CHAPTER 5

ELECTROSTATIC PRECIPITATORS

Electrostatic precipitators are used in many industries for the high efficiency collection of particulate matter. They were originally developed in the early 1900s for acid mist control. During the 1940s, precipitators began to be used for particulate matter control at coal-fired boilers, cement kilns, and kraft recovery boilers. The applications of precipitators have steadily increased since the 1940s due to their ability to impart large electrostatic forces for particle separation without imposing gas flow resistance. Electrostatic precipitator efficiency and reliability have improved steadily since the 1970s as a result of research and development programs sponsored by equipment manufacturers, trade associations, and the USEPA.

Operating Principles

In all types of electrostatic precipitators, there are three basic steps to particulate matter collection:

- **Step 1** is the electrical charging and migration of particles toward a vertical collection surface.
- **Step 2** involves the gravity settling (or draining in the case of liquids) of the collected material from the vertical collection surfaces.
- **Step 3** is the removal of the accumulated solids or liquids from the hopper or sump below the electrically energized zone.

Precipitator Energization

The purpose of the high voltage equipment of an electrostatic precipitator is to cause particle-charging and migration (Step 1). A simplified drawing of the circuitry from the primary control cabinet to the precipitator field is shown in Figure 5-1.

The alternating power supplied to the primary control cabinet is at a constant 480 volts and 60 cycles per second. This electrical power is supplied to the transformer-rectifier (T-R) set when the main switch and the circuit breaker in the primary control cabinet are both on. If an electrical problem is sensed in the power supply or the precipitator field, the circuit breaker automatically opens. This is called tripping the field.

In the primary control cabinet, the automatic voltage controller, the silicon controlled rectifiers (SCRs) and the SCR trigger and pulse controller alter the A.C. line voltage and adjust the waveform of the voltage to control electrical conditions on the primary side of the
transformer in the T-R set. The result is a primary voltage that can range from zero to more than 400 volts.

The primary alternating power is converted to a secondary pulse-type direct power in the T-R set. The relatively low primary voltage is stepped up to a secondary voltage of more than 50,000 volts. The voltage applied to the discharge electrodes is called the secondary voltage because the electrical line is on the secondary side (high voltage generating side) of the transformer. For convenience, the secondary voltage gauges are usually located on the primary control cabinets.

As the primary voltage applied to the transformer increases, the secondary voltage applied to the discharge electrodes increases. Stable electrical discharges begin to occur when the secondary voltage exceeds the onset voltage, which can be between 15,000 and 25,000 volts depending partially on the sharpness or extent of curvature of the discharge electrode. The relationship between the secondary voltage and the secondary current is shown in Figure 5-2.

The automatic voltage controller in the primary control cabinet is designed to increase the primary voltage applied to the T-R set to the maximum point possible at any given time. One of the following six factors will always limit the maximum secondary voltage:

**Basic Steps in Energizing a Precipitator Field**
- Open/close 480 volt A.C. power supply to the primary control cabinet
- Control voltage and adjust voltage and current waveforms in primary line to the transformer
- Control current flow during sparking
- Increase voltage
- Convert electricity to direct current form

**Components**
- Main power switch and circuit breaker
- Automatic voltage controller, silicon controlled rectifiers (SCRs), trigger/pulse control for SCRs
- Linear reactor (located adjacent to primary control cabinet)
- Transformer
- Rectifier bridge

**Figure 5-1. Precipitator field energization**
- Primary voltage limit
- Primary current limit
- Secondary voltage limit
- Secondary current limit
- Spark rate limit
- SCR conduction angle

The upper limit of the primary voltage is set by the 480 volt power line leading to the primary control cabinet. The primary current limit is set by the operator at a level below the current value that could damage the primary control cabinet components. The secondary voltage and current limits are also set at levels necessary to protect the T-R set components.

The spark rate limit is an arbitrary limit selected by the operator to optimize performance. Some electrical sparking is generally indicative of good operation. Excessive sparking can cause premature component failure. Whenever any one of these limits is reached, the automatic voltage controller decreases the applied primary voltage to protect the electrical circuitry. The applied primary voltage moves up the voltage-current curve until one of the limits is reached.

Operating conditions at any given time are determined by one of the six operating limits. The primary voltage, primary current, secondary voltage, secondary current, and spark rate are indicated by gauges mounted on the front of the primary control cabinet. Most of the new installations also have indicator lights to show the operating limit that is presently limiting the secondary voltage. The electrical conditions and the limiting factor vary at any one field over time, and they vary substantially from field-to-field. This information is very useful for

Figure 5-2. Voltage-current curve
evaluating precipitator performance and is, therefore, discussed in more detail later in this chapter.

If there is no electrical sparking in a field, the electrical conditions in the field will remain very stable until dust loadings or other changes affect the electrical conditions. If electrical sparking occurs, there will be short-term variations in these indicated operating conditions. After each spark in a precipitator field, the automatic voltage controller shuts off the primary voltage for a short period of time (milliseconds) to prevent the short-term spark from becoming a sustained, damaging power arc. Once this quench period is over, the voltage is ramped up quickly to a voltage very close to the previous point at which the spark occurred. The voltage is then gradually increased to the point where another spark occurs. Generally, these variations appear as very brief fluctuations in the secondary voltage meter.

Protective equipment is included in the primary control cabinet. If a problem is sensed in the power supply of the precipitator field, this protective circuitry trips the power supply and the T-R set off-line. For example, a short circuit across the surface of a high voltage frame support insulator would create very low voltages and high currents. The under-voltage sensors would detect this condition and shut down the field to prevent damage to the insulator or to the power supply itself.

**Particle Charging and Migration**

The electrical discharges from the precipitator discharge electrodes are termed *corona discharges* and are needed to electrostatically charge the particles. Within the negative corona discharge, electrons are accelerated by the very strong electrical field and strike and ionize gas molecules. Each collision of a fast-moving electron and a gas molecule generates an additional electron and a positively charged gas ion. The corona discharges are often described as an *electron avalanche* since large numbers of electrons are generated during multiple electron-gas molecule collisions.

The positive gas ions generated in the ionization process move back toward the discharge electrode. Some of these positive gas ions will deposit on particles inside the corona and charge them positively. These positively charged particles deposit on the negative discharge electrodes, requiring them to be cleaned periodically.

Slightly farther away from the discharge electrode, where the electrical field strength is lower, electrons released in the corona discharges are captured by gas molecules. These negatively-charged gas ions move rapidly toward the grounded collection plates. Some of these gas ions are captured by particles, charging them negatively. The particles quickly reach a maximum charge called the *saturation charge*. This is the charge at which the electrostatic field created by the captured ions is strong enough to deflect additional gas ions that are approaching the particle.

The magnitude of the saturation charge is dependent on the particle size. Small particles have a low saturation charge, since the gas ions have only a small surface on which to
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deposit. The saturation charge increases with surface area or with the square of the particle diameter. Large particles accumulate higher electrical charges on their surface and, therefore, are more strongly affected by the applied electrical field.

Particle larger than about 1.0 μm diameter, accumulate charged gas ions by locally disrupting the electrical field, causing the gas ions to be momentarily directed to the particle surface rather than the collection plate. This mechanism is termed contact charging. Particle less that 0.1 μm diameter do not have sufficient mass to disrupt the electrical field. Instead, they accumulate charges as they randomly diffuse through the gas ions. This mechanism is termed diffusional or ion charging.

Once the particles have attached ions, they are influenced by the strong, nonuniform electrical field between the discharge electrode and the grounded collection plate. Accordingly, the charged particles begin to migrate toward the grounded plates. At the same time, drag forces, which depend on the particle mass or the cube of the particle diameter, are trying to move the particles straight through the precipitator. As a result, the smaller micrometer-sized particles are deposited near the inlet and progressively larger particles are deposited farther into the precipitator. Usually, particles larger than about 30 μm diameter are removed in a precleaner in order to avoid having an excessively long precipitator. Submicrometer-sized particles charge more slowly but, once charged, move rapidly to the collection plate.

