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Air

Inspection of Particle Control Devices

Student Manual

APTI Course 445
Third Edition

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CHAPTER 1

BASELINE INSPECTION TECHNIQUES

Air pollution source inspection is not easy. Agency inspectors must have the technical skill to quickly and accurately evaluate the compliance status of a wide range of industrial sources that are subject to many complex regulations. They must compile the necessary information in strict accordance with established legal and procedural requirements. The job often demands substantial physical exertion to observe tests in elevated areas and to evaluate equipment operating conditions. Occasionally, the job involves working with adversarial or emotional people who can test the inspector's patience and professionalism.

Source inspections can have a very beneficial impact when performed well. Inspectors have a key role in encouraging compliance without the expense and time commitment involved with litigation. Inspectors can clarify regulatory requirements and improve communication between the source, the agency, and the community. Inspectors can also provide important “feedback” to the agency concerning the adequacy of the promulgated regulations.

Inspections can have a negative impact on the agency’s overall compliance program when performed poorly. Superficial inspections can inadvertently convince some source owners or operators that the agency is unable or unwilling to enforce environmental regulations. Conscientious operators who install and maintain environmental controls compete at an economical disadvantage with those who choose to ignore the requirements. Residents close to noncomplying facilities can be subject to both health risks and nuisance problems. Furthermore, the inability to achieve National Ambient Air Quality Standards because of the lack of compliance at certain facilities could result in stringent regulations on all sources in the Air Quality Control Region.

Effective and methodical inspections can be performed well by people with a wide range of educational backgrounds and experience. This section presents some of the basic procedures necessary to compile compliance related data and observations into a form that can be readily evaluated. Introductory material concerning on-site source inspections is also provided.

Responsibilities of Inspectors

Inspectors do not only conduct compliance inspections; they balance a variety of job responsibilities that compete for available time. Many aspects of the agency’s overall enforcement program are affected by some role played by the inspector:

- Compliance evaluation
- Testing and sampling
- Agency representation
- Litigation assistance
- Citizen complaint investigation

Due to these responsibilities, the job demands a broad range of skills and an ability to use time wisely.

Compliance Evaluation

One of the primary duties of an agency inspector is to compile technically defensible conclusions regarding the compliance status of the facility being evaluated. These conclusions must be reached in a manner fully consistent with all legal requirements. These requirements include the need to conduct the inspections and ancillary work in a manner that protects all legal rights of the source and its employees and in a manner consistent with agency policies. One of the most important of these policies is the agency's health and safety plan. Inspections must be conducted in accordance with all OSHA requirements and agency and plant health and safety policies. Agency personnel should not make any requests or take any actions that endanger plant personnel or themselves.

Testing and Sampling

Agency personnel are often called on to observe emissions tests to determine compliance with promulgated rules and regulations. These tests must be conducted in strict accordance with applicable reference methods to ensure that the emission rate data represent an accurate and fair measurement of the actual emissions. Agency personnel must understand the many complex testing methods and the types of sampling errors that can affect the results.

Agency Representation

The inspector is a professional representative of the agency. Often, the inspector conducting an on-site inspection is the only employee of the agency whom plant personnel meet. The ability of the inspector to convey the interests of the agency in a calm, firm, and professional manner can have an impact on the extent to which source personnel cooperate.

Litigation Assistance

Agency personnel must prepare enforcement cases and present expert testimony when regulated sources are not making adequate progress toward achieving compliance. The inspection report and the emission test report are often the foundation of the enforcement case. All data and observations from on-site inspections and observed emission tests must be fully documented and properly evaluated. Inspectors might need to provide additional information and assistance to agency attorneys in order to prepare the technical aspects of the case. Agency personnel might also be requested to present expert testimony concerning the case.

Citizen Compliant Investigation

Citizens expect and deserve prompt attention to their complaints concerning air quality. Agency inspectors responding to complaints, both over the telephone or in person, must document the complaint accurately and determine if a follow-up investigation is warranted. Localized air quality problems leading to complaints are often intermittent and short in duration. This means that the follow-up investigations often have to be performed at inconvenient times. After completing the investigation, it is important to advise the complainant of the results and summarize any actions that will be taken by the sources to minimize future occurrences.

Agency personnel must remain calm and conduct themselves professionally when responding to complaints. Occasionally, the complainants vent their frustration and anger at the agency. Sometimes, the source owners or operators vent their frustration with both the agency and the citizens making the complaints. The agency inspector must encourage all parties involved to remain calm, to communicate with each other, and to comply with all regulations.

Other Responsibilities

The inspector plays a key role in developing good working relationships with the various levels of government often involved in air pollution control work. For example, states have primary responsibility for enforcement, but EPA has the authority to oversee some compliance situations. In some cases, state and local agencies must work together closely on enforcement actions.

On-Site Compliance Inspections

Because of the various responsibilities of the inspector, the on-site inspection can address one or more of the following:

- Evaluation of compliance status with regulatory requirements
- Confirmation that all emission units are included on the permit and that the source is complying with all permit stipulations
- Follow-up evaluation of citizen complaints
- Compilation of information needed for litigation or for formal compliance negotiations
- Collection of information needed for regulation development

Levels of Inspection

Levels of inspection have been developed by EPA to adapt on-site inspections to these different responsibilities. The inspections have been divided into four distinct groups: Levels 1, 2, 3 and 4. The majority of source inspections presently being conducted by regulatory agencies are classified as Level 2. The course focuses almost entirely on Level 2 inspections.

Level 1

Level 1 is defined as a driveby surveillance inspection. It is not necessary to enter the facility. The inspection consists primarily of visible emission observations of stacks and vents visible from public roads, and odor surveys both upwind and downwind of the plant. If conditions warrant further investigation, the inspector submits the information to the appropriate agency personnel to schedule an inspection. Level 1 is not considered an on-site inspection because of its limited scope; however, it is particularly useful for investigating citizen complaints and for determining the best use of limited agency resources.

Level 2

Level 2 inspections are used primarily to gather compliance data and identify violations. They are also used to determine if all the regulated emission units are included on the operating permit. The inspector must enter the plant grounds and do a walkthrough evaluation of emission sources, control devices, and plant records. The initial walkthrough evaluation determines if further investigations are warranted. The inspector must determine the validity of the data collected from plant instrumentation. If emissions problems or other inconsistencies exist, the scope of the inspection is expanded to include one or more follow-up inspection steps.

Level 3

When problems or potential problems are identified by an inspector in either Level 1 or Level 2 inspections, a Level 3 inspection might be performed. A Level 3 inspection has the following characteristics:

- Detailed
- Narrow scope
- Targeted to particular emission units
- Enforcement case development oriented

The inspector might request that plant personnel use portable instruments to measure important operating parameters and to verify that on-site permanent monitors are performing properly. A number of portable instruments are often available to obtain supplemental data:

- Differential pressure gauges
- Thermocouples and thermometers

- Combustion gas analyzers (oxygen and carbon monoxide monitors)
- Hydrogen-ion concentration (pH) meters
- VOC analyzers

Stack effluent characteristics, continuous emissions monitoring (CEM) data, control device operating data, process operating data, ash analyses, and fuel analyses are evaluated for a period of 6 months to more than 2 years prior to the inspection. In some cases, it is also helpful to review air pollution control device maintenance records concerning the rate, spatial distribution, and characteristics of component failure. The entire set of data is reviewed to evaluate the compliance status of the unit and to determine if corrective actions planned by the source operators have a reasonable probability of expeditiously minimizing emission problems.

Level 4

Level 4 is the only type of inspection not used directly for compliance determination or enforcement. The purpose of the Level 4 inspection is primarily to gather data that will be used to facilitate future inspections conducted by less experienced field personnel. Because of the nature of this type of inspection, Level 4 is performed by senior managers and agency personnel with responsibility for a specific plant. Level 4 inspections should include the preparation of general process and control device flowcharts, measurement of operating parameters by plant personnel, and determination of the normal ranges of important operating parameters. Health and safety concerns are addressed to encourage source operators to eliminate the hazards when possible and to help inspectors conducting future Level 2 inspections avoid the hazards. Level 4 should be performed in conjunction with stack tests or at times when the source is believed to be operating in compliance.

Major Elements of Inspection

There are several major steps in the routine Level 2 inspection of stationary sources:

- File review
- Inspection preparation
- Pre-inspection meeting
- Plant inspection
- Post-inspection meeting
- Inspection report preparation

File Review

The file review helps to determine the most appropriate scope and timing of the inspection. As discussed earlier, there is generally insufficient time to evaluate all the individual emission units present in moderate-to-large facilities. During the pre-inspection file review, the issues to be included within the scope of the inspection are selected, and the most appropriate time to conduct the inspection is determined. Also, the types of safety equipment necessary for the specific areas of the plant to be inspected are determined. An important part of the pre-inspection file review is a check of the operating permit.

Inspection Preparation

During the inspection preparation phase, the equipment needed for the job is packed, and travel plans are optimized to the extent possible to minimize travel costs and travel time.

Pre-Inspection Meeting

The pre-inspection meeting should be conducted with responsible plant officials immediately after entering the facility. The scope of the inspection should be discussed. All records and other information necessary to fully evaluate the facility should be requested so that plant personnel can gather and, if necessary, photocopy all records while the inspector is on-site. As part of the pre-inspection meeting, the agency inspector should explain the general reasons for the inspection and any specific issues that will be addressed. Also, the inspector should be prepared to provide general information concerning the agency's requirements and to provide other information helpful to the source in satisfying agency requests. Legal and administrative issues should be discussed during the pre-inspection meeting so that there are no surprises during the inspection. These issues often include, but are not limited to, confidentiality, use of photographs, and inspector authority.

Plant Inspection

During the plant inspection, the inspector should conduct himself or herself professionally. It is important to always keep in mind that, despite the agency's right to inspect, the inspector is still a visitor at the facility. The inspector must compile all the information necessary to technically evaluate the compliance status of the facility. This often requires numerous questions to obtain data and to clarify operating conditions. The inspector must not be reluctant to ask questions. However, these questions should be directed toward valid technical concerns.

Post-Inspection Meeting

Following the plant inspection, a post-inspection interview should be conducted. This meeting is primarily for the benefit of the inspector to clarify issues raised during the record evaluation and plant inspection. This meeting should not include a presentation of the inspection results to plant personnel. They should be able to reach their own conclusions regarding their compliance status. Furthermore, in most jurisdictions, the agency inspector is not authorized to reach conclusions regarding compliance status of a plant without discussing the data and information with agency supervisors and/or agency attorneys. Accordingly, the post-inspection interview should be restricted to clarifying questions and follow-up requests for more information from the plant.

Inspection Report Preparation

A concise inspection report should be prepared as soon as possible after the on-site inspection. This report should summarize the purpose, scope, and findings of the inspection. All calculations necessary to document the findings should be presented in a clear and complete manner. A consistent report format should be used, to the maximum extent possible, to facilitate supervisory review.

Inspection Analyses

There are three basic approaches to evaluating compliance:

- Direct comparison with promulgated standards
- Comparison of inspected units with similar units
- Evaluation of shifts from baseline operating conditions

Direct Comparisons

Direct comparisons are possible when there is a promulgated regulation or a permit provision that presents requirements in a form and format directly measured by either plant instruments or plant chemical analyses. One of the most common of these regulatory requirements is the sulfur-in-fuel regulation. Many agencies have limited the sulfur content of the coal or oil being burned in industrial boilers. The sulfur content can be accurately measured by ASTM reference method procedures. Other examples of types of regulations that can be directly enforced are listed in Table 1-1. A direct comparison of these analyses with the promulgated limit provides a clear indication of the compliance status.

It is important to note that data used for direct comparison-type analyses can be used as the basis for enforcement actions. When the data are provided by plant continuous emission monitors or other instruments, it is important to obtain information concerning the operator's quality assurance practices and the instrument’s on-line availability. Inadequacies in either of these areas can also be the basis for enforcement actions.

The inspection procedures based on direct comparison analyses use primarily CEMs or plant instrumentation data or sample analyses (e.g., fuel sulfur content, coating VOC content). Information concerning CEMs is provided in APTI Course 474, “Continuous Emission Monitoring.” Information concerning other types of direct comparison inspections is available in APTI Course 444, “Air Pollution Field Enforcement.” Direct comparison inspection analyses are not emphasized in this course because of the availability of these other training materials.

Table 1-1. Examples of Direct Comparison Type Inspection Analyses

Regulation	Parameter	Type of Instrument or Analysis Used for Direct Comparison
Municipal Waste Incinerators 40 CFR Part 60, Subpart Ea	Incinerator operating rate	Steam rate gauge
	CO concentration	CO continuous emission monitor
	Control system inlet gas temperature	Thermocouple or equivalent temperature monitor
Fossil Fuel Fired Boilers 40 CFR Part 60, Subparts Da and Db	Sulfur dioxide concentration	Sulfur dioxide continuous emission monitor
	Nitrogen oxides concentration	Nitrogen oxides continuous emission monitor
	Visible emissions	Opacity monitor
Asbestos Removal	Visible emissions	Visible emissions observer
	Adequately wet asbestos-containing material during removal	Observation of work practices

Comparison with Similar Units at Other Plants

An alternative means of evaluating compliance of a specific source is to compare its operating characteristics with those at similar industrial facilities. This can, however, be time consuming and error prone. It takes a substantial investment of time to determine exactly which units are similar, and very often these assumptions are subject to error due to subtle factors that can affect performance. Furthermore, it takes time to compile all the comparative data.

Comparisons with similar units are useful primarily in extreme cases. For example, if a venturi scrubber on an asphalt plant is operating at 8 inches H_2O, and the industrial average is 22 inches H_2O, there is some cause for concern about the low pressure drop at the unit being inspected.

Similar unit comparison type inspection analyses will be used with caution in this course due to the site-to-site variations that can make these analyses irrelevant or in significant error. Comparisons with similar units can not generally be used as a stand-alone basis for enforcement actions. Emission tests using applicable reference methods are needed to prove the suspected compliance problem.

Baseline Analyses

Many air pollution control regulations cannot be stated in a format compatible with direct comparison type inspection analyses. Air pollution control regulations are often expressed in terms such as pounds of pollutant emitted per hour or pounds of pollutant emitted per ton of product. In these cases, there are no plant instruments that read out directly in the format specified in the regulation. Instead, indirect means are needed to evaluate compliance potential. Shifts from baseline conditions are used to provide an imperfect, but often revealing, indication of the unit performance.

Technical analysis based on shifts from baseline conditions is not a new procedure. It is a fundamental diagnostic technique that has been used successfully for many years in practically all aspects of equipment maintenance. It is even used now in health care. For example, the first physical administered by an occupational physician is called the “baseline” examination. A shift in the medical condition over time for the individual is called a “baseline shift.” These types of analyses are also used for monitoring changes in processing equipment performance.

Baseline analyses are especially useful for air pollution control equipment and sources since there are many subtle factors that vary from unit to unit that can strongly influence performance. These factors include, but are not limited to, the following:

- Particle size distributions
- Adequacy of gas distribution
- Liquid surface tension (wet scrubbers)
- Liquid droplet size distribution (wet scrubbers)
- Gas temperature spatial differences
- Gas flow temporal variations
- Particulate composition
- Particulate resistivity (electrostatic precipitators)
- Dust cake cohesiveness (filtration systems and electrostatic precipitators)
- Distribution of cleaning energy (filtration systems and electrostatic precipitators)
- Mist eliminator efficiency
- Venturi throat damper condition (wet scrubbers)
- pH (wet scrubbers)

Most of these variables are not monitored directly by plant instruments and can vary substantially from unit-to-unit, even in the same plant operating under supposedly similar conditions. All these variables can have an influence on pollutant removal performance.

The first principle of baseline analysis is that changes over time are evaluated for individual units. The performance conditions today are compared against the performance levels during the baseline period. For example, a shift in the static pressure drop across a wet scrubber from a baseline level of 30 inches H_2O to the present level of 24 inches H_2O would be a possible symptom of scrubber performance problems and would indicate the need to investigate further. This is more meaningful than trying to determine if a pressure drop of 24 inches H_2O is consistent with other similar scrubbers at different plants or on different process lines in the same plant being inspected. Comparing different units is difficult because there can be subtle differences in the gas streams that have a strong influence on performance. It is rare that units at different plants or even units at the same plant can be directly compared.

The second principle of baseline analysis is that sets of data are evaluated, as opposed to relying on a single measurement A shift in a single parameter is rarely a good basis for a decision concerning compliance status. The instrument that is generating the data could be operating out-of-calibration or entirely in error. Even if the data are correct, the measurement might not be directly relevant to compliance. A number of different parameters need to be evaluated to accurately determine compliance. In the above case of the wet scrubber, a decrease from 30 inches H_2O to 24 inches H_2O may not be sufficient to conclude that there is a compliance problem. However, if this shift in pressure drop is accompanied by the changes listed below, there is more justification for requesting a compliance test or other actions:

- Increased plume opacity from the baseline level of 5% to the present level of 10% to 15%
- Increased outlet gas temperature from the baseline level of 135°F to the present level of 145°F
- Decreased scrubber liquor flow rate from 110 gpm to 60 gpm

All these changes are related to increases in particulate emissions. Accordingly, the inspector would be justified in concluding that the scrubber is not operating as well as it has in the past and that a new compliance test is needed.

The third principle of baseline analysis is that the inspection scope should include component failure information and general observations and should not be limited to operating data alone. In addition to data provided by plant instrumentation, general observations of the facility and interviews with plant personnel are often helpful in evaluating compliance. For example, large holes in the shell of an electrostatic precipitator or fabric filter are clearly a sign of air infiltration related performance problems on a negative pressure system. Severe rainout of solids-laden droplets from the stack of a wet scrubber clearly indicates mist eliminator failure. Perhaps less obvious, but equally important, is a sudden increase in the failure rate of individual components such as fabric filter bags, electrostatic precipitator support insulators, and scrubber nozzles. These conditions all either contribute to or are directly related to pollutant removal problems. Accordingly, these observations and this information should be included in the inspection report because they provide at least part of the basis for the decision regarding compliance status.

The fourth principle of baseline analysis is that inspection data and observations must be organized in a coherent fashion and evaluated during the compliance inspection. The inspection procedures discussed in this course are divided into basic and follow-up categories. The inspection points included in the basic category should be included in all inspections. These inspection parameters are fundamentally important to all types of air pollution control sources and are useful in identifying changes that might accompany increases in pollutant emissions. There are numerous follow-up inspection points for each different type of air pollution control device and source. Only those follow-up inspection points directly relevant to the suspected compliance problems are actually included in the scope of the inspection. It is possible that none of these are performed on a specific inspection, if the basic inspection data indicate that there have been no specific shifts from baseline conditions and that there are no apparent violations of the standards. Based on an evaluation of the basic data, the need for the specific follow-up inspection points can be determined.

By organizing the inspection data, it is also possible to identify data that are probably in error. Certain trends are expected in inspection parameters. For example, static pressure is expected to decrease in the direction of flow, as is the temperature of hot gases. Data that do not follow expected trends are likely in error. It is important to note that incorrectly operating instruments are common in the air pollution control industry due to erosive particles, sticky particles, condensable vapors, and corrosive compounds that are often present inside ductwork and air pollution control systems. Even the most conscientious operator can have a few of the instruments in an air pollution control systems malfunctioning at any one time. One aid to organizing the inspection data is the inspection flowchart. Preparation of inspection flowcharts is discussed in Chapter 7.

The fifth principle of baseline analysis is that inspectors must have the flexibility to exercise professional judgment during the inspection. It is impractical and potentially dangerous to restrict an inspector to a rigid checklist. Completion of the checklist can take the individual to areas in the plant that are unsafe or unhealthy. Furthermore, the rigid checklist might not address the specific follow-up issues that are most relevant to the compliance status of the facility. In these cases, the rigid checklist is even counterproductive. Inspectors must have the flexibility to investigate suspected compliance problems. For these reasons, the inspection procedures discussed in this manual include limited flexibility so that agency personnel can exercise their professional judgment.

The sixth principle of baseline analysis is that baseline analyses or other indirect compliance analyses are not generally used as a stand-alone basis for enforcement actions. Typically, emission tests using applicable reference methods are conducted when the baseline analysis indicates probable compliance problems. However, under the Credible Evidence Rule, it is possible that baseline analyses could be used as evidence in an enforcement action.

Limitations of Inspections

There are practical limits to the scope of an inspection:

- Time constraints that complicate full evaluation of issues
- Health and safety hazards in certain areas of the facility
- Lack of plant instrumentation

The most significant limitation to on-site inspections is time. There is usually not enough time to fully evaluate all the permitted emission units at moderate-to-large industrial facilities. Agency personnel must be skilled in prioritizing the work so that they use their limited on-site time efficiently. Prioritization starts with an effective file review to identify the most likely compliance issues. Agency personnel must be able to adjust the scope of the inspection while on-site to use their time wisely.

Health and safety issues can be a significant limitation. When these issues are recognized, agency personnel should adjust the inspection procedures and even the scope of the inspection as necessary to avoid potential problems. It should be request that the hazards be eliminated or minimized in the future so that such limits will not affect future visits. Agency personnel should, under no circumstances, ignore health and safety concerns involving themselves or plant personnel accompanying them.

Some inspections are limited by the lack of plant instrumentation. When the plant does not have the portable instruments necessary to provide the missing information, the scope of the inspection can be limited.

Review Problems

1. What are the purposes of a Level 2 inspection?

   a. Routine compliance evaluation
   b. Visible emission and/or odor surveillance
   c. Enforcement case development
   d. Complaint investigation
   e. Regulation development

2. What types of compliance analyses are not generally used alone as the basis for an enforcement case?

   a. Baseline analyses
   b. Comparison with similar units
   c. Direct comparisons

3. What is an example of a direct comparison-type compliance evaluation?

   a. Evaluation of wet scrubber pressure drop changes since an emissions test
   b. Evaluation of the plant's wet scrubber pressure drop against the pressure drops of similar units in the same geographical area
   c. Comparison of a boiler's fuel sulfur content against the regulatory limits
   d. Comparison of a boiler's fuel sulfur content against similar units in the same geographical area

4. A source barely passed a USEPA Method 5 particulate emission test. The scrubber pressure drop averaged 26 inches H_2O during this test. Six months later, an inspector notices that the scrubber pressure drop is now 18 inches H_2O. Is this unit out of compliance?

   a. Yes
   b. No
   c. Maybe

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CHAPTER 2

CYCLONES

Cyclone collectors use inertial force to separate particles from a rotating gas stream. There are two main types of cyclones: (1) large diameter cyclones and (2) small diameter multi-cyclones. Large diameter cyclones range in size from approximately 1 foot in diameter to more than 12 feet in diameter and are used for the collection of large diameter particulate matter that would otherwise settle out near the source and create a nuisance in the immediate area. Large diameter cyclones typically have operating pressure drops of 2 in. H_2O to 4 in. H_2O. Multi-cyclone collectors are groups of small diameter cyclones, typically 6 inches to 12 inches in diameter, which have better particulate removal capability than large diameter cyclones. The multi-cyclone units are used as stand-alone collectors on sources generating moderate-to-large particulate matter and are also used as pre-collectors to reduce the particle loading into fabric filters and electrostatic precipitators. Multi-cyclones typically have operating pressure drops greater than 4 in. H_2O.

Cyclone collectors are occasionally used as pre-collectors in air pollution control systems vulnerable to ember entrainment. While the embers do not damage cyclone components, the hoppers must be properly designed to prevent the accumulation of combustible material that could be ignited. Simmering fires in the hoppers could warp the tube sheet supporting the multi-cyclone tubes, crack welds and gaskets used to seal the tubes to the tube sheet, and damage the hopper casings.

Operating Principles

Cyclones use inertial force to separate particles from a gas stream. Because the inertial force is applied in a spinning gas stream, the inertial force is often termed centrifugal force. The first step in particle capture is the accumulation of particles along the inner wall of the cyclone due to centrifugal force.

For vertically oriented cyclones, settling the particles into a hopper is the second step in the overall process of particle capture. However, unlike electrostatic precipitators and fabric filters, there is little if any particle agglomeration to facilitate gravity settling, until the particles reach the cyclone tube discharge. The particles settle at a rate that is dependent partially on their terminal settling velocities. These settling rates are quite small for particles less than 10 micrometers in diameter. Fortunately, most particles in vertical cyclones also retain some momentum toward the hopper due to the motion of the gas stream passing through the cyclone. The combined effect of gravity settling and the momentum from the gas stream are sufficient to transport the particles from the cyclone wall to the cyclone tube discharge, and eventually to the hopper.

The third step in the overall particulate matter control process is the removal of accumulated solids from the hoppers. This is an especially important step because the cyclone outlets extend directly into the hoppers. The presence of high solids levels due to hopper discharge problems could block the outlets and make the cyclone entirely ineffective for particulate removal.

Several factors affect the performance of a cyclone collector. The more important ones are the size and mass of the particles, the gas velocity through the unit, the cyclone diameter, and the residence time of the gases in the cyclone. Since inertial forces are used to separate the particles from the gas stream, collection efficiency increases as the size and mass of the particle increases and as the gas velocity through the unit increases. Centrifugal force increases as the radius of turn decreases. As a result, smaller diameter cyclones are more efficient than larger diameter cyclones. Cyclones that have bodies and cones, that are long relative to their diameter have longer residence times and higher collection efficiencies. As a result of these factors and others, a range of performance can be achieved with cyclones, as shown in Figure 2-1.

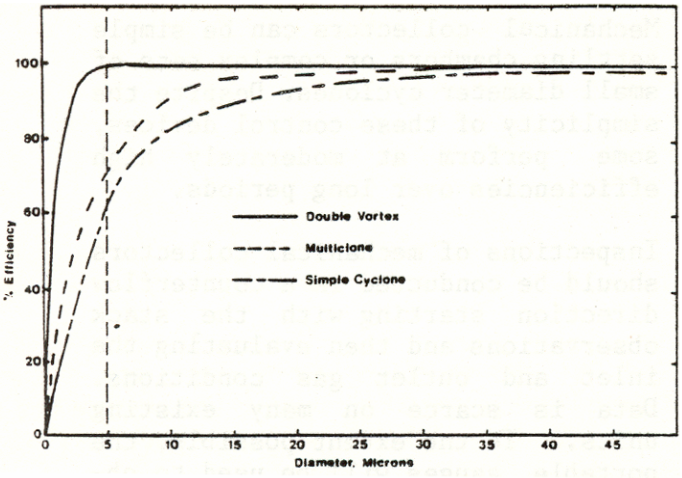


Figure 2-1. Cyclone fractional efficiency curves

In general, cyclones are not useful for the collection of sticky particulate matter. The main difficulties associated with these materials involve removal from the hoppers and build-up along the inner wall of the cyclone. Examples of hard-to-collect sticky material include partially polymerized oils, condensed high molecular weight organics, and ammonium sulfate and bisulfate particles. Sources emitting stringy material can cause build-up of material in the inlet vanes of multi-cyclone collectors. Partially blocked inlet spinner vanes do not generate the cyclonic flow patterns necessary for proper inertial separation.

Small diameter cyclones, including all multi-cyclone collectors, are vulnerable to severe erosion when treating gas streams having very large diameter particulate matter. Particles over twenty micrometers in diameter are very abrasive at the high tangential velocities achieved in the small diameter cyclones. The abrasiveness of particulate matter increases with the square of the particle diameter. Accordingly, cyclones handling particles in the twenty to more than one hundred micrometer size range can be vulnerable to high erosion rates.

Cyclone Systems

Large Diameter Cyclones

The inlet gas stream enters the large diameter cyclone through a tangentially mounted duct that imparts a spin to the gas stream. The inlet duct is usually at the top of the cyclone body, but large diameter cyclones may also have bottom inlets. Both arrangements are shown in Figure 2-2.

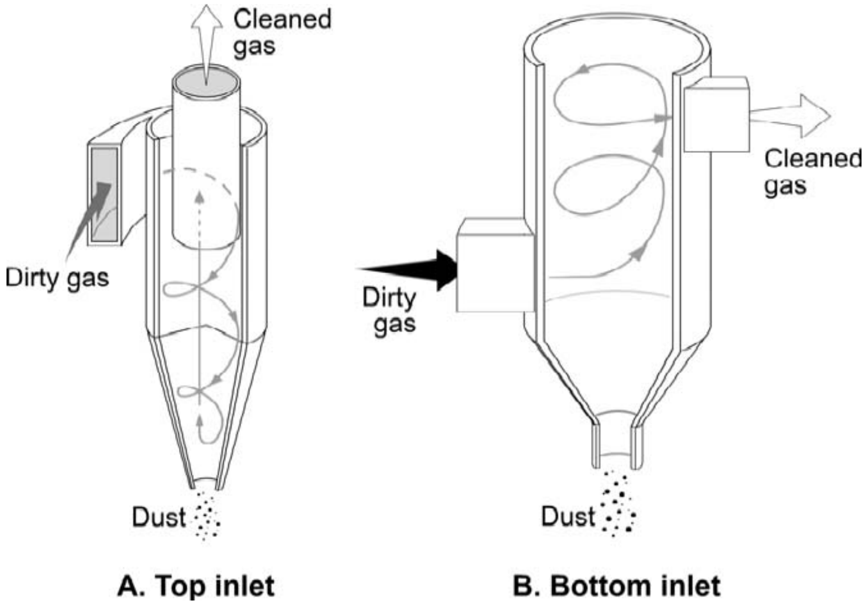


Figure 2-2. Large diameter cyclones

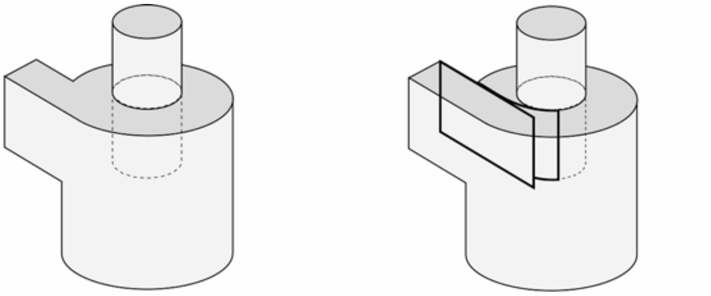
With the normal inlet gas stream velocity of 20 to 50 ft/sec, the gas stream spins approximately one-half to two complete rotations within the cyclone body of both types. An increase in the gas inlet velocity increases the spinning action of the gas stream, thereby improving inertial separation of the particles.

The gas flow pattern in a bottom inlet large diameter cyclone is relatively simple. The inlet gas stream begins to spin in the cyclone body because of the tangential inlet duct configuration. The gas stream forms an ascending vortex that rises up in the cyclone body to the outlet duct at the top of the unit. The particles that migrate across the gas streamlines settle by gravity when they approach the surface of the cyclone body where the gas velocity is low.

In the top inlet design, the gas stream spins in two separate vortices. The inlet stream creates an outer vortex due to the tangential location of the inlet duct and due to the presence of the outlet tube extension that prevents gas movement into the center of the cyclone body. As the gas stream passes down the cyclone body, it turns 180^{o} and forms an inner vortex that moves toward the gas outlet tube at the top of the cyclone. The outlet tube must extend sufficiently far into the cyclone to facilitate formation of the outer vortex and to prevent a short-circuit path for the gas stream.

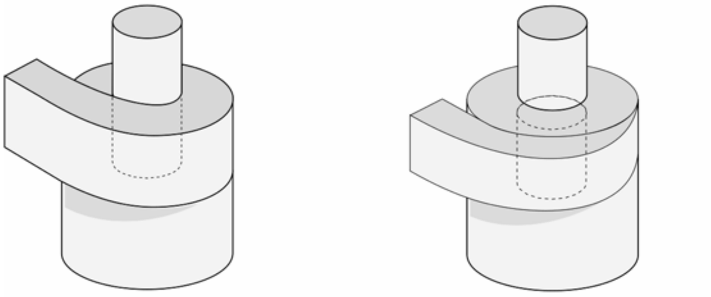
The particles that have migrated toward the outer portion of the outer vortex break away from the gas stream when it turns 180^{o} to enter the inner vortex. Due to their inertia, the particles continue to move downward toward the cyclone hopper as the gas stream turns from the outer vortex to the inner vortex. The movement of the particles toward the hopper is controlled partially by inertial forces. The force of gravity also assists in particle movement toward the hopper.

Top-inlet, large-diameter cyclones can have a number of different inlet designs, as shown in Figure 2-3. The most common design is the simple tangential inlet (A). The deflector vane (B) reduces the gas stream turbulence at the inlet and can reduce the overall pressure drop. However, the deflector vanes can also impair vortex formation and thereby reduce particulate collection. Helical inlets (C) have been used in an attempt to reduce cyclone pressure drop and to improve performance. Involute entries (D) can also reduce turbulence-related pressure drop at the inlet. However, they usually provide improved efficiency due to the manner in which the outer vortex develops.



