a) The most common approach to the selection of the area of collecting plate required is to utilize the so-called Deutsch-Anderson equitation;
(b) Modified Deutsch-Anderson equation:
    a. Using the effective precipitation rate (ω_e) proposed by Dr. White;
    b. Using so-called ω_k proposed by Matts and Ohnfeldt;
(c) Using pilot plants, and
(d) Using computer programs and models.

6.1 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:

$$\eta = 1 - e^{-\omega\frac{A}{Q}}$$ **Equation 3**

Where: η - collection efficiency of the precipitator
e - base of natural logarithm = 2.718
ω - 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, m3/s (ft³/sec)

The critical parameter in the Deutsch-Anderson equation is the precipitation rate ω, or migration velocity as it called more often. This parameter caries with each installation depending upon resistivity and particle size of the dust, quality and quantity of the gas flow, reentrainment losses, and sectionalization, among other factors. The values of ω are selected by the equipment manufacturers on the basis of past experience with a particular dust, or from the composition of the dust that can be related to past experience. Each manufacturer therefore has a file of experience (a "black" book) from which a precipitation parameter can be selected, and this file of information is kept as proprietary data.

The major problem in the design of precipitators based on the Deutsch-Anderson approach is in the selection of the migration velocity for the specific application. Several techniques can be used to narrow the uncertainty of the value of ω to be used.

The Deutsch-Anderson 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.

6.2 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 (ω_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 ω_e instead of ω in the Deutsch-Anderson equation.

$$\eta = 1 - e^{-\omega_e \frac{A}{Q}} \qquad \textbf{Equation 4}$$

Where: η - collection efficiency of the precipitator
e - base of natural logarithm = 2.718
ω_e - migration velocity, cm/s (ft/sec)
A - the effective collecting plate area of the precipitator, m^2 (ft2)
Q - gas flow through the precipitator, m^3/s (ft^3/sec)

In contrast to the migration velocity (ω), which refers to the speed at which *an individual charged particle* migrates to the collection electrode, the effective precipitation rate (ω_e) refers to the *average* speed at which all particles in the entire dust mass move toward the collection electrode. The variable, ω_e, is calculated from field experience rather than from theory; values for

we 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.

6.3 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 (M-O) equation is

$$\eta = 1 - e^{-\omega_k (\frac{A}{Q})^k} \qquad \textbf{Equation 5}$$

Where: η - collection efficiency of the precipitator
e - base of natural logarithm = 2.718
ω_k - average migration velocity, cm/s (ft/sec)
k - a constant, usually 0.4 to 0.8
A = collection area, m^2 (ft^2)
Q = gas flowrate, m^3/s (ft^3/sec)

The term, ω_k, the average migration velocity in the Matts-Ohnfeldt equation, is determined from information obtained from similar installations. The terms ω_k and ω_e are similar in that both are average migration velocities.

Table 1. Collection Efficiency Estimations using the D-A and M-O 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

The constant, k, is usually between 0.4 and 0.86, 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 = 0.5 gives satisfactory results. In an 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 presented in the Table 1.

Note 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. Table 1 confirms

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.

7.0 DESIGN FACTORS AFFECTING ESP PERFORMANCE

7.1 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.

Resistivity is commonly used as a guide when evaluating the likely performance of coal's fly ash in an electrostatic precipitator. However, resistivity is only one of many factors which influence electrostatic precipitator performance and the actual resistivity of particles collected on the plate of an electrostatic precipitator at operating conditions can be significantly less than the resistivity measured by laboratory test apparatus. 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. Nevertheless, 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. Dr. White proposed the following (Table 2) value ranges for low, normal, and high resistivity.

Table 2. Resistivity Ranges

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)

7.1.1 Dust Layer Resistivity

Clearly, 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 (Figure 23 and Figure 24). 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.

Electrical resistivity of the fly ash collected on the precipitator plates causes a voltage drop across the dust layer and if the resistivity is sufficiently high this will cause an electrical breakdown resulting in back corona or sparking at the surface of the dust layer causing particle re-entrainment. It is normal with higher resistivity fly ash to operate the precipitator at a voltage, which initiates the onset of back corona, and to control it at this variable condition by setting the precipitator at a specific sparking rate in order to maintain electrical stability. Therefore, the electrical resistivity of the collected layer is important to proper precipitation, thus leading to the dependence on fly ash resistivity as an indicator of electrostatic precipitability.

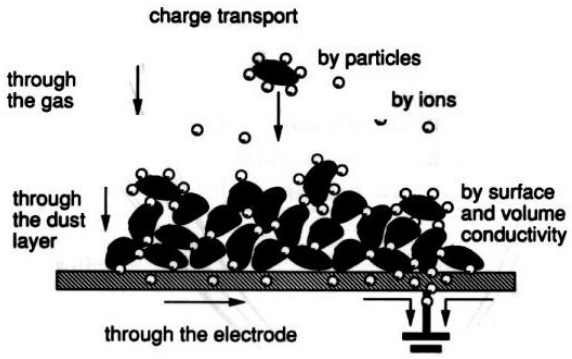


Figure 23. Charge Transport.

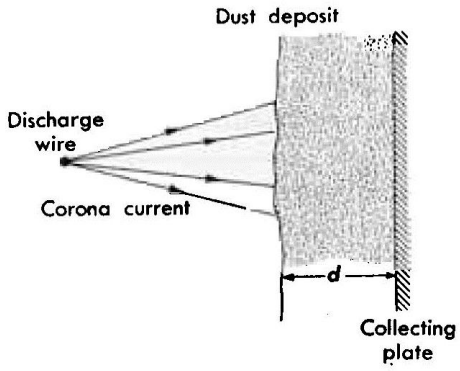


Figure 24. Voltage Drop Across the Collected Dust Layer

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 re-entrained in the gas stream.

The following discussion of normal, high, and low resistivity applies to ESPs operated in a dry state.

7.1.2 Normal Resistivity

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.

7.1.3 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%.

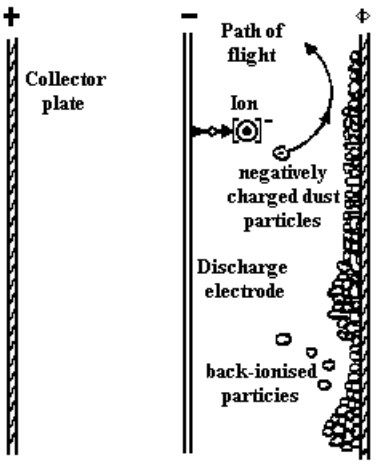


Figure 25. Back Corona/Back Ionization Development

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)

7.1.4 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 re-entrained 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 ammonia (NH_3), or Dual FGC 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 to form an

ammonium sulfate compound that increases the resistivity of the dust. *A separate White Paper on the subject Ammonia/Dual FGC is also available*.

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

Table 3. ESP Operating 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:	30 to 70 kV, dependent on design factors
Operating current density:	5 to 50 nA/cm^2
Dust layer thickness:	1/4 to 1 inch

7.2 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 the following Equation:

$$SCA = \frac{Total\ Collection\ Surface}{Gas\ Flow\ Rate}$$

Expressed in metric units:

$$SCA = \frac{Total\ Collection\ Area\ (m^2)}{1{,}000\ \frac{m^3}{hr}}$$

Expressed in English units:

$$SCA = \frac{Total\ Collection\ Area\ (ft^2)}{1{,}000\ \frac{ft^3}{min}}$$

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^2/1,000 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^2/1,000 m^3/hr (200 and 800 ft^2/1,000 acfm), depending on precipitator design conditions and desired collection efficiency.