The combined effect of contact and diffusion charging creates a particle size-collection efficiency relationship similar to Figure 5-3. There are very high collection efficiencies above 1.0 μm due to the increasing effectiveness of contact charging for large particles. Increased diffusion charging causes collection efficiency to increase for particles smaller than 0.1 μm. There is a difficult-to-control range between 0.1 to 1.0 μm due to the size dependent limitations of both of these charging mechanisms. The precipitator is least effective for the particles in this size range.

The extent of the efficiency limit in the difficult-to-control size range is related to the size of the precipitator, the extent of sectionalization, the operating conditions, and the physical conditions. Well designed and operated precipitators can have size-efficiency relationships with only a slight efficiency decrease in the difficult-to-control size range. Undersized precipitators or units in poor condition can have a more pronounced efficiency decrease in this size range.

Dust Layer Resistivity

The gas ions arriving on the surfaces of particles and arriving as uncaptured ions must pass through the dust layers on the collection plates. At the metal surface of the collection plate, the voltage is zero since the plate is electrically grounded. 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 more than 10,000 volts.
It is this electrostatic voltage difference across the dust layer that holds the dust layer on the vertical surface of the collection plate. The same type of voltage difference is created when a child rubs a balloon on his or her hair and then sticks the balloon on a wall. It does not fall because of the very slight charge difference between the side of the balloon and the wall. Eventually, however, the balloon falls off the wall. The electrons that were initially on the balloon find a path for reaching the wall. As the electrons flow off the balloon, the force holding it to the wall becomes weak.

Essentially the same phenomenon occurs in the dust layers on precipitator collection plates. When the electrical charges from the gas ions can readily move through the dust layer to the plate, the charge difference across the dust layer is relatively low (i.e., several thousand volts). This means that the dust layer can be easily dislodged. When the electrical charges move very slowly through the dust layer, there are a large number of electrical charges on the outer surface, and the voltage difference can be very high (more than 10,000 volts). This means that the dust layer is held very tenaciously.

The ability of the electrical charges to move through the dust layer is measured in terms of the dust layer resistivity. When the resistivity is very low, the electrons are conducted very readily, and there is only a slight charge difference across the dust layer. When the resistivity is very high, the electrons have difficulty moving through the dust layer and create very high forces as they accumulate on the outer surface of the dust layer.

Very high and very low resistivity conditions are harmful to electrostatic precipitator performance. Electrostatic precipitators work best when the dust layer resistivity is in the moderate range: not too high and not too low. This is because of the various ways that the dust layer electrostatic field affects both dust layer rapping and particle charging migration.
During rapping of weakly held low resistivity dust layers, many of the particles are released back into the gas stream as individual particles or small agglomerates that do not settle fast enough to reach one of the hoppers before the gas stream leaves the precipitator. Even large particles of 100 μm diameter do not fall sufficiently fast to reach the hoppers. Accordingly, it is very important that the particles agglomerate in the dust layer and settle as large clumps or sheets rather than as discrete particles.

If the resistivity is too low and particles are redispersed during rapping, there can be a short term emission spike, called a puff. As the resistivity increases into the moderate range, the voltage drop across the dust layer increases, and the dust cake is dislodged as cohesive sheets or clumps that are large enough to fall rapidly and be collected in the hoppers of the precipitator.

If the voltage drop across the dust layers becomes too high (high resistivity), there can be a number of adverse effects. First, as the dust layer builds up and the electrical charges accumulate on the surface, the voltage difference between the discharge electrode and the dust layer decreases, reducing the electrostatic field strength used to drive the gas ion-carrying particles over to the dust layer. The migration velocities of small particles are especially affected by the reduced field strength.

Another adverse impact of high resistivity dust layers is called back corona. This occurs when the electrostatic voltage across the dust layer is so great that corona discharges begin to appear in the gas trapped within the dust layer. When the voltage in the dust layer reaches sufficient levels, electrons are accelerated and ionization begins. Positive gas ions formed by the electron collisions stream toward the negatively charged discharge electrode. Along the way, these positive ions neutralize some of the negative charges on the dust layer particles. They also neutralize some of the negative ions on the particles approaching the dust layer and reduce the space charge near the dust layer surface. The net result of back corona is severely impaired particulate matter removal efficiency.

The third and generally most common adverse impact of high resistivity dust layers is increased electrical sparking. Once the sparking reaches the arbitrarily set spark rate limit, the automatic controllers limit the operating voltages of the field. This causes reduced particle charging effectiveness and reduced particle migration velocities toward the collection plates. High resistivity-related sparking is due primarily to the concentration of electrical field lines in localized portions of the dust layer on the collection plates. Any misalignment problems or protrusions of the collection plate surface make those areas especially vulnerable to sparking. This is why proper alignment of precipitator collection plates and discharge electrodes is so important when the resistivity is high.

There is another adverse characteristic of high resistivity dust layers. Since the dust layers are so strongly held by the electrostatic fields, it is hard to dislodge the dust. As more charged dust continues to arrive, the depth of the dust layer increases, and it becomes even harder for electrons to pass through to the collection plates. There can be some temptation to
rap the collection plates frequently and severely to reduce the dust layer quantities. In severe cases, this practice can have very little beneficial impact on the dust layer depths, and it can lead to rapid mechanical failure of the rappers or misalignment of the collection plates. If this practice causes misalignment, the problems caused by high resistivity become even greater.

Electrostatic precipitators work best when the dust layer resistivity is in the moderate range. It should resist current flow a little, but not too much. It is helpful to describe the dust layer resistivity based on units of ohm-centimeters. This is simply the ohms of resistance created by each centimeter of dust in the dust layer. High resistivity is generally considered to be equal to or above $5 \times 10^{10}$ ohm-cm. Low resistivity is generally considered to be equal to or below $5 \times 10^8$ ohm-cm. The region between $5 \times 10^8$ and $5 \times 10^{10}$ ohm-cm is, therefore, the moderate or preferred range.

There are actually two basic paths that electrons can take in passing through the dust layer to the collection plate surface. They can pass directly through each particle until they reach the metal surface. This is called bulk conduction and occurs only when there are one or more constituents in the particles that can conduct electricity. Conversely, the electrons can pass over the surfaces of various particles until they reach the metal surface. This is called surface conduction and occurs when vapor phase compounds that can conduct electricity adsorb onto the surfaces of the particles. Both paths of current dissipation are illustrated in Figure 5-4.

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One of the most common electrical conductors responsible for bulk conduction in particles is carbonaceous material. If the concentration of this material is sufficiently high, the electrons can pass from particle to particle to reach the collection plate. Electrical conduction through the inorganic oxides and other compounds that comprise the majority of ash particles from
combustion sources and other industrial sources is sufficiently rapid when the temperatures are above 400°F and preferably in the range of 500°F and 700°F. This resistivity-temperature relationship is indicated in Figure 5-5.

![Resistivity-temperature relationship](image)

**Figure 5-5. Resistivity-temperature relationship**

On the low temperature side of the typical resistivity curve, the resistivity can decrease dramatically as the gas temperature drops slightly. This is due to the increased adsorption of electrically conductive vapors present in the gas stream. One of the most common compounds responsible for surface conduction is sulfuric acid. It adsorbs to particle surfaces very readily, even at gas temperatures of 250°F to 350°F. Even vapor phase concentrations of only 5 to 10 ppm are often sufficient to affect the dust layer resistivity. The ability of sulfuric acid to electrically condition the particle surfaces is due, in part, to its hygroscopic tendencies. Each sulfuric acid molecule can be attached to a cluster of water molecules, which can also be electrically conductive.