A. Tangential entry

B. Tangential entry
with deflector vanes

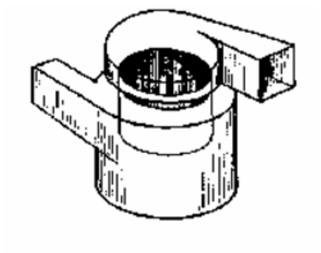


C. Helical entry

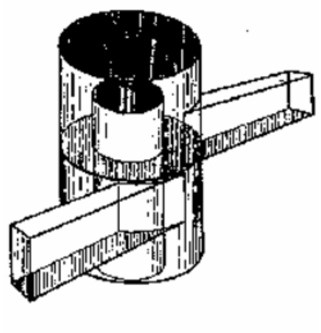
D. Involute entry

Figure 2-3. Types of cyclone inlets

The outlet gas tube is also an important consideration in the design of a large diameter cyclone. Some of the energy due to the radial motion of the ascending gases can be recovered by scroll devices (A) or outlet drums (B) placed on top of the outlet tube. These two cyclone enhancements, which are shown in Figure 2-4, are essentially flow straighteners that can effectively reduce the overall pressure drop across the unit without affecting the particulate matter removal efficiency.



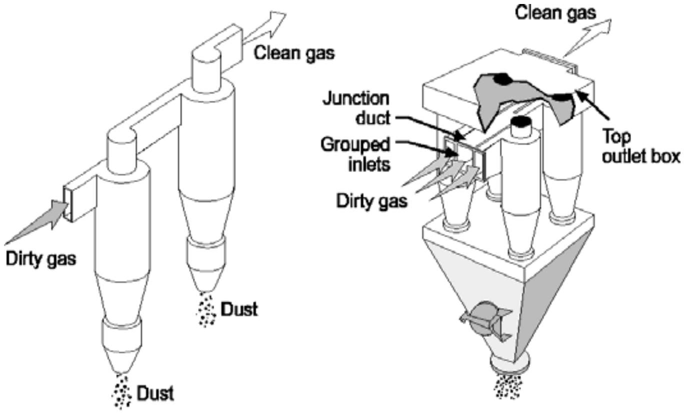
A. Involute scroll outlet



B. Outlet drum

Figure 2-4. Special outlet configuration for large diameter cyclones

Large diameter cyclones can be used in series or parallel arrangements in order to increase particulate matter removal efficiency or to increase gas flow capability. A series arrangement (A) of two cyclones of equal size and a parallel arrangement (B) of four cyclones of equal size are shown in Figure 2-5.



A. Two cyclones in series

B. Four cyclones in parallel

Figure 2-5. Series and parallel arrangement of cyclones

The dust discharge system for a large diameter cyclone is similar to that used in other dry particle collectors and consists of a hopper for receiving the collected solids and a solids discharge valve that allows solids to be removed from the hopper without letting air in or out of the system. Four common types of solids discharge valves are shown in Figure 2-6. The slide gate (A), the rotary discharge valve (B), and the double flapper valve (D) are all capable of providing an airtight seal. The screw conveyor arrangement (C) cannot provide an airtight seal unless a solids discharge valve is placed between the bottom of the cyclone and the screw conveyor.

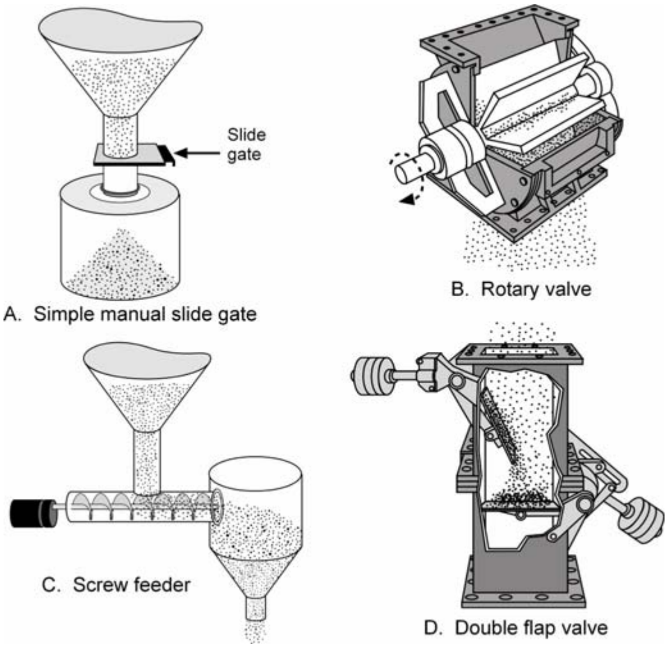


Figure 2-6. Types of solid discharge valves

Air infiltration into negative pressure cyclones, either through the solids discharge valve or through holes in the casing, can significantly reduce collection efficiency by disrupting the vortex and by entraining particles and carrying them toward the outlet flow. Also, collection of very large particles in high velocity vortexes can be difficult because of the tendency for the particles to bounce off the wall.

Small Diameter Multi-Cyclones

The particulate matter removal capability of a small diameter cyclone is greater than that of a large diameter cyclone because the gas stream is forced to spin in smaller vortices, imparting greater inertial force to the particles. However, it is not possible to handle a large gas volume in a single small diameter tube. In order to treat the entire gas stream, a large number of small diameter tubes can be used in a single collector in which the tubes are in a parallel arrangement. Multi-cyclone collectors have cyclone tubes that range in size from 6 to 12 in. in diameter. A small multi-cyclone collector, such as the one shown in Figure 2-7, can have as few as 16 tubes. Large units may have several hundred tubes.

These units are divided into three separate areas by two tube sheets. The *dirty gas tube sheet* is mounted horizontally, supporting the cyclone tubes and separating the inlet gas stream from the hopper area of the unit. The *clean gas tube sheet* stair-steps down from front to back at approximately a 45^o angle, dividing the inlet gas stream from the treated outlet gas stream. The outlet gas tubes from each of the cyclones pass through the clean gas tube sheet.

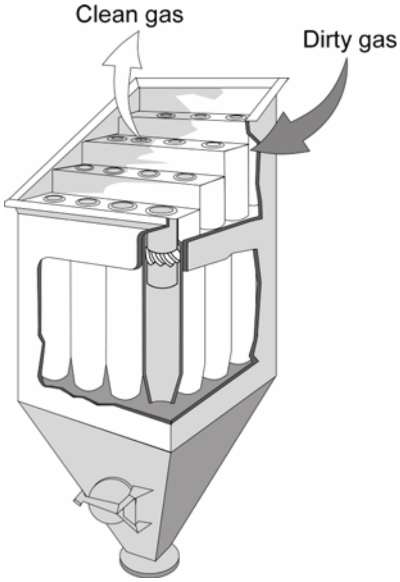


Figure 2-7. Multi-cyclone collector

Solids discharge valves are necessary under each of the multi-cyclone hoppers to prevent air infiltration upward through the hoppers and into each of the cyclone tubes. This air would impair cyclone particulate matter collection by disrupting the vortex of the inlet gas stream. Also, particles already in the hoppers could be entrained in the upward flowing air stream and driven out of the cyclone tube toward the outlet gas plenum. Air infiltration through broken welds, access hatches or corroded panel below the dirty gas tube sheet will have a similar effect on performance.

A small diameter cyclone tube used in multi-cyclone collectors is shown in Figure 2-8. The gas stream entering the cyclone is spun as it passes over the turning vanes mounted at the inlet. The gas stream turns one-half to three times depending on the gas flow rate and the length and diameter of the cyclone. As in the case with large diameter cyclones, particles move toward the wall of the cyclone and subsequently fall by gravity. The gas stream turns 180^o and passes out the center tube.

A variety of mechanical problems can reduce the performance of the small diameter cyclone tubes. The particulate-laden inlet gas stream can erode holes in the outlet tubes that pass through the inlet gas plenum. Once these holes develop, they can increase in size rapidly due to the static pressure drop across the unit. This will result in an increase in visible emissions and a decrease in static pressure drop, if the holes become large enough.

Increased visible emissions can also occur because of leaks in the gasketed or welded joints between the outlet tube and the clean gas tube sheet. Since the size of these leaking areas is typically small, there is usually no effect on static pressure drop.

Material that deposits on the turning vanes of the cyclone tubes can seriously disrupt the vortex. If the gas stream does not spin properly in the cyclone body, the collection efficiency will be significantly reduced, increasing visible emissions. These deposits also increase the static pressure drop through the collector by reducing the area available for flow through the turning vanes. Similarly, eroded turning vanes will disrupt the vortex in the cyclone tube and reduce collection efficiency. The static pressure drop will be reduced if the inlet turning vanes are significantly eroded.

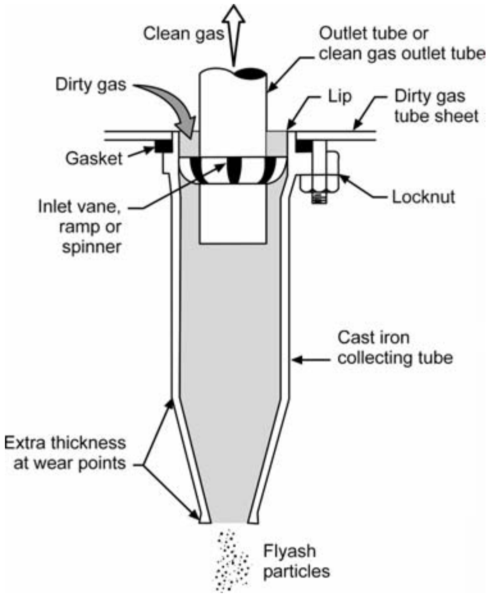


Figure 2-8. Cyclone tube used in multi-cyclone collector

Deposits that block the dust discharge into the hopper can completely impair the affected tubes. Collected particles that would normally exit the cyclone tube are reentrained in the spinning gas and discharged. These deposits usually occur when the hopper solids accumulate and block the cyclone dust outlets. However, after the solids are removed from the hopper, hardened deposits can remain at the tube outlet and continue to impair performance. There will generally be no effect on the static pressure drop.

Deposits that accumulate on the inner surfaces of the cyclone body can also reduce performance. These deposits increase wall roughness and increase turbulence near the wall. Particles attempting to move out of the gas vortex can bounce off these deposits and become reentrained in the gas stream. Significant deposits would result in an increase in static pressure drop; however, even modest deposits can reduce collector performance.

In large scale multi-cyclone collectors, the gas flow resistance of the outlet tubes can create an undesirable gas flow pattern called cross-hopper recirculation. As shown in Figure 2-9, the treated gas stream in the rows of cyclone tubes near the inlet can exit the bottom of the tube instead of the top, travel across the upper portions of the hopper, and pass upward through cyclone tubes near in the back rows. This is possible due to the low gas flow resistance of the short outlet tubes for the cyclones on the back rows and the high gas flow resistance of the long outlet tubes for the inlet rows.

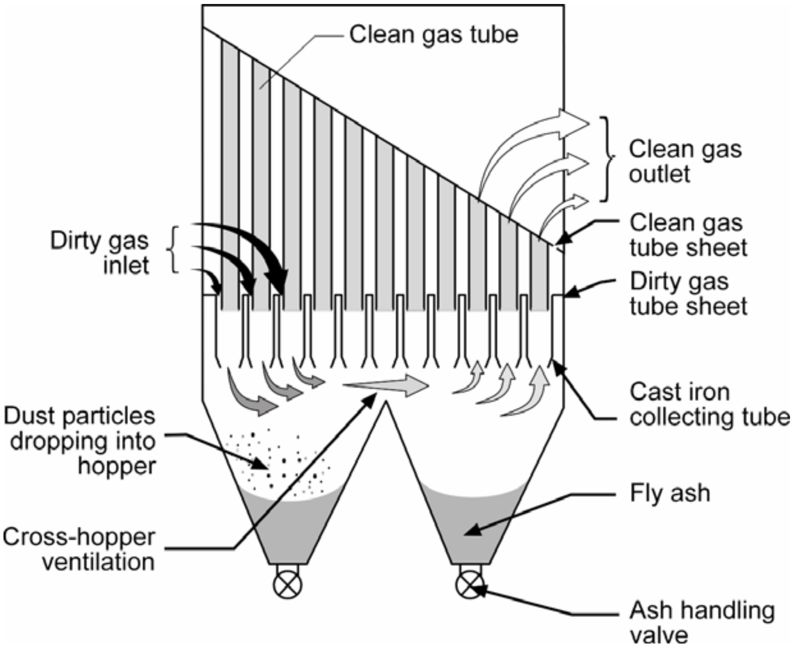


Figure 2-9. Cross hopper recirculation

Particulate matter emissions are increased substantially by cross-hopper recirculation because the gas stream passing through the hopper reentrains dust from the hopper and because this gas disrupts the vortex in the cyclone tube it reenters. Cross-hopper recirculation can be avoided by designing the outlet tubes to be of equal length throughout the collector or by placing baffles in the hopper to prevent gas flow from the front to the back of the unit.

Inspection

Cyclone collectors are simple units with limited instrumentation. Most of the data and information necessary to evaluate performance are obtained during the walkaround inspection. With the possible exception of static pressure drop data, the operating conditions are not usually monitored in the control room of the process served by the collector.

Unlike the more complicated control systems, the inspection procedures for cyclones are not divided into basic and follow-up lists.

- Visible emissions
- Fallout of large diameter particles (large diameter cyclones)
- Static pressure drop

- Gas inlet and outlet temperatures
- Gas inlet and outlet oxygen concentrations
- Air infiltration
- Dents or weld failures (large diameter cyclones)
- Solids discharge problems
- Internal inspection reports

Level 2: Visible Emissions

The stack visible emissions should be observed for at least 6 to 12 minutes using USEPA Reference Method 9 or an equivalent method. High opacities could indicate either multi-cyclone performance problems or a shift in the particle size distribution due to operational problems at the process source.

Large diameter cyclones are not designed to control particulate matter in the size range that exhibits significant opacity. Large particles have very little opacity, even at high mass loadings in the gas stream. The presence of a high opacity plume usually indicates that there is a high concentration of small particles and that the large diameter cyclone is an inappropriate control device for the process source.

Level 2: Fallout of Large Diameter Particles (Large Diameter Cyclones)

Large particles collected in large diameter cyclones have high terminal settling velocities. If these particles penetrate the cyclone, they usually deposit on adjacent surfaces or fall out in the immediate vicinity of the cyclone discharge. The presence of deposition patterns or piles of material near the discharge usually indicates that the cyclone is not working properly.

Level 2: Static Pressure Drop

As shown in Figure 2-10, the static pressure drop varies with the square of the gas flow rate and may be used to evaluate flow rate changes. However, the static pressure drop observed during the inspection must be corrected to the baseline flow rate condition, using the following equation, before it can be compared to the baseline value.

$$\Delta P_{\text{expected}} = \Delta P_{\text{baseline}} \left(\frac{Q_{\text{inspection}}}{Q_{\text{baseline}}} \right)^2 \qquad (2\text{-}1)$$

The static pressure drop expected as a result of the flow rate change would be compared to the baseline value. If there is no difference, then the static pressure drop change is due solely to the flow rate change. If there is a difference, then there is something else affecting the static pressure drop in addition to the flow rate change. If flow rate information is not available to make the correction, a parameter that changes proportionally with flow rate can be used. For example, with a boiler it is reasonable to assume that the flow rate varies directly with the steam production rate.

Plugging of some of the inlet turning vanes in a multi-cyclone collector is probable if the static pressure drop is well above the baseline data. Deposits in this area prevent the formation of a proper vortex, and particulate matter emissions through the affected cyclone tubes are high. The static pressure drop increases because the area for gas flow is smaller because of these deposits.

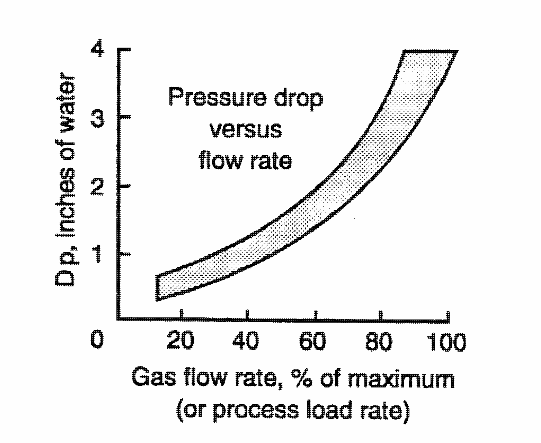


Figure 2-10. Static pressure drop of a cyclone collector

Erosion of the turning vanes will also prevent the formation of a proper vortex and cause increased emissions. In addition eroded turning vanes will cause reduced static pressure drop. Erosion of the outlet tubes is another possible problem if the static pressure drop has decreased. Gas short-circuiting through the unit will also cause increased visible emissions. The static pressure drop is low in this case because the gas does not pass through the turning vanes. Likewise, significant air infiltration into the hopper will cause reduced static pressure drop, since the quantity of gas going through the turning vanes is reduced.

Level 2: Gas Inlet and Outlet Temperatures

A significant increase in the difference between inlet and outlet gas temperatures, or a gas temperature difference greater than about 25°F, indicates air infiltration into the unit. Usually, temperature monitors are not placed immediately before and after the collector, so data must be obtained using available upstream and downstream gauges. For example, there are often temperature gauges at the economizer outlet of a boiler and at the induced draft fan inlet. The temperature drop between these two instruments should be compared with baseline data to determine if air infiltration has increased since the last inspection.

Changes in gas flow rate should be considered in evaluating temperature data. This is necessary because the gas temperature drop across the unit is a function of the gas flow rate. At high gas flow rates, the temperature drops are slightly lower than at low gas flow rates.

Level 2: Gas Inlet and Outlet Oxygen Concentrations

For combustion sources, air infiltration problems in cyclone collectors can be evaluated using oxygen concentration data. Many combustion sources have an oxygen monitor downstream of the economizer. If there is an additional oxygen monitor in the stack, the change in oxygen concentration between the two locations can be checked. If the oxygen level increases more than 0.5 percent (i.e. from 6 percent to >6.5 percent), air infiltration is probable.

Level 2: Air Infiltration

When the temperature drop across the unit is above the baseline range, air infiltration is highly probable somewhere between the two temperature gauges. Air infiltration may directly affect the efficiency of the cyclone by disrupting the vortex. However, it almost always reduces the air flow from the source, possibly resulting in fugitive emission losses. The most common sites of air infiltration include the following:

- Induced draft fan
- Solids discharge valves and hopper poke holes
- Hopper access hatches
- Side wall welds
- Ductwork expansion joints

Determining the specific location of these leaks is not the responsibility of the agency inspector. Cyclones are often mounted in areas that are difficult to reach or near hot surfaces. Furthermore, the walls of collectors serving some processes are hot. Checks for audible air infiltration are limited to units with safe and convenient access to the equipment.

Level 2: Dents or Weld Failures (Large Diameter Cyclones)

If it is safe to approach a large diameter cyclone, the body and conical sections should be checked for large dents or weld failures. These problems are often caused by operator inflicted hammer blows in order to dislodge solids building up inside the unit. The dents disrupt the vortex and provide a surface for particles to bounce back into the gas stream. Weld failures provide a location for air to infiltrate negative pressure units and impair the vortex or serve as a location for fugitive emissions from positive pressure units.

Level 2: Solids Discharge Problems

Solids bridging over the cyclone discharge can result in the reentrainment of particles attempting to settle into the hopper and is usually caused by overflow of the hopper or receiving enclosure that is used underneath the cyclone. In large diameter cyclones, moisture condensation on uninsulated metal walls of the body and conical section can also contribute to solids discharge problems.

Air infiltration through the solids discharge valve prevents solids discharge from the cyclone system, reentrains dust, and disrupts the cyclone vortex. In some cases, air can be heard rushing in through poorly sealed solids discharge valves.

Internal Inspection Reports

There are a variety of multi-cyclone problems that can not be easily detected as part of the Level 2 inspection:

- Deposits on the inside surfaces of the cyclone tubes
- Plugging of the bottom of the cyclone tubes
- Cross hopper recirculation

An internal inspection is needed to see these conditions or the symptoms of these conditions. Internal inspection reports prepared by plant maintenance personnel should be requested and reviewed if there have been chronic emission problems from the source. Agency personnel should not conduct internal inspections of air pollution control equipment.

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Review Problems

1. A Level 3 inspection is being conducted on a multi-cyclone collector serving a coal fired boiler. The Level 1 inspection indicated that the visible emissions have increased from the previous range of 12% to 15% to a range of 25% to 35% at the present time. There is no instrumentation on the collector. The following data were obtained by plant operators using portable instruments at the inlet and outlet ports of the collector.

	Inlet	Outlet
Static Pressure, in. H_2O	-5	-9
Gas Temperature, ^oF	412	403
Oxygen, %	7.5	8.0
Carbon Dioxide, %	11.0	10.9

During the previous inspection, the observed pressure drop was 3.8 in. H_2O, and the boiler steam rate was 100,000 pounds per hour. Now the steam rate of the boiler is 57,000 pounds per hour. What are possible causes of the increased opacity?

2. Level 2 inspection data for a multi-cyclone collector serving a bark boiler are summarized below. What are possible causes of the increased opacity?

	Inspection Data	Baseline Data
Visible Emissions, %	35	10
Static Pressure Drop, in. H_2O	2.5	3.5
Inlet Gas Temperature, ^oF	508	505
Outlet Gas Temperature, ^oF	501	500
Boiler Load, lb/hr	45,000	41,000
Boiler Draft, in. H_2O	-0.15	-0.10
Fuel Type	Bark	Bark

3. A large diameter cyclone is being used to collect wood chips and sawdust. Material is penetrating the cyclone and falling out near the discharge, despite the fact that it appears to be sufficiently large to be collected in the unit. The static pressure drop is presently 2.0 in. H_2O. This is close to the value of 2.2 in. H_2O observed during the last inspection. There are no obvious dents or side wall weld failures on the unit. What are possible explanations for the increased emissions?

4. The following Level 2 data were obtained during the inspection of a multi-cyclone collector serving a bark and oil fired power boiler at a pulp mill. What are possible causes of the increased opacity?

	Inspection Data	Baseline Data
Visible Emissions, %	50	10
Static Pressure Drop, in. H_2O	3.5	3.7
Inlet Gas Temperature, ^oF	510	500
Outlet Gas Temperature, ^oF	480	495
Boiler Load, lb/hr	44,000	40,000
Boiler Draft, in. H_2O	-0.05	-0.10
Fuel Type	Bark	Bark
Overfire Air Pressure, in. H_2O	25	28

CHAPTER 3

FABRIC FILTERS

Fabric filters, also referred to as *baghouses*, are capable of high-efficiency particulate matter removal in a wide variety of industrial applications. Uses for fabric filters have steadily expanded since the 1960s, because of the development of new, highly effective fabrics capable of efficiently collecting particles over the size range of 0.1 μm to 1,000 μm. This particle collection efficiency, even in the difficult-to-control range of 0.2 μm to 0.5 μm, is due to the multiple opportunities for a particle to be captured as it attempts to pass through a dust cake and fabric and the multiple modes of particle capture that occur within the dust cake and fabric. These modes of capture include impaction, Brownian diffusion, and electrostatic attraction.

The conceptual simplicity of fabric filters belies the complexity of the equipment design and the operating procedures necessary to achieve and maintain high particulate removal efficiencies. Serious performance problems can develop relatively rapidly. Holes and tears in the bags can develop due to chemical attack, high temperature excursions, or abrasion and flex damage. Cleaning system problems can result in excessive static pressure drops. Particles can also seep through the dust cake and fabric due to improper design or cleaning.

This chapter emphasizes four of the major types of fabric filters: shaker, reverse air, pulse jet, and cartridge. There are many other types that are not explicitly discussed in this manual. However, the operating principles and inspection procedures discussed are generally applicable to all types of fabric filters. All fabric filters designs typically operate with a static pressure drop of about 4-6 in. H_2O.

Operating Principles

Particle Collection

Multiple mechanisms are responsible for particle capture within dust layers and fabrics. Impaction is an inertial mechanism that is most effective on particles larger than about 1 μm. It is effective in fabric filters because there are many sharp changes in flow direction as the gas stream moves around the various particles and fibers. Unlike some types of particulate collection devices, there are multiple opportunities for particle impaction due to the numbers of individual dust cake particles and fabric fibers in the gas stream path.

Brownian diffusion is moderately effective for collecting submicrometer particles because of the close contact between the gas stream and the dust cake. The particle does not have to be displaced a long distance in order to come into contact with a dust cake particle or fiber.

Furthermore, the displacement of submicrometer particles can occur over a relatively long time as the gas stream moves through the dust cake and fabric.

Electrostatic attraction is another particle collection mechanism. Particles can be attracted to the dust layer and fabric due to the moderate electrical charges that accumulate on the fabrics, the dust layers, and the particles. Both positive and negative charges can be generated, depending on the chemical make-up of the materials. Particles are attracted to the dust layer particles or fabric fibers when there is a difference in charge polarity or when the particle has no electrical charge.

Sieving of particulate matter can occur after the dust cake is fully established. The net result of the various types of collection mechanisms is shown in Figure 3-1, which indicates relatively high removal efficiency levels even in the difficult-to-control particle size range of 0.2 μm to 0.5 μm.

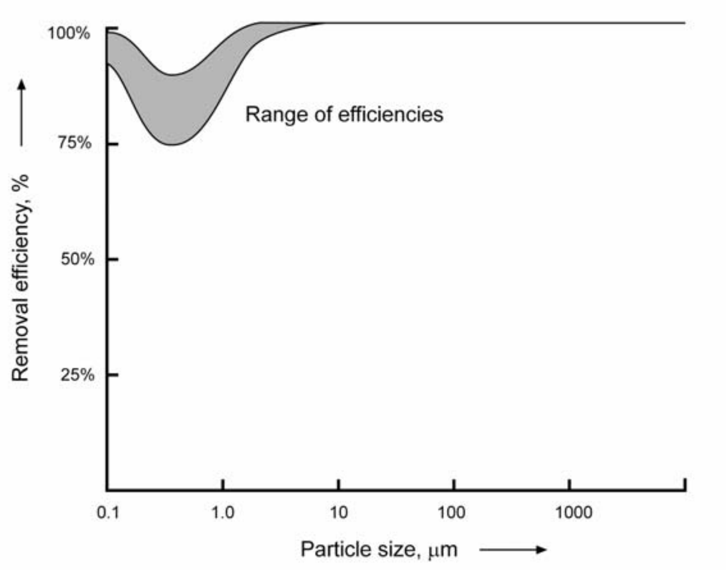

Figure 3-1. Fabric filter fractional efficiency curve

For new bags, the initial particle removal efficiency is not nearly as high as suggested in Figure 3-1. Time is needed to establish residual dust cakes on the surfaces of the fabric. These particles provide the foundation for the accumulation of the operating mode dust cake, which is ultimately responsible for the high efficiency particulate matter removal. The particles on the fabric surface are termed the *residual dust cake* because they remain after normal cleaning of the bag.

The fractional efficiency curve shown in Figure 3-1 applies only when an adequate dust cake has been established. Immediately after cleaning, patchy areas of the fabric surface may be exposed. Only the residual dust cake remains in these patchy areas. Depending on the particulate matter concentration, it may take several seconds to a minute for the dust cake to repair over these patchy areas and thereby reduce emissions. During the time that the dust cake is being reestablished, particle removal efficiency can be low, especially for small particles. For this reason, excessive cleaning intensity, frequency, or duration can increase particulate emissions.

Particulate matter emissions can be increased dramatically by related phenomena such as particle seepage and pore collapse. Both phenomena are related to the quantity of gas passing through a given area of the cloth. This gas flow rate is normally expressed as the air-to-cloth ratio, as defined in Equation 3-1:

$$\text{A / C Ratio}\left(\frac{\text{ft}}{\text{min}}\right)=\frac{\text{Actual Gas Flow Rate}\left(\frac{\text{ft}^3}{\text{min}}\right)}{\text{Fabric Surface Area}\left(\text{ft}^2\right)} \tag{3-1}$$

As the air-to-cloth ratio increases, the localized gas velocities through the dust cake and fabric increase. At high air-to-cloth values, some particles, especially small particles, can gradually migrate through the dust layer and fabric. This is possible because dust particles within the cake are retained relatively weakly. After passing through the dust cake and fabric, these particles are re-entrained in the clean gas stream leaving the bag. Some of the factors that increase the tendencies for particle bleed-through include the following:

- Small particle size distribution
- Fabric flexing and movement
- Small dust cake quantities

Pore collapse in woven fabrics is also caused by high air-to-cloth ratios. At high air-to-cloth ratios, the forces on the particle bridges that span the holes in the fabric weave can be too large. Once a bridge is shattered and pushed through the fabric, an uncovered hole is created. The gas stream channels through this low resistance path through the bag.

The net result of seepage and pore collapse is increased particulate matter emissions at high air-to-cloth ratios. The general nature of the relationship is shown in Figure 3-2. The effect is relatively minor until a threshold air-to-cloth ratio is reached. Above this value, emissions can increase rapidly. A baghouse that is severely undersized for the gas flow being treated (high air-to-cloth ratio) can have abnormally low removal efficiency.

Emissions Through Holes, Tears and Gaps

Low resistance paths for gas flow are created when holes or tears develop in the bags. Gaps in bag seals or in the welds around the tube sheet also create paths for unfiltered gas to pass through the baghouse. The fraction of the total gas stream passing through these openings will increase until the pressure drop across the opening is equivalent to the average pressure drop across the undamaged bags in the compartment.

It is important to note that holes, tears, and gaps can allow significant particulate emissions without major changes in the observed static pressure drop across the fabric filter. Because of the balancing of the gas flows between the opening and the undamaged cloth, the overall static pressure drop does not decrease dramatically. It is often difficult to identify these slight drops since the static pressure drop across a baghouse is not usually a constant value.

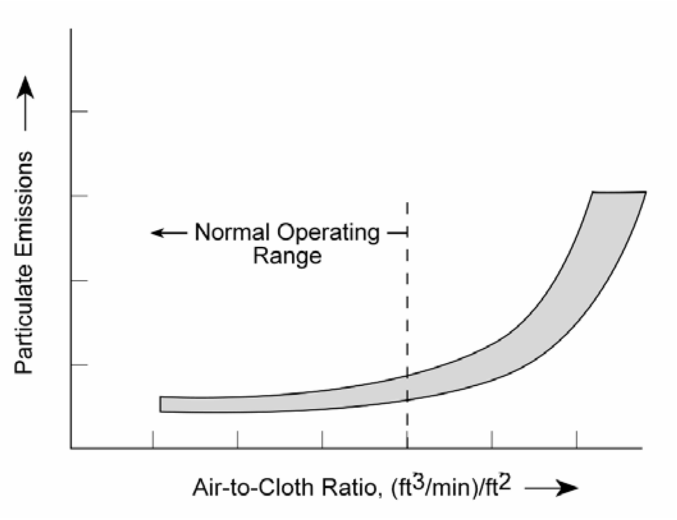

Figure 3-2. Emissions as a function of air-to-cloth ratio

Filter Media Blinding and Bag Blockage

Water droplets in the dust cake can severely increase the resistance to gas flow. At the very least, the water can fill the voids in the dust cake where the gas would normally flow. If the quantity of water is high, the dust cake can be packed tightly together or even form a muddy layer. At this point, the affected portion of the bag is essentially impervious to gas flow. This is termed *fabric blinding*.

Water is not the only substance that can cause blinding, but it is one of the most common. Condensed water droplets can be entrained from the process being treated, or they can be carried in with the compressed air in pulse jet fabric filters. Excessive gas cooling in baghouses serving combustion sources and other sources generating high vapor concentrations can cause water condensation in the dust cakes.

Another common blinding agent is the lubricating oil often present in pulse jet fabric filter compressed air supplies. The oil droplets can deposit in the upper, clean side surfaces of the bags and prevent gas flow. The entire inlet gas stream must, therefore, be filtered in the unaffected lower portions of the pulse jet bag.

Wet materials are not the only blinding agents. Submicrometer particles can be driven deep into the fabric if the bag is exposed to a high velocity particulate-laden gas stream before a protective residual dust layer is present. This type of blinding often occurs when a new bag is installed in a compartment with a large number of seasoned bags. Due to the resistance caused by the seasoned bags' residual dust cakes, the gas velocities through the new bag are excessively high. Submicrometer particle blinding can also occur following the installation of new bags at sources that generate high concentrations of submicrometer particulate matter.

In these cases, the new bags can be conditioned prior to service by exposing them to resuspended large diameter particles.

Hopper overflow or solids bridging in hoppers can cause high dust levels. A portion of the filtering area will be inadvertently isolated if these solids block some of the bag inlets in shaker or reverse air baghouses. This occurs most often around the exterior walls of the hoppers where cooling of the solids is most severe. If moisture is present, these deposits can become crusty and remain even after the solids in the hopper have been removed. Proper hopper design and frequent emptying are important in minimizing the occurrence of this condition.

The net effect of these operating problems is to remove fabric area from service. This increases the air-to-cloth ratio in the unaffected fabric and can lead to seepage or pore collapse problems. The higher air-to-cloth ratios will also result in increased pressure drop across the baghouse.

Fabric Filter Applicability Limitations

There are several limitations that should be considered when working with fabric filters. Clogging or blinding of the fabric can occur when the particulate is sticky or if moisture is present. Blinding can also occur when large quantities of small particles (0.1 μm to approximately 2 μm) pass through new bags that are not protected by a dust cake. Fabric filters can be designed to operate with moderate blinding conditions. However, they may not be appropriate for very sticky conditions.

Excessive quantities of large particles moving at high velocities can be abrasive and cause erosion of the fabric, especially near the bottoms of the bags. The gas velocities are usually highest near the bottom because of the way the particulate-laden gas stream enters the baghouse. Large particles are the most abrasive and can strike exposed fabric yarns and fibers with considerable force.