Figure 26. Graphical Plot of the Deutsch-Anderson Equation vs. SCA

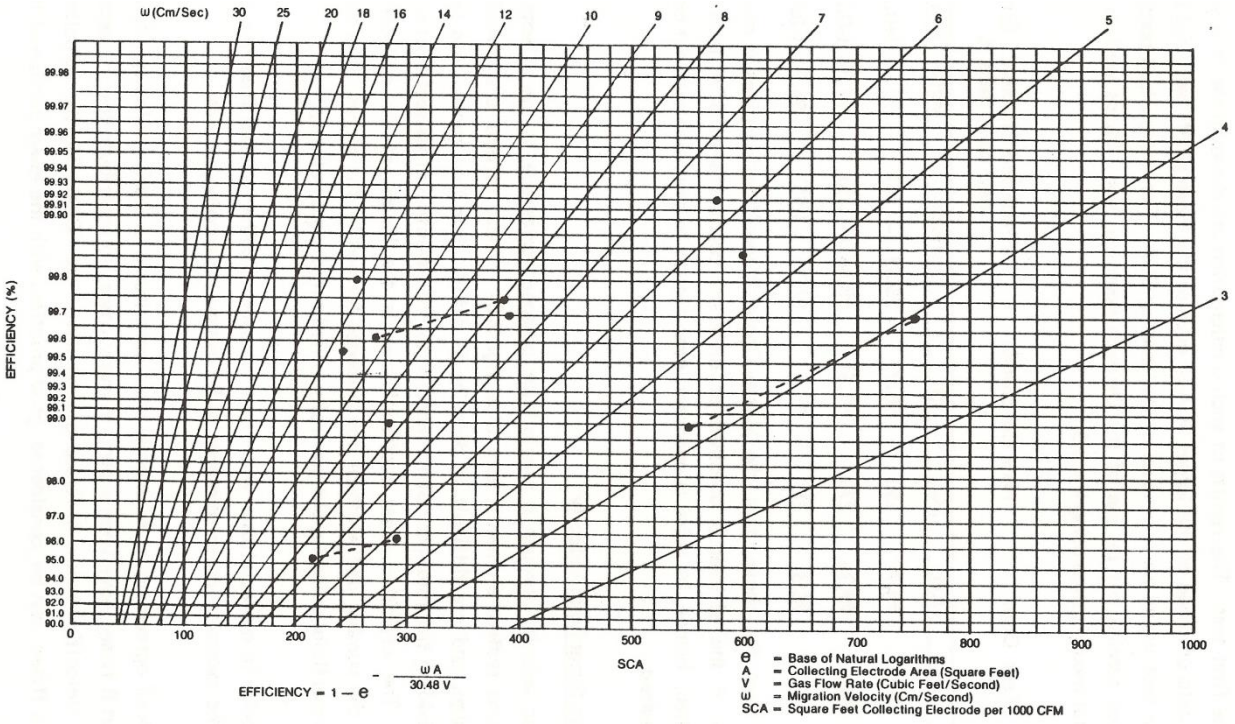


Figure 26 presents the Deutsch-Anderson equitation plotted graphically indicating Deutsch mathematical relationship between SCA, migration/drift velocity (ω), and efficiency (η).

7.3 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 re-entrained 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. In another words, it can be defined as the effective length of the precipitator divided by its effective height. Figure 27 presents a diagram defining the precipitator aspect ratio (AR):

$$AR = \frac{L}{H} = \frac{L_1 + L_2 + L_3}{H}$$

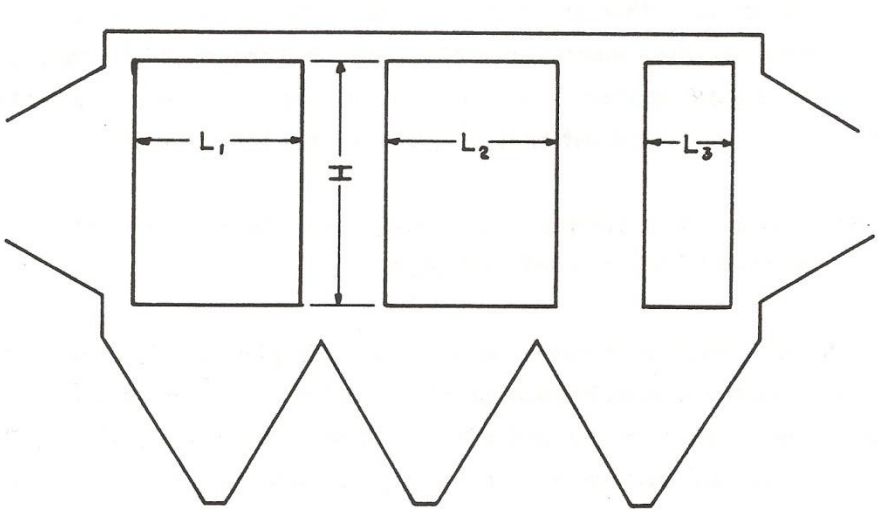


Figure 27. Components of the Aspect Ratio

7.4 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 28). 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).

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.

7.5 OTHER FACTORS AFFECTING ELECTROSTATIC PRECIPITABILITY

A number of factors affect the performance of electrostatic precipitators and all must be taken into consideration before the constraints on precipitator performance can be determined. Some of these factors are described.

7.5.1 Particle size

The particles flowing to a precipitator vary in both size and shape but lie within a specific size distribution range. By and large the particles collect independently with each size fraction collecting at a different rate, the larger ones more efficiently than the smaller ones. It is usual to use the mass median diameter (MMD) to represent the size distribution of any fly ash. The MMD is the diameter above and below which 50% of the weight of the particles lie. Studies of the effect of changing MMD on the efficiency of a precipitator show that at constant operating conditions if a dust with an MMD of 5 microns (μκm, micrometers) exhibits a collecting efficiency of 96%, then with the same dust at an MMD of 10 microns the efficiency is increased to 98.5% and at 15 microns it is 99.4%.

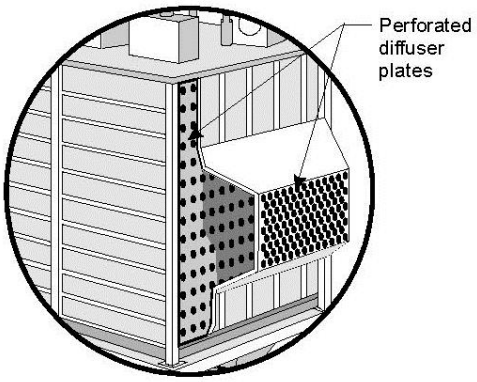


Figure 28. Gas Inlet with Perforated Plates

The precipitator alters the particle size distribution of the dust so that as the material passes through the precipitator the dust becomes finer. Therefore, the latter stages of a precipitator collect material at a much lower efficiency than the earlier stages.

7.5.2 Particle shape

The shape of the collected particles can have an impact on the performance of the precipitator. It is thought that angular particles tend to interlock in the collected layer on the electrostatic precipitator plates and are rapped off in a more coherent agglomerate, giving less re-entrainment than for more spherical particles.

7.5.3 Particle cohesivity

Particle cohesivity (the ability to adhere to one another) on the plate of an electrostatic precipitator is an important determinant in minimizing re-entrainment. The more cohesive the ash particles, the less likely they are to re-entrain with the gas stream.

7.5.4 Temperature

The temperature at which electrostatic precipitation occurs will have a significant effect on the collection efficiency and affects a number of other properties related to precipitability e.g., the viscosity of the flue gas rises slowly as the temperature increases, giving greater drag forces on the particles and hence reduces the velocity of the particles as they migrate to the collecting plate. This means that low sulphur coals which, due to practical considerations can operate at lower temperatures than high sulphur coals, can potentially operate at higher collection efficiencies than the higher sulphur coal, if no other factors affect the precipitator performance.

The electrical characteristics of fly ash particles are affected by temperature. Electrostatic precipitators for practical reasons must operate above the acid dew point of the flue gas, but at the lowest safe level above this point for greatest plant operating efficiency. Within this region of operation, as temperature increases, resistivity of the fly ash that is collected on the plates will reduce. However, the precipitator operating temperature is determined by plant design and the sulphur content of the coal being used.

7.5.5 Mechanical difficulties

The flash over voltage within the precipitator is reduced by decreasing the wire to plate distance. Hence any distortions or misalignment of wires and plates within the precipitator can cause a loss of voltage in a precipitator stage. Moreover, persistent flash over at any one spot on a wire can weaken it to breaking point.

Rapping is the term used for the mechanical agitation of the collector plates to dislodge accumulated deposits. Accumulation of irregular and fixed deposits on wires and plates can also lead to serious operating problems if they cannot be removed by rapping. Corona is impeded by such deposits becoming discontinuous and corrosion may occur under them.

7.5.6 Re-entrainment

Re-entrainment of dust from the collecting plates may be followed by successful recollection or by emission. Re-entrainment may be caused by maladjusted rapping, which is either premature or too violent, and then the re-entrainment may be detected as a "puff" emitted from the precipitator on rapping. On the other hand, if the re-entrainment happens because the gas velocity is too high or because the dust deposit is weak and fluffy, then the effect is continuous and the efficiency of the precipitator would be significantly reduced.

7.5.7 Maintenance

Not all collected fly ash is removed from the plates of an electrostatic precipitator on rapping. A layer of increasing thickness and resistivity builds up over time and must be physically removed (washed or “scraped off”)at intervals to enable the precipitator to operate efficiently.

Electrostatic precipitator plates and wires may become distorted or misaligned. Periodically they need to be checked and restored to ensure satisfactory precipitator performance.

8.0 ELECTRICAL RESISTIVITY

Resistivity of the collected particulate layer has a significant importance on the operation of electrostatic ESPs. The amount of useful electrical power that can be supplied to an ESP is limited for the most part by the electrical resistivity of the fly ash layer of the collecting plates.

Corona current from the discharge electrodes must pass through a collected dust layer on the plates to reach grounded collecting plate surfaces. Passage of the current builds up a voltage across a dust layer according to Ohm's law. Theory and experience suggest that when the dust resistivity exceeds a critical value of about mid 10^{10} Ohm-cm, corona current is limited by electrical break down in the collected dust layer. This, in turn, limits useful operating voltage and reduces ESP efficiency. The loss in performance increases quite rapidly for resistivity levels greater than 10^{10} Ohm-cm, and resistivity is therefore a major factor in ESP design [4]. Following is the generally accepted dust resistivity classification [1] in Ohm-cm:

Conductive	10^4	to	10^8
Normal	10^8	to	10^{10}
Moderate	10^{10}	to	10^{11}
High	10^{11}	to	10^{13}

The electrical resistivity of any PM is controlled by one of two mechanisms. One is the bulk volume conductivity, which is a function of the particle matrix constituents, and the other is surface conduction, which is controlled by the particle surface reactivity and gas components.