Many air pollution sources using electrostatic precipitators generate enough sulfuric acid or other particle surface conditioning agents to reduce the dust layer resistivities into the moderate range at operating temperatures of 250°F to 350°F. However, if they generate too much sulfuric acid vapor, or if the gas temperature drops too much, the resistivity can be too low. If, for some reason, enough sulfuric acid is not generated, or the gas temperature is relatively high, the resistivity can be very high.
In sources that do not inherently generate enough vapor phase compounds for surface conditioning, it is necessary to inject the materials into the precipitator inlet. The most common material used to condition precipitators is sulfur trioxide, which quickly forms vapor phase sulfuric acid upon entering the inlet gas stream. Ammonia is also used either alone or in combination with sulfur trioxide. These materials adsorb on the surfaces of the particles as they enter the precipitator and are being collected. Once the particle is in the dust layer, electrons pass through these adsorbed molecules.

The very strong temperature dependence of surface conditioning can create some very non-uniform dust layer resistivities in different portions of the unit. It is common for portions of the precipitator to be 30 to 50°F different from the average temperature indicated by the plant instrumentation. In the hot areas, very little vapor phase material adsorbs, and the resistivity can be relatively high. In the cold areas, too much conductive material can be on the particle surfaces, and the resistivity can be relatively low. Spatial differences of more than three orders of magnitude in dust layer resistivity have been found.

**Sectionalization**

The performance of an electrostatic precipitator is not solely a function of the quantity of collection plate surface area. It is also dependent on how that surface area is used. There are a variety of design factors that must be taken into account to ensure proper particulate matter removal capability. Proper sectionalization is one of the most important of these design factors.

The electrostatic precipitator is divided into separately energized areas, termed *fields*, arranged in series along the direction of gas flow. Almost all commercial precipitators have at least three fields in series. Some large units used for high resistivity conditions can have has many as fourteen fields in series. The inlet field removes 60% to 75% of the incoming particulate matter, and each subsequent field removes 50% to 80% of the particulate matter penetrating through the preceding field.

Due to these differences in mass collection rates, there can be significantly more dust on the collection plates in the fields on the inlet side of the precipitator than on the outlet side. These thick dust layers suppress current flow. In addition, the electrical charges residing on the particles moving through the space between the discharge electrode and the collection plate produce what is termed a *space charge* that also suppresses current flow in the inlet fields. By dividing the precipitator into separate electrical fields, the effect of the heavy dust layers and the particle space charge can be minimized.

Electrical sparking occurs preferentially on the inlet side of the precipitator. This sparking is due primarily to the accumulation of electrical charge on the outer surface of the dust layer on the collection plate. Sparking near the inlet is also due to the disturbances caused when large quantities of dust are dislodged during each rapping cycle. Rapping in the inlet fields is more frequent than in the outlet fields. As noted earlier, the automatic voltage controller detects
the electrical spark as a current surge and shuts off the applied secondary voltage for a few milliseconds. There is also a short period when the secondary voltage is ramping back to its maximum pre-spark levels. During these short time periods, the field strength is not at optimum levels for collection of particulate matter. By sectionalizing the precipitator into separate fields, the field energization problems associated with frequent sparking can be isolated to the first few fields with high spark rates.

On an infrequent basis, an internal mechanical problem in a field can cause an electrical short circuit. Several conditions can cause shorts:

- Mechanical flex failure of a discharge wire
- Chemical corrosion failure of a discharge wire
- Electrical sparking related erosion failure of a discharge wire
- Electrical tracking and failure across a support insulator surface or an anti-sway insulator surface
- Presence of solids bridging between the high voltage frame and the grounded collection plates due to hopper overflow

The field is automatically taken offline by the primary control cabinet to prevent component damage caused by the high current condition. The field can not be reenergized until maintenance personnel enter the unit to retrieve the failed wire, fix the insulators, or clear the hopper solids bridged material. Often the precipitator must operate for a long period of time before this maintenance work can be completed. If the precipitator has a high degree of sectionalization, the amount of the unit out-of-service is relatively small, and the emission rates do not increase substantially. If there are only a few fields in service, the impact of the loss of a field on performance can be quite high.

In addition to standard sectionalization, most electrostatic precipitators also divide individual fields into bus sections. A precipitator field has either one or two bus sections. This is the smallest section of the field that can be energized by the T-R set serving the field. The term bus section is derived from the fact that each of these sections has a separate electrical bus (electrical conduit line) from the T-R set. Precipitators often have two bus sections per field so that these two different areas can be separately energized using half-wave rectified power. The advantages and disadvantages of half wave versus full wave rectification are outside the scope of this course.

**Discharge Electrodes**

Discharge electrode designs have evolved substantially since the early 1970s, when discharge wire failure was a common problem. The introduction of rigid discharge electrodes and electrode frames has substantially reduced this problem. The use of protective shrouds (shown in Figure 5-6) over the top and bottom 18 inches of the wire-type discharge electrodes has also reduced the frequency of failure. Because of these improvements, present-day failures are usually due to either corrosion or misalignment problems. The
failure of discharge wires has become a symptom of other problems rather than a fundamental problem.

![Collector Plate Spacing](image)

**Collector Plate Spacing**

A trend toward increased plate-to-plate spacings started in the 1980s because of the interest in rigid frame type discharge electrode supports. Due to the width of the support tube, the plate spacings were increased from a typical value of 9 in. to the 11 to 12 in. range. This practical consideration was not the only motivation for increased plate spacings. It has been recognized for more than 30 years that improved electrical field strengths could be obtained by increased discharge electrode-to-collection plate spacing. Due, in part, to stringent particulate matter control requirements, many new units will have plate-to-plate spacings in the range of 10 to 20 inches.

**Specific Collection Area**

The specific collection area (SCA) is defined as the ratio of the collection surface area to the actual gas flow rate passing through the unit. As shown in Equation 5-1, it is usually expressed in terms of square feet per 1,000 acfm of gas flow.

\[
SCA = \frac{A}{Q} \tag{5-1}
\]

where SCA = specific collection area ($ft^2/10^3$ acfm)
A = total collection plate area (ft²)  
Q = total gas flow rate (10³ acfm)

There has been a substantial increase in SCAs from levels of 100 to 200 ft² per 1,000 acfm in the 1960s to present-day levels of 300 to 1400 ft² per 1,000 acfm. There is no single value of SCA that guarantees adequate performance for all precipitators. Instead, the SCA must be based on unit-specific factors such as the dust layer resistivities and the particle size distribution. Sources that generate particulate matter with high resistivities or small particle sizes generally use a high SCA.

**Aspect Ratio**

Precipitators with the proper aspect ratios are less sensitive to gravity settling problems. The aspect ratio is defined as the total length of the collection plates (all fields added together) divided by the collection plate height:

\[
AR = \frac{\sum_{i=1}^{n} L_i}{H}
\]

where  
AR = aspect ratio (dimensionless)  
L_i = length of plates in field i (ft)  
H = collection plate height (ft)  
n = number of fields in series

Modern precipitators are designed with aspect ratios of at least 1.0, and the normal range extends to more than 1.5. This means that they are longer than they are high. This provides more time for gravity settling to carry the particulate agglomerates to the hoppers. The average gas velocities in new designs are also slightly lower than pre-1970 units in order to provide more time for settling and reduce rapping reentrainment losses.

A summary of the typical sizing parameters for electrostatic precipitators is provided in Table 5-1. However, some caution is warranted in comparing an existing unit with the ranges shown in this table. The necessary precipitator size and design characteristics vary substantially from site-to-site due to factors such as differences in particulate resistivity distributions, particle size distributions, and process operating rate variations.