Fires and explosions can occur in fabric filters due to the high concentration of dust on the bags and in the upper elevations of the hoppers. These fires and explosions can be ignited by embers from process equipment and even by static electricity generated inside the baghouse. Baghouses can be designed to minimize the risks of fires and explosions. However, when the risk is very high, alternative particulate control systems or combinations of control systems may be necessary.

There are gas temperature limits to the application of fabric filters because of the limits of the fabric itself. At high temperatures, the fabric can thermally degrade, or the protective finishes can volatilize. Accordingly, fabric filters have usually been limited to gas temperatures below approximately 500°F, which is the maximum long-term temperature of the most temperature-tolerant fabric. Recently commercialized fabrics can tolerate much higher temperatures.

Fabric Filter Systems

One way of distinguishing between different types of fabric filter collectors is the method used to clean the filter material. As dust builds up on the filter surface, the pressure drop across the filter increases. In order to avoid excessively high pressure drops, the filter material is cleaned periodically. The most common methods of cleaning are shaking, reverse air, and reverse pulse or pulse jet.

Another way of distinguishing between different types of fabric filter collectors is based on the way they operate. The three modes of operation are intermittent, periodic and continuous. Intermittent collectors are used on processes that operate intermittently. When the process shuts down, the collector goes through a cleaning cycle and then shuts down and waits for the next processing cycle before starting up. Most intermittent collectors clean by shaking, but could also clean by reverse pulse.

Periodic collectors are used on processes that operate continuously. The total fabric is divided between several modules or compartments. This allows a compartment to be taken off line and cleaned, while the remaining compartments stay on line to provide filtration. Most periodic collectors clean by shaking or reverse air, but could also clean by reverse pulse.

Continuous collectors are also used on processes that operate continuously, but they do not have compartments that shut down for cleaning. Instead, individual rows of bags in the collector are cleaned, while the remaining bags continue to provide filtration. Continuous collectors usually clean by reverse pulse, but could also clean by reverse air.

Shaker Fabric Filters

Figure 3-3 shows the typical components of a shaker cleaned fabric filter. The tube sheet provides the seal which separates the bags in the upper portion of the collector from the hoppers. The open bottoms of the bags are attached to the tube sheet and the closed tops are attached to the shaker mechanism. The dust laden gases enter through the hopper, where some of the larger particles in the gas stream settle out. Most of the dust will be carried by the gas stream as it passes up through the filter bag and will be deposited on the inside of the bag. The cleaned gases then exit the collector through an outlet duct or through louvers, if the collector is operating under positive pressure. Shaker collectors use woven fabrics and generally operate with an air-to-cloth ratio of 2-4 ft/min.

During the cleaning cycle, gas flow to the collector is stopped. In compartmentalized collectors, this is accomplished with a shut-off damper in the inlet duct, for a positive pressure unit, or in the outlet duct, for a negative pressure unit. It is critically important that this damper seals effectively, so that there is no air flow through the compartment during cleaning. A leaking damper will cause the bag to remain inflated during shaking and will significantly reduce the cleaning effectiveness. It may also cause particles to be driven through the fabric and carried out of the collector.

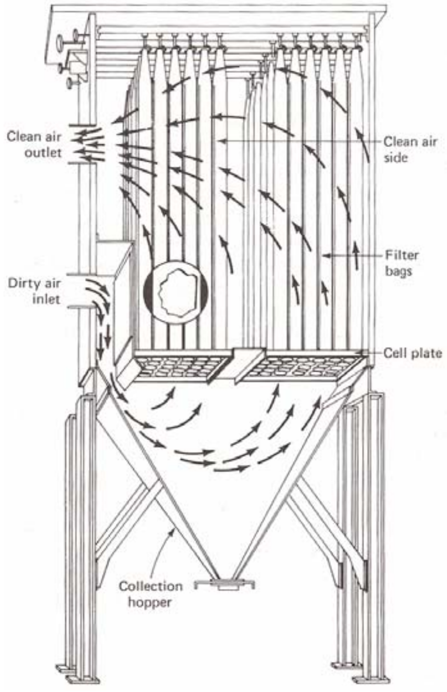

Figure 3-3. Shaker fabric filter

After a null period of 15-30 seconds to allow the bags to relax, the bags are mechanically shaken, and the dislodged dust cake falls into the hopper. This type of cleaning usually involves the use of a rocker-arm lever assembly to produce a motion at the top of the filter bag that is roughly horizontal. However, other shaker mechanisms may impart vertical motion or may follow an arc. The bags are usually installed slightly slack to be able to accommodate the shaking motion without tearing or pulling loose from the tube sheet. Typically, the bags are shaken from 10 to 100 cycles at a rate of 1 to 5 cycles per second with an amplitude of up to 2 inches. After shaking is completed, a second null period of 1-2 minutes is provided to allow the dust to settle before the collector or compartment is returned to service. In compartmentalized collectors, the cleaning interval for each compartment is typically 30 minutes to 2 hours.

Reverse Air Fabric Filters

The construction and operation of reverse air fabric filters is very similar to shaker collectors. There is a tube sheet that separates the bags in the upper portion of the collector from the hoppers. The open bottoms of the bags are attached to the tube sheet and the closed tops are attached to an upper support structure (see Figure 3-4). The dust laden gases enter through the hopper and pass up through the filter bag, depositing the dust cake on the inside of the bag. The cleaned gases then exit the collector through an outlet duct. Reverse air collectors usually use woven fabrics; however, membrane bags and felted bags may be used in some applications. They typically operate with an air-to-cloth ratio of 1½-3½ ft/min.

Figure 3-4. Reverse air collector hangers and tube sheet attachment

The main components of the cleaning system for a reverse air fabric filter are shown in Figure 3-5. The system consists of one or more reverse air fans, a set of dampers to control gas flow to each compartment, and instrumentation to monitor compartment conditions before and after cleaning.

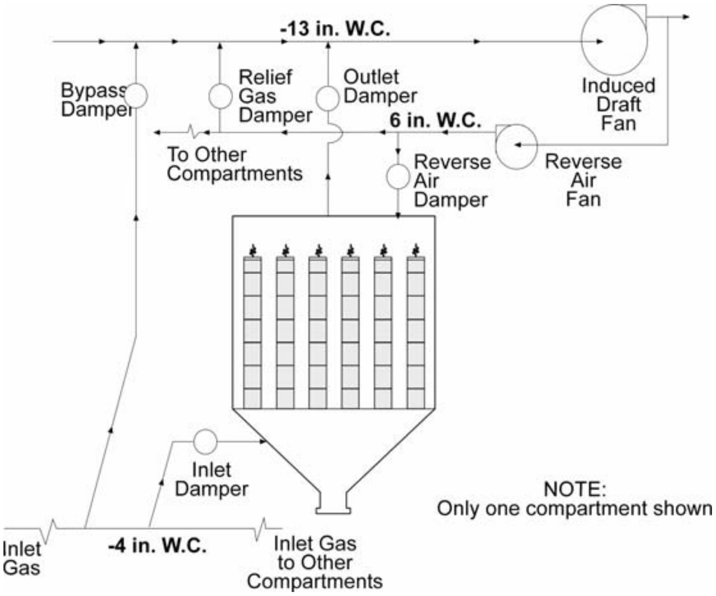

Figure 3-5. Reverse air cleaning system

The cleaning cycle is initiated by closing the outlet damper on the compartment to be cleaned, stopping the gas flow into the compartment. After a null period of 15-30 seconds to allow the bags to relax, the reverse air damper is opened. For a period of 30 seconds to a few minutes, filtered gas is passed from the outside of the bags to the inside in order to remove some of the dust cake. The dislodged dust cake drops into the hopper, and the reverse gas passes through the open inlet damper and enters the gas stream inlet duct leading to other compartments that are in the filtering mode. To prevent the bag from collapsing during the reverse air flow, it is held under a tension of 60-120 pounds of force and has anti-collapse rings sewn into it every 4-6 feet. After cleaning is completed, there is a second null period of 1-2 minutes to allow time for particles to settle before the compartment is returned to filtering service. As with shaker collectors, the cleaning interval for each compartment is typically 30 minutes to 2 hours.

Sealing the outlet and reverse air dampers is critical to the performance of the baghouse. If the reverse air dampers do not seal properly, the cleaning air supplied by the reverse air fan can be lost to compartments in filtering service. If the outlet dampers do not seal properly, the cleaning gas short-circuits through these openings rather than passing through the bags to be cleaned.

Pulse Jet Fabric Filters

There are two major types of pulse jet collectors: top access and side access. The top access design includes a number of large hatches across the top of the baghouse for bag replacement and maintenance. The side access design has one large hatch on the side for access to the bags. The side access units often have a single small hatch on the top of the baghouse for routine inspection.

A cutaway drawing of a typical top access type pulse jet fabric filter is shown in Figure 3-6. In pulse jet collectors, the tube sheet is located near the top of the unit and the bags are suspended from it. In top access designs, the bags are clamped and sealed to the top of the tube sheet to allow for bag removal and replacement from the top of the unit. A proper bag seal is very important to prevent dust-laden gases from short-circuiting to the clean side of the baghouse without passing through the dust cake and bag.

The gas stream enters either into the side of the casing or into the hopper. The gas flows into the bags and moves upward into the clean gas outlet plenum at the top, leaving the dust cake on the outside of the bag. The bags are supported on metal cages to prevent them from collapsing. Because the fabric flexes around the cage wires during filtering, some fabric wear is possible. To minimize this potential problem, cages with closely-spaced wires are used for fabrics that are especially vulnerable to flex-type wear. More economical cages are used for fabrics that are very tolerant of flex. There are no frames or attachments at the bottom of the pulse jet bags. Pulse jet collectors use felted fabrics and generally operate with an air-to-cloth ratio of 3-10 ft/min.

A portion of the dust must occasionally be removed from the bags in order to avoid excessively high pressure drops. The bags are cleaned by introducing a high-pressure pulse of compressed air at the top of each bag. The sudden pulse of air generates a pressure wave that travels down inside the bag. The pressure wave also induces some filtered gas to flow downward into the bag. Because of the combined action of the pressure wave and the induced gas flow, the bags are briefly deflected outward. This cracks the dust cake on the outside of the bags and causes some of the dust to fall into the hopper. Cleaning is normally performed on a row-by-row basis while the baghouse is operating. However, with this operating practice, dust released from one row of bags can either return to the bag because of settling problems or be recollected on a bag in an adjacent row that remains in filtering service. Both problems can be avoided by using off-line cleaning. This is accomplished by dividing the pulse jet baghouse into compartments and isolating the compartment being cleaned to prevent gas flow through it.

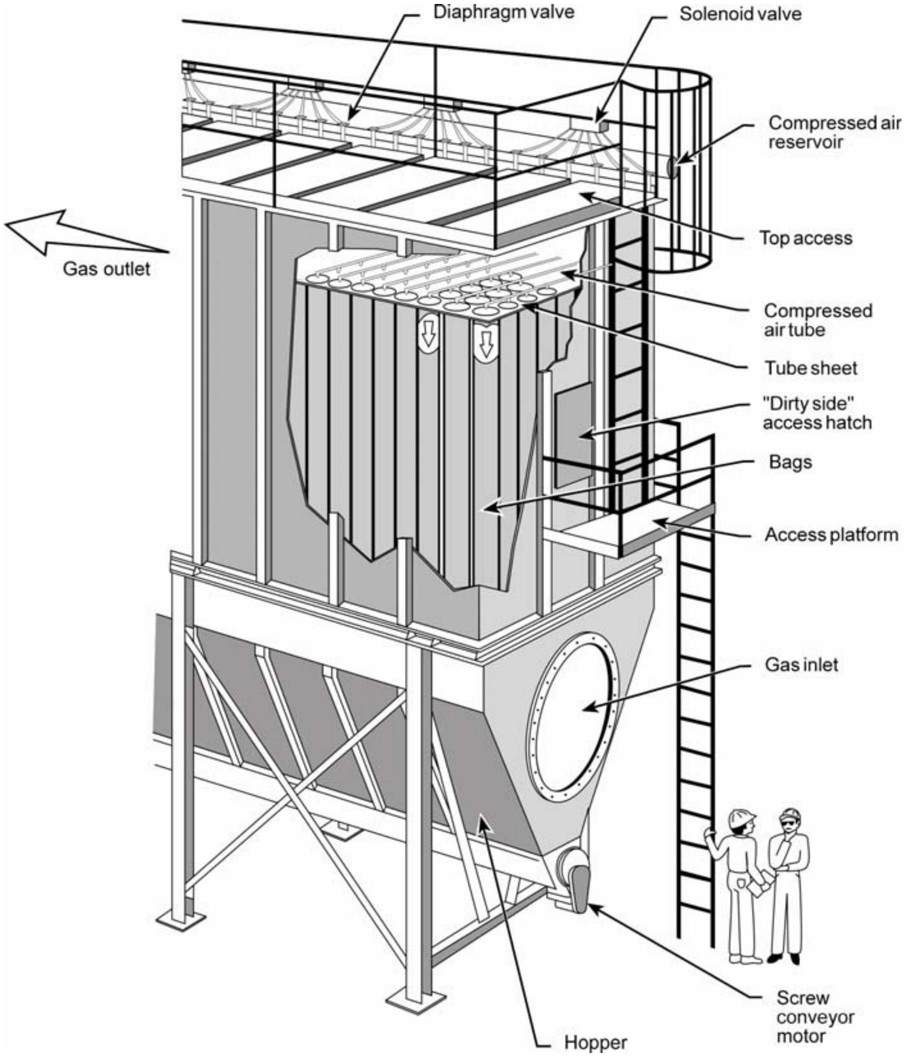

Figure 3-6. Pulse jet fabric filter

Excessive cleaning of pulse jet bags can simultaneously cause higher-than-normal emissions, higher-than-normal static pressure drop, and accelerated bag wear. If there is insufficient dust cake on the bag when it is cleaned, particles or small agglomerates of particles can be dispersed. These particles do not settle by gravity and simply return to the bag at an area where the dust cake is thin. Here, they can accumulate as a low porosity cake, increasing the pressure drop. Over time, these fine particles can seep through the bag and cause opacity spiking after the cleaning pulse. The seeping of emissions is caused, in part, by the deceleration shock occurring when the just-pulsed bag snaps back against the cage as the bag returns to filtering service.

The main components of the pulse jet cleaning system are illustrated in Figure 3-7. The major components include (1) a source of compressed air, (2) a drier, (3) a coalescing oil filter, (4) a compressed air header, (5) diaphragm and solenoid valves, (6) a solenoid valve controller, (7) compressed air delivery tubes, and (8) instrumentation.

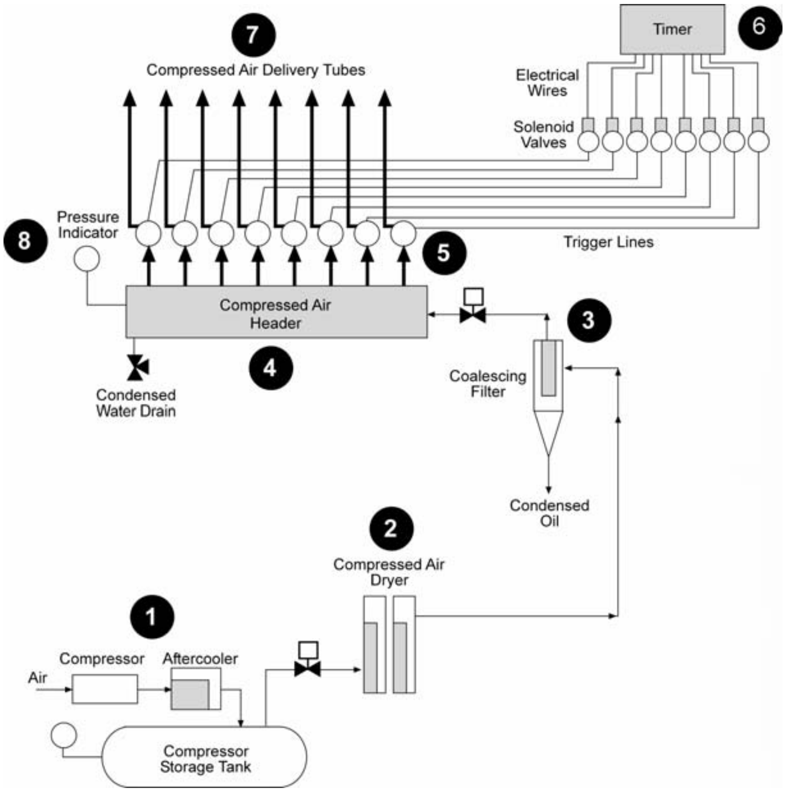

Figure 3-7. Components of a pulse jet cleaning system

The source of compressed air for bag cleaning can be an air compressor dedicated to the specific baghouse or the plant air system. Dedicated compressors usually include an aftercooler to reduce the high temperature caused by compression, a pressure regulator to control the compressor, and a compressed air storage tank. The compressed air is piped from the storage tank to the compressed air header mounted on the side wall of the pulse jet unit. A drier is usually used on the compressed air supply to reduce the water content, and a coalescing filter is used to remove entrained oil droplets.

A typical compressed air header is shown in Figure 3-8. This provides a reservoir of compressed air to support the operation of the diaphragm valves during a cleaning cycle. There is a connection to each diaphragm valve serving each row of the baghouse. It is important that these connections and the header itself be leak free to ensure that the header remains at the necessary air pressure. In most systems, the compressed air pressure is in the range of 60 to 90 psig.

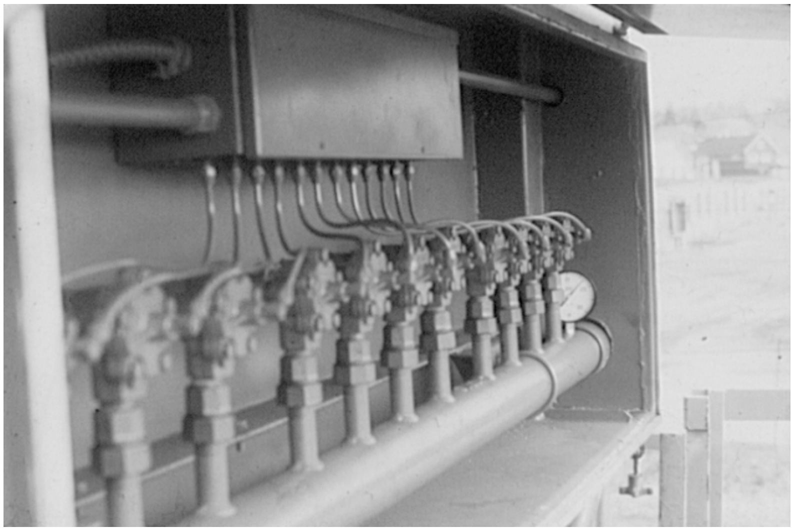

Figure 3-8. Pulse jet compressed air manifold and valves

The opening and closing of the diaphragm valve serving each row of bags is controlled by a solenoid valve. The cleaning cycle controller sends an electrical signal to the solenoid to open the valve. This allows compressed air to flow from the trigger line that connects the diaphragm valve to the solenoid valve. The release of compressed air from the back of the diaphragm valve causes the diaphragm valve to open, allowing the compressed air to enter the delivery tube passing above the row of bags.

The compressed air delivery tube, usually called a *lateral* or *blow tube*, transports the compressed air from the discharge side of the diaphragm valve to the inlet of each bag in the row. These tubes have either a small orifice or an extension tube on the lower side. This hole or extension tube directs the compressed air to the center of the bag. After a period of 0.1-0.2 seconds, the cleaning cycle controller sends a signal to close the solenoid valve. The causes pressure to buildup in the trigger line, closing the diaphragm valve. Bags are cleaned on a relatively frequent basis, with each row being cleaned from once every few minutes to once every several hours. Cleaning usually starts with the first row of bags and continues through the remaining rows in order.

It is important that the delivery tube be oriented so that the orifice or extension tube points straight into the bag. Rotation of the delivery tube causes the compressed air pulse to strike the side of the bag near the top and holes are created. It is also important to securely fasten the compressed air delivery tube. This tube experiences a pressure rise from ambient pressure to more than 60 psig in a time period of 10 to 50 milliseconds. If this tube is not firmly secured, it can break free.

Breakage of the trigger lines between the diaphragm valve and solenoid valve can adversely affect cleaning by leaking compressed air needed for cleaning other bag rows. When the solenoid valve is closed, compressed air fills the trigger line and a small portion of the diaphragm valve. This pressure keeps the diaphragm valve closed. If the trigger line is broken, the diaphragm valve cannot be closed, and compressed air continues to flow through the affected valve.

The instrumentation for the compressed air pulsing system is usually quite limited. There is usually a compressed air pressure gauge on the storage tank of the compressor and on the compressed air header serving the baghouse. The compressed air pressure data can be used in conjunction with the overall static pressure drop data for the baghouse to confirm that the baghouse cleaning system is performing properly.

Cartridge Filters

Cartridge filter systems are similar to pulse jet fabric filter systems. The filter elements are supported on a tube sheet that is usually mounted near the top of the filter housing. The gas stream to be filtered passes from the outside of the filter element to the inside. Filtering is performed by the filter media and the dust cake supported on the exterior of the filter media. The filter media is usually a felted material composed of cellulose, polypropylene, or other flex-resistant material.

The unique feature of a cartridge filter is the design of the filter element. Essentially all cartridges are shorter than pulse jet bags. Some cartridges have simple cylindrical designs. Others can have a large number of pleats as shown in Figure 3-9 or other complex shapes as shown in Figure 3-10 in order to increase the filtering surface area. Due to the shortness of the cartridge filter elements, they are usually less vulnerable to abrasion caused by the inlet gas stream. The shorter length also facilitates cleaning by a conventional compressed air pulsing system identical to those used on pulse jet collectors.

Figure 3-9. Pleated cartridge filter element

Figure 3-10. Flat cartridge filter element

Cartridge filter elements are used in a wide variety of industrial applications. Due to their inherently compact design, they can be used in small collectors located close to the point of particulate matter generation. They are generally used on gas streams less than approximately 400°F. This temperature limit is due to the capabilities of the flex resistant, high temperature fabrics and by the limitation of the gasket material used to seal the cartridge filter element to the tube sheet.

Fabrics

There is a wide variety of commercially available filtration media. These can be categorized into five different groups:

- Woven fabric
- Felted fabric
- Membrane fabric
- Sintered metal fiber
- Ceramic cartridge

A **woven fabric** is composed of interlaced yarns, as shown in Figure 3-11. The yarns in the warp direction provide strength to the fabric, and the yarns in the fill direction determine the characteristics of the fabric. The pores, which are the gaps between the yarns, can be more than 50 μm in size. Small particles can easily pass through these pores until particles are captured on the sides of the yarns and bridge over the openings. The dust cake is critical for proper filtration by woven fabrics.

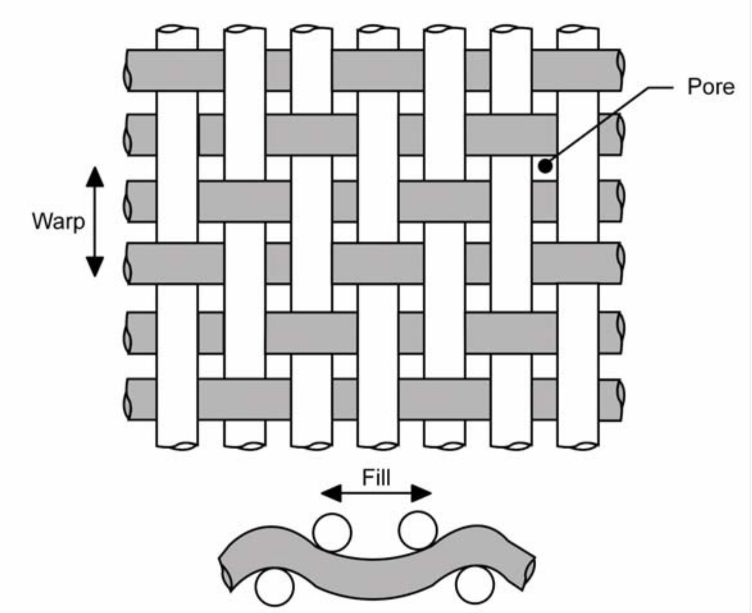

Figure 3-11. Woven fabric

There are a variety of weave types used to modify the characteristics of the fabric. For example, the twill weave shown in Figure 3-11 is less vulnerable than other weaves to fabric blinding due to the penetration of fine particles into the fabric. Overall, the weave characteristics influence the strength of the cloth, the difficulty of dust cake release during cleaning, and the resistance to gas flow.

Felted fabrics are composed of randomly oriented fibers attached to a very open weave termed the *scrim*. The felted fabrics are usually much thicker than woven cloths because of the layer of fibers on both sides of the scrim. With this type of fabric construction, there are no pores as indicated in Figure 3-12. The fibers on the filtering side provide a large number of targets for particle impaction, Brownian diffusion, and electrostatic attraction. However, even with felted fabrics, the dust cake that accumulates on the surface is primarily responsible for particle capture.

Membranes are another major category of fabrics used in air pollution control. These are composed of a polytetrafluoroethylene (PTFE) membrane that is laminated to either a woven or felted support fabric. The membrane is placed on the filtering side of the fabric. Particle collection occurs primarily due to the sieving action of the membrane's very small pores (less than 5 μm). In membrane fabrics, the dust layer is not especially important in particulate removal. Furthermore, static pressure drop is relatively low due to the good dust cake release properties.

Sintered metal fiber bags are composed of small metal fibers randomly oriented on a cylindrical surface. The bags are heated to high temperatures to bond the fibers together. The bags are rigid and require specially designed pulse jet type cleaning systems. Sintered metal fiber bags can be used for hot gas streams. They can also be aggressively cleaned if they become blinded by sticky or moist dust.

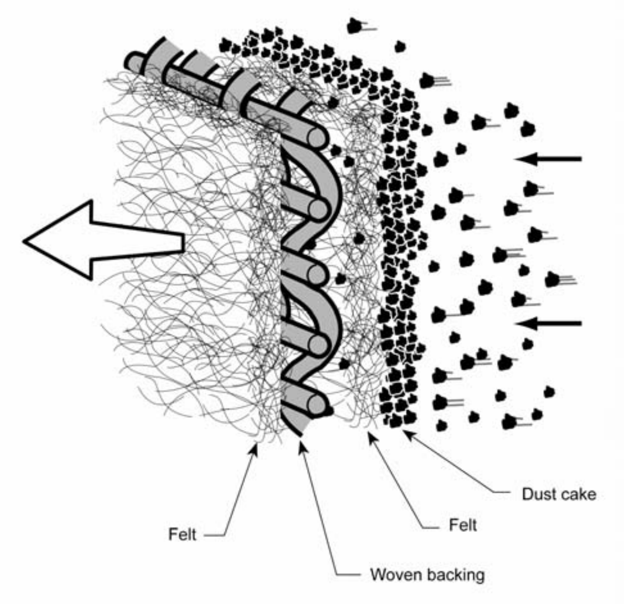

Figure 3-12. Felted fabric

Ceramic cartridge filters are fabricated in cylindrical candle or honeycomb forms. Particle capture occurs as the dust passes through the dust cake on the exterior surface and through the pores through the ceramic media. These filters are designed for applications where the gas temperatures are extremely hot.

The fabrics used for baghouses can be composed of a variety of synthetic and natural materials. Selection of the fabric material is based primarily on three criteria:

- Maximum gas temperatures of the gas stream
- Corrosive chemical concentrations in the gas stream
- Physical abrasion and fabric flex conditions

The various fabrics differ substantially with respect to their ability to tolerate temperature, chemical attack, and physical abrasion and flex. The temperature and acid-resistant capabilities of some of the commercially available types of fabrics are summarized in Table 3-1. The continuous temperature rating shown in the table is intended only as a general indicator of the fabric's capability. To optimize bag life, the normal operating temperatures should be slightly below this limit. The resistance to acids primarily involves inorganic acids such as sulfuric acid and hydrochloric acid.

The ability to handle temperature surges is a function mainly of the fabric's dimensional stability and protective coatings. For example, the limiting maximum surge temperature for fiberglass fabrics is due, in part, to the need to avoid volatilization of lubricants on the fiber surfaces. These lubricants are necessary to prevent fiber-fiber abrasion during cleaning. Also, the ability of the fabric to withstand short-term temperature spikes depends on the quantity of dust cake present. The dust can absorb some of the heat and thereby moderate the maximum temperature while slightly extending the time period that the fabric is exposed to elevated temperature.

Table 3-1. Temperature and Acid Resistance Characteristics

Generic	Common or	Maximum Temperature, °F		Acid
Name	**Trade Name**	**Continuous**	**Surges**	**Resistance**
Natural Fiber, Cellulose	Cotton	180	225	Poor
Polyolefin	Polyolefin	190	200	Good to Excellent
Polypropylene	Polypropylene	200	225	Excellent
Polyamide	Nylon®	200	225	Excellent
Acrylic	Orlon®	240	260	Good
Polyester	Dacron®	275	325	Good
Aromatic Polyamide	Nomex®	400	425	Fair
Polyphenylene Sulfide	Ryton®	400	425	Good
Polyimide	P-84®	400	425	Good
Fiberglass	Fiberglass	500	550	Fair
Fluorocarbon	Teflon®	400	500	Excellent
Stainless Steel	Stainless Steel	750	900	Good
Ceramic	Nextel®	1300	1400	Good

The ability of fabrics to withstand physical abrasion and flex is summarized in Table 3-2. Fabrics listed as fair must be cleaned gently, and the bags must be handled carefully during installation. Most of the fabrics have good to excellent capability with respect to abrasion and flex. The two main exceptions are fiberglass, Teflon®, and ceramic fabrics which are often used for moderate-to-high gas temperature applications.

Some of the fabrics are coated to improve their ability to withstand acid attack and abrasion and flex type physical damage. All fiberglass fabrics must have coatings to protect the relatively brittle fibers that can easily be broken by fiber-to-fiber abrasion. Silicone-graphite finishes for fiberglass fabrics have been used for more than 40 years. Other coatings that have been developed and used successfully over the last 20 years include Teflon-B® coating, I-625®, Blue Max®, and Chemflex®. Some of these newer coatings also protect the fabric from acid attack.

Table 3-2. Fabric Resistance to Abrasion and Flex

Generic Name	Common or Trade Name	Resistance to Abrasion and Flex
Natural Fiber, Cellulose	Cotton	Good
Polyolefin	Polyolefin	Excellent
Polypropylene	Polypropylene	Excellent
Polyamide	Nylon®	Excellent
Acrylic	Orlon®	Good
Polyester	Dacron®	Excellent
Aromatic Polyamide	Nomex®	Excellent
Polyphenylene Sulfide	Ryton®	Excellent
Polyimide	P-84®	Excellent
Fiberglass	Fiberglass	Fair
Fluorocarbon	Teflon®	Fair
Stainless Steel	Stainless Steel	Excellent
Ceramic	Nextel®	Fair

Inspection

The inspection of fabric filter systems is divided into Basic and Follow-up Level 2 procedures. The relatively time-consuming follow-up procedures are conducted only when a basic inspection indicates that compliance problems are present or anticipated in the immediate future.

Basic Level 2

- Stack visible emissions
- Opacity monitor data
- Static pressure drop
- Inlet and outlet gas temperatures
- Compressed air pressures (pulse jet systems)
- Air infiltration
- Corrosion
- Fugitive emissions

Follow-up Level 2

- Opacity monitor quality assurance checks
- Operating and cleaning cycle times
- Compressed air leaks (pulse jet systems)

- Inoperative diaphragm valves (pulse jet systems)
- Clean side conditions
- Bag failure records
- Internal inspection reports
- Start-up/shut-down practices
- Tracer dust test results

Basic Level 2: Stack Visible Emissions

If weather conditions permit, the average opacity should be determined in accordance with USEPA Method 9 or other required procedures. The observations should be long enough or frequent enough to account for compartment-by-compartment cleaning cycles. The timing and duration of all significant opacity spikes should be noted.

In the case of pulse jet baghouses, short duration puffs of approximately 10 to 30 percent opacity are usually due to small holes in the bags. The opacity spikes cease when the dust bridges over the hole and reestablishes an effective dust cake. In most cases, these holes will increase in size over time and will eventually cause continuous emissions.

As part of the visible emission observations, condensing plume characteristics at the stack discharge should be evaluated. This type of plume 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. Immediately following the clear zone, the opacity increases rapidly due to the formation of particulate matter from the vapors in the gas stream. These vapors can rarely be collected in a baghouse; therefore, the presence of a condensing plume indicates the need to evaluate process operating conditions that could contribute to the formation of the vaporous material.

Basic Level 2: Opacity Monitor Data

There are two basic types of opacity monitors used on fabric filter systems: (1) bag break indicators, and (2) double pass transmissometers that comply with 40 CFR Part 60 requirements for continuous emission monitors. The double pass transmissometers are used only on the moderate-to-large systems subject to specific regulatory requirements. The bag break indicators are used on some small-to-medium sized units.

The bag break indicators provide only a qualitative measure of the operating status. They do not provide accurate opacity measurements. Furthermore, they can be subject to operational problems that indicate a false emission limit exceedance reading. The data from the bag break indicators should be noted on the inspection forms but should not be used as a substitute for the more accurate visible emission observation.