Figure 29 illustrates the effects of moisture and temperature on a typical high-resistivity fly ash. On the left side of the curves, surface conduction dominates, while bulk volume conductivity dominates on the right side. What is obvious is that the resistivity is at its peak level for the usual operating temperature of about 150 °C (about 300 °F) and typical moisture levels.

Some ESPs that operate with high resistivity fly ash are designed to operate at temperatures more than 350 °C (662 °F), to take advantage of the lower bulk volume conductivity. ESPs operating at these high temperatures, or on the right side of the curve, are commonly referred to as “hot side” ESPs.

More commonly encountered are ESPs that operate on the left, or “cold side,” of the curve where surface conduction dominates. As far as “cold side” ESP performance is concerned, the surface condition of the particle is generally more important than the chemical composition of the matrix. For applications firing sulfur-containing carbonaceous fuels, the flue gas on cooling can pass through an acid dew point temperature. Any resultant sulfuric acid mist produced subsequently uses the particles as condensation nuclei to deposit a thin layer of highly conductive material on their surface.

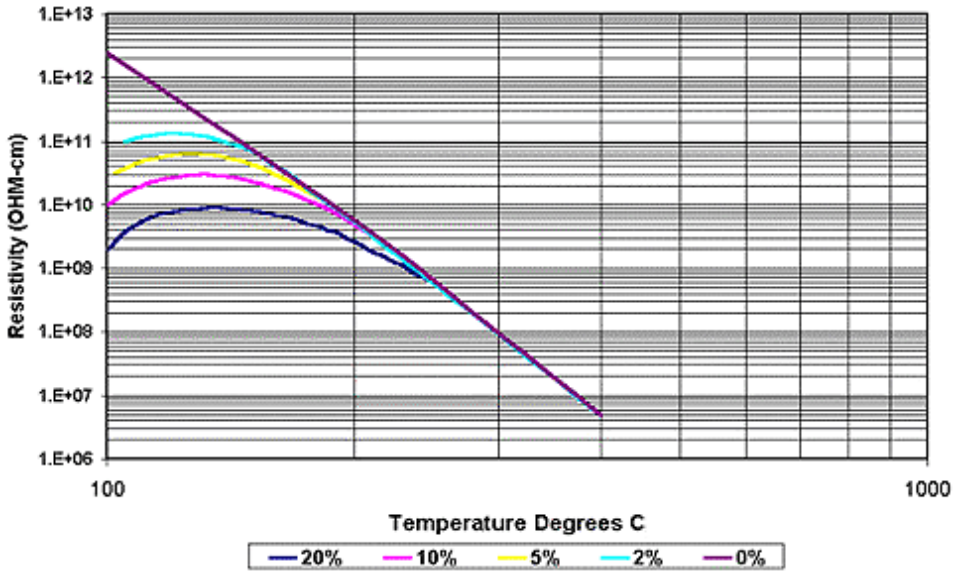


Figure 29. Effects of Temperature and Moisture on Fly Ash Resistivity

8.1.1 Prediction of Fly Ash Resistivity.

It is frequently necessary to estimate the fly ash resistivity of coals that may not be available for such measurements until the ESP and/or Flue Gas Conditioning (FGC) system have been sized, designed, and installed.

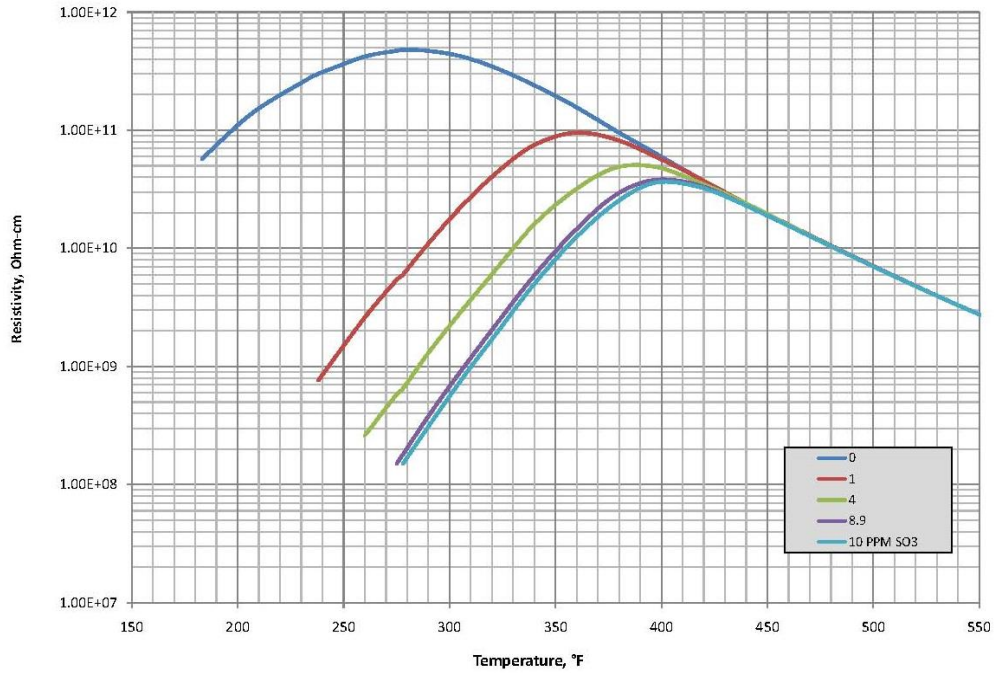


Figure 30. Predicted Fly Ash Resistivity

The U.S. EPA has sponsored development by Dr. Roy E. Bickelhaupt at the Southern Research Institute (SoRI) of a method for fly ash resistivity prediction using analysis of coal and ash [1]. Resistivity calculated by this method is in good agreement with actual field measurements, and form the basis for estimating ESP performance.

Figure 30 illustrates results of this procedure, showing predicted resistivity as a function of temperature calculated using this procedure. The right-hand portion of the traces is essentially a straight line descending from left to right, and represents the effect of volume conduction through the body of the fly ash material. Five lines are shown, which descend from right to left. The leftmost line shows the effect of water vapors present in the flue gas, depicted as though no SO_3 were present. The inner lines illustrate the added effect of SO_3 for different concentrations. It is seen that the chemical composition of the ash and the water vapor content of the flue gas act to determine an upper boundary for the resistivity values. The SO_3 quantities present, on the other hand, reduce the resistivity below the boundary values.

Thus, if the resistivity resulting from the combination of flue gas and ash properties with the SO_3 naturally produced by combustion is higher than desired for best ESP operation at a particular temperature, a suitable lower value can be obtained by the introduction of additional SO_3.

8.1.2 Factors that Affect Particle Resistivity

During combustion, most of the coal's pyritic sulfur burns to produce sulfur dioxide, although a small percentage converts to sulfur trioxide. Sulfur trioxide may reduce the fly ash electrical resistivity in "cold side" ESP applications. There is generally at least 6 percent moisture present in boiler flue gas, either from the moisture or converted hydrogen in the coal or from atmospheric moisture in the combustion air. At the equivalent dew point temperature, any free gaseous SO_3 reacts with this gas phase moisture to produce sulfuric acid mist, which then uses the particles as condensation nuclei. The subsequent thin layer of highly conductive sulfuric acid deposited on the fly ash enables charge transference to occur. The actual effect of surface conditioning in this case depends on the amount of sulfur trioxide and moisture present and on the gas temperature, which dictates the saturation vapor pressure.

For coals containing in excess of 1% sulfur, there is generally sufficient natural surface conditioning at normal operating temperatures of around 130 °C (266 °F) to give acceptable values of resistivity for effective precipitation. Although this is generally true, there are incidents where the fuel can promote a severe reverse ionization type of operation. This may particularly be the case if the hydrocarbon content is not totally combusted but is initially volatilized and later condenses on the fly ash particles as an insulating type of coating. This phenomena/occurrence is probably more prevalent during plant start-up, when the furnace is cold and the oil start-up burners are not ideally set up; however, the situation can arise at other times, so one must be aware of this potential problem.

Calcium and magnesium present in the ash tend to produce sulfates with exposure to and reaction with sulfur trioxide in the gas stream. These sulfates are chemically produced and, having low conductivity, tend to interfere with the potential resistivity reduction from sulfur trioxide condensing as sulfuric acid mist onto the fly ash. Calcium and magnesium components present in the fly ash, therefore, must be considered as leading to lower ESP performance through increased resistivity effects and requiring appropriate adjustments in the design/sizing of any installation. The ash from certain lignite and sub-bituminous coals can have calcium oxide contents of around 20 percent, which have a significant impact on the initial ESP sizing. Bituminous fuels, however, seem to be free from these negative effects.

The presence of sodium in the ash behaves in a very different manner. The sodium ions within the particle matrix act as charge carriers instead of surface conditioners, which assist in negating the effect of high resistivity fly ash to a certain extent.