**Instrumentation**

New state-of-the-art automatic voltage controllers include digital gauges for all of the following electrical parameters of interest in the precipitator field:

- Primary voltage, volts A.C.
- Primary current, amperes A.C.
- Secondary voltage, kilovolts D.C.
- Secondary current, milliamps D.C.
- Spark rate
- SCR Conduction angle, degrees
- Field limiting condition
- Power input, kilowatts

In a few new systems, these parameters are logged and processed in data acquisition systems to provide routine operating records for the unit. In most existing units, the electrical data is logged manually by plant operators.

Information concerning the rappers is usually provided by instrumentation mounted in the rapper control panel. New microprocessor-based control cabinets provide visual information concerning the rapper program in use at the present time, the specific rappers being activated, the presence of any probable rapper activation faults, and the rapping intensities.

| Table 5-1. Typical Sizing Parameters for Dry Negative Corona ESPs |
|---------------------------------|-----------------------|
| Sizing Parameter                | Common Range          |
| Specific Collection Area, (ft$^2$/1,000 acfm) | 400 - 1000 |
| Number of Fields in Series      | 3 - 14                |
| Aspect Ratio                    | 1 - 1.5               |
| Gas Velocity, ft/sec            | 3 - 6                 |
| Plate-to-plate spacing, inches$^1$ | 9 - 16               |

$^1$One manufacturer uses 6 in. spacing.

**Precipitator Systems**

There are three categories of electrostatic precipitators (ESP). These units serve entirely different industrial applications.

- Dry, negative corona
- Wet, negative corona
- Wet, positive corona

General operating characteristics and components of these three ESPs as well as operating procedures and performance problems, are discussed in this section. The emphasis is on dry, negative corona units since this type is used on the largest systems and these are the most common type of units presently in service.

Dry, negative corona units are used in large industrial facilities such as cement kilns, kraft pulp mills, and coal-fired utility boilers. They are termed dry because the collected solids are removed from the collection plates as a dry material. The term negative corona means that
the particles are collected by forcing them to move from a high negatively charged area to an electrically grounded collection plate.

Wet, negative corona units use water on the collection plates to remove the collected solids. This approach eliminates several of the major problems that can affect dry, negative corona units. However, with the use of water in close proximity to high voltage insulators, it adds to the system complexity and it increases the potential problems associated with corrosion. Most wet, negative corona units are used for small-to-moderately-sized industrial sources that produce particulate matter that is sticky or that is too carbonaceous for a dry, negative corona application.

Wet, positive corona units are sometimes termed two-stage precipitators. Particle charging occurs in a pre-ionizer section, and particle collection occurs in a downstream collection plate section. The pre-ionizer operates at a high positive voltage. The wet, positive corona units are used to remove organic compound droplets and mists. The collected material drains from the vertical collection plates. These precipitators are used on small sources.

**Dry, Negative Corona Precipitators**

A dry, negative corona electrostatic precipitator consists of a large number of parallel gas passages with discharge electrodes mounted in the center and grounded collection surfaces called plates on either side. The discharge electrodes are spaced 4.5 to 6 in. away from each of the collection plates as shown in Figure 5-7. A high negative voltage is applied to the discharge electrodes. The voltage difference between the discharge electrodes and plates creates continuous electrical discharges termed coronas.

Negatively charged gas ions formed in and near the corona discharge impart an electrical charge to the particles and cause them to move toward the electrically grounded collection plates. Mechanical hammers called rappers are used to remove a portion of the dust layer accumulating on these plates and the small quantities of dust that also collect on the discharge electrodes. Particle agglomerates and dust layer sheets fall by gravity into the hoppers during rapping.

![Figure 5-7. Gas passage between collection plates](image-url)
The dry, negative corona electrostatic precipitator shown in Figure 5-8 is typical of units used on large-scale processes such as coal-fired utility boilers, coal-fired industrial boilers, kraft pulp mill recovery boilers, cement kilns, and municipal incinerators. They are generally quite large and are often designed for gas flow rates from 100,000 acfm to more than 3,000,000 acfm.

![Typical dry, negative corona type electrostatic precipitator](image)

**Figure 5-8. Typical dry, negative corona type electrostatic precipitator**

The gas stream passing through the duct toward the precipitator is moving too fast for effective treatment. Deceleration occurs in the inlet nozzle section immediately upstream of the precipitator by expanding the gas flow area. The gas velocity decreases by a factor of approximately 10 so that the average velocity through the treatment zone is usually between 3 to 6 feet per second.

In addition to slowing down the gas stream, the inlet nozzle is used to distribute the gas flow as uniformly as possible so that there are no significant cross-sectional variations in the gas velocities at the entrance of the precipitator. Proper gas distribution is achieved by proper inlet nozzle design, by proper inlet ductwork design, by turning vanes in the inlet nozzle, and by a series of gas distribution screens mounted in the inlet nozzle. Perforated plate gas distribution screens are shown in Figure 5-9.

As the gas stream enters the precipitator, it goes through passages formed by the large, parallel collection plates. High voltage discharge electrodes are centered between each of the plates. In the precipitators shown in the figures, small diameter wires serve as the discharge electrodes. In other precipitator designs, rigid masts or wires in rigid frames are used. The high voltages applied to the discharge electrodes create a negative corona that ultimately charges most of the particles negatively. The charged particles migrate to the collection plates and
build-up as dust layers on the plate surfaces. A small fraction of the particulate matter also accumulates on the discharge electrodes.

Figure 5-9. Gas distribution screens at the precipitator inlet

The discharge electrodes are divided into fields. These are portions of the precipitator energized by a single transformer-rectifier (T-R) set power supply. Most units have three to four fields in series as shown in Figure 5-10. However, some especially large units have as many as fourteen fields in series. The precipitator can also be divided into separate chambers that are separated by a solid wall. Chambers may also be designed as separate precipitator shells.

Figure 5-10. Arrangement of fields and chambers
Each of the fields is energized by a T-R set (Figure 5-11). The primary control cabinet circuitry controls the voltage in the alternating current power line applied to one side of the transformer in the T-R set. The high voltage generated in the transformer is converted into direct current in the rectifier and is then sent to the precipitator field.

![Diagram of T-R set, support insulator, discharge electrode frame, discharge electrodes](image)

**Figure 5-11.** T-R set, support insulator, discharge electrode frame, discharge electrodes

The gauges on the control cabinet for each T-R set provide much of the data necessary to evaluate performance. Figure 5-12 illustrates the analog gauges common in many older units. Some new precipitators have digital gauges used alone or in combination with the analog gauges.

The distance between the high voltage discharge electrodes and the grounded collection plates affects the electrical charging and migration of the particles. If some portions of the discharge electrodes and collection plates are closer than others, a spark will occur frequently at the close approach point. The automatic voltage controller will respond to this condition by reducing the applied voltage. This reduces the affected field's ability to electrically charge and collect particles. For example, if the designers intended discharge electrode spacing to the collection plates is 4.5 in., it is usually necessary to maintain all the discharge electrodes with an allowable spacing deviation of only ± 0.5 in. In other words, all discharge electrodes in this unit must be between 4 and 5 in. away from all portions of the adjacent collection plates. This is not easy to maintain.
The discharge wires are suspended between the grounded collection plates using insulators called high voltage frame support insulators. There are usually at least two high voltage frame support insulators for each bus section in a field. The location of these insulators is shown in Figure 5-13.