Double pass transmissometers are used at plants subject to specific opacity monitoring requirements. In many cases, the data from these units is directly enforceable. In other cases, the data is used simply to determine if there has been a shift from the baseline performance levels. Even slight increases in the opacity could indicate problems that could lead to noncompliance in the future.

The compartment-by-compartment cleaning cycle opacities should be checked as part of the evaluation of the opacity monitoring data. Short term spikes immediately after a compartment is brought on-line for filtering could indicate damper sealing problems or small holes or tears developing in the bags of the compartment.

Basic Level 2: Static Pressure Drop

The first step in evaluating the static pressure drop is to qualitatively confirm that the monitoring instrument is working properly. In the case of shaker and reverse air systems, normal fluctuations in the static pressure drop occur as compartment after compartment is taken off-line for cleaning. The lack of any fluctuations usually indicates a malfunctioning static pressure drop gauge. In the case of pulse jet units, normal operation of the static pressure drop gauge is indicated by small fluctuations in the static pressure drop during pulsing of each row.

The baghouse overall static pressure drop should usually be less than 6 in. H_2O. An increase of 1 to 2 in. H_2O from baseline operating levels could indicate important changes in baghouse operating conditions. If the baghouse static pressure drop is high (>6 in. H_2O), gas flow rates through the system could have been suppressed by the high flow resistance. Fugitive emissions are possible from the process equipment, and the inspection should include a check of all process areas that can be observed safely. If the baghouse static pressure drop is low, severe air infiltration could be occurring. This is addressed in one of the later inspection points included in the scope of the Basic Level 2 inspection.

For shaker and reverse air collectors, and any other collector that cleans off line, there is a normal cycle in the static pressure drop. The pressure drop is lowest after a unit comes back on line after cleaning and is highest just before a unit goes off line for cleaning. The difference between the high and low pressure drops depends of the number of compartments in the collector. In comparing the static pressure drop on off-line cleaning units to baseline values and values obtained in other inspections, it is important that these values are taken at the same point in the normal cycle.

For shaker and reverse air filtration systems, the static pressure drops during the cleaning of each compartment should be observed. For reverse air collectors, the compartment static pressure drop data should have the general pattern indicated in Figure 3-13. The pattern for shaker collectors should be similar; however, the static pressure drop should remain at zero all the time the collector is off line.

If the static pressure drop is not below zero during the cleaning cycle of a reverse air collector, as indicated by line labeled *normal profile* in Figure 3-13, then cleaning air is not passing backward through the bags in that compartment. If the static pressure drop does not remain at zero during the cleaning cycle of a shaker unit, air is continuing to flow through the bags during shaking. In both cases, cleaning will be significantly impaired by the continued in-flow of particulate-laden air.

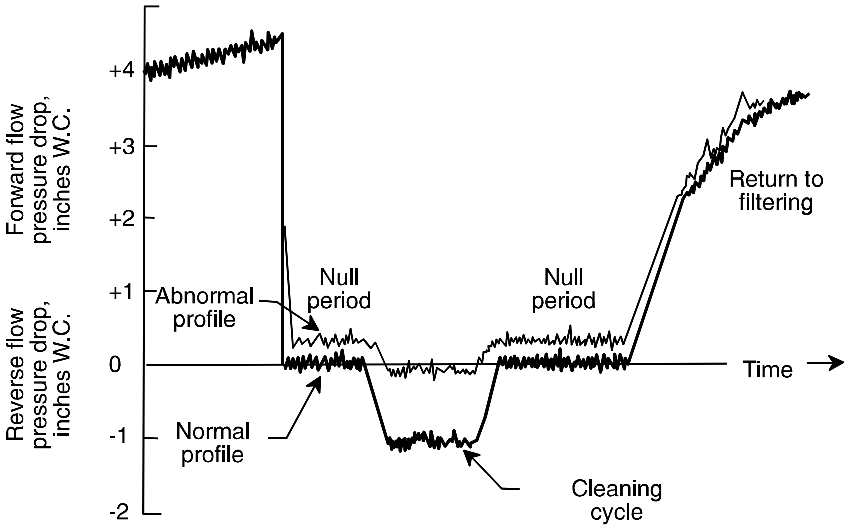

Figure 3-13. Reverse air system static pressure drop profile

Damper leakage causes these abnormal profiles. In shaker collectors, a leaking inlet or outlet damper allows process gas to continue to flow through the collector during the cleaning period. The severity of damper leakage is indicated by the pressure drop during cleaning. In reverse air collectors, the reverse air flow passes out of the poorly sealed outlet damper, rather than passing through the bags. Here, the severity of the damper leakage is indicated by the null period pressure drops. Null period static pressure drops that are above zero in reverse air collectors and cleaning period static pressure drops that are above zero in shaker collectors indicate that the damper has not fully closed.

Basic Level 2: Inlet and Outlet Gas Temperatures

Filter bags are not tolerant of either very high or very low gas temperatures. The inlet and outlet gas temperatures must be maintained within the moderate range.

Short term excursions of more than approximately 25°F above the filter media temperature limits shown in Table 3-1 can cause volatilization of protective coatings, yarn degradation, fabric shrinkage, or fabric stretching. All these conditions lead to premature bag failure. These same problems can develop slowly even if the bags are operated at their rated temperatures for long time periods. Generally, the inlet gas temperature should be slightly below the maximum temperature rating of the fabric.

Acid attack occurs when the gas temperature drops below the acid vapor dewpoint. Baghouse outlet gas temperatures should be checked to confirm that they are well above the normal dewpoint temperatures, especially during low flow rate periods when the gas stream may be cooler. A slight margin of safety is needed with respect to gas temperatures because they are not necessarily uniform throughout the baghouse, as indicated in Figure 3-14.

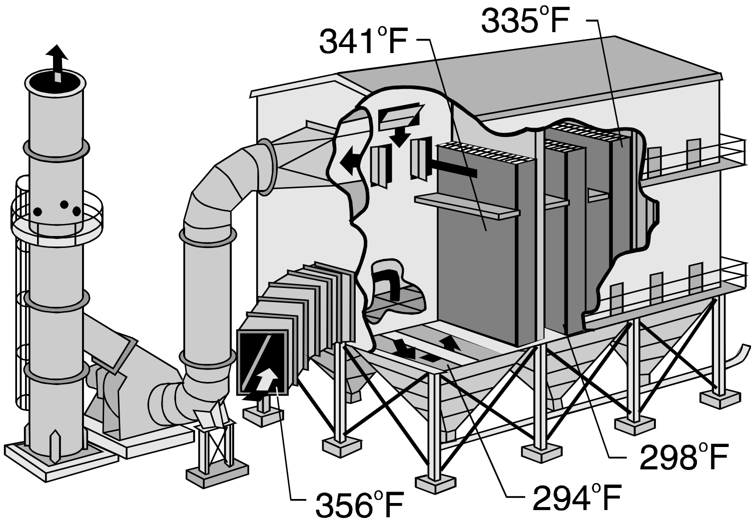

Figure 3-14. Possible temperature nonuniformity in a fabric filter system

Basic Level 2: Compressed Air Pressures (Pulse Jet Systems)

The compressed air pressure in the compressed air manifold should be recorded during the inspection and compared with baseline levels. Overcleaning is possible if the pressure has increased substantially since the baseline period. Inadequate cleaning could be occurring if the compressed air pressure has decreased. In most designs, the normal air pressures range from 60 to 90 psig. However, there are a number of commercial pulse jet baghouses that operate with much lower compressed air pressures and higher compressed air flow rates. Accordingly, shifts from the baseline values for the specific unit are generally the most reliable means of evaluating bag cleaning conditions.

The compressed air pressure is available from a gauge on the compressed air manifold. Compressed air pressure data are virtually never converted to an electrical signal and transmitted back to the main control room. If there is no compressed air gauge on the manifold, the discharge pressure gauge on the air compressor can be used as a general indicator. The compressor discharge pressure is higher than the pressure in the compressed air manifold.

If the compressed air pressure is much lower than the baseline value, the follow-up inspection should include an evaluation of compressed air leaks in the pipe fittings and diaphragm valves.

Basic Level 2: Air Infiltration

One of the most useful ways to evaluate air infiltration into negative pressure collectors is to compare the difference between the inlet and outlet gas temperatures to the baseline difference. If the temperature difference is significantly higher than during the baseline condition, excessive air infiltration may be occurring. If baseline data are not available, excessive air infiltration may be indicated by an inlet and outlet temperature difference that is greater than about 25°F.

A visual inspection of the fabric filter system is often useful for identifying conditions that could be contributing to air infiltration. Areas that commonly have air leakage include solids discharge valves, hopper poke holes, hopper access hatches, compartment access hatches, broken welds or corrosion in the casing and hopper walls, and expansion joints in the ductwork upstream and downstream of the baghouse. In severe cases, air infiltration sites can be identified by the sound of in-rushing air.

The top access hatches on a pulse jet collector are especially prone to leakage because they are usually at the highest negative static pressure in the system. When the fan is downstream of the baghouse, the static pressure in the clean gas plenum and the outlet duct is almost identical to the fan inlet static pressure. Large quantities of air can leak through small gaps in the gaskets because of the large difference between the ambient air pressure and the clean gas plenum static pressure.

Basic Level 2: Corrosion

Corroded areas on the casing and hopper walls, top access hatches, and other portions of the baghouse should be noted during the visual inspection of the unit. The presence of corrosion indicates that the unit is occasionally operating at a low temperature and that moisture or acid vapors are condensing and chemically attacking the baghouse shell. Blinding and chemical attack of the bags is also possible.

Basic Level 2: Fugitive Emissions

Fugitive emissions from the baghouse solids handling system and from the process equipment served by the baghouse should be checked. Solids accumulation in areas adjacent to the equipment provides an indication that fugitive emissions have occurred recently.

Follow-up Level 2: Opacity Monitor Quality Assurance Checks

Units with double pass transmissometers should be checked if the opacity monitoring data is not similar to the visible emission observations. The source and retroreflector units of the instruments should have operating purge air blowers, intact purge air holes, and dust filters. On new units, it is possible to check the alignment of the source and retroreflector with the permission and assistance of plant personnel.

Output data from strip charts or data loggers should be reviewed to confirm that the daily span and zero checks are being conducted. Fault codes in the data should also be checked for to confirm that there have been no major malfunctions. If the instrument has been working properly, the opacity monitoring records since the previous inspection should be reviewed.

Follow-up Level 2: Operating and Cleaning Cycle Times

The frequency and duration of cleaning should be compared to baseline values. For the pulse jet this is simply the frequency and duration of the pulse. For units that clean offline, the frequency of cleaning should be noted, as well as the null period and cleaning period times. Changes in these parameters can significantly change dust cake thickness, and, as a result, the pressure drop and, potentially, the collection efficiency.

Follow-up Level 2: Compressed Air Leaks (Pulse Jet Systems)

A visual inspection for compressed air pipe leaks should be conducted if the static pressure drop across the baghouse is higher than baseline levels or the compressed air pressure is lower than baseline levels. The most common leak sites include the threaded fittings leading to the compressed air manifolds and the threaded fittings leading from the manifolds to the diaphragm valves. Severe leaks can be detected audibly. Small leaks are often indicated by localized oil deposition and dust accumulation on the outside of the fittings.

Fluctuations in the compressed air pressure can occur when there is competition for compressed air between the baghouse and the process equipment. Since the compressed air pressure is rarely recorded, the only way to identify these fluctuations in pressure is to observe the baghouse compressed air pressure gauge for a reasonable period of time when the process equipment is operating.

Follow-up Level 2. Inoperative Diaphragm Valves (Pulse Jet Systems)

The operating status of the diaphragm valves should be checked if the static pressure drop across the baghouse is significantly above baseline levels. The simplest way to do this is to listen for a regular sequence in the pulsing sound as the solenoid and diaphragm valves are actuated. Any time break or unusual sound in the sequence, except at the end of the cycle, indicates that the valve is not actuating properly.

During cold weather, it is possible for moisture that condensed in the compressed air lines to drain into the diaphragm valve and freeze it in the closed position. When this happens, the row of bags served by the frozen diaphragm valve is not cleaned. If a large number of the diaphragm valves are affected, cleaning is impaired, and the static pressure drop across the unit increases. Diaphragm valve freezing is usually a problem only on those units that do not have compressed air dryers and that have the diaphragm valves mounted below the compressed air manifolds. The arrangement allows the condensed water to drain into the back side of the diaphragm valve.

Follow-up Level 2: Clean Side Conditions

When the baghouse is offline, it is possible to open one or more of the access hatches to check clean side conditions. Plant personnel must give permission for this check because opening the unit requires significant effort to lock-out all of the associated equipment. If it is possible to conduct a clean side check, agency personnel should not enter the baghouse, but simply look in from the outside. Breaking the plane of the open hatch constitutes confined space entry and is strictly regulated by the OSHA Permit Required Confined Space Regulation.

Inspection of the clean side conditions in a shaker or reverse air baghouse will be limited, since it must be done from access doors located in the side of the casing. To the extent possible, the evaluation should include the following items:

- Quantity and distribution of fresh dust deposits
- Bag tension
- Bag attachment leakage
- Bag holes and tears
- Tube sheet holes and weld failures
- Hopper overflow indications

There is good access to clean side of a top access pulse jet baghouse; however, access to the clean side of a side access unit will be limited. Evaluation of the clean side conditions should include the following items:

- Quantity and distribution of fresh dust deposits
- Misaligned blow tubes
- Disconnected or broken blow tubes
- Poor bag sealing
- Oil or moisture blinding of the bags
- Tube sheet holes and weld failures

A view of the clean side of a top access pulse jet baghouse is shown in Figure 3-15.

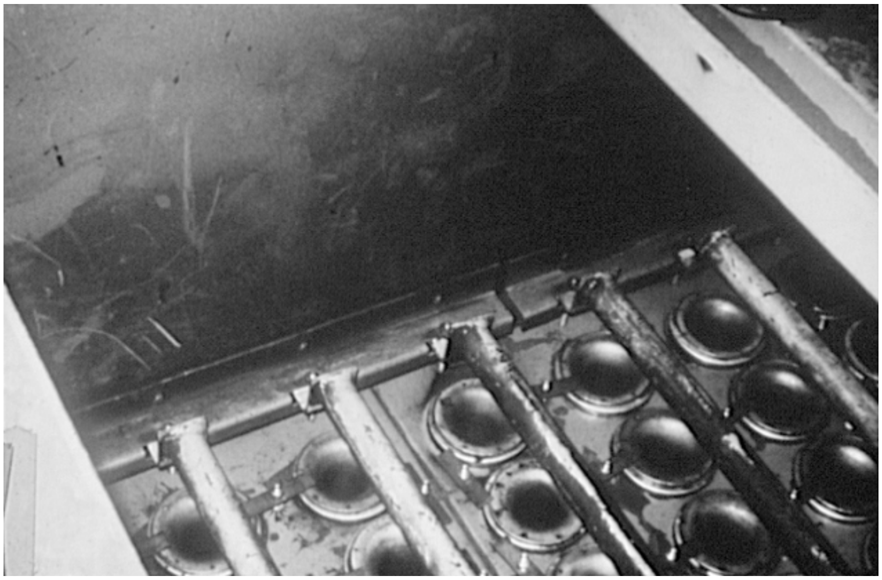

Figure 3-15. Clean side of a top access pulse jet baghouse

Follow-up Level 2: Bag Failure Records

If there are indications of frequent bag failures, bag failure records should be reviewed. Simply replacing the bags is usually not sufficient because each failure can result in excessive emissions before the maintenance staff can replace or tie-off the bag. Furthermore, the installation of a new bag in a compartment with seasoned bags can lead to the rapid failure of the new bag due to high air-to-filter ratio conditions. For these reasons, it is important to solve the fundamental problem causing the bag failures.

One commonly used type of bag failure record is shown in Figure 3-16. This is a plan view drawing of a compartment showing the bag layout. A letter and number system is used to assign a unique identification code to each bag location. When a bag is removed or tied off, a mark is placed in the affected location. They may also use a code to identify the portion of the bag where the failure occurred. The date can also be recorded so that the timing of the bag failures can be evaluated in the future. After several failures in a compartment have been entered, the spatial pattern of the failures can be evaluated. This is helpful for identifying the fundamental problems leading to the bag failures.

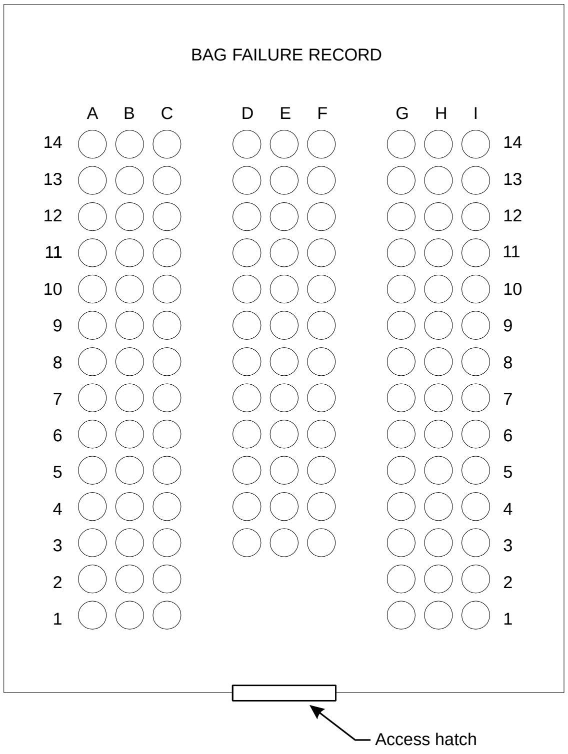

Figure 3-16. Compartment bag layout sketch

The frequency of bag failure can be plotted on a time line. As shown in Figure 3-17, there is usually a long time period after the installation of new bags when there are few failures.

During this period, failures are typically address by replacing individual bags. It would be helpful for plant personnel to send bag samples to a fabric testing laboratory if there have been chronic excess emission problems caused by frequent bag failures. Identifying the cause of bags failures should help plant personnel to reduce their frequency. The results of any bag testing should be reviewed while on site. When the rate of failure begins to increase significantly, this is an indication that the bag set is reaching the end of its useful life and it is time to replace all of the bags in the compartment.

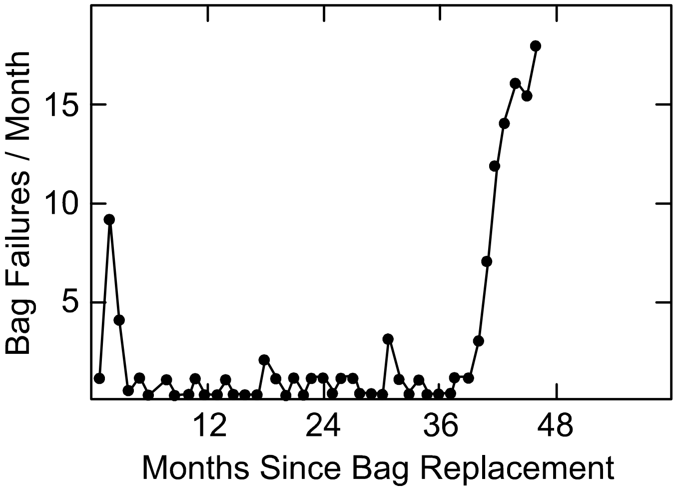

Figure 3-17. Bag failure rate chart

The *rip test* is a test that can be applied to failed bags in order to determine their general mode of failure. Take a failed bag that has been removed from the collector and search its surface to locate the point of failure—the hole. Go a few inches away from the hole and jab a screwdriver through the fabric. While holding the bag with one hand, try to tear the fabric with the screwdriver. If the fabric does not tear easily, it indicates that the fabric is in good condition and the hole likely formed through some sort of abrasive action. If the fabric tears easily or shreds, it indicates that all of the fabric has been damaged, either by high-temperature or chemical exposure.

Follow-up Level 2: Internal Inspection Reports

For many health and safety reasons, agency personnel should not conduct internal inspections of baghouses. However, the inspection reports prepared by the plant maintenance staff could be helpful in confirming that the plant has identified the fundamental operating problems and has taken the appropriate steps to prevent future excess emission incidents.

Follow-up Level 2: Start-up/Shut-down Practices

Baghouses may be bypassed during the early stages of process start-up and the later stages of process shut-down. During these time periods, the gas temperatures may be below the moisture or acid vapor dewpoint, and the particulate matter may be sticky or otherwise difficult to remove from filter surfaces. The frequency of start-up/shut-down cycles should be reviewed with plant representatives to confirm that all reasonable efforts are being made to reduce the time that the baghouse is bypassed.

Follow-up Level 2: Tracer Dust Test Results

Many plant operators use tracer dusts and black light kits to locate small bag holes and gas leak sites. These tests are conducted by injecting fluorescent dust into the baghouse inlet duct while the unit is operating. In less than one minute after injection, the baghouse is shut-down, and the clean side area of the baghouse is checked for traces of the dust. Bag holes or gas leak sites are indicated by deposits of the fluorescent dye. These tests are usually conducted at night or under moderately dark conditions and are usually helpful in locating emission points. Reports concerning these tests may be helpful to agency inspectors in confirming that the plant is correcting conditions that have previously contributed to excessive emission incidents.

Review Problems

Video Problem

This inspection concerns two relatively small material handling type sources at a foundry. In addition to the sources shown, there is a cupola controlled with a reverse air baghouse and a variety of small sources. The plant is located in a residential community that has grown around this facility and several other plants.

The pulse jet baghouse is a top access, single compartment unit with four rows of bags. The induced draft fan for the baghouse and the sand reclaim unit are mounted beside the baghouse.

The reverse air baghouse is an old multi-compartment unit. The bags are cylindrical envelopes mounted horizontally. Each horizontal row of bags is subject to reverse air flow by a moving cartridge containing a reverse air blower. The induced draft fan for the reverse air baghouse is mounted inside the main structure that includes the three compartments. A single screw conveyor is used to collect the solids from the three compartments and transport them to a waste bin for eventual disposal.

1. What instruments would be helpful in monitoring the compliance status of the pulse jet baghouse serving the sand reclaim operation?

    a. A thermocouple
    b. A compressed air pressure gauge
    c. A differential static pressure gauge
    d. All of the above

2. Should the operator of the pulse jet baghouse be asked to install on-site, permanently mounted instruments?

    a. Yes. This is necessary to facilitate future Level 2 inspections.
    b. No. This information could be obtained during future Level 2 inspections by plant personnel using portable gauges.

3. Are the measurement ports shown in the videotape in the appropriate locations for measuring the baghouse inlet and outlet static pressures during a Level 3 inspection?

    a. Yes
    b. No

4. Does the plant representative accompanying the inspector have the right to refuse to open the top access hatches to observe clean side deposits and other internal conditions?

   a. Yes
   b. Yes. But only when the unit is operating during the inspection and can not be conveniently and safely shut down.
   c. No

5. Should the inspector demand that the plant repair the misrotated compressed air tubes and the top access hatch air infiltration problems?

   a. Yes. This can lead to fugitive emissions from the process equipment.
   b. Yes. The air pollution control equipment should be in perfect working condition at all times.
   c. No. There are no indications of noncompliance.
   d. No. Inspectors are on-site to gather information, not to make demands or to initiate actions that may obligate the agency or create liabilities for the agency.

General Problems

6. A reverse air baghouse serving a 300 megawatt pulverized coal-fired boiler is having visible emissions of 60% to 70% opacity for 3 to 5 minutes after each compartment is cleaned. The Level 2 inspection data are provided below. What are possible causes of the opacity problem and how would you check each possibility?

	Inspection Data	Baseline Data
Stack Visible Emissions[1], %	5	5
Opacity Monitor		
Average Opacity (6-min.), %	5	3
Spiking Opacity, %	60-70%	None
Condensing Plume	No	No
Overall Pressure Drop, in. H_2O	5.5	4
Gas Inlet Temperature, ^oF	300	310
Gas Outlet Temperature, ^oF	289	301

[1] Non-spiking periods

7. An operator of a multi-compartment pulse jet baghouse has been attempting to correct a high baghouse static pressure problem in order to reduce fugitive emissions from the process system. The operator plans to convert to offline cleaning. Is this a reasonable action?

8. A clinker cooler pulse jet baghouse has a stack opacity that ranges between 0% and 5% opacity. There have been some shifts from the baseline operating conditions. What are possible causes of the decrease pressure drop and how would you check each possibility?

	Inspection Data	Baseline Data
Static Pressure Drop, in. H_2O	2.5	4.2
Inlet Gas Temperature, °F	260	330
Compressed Air Pressure, psig	85	85

9. Opacity from a pulse jet fabric filter on a coal-fired industrial boiler has increased substantially from previously recorded levels. The static pressure drop across the collector is now 11 in. H_2O, and the operator has found it necessary to operate at reduced boiler load due to fan limitations. The compressed air system includes an oil filter, but no drier. The compressed air pressure is at the baseline value of 90 psig. The baghouse inlet temperature is presently 354°F; however, records indicate that the temperature sometimes drops to 295°F. The boiler is fired with low sulfur coal. What are possible causes of the increased pressure drop and how would you check each possibility?

10. A reverse air unit serving a cupola is now operating with an average opacity of 12%, compared with historical levels of 1-3%. The static pressure drop has increased from 6 in. H_2O to 7 in. H_2O. The gas inlet temperature is normally 495°F, but there are 15-30 minute excursions to 600°F. There are no signs of air infiltration through the shell or the solids discharge valves. What are possible causes of the increase in opacity?

11. A shaker fabric filter serving a drier has an average opacity of 25%, with short-term spikes to 60% during the cleaning of certain compartments. The gas inlet temperature is 240°F and the outlet temperature is 125°F. The compartment-by-compartment static pressure drops during cleaning are as follows:

Compartment	Pressure Drop
1	-1.3
2	-1.9
3	-0.9
4	-0.2
5	-0.2
6	-1.2
7	-1.3

The pressure drop during operation is 3.3 in. H_2O. The baseline pressure drop is 3.1 in. H_2O. The shaker motors operate for a period of 5 minutes, beginning immediately after the compartment is isolated. What are possible causes of the high opacities?

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CHAPTER 4

WET SCRUBBERS

Wet scrubbers are a diverse set of control devices that can be used to collect both particles and gases, but usually not simultaneously at high efficiency for both. This is because particulate scrubbers are designed to generate high inertial forces or electrostatic forces on particles to drive them into droplets or sheets of liquid. Gas absorbers are designed to have high liquid surface areas and relatively long residence times to maximize the absorption of contaminants into liquid droplets or sheets. Despite the fundamental operating differences, most particulate scrubbers have at least modest efficiencies for gaseous contaminant removal, and most gaseous absorbers have modest efficiencies for the removal of particulate larger than approximately 3 micrometers. In this chapter we will focus on wet scrubbers used for particle collection; however, the inspection procedures for the two categories of wet scrubbing systems are very similar.

Wet scrubbers use a three-step process for the treatment of particulate-laden gas streams:

- Particle capture in either droplets, liquid sheets, or liquid jets
- Capture of the liquid droplets entrained in the gas stream
- Treatment of the contaminated liquid prior to reuse or discharge

Particle capture is accomplished in a contacting vessel, such as a venturi scrubber, a tray tower scrubber, or a spray tower scrubber. Mist eliminators built into the scrubber vessel or provided as a separate vessel are used to collect the entrained water droplets after the scrubber. Clarifiers, vacuum filters, or settling ponds are used to treat the wastewater stream from the scrubber. Particle size is an important factor in all types of scrubbing systems. This is because they all use the same basic collection mechanisms--inertial impaction and Brownian motion, both of which are highly dependent on particle size.

Operating Principles

Inertial Impaction

Impaction occurs when a particle has too much inertia to avoid a target that it is approaching. It crashes into the target instead of flowing around it on the gas streamlines. If the particle is retained by the target (in this case, a droplet), a successful impaction has occurred. The efficiency of particle collection by impaction is proportional to the inertial impaction parameter shown in Equation 4-1.

$$\Psi_I = \frac{C_c d_p^2 \rho_p V_r}{18 \mu_g d_d} \tag{4-1}$$

where:

Ψ_I = inertial impaction parameter (dimensionless)
C_c = Cunningham slip correction factor (dimensionless)
d_p = physical particle diameter (cm)
ρ_p = particle density (gm/cm^3)
V_r = relative velocity between particle and droplet (cm/sec)
d_d = droplet diameter (cm)
μ_g = gas viscosity (gm/cm sec)

This equation indicates that impaction effectiveness is related to the square of the particle diameter. Impaction is much more efficient for large particles than for small particles, especially those particles less than 0.5 µm. Impaction rapidly becomes less efficient as the particle size decreases in the submicron range. To overcome this inherent limitation, the differences in droplet and particle velocities must be high when most of the particulate matter in the submicron range.

The impaction parameter indicates that impaction is directly proportional to the difference in the velocities of the particle and the droplet or liquid sheet target. There are substantial differences among the various types of scrubbers with respect to this relative velocity term. Furthermore, the difference in velocity does not remain constant throughout some types of scrubbers.

The effectiveness of impaction is inversely related to the diameter of the target. Small water droplets serve as better targets than large droplets. The formation of small droplets is favored by droplet atomization in high-velocity gas streams and droplet atomization in high-pressure nozzles. Low surface tension conditions in the liquid also favor small droplet size distributions.

Brownian Motion

Brownian motion, or diffusion, is the particle movement caused by the impact of gas molecules on the particle. Only very small particles are affected by the molecular collisions, since they posses little mass and, therefore, little inertial tendency. Brownian motion begins to be effective as a capture mechanism for particles less than approximately 0.3 µm, and it is significant for particles less than 0.1 µm. Most industrial sources of concern in the air pollution field do not generate large quantities of particulate matter in the less than 0.1 µm size range. Therefore, in most cases, Brownian motion is not a major factor influencing overall scrubber collection efficiencies.

Liquid-to-Gas Ratio

The rate of liquid flow to a scrubber is often expressed in terms of the liquid-to-gas ratio, with units of gallons of liquid per 1,000 actual cubic feet of gas flow. Most wet scrubber systems for particle collection operate with liquid-to-gas ratios between 4 and 20 gal/1,000 acf. Higher values do not usually improve performance, and they may have a slightly adverse impact due to changes in the droplet size distribution formed in the scrubber. Low values can have a highly adverse impact because there are simply too few impaction targets available. At low liquid-to-gas ratio conditions, a portion of the particle-containing gas stream may pass through the collection zone without encountering a liquid target.

Mist Elimination

Essentially all scrubber vessels generate relatively large water droplets that are entrained in the gas stream. Most of these droplets contain captured particles and must be removed from the gas stream prior to discharge to the atmosphere. A mist eliminator is used for this purpose. In addition to minimizing the carry-over of solids-containing droplets to the atmosphere, mist eliminators also protect downstream equipment, such as fans, from solids-containing droplets and minimize the amount of water lost from the system. Mist eliminators are usually equipped with one or more sets of spray nozzles to remove accumulated solids. Solids build-up is due to impaction of solids-containing water droplets and due to the chemical precipitation of dissolved solids from the scrubbing liquid. The three most common types of mist eliminators are chevrons, mesh or woven pads and cyclones.

Chevrons

Chevrons are simply zig-zag baffles that force the gas to turn sharply several times while passing through. As the gas stream turns to pass through the baffles, droplets impact on the baffles and run together to form large droplets that drain back into the scrubber. Chevrons are usually designed with one to four changes in gas stream direction, termed a *pass*. Separation efficiency increases with the number of passes. A three-pass chevron mist eliminator is shown in Figure 4-1.

Essentially all of the chevron mist eliminator designs are limited to gas velocities of less than approximately 20 ft/sec. At higher velocities, liquid on the blades can be driven toward the outlet side of the chevron where it can be reentrained into the gas stream. Higher velocities can occur in an operating system because of solids accumulation on the blades.

Mesh and Woven Pads

Mesh pads are composed of randomly interlaced metal fibers and can be up to 6 inches thick. As the gas stream turns to pass by the elements of the mesh, droplets impact on the baffles and run together to form large droplets that drain back into the scrubber. As in the case with the chevrons, there is a maximum gas velocity above which reentrainment is possible. That maximum velocity is usually in the range of 12 ft/sec. A mesh pad mist eliminator pad is shown in Figure 4-2.