8.1.2.1 Fly Ash Resistivity as it affected by the Sulfur Trioxide

The most common agent used for modifying high dust resistivity is sulfur trioxide [2]. In a typical utility application, two major factors control dust resistivity: the sulfur content of a coal, and the overall elemental composition of a dust.

Sulfur occurs in coal as organic and inorganic compounds - notably pyrite and sulfate salts. When coal is burned, more than 95% of the sulfur appears in the flue gas in the form of sulfur dioxide. The kinetics of sulfur oxidation in boiler flue gas does not allow more than a small fraction of the oxides to appear as sulfur trioxide. When the temperature of flue gas drops to around 300 °C (about 572 °F), a significant fraction of the sulfur trioxide gas reacts with water vapor to produce sulfuric acid vapor. This process is essentially complete at temperatures around 150 °C (about 300 °F) where electrostatic precipitators normally operate (Table 4 [7]).

Table 4. Equilibrium Distribution of Oxidized Forms of Sulfur at Various Temperatures [(a)]

Temperature		Relative Concentration of Sulfur Compounds, %		
°C	°F	SO_2	SO_3	H_2SO_4
1,400	2,552	99.7	0.30	0.00
1,000	1,832	97.6	2.4	0.0
800	1,472	88.7	11.3	0.
600	1,112	42.2	57.7	.1
500	932	12.3	87.3	.4
400	752	1.6	94.8	3.6
300	572	.1	59.3	40.6
200	392.	0.	6.5	93.5
100	212	0.	0.	100.

[(a)]Calculated from the data in JANAF Tables [2], assuming concentration of oxygen and water vapor equal to 4% and 10% by volume, respectively.

The subject of SO_2 to SO_3 conversion in the combustion process was never clearly defined. In the literature [8], varying and sometimes conflicting estimates exist regarding the conversion of SO_2 to SO_3. For example, in one publication the conversion rate is estimated to vary from 3 to 5 percent, from 1.25 to 5 percent, and from 1 to 4 percent, depending on the section of the book being read. In other reports, which focus on the performance of cold-side ESPs, the ratio of SO_2 to SO_3 at the air heater outlet is presented. These ratios are lower since a portion of the SO_3 generated during the coal combustion process condenses onto the cold sections of the air heater baskets as the flue gas temperature drops. For example, in one evaluation average flue gas SO_3 concentrations dropped from 25 ppm to 11 ppm (56%) across a hot-side ESP and an air heater. Other reports, such as an EPA-documented SO_2 to SO_3 ratio of 0.4 percent, confirm these pilot-scale results.

The same EPA study reports that the SO_3 levels from six different power stations varied from undetectable levels to 0.67 percent of the SO_2 concentration (Table 5). Other full-scale ex-

perimental results based on measurements during 16 field tests showed concentrations ranging from 0.1 to 0.41 percent of the SO_2 levels (Table 6). In both of these examples, the SO_3 concentrations when burning western coals were lower than the SO_3 concentrations when burning eastern coals. Laboratory analyses have confirmed the directly proportional relationship between the SO_2 to SO_3 conversion rate and the sulfur content of the fuel. In our calculations, to be on a conservative side, we elected to use 0.4% SO_2 to SO_3 conversion.

Table 5. SO_2 and SO_3 Measurements From 6 Different Power Stations

Station Number	SO_2, ppm	SO_3, ppm	SO_3 / SO_2 ratio
1 (western coal)	262	<1	<0.0038
5 (western coal)	480	<1	<0.0021
13 (western coal)	430	<1	<0.0023
3 (eastern coal)	2440	6-9	0.0025 – 0.0037
4 (eastern coal)	755	2-3	0.0026 – 0.0040
7 (eastern coal)	600	3-4	0.0050 – 0.0067

The sulfuric acid vapor is adsorbed or condensed on an otherwise poorly conducting dust surface and directly participates in the electrical conduction process. At very low concentrations of sulfuric acid, vapor conduction in dust is principally influenced by the charge-carrying ability of the alkali metal ions as affected by the interaction of water vapor and the dust surface. At high concentrations of sulfuric acid vapor, the conduction process is principally controlled by the adsorbed acid. At intermediate concentrations of acid vapor, both mechanisms contribute to the conduction process. Thus, in a strict sense, in cold-side precipitators resistivity modification results from sulfuric acid, rather than sulfur trioxide, effects.

Table 6. Ratio of SO_2/SO_3 Based on In-Situ Measurements for 16 Field Tests

	SO_3 / SO_2 ratio	
Coals Burned	average	standard deviation
9 eastern bituminous coals	0.0041	0.0027
7 western subbituminous and lignite coals	0.0011	0.0005

The acid may, however, react with basic constituents of the dust and thus undergo conversion to a poorly conducting layer of sulfate salts. Calcium oxide, a fairly common component of dust from many coals, is a probable cause of acid neutralization and its nullification as a conductor. Thus, two materials similar in chemical content may produce similar concentrations of sulfur trioxide, but the one containing a more alkaline dust is likely to have a substantially higher resistivity.

The sulfur trioxide conditioning is effective at flue gas temperatures below about 400 °F (204 °C) where surface conduction prevails. At higher temperatures, effectiveness of sulfur trioxide conditioning is decreased because the dust resistivity is partly or wholly determined by volume conduction, and also because the fraction of the available acid which condenses on the particles is reduced due to vapor pressure and equilibrium characteristics.

8.1.3 SO_3 Requirement Prediction

Since it is possible to make empirical estimates of the quantity of SO_3 naturally generated from native fuel sulphur, the expected resistivity of the ash without the addition of a conditioning agent can be estimated, and a decision can be made regarding the necessity for reducing resistivity to improve collection.

The Bickelhaupt method cannot be directly applied to determining SO_3 injection rates because the SO_3 quantities used in the method are amounts in equilibrium with the gas-and-ash environment of a laboratory vessel, and these differ from injection requirements for flue gases containing suspended fly ash. Having an estimate of the ash resistivity without conditioning and knowing from experience the desired final resistivity to obtain best ESP performance, both at the intended operating temperature, simple subtraction gives the amount the resistivity is to be changed, and common sense says that the injection rate will be a function of this change. Similarly, the required injection will be a direct, but not necessarily linear, function of the quantity of ash to be treated. Other factors than these two will enter into determination of injection rates [6, 9].

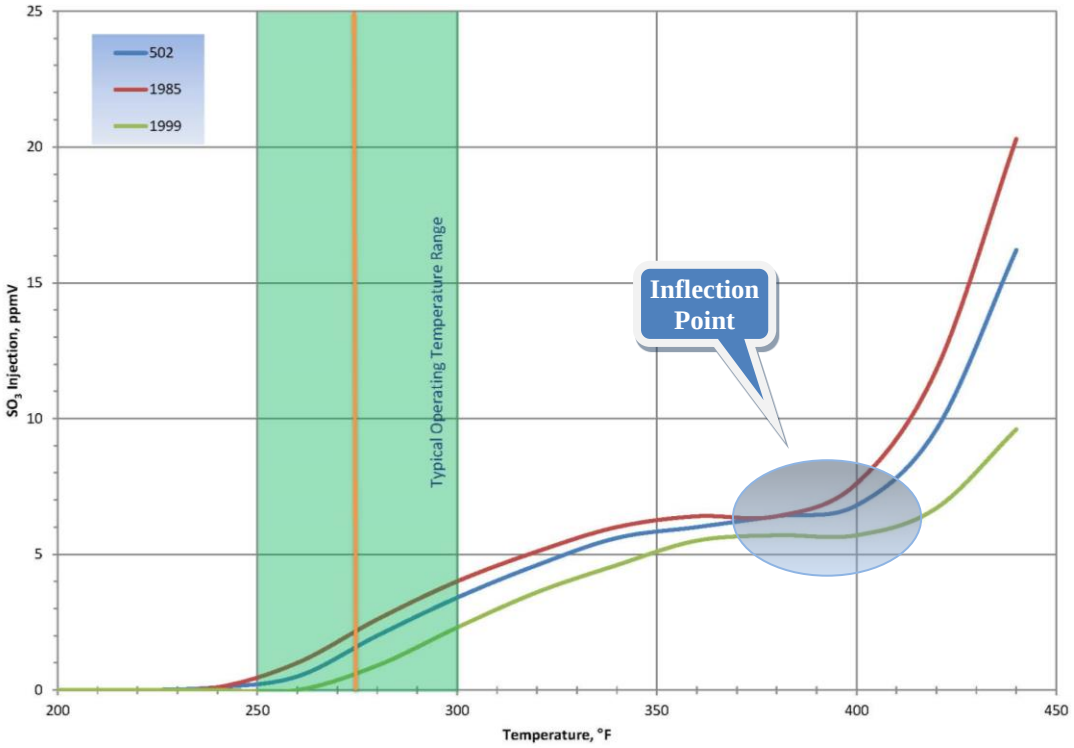


Figure 31. Computer Estimated SO_3 Requirement

Figure 31 presents predicted injection rates for the subject coals under evaluation. In essence, these are the iso-resistivity curves constructed based on the design fly ash resistivity of $1x10^{10}$ and $5x10^{10}$ Ohm-cm. Each of the plots shows a low temperature region that is essentially a reflection of the ash resistivity curve. As temperature is increased, both curves come to an inflection point at which transition is made to a rapidly rising characteristic that approximates a straight line. At temperatures below the inflection point, nearly all of the injected SO_3 attaches to the ash. At higher temperatures, SO_3 injected in excess of the SO_3, level below the inflection point is necessary to provide additional partial pressure for attachment of sufficient SO_3 to the ash to obtain the desired resistivity. The difference between the injection level at low temperatures and that at a high temperature is a measure of excess sulfur trioxide that will escape from the stack at the higher temperature. The excess SO_3 above the inflection point level remains in the gas stream and, if the excess is about ten (10) parts per million or more, may be visible as a white-blue condensation plume from the stack.