![Gauges present on the control cabinet for each precipitator field](image)

**Figure 5-12.** Gauges present on the control cabinet for each precipitator field

![High voltage frame support insulators](image)

**Figure 5-13.** High voltage frame support insulators
Chapter 5: Electrostatic Precipitators

The accumulation of moisture or dust on the surfaces of support insulators can cause a short circuit. These shorts start as a small current and are identified by reduced voltage in the field and reduced spark rates. As the current flow increases, it heats the surface of the insulator and can cause it to shatter. The development of a short circuit across the insulator surface can also cause the field to automatically shut down. The high voltage frame support insulator must be kept clean at all times to prevent these problems.

There are a variety of design approaches for minimizing the failure of high voltage frame support insulators. Most of these involve minimizing the quantities of moisture and solids that deposit on the inner and outer surfaces. Purge air blowers are used to provide a constant flow of hot air into the insulator penthouse or compartment. This hot air flows through holes in the insulator top cover, keeping the inner surface hot and reducing the particulate matter flowing upward into this area. In some units, unheated purge air is used with electrical resistance heaters around the high voltage frame support insulators to prevent moisture accumulation on the exterior surface. Purge air is usually supplied at a rate of 50 to 100 acfm per insulator.

Movement of the wire-type discharge electrodes is minimized by hanging bottle weights on each wire. These provide 25 to 30 pounds of tension on the wire so that it does not move excessively. In other precipitator designs, the discharge electrodes are mounted in rigid frames or are constructed as rigid masts. In these designs, there are usually several anti-sway insulators at the bottom of each high voltage frame to prevent a pendulum action that would reduce clearances between the high voltage electrodes and the grounded plates. The anti-sway insulators must inherently be located in the hopper area where it is difficult to provide supplemental heat or hot purge air. Accordingly, these insulators are vulnerable to electrical leakage and failure. For example, the anti-sway insulator shown in Figure 5-14 has electrical short-circuiting lines (leakage current) across the surface, which disabled the precipitator field. Short-circuits are normally minimized by using relatively long anti-sway insulators. In some designs, the anti-sway insulators have been eliminated by designing more rigid discharge electrode frame supports.

The collection of particulate matter is not complete once the particles are removed from the gas stream and accumulate on the collection plates. The solid material must be dislodged from the plates and fall by gravity into the hopper. This important second step often significantly influences the particulate emission rates from the precipitator.

Rapping intensities and frequencies must be adjusted for the approximate resistivity range that exists in the precipitator. If the resistivity is too low, the dust is weakly held and can be easily redispersed into the gas stream by excessive intensity or frequency of rapping. This is often indicated by routinely occurring puffs from the stack. If the resistivity is high, relatively high intensity and frequent rapping is needed. However, the mechanical limits of the rappers, rapper rods, and collection plates must be considered in maintaining this type of rapping practice.
The rapping frequency is not constant throughout the precipitator. The inlet fields should be rapped much more frequently, since they collect large quantities of particulate matter, than the middle and outlet fields. If the rapping is too frequent in the outlet fields, the accumulated dust layer between rapping cycles will be very thin. During rapping, these thin dust layers can be easily redispersed since they are not very cohesive.

![Anti-sway insulator with short-circuiting across the surface](image)

Figure 5-14. Anti-sway insulator with short-circuiting across the surface

Separate groups of rappers are used to clean the collection plates, discharge electrodes, and gas distribution plates. There are two basic types of rappers: (1) roof-mounted rappers and (2) side-mounted rappers. Roof-mounted rapper designs incorporate a large number of individual rappers, each connected to a single high voltage discharge electrode support frame or a section of collection plates. For collection plate rappers, the energy of roof-mounted rappers (Figure 5-15) is transmitted down a metallic rod. For discharge electrodes, the energy must be transmitted through an insulator rod to prevent carrying high voltage to the rapper and the accessible areas on the roof of the precipitator.

A side-mounted rapper system is shown in Figure 5-16. Motors are mounted on the exterior of the precipitator and turn shafts that run across the precipitator. A set of hammers is mounted on these rotating shafts in order to rap each individual collection plate and discharge electrode frame.

The removal of solids from the hopper is the important third step in the overall electrostatic precipitation process. Failure to remove solids from the hoppers in a timely manner can cause collection plate misalignment and discharge electrode frame misalignment. Short circuit paths between the high voltage electrodes and the electrically grounded collection plates can result in the formation of large fused clinkers, which usually have to be removed manually. Hopper overflow can also cause deposition on anti-sway insulators.
There are a variety of design features that can reduce the vulnerability to hopper overflow. Hoppers should have steep sides to facilitate solids movement. They should have thermal insulation and an outer protective lagging to prevent heat loss. Hopper heaters are often mounted in the bottom portions of the hopper to provide supplemental heat in the area where convective and conductive cooling is most rapid. Maintaining proper solids temperatures in the hoppers is important because the hot area partially surrounding the deposited solids facilitates solids flow into the small throat at the bottom. If the solids and trapped air cool,
the solids flow less readily and may bridge over the throat. One of the most useful techniques for minimizing hopper overflow is to empty the hoppers as frequently as practicable.

A center division plate is used in each hopper to prevent untreated gas from evading the electrically energized zone by passing through the upper regions of the hopper. This is termed the *anti-sneakage baffle*. The components of a typical hopper are illustrated in Figure 5-17.

![Components of a precipitator hopper](image)

**Figure 5-17. Components of a precipitator hopper**

**Wet, Negative Corona Precipitators**

A wet, negative corona precipitator is useful for industrial applications where mists or fogs must be controlled or when solid particulate matter in the gas stream has undesirable electrical or physical properties. Undesirable physical properties include moderate stickiness or a high carbonaceous composition. A washing system, rather than rappers, is used for dust removal. These units, termed either wet or *wetted wall*, use power supplies that generate high negative voltages on the small discharge electrodes. The power supplies are essentially identical to those used on dry, negative corona precipitators.

Wet, negative corona ESPs are usually preceded by a quench chamber to ensure that the gas stream is saturated prior to entering the unit. This quench chamber can either be a separate stand-alone vessel as shown in Figure 5-18 or an initial compartment within the wet ESP itself. Due to the presaturation sprays, the operating gas temperatures are usually 130°F - 170°F. This substantially reduces the vulnerability of the system to drying of the collection surfaces. Some systems use a liquid recirculation system and liquid additives to maintain the
proper pH in the collection plate sprays. Liquid additives can also help minimize the viscosity of the materials draining from the collection plates and can help minimize foaming in some industrial applications.

Recirculation liquid must be purged to maintain the solids levels. The rate of liquid purge depends primarily on the rate of collection of solids. Usually, the rate of purge is quite small because the overall recirculation rate of liquid is quite small. A normal liquid-to-gas ratio for a wet, negative corona precipitator is less than 2 gallons per thousand acf.

The gas passages in wet precipitators can be concentric circles, tubes, or parallel rows. Alignment of the negatively charged discharge electrodes and the electrically grounded collection plates is very important to ensure that the field can operate at the necessary voltage. The alignment tolerances are similar to those for dry precipitators.

There are two main design styles for wet, negative corona electrostatic precipitators: (1) vertical flow and (2) horizontal flow. A conventional vertical flow design is illustrated in Figure 5-19. The gas stream enters the presaturator chamber at the top of the unit. The saturated particulate-laden gas stream is distributed to a set of vertical tubes extending to the bottom of the unit. High voltage discharge electrodes are mounted in the center of each tube to generate the negative corona that electrically charges the particles moving down each tube. The charged particles migrate to the wet inner surface of the tube and are collected. Liquid moving down the tube surfaces carries the collected material to the wet ESP sump. Sprays above the tubes are activated on a routine frequency to further clean the tube surface and thereby maintain the required electrical clearances between the high voltage electrode and the electrically grounded tube surface.
Vertical flow wet ESPs have three or more support insulators to suspend the high voltage frame energizing each of the tube discharge wires. These insulators are similar to those used in dry, negative corona units. It is especially important to provide heat and purge air to these insulators due to the relatively cold gas temperatures and the presence of liquid sprays near the tops of the gas passage tubes.
Vertical flow wet, negative corona precipitators use electrical sectionalization differently than dry, negative corona systems. The wet ESPs often have two fields arranged in parallel and only one field in the direction of gas flow. This approach is due, in part, to the difficulty of protecting the high voltage frame support insulators in vertically stacked fields from descending liquid from an upper field.