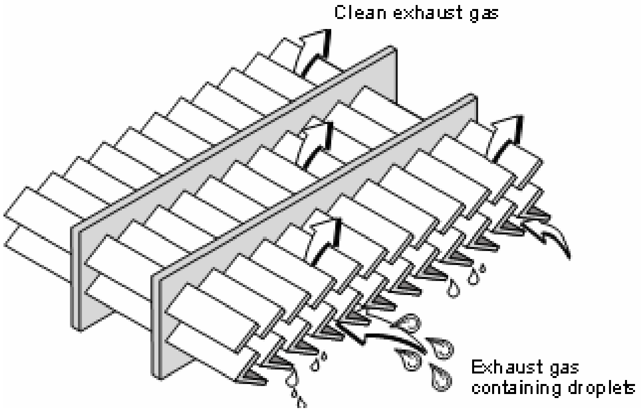


Figure 4-1. Chevron mist eliminator

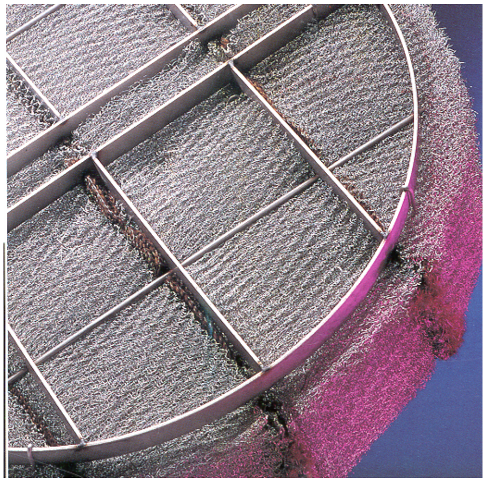


Figure 4-2. Mesh pad mist eliminator

Woven pads have complex, interlaced synthetic fibers that serve as impaction targets. Mist eliminators composed of these materials are often layered. The inlet side layers are open weaves that are capable of removing large quantities of large- diameter material without overloading. The middle and outlet side layers have more compact weaves, which have high removal efficiencies for the small liquid droplets. These units have maximum velocities of 8 to 15 ft/sec, depending on the pad construction characteristics.

Cyclones

The smaller droplet size distributions created in venturi scrubbers are usually collected in a separate large diameter cyclone. The gas stream enters tangentially at the bottom of the vessel and, depending on the gas velocity, turns one-half to two revolutions prior to discharge. They have reasonable efficiency when operated at close to the design inlet gas velocity. However, droplet removal decreases rapidly at gas flow rates less than 80% or more than 120% of the design value. As long as the drain is properly sized and remains open, the mist eliminator is not vulnerable to plugging caused by excessive carryover of solids-containing droplets from the scrubber vessel.

Gas Cooling

Process gases that are at elevated temperature are usually passed through an evaporative cooler before entering the scrubber. The primary purpose of the evaporative cooler is to reduce the gas temperature to protect temperature-sensitive components in the scrubber vessel, mist eliminators and other components. For example, it is common to have corrosion-resistant liners on the scrubber vessels that can volatilize at temperatures exceeding 400°F to 1,000°F. Some scrubber vessels and many mist eliminators are fabricated with fiberglass reinforced plastics (FRP) that have temperature limitations of 180°F to 250°F. The evaporative cooler is provided to ensure that the gas temperatures in the scrubber vessel, mist eliminator, and other portions of the system do not exceed their design limitations even if the liquid recirculation system in the scrubber fails.

The evaporative cooler provides a secondary benefit in particulate matter control systems. By cooling the gas stream prior to particulate matter removal, the evaporation of droplets in the scrubber vessel is significantly reduced. The mass flux of water vapor away from evaporating droplets impedes particle capture by the droplets. Accordingly, the minimization of evaporation has a slight beneficial impact on the particulate matter collection efficiency.

Liquid Recirculation

The scrubbing liquid is recirculated to minimize the amount of liquid that must be treated and discharged. The scrubbing liquid is collected in the sump of the scrubber and mist eliminator. Most systems use a recirculation tank having a liquid residence time of several minutes. This provides sufficient time to introduce alkali additives to adjust the pH back to the proper range. The tank also supplies the recirculation pump used to recirculate the liquid back to the scrubber vessel.

Alkali Addition

An alkali addition system is used on wet scrubber systems that collect acidic particulate matter or treat gas streams that have acidic gases or vapors that could absorb in the liquid stream. The most common acid gases include sulfur dioxide, hydrogen chloride, and hydrogen fluoride. Carbon dioxide formed in most combustion processes is also mildly acidic.

The most common alkalis used for neutralization of acidic material in scrubbers include lime, soda ash, and sodium hydroxide. In some cases, limestone and nahcolite are used. With the exception of sodium hydroxide, all of these materials are typically stored and fed to the recirculation tank in a powder form. Sodium hydroxide is usually fed in solution. The rate of addition of alkali is controlled by a pH meter that is usually mounted in the scrubber recirculation tank or the recirculation pipe leading to the scrubber vessel.

Wastewater Treatment

There is a wide variety of wastewater treatment systems for particulate matter wet scrubbers. Some small scrubbers at large industrial facilities discharge directly to the plant wastewater system, rather than using a dedicated system. Small scrubbers collecting nontoxic particulate matter, such as those at asphalt plants, sometimes use a small two-zone settling pond for wastewater treatment. In these cases, the effluent overflowing the second zone of the pond is returned to the scrubber system.

A small wastewater treatment system is usually installed for large wet scrubber systems. A clarifier is used for removal of the suspended solids that will settle by gravity. The overflow from the clarifier is returned to the scrubber recirculation tank. The clarifier underflow containing the concentrated solids is often sent to a rotary vacuum filter for removal of the suspended solids. The sludge from the rotary vacuum filter is sent to a landfill for disposal.

In some cases, a flocculent is added to the clarifier to optimize solids removal. However, addition of flocculates must not exceed the levels that cause an increase in the liquid surface tension. This can have an unintended detrimental effect on particulate removal efficiency of the scrubber by decreasing the effectiveness of particle impaction into the liquid droplets and by changing the droplet size distribution formed in the scrubber.

Wet Scrubber Capabilities and Limitations

Particulate matter wet scrubbers can provide high efficiency control in a wide variety of industrial applications. Certain types of scrubber systems can provide simultaneous control of both particulate matter and gaseous contaminants. Wet scrubbers are often the control device of choice if there is the potential for embers and/or explosive gases and vapors in the gas stream to be treated.

The main limitation that must be considered in a specific type of wet scrubber is the particle control capability in the submicrometer size range. Many types of wet scrubbers have very limited efficiencies when the inlet gas stream has particles that are mostly in the difficult-to-control size range of 0.1 to 1.0 μm. A typical fractional efficiency curve illustrating the range for performance for the various types of wet scrubbers is shown in Figure 4-3.

The extent of the efficiency decrease in this size range depends primarily on the intensity of the gas liquid contact in the scrubber vessel. Scrubber vessel types that use high energies to develop large differences in the particles and the liquid targets have excellent inertial impaction efficiencies in the difficult to control range. Those scrubbers designed primarily for gaseous contaminant control have low differences in particle-liquid velocities and little or no particle collection in the difficult-to-control size range.

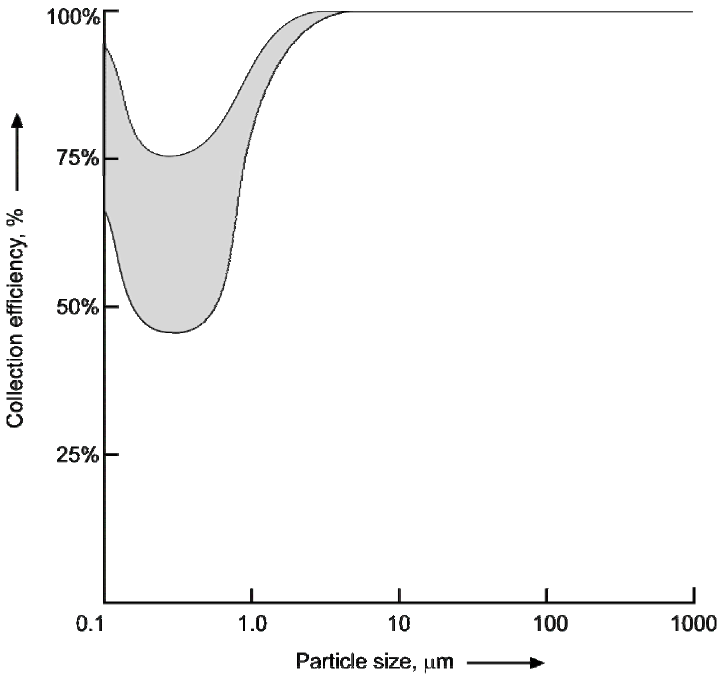


Figure 4-3. Wet scrubber fractional efficiency curve

Another limitation of wet scrubbers is the availability of water. Make-up water is needed to replace water evaporated with the effluent gas stream, water lost as part of the discharged wastewater, and water lost as part of sludge from rotary vacuum filters or similar processing units. In arid climates, there might be insufficient water to use a wet scrubber.

The ability to economically dispose of the wastewater stream in an environmentally sound manner is another limitation of wet scrubbers in some locations. The purge stream from the scrubber recirculation liquid stream might contain dissolved species that have poor leachability characteristics in disposal ponds.

Wet scrubbers usually generate very visible plumes composed of condensed water droplets. The highly visible water droplet plumes that can be quite persistent in cold weather and high humidity conditions can cause visibility problems for nearby roads and airports. Water droplet fallout from the plumes can, in unusual cases, cause freezing problems on walking surfaces and roadways near the facility.

Scrubber Systems

There are many equipment designs for contacting the liquid with the contaminated gas stream. The capability of a particular design can be approximated from the gas stream pressure drop across the scrubber. In general, higher pressure drops indicate more aggressive contact between the liquid and the gas stream, causing smaller particles to be collected with greater efficiency.

Scrubbers with pressure drops less than about 5 in. H_2O are capable of efficiently removing particles greater than about 5-10 μm in diameter. These are referred to as *low energy wet scrubbers*. *Medium energy wet scrubbers* have pressure drops from 5 to 25 in. H_2O. These collectors are capable of removing micrometer-sized particles, but are not very efficient on sub-micrometer particles. Removal of sub-micrometer particles requires significant energy input, ranging from 25 to over 100 in. H_2O, depending on the particle size. These collectors are referred to as *high energy wet scrubbers*.

The following sections discuss common designs that represent each of these categories. Not all scrubber designs will conform to these generalized categories. Collectors that may collect smaller particles than their pressure drop would indicate include electrostatically enhanced scrubbers and condensation growth scrubbers.

Spray Tower Scrubbers

The spray tower scrubber shown in Figure 4-4 is an example of a low energy wet scrubber. The scrubber consists of an open vessel with an array of spray nozzles mounted on multiple headers that are usually spaced about three feet apart. Full cone spray nozzles are used to generate droplets with a mean size of several hundred micrometers. As these droplets fall downward, they are contacted with the particle-laden gas stream passing upward. The particles are collected by impaction onto the droplets

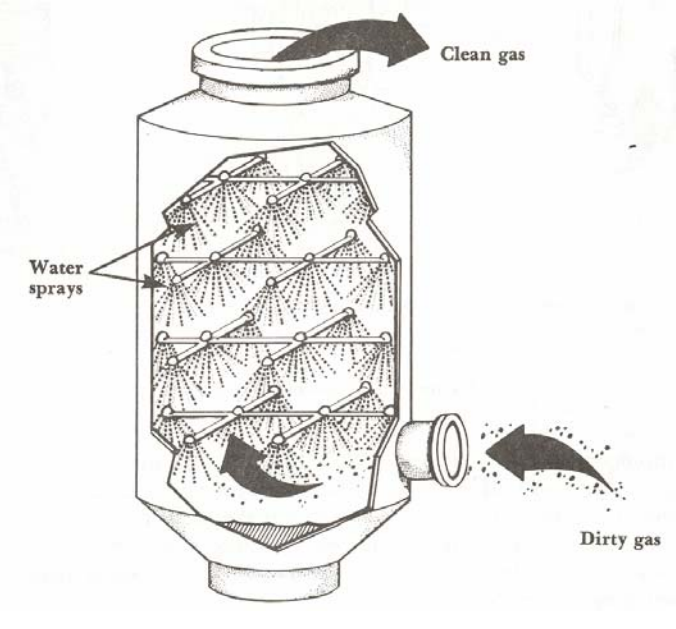


Figure 4-4. Spray tower scrubber

Because of the large size of the droplets produced in the spray tower, mist eliminators may not be used. Instead, sufficient space is provided above the last spray header to allow any droplets carried upward by a turbulent eddy the time to drop downward. Also, because of the relatively low volume occupied by the droplets, changes in the liquid flow rate do not significantly change the pressure drop.

Packed Bed Scrubbers

The packed bed scrubber is an example of a medium energy wet scrubber. In a typical packed bed scrubber, scrubbing liquid is introduced above the bed and trickles down over packing contained in one or more beds arranged in series. The beds can be in either a vertical tower or in a horizontal vessel. These packing materials are designed to provide the largest possible exposed liquid surface area per unit volume of bed, while maintaining a reasonable pressure drop. Some common types of packing materials are shown in Figure 4-5.

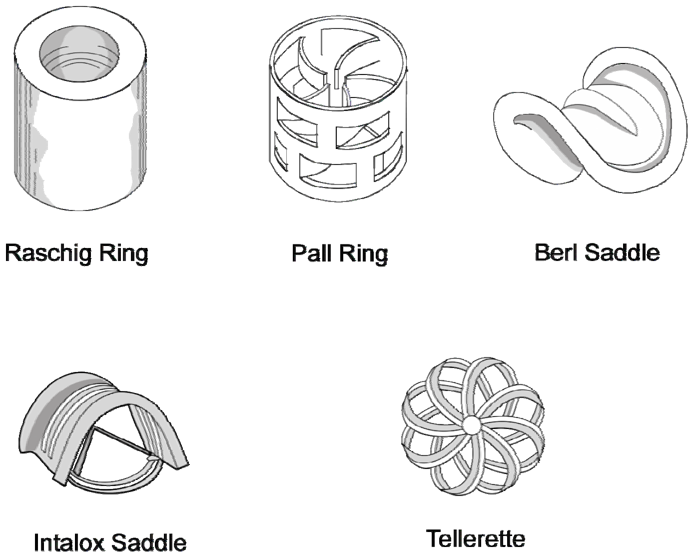


Figure 4-5. Common types of packing materials

In the vertical packed bed scrubbers shown in Figure 4-6, the contaminated gas streams moves upward through the irrigated packing. This arrangement provides the best collection of gases and vapors, but has the lowest collection efficiency for particles. Because of hydrostatic limitations, there is a limit on the upward velocity that can be used for a given quantity of liquid. This limit results in reduced impaction efficiency. Removal efficiencies for particulate matter less than approximately 3 µm are very low. In addition, a portion of the bed can become plugged if the particulate matter concentration is high. The scrubbing liquid flowing downward over the packing moves too slowly to purge out large quantities of particulate matter.

Somewhat better particle removal performance can be achieved in the crossflow packed bed scrubber shown in Figure 4-7. In the crossflow scrubber, the gas stream passes horizontally through the bed, while the scrubbing liquid is distributed on the top of the packing and passes downward. Since the hydrostatic limitations of the vertical arrangement are not present, larger quantities of liquid and higher gas velocities can be used. This provides a modest increase in collection efficiency and helps reduce plugging problems.

The most effective use of the scrubbing liquid is to have it spread out as a thin film on the surface of the packing. As long as this condition is maintained, increasing the liquid flow rate does not significantly affect pressure drop. However, if the liquid begins to accumulate in the spaces within the packing, the pressure drop will increase. This condition generally results in reduced collection efficiency.

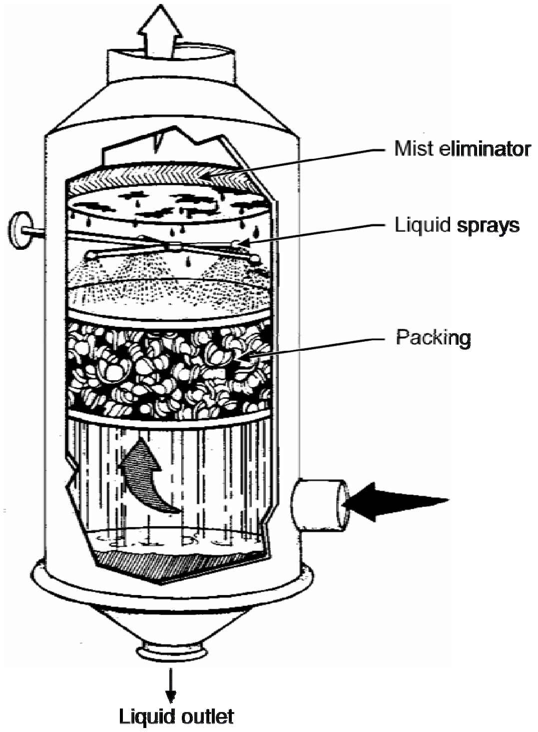


Figure 4-6. Vertical packed bed scrubber

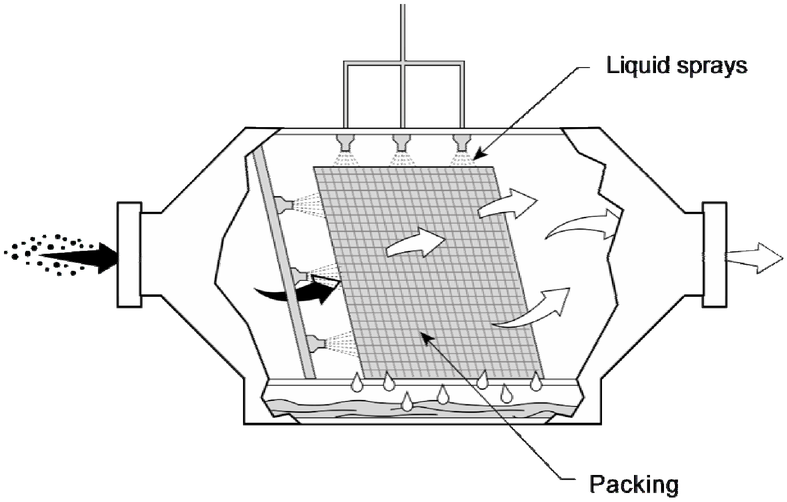


Figure 4-7. Horizontal packed bed scrubber

Tray Scrubbers

Another example of a medium energy scrubber is the tray scrubber. Tray scrubbers are vertical towers with multiple trays for contacting the gas and liquid streams. The liquid stream enters from the top, flows across the tray and then down to the next tray. The gas moves upward through holes in the tray, creating a bubbling action that provides for particle collection by impaction. Tray scrubbers are usually selected for applications involving particulate matter greater than approximately 1 μm. They have limited efficiency below 1 μm due to the limits to the gas stream velocities through the openings in the trays.

There are several tray designs to contact the gas with the liquid. A typical impingement tray scrubber is shown in Figure 4-8. The trays are metallic plates with numerous holes approximately 3/16 inches in diameter. Small baffle plates are mounted directly above each of the holes. Scrubbing liquid enters as a stream at the top of the unit. Overflow weirs set the height of the liquid on each tray to approximately 1 to 1.5 inches. After passing across the tray, the liquid passes down a vertical passage called the *downcomer*. A liquid seal at the bottom of each downcomer allows the liquid to flow freely to the next tray while preventing the gas stream from short-circuiting up the downcomer.

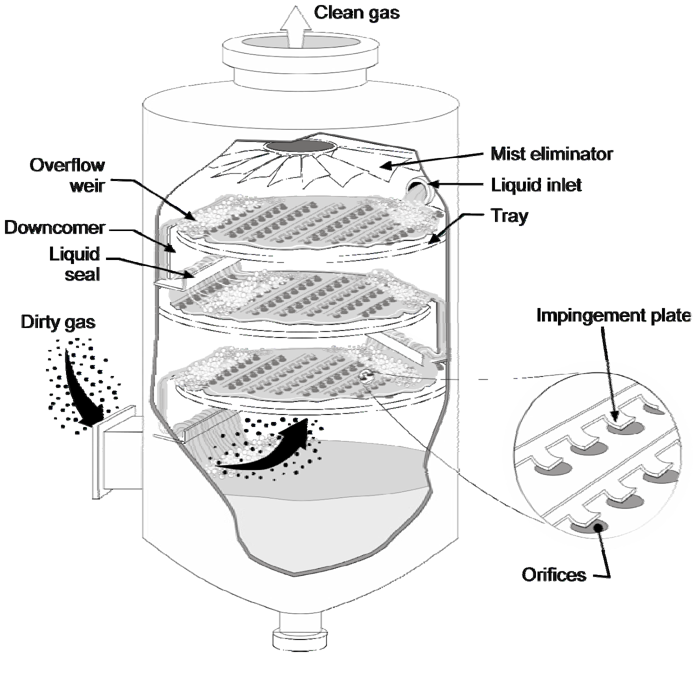


Figure 4-8. Impingement plate scrubber

The gas stream is accelerated as it passes through the impingement tray holes. The gas jets atomize a portion of the liquid above the tray, creating droplets that serve as the impaction targets. The gas velocity through the holes must be high enough to provide for efficient atomization of the liquid and must have sufficient force to prevent liquid from dripping through the holes. Excessive liquid dripping, termed *weepage*, reduces collection efficiency, particularly for gases and vapors.

Sieve tray scrubbers are conceptually similar to impingement tray scrubbers, but do not have baffle plates over the holes. These trays have larger holes and are, therefore, less vulnerable to pluggage. However, the gas velocities are slightly lower than impingement tray scrubbers, reducing the collection efficiency.

The performance of tray scrubbers is dependent on the physical condition of the tray and the holes in the tray. Bowed or sloped trays will imbalance the height of the scrubbing liquid. The gas stream will preferentially pass through the holes with the lowest liquid height, because this is the low resistance path. The portion of the gas stream that continues to pass through the holes with high liquid levels will be slow and have reduced collection efficiency.

Plugging the holes in the tray must be avoided. Tray scrubbers are vulnerable to plugging due to the small diameters of the holes. Suspended solids can accumulate in these holes and harden, making it necessary to drill or rod them out. Due to the vulnerability to solids accumulation, the liquor recirculation system and treatment system are especially important. The suspended solids must be restricted to low levels by use of clean scrubbing liquid, to the extent possible, and by effective treatment of the recirculated liquor.

Increasing the liquid flow rate into a tray scrubber will result in a modest increase in pressure drop. As the flow rate increases, flow over the weir causes the liquid level on each tray to rise slightly.

Ionizing Wet Scrubbers

The ionizing wet scrubber, shown in Figure 4-9, is the only type of scrubber that uses electrostatic attraction as the primary technique for particle capture. The inlet gas stream passes through a short ionizer section composed of a number of high voltage discharge electrodes separated by small, grounded collection plates. The ionizer section is conceptually similar to a conventional negative corona electrostatic precipitator field; however, it is designed to impart a high negative electrical charge to the particles and not to collect them. The ionizer section usually operates at secondary voltages of 20 to 30 kilovolts DC.

Following the ionizer section, the gas stream passes through a crossflow packed bed section. The particles are captured in the liquid layers surrounding the packing material due to the induced static charge in the liquid layers caused by the highly charged particles. These units are capable of the removing particles extending into the submicron range. However, they are not intended for sources generating high concentrations of submicron particulate matter.

Venturi Scrubbers

The venturi scrubber is an example of a high energy wet scrubber, although it can also be operated as a medium energy scrubber. The fixed throat venturi, shown in Figure 4-10, is one of the most common designs. The gas stream entering the converging section of the venturi is accelerated to a velocity between 300 and 600 feet per second at the throat inlet. Liquid is injected into the throat and atomized into droplets with a mean size of 50 to 75 micrometers by the impact of the gas stream. These droplets are initially moving relatively slowly, and it takes time for them to accelerate to the same velocity as the rapidly moving particles entrained in the gas stream. Impaction occurs on the droplets due to the large difference in the gas stream velocity and the velocity of the accelerating droplets. The gas stream leaving the throat enters the diverging section. Here, the velocity of the gas stream is gradually reduced and the velocities of the particles and the droplets approach one another. Impaction does not occur efficiently in this section because the particles and droplets are moving at similar velocities and in the same direction.

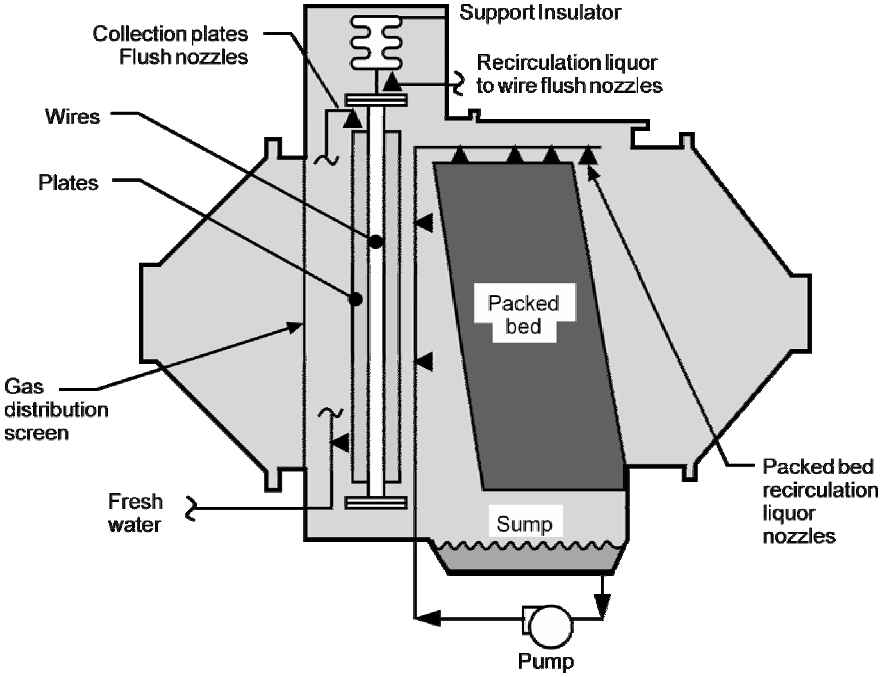


Figure 4-9. Ionizing wet scrubber

The effectiveness of venturi scrubbers is related to the maximum difference in the droplet and gas stream velocities. Because the fixed throat has a constant open area, the actual gas velocity achieved in the throat section depends on the gas flow rate. Particle collection efficiency is, therefore, gas flow rate dependent. Fixed throat venturi scrubbers are used on sources where the gas flow rate is relatively constant or where the particle size distribution is sufficiently large that some variation in gas velocity is tolerable.

Proper liquid distribution is essential in obtaining optimum performance in a venturi scrubber. Because of the high gas velocities, the residence time of the gas stream in the venturi throat, where most collection occurs, is only 0.001 to 0.005 sec. Most of the particles that penetrate the throat will pass through the remainder of the scrubbing system uncollected.

Obviously, portions of the venturi throat without any atomized scrubbing liquid will have no capability for collecting particulate matter.

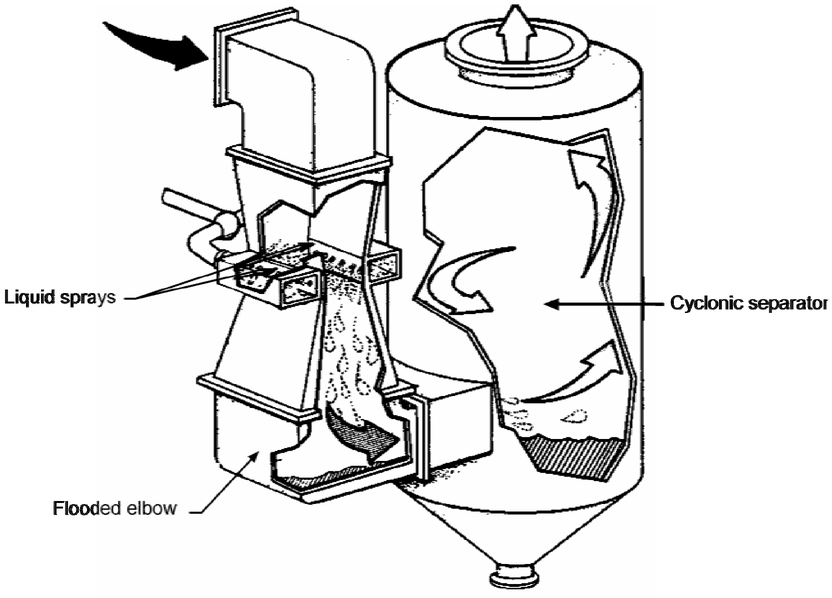


Figure 4-10. Fixed throat venturi scrubber

The venturi scrubber system shown in Figure 4-10 includes a flooded section in the elbow directly below the venturi. This elbow leads from the diverging section to the mist eliminator. This 6 to 12 inch deep section is termed a *flooded elbow* and provides abrasion protection. Droplets that have accelerated to a high velocity in the venturi will erode the bottom of this duct if it is not protected.

One option for dealing with varying gas flow rate while maintaining good efficiency is the adjustable throat venturi shown in Figure 4-11. In this type of unit, moveable dampers are used to vary the throat area in order to control the gas velocity. The position of the dampers is usually set automatically to maintain a set pressure drop across the unit, although in some units they are positioned manually. These damper blades, and other types of flow restrictors, must be made of abrasion resistant materials because of the high velocities through the throat.

It should be recognized that, if the flow rate is varying, so is the liquid-to-gas ratio. If the variation in flow rate is large, the liquid-to-gas ratios at the extreme ranges of operation may result in reduced collection efficiency. Systems with large flow rate variation must also modulate the liquid flow in order to keep the liquid-to-gas ratio in an acceptable range for optimum performance.

The venturi shown in Figure 4-11 uses spray headers to distribute the liquid onto the side walls of the converging section. This technique is called *wetted approach* and serves to protect the section from abrasion by the entering particles. The liquid is sheared off the side walls and entrained in the gas stream as it enters the throat. Alternatively, the liquid can be introduced from a series of tangentially oriented pipes and swirled down the converging section of the venturi until the liquid is entrained. In addition, a centrally mounted nozzle is used to distribute liquid to the center of the throat. Because of the very high gas velocities in the throat, it is difficult for the liquid droplets entrained from the wall to penetrate to the center.

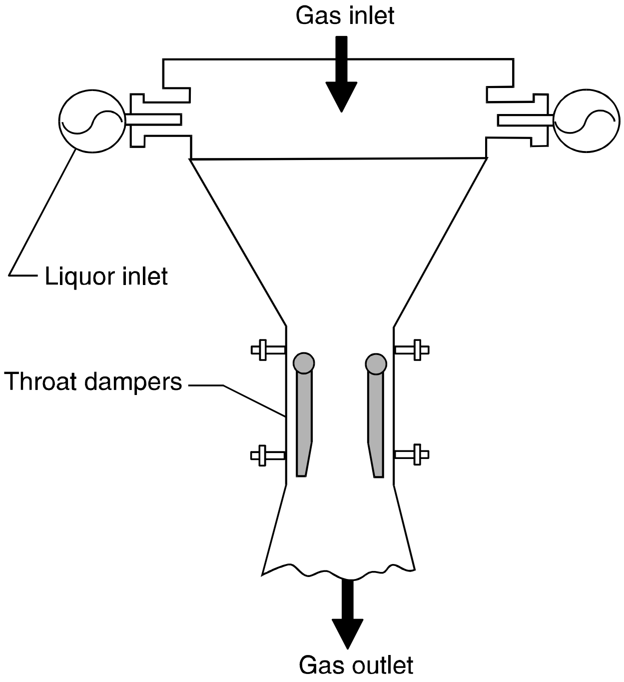


Figure 4-11. Adjustable throat venturi scrubber

The typical static pressure drop across a venturi scrubber varies from a low of 5 in. H_2O to values exceeding 100 in. H_2O. High static pressure drops are used only in situations demanding high efficiency removal of very small particulate matter. The static pressure drop is related to the gas velocities in the throat and the quantity of scrubbing liquid used. Because the energy for atomization comes from the gas stream, changes in the liquid flow rate will cause significant changes in the pressure drop.

Inspection

High efficiency particulate scrubber systems are relatively complex. There are a number of inspection points included in the Basic Level 2 inspection partly because of the complexity of the systems and partly because of monitoring requirements included in NSPS regulations.

Basic Level 2

- Visible emissions
- Droplet reentrainment

- Scrubber static pressure drop
- Liquid flow rate
- Inlet and outlet gas temperature

Follow-up Level 2

- Mist eliminator static pressure drop
- Spray nozzle supply header pressure
- Recirculation pump discharge pressure
- Gas cooler outlet temperature
- Evaporative cooler spray liquid quality
- Liquid pH
- T-R set electrical data (ionizing wet scrubbers)
- Corrosion and erosion
- Component failure records
- Internal inspection reports

This list of inspection points does not include opacity monitoring systems. These are not used on particulate scrubber systems or absorber systems since the condensed water droplets (that are often present in the gas stream) scatter light. It is not possible to differentiate between light scattering caused by particulate matter and by water droplets. Accordingly, opacity data are limited to visible observations.

Basic Level 2: Visible Emissions

The condensed water droplets in the gas stream that preclude the use of an opacity monitor also complicate visible emission observations of the plume. It is necessary to observe the plume at a point immediately downwind of the point where the condensed water droplets evaporate. The point of droplet evaporation is clear in Figure 4-12.

Figure 4-12. Visible emission of a scrubber plume

The point at which the water droplet plume (often termed a steam plume) dissipates is often characterized by a change in the color and texture of the plume. A residual plume caused by particulate matter or nucleated acids is often bluish-white, brownish-white, or gray. The portion of the plume dominated by water droplets is often a bright white. When the relative humidity is high, the water droplet plume does not dissipate until the plume has traveled a long distance. In this case, the observed opacity can be substantially below the true value that would be visible at the stack discharge if the water droplets were not present. Visible emission observations of the residual plume are not always possible. In Figure 4-12, plumes from several sources have merged into a single plume. Therefore, the observed opacity is higher than the true opacity from any one of the sources.