It seems logical that the temperature at which inflection occurs is a function of ash surface conditions. It is a measure of susceptibility to attachment of acid, perhaps, inasmuch as the lower inflection temperatures occur for ashes having low base-to-acid ratios and the higher points correspond to higher ratios. The traces having the inflection point at lower temperatures represent coal ashes having very low base-to-acid ratios, typically, if Si + Al is more than 85% and/or Si + Al + Fe are over 90-92%. Although it is convenient to refer to these effects in terms of base-to-acid ratio, it should be remembered that this is only a rough general index to the inflection point temperature for discussion purposes; other factors appearing in the injection rate equation must be included for accurate determinations.

The inflection point effect explains some difficulties many experimenters have encountered in attempting adjustment of ash resistivity with a sulfur trioxide alone. In some low sulfur coals, the percentage of acidic compounds in the ash (aluminum oxide, iron oxide, and silicon oxide) is high (above about 90%). Here, the injection of a sulfur trioxide alone to reduce resistivity loses some of its effectiveness because the acidic sulfur trioxide cannot readily attach to the highly acidic ash at higher temperatures. Substantial amounts of excess sulfur trioxide must be injected while treating such ashes to produce a conductive film on the surface. If the operating temperature is much higher than the inflection point, no reasonable amount of injected SO_3 will be effective in reducing the resistivity.

8.2 ESPs Performance Evaluation, Prediction and Data Extrapolation

The method of predicting ESPs performance has traditionally been based on preserving the precipitation characteristics using sizing factors (effective migration velocity), derived from efficiency measurements using ESPs operating on similar process plants. Originally, the approach was based on the Deutsch equation, but as higher efficiency/lower emissions were demanded to satisfy legislative levels, sizing based on the Deutsch equation was found unsatisfactory and over the past 30 years, suppliers have found it necessary to use a modified equation, such as those derived by Maats-Ohnfeld of ABB Flakt or other.

Pilot ESPs are often used in the case of existing plants, or where new technological processes are being developed, as a means of determining the designs of full-scale ESPs and discovering any peculiarities of the particles. The main problem in the pilot ESP technique is determination of the scale-up factor to be used in going from the pilot unit to the full-size ESP, since it is well known that pilot units have the potential of operating much better per unit size than do full-scale ESPs. Particularly, the pilot unit will usually exhibit better electrical characteristics, gas velocity distribution and in many cases lower rapping re-entrainment losses than a full-scale unit. On the other hand, gas sneakage past electrical regions is usually greater in the pilot unit than in the full-scale.

In addition to determining performance characteristics from installed and operating plant, investigators have operated pilot sized ESPs in the field and laboratory, handling reduced gas flow, not only derive the precipitation factor or effective migration velocity, but also to evaluate the effect of process variables, e.g. temperature, gas velocity, contact time, moisture, etc. Over the years, the use of pilot ESPs has produced significant amounts of data, but to be fully representative for plant sizing purposes, the inlet conditions to the pilot should be identical to those the full-scale ESP will meet in practice.

9.0 UPGRADING PERFORMANCE – NOVEL TECHNOLOGIES

Lately, the main technology options for particulate control have been either electrostatic precipitators or baghouse filters (baghouses). Both are effective for capturing and controlling the particulate down to 2.5 µm in dia. The challenge is to capture very fine particulate below that diameter, which are small enough to penetrate deep into lungs and threaten human health.

For that purpose, baghouses and other forms of barrier filtration are inherently more efficient than conventional ESP's. However, the baghouses are not completely free of the maintenance and operation problems, for example high-pressure losses. In the retrofit cases the available footprint (old small ESPs situated between the boiler and the stack) is often is not large enough to accommodate the required number of the bags needed to handle the boiler gas flow. Thus, necessitating placing the retrofit equipment well outside the plant's boundaries and connecting it back to the boiler via long train of the ductwork.

In an effort to overcome the above deficiencies (i.e., increasing collection efficiencies without a corresponding increase in pressure drop), a number of efforts have been, and are, underway to develop hybrid particle collectors. These hybrid devices attempt to integrate electrostatic and barrier filtration into a single device or system. The hybrid particulate collection concepts of interest include:

- Electrostatically Enhanced Fabric Filter (EEFF);
- EPRI's COHPAC-1 and COHPAC-2 systems;
- UNDEERC Hybrid Collector (AHPC);
- Multi Stage Collector MSC™ Technology developed by Allied Environmental Technologies, Inc.

The principal objective of the MSC™ design is to substantially improve fine particulate collection by combining electrostatic charging-collection and filtration processes not only by separating zones for particles charging and collecting, but, by providing new, unique collector design with improved efficiency to collect fine dust particles independent of their electrical properties. Figure 32 presents a conceptual MSC™ arrangement.

The MSC™ offers a uniquely compact concept. Each of the multiple stages utilizes an upstream stage comprised of a conventional electrostatic precipitator, followed by a downstream zone of parallel surfaces creating uniform electric field, followed by yet another sub-stage, which incorporates barrier filter conductive surfaces which provide a uniform electric field (Figure 33).

By providing continuously repeated stages in series, the downstream zones effectively charge and collect the particles that are either uncollected or re-entrained and collect those particles after they have been charged. In the MSC™, particles are deposited onto the **B**arrier **F**ilter **E**lement (**BFE**) by two mechanisms, electrostatic and diffusional deposition, that act simultaneously. Collection by diffusion occurs as a result of both fluid motion and the Brownian (random) motion of particles. Diffusional collection effects are most significant for particles less than 1

micrometer (µm) in diameter. Another collection mechanism, direct interception, occurs when a particle comes within one particle radius of an obstacle.

The path that the particle takes can be a result of inertia, diffusion, or fluid motion. Electrostatic deposition is effective for relatively large particles, but it is quite ineffective for the ultra-fine ones because their charging probability in the corona field is too low. However, the diffusional collection efficiency of particles on fibers is high for small particles but low for the larger ones. Therefore, the simultaneous diffusional-electrostatic collection is a useful technique for efficient filtration of particles below 0.1µm.

The MSC™ assembly is made up of discharge electrodes placed between oppositely collecting electrodes. The discharge electrodes are followed by BFE located in the wide zones placed between the collecting electrodes. The collecting plates are held at a first electrical potential while the discharge electrodes and the BFEs are held at a second electrical potential. Both the flat sides of each of the discharge electrodes, collecting plates and the surfaces of the BFE form surfaces where the electric field is relatively uniform. The surfaces of the BFEs may be formed with electric field forming parts that may be suitably rounded and convex in the direction of the collecting electrode. The collecting electrodes are formed with narrow and wide sections to accommodate both the discharge electrodes and BFEs. By using an electrode with a cross-section that is relatively wide, a uniform electric field can form in the region of the center of the electrode, and a non - uniform field of high intensity can form at the sharp leading and/or trailing edge (Figure 33). At sufficiently high field strength in this non - uniform field region, a corona discharge can take place between the electrode and the plates acting as an ion-charging source for dust particles passing through it. The center region of uniform field on the other hand acts in a manner similar to the field between parallel capacitor plates with charged dust particles collecting on the plates.

Figure 32.MSC™ Concept

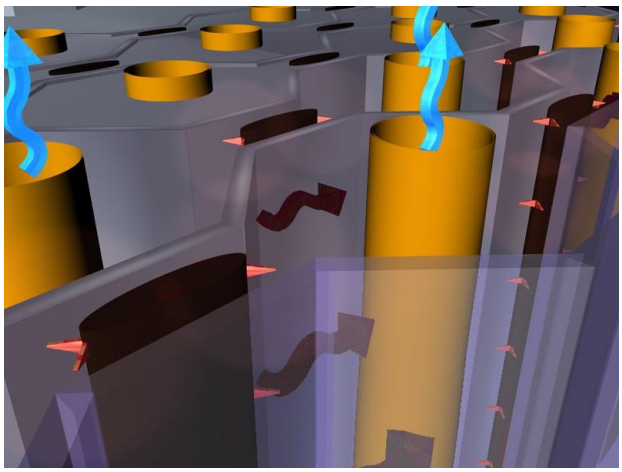
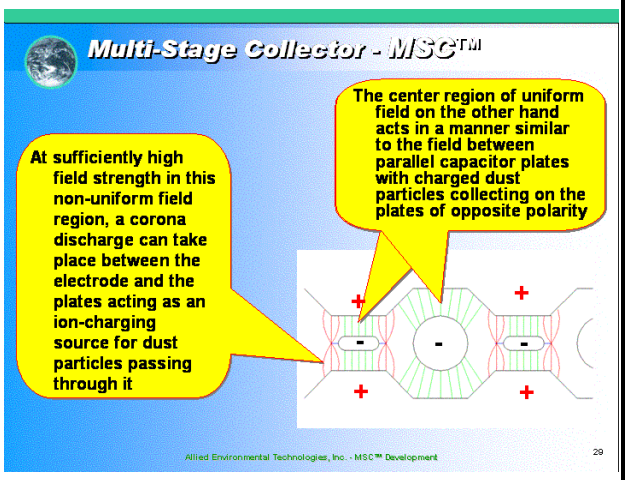


Figure 33. Schematic of the MSC™ Operation



To sum up, the MSC™ particulate collector is a hybrid electrostatic precipitator (ESP) barrier filter device. Devices currently used in industry to remove particulate matter from various process gases include electrostatic precipitators (ESPs) and Fabric Filters (FFs). While these devices are widely used, they have a number of shortcomings. The MSC™ collector on the other hand, entails a unique integration of both electrostatic precipitation and barrier filtration. The

MSC™ concept overcomes not only the shortcomings of conventional ESPs and FFs, but is also technically superior to hybrid ESP/FF concepts currently under development. Table 7 summarizes the relative merits of each of these particulate collection approaches.