A horizontal flow wet, negative corona precipitator is shown in Figure 5-20. This unit uses alternating high voltage plates and electrically grounded collection plates to form gas passages. The high voltage plates have discharge electrode points extending from the leading edge of each plate which are energized by a conventional T-R set. The negative corona generated around these discharge points electrically charges particles passing through the unit. The particulate matter is collected on electrically grounded collection plates and drains into the ESP sump. Cleaning of the collection plates is performed by a set of overhead sprays and by a set of sprays on a traversing header on the inlet side of each field.

Figure 5-20. Horizontal flow wet, negative corona precipitator

Horizontal flow wet ESPs usually have two or more fields in series. The sectionalization of the fields is similar to the design approach used in dry, negative corona units. The high
voltage collection plate support insulators are mounted in insulator boxes on the roof of the unit. As with all wet ESPs, the insulators are heated to minimize the vulnerability to electrical tracking across wet insulator surfaces. Both vertical and horizontal gas flow wet ESPs often use perforated plates to distribute the gas flow entering the units. Sprays are used to occasionally clean these plates.

A set of mist eliminators is often used immediately after a wet, negative corona ESPs. The mist eliminators remove the entrained spray droplets and other solids-containing droplets that would otherwise be emitted to the atmosphere. Mist eliminators have clean water sprays to occasionally clean the droplet-contacting surfaces. Common types of mist eliminators used in wet ESPs include chevrons, tube banks, and baffle plates.

Wet, negative corona electrostatic precipitators are often used on industrial driers and boilers. They are used either as primary collectors or as particulate matter collectors ahead of regenerative thermal oxidizers and regenerative catalytic oxidizers. The regenerative systems are prone to solids accumulation at the bed inlet.

**Wet, Positive Corona Precipitators**

Wet, positive corona precipitators are used for the collection of organic droplets and mists from relatively small industrial applications such as textile mill tenter frames. As shown in Figure 5-21, the discharge electrodes are separated from the electrically grounded collection plates. The positive voltages applied to the discharge electrodes of the preionizer are in the range of 12 to 15 kilovolts, considerably lower than the negative voltages used in the dry, negative corona or wet, negative corona designs. Electrical charges are applied to particles as they pass through the preionizer discharge electrodes. These particles are then collected on the downstream collection plates. Since wet, positive corona precipitators only collect liquid particles that drain from the plates, they do not require rappers or liquid distributors. The collection plates are designed to allow for easy removal and manual cleaning. The plates are often cleaned on a weekly or monthly basis, depending on the stickiness and viscosity of the collected material.

**Applicability Limitations**

Electrostatic precipitators can provide high efficiency, reliable particulate matter control in a wide variety of industrial applications. However, there are a few conditions that limit their industrial applicability:

- Extremely low fly ash resistivities
- Potential fire and explosion hazards
- Sticky particulate matter
- Ozone formation

In industrial sources that generate highly carbonaceous particulate matter, the fly ash resistivities can be extremely low due to the high bulk conductivity of this material at all
temperatures. These resistivities can be below the levels where good performance can be obtained by flue gas conditioning. Severe rapping reentrainment problems can persist during routine operation due to the weak electrical forces bonding the dust layer to the collection plate and the ease of particle dispersion during rapping. Electrostatic precipitators are not an ideal choice for particulate matter control in these applications due to the probable emission problems.

Applications involving the routine or intermittent presence of highly carbanaceous particulate matter or other easily combusted material should be approached with caution. Fires can occur in dust layers on the collection plates or in the accumulated solids in a hopper. These fires can create high temperature areas in the affected part of the unit, which can result in severe warpage and misalignment of the collection plates. Electrostatic precipitators are not appropriate for sources that have potentially explosive concentrations of gases or vapors. The routine electrical sparking in the fields provides numerous opportunities to ignite the explosive materials. For these reasons, electrostatic precipitators are rarely used for sources generating highly combustible or potentially explosive contaminants in the gas streams.

The presence of highly sticky material, such as some oils and compounds like ammonium bisulfate, can present major operating problems in dry, negative corona precipitators. Rapping of the solids from the collection plates must be readily possible. The accumulation of sticky material on the collection plates and other components in the precipitator would soon cause collection plate-to-discharge electrode clearance problems that would adversely
affect the electrical conditions in the affected field. For this reason, dry, negative corona precipitators are rarely used on sources that generate high concentrations of sticky particulate matter. Wet, negative corona precipitators and wet, positive corona precipitators can operate very well with moderately sticky material. However, it must be possible to remove the contaminants either by normal drainage or by occasional cleaning sprays.

Dry, negative corona and wet, negative corona precipitators generate very small quantities of ozone due to the characteristics of the corona discharge. Generally, the concentration of ozone is limited by the relatively low oxygen levels in the gas stream being treated. Due to the presence of ozone, these types of electrostatic precipitators are not used for standard air cleaning operations where the oxygen concentrations are at ambient levels, and it is necessary to recirculate the treated air stream to an occupied work area.

**Inspection**

Level 2 inspections of electrostatic precipitators are divided into two categories: basic inspection points, and follow-up inspection points. Two categories of inspection points are necessary to conserve time during the inspection of units that are operating well. Electrostatic precipitators are moderately complicated devices, and it is not practical to conduct a comprehensive inspection of each unit. Field time should be conserved for those units that could be out of compliance now or in the near future. The data and information usually included in the inspection of an electrostatic precipitator include the following:

**Basic Level 2**

- Visible emission observations
- Opacity monitor data
- Precipitator T-R set electrical data

**Follow-up Level 2**

- Rapper operation
- Alignment records
- Component failure records
- Symptoms of air infiltration
- Start-up/shut-down procedures

Essentially all the precipitator data are evaluated with respect to baseline shifts. Significant unit-to-unit differences complicate comparison to similar units.

**Basic Level 2: Visible Emission Observations**

If weather conditions permit, the precipitator effluent average opacity should be determined in accordance with required procedures. The observation should persist for twelve to twenty-four minutes to account for process cycles or rapping operating cycles. The timing and
duration of all significant opacity spikes should be noted. This information is useful in evaluating potential rapping reentrainment problems. In some cases, however, light puffing can occur even when the precipitator operating conditions are optimal.

As part of the visible emission observations, check for any condensing plume at the stack discharge. This is often indicated by a clear zone directly above the stack in a portion of the plume that is still too hot to cause vapor nucleation. Condensing plumes are often bluish-white or yellow-white and do not disperse like steam. In some cases, condensing plume conditions are indicated by large differences between the opacity indicated by the visible emission observation and by the opacity monitor located in the stack or in the ductwork after the precipitator. Sulfuric acid vapor is often the cause of the condensing plumes. Other materials that can nucleate include ammonia compounds and organic vapor.

**Basic Level 2: Opacity Monitor Data**

Before evaluating the sometimes voluminous opacity monitoring data compiled since the previous inspection, the operating condition of the transmissometer should be checked to the extent possible. If the unit is in a readily accessible location, the instrument should be checked to confirm that the purge air blowers are operating, the filters are in place, the air delivery hoses are intact, and the instrument is in alignment. The instrument data sheets should also be checked to confirm that zero and span checks are being conducted at the required frequency (at least daily).