Basic Level 2: Droplet Reentrainment

The symptoms of droplet reentrainment include the following:

- Fallout of droplets within 50 yards downwind of the stack
- Discoloration of adjacent surfaces
- Mud lip around the stack
- Heavy drainage from open ports on the stack

During cold weather, droplet reentrainment could also be indicated by the build-up of ice on structural steel and adjacent surfaces near the scrubber stack. It is important to note that many particulate scrubbers and gaseous absorbers serve batch processes, and the reentrainment emissions can be very intermittent. Therefore, the long-term symptoms such as deposition patterns and drainage patterns are especially useful. A stack with droplet reentrainment problems is shown in Figure 4-13.

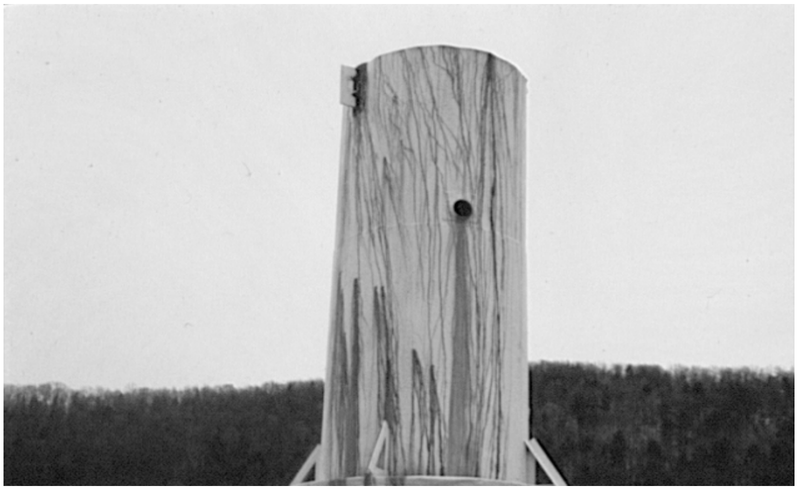


Figure 4-13. Drainage pattern on wet scrubber stack

When droplet reentrainment is noticed, it is usually helpful to conduct a follow-up check for mist eliminator cleaning frequency. Solids build-up on the mist eliminator can increase the localized gas velocities and cause droplet reentrainment off the trailing edges of the mist eliminator.

Basic Level 2: Scrubber Static Pressure Drop

The static pressure drop is a useful indirect indicator of scrubber performance. High values of static pressure drop are associated with the high gas velocities that favor high efficiency particle impaction.

The relationship between particulate emissions and static pressure drop is indicated by the test data shown in Figure 4-14. These data are from two high efficiency venturi scrubber systems serving two identical Q-BOPF furnaces in a single plant and were taken during the oxygen blowing cycle when the emission quantities peaked.

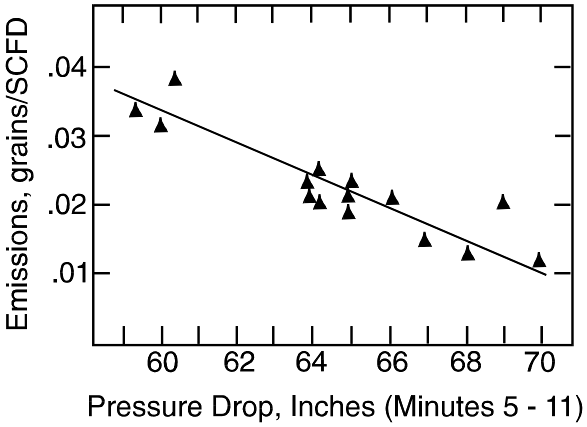


Figure 4-14. Efficiency of two venturi scrubbers serving BOPF operations

Static pressure drop-removal efficiency graphs like this one can only be prepared when the source has been tested on numerous occasions. If only a few tests on a specific site have been conducted, the statistical confidence interval is too large, and conclusions can not be based on the correlation. Also, data from units at different plants cannot be combined into a single correlation because there are site specific differences in particle size distributions, gas-liquid distributions, and liquid surface tension. All four factors can have a large impact on the particulate emissions without necessarily influencing the observed static pressure drop. Accordingly, the static pressure drop data can only be evaluated for a specific site.

Static pressure drop data are a useful qualitative indicator of scrubber performance as long as the process operating conditions are similar to baseline conditions. A decrease of more than several inches of water in the static pressure drop during peak gas flow periods could be associated with decreased collection efficiency. An increase in the residual opacity of the stack further supports this conclusion. Changes in static pressure drop can occur because of a variety of problems:

- Erosion of adjustable throat mechanisms
- Intentional changes in the position of adjustable throat mechanisms
- Decrease in gas flow rates
- Severe decrease in the liquid flow rate
- Malfunctioning static pressure drop gauge

Evaluation of changes in the gas flow rate and liquid flow rate will be discussed in later sections of the Basic Level 2 inspection. This information will be helpful in evaluating changes in the static pressure drop.

The adequacy of the gauge should be evaluated to confirm that there has, in fact, been a significant change in scrubber performance. The monitoring conditions inside particulate scrubbers are relatively hostile, and a variety of instrument problems are possible:

- Plugging of the upstream or downstream ports
- Water condensation within the gauge
- Freezing of condensed water within the gauge
- Heat-related damage to a gauge mounted too close to a hot surface
- Evaporation of water from the manometer

The adequacy of the gauge can be checked by comparing the static pressure gauges and static pressure drop data throughout the entire system. For example, the sum of all of the static pressure drops across cyclones, scrubbers, absorbers, evaporative coolers, and other vessels should be slightly less than the fan inlet static pressure. The difference between the two values is the frictional loss encountered by the gas stream passing through the ductwork and the loss associated with accelerating the pollutant-laden gas stream into the hood. Obviously, the accuracy of this mathematical check is limited because all the gauges are subject to some error.

Changes in the static pressure drop are typically due to changes in the gas flow rate or to significant physical problems with the components. These changes usually impair the gas-liquid contact and thereby reduce the collection efficiency of the system. For example, high static pressure drop in packed bed scrubbers is often due to partial plugging of the bed. This causes poor gas-liquid distribution. Low static pressure drop across the bed can be due to the corrosion and collapse of the retention screens supporting the bed. In the case of tray scrubbers, low static pressure can be due to bowing, warping, or sloping of the trays or corrosion of the tray overflow weirs that maintain adequate liquid levels on the trays. Erosion of adjustable throat mechanisms in venturi scrubbers can cause reduced static pressure drop. All of these potential problems should be checked by plant personnel during each major scrubber outage.

Basic Level 2: Liquid Flow Rate

Monitoring the liquid flow rate is required by New Source Performance Standards (NSPS) and is also included in many operating permits for existing sources. The rationale for these requirements is that scrubber performance is impaired when the liquid recirculation rate is low.

The liquid flow rate is monitored in terms of gallons per minute and is evaluated in terms of the gallons per minute per 1,000 actual cubic feet per minute of gas flow. High efficiency particulate scrubbers usually operate with liquid-to-gas ratios of 5 to 20 gallons per 1,000 acf. Particulate removal efficiency decreases significantly at liquid-to-gas ratios less than 4 gallons per 1,000 acf. The liquid-to-gas ratio for gaseous absorbers ranges from 5 gallons per 1,000 acf to more than 100 gallons per 1,000 acf.

On moderate-to-large particulate scrubbers and gaseous absorbers, the liquid flow rate is monitored continuously. The types of flowmeters include the following:

- Magnetic flowmeters
- Ultrasonic flowmeters
- Swinging vane flowmeters
- Rotameters
- Orifice meters

Liquid flow rate data are usually included on process log sheets. On large systems, it may also be recorded continuously. The available data should be reviewed for the time period since the last inspection to confirm that the scrubber has been operated properly. Also, calibration data for the flowmeter should be evaluated whenever it is available.

The liquid flow rate during the inspection should be compared with baseline values. If the flow rate has decreased, the present liquid-to-gas ratio should be calculated using estimated gas flow rate data in the agency files. If the value is significantly below the baseline level, the following additional inspection data should be evaluated:

- Liquid supply header pressures at the scrubber inlet
- Recirculation pump discharge pressures
- Symptoms of pipe freezing or blockage
- Symptoms of centrifugal pump cavitation

The liquid pH levels during the previous several weeks should also be checked. Liquid pH levels above 9 can lead to the precipitation of calcium and magnesium solids. Solids build-up in piping, nozzle supply headers, and nozzles can restrict liquid flow.

Malfunctions of the liquid flow rate meter can lead to low indicated flow rates. For example, solids build-up problems in the piping can blind the sensors of magnetic flow meters and can cause low readings. If the recirculation flow rates are low, there should be other symptoms of problems. These symptoms could include increased plume residual opacity, increased scrubber outlet gas temperature, decreased pump discharge pressure, and decreased supply header pressures.

Basic Level 2: Inlet and Outlet Gas Temperature

The inlet gas temperature should be compatible with the scrubber materials of construction. It should also be below the vaporization temperature of the liquid, if a cooling section has not been provided inside the scrubber. Inlet gas temperature is additionally important for absorbers, since the solubility of gaseous contaminants is inversely related to the gas temperature. Increases of 10°F to 30^{o}F over the baseline temperature can reduce the collection efficiency of the absorber.

Temperature information is also a useful indicator of gas-liquid distribution problems. If the liquid distribution is not adequate, collection efficiency will be reduced. When the gas-liquid distribution is good, the outlet gas stream temperature will be at the adiabatic saturation temperature. This simply means that the gas stream will be saturated with water vapor. The adiabatic saturation temperature can be easily determined with a psychometric chart, if the inlet gas stream dry bulb temperature and absolute humidity are known. Unfortunately, the absolute humidity of the entering gas stream is rarely available. While it could be estimated, errors can significantly affect the value of the saturation temperature determined from the psychometric chart, possibly leading to erroneous conclusions.

A more direct way to evaluate liquid distribution problems is to look at the difference between the inlet and outlet gas temperatures. If that temperature difference has decreased, liquid distribution problems are likely. Other symptoms that are useful for identifying possible distribution problems include:

- Higher-than-normal supply header pressures
- Apparent pipe or header freezing
- Malfunctioning adjustable throat linkages or actuators

During outages, plant maintenance personnel can conduct internal inspections to search for symptoms of maldistribution. In some cases, erosion patterns on the inlet ductwork provide a clear indication of maldistribution. Other symptoms of maldistribution include severely eroded or corroded adjustable throat mechanisms and solids deposits.

Follow-up Level 2: Mist Eliminator Static Pressure Drop

The static pressure drop across the mist eliminator is used as an indicator of the physical condition of the mist eliminator. The static pressure drop is strictly a function of the geometry of the mist eliminator, the gas flow rate through the mist eliminator, and the gas density.

Deviations from the baseline static pressure drop levels indicate either changes in the gas flow rates or buildup of solids on the mist eliminator. Usually, the pressure drops across mist eliminators vary from 0.5 in. H_2O to 2 in. H_2O. Some commercial designs have pressure drops as high as 4 in. H_2O. Increases in the static pressure drop of more than 1 in. H_2O could indicate the potential for reentrainment. Increases of more than this value could indicate that excessive forces are being placed on the mist eliminator elements and supports. Because of the large area of the mist eliminator, a large pressure differential across the unit can cause damage.

Mist eliminator static pressure drop records should be evaluated for a number of operating days since the last inspection to confirm that the static pressure drop levels have increased from baseline levels. If high pressure drop is occurring, it might be necessary to activate the cleaning system more frequently or for a longer operating time. Usually, mist eliminator washing lasts from several minutes to more than 15 minutes. When there is a chronic problem with high static pressure drop, it might be advisable for plant maintenance personnel to inspect the spray nozzles used to clean the mist eliminator elements. The solids deposition pattern remaining on the mist eliminator provides a clear indication of inadequate coverage. In addition, problems with the nozzles or supply headers can be identified during these internal inspections.

Values well below the baseline range suggest that part of the mist eliminator has fallen apart or otherwise been damaged. Structural failure of the mist eliminator is possible because of the forces that can be imposed on the surface when it is significantly blinded. For example, a 6-foot diameter mist eliminator immediately upstream of a fan with an inlet static pressure of -10 in. H_2O can be subject to a force of more than 1,400 pounds if it is totally plugged. Corrosion related weakening of the supporting frame on the mist eliminator can cause the entire mist eliminator to break into parts and be pulled toward the fan. Also, some mist eliminators constructed of FRP and other synthetic materials can suffer adhesive failure if there is a gas temperature spike. This can cause part of the mist eliminator to break away. The gaps left in the mist eliminator have a very low static pressure drop, and most of the gas stream channels through this area. Accordingly, the effectiveness of the mist eliminator is compromised.

Follow-up Level 2: Spray Nozzle Supply Header Pressure

The supply headers are the pipes that deliver recirculation liquid to the groups of nozzles surrounding the inlet of the scrubber or absorber. The supply header pressures are used primarily as indicators of the physical condition of the spray nozzles and piping. Assuming that the recirculation liquid flow rate is relatively constant at the baseline levels, an increase in the supply header pressure suggests solids build-up. If the supply header pressure is lower than baseline values, the nozzle orifices could have eroded.

Nozzle spray angles are distorted when solids begin to build-up in the nozzle. If the problem continues, it is possible for the solids to completely block the nozzle or a portion of the header supplying some of the nozzles. The latter condition is common when the suspended solids levels in the liquid are high and there is a dead end in the header where solids can accumulate and pack tightly. Build-up of solids within the nozzle and the blockage of flow to a group of nozzles can adversely affect gas-liquid distribution in the scrubber or absorber.

Erosion of the nozzle orifices can be caused by the erosive action of the suspended solids in the liquid stream or by corrosive action at low liquid pH levels. Erosion and corrosion of the nozzle orifices also disturbs gas-liquid distribution.

Pressure gauge malfunctions can cause apparent changes from baseline pressure levels. The accumulation of either solids or ice in the inlet line to the pressure gauge can cause false readings.

Changes in the liquid flow rate and pressure obviously affect the pressures in the supply headers. Changes in the recirculation liquor flow rate can be identified based on the discharge pressures of the recirculation pumps and based on the recirculation liquid flow rate meter.

Follow-up Level 2: Recirculation Pump Discharge Pressure

Most centrifugal pumps have a discharge pressure gauge to provide a general indication of pump operations. Problems that reduce the pumping rate usually decrease this pressure:

- Pump cavitation
- Air infiltration into the pump
- Pump impeller erosion and corrosion
- Pump inlet strainer blockage

Pump cavitation is the vaporization of liquid as it passes over the pump impeller. Vaporization is caused by the reduced pressure that occurs as the liquid enters the pump. Cavitation is possible whenever the liquid temperature is relatively high or when there is insufficient Net Positive Suction Head (NPSH). The latter is simply a measure of the pressure existing in the inlet piping to the centrifugal pump. This pressure must be sufficiently high so that the suction effect at the pump inlet is not large enough to reduce the pressure to a level where vaporization can occur. The vapor bubbles created during passage across the pump impeller can cause severe metal erosion. The presence of cavitation is indicated by a distressed pump sound and by reduced liquid flow rates and discharge pressures.

Pump impeller erosion and corrosion are caused primarily by the abrasive action of suspended solids in the recirculation liquid or by corrosive fluorides, chlorides, or other materials present in the liquid. The rate of corrosion is relatively fast at low pH levels.

Pockets of air trapped in the inlet piping to scrubbers can impede recirculation liquid flow. The entrainment of air in the liquid stream can be caused by poor pump intake piping from the recirculation tanks or by air infiltration into the piping. The pump inlet piping is usually sloped at least one degree to ensure that air does not build up in pockets within the pipe and suddenly move into the pump.

Strainers are used on piping to protect the pump impellers from abrasive particles of metal that become entrained in the recirculation liquid stream. Bypass lines around the strainers are sometimes used to allow for cleaning. Strainers are not appropriate for all scrubber applications.

Follow-up Level 2: Gas Cooler Outlet Gas Temperature

The outlet temperature of the cooling system must be below the temperature limits for the materials of construction used in the scrubber or absorber system. In some cases, corrosion and erosion resistant linings are used on metal components. These can be damaged at high temperatures. High temperatures also cause water evaporation from the atomized droplets in the scrubber, impeding particle impaction. For both of these reasons, the outlet gas temperature of the cooling system must be below the limits for the specific system being inspected.

Cooling system outlet gas temperatures should be evaluated using the temperature monitoring data recorded in the control room for the process being inspected. Peak gas temperatures are most important for those processes with cyclic operations such as charging and tapping.

Follow-up Level 2: Evaporative Cooler Spray Liquid Quality

Suspended or dissolved solids contained in water sprayed into evaporative coolers can be released as difficult-to-control submicron particles as the droplets evaporate to dryness. The spray water used in evaporative coolers should be as clean as possible. A sample of the water should have little, if any, turbidity.

This particle formation mechanism can have a significant impact on the overall scrubber performance if recirculation liquid from the scrubber is used for evaporative cooling. The typical solids levels in the recirculation liquid are relatively high. Accordingly, the type of liquid being used in the evaporative cooler should be determined.

Follow-up Level 2: Liquid pH

The liquid pH should usually be in the range of 5 to 9, with higher values at the inlet to the scrubber and lower values at the outlet. If the pH is too high, calcium and magnesium compounds precipitate to form scale deposits in piping, headers, nozzles, and tanks. If the pH is too low, the reactions in absorbers of acid compounds such as sulfur dioxide and hydrogen chloride can stop, and some of the dissolved acid gases can volatilize back into the gas stream. Also, the rate of corrosion increases as the pH decreases below 5.

Some variations in the liquid pH are common due to variations in the rate of acid gas generation in the process and variations in the rate of alkali feed to the scrubber. Short term excursions below 5 or above 9 will not cause significant damage. However, long term operation outside of the normal pH range can lead to a variety of scrubber performance problems. The operating records should be evaluated for the time period since the last inspection to determine if pH fluctuations are chronic or severe.

Instruments for measuring pH are prone to mechanical damage, scale-related blinding, and drift. The instruments must be checked frequently to ensure that the data are accurate and representative of the liquid at the monitoring location.

Follow-up Level 2: T-R Set Electrical Data (Ionizing Wet Scrubbers)

The secondary voltage, secondary current, and spark rate of ionizing wet scrubbers should be checked if high opacity is observed. The packed bed scrubber section of this unit has a limited ability to collect small particles unless the particles are highly charged.

The secondary voltage should be compared with the baseline value and with industrial averages for this type of collector. Secondary voltages lower than 18 kilovolts are often associated with increased particulate emissions.

The secondary current should also be compared with baseline data. Low values are usually caused by solids build-up on the small plates or on the small diameter discharge wires. The plates are cleaned approximately once every four hours. The discharge wires are cleaned approximately once every eight hours, unless solids loadings in the inlet gas stream are high. During cleaning of the discharge wires, the T-R set is deenergized for a period of approximately 5 minutes.

High sparking rates are due primarily to misalignment problems in the ionizer section. Unlike conventional precipitators, the solids build-up on the surfaces should be small, and dust layer resistivity related sparking is not an issue.

Follow-up Level 2: Corrosion and Erosion

Corrosion or erosion damage to the scrubber or absorber shell can occur due to high gas velocities and the potentially corrosive chemicals in the system. A visual inspection should be conducted to visually identify any areas with apparent damage.

In addition to the obvious financial implications for the operators, the corrosion and erosion damage can contribute to particulate emissions. Air infiltration through the gaps and openings can reduce the total quantity of gas being pulled from the process hoods. Air infiltration can be especially severe in the case of high efficiency venturi scrubbers because the outlet static pressures are often -40 in. H_2O to -80 in. H_2O. It is often possible to hear the air infiltration leaks caused by these high differences between the ambient pressure and the system pressure.

Follow-up Level 2: Component Failure Records

When frequent scrubber or absorber malfunction or upset reports have been submitted, it might be helpful to evaluate the component failure records. The purpose of this review is to confirm that plant personnel have identified the fundamental problems and that there is reason to believe that the frequency of these excess emission incidents will decrease.

For example, records should be maintained indicating the locations of all spray nozzles that plug or erode. All the nozzles removed should be inspected to evaluate possible causal factors. If deposits are present, it might be helpful to chemically identify the materials responsible. The nozzle failure spatial distribution data and other analyses will be helpful for determining means to correct the problem by redesigning the supply header, by switching to a different type of nozzle, or by improving the recirculation liquid quality.

The rate of component failure should be carefully tracked by plant personnel. An increase from the normal or baseline rate should initiate a detailed evaluation of the scrubber system. For example, scale build-up in piping or around pH sensors could create erroneous instrument pH readings. Unexpectedly high levels could be causing solids build-up in nozzles, headers, and scrubber internals. Unexpectedly low pH levels or high chloride levels could cause rapid corrosion related damage. In either case, it is advantageous for plant personnel to identify and correct the problem before significant equipment damage and excessive emissions occur.

Follow-up Level 2: Internal Inspection Reports

These should be reviewed by agency personnel when chronic emission problems have been occurring. The scope of these internal inspections often includes the following:

- Physical condition of liquid distributors in packed bed scrubbers
- Physical condition of spray nozzles
- Solids accumulation in mist eliminators or packed beds
- Bows, warps, and slopes in impingement trays
- Corrosion of packed bed retention screens
- Obvious gas maldistribution patterns

The reports prepared by plant maintenance personnel are useful in reviewing the plant's proposed correction actions. Agency personnel should not, under any circumstances, accompany plant personnel during the internal inspections. Therefore, these reports are the only source of information concerning physical problems that are not directly indicated by the operating data for the absorber system.

Review Problems

1. An impingement tray scrubber has the following operating conditions. Is there any reason to conduct a follow-up inspection of this unit?

	Inspection Data
Visible emissions, %	5
Mist eliminator pressure drop, in. H_2O	0.6
Outlet gas temperature, ^oF	91
Inlet gas temperature, ^oF	86
Tray pressure drops, in. H_2O	
Tray 1	0.6
Tray 2	1.4
Tray 3	0.8
Recirculation liquid pH	7.0
Recirculation liquid flow, gpm	30

2. An adjustable throat venturi scrubber serving a hot mix asphaltic concrete plant dryer has the following operating conditions. What are possible causes of the increased opacity?

	Inspection Data	Baseline Data
Visible Emissions, %	15	5-10
Static Pressure Drop, in. H_2O	23	16
Inlet Gas Temperature, °F	290	310
Outlet Gas Temperature, °F	142	131
Mist Elim. Pressure Drop, in. H_2O	1.0	1.3
Recirculation Liquid Flow, gpm	100	105
Recirculation Liquid pH	6.0	6.5
Dryer Aggregate Outlet Temp., ^oF	295	300
Asphalt Binder	AC 40	AC 40
Production Rate, ton/day	100	100

3. The pressure gauge on the liquor line leading to the nozzles of a spray tower scrubber increased from a baseline value of 60 psig to a present value of 88 psig. What is one possible explanation for this condition?

   a. Plugging of some of the nozzles
   b. Erosion of the pump impeller
   c. Erosion of the nozzles

4. Why are the inlet and outlet gas temperatures used in the evaluation of wet scrubbers?

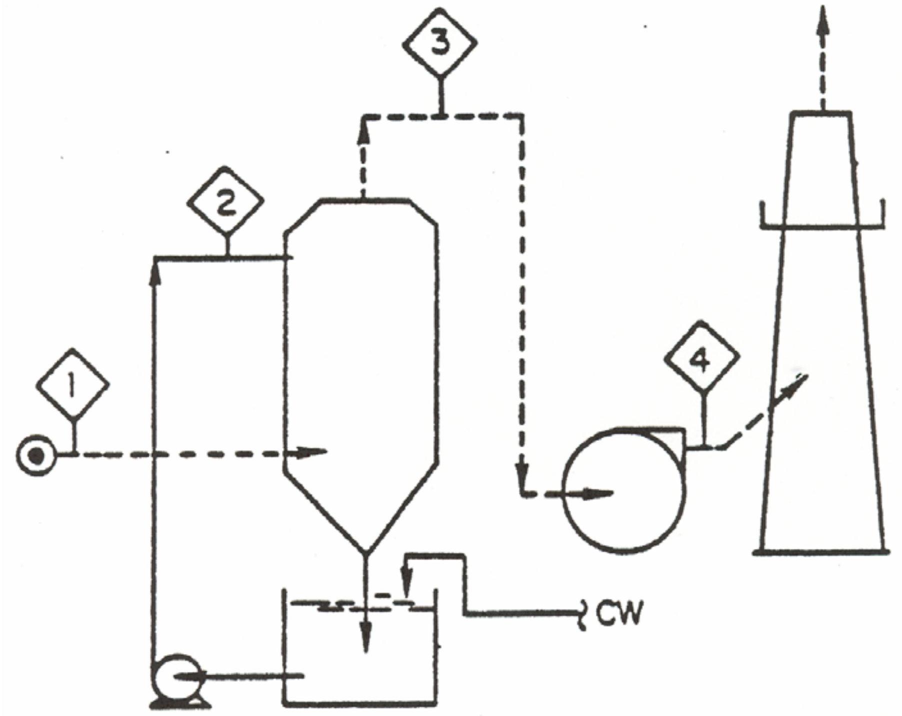
   a. To evaluate gas-liquid distribution in the scrubber
   b. To evaluate mass transfer driving forces in the scrubber
   c. To evaluate the solubility of dissolved solids in the recirculated liquor
   d. None of the above

5. What is the normal liquid-to-gas ratio for high static pressure drop venturi scrubbers used for particulate matter control?

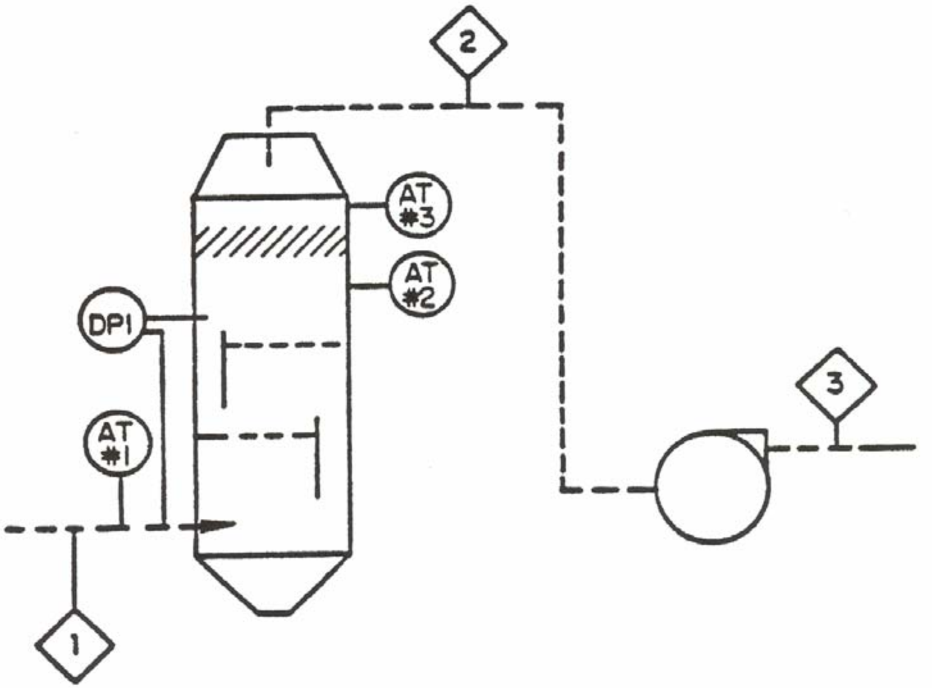
   a. 1 to 2 gallons per 1,000 acf
   b. 2 to 5 gallons per 1,000 acf
   c. 5 to 20 gallons per 1,000 acf
   d. 20 to 50 gallons per 1,000 acf
   e. 50 to 75 gallons per 1,000 acf
   f. 75 to 150 gallons per 1,000 acf

6. What is the pressure drop across the scrubber shown below if the static pressure at Point 1 is -16 in. H_2O and the static pressure at Point 4 is -0.5 in. H_2O?

7. A static pressure measurement at Point 1 indicates a value of +4 in. H_2O. Can this be dismissed as being obviously in error?



8. The differential pressure indicator (DPI) on the system below is reporting 18 in. H2O. Using portable instruments, the measured static pressure at AT#1 is -12 in H2O and at AT#3 is -20 in. H2O. Is there reason to suspect the accuracy of the permanently mounted gauge?



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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:

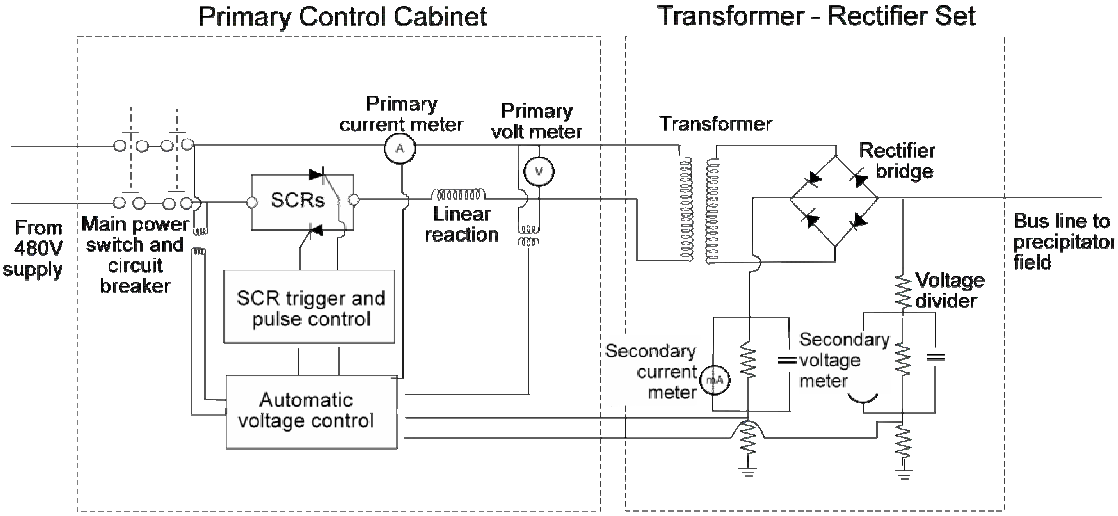
- ***Step 1*** is the electrical charging and migration of particles toward a vertical collection surface.
- ***Step 2*** involves the gravity settling (or draining in the case of liquids) of the collected material from the vertical collection surfaces.
- ***Step 3*** is the removal of the accumulated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



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

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:

- Primary voltage limit
- Primary current limit
- Secondary voltage limit
- Secondary current limit
- Spark rate limit
- SCR conduction angle

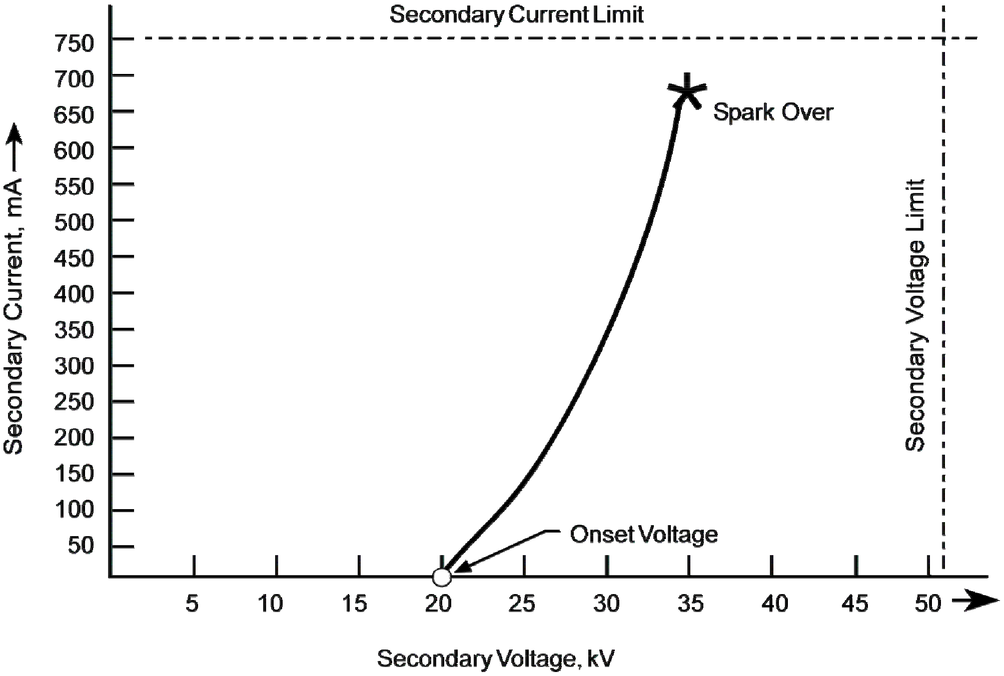


Figure 5-2. Voltage-current curve

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 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 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.