Table 7. Hybrid Technologies Comparison

DEVICE/APPROACH	OPERATING PRINCIPLE	ADVANTAGES	DISADVANTAGES
Electrostatically Enhanced FF	• Pre-charging particles entering FF • Charging wires arranged between groups of four bags creating an electric field between the wires and bag cages	• Higher collection efficiency than conventional FF • Lower pressure drop	• Bags can suffer electrical discharge and puncture • Charging is dependent on the material properties (resistivity) • Back Corona
EPRI COHPAC	• ESP followed by a small FF • ESP with the last field converted to a FF • Particulate collected in series	• FF adds pressure drop	• ESP performance dependent on dust resistivity • FF removes mainly small particulate increasing ΔP • High efficiency requires large footprint • Not able to collect bi-polar charged particles
UNDEERC Hybrid Collector	• Small ESP and FF in a single enclosure • Particulate collected in series	• More efficient than ESP alone	• FF section must collect fine particles • Vulnerable to back corona • Not able to collect bi-polar charged particles • Bags can suffer electrical discharge and puncture
MSC™	• Integrated ESP and Barrier filter • Both collecting particulate in parallel with FF additionally providing final clean-up stage	• ESP and barrier filter integrated • Both collect in parallel with FF being a final clean-up stage • Independent of ash resistivity	• More complex electrode geometry than conventional ESP

Evidently, the MSC™ concept offers a number of significant advantages over the other hybrid technologies currently under development.

10.0 REVIEW OF DESIGN VARIABLES

The combustion of coal for power generation produces fly ash, which must be collected prior to discharge to the atmosphere. The most common method of collection is electrostatic precipitation but bag filters are also popular. The quantity of fly ash that needs to be collected depends largely on the ash content of the coal. The collection characteristics of the fly ash will depend on the coal and the combustion system.

The principal design variables are the dust concentration, measured in g/m^3 (lb/ft^3 or gr/ft^3) and the gas flow rate to the ESP, measured in m^3/min (ft^3/min or acfm). The gas volume and dust concentration (loading) are set by the process exhaust gas flow rate. Once these variables are known, the vendor can begin to design the precipitator for the specific application. A thorough review of ESP design plans should consider the factors presented below.

Physical and chemical properties of the dust such as dust type, size of the dust particles, and average and maximum concentrations in the gas stream are important ESP design considerations. The type of dust to be collected in the ESP refers to the chemical characteristics of the dust such as explosiveness. For example, a dry ESP should not be used to collect explosive dust. In this case, it might be a better idea to use a baghouse or scrubber. Particle size is important; small particles are more difficult to collect and become re-entrained more easily than larger particles. Additional fields may be required to meet regulatory limits. The dust loading can affect the operating performance. If the dust concentration is too high, the automatic voltage controller may respond by totally suppressing the current in the inlet fields. Suppressed current flow drives the voltage up, which can cause sparking. For this reason, it might be a good idea to install a cyclone or multi-cyclone to remove larger particles and reduce the dust concentration from the flue gas before it enters the ESP. The facility could install a larger ESP (with more plate area), however, this technique would be more costly.

Resistivity is a function of the chemical composition of the dust, the flue gas temperature and moisture concentration. For fly ash generated from coal-fired boilers, the resistivity depends on the temperature and moisture content of the flue gas and on the sulfur content of the coal burned; the lower the sulfur content, the higher the resistivity, and vice versa. If a boiler burns low-sulfur coal, the ESP must be designed to deal with potential resistivity problems. High resistivity can be reduced by spraying water, FGC: SO_3or some other conditioning agent into the flue gas before it enters the ESP.

Predicting the **gas flow rate** and **gas stream properties** is essential for proper ESP design. The average and maximum gas flow rates through the ESP, the temperature, moisture content, chemical properties such as dew point, corrosiveness, and combustibility of the gas should be identified prior to final design. If the ESP is going to be installed on an existing source, a stack test should be performed to determine the process gas stream properties. If the ESP is being installed on a new source, data from a similar plant or operation may be used, but the ESP should be designed conservatively (with a large SCA, a high aspect ratio, and high corona power). Once the actual gas stream properties are known, the designers can determine if the precipi-

tator will require extras such as shell insulation for hot-side ESPs, corrosion-proof coatings, and installation of heaters in hoppers or ductwork leading into and out of the unit.

The type of **discharge electrodes** and electrode support are important. Small-diameter wires should be firmly supported at the top and connected to a weight heavy enough (11.4-kg weights for 9.1-m wires) to keep the wires from swaying. The bottom and top of each wire should be covered with shrouds to help minimize sparking and metal erosion at these points. Newer ESPs are generally using rigid-frame or rigid-electrode discharge electrodes.

Collection electrodes - type (either tube or plate), shape of plates, size, and mechanical strength—are then chosen. Plates are usually less than 9 m (30 ft) high for high-efficiency ESPs. For ESPs using wires, the spacing between collection plate electrodes usually ranges from 15 to 30 cm (6 to 12 in.). For ESPs using rigid-frame or rigid electrodes, the spacing is typically 30 to 38 cm (12 to 15 inches). Equal spacing must be maintained between plates throughout the entire precipitator. Stiffeners may be used to help prevent the plates from warping, particularly when hot-side precipitators are used.

Proper **electrical sectionalization** is important to achieve high collection efficiency in the ESP. Electrical sectionalization refers to the division of a precipitator into a number of different fields and cells, each powered by its own T-R set. ESPs should have at least three to four fields to attain a high collection efficiency. In addition, the greater the number of fields the better the chance that the ESP will achieve the designed collection efficiency. There should be approximately one T-R set for every 930 to 2970 m^2 (10,000 to 30,000 ft^2) of collection-plate area.

The **specific collection area (SCA)** is the collection area, in m_2 per 1000 m^3/h (ft^2 per 1000 ft^3/min), of flue gas through the precipitator. The typical range for SCA is between 11 and 45 m^2 per 1000 m^3/h (200 and 800 ft^2 per 1000 acfm). The SCA must be large enough to efficiently collect particles (99.5% collection efficiency), but not so large that the cost of the ESP is too high. If the dust has a high resistivity, vendors will generally design the ESP with a higher SCA [usually greater than 22 m^2 per 1000 m^3/h (400 ft^2 per 1000 acfm)] to help reduce resistivity problems.

Aspect ratio is the ratio of effective length to height of the collector surface. The aspect ratio should be high enough to allow the rapped particles to settle in the hopper before they are carried out of the ESP by the gas flow. The aspect ratio is usually greater than 1.0 for high-efficiency ESPs. Aspect ratios of 1.3 to 1.5 are common, and they are occasionally as high 2.0.

Even **distribution of gas flow** across the entire precipitator unit is critical to ensure collection of the particles. To assure even distribution, gas should enter the ESP through an expansion inlet plenum containing perforated diffuser plates (Figure 28). In addition, the ducts leading into the ESP unit should be straight. In situations where a straight-line inlet is not possible and a curved inlet must be used, straightening vanes should be installed to keep the flue gas from becoming stratified. The gas velocity through the body of the ESP should be approximately 0.6 to 2.4 m/s (2 to 8 ft/ sec). For ESPs having aspect ratios of 1.5, the optimum gas velocity is usually between 1.5 and 1.8 m/s (5 and 6 ft/sec). The outlet of the ESP should also be carefully designed to provide even flow of the gas from the ESP to the stack without excessive pressure buildup.

TYPICAL RANGES OF DESIGN PARAMETERS

Table 8 presents typical ranges of the basic design parameters for fly ash precipitators.