If the opacity monitor appears to be working properly, the average opacity data should be evaluated. Average opacity data for selected days should be evaluated with respect to baseline values for the same process operating load. This type of comparison is demonstrated in Figure 5-22. If the average opacity has increased outside the baseline range, particulate emissions have probably increased.

The range illustrated in Figure 5-22 is compiled by plotting six minute average opacities over a wide range of operating loads. The precision of the baseline range improves when many data points are used, thus improving the predictive nature of this baseline evaluation. One of the main values of the curve shown in Figure 5-22 is that it provides an early warning of emission problems before compliance is compromised and possibly before damage has occurred to precipitator components.

**Basic Level 2: Precipitator T-R Set Electrical Data**

Precipitator T-R set electrical data are combined with the opacity and visible emissions data to evaluate the general performance of the precipitator. The first step in evaluating the electrical data is to obtain or prepare a sketch that indicates the arrangement of the T-R sets on the precipitator. This sketch should indicate the number of chambers in the precipitator and the number of fields in series. The T-R set numbers should be indicated on the sketch.
The T-R set electrical data are recorded for each chamber, starting with the inlet field and proceeding to the outlet field. A tabular format similar to the one shown below is useful for recording the data.

<table>
<thead>
<tr>
<th>Field</th>
<th>Chamber</th>
<th>Unit</th>
<th>Date</th>
<th>Time</th>
<th>Primary Data (A.C.)</th>
<th>Secondary Data (D.C.)</th>
<th>Spark Rate (#/min)</th>
<th>Limit$^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Voltage (Volts)</td>
<td>Current (Amps)</td>
<td>Voltage (Kilovolts)</td>
<td>Current (Milliamps)</td>
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<tr>
<td>1</td>
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</tr>
</tbody>
</table>

$^1$spk = spark limited  
pc = primary current limited  
pv = primary voltage limited  
sc = secondary current limited  
sv = secondary voltage limited

The voltages and currents should be recorded when the analog gauge or digital gauge reaches the highest stable value for a fraction of a second. The fluctuations in the data are caused mainly by the automatic voltage controller returning the field to the maximum operating voltage following a spark.

Figure 5-22. Opacity baseline data
The primary and secondary voltages should be compared with baseline values to determine if there have been decreases. Usually, a decrease of 5 kilovolts (secondary voltage) or 30 volts (primary voltage) can be associated with performance problems. Records since the last inspection should be evaluated to confirm that voltages have decreased.

The dust layer resistivity conditions should be evaluated qualitatively. Voltage, current, and spark rate data should be plotted for each of the chambers. These plots should be compared against baseline plots, as indicated in Figures 5-23 and 5-24.

If all or most fields in a chamber have shifted in the same direction at about the same time, a shift in the prevailing resistivity range has probably occurred. Outlet fields often lag behind inlet fields by several hours. The symptoms of resistivity shifts are summarized below:

Higher resistivity
- Reduced primary and secondary voltages
- Significantly reduced primary and secondary currents
- Increased spark rates, especially in outlet fields
- All or most fields at the spark limit

Lower resistivity
- Reduced primary and secondary voltages
- Significantly increased primary and secondary currents, especially in inlet fields
- Decreased spark rates, especially in inlet fields
- All or most fields at either the primary current or secondary current limits

In some units, the resistivity conditions in one chamber are quite different from the resistivity conditions in adjacent chambers. This condition is often caused by slight differences in the flue gas temperature and by the maldistribution of conditioning agents added to the gas steam.

When only one field is inconsistent with others in the same chamber, the shift from baseline conditions is caused by mechanical or electrical problems inside the field. Symptoms of various mechanical or electrical problems are summarized below.

Misalignment
- Significantly reduced primary and secondary voltages
- Increased primary and secondary currents
- Increased spark rate

Short
- Reduced primary and secondary voltages
- Increased primary and secondary currents
- No sparking
Figure 5-23. Low resistivity related data shifts
Figure 5-24. High resistivity related data shifts
Rapper failure

- Significantly reduced primary and secondary voltages
- Increased primary and secondary currents
- Increased spark rate

Under certain conditions, the total power input to the precipitator can affect emissions. The power input to each field may be calculated in two ways:

\[
\text{Secondary voltage (kilovolts)} \times \text{Secondary current (milliamps)} = \text{Corona power (watts)} \quad (5-3)
\]

\[
\text{Primary voltage (volts)} \times \text{Primary current (amps)} \times 0.75 = \text{Corona power (watts)} \quad (5-4)
\]

Total power input is the sum of the power inputs to each field. When particle resistivity is high, both voltage and current flow are low. This results in low power input, typically less than about 400 watts/10^3 acfm. When particle resistivity is low, voltage is low, but current flow is high. This results in high power input, typically greater than about 1,000 watts/10^3 acfm. Power inputs between 400 watts/10^3 acfm and 1,000 watts/10^3 acfm are typical of moderate resistivity particles.

As shown in Figure 5-25, when particle resistivity is high or moderate, increasing power input reduces particle penetration (increases collection efficiency). When particle resistivity is low, increasing power input does not significantly affect emissions. This is because the limit to performance in this range is particle re-entrainment, and this is not affected by increasing the power input.

![Figure 5-25. Effect of power input on particle penetration](image)

The visible emissions data, opacity monitoring data, and T-R set electrical data should be evaluated to determine if there is a need to go beyond the Basic Level 2 inspection. Follow-up inspection points should be included if there are (1) high visible emissions or a condensing plume, (2) average opacities significantly above baseline levels, or (3) impaired
electrical conditions due either to resistivity shifts or component failures in one or more fields.

**Follow-up Level 2: Rapper Operation**

The collection plate, discharge electrode, and gas distribution plate rapping systems should be evaluated when there are frequent opacity spikes (puffing), when the currents are low in isolated areas, or when the resistivity appears to be particularly high or low.

An inspection of the rappers should be conducted to determine if they are working. Some rappers are activated infrequently so this check can be done efficiently only when the plant representative is willing to arrange for an operator to activate the diagnostic routine in the rapper control system. This system activates all the rappers one-by-one in a sequential pattern so that the performance of each can be checked. In some systems, this diagnostic feature is called the *walk-around mode*. Rappers that are not working or that sound like they are physically bound (detected by a dampened “thud” rather than a crisp impact sound) should be marked on a plan-view type drawing. A typical inspection drawing is shown in Figure 5-26.

The rapper activation frequencies and intensities should be recorded based on data included in the rapper control microprocessor. Usually, several activation programs are recorded. The program in use during the inspection should be recorded along with the criteria used in going from one program to another. The activation frequencies should be compared with the opacity spiking frequency indicated by the opacity monitor.

The rapping frequencies and intensities should be adjusted for the resistivity conditions in each portion of the precipitator because resistivity levels determine the forces holding the dust layers on the collection plates. When the dust resistivity is low, rapping is minimized since little force is necessary to dislodge the dust, and there is a risk of rapping reentrainment. When the dust resistivity is high, rapping is normally frequent and relatively intense. There are, however, practical limits to the frequency and intensity of rapping.

**Follow-up Level 2: Alignment Records**

The alignment of the collection plates and discharge electrodes is critical to the operation of the precipitator, especially when the resistivity is in the moderate-to-high range. Plant personnel should make alignment measurements whenever there is a major outage and it is possible to safely work inside the unit. These measurements consist of simply comparing the discharge electrode to collection plate spacings with the original unit specification. Misalignment can be caused by a variety of problems:

- Improper position of the upper discharge electrode frames due to improper support electrode placement
- Failure of lower high voltage frame anti-sway insulators (not used in all designs)
- Bowed or warped collection plates
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- Bent components in the lower high voltage frames

Plant personnel should mark all areas with alignment problems using plan-view drawings or similar procedures. When the resistivity is moderate-to-high, all discharge electrodes and plates should be within a tolerance of approximately $x \pm 0.5$ inches, where $x$ is the design electrode-to-collection plate spacing. When the resistivity is low, alignment is slightly less critical, and spacing tolerances can usually be $x \pm 1.0$ inches.