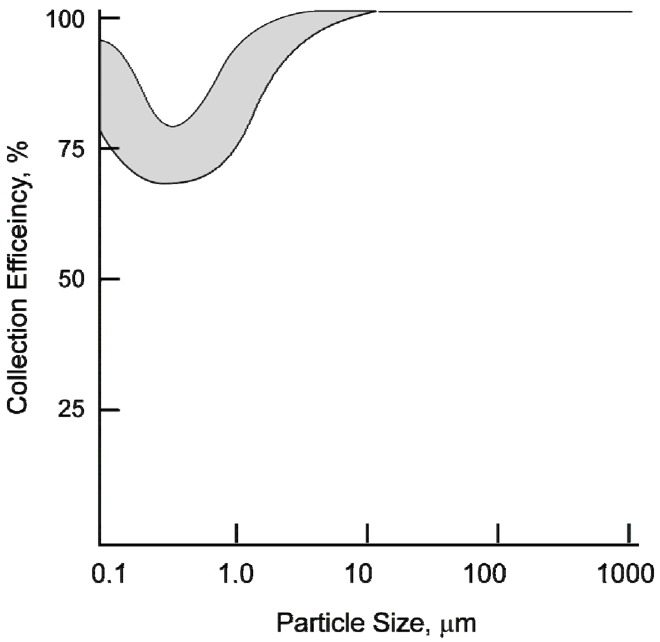


Figure 5-3. Typical particle size efficiency relationship for electrostatic precipitators

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 5×10^{10} ohm-cm. Low resistivity is generally considered to be equal to or below 5×10^{8} ohm-cm. The region between 5×10^{8} and 5×10^{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.

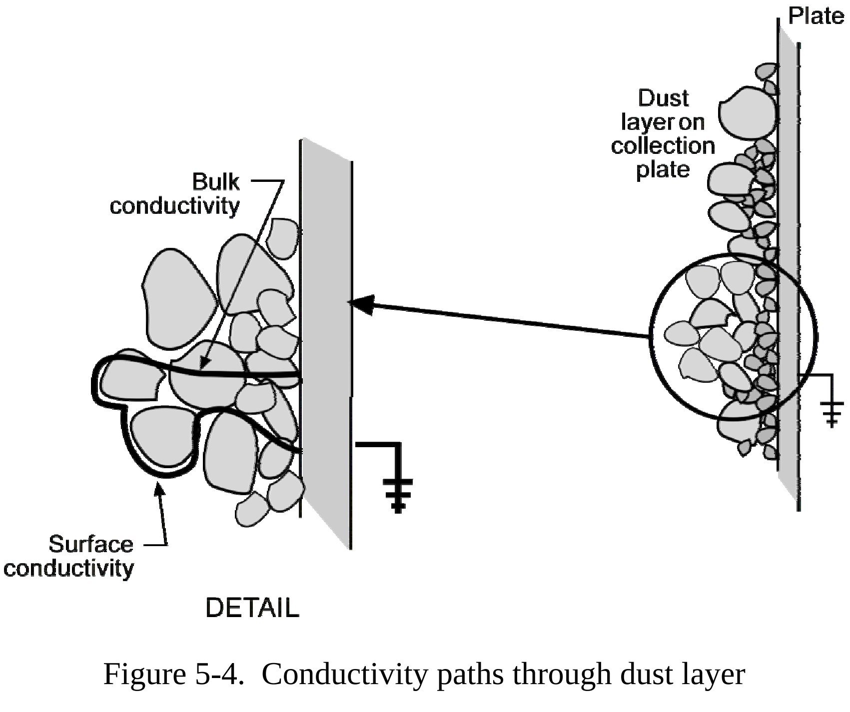


Figure 5-4. Conductivity paths through dust layer

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.

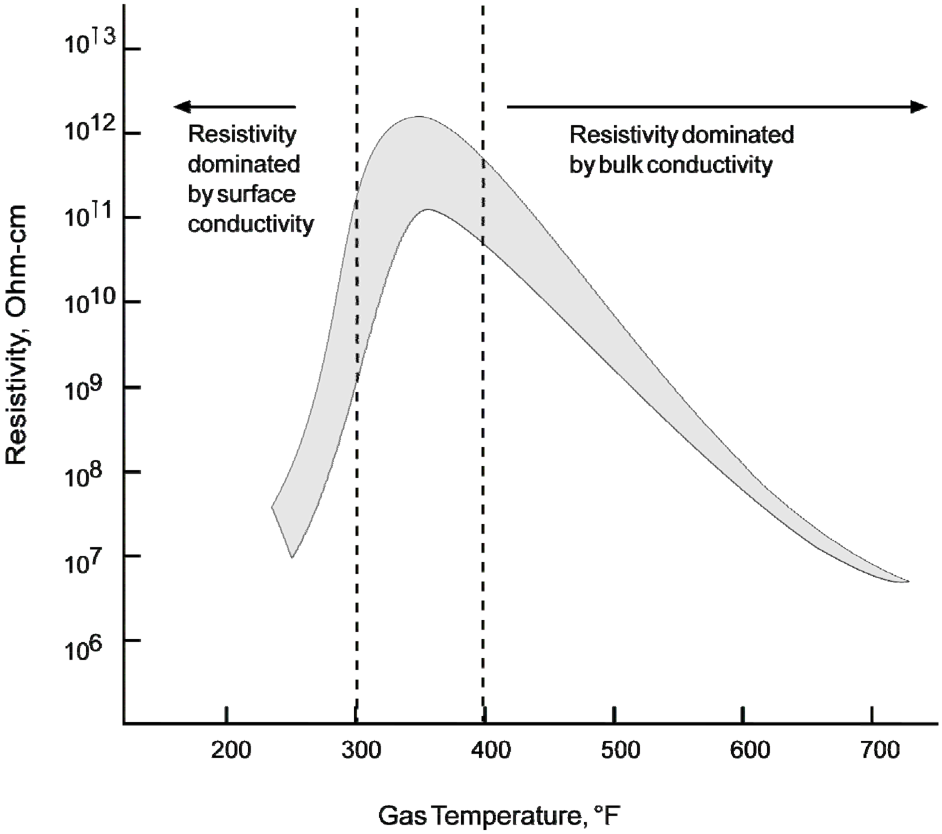


Figure 5-5. Resistivity-temperature relationship

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.

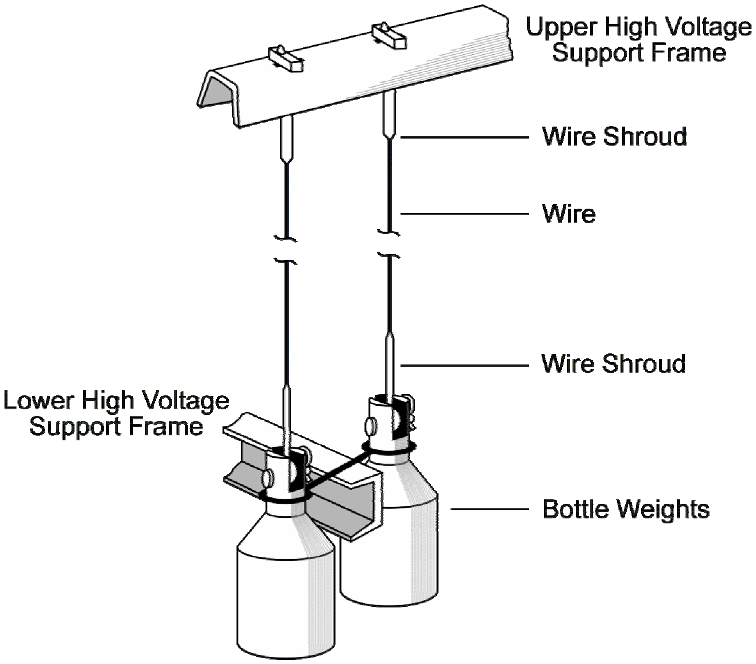


Figure 5-6. Wire-type discharge electrodes

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.

$$\mathrm{SCA} = \frac{A}{Q} \qquad (5\text{-}1)$$

where SCA = specific collection area ($\mathrm{ft}^2/10^3$ acfm)
A = total collection plate area (ft^2)
Q = total gas flow rate (10^3 acfm)

There has been a substantial increase in SCAs from levels of 100 to 200 ft^2 per 1,000 acfm in the 1960s to present-day levels of 300 to 1400 ft^2 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:

$$AR = \frac{\sum_{i=1}^{n} L_i}{H} \tag{5-2}$$

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 (ESPs). 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

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.

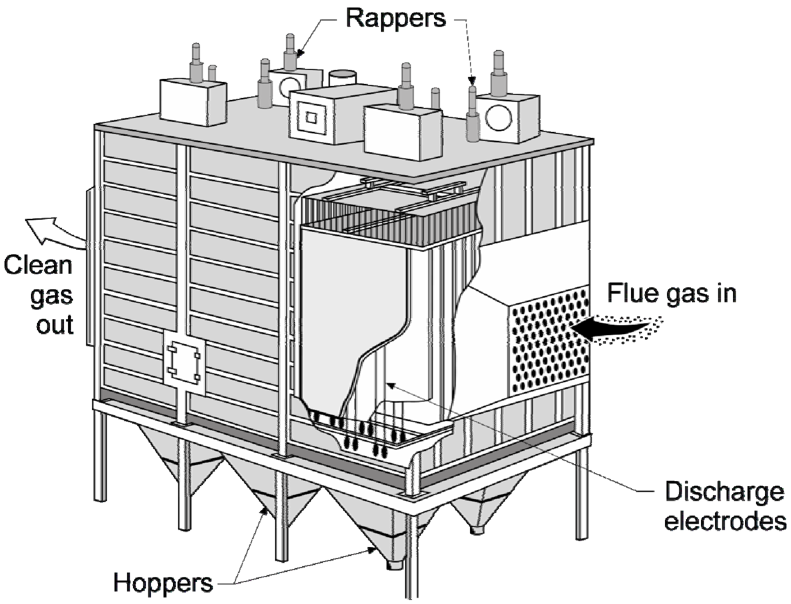


Figure 5-8. Typical dry, negative corona type electrostatic precipitator

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.

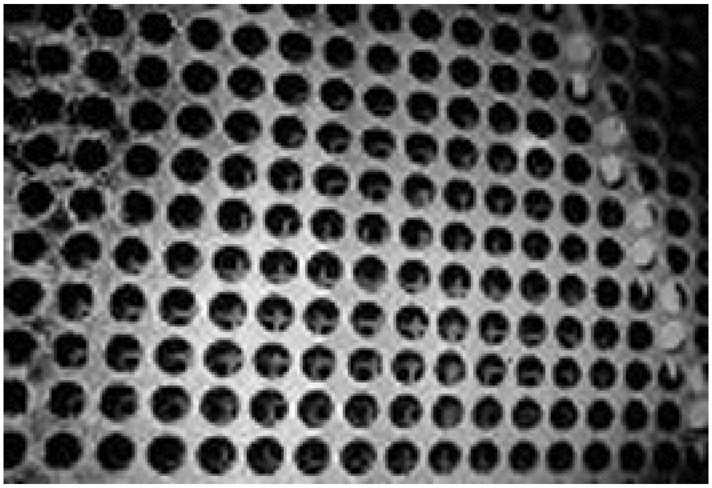


Figure 5-9. Gas distribution screens at the precipitator inlet

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.

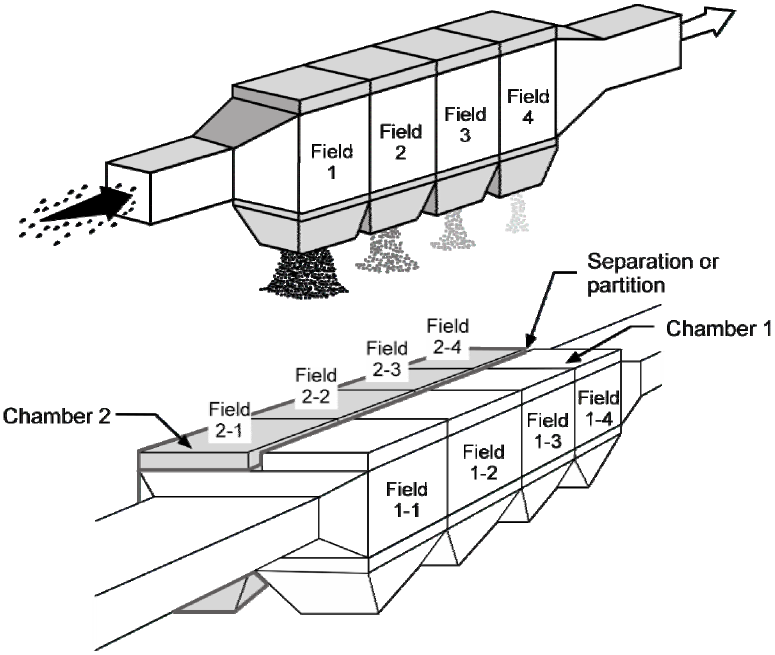


Figure 5-10. Arrangement of fields and chambers

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.

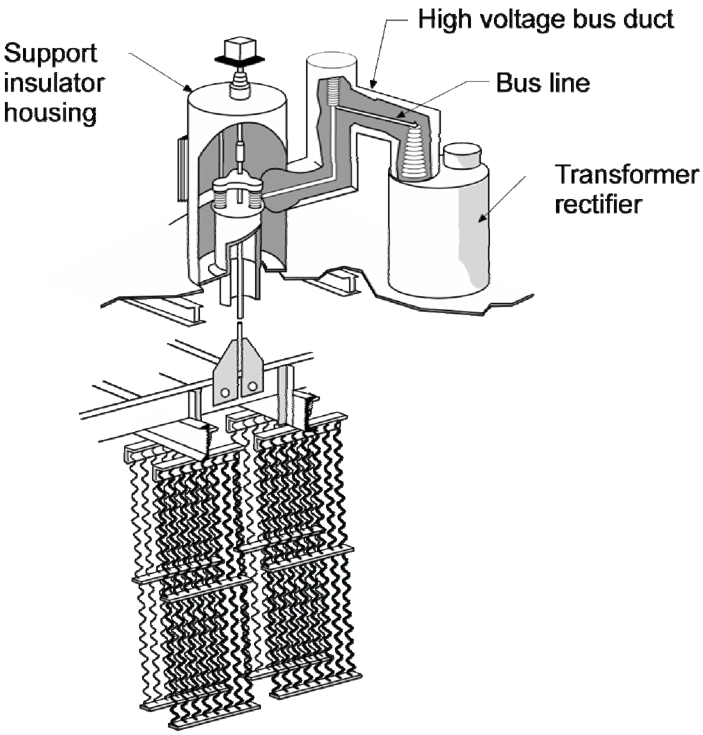


Figure 5-11. T-R set, support insulator, discharge electrode frame, discharge electrodes

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.

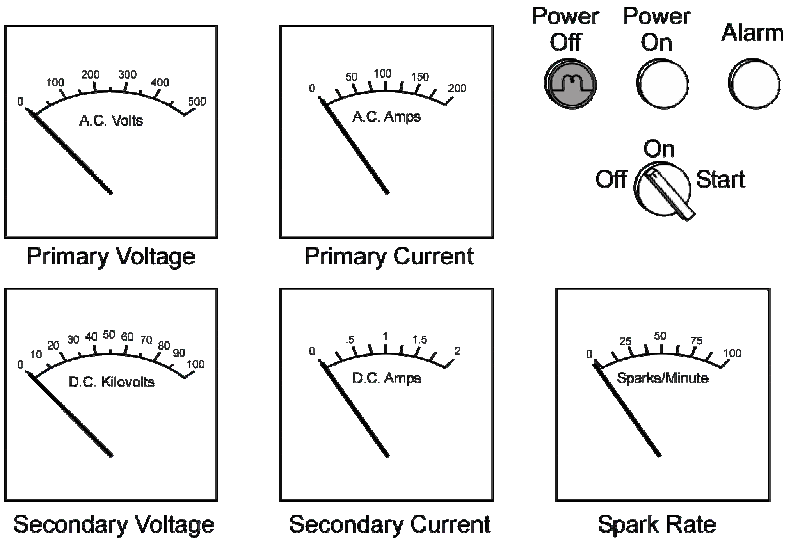


Figure 5-12. Gauges present on the control cabinet for each precipitator field

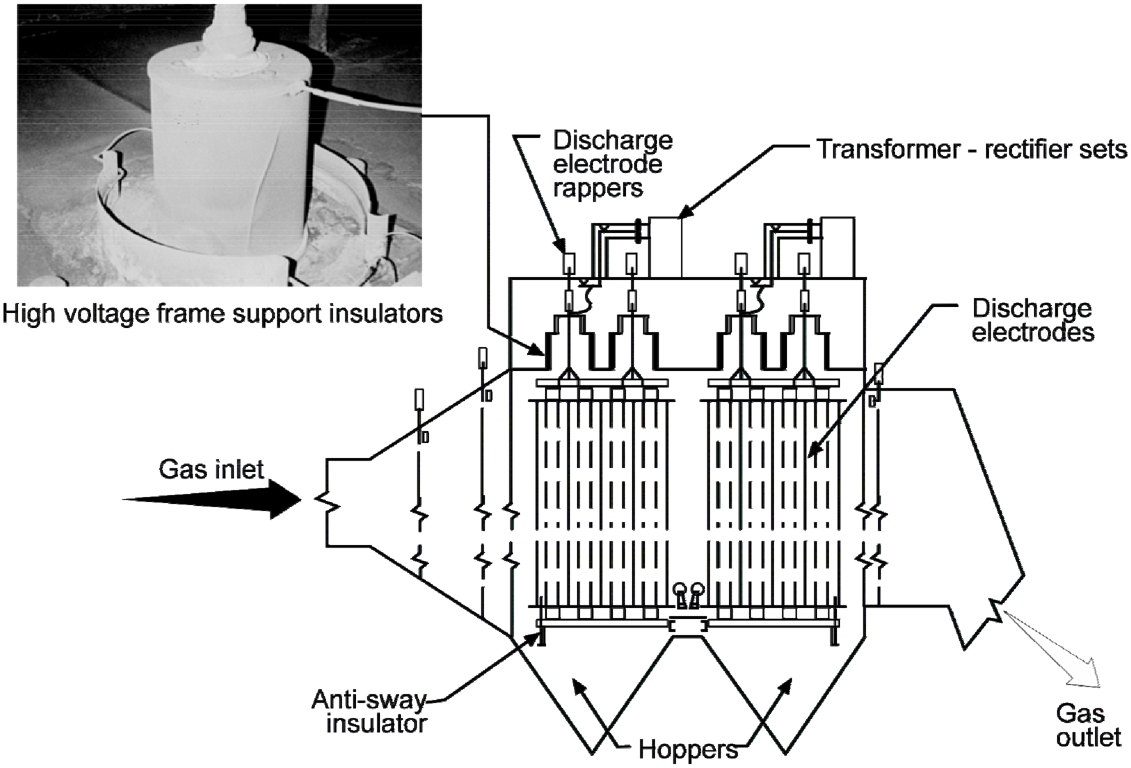


Figure 5-13. High voltage frame support insulators

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.

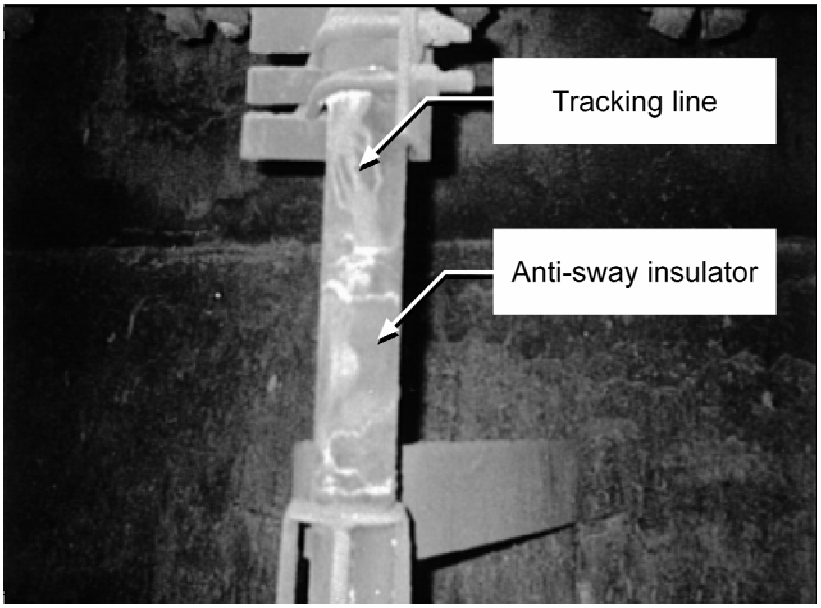


Figure 5-14. Anti-sway insulator with short-circuiting across the surface

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.

Figure 5-15. Roof-mounted rapper

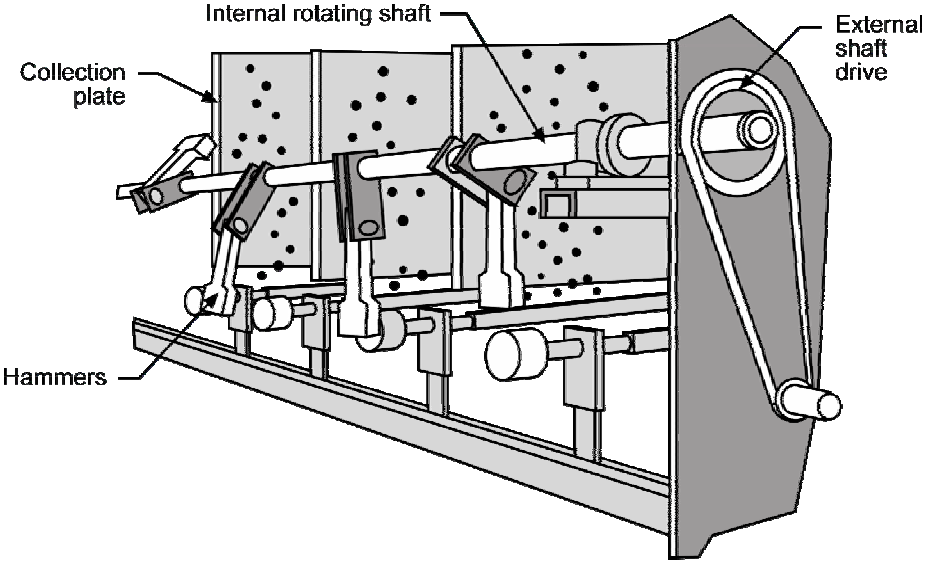


Figure 5-16. Side-mounted rapper

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.

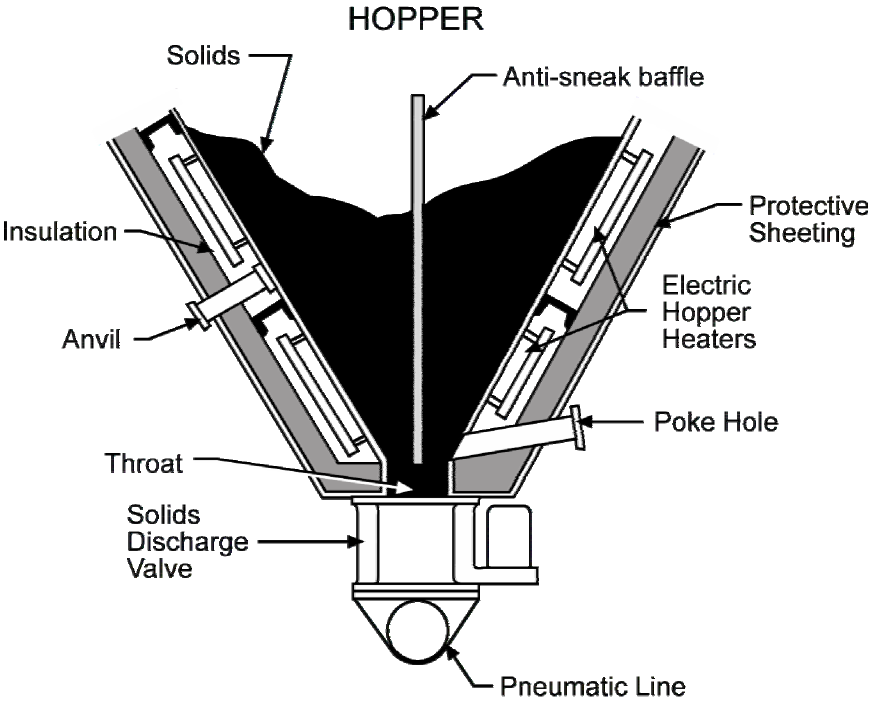


Figure 5-17. Components of a precipitator hopper

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.

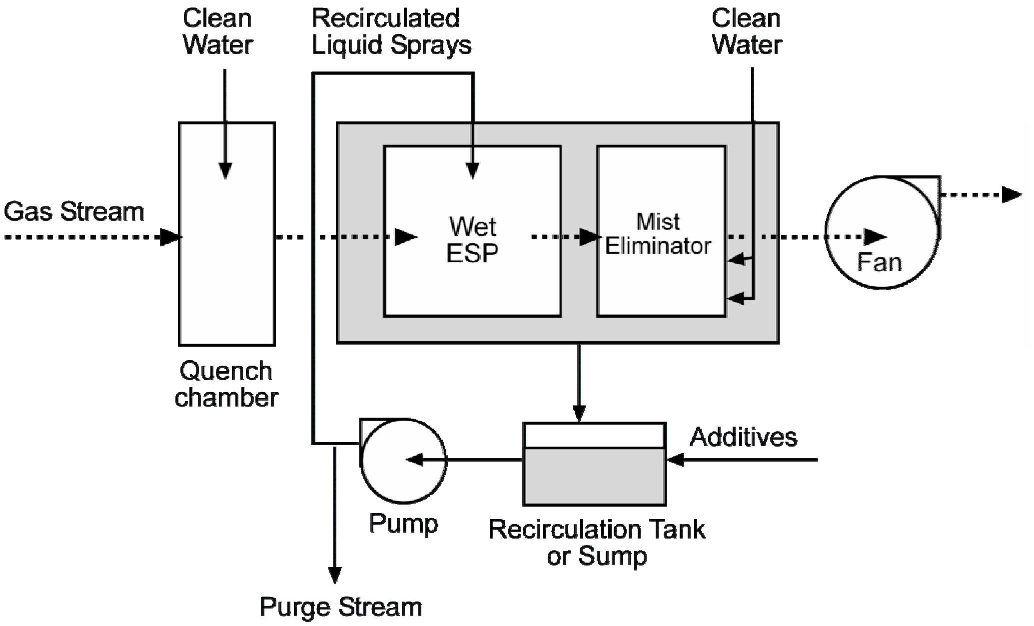


Figure 5-18. Flowchart of a wet, negative corona precipitator

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.

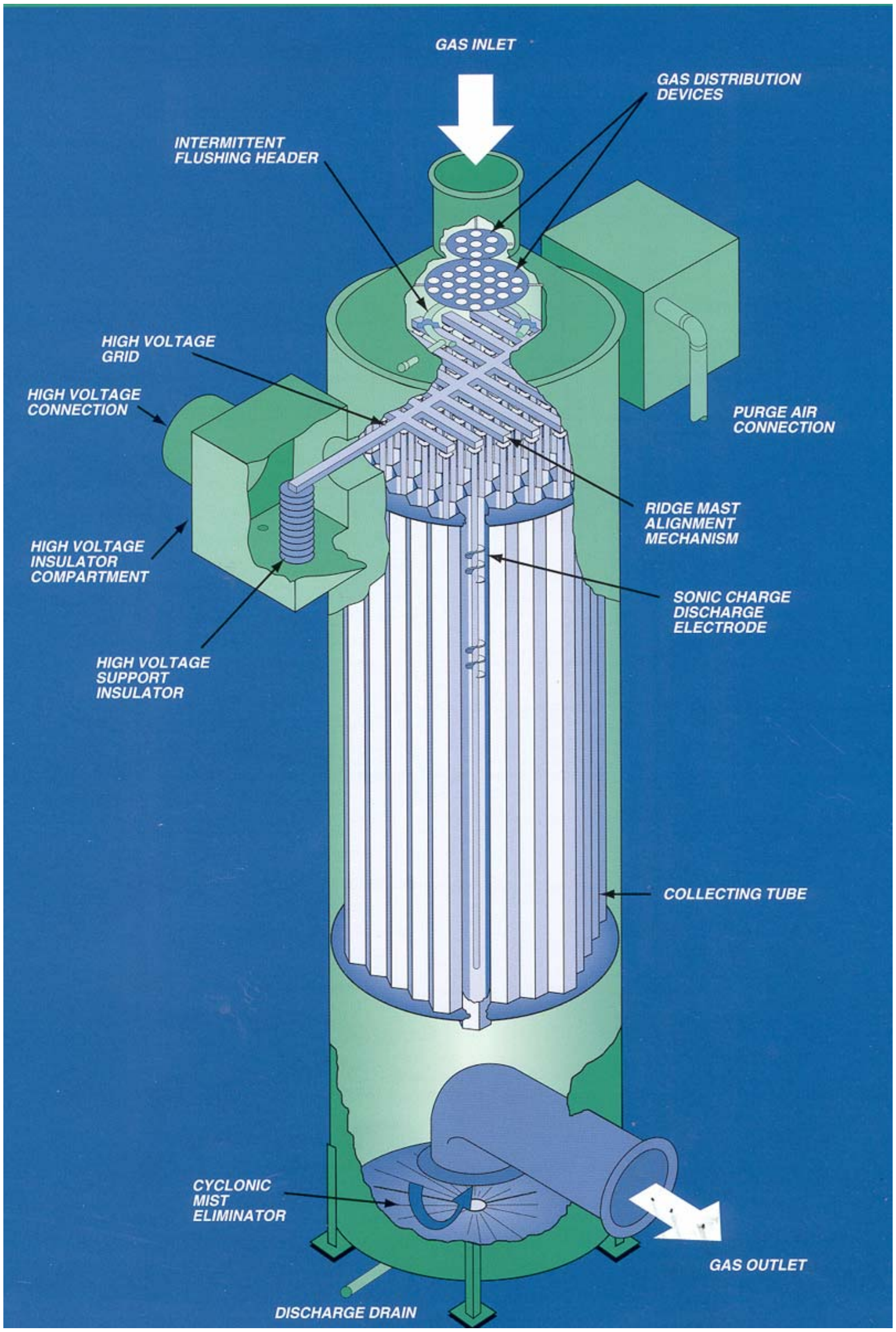


Figure 5-19. Vertical flow wet, negative corona precipitator

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.

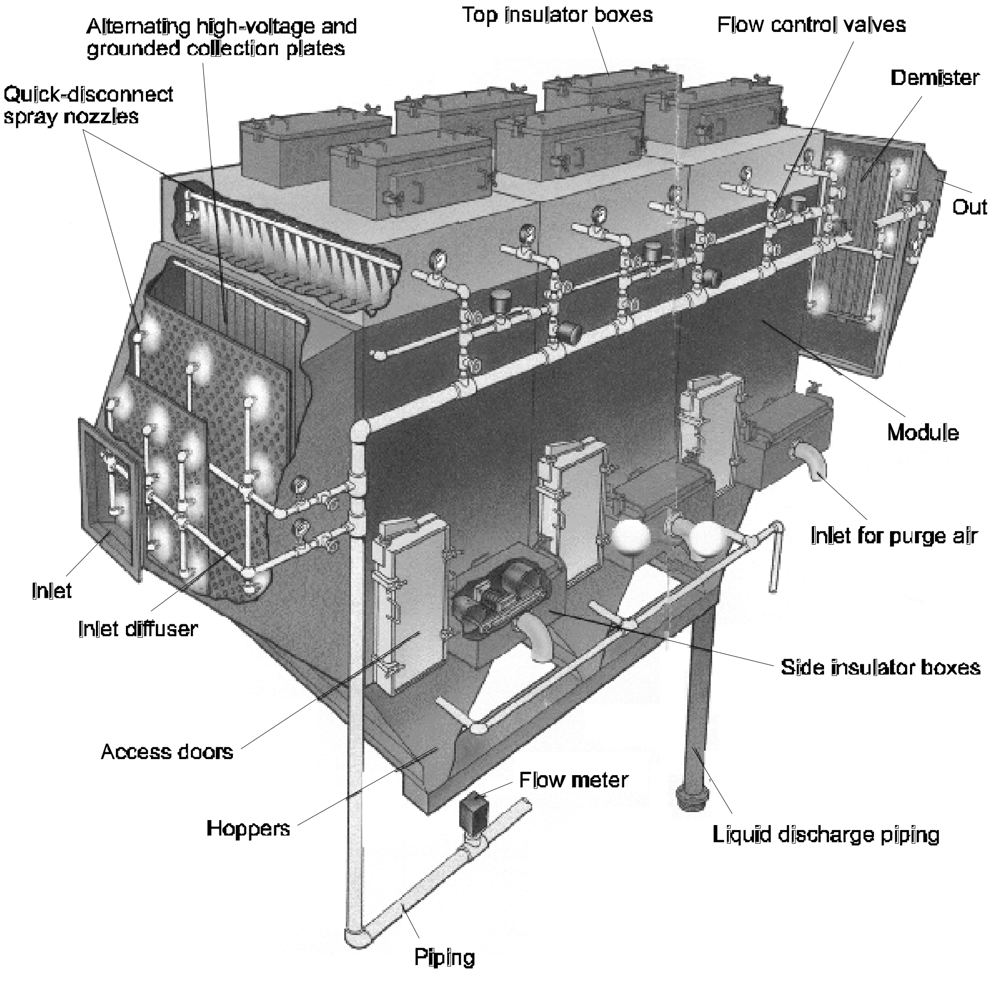


Figure 5-20. Horizontal flow wet, negative corona precipitator

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.