Table 8. Typical Ranges of Design Parameters for Fly Ash Precipitator

Parameter	Range (metric units)	Range (English units)
Distance between plates (duct width)	20-30 cm (20-23 cm optimum)	8-12 in. (8-9 in. optimum)
Gas velocity in ESP	1.2-2.4 m/s (1.5-1.8 m/s optimum)	4-8 ft/sec (5-6 ft/sec optimum)
SCA	11-45 m^2/1000 m^3/h (16.5-22.0 m^2/1000 m^3/h optimum)	200-800 ft^2/1000 cfm (300-400 ft^2/1000 cfm optimum)
Aspect ratio (L/H)	1-1.5 (keep plate height less than 9 m for high efficiency)	1-1.5 (keep plate height less than 30 ft for high efficiency)
Particle migration velocity	3.05-15.2 cm/s	0.1-0.5 ft/sec
Number of fields	4-8	4-8
Corona power/flue gas volume	59-295 watts/1000 m^3/h	100-500 watts/1000 cfm
Corona current/ft^2 plate area	107-860 microamps/m^2	10-80 microamps/ft^2
Plate area per electrical (T-R) set	465-7430 m^2/T-R set (930-2790 m^2/T-R set optimum)	5000-80,000 ft^2/T-R set (10,000-30,000 ft^2/T-R set optimum)

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12.0 APPENDIX GLOSSARY - PRECIPITATOR TERMINOLOGY

Figure 34 presents a graphical description (EPRI) of the electrostatic precipitators' nomenclature with a brief description to follow below.

ACCESS DOORS	Gas tight entry points to allow inspection of the ESP normally fitted with interlocks and hand operated fastening devices
AIR PURGE SYSTEM	Set of fans used to pressurize the insulator compartment so as to keep the support insulator free from abrasive and conductive dust
ALIGNMENT	This term refers to the maintenance of optimum clearances between the high voltage system and the grounded surfaces of the precipitator
ANVILS	Rapper striking plates which transmit the rapping impulse to the collective electrodes.
ARC	Disturbance which causes a lowering of the electrode voltage for a short period (up to 250 milliseconds)
ASPECT RATIO	The length of a precipitator divided by its height. Aspect ratio ranges from about 0.5 to about 1.5 and is thought to affect the amount that rapping re-entrainment contributes to the outlet burden
BACK-CORONA	Back-ionization
BACK IONIZATION	Discharge originating from the collecting electrode, with a polarity opposite to that of the collecting electrode. Back ionization is caused when the potential gradient through the dust deposited on the collecting electrode exceeds the breakdown strength of the gas. This generally occurs when the dust resistivity is greater than $10^{12}\Omega$m.
BAFFLES	Plates used inside the ESP to prevent the dust-laden gas from bypassing the active fields
BRIDGING	The blockage of a hopper by the formation of an arch or 'bridge' of compacted dust over the hopper exit
BUS SECTION	The smallest portion of high voltage structure, containing a fixed group of DISCHARGE ELECTRODES, that can be independently energized by a single High Voltage TR SET
CARRIER BEAM	Mechanical bar used to attach each collector plate. The carrier beam is also attached to the roof beams by means of relevant bolts
CASING	Airtight box-like structure fabricated from steel or concrete

	through which the gas flows
CELL	A longitudinal row of bus sections extending from the front to the rear of a precipitator
CHAMBER	Subdivision of a casing achieved by means of a gas-tight longitudinal wall installed in the direction of gas flow (a precipitator without any internal dividing wall is a single chamber precipitator, a precipitator with a single internal dividing wall is a two chamber precipitator
CHAR	Carbonaceous material in dust, usually incompletely burnt fuel and having larger particles then the rest of the dust
CHEMICAL CONDITIONER	A chemical used to lower the resistivity of dust so as to reduce or eliminate back ionization
COLLECTING ELECTRODE	The electrode (usually earthed) on which the charged dust is deposited in an electrostatic precipitator. It refer normally to a sheet metal collector plate
CONDUCTIVITY	The reciprocal of resistivity
CONTROL EQUIPMENT	Electrical components used to regulate the DC potential supplied to the discharge electrode system
CORONA	A 'crown' of electrical discharge from the places on the surface of a conductor (usually sharp edges) at which there is an electric field high enough to ionize the surrounding gas
CORONA CURRENT	The current flowing in a corona discharge
CURTAIN	**A** single 'simple' collecting electrode or an assembly of 'composite' collecting electrodes that make up one element of an electrical zone of a precipitator. A curtain extends from the inlet to the outlet of the zone and usually also extends from the top to the bottom of the casing
CURRENT DENSITY	Current per unit area, usually per unit area of collecting electrode. Units often used are micro-amps per square meter ($\mu A/m^2$)
DISCHARGE ELECTRODE	The precipitator electrode from which the corona current is emitted. Various types are available e.g. barbed wire, square section with sharp edges, helical elements, rigid discharge elements, etc.
DUCT	(1) A tube in which gases flow to and from the precipitator. The cross-section of a duct is usually rectangular, but may be circular, triangular, or polygonal, as circumstances or cost dictate. 2) That part of a precipitator bounded on either side by collecting electrode assemblies. The electrodes of one zone are usually aligned with the electrodes of the zones upstream and/or downstream, so that a duct runs from the inlet to the outlet of a precipi-

	tator and includes all the electrical zones.
DUST	Any particulate substance (it could be droplets of sulphuric acid) that a precipitator is collecting
DUST BURDEN	The concentration of dust suspended in a gas. It is usually expressed as mass per unit volume. The metric units are grams per cubic meter (g/m^3). The imperial units are grains per cubic foot (1 grain=15.432 grams). The gas volume is usually expressed at normal temperature and pressure (0℃ and 760 mm Hg pressure) in a dry atmosphere
EARTHING DEVICE	Safety switch for effectively earthing the higher voltage system prior to personnel entering an ESP chamber
EARTHING SWITCH	Device normally associated with the transformer rectifier and used to earth the unit at the high voltage source. Also used to earth the ESP during high level of CO
EFFECTIVE CROSS-SECTIONAL AREA	Effective width times effective height.
EFFECTIVE LENGTH	Total length of collecting surface, as measured in the direction of the gas flow.
EFFECTIVE HEIGHT	Total height of collecting surface, as measured from top to bottom.
EFFECTIVE WIDTH	Total number of gas passages multiplied by the center-to-center spacing of the collecting surfaces
EFFECTIVE MIGRATION VELOCITY	This parameter, defined by the Deutsche—Anderson relationship, is related to the average speed with which dust particles in an electrostatic precipitator move towards the collecting electrode
EFFECTIVE PLATE AREA	Flat projected area of the collector plates multiplied by two and by the number of gas passages between the plates
EFFICIENCY	The collecting efficiency of a precipitator is the percentage of the dust entering the precipitator inlet that is caught by the precipitator. It is usually estimated by subtracting the outlet dust burden from the inlet dust burden and then dividing the result by the inlet dust burden. This method of calculation is made inaccurate by air leaking into the precipitator, but the errors due to this cause are usually small
ELECTRIC WIND	The gas flow in the direction of the electric field that accompanies a corona or sharp edge discharge, caused by the entrainment of gas moving ions
EMITTING ELECTRODE	Discharge electrode

END PLATES	Used for attaching the inlet and outlet ductwork. They are located at the top and bottom of the inlet and outlet openings of the casing
EVASE	A transition-piece from ductwork to precipitator. In tunnel engineering, an exhaust stack for air having a cross section that increases in the direction of airflow at a rate to regain pressure
FIELD	A lateral row of bus sections extending across the width of a precipitator and energized separately from those preceding or following. Refers to an arrangement of one or more BUS sections, oriented perpendicular to the direction of flue gas flow, which is energized by one or more High Voltage (HV) TR sets. The number of HV TR sets positioned in series, each one controlling the collection of particles in a specific area, will typically identify the number of fields of a precipitator
FLUE GAS	The products of combustion, usually from a furnace (as contained in a flue)
FLY ASH	Dust from a furnace—the term distinguishes the ash that flies from that which remains in the grate
FRACTIONAL PENETRATION	Fractional penetration is defined as the fraction of particles or droplets of a given size that avoid capture when challenging an air cleaning device; e.g., a filter or separator.
GAS DISTRIBUTION	The distribution of the gas flow over the cross-section of a duct, or ESP
GAS DISTRIBUTION DEVICES	Special devices installed within the ESP and associated ductwork in order to achieve the required gas distribution
GAS PASSAGE	The passage formed by two adjacent collector plates or curtains. This passage is where the action takes place within the precipitator
GAS VELOCITY	A figure obtained by dividing the volume rate of flow through the precipitator by the effective cross sectional area of the precipitator . This is not really a vector quantity. It is the average speed of the gas through a precipitator. Care must be taken to establish upon what basis the velocity is calculated. Two definitions are generally recognized; the 'unobstructed' gas velocity and the 'obstructed' gas velocity. The unobstructed gas velocity is the average speed of gas, calculated as if the precipitator where an empty box. The obstructed velocity is calculated the electrodes take up taking into account the proportion of the cross-sectional area that. For any given precipitator, the obstructed gas velocity is greater than the unobstructed gas velocity
HIGH VOLTAGE CONNECTION	This is used to connect the output from the transformer rectifier unit to the ESP discharge electrode system