Figure 5-26. Example layout of roof mounted rappers

**Follow-up Level 2: Component Failure Records**

Component failure records should be requested when the T-R set electrical data indicate that chronic problems have resulted in the temporary loss of fields. Keeping records indicating where and when component failures occur is a good maintenance practice. The failure patterns can then be evaluated to identify the underlying causes. For example, the support insulator failure chart shown in Figure 5-27 indicates that there is a distinct spatial pattern to the failures.
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In this case, the problem was caused by the condensation of water on the insulators. Air infiltration through a poorly sealed access hatch was allowing the cold air and ambient moisture to enter the insulator area. Similar records can be kept for the discharge electrodes, anti-sway insulators, and other precipitator components.

**Follow-up Level 2: Symptoms of Air Infiltration**

A walk-around inspection of the precipitator is often useful for identifying conditions that could be contributing to chronic performance problems or that could threaten the plant’s ability to maintain compliance in the immediate future. Air infiltration is a common problem due to the frequent thermal expansion and contraction and the potential for corrosion damage. Air infiltration can cause a variety of problems:

- Warpage of collection plates
- Condensation of corrosive vapors from the gas stream
- Moisture deposition on electrical insulators
- Hopper bridging
- Reentrainment of dust being discharged to hoppers
- Inability of induced draft fans to ventilate the process equipment (boiler, incinerator)
There are several ways to check for air infiltration. A comparison of the inlet and outlet temperatures provides a general indication. The industry average for the temperature drop for any well insulated collector operating in the 250°F to 600°F temperature range is 5°F to 25°F. A more sensitive evaluation is possible by checking for a shift in the baseline value for the temperature drop across this specific unit. For example, if the present temperature drop is 18°F, and it was previously 9°F, there could be an infiltration problem.

Another indication of air infiltration is an increase of approximately 0.5 percent oxygen from the inlet to the outlet. For example, an increase from 4.5 percent oxygen at the inlet to 6 percent at the outlet would indicate probable infiltration problems. Unfortunately, oxygen monitors at either the inlet or the outlet are rare. Also, some combustion sources have severe stratification of flue gases, which means that the oxygen concentration varies substantially across the inlet duct.

Some of the most severe air infiltration sites can be found audibly; there is a characteristic air rushing sound near the site. Common sites having air inleakage include hopper poke holes, hopper access hatches, precipitator side access hatches, and expansion joints in the ductwork. While walking around the unit, corroded areas should be noted because these areas are subject to air infiltration.

**Follow-up Level 2: Start-up/Shut-down Procedures**

Start-up/shut-down practices should be evaluated with plant personnel if there have been citizen complaints or if the opacity monitor records indicate that start-up/shut-down cycles are frequent and that excessive emissions are persistent.

In general, the precipitator should be energized in a reasonable time after start-up of the boiler, incinerator, or other process source. Inspectors must be aware that energizing too quickly can lead to precipitator explosions or to hard-to-remove collection plate deposits that significantly impair long term performance. However, excessive time periods before energizing cause very high particulate emissions. There are no standard industry practices concerning start-up times for precipitators because the controlling factors are the characteristics of the particulate matter and the concentrations of the explosive gases generated by the process equipment. Each process can be different; therefore, the appropriate time period before energizing the unit must be determined by the operating personnel.

One of the best ways to minimize start-up/shut-down emissions is to minimize the number of start-up/shut-down cycles. The frequency of occurrence could be easier to control than the duration of excessive emissions during any one start-up/shut-down cycle.
Review Problems

Video Problem

This example concerns a conventional electrostatic precipitator. There are two fields in series, each having transformer-rectifier sets (T-R sets) with secondary current ratings of 1,500 milliamps. There are magnetic impulse-gravity impact rappers (often termed MIGI rappers) for the collection plates and electric vibrators for the high voltage wire frames.

Unlike most pulverized coal-fired units, the boiler operates entirely at positive pressure. The coal being burned is a typical low sulfur eastern bituminous coal. Since this is an older facility, it is not required to have an opacity monitor on the stack.

The unit is subject to occasional visible emission spikes. During these periods, the average opacity is 12%, and short term spikes to 50% occur every three minutes. The duration of the visible emission spikes is approximately 15 seconds. During routine operating periods, the average opacity is 3%, and the emission spikes are not noticeable.

1. Why do the current and voltage needles fluctuate on ESPs?
   a. Electrical sparks within the field cause short term transient currents.
   b. The automatic voltage controller shuts down the field for a very short time when it senses an electrical spark. It then ramps the fields operating voltage back up to levels close to the pre-spark values.
   c. The electrical spark drains the capacitor in the power supply.

2. What Level 2 inspection data are necessary to evaluate the intermittent visible emission problems being experienced at this plant?

3. Is it necessary to inspect the rappers on the precipitator roof?
   a. Yes
   b. No

4. Is it necessary to inspect the small pulse jet fabric filter serving the ash handling operation of this plant?
   a. Yes
   b. No
General Problems

5. An electrostatic precipitator has the following T-R set electrical data. What is the general resistivity range at this time?

<table>
<thead>
<tr>
<th>Field</th>
<th>Primary</th>
<th>Secondary</th>
<th>Spark</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Volts)</td>
<td>(Amps)</td>
<td>(Milliamps)</td>
<td>(#/min.)</td>
</tr>
<tr>
<td>Inlet</td>
<td>310</td>
<td>60</td>
<td>480</td>
<td>30</td>
</tr>
<tr>
<td>Second</td>
<td>350</td>
<td>100</td>
<td>750</td>
<td>0</td>
</tr>
<tr>
<td>Third</td>
<td>330</td>
<td>95</td>
<td>730</td>
<td>0</td>
</tr>
<tr>
<td>Outlet</td>
<td>310</td>
<td>105</td>
<td>770</td>
<td>0</td>
</tr>
</tbody>
</table>

Note:  spk= spark limited
sc  = secondary current limited
pc  = primary current limited

6. What can be concluded by comparing the current inspection data with the baseline values?

<table>
<thead>
<tr>
<th></th>
<th>Inspection Data</th>
<th>Baseline Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Load, MW</td>
<td>318</td>
<td>316</td>
</tr>
<tr>
<td>Fuel Sulfur, %</td>
<td>0.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Fuel Ash, %</td>
<td>13.1</td>
<td>11.9</td>
</tr>
<tr>
<td>Inlet/Outlet Oxygen, %</td>
<td>4.1/4.3</td>
<td>4.1/4.5</td>
</tr>
<tr>
<td>Inlet/Outlet Temp., °F</td>
<td>329/323</td>
<td>312/308</td>
</tr>
<tr>
<td>Gas Velocity, fps</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Power Input, kW</td>
<td>1,810</td>
<td>2,635</td>
</tr>
<tr>
<td>Average Opacity, %</td>
<td>16.8</td>
<td>7.9</td>
</tr>
<tr>
<td>Spiking</td>
<td>Moderate</td>
<td>Minor</td>
</tr>
</tbody>
</table>

7. During the baseline inspection of a cold side electrostatic precipitator on a utility pulverized coal-fired boiler, the precipitator inlet gas temperature averaged 306°F. During the present inspection, the average inlet gas temperature is 324°F. The boiler load is similar to that during the baseline inspection. What impact could this have on the precipitator performance?

a. None. The precipitator is designed to handle these small temperature changes.
b. This could increase the chances for corrosive attack of the precipitator.
c. This could impair performance due to a major increase in the resistivity.
d. This will cause a dramatic increase in the gas velocity and, thereby, decrease precipitator performance.