HIGH VOLTAGE RECTIFIER SYSTEM (HV TR Set)	Comprises the transformer, rectifiers, current limiting devices and control equipment necessary to supply and control the high voltage DC current to the discharge electrodes
HOPPER	The vessel at the bottom of a precipitator into which falls the dust that is rapped from the electrodes
INLET DUST BURDEN	The concentration of dust in the gases at the inlet to the precipitator, usually measured in the duct just upstream of the inlet evasé
ISOKINETIC SAMPLING	Sampling of the flue gases in such a way that the sample is drawn from the mainstream of the gas into the sampling apparatus with no change of velocity
MIGRATION VELOCITY	Defined as the transverse velocity with which the charged dust particles move towards the collector plates
OUTLET DUST BURDEN	The concentration of dust in the gases at the outlet of the precipitator, usually measured in the duct just downstream of the inlet evasé
PARTICLE SIZE	The average size of the particles of dust
PENETRATION	Slip
PLATE	Collecting electrode
PROJECTED COLLECTING AREA	Total available area for collecting electrodes
RAPPER BARS	Bars attached to lower ends of the collecting plates to which the anvils are attached
RAPPERS: COLLECTING SURFACES	Devices which are generally located at the top of the ESP or bottom of the collecting plates, which periodically impart a chock to the collecting surfaces to help dislodge the collected material into the hopper system
RAPPERS: DISCHARGE SURFACES	Devices which impart vibration or shock to the high voltage frame supporting the discharge electrodes. The object is to keep the build-ups on these electrodes from affecting the corona discharge pattern
RAPPER INSULATOR	Device used to provide electrical isolation as well as transmit the mechanical force necessary to clean the discharge electrodes
RAPPING	The process of striking an electrode to dislodge the collected dust
RE-ENTRAINMENT	Re-entrainment to the gas-stream of dust rapped from the electrodes. This process cans substantially the collecting efficiency of a precipitator
RECEIVING ELEC-	Collecting electrode

TRODE	
RESISTIVITY	The electrical resistance that a meter cube of a substance (usually of packed dust) has when measured between opposite faces of the cube. The units are ohm-meters (or ohm-centimeters—a resistivity of 1 Ωcm is equivalent to a resistivity of 100 Ωm)
RIGID DISCHARGE ELECTRODE (RDE) DESIGN	This term refers to precipitators utilizing rigid discharge electrodes, such as the pipe and spike variety, for it's discharge electrode rather than a weighted wire type of high voltage system
RIGID FRAME DESIGN	This term refers to precipitators utilizing rigid frames with tensioned discharge electrodes between supporting members
ROOF SECTION	Used to suspend the electrodes and support the high voltage equipment when this is mounted on top of the ESP
SAFETY INTERLOCKS	Devices that must be removed when the high voltage system has been isolated and earthed and then used to unlock the access doors to the ESP chamber
SCOURING	The process in which collected dust is removed from the collecting electrodes by the gas-flow or by the impact of particles of dust or char suspended therein
SHORT CIRCUIT	Occurrence when a permanent connection is maintained between the emitting wire and the collection plates or in the connecting cable or duct. (Note: the field should trip on UNDERVOLTAGE condition with a 5 to 8 seconds delay)
SLIP	The proportion of the dust entering an electrostatic precipitator that escapes from the precipitator outlet. Slip may be expressed as a decimal fraction, or a percentage. It is usually estimated by dividing the outlet dust burden by the inlet dust burden
SNEAKAGE	The process in which dust-laden gas passes between the precipitator casing and the electrode system, either over the top or around the edges. Each per cent of gas sneakage reduces the attainable precipitator collecting efficiency by almost one per cent
SPACE CHARGE	The charge present (as charged dust particles, gas ions, and free electrons) in the space between the electrodes. Space charge modifies the local electric field in an electrostatic precipitator in a way analogous to the way that space charge modifies the field inside a thermionic diode. The space charge strengthens the field near to the collecting electrode (anode) and weakens that near to the discharge electrode (cathode)
SPECIFIC COLLECTING AREA (SCA)	The area of collecting electrode that a precipitator has per unit volume flow-rate of gas. he metric units used are square meters per cubic meter per second. The imperial units used are square feet per thousand cubic feet per second

SPARK	Discharge of short duration (no more than 50 milliseconds) from the high voltage system to the earthed system which is also self-extinguishing.
STACK	The flue through which waste gases are discharged to the atmosphere. To minimize pollution by dispersing the flue gases and residual particulate matter over as wide an area as possible, stacks are built as high as possible (today – 300m plus)
STILL AIR LOAD	This term refers to energizing the ESP during an outage period (no gas flow) at ambient temperature. The object is to verify the electrical integrity of the bus section, to obtain electrical readings of voltage and current and to determine whether spark over occurs before reaching a specific limit of the HV TR set rating. Measurements can be recorded as maximum readings or as V-I CURVES. Generally, SPARKOVER should not be observed during these readings
SUPPORT INSULATOR	Since the discharge electrodes are energized above ground potential, they are supported by means of support insulators, which are housed in an insulator compartment situated in the roof of the ESP
SWEEPAGE	Sweepage is the process by which gases passing beneath the electrodes of a precipitator pick up dust from the hoppers and carry it out of the precipitator exit. Sweepage can severely limit the efficiency of a precipitator and is usually controlled by means of baffles
TERMINAL VELOCITY	The speed with which a particle falls in still air (or gas) under the influence of gravity, or the speed with which a charged particle traverses a gas under influence of an electric field
TRANSFORMER RECTIFIER (TR) UNIT	Comprises the transformer for stepping up normal service voltage to the required kilovolt range and a rectifier to convert the high AC voltage to a direct current (DC) supply
TREATMENT TIME	Value, in seconds, obtained by dividing the effective plate length (in meters) by the gas velocity (in meters per second)
V-I CURVE	Usually refers to a plot of secondary voltage versus secondary current for a single HV TR Set in which the shape of the plotted curve might indicate a number of internal operating characteristics of the precipitator. An important part of these measurements is the indicated voltage at the threshold of corona current.
VISIBLE EARTH/GROUND	Attachment of the high voltage elements consisting of a flexible cable and clamps installed to protect personnel in the working area inside the ESP
WEDGE HOPPER	A hopper, which is rectangular in cross-section. Wedge hoppers usually extend for the full length or width of the precipitator.

Wedge hoppers are less prone to blockages than are pyramid or conical hoppers

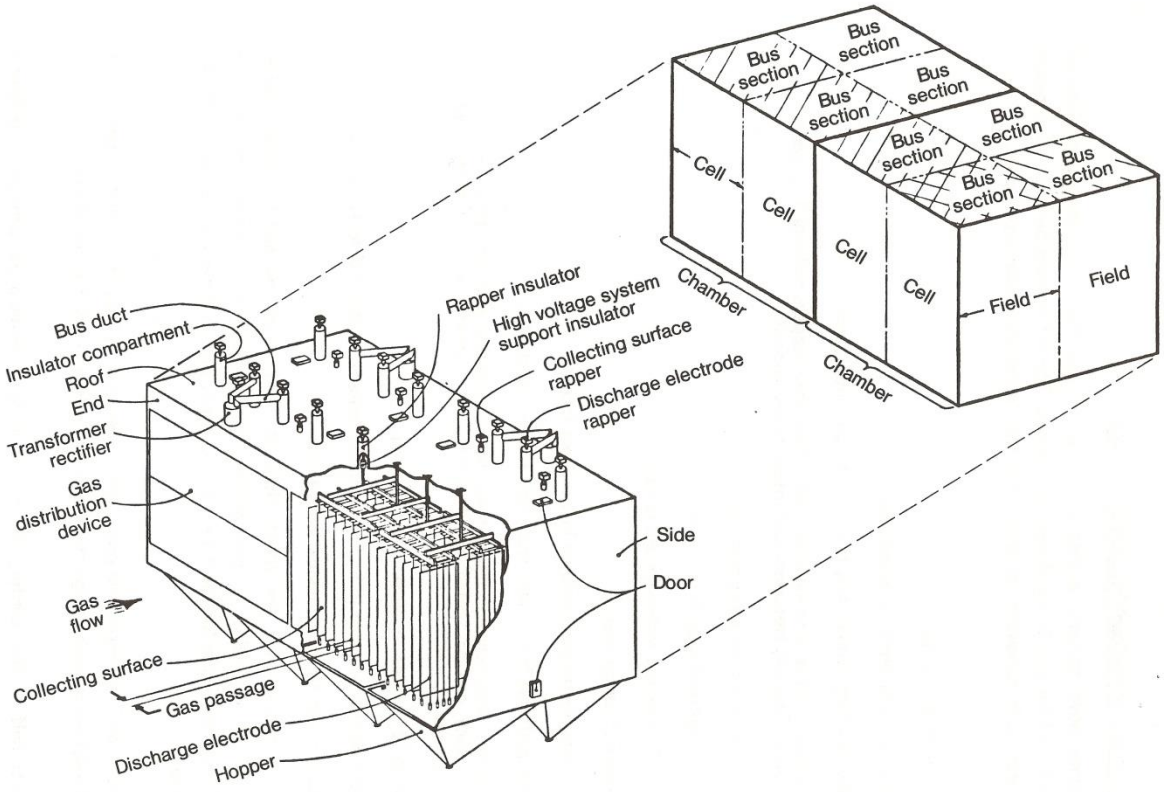


Figure 34. Precipitator Nomenclature