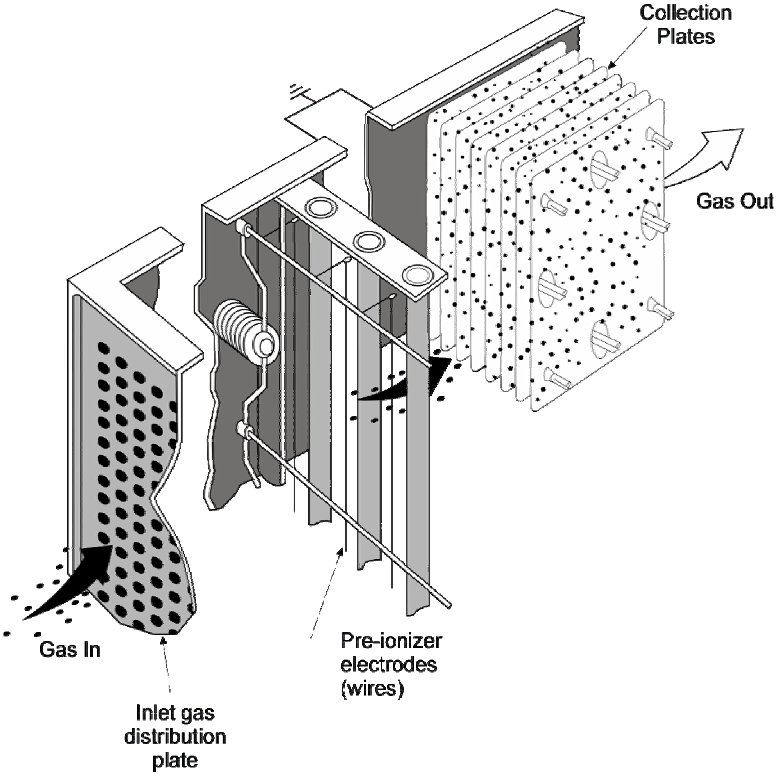


Figure 5-21. Wet, positive corona precipitator

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 misalighnment 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.

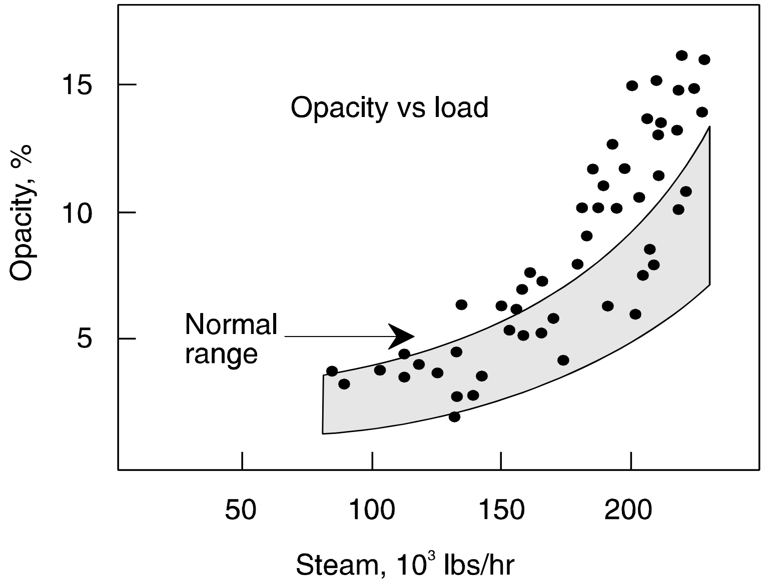


Figure 5-22. Opacity baseline data

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.

Chamber ______ Unit _____
Date__________ Time_____

Field	Primary Data (A.C.)		Secondary Data (D.C.)		Spark Rate (#/min)	Limit[1]
	Voltage (Volts)	Current (Amps)	Voltage (Kilovolts)	Current (Milliamps)		
1						
2						
:						
n						

[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.

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

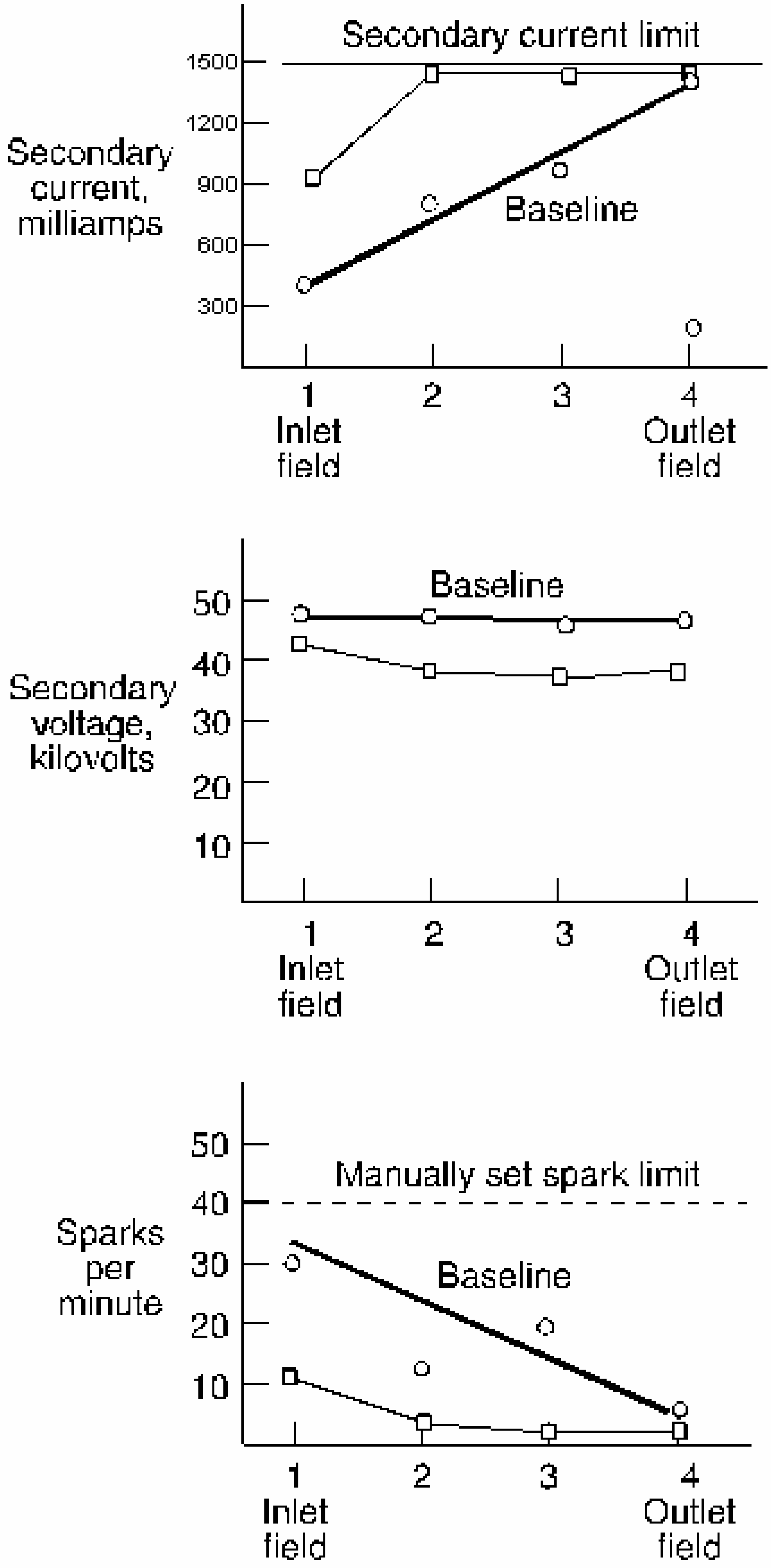


Figure 5-23. Low resistivity related data shifts

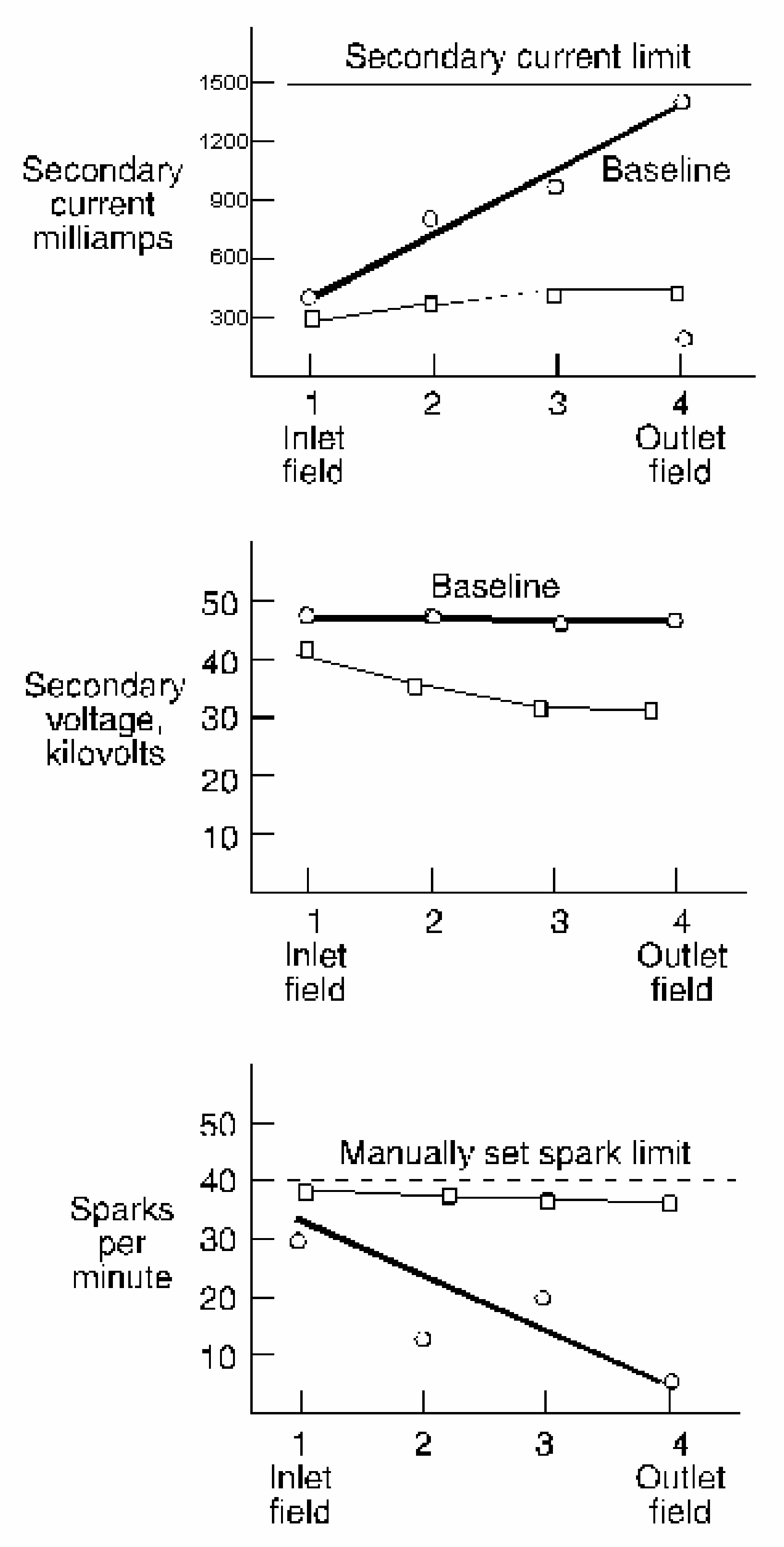


Figure 5-24. High resistivity related data shifts

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:

[Secondary voltage (kilovolts)][Secondary current (milliamps)] = Corona power (watts) (5-3)

[Primary voltage (volts)][Primary current (amps)][0.75] = Corona power (watts) (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.

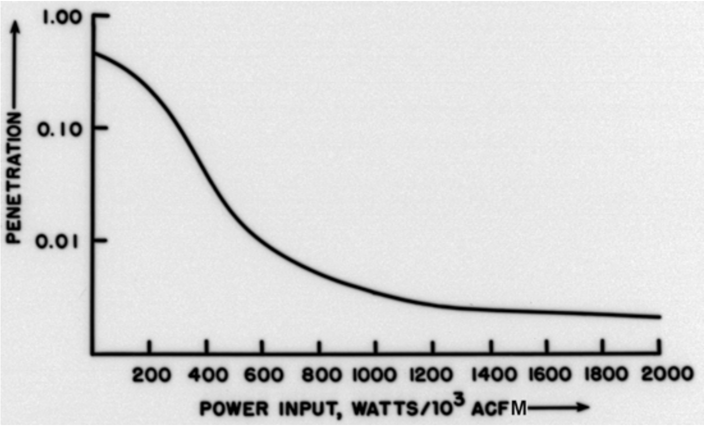


Figure 5-25. Effect of power input on particle penetration

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
- 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* ± 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* ± 1.0 inches.

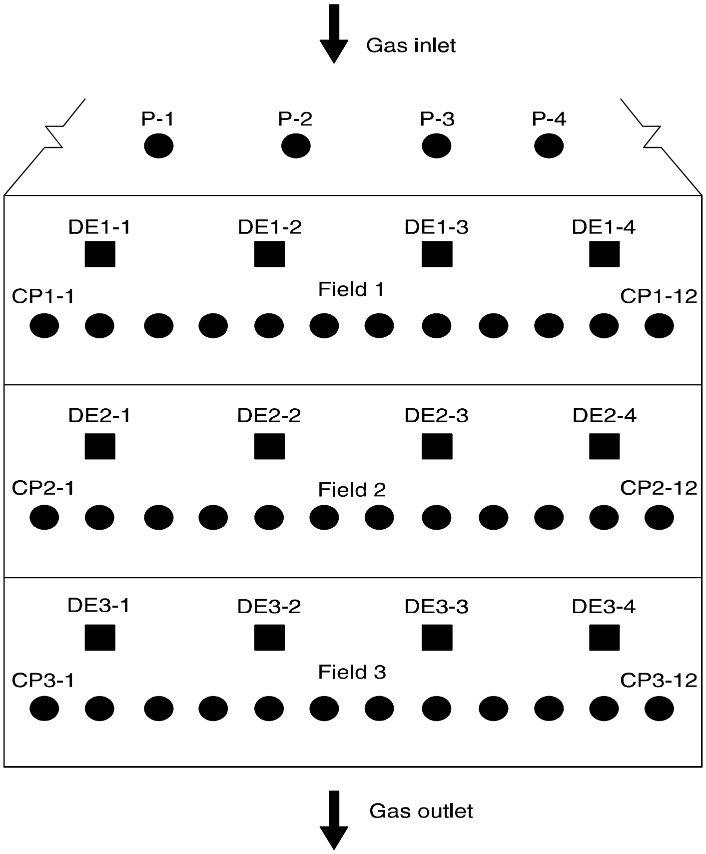


Figure 5-26. Example layout of roof mounted rappers

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.

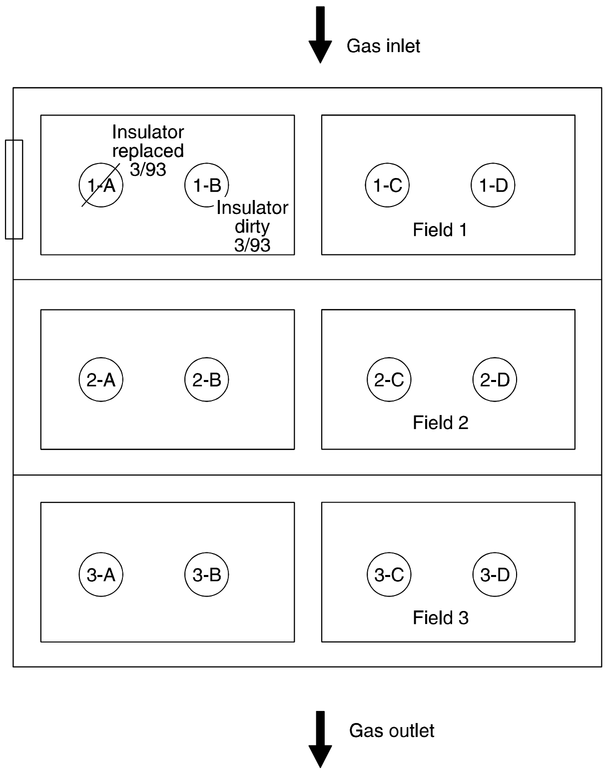


Figure 5-27. Support insulator failure chart

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.

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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?

Field	Primary (Volts)	Primary (Amps)	Secondary (Milliamps)	Spark (#/min.)	Limit
Inlet	310	60	480	30	spk
Second	350	100	750	0	sc
Third	330	95	730	0	sc
Outlet	310	105	770	0	pc

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?

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

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^{o}F. During the present inspection, the average inlet gas temperature is 324^{o}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.

CHAPTER 6

MEASUREMENT OF INSPECTION PARAMETERS

In previous chapters, the use of various parameters to evaluate the performance of control devices has been suggested. In this chapter, the methods available for making these measurements will be discussed and recommendations on the most appropriate techniques and procedures will be made. Where appropriate, additional techniques for estimating some parameters will be given.

Measurement Ports

When a control system is first inspected, it is unlikely that measurement ports will be available. If some ports are available, they are not likely to be in the locations needed or of an appropriate size. The most likely port to be found is a 3 or 4 inch diameter sampling port located on or near the stack. Although a port in this location may be useful for some inspection measurements, ports of this size should, in general, be avoided. They present difficulties in sealing under both positive and negative conditions, and they may be quite difficult to open because of the large thread area.

The most useful port size for inspections is 1½-2 inches in diameter, and this size is needed only if measurements of velocity pressure are anticipated. For the more routine measurements of temperature and static pressure, ports of ¼-½ inch diameter will accommodate most measurement probes. The larger inspection ports will require the installation of a pipe stub with a threaded plug for closing. The smaller ports should simply be drilled and then covered with duct tape when not in use. Because of the potential for fire or explosion from sparks and because of possible damage to downstream equipment, the inspector should not request that ports be installed while the equipment is running. Rather, the locations and sizes needed should be marked for plant personnel, so that they may install them the next time the system is shut down.

Ports of a proper size may already be installed in some locations and used by the plant for continuous monitoring of certain parameters. In general, these ports should be avoided by the inspector. If they must be used, they should be opened only by plant personnel. Never open a port that was not placed there for your exclusive use. Plant monitoring ports may be connected to controllers that initiate equipment shut-down if the signal from them is lost.

Measurement ports are subject to the accumulation of material that may cause them to become plugged, even if they are on the clean side of the control device. Before using any port, it should be cleaned out with a non-sparking rod to assure unobstructed access to the gas stream. Also, while making measurements the port should be sealed to prevent flow in or out around the probe. Flow into or out of the port may cause an interference with the measurements being made. For inspection ports, the best sealing technique is to insert the probe through a rubber stopper and then place that stopper into or against the port. For the larger stack-sampling ports, a rubber sanding disc may be used to cover the opening. The probe, equipped with a rubber stopper, would then be inserted through the center of the sanding disc, using the stopper to complete the seal.

Finally, the inspector should not make heroic efforts to reach existing ports and should not have ports installed in locations that cannot be reached and used in safety. This should include consideration of hazards to walking and climbing, as well as the potential for exposure to inhalation, vision, hearing, and fire and burn hazards.

Static Pressure Measurement

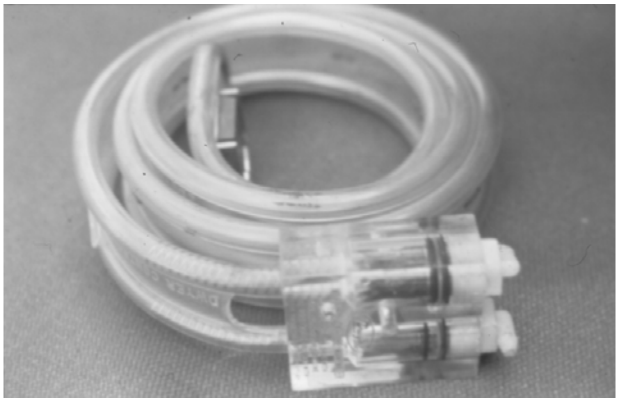
Static pressure measurements must be made with a square-ended probe placed at a right-angle to the flow direction. If measurements of velocity pressure are also being made, the static pressure ports on a standard commercial pitot tube that is oriented into the oncoming flow may also be used, as could one leg of the S-type pitot, if it is turned at a right-angle to its normal position. The purpose of the probe orientation is to be sure that no component of velocity pressure is impacting the probe during static pressure measurements.

The area between the probe and the port opening should be sealed to avoid errors associated with flow into or out of the duct. Errors resulting from improper sealing can be as large as 10-30 percent. Flow into the duct can result in an aspiration effect at the end of the probe that can increase (make more negative) the negative pressures being measured, while flow out of the duct can add a component of velocity pressure to the measurement of positive pressures. To further mitigate this problem, the probe should be extended well into the duct while making measurements.

There are two widely used techniques for sensing the pressures measured by the probe: (1) a U-tube manometer or (2) a Magnehelic® pressure gauge. The U-tube manometer is a reference instrument that is available in a flexible or slack-tube configuration, shown in Figure 6-1, to enhance its portability. The manometer is equipped with magnets at the top and bottom to facilitate temporary mounting and is equipped with threaded connectors that are used to seal the manometer during transport.

The manometer indicates the static pressure by displacing the fluid in the tube. In making static pressure measurements, one leg of the manometer is connected to the probe and the other is left open to the atmosphere. The height difference between the levels in the two columns is the pressure in height of fluid, usually expressed in inches of water. One of the principal difficulties with the U-tube manometer relates to the fluid. If the pressure in the duct exceeds the capacity of the manometer, fluid will either be drawn into the duct or blown out onto the inspector. Also, the inspector must remember to close the seals when transporting the manometer to prevent loss of fluid and to open them before making a measurement.

Figure 6-1. Slack-tube manometer



The Magnehelic® pressure gauge, shown in Figure 6-2, is a product of Dwyer Instruments, Inc. It senses pressure difference by deflecting a silicone rubber diaphragm and then translating that deflection to a needle indication through a magnetic linkage. Although not as accurate as the U-tube manometer, it is much more forgiving, making it easier to use in field situations. The Magnehelic® is accurate to within 2 percent of full scale and has a high resistance to shock and vibration. It is available in over 70 ranges, from 0-0.25 in. H_2O to 0-20 psig. The most useful ranges for ventilation system inspection are 0-5, 0-20 and 0-50 in. H_2O. For inspection of high pressure drop wet scrubber systems, a 0-100 in. H_2O range may be needed.

Except for the 0-0.25 and 0-0.50 in. H_2O ranges, the Magnehelic® may be used in any orientation and can accept pressures up to 15 psig without being harmed. This property allows gauges with different ranges to be combined in one instrument package, with the gauge giving the most readable indication used for recording the measurement.

Because of the silicone rubber diaphragm, the ambient temperature range is limited to 20° to 140°F. This lower limitation can be accommodated when conducting inspections in cold environments by keeping the gauge in a location that is within the range and then taking it out briefly for making the measurement. For extended use under cold conditions, gauges with a lower temperature limit of -65°F are available on special order.

The Magnehelic® is not a reference instrument, so its calibration should be checked periodically. The simplest way of doing this is to check its indications against a U-tube manometer, using the set-up shown in Figure 6-3. Using a laboratory squeeze-bulb equipped with check valves, pressures from -40 to +40 in. H_2O can be easily generated. The Magnehelic® indications should be plotted against those of the manometer to check for accuracy and linearity. Gauges that give inaccurate or non-linear indications should be discarded. Also, while using the gauge its zero should be checked frequently and adjusted as needed using the set-screw on the front plate. Adjusting the zero will not affect the calibration of the gauge.

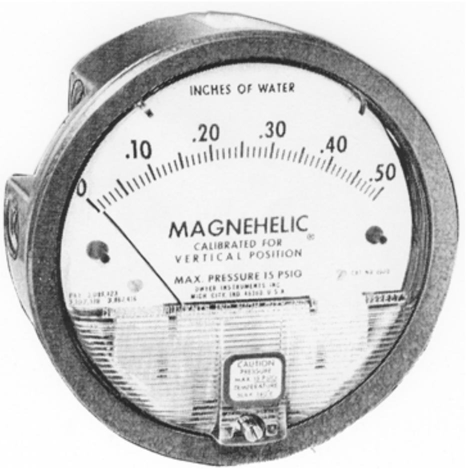


Figure 6-2. Magnehelic® pressure gauge

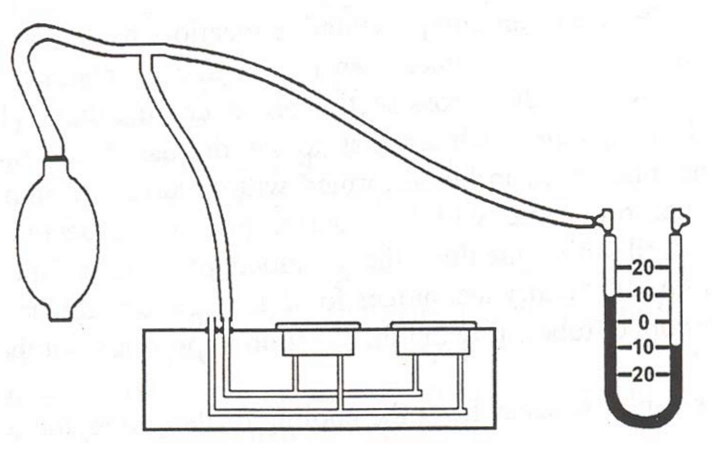


Figure 6-3. Magnehelic® calibration apparatus

Temperature Measurement

There are several techniques available for measuring temperature, including: (1) mercury thermometers, (2) dial thermometers, (3) thermistors and (4) thermocouples. Unfortunately, each of these techniques has some limitation when applied to the inspection of air pollution control systems. The mercury thermometer is constructed of glass and is subject to breakage, with resulting exposure to a toxic material. Also, both the mercury and dial thermometers have a limited probe extension, making the measurement of temperatures across large ducts impossible. Since locations near the wall of a hot duct will be cooler than near the center, measurements made there may not be representative of actual temperatures. The thermistor, which measures temperature through the change in resistance of a fine wire sensor, is easy to use but its response becomes non-linear over some part of its temperature range, making data interpretation difficult. Finally, the potentiometer used to measure the output of a thermocouple is not available in an intrinsically-safe construction and cannot be used in areas where explosive or ignitable materials may be present.

Despite its limitations, the thermocouple is recommended as the primary method for measuring temperatures in the inspection of air pollution control systems. In situations where explosive or ignitable materials may be present, use of the dial thermometer is suggested, but the inspector should be aware of the potential problems in obtaining representative measurements on large hot ducts. The thermocouple sensor is formed by joining two wires made of different metals or alloys. If the junctions at the ends of these two wires are then held at different temperatures, an electric current flows in the wire loop. This current is produced by an electromotive force whose value depends on the difference in temperature between the junctions.

The electromotive force generated by a thermocouple is measured with a potentiometer. A variety of metals and alloys are used in the construction of thermocouples, providing for measurements over different temperature ranges. The most common thermocouple, and the one recommended for use in inspections, is Type K. The Type K thermocouple has a temperature range of -400°F to +2,300°F and is constructed with a positive wire of chromel and a negative wire of alumel. Most hand-held potentiometers are calibrated for certain thermocouple types and internally convert the measured electromotive force to a temperature indication.

The thermocouple/potentiometer is not a reference instrument and must be calibrated against a National Institute of Standards and Technology (NIST) traceable thermocouple to assure highest accuracy. Since the equipment required to do this is expensive and not likely to be available to the inspector, it may be necessary to send the unit to a specialized laboratory for calibration. For most inspection situations, however, high accuracy is not required. In these cases, an acceptable evaluation of instrument accuracy may be conducted by checking its response in an ice bath and a boiling water bath. Under frequent use, this check should be done on a weekly basis. For less frequent use, it should be done prior to taking the instrument into the field.

There are several potential sources of error in making temperature measurements. One of these, use of an unrepresentative location, has already been mentioned. With the thermocouple this problem can be avoided by making measurements at several locations across the duct cross-section and averaging them. This can be done through a formal procedure, such as that used for making velocity pressure measurements, or it can be performed with random locations and mental averaging. The formal procedure will, of course, give more accurate averages. To reach locations well within the duct, the thermocouple wire will need to be supported. One of the more satisfactory techniques for doing this is to thread the wire through a small diameter copper tube, allowing the junction to protrude out the end.

Problems can also occur from the cooling of the probe due to air infiltration through the port or through leaks into the duct upstream of the measurement point. The former problem can be avoided by sealing the port in the manner described in the section on static pressure measurements. In addition, if a copper tube is used to support the thermocouple, it could be bent slightly so that it extends into the oncoming gas stream. To avoid problems from upstream leaks, the area near the measurement location should be inspected for holes in the duct or leaks in inspection hatches or expansion joints. If these are found to exist, the measurement location should be changed to an area where these leaks will have mixed into the flow. If this is not possible, the number of measurement points used to obtain an average should be increased.

Measurements downstream of evaporative coolers or wet scrubbers can be complicated due to the presence of water droplets. As these droplets impact on the sensor, the temperature will vary between the dry-bulb and wet-bulb values. However, since the degree of wetting will not be known and cannot be controlled, the exact condition of the measurement cannot be ascertained. Under these conditions, the most reasonable option is to shield the sensor from the water droplets. It should be realized, however, that doing this will likely slow the response of the sensor, requiring longer times to make the measurements.

Oxygen Measurement

Techniques for the measurement of the oxygen concentration in a gas stream include: (1) an Orsat analyzer, (2) a Fyrite® analyzer and (3) an electroconductivity analyzer. The electroconductivity analyzer determines the concentration of oxygen and other gases by bubbling the sampled gas stream through a liquid-filled cell and measuring the change in conductivity of the fluid as a result of gas absorption. In general, each gas requires a specific conductivity cell for its measurement. This instrument is moderately expensive and not likely available to compliance personnel, so it will not be discussed further.

In addition to oxygen, the Orsat analyzer can also measure carbon monoxide and carbon dioxide. The technique involves measuring the change in the volume of a gas sample as it is sequentially contacted with different absorbent fluids. The analyzer is cumbersome and somewhat fragile. The measurement method is time consuming, and the results of the analysis are influenced by the operator’s skill. For these reason, the Orsat analyzer is not recommended for field inspections.

The Fyrite® analyzer is a product of Bacharach Instrument Company. Like the Orsat analyzer, the Fyrite® analyzer measures gas concentrations using an absorption technique. The absorbing fluids are similar to those used in the Orsat, but they are enclosed in separate, self-contained units. There are units for oxygen and carbon dioxide, but not for carbon monoxide. Each unit is about 7½ inches tall and 3½ inches in diameter. The fluid used in the oxygen unit is a mixture of cuprous chloride, zinc chloride and hydrochloric acid and usually lasts for 50 to 100 measurements. The fluid in the carbon dioxide unit is potassium hydroxide and usually lasts for 200 to 400 measurements. Since both solutions contain corrosive constituents, care must be exercised when changing them.

A cutaway sketch of a Fyrite® analyzer unit is shown in Figure 6-4. The plunger valve is depressed from the top with a fitting on the sampling line, and the gas stream to be tested is pumped into the top reservoir using a battery- or hand-powered pump. Once a representative sample is obtained, the plunger valve is released and the unit is inverted several times to mix the solution with the gas. Absorption of the component being measured causes a pressure decrease in the unit, drawing the fluid up into the center column. A scale along the side of the center column indicates the concentration in percent.

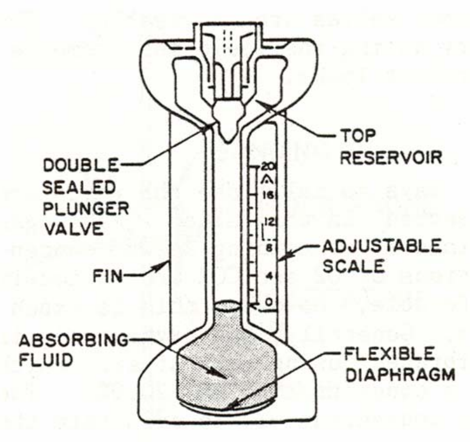


Figure 6-4. Cutaway of Fyrite® analyzer unit

The absorption of gases is a temperature dependent process. It is important that the solution be at approximately the same temperature as the sample being tested. If the solution is colder, the observed reading will be higher than actual. Conversely, if the solution is warmer, the observed reading will be lower than actual.

The analyzer can be calibrated using gas cylinders containing known concentrations of oxygen and carbon dioxide. While this assures an accurate calibration, it is expensive. For inspection purposes, the oxygen unit it typically calibrated using ambient air, which has a concentration of 20.9 percent. The carbon dioxide unit is calibrated using exhaled breath, which has a concentration of 4-5 percent. In each case, the position of the indicating scale is adjusted to the calibration value.

One quick check on the accuracy of measurements is to sum the oxygen and carbon dioxide concentrations. As shown in Table 6-1, the value of the sum should fall within a certain range, depending on the type of fuel being fired. The sum of oxygen and carbon dioxide concentrations in exhaled breath should fall into the same range as for wood fired boilers. If the sum of the measurements does not fall into the indicated range, a measurement error has probably occurred, and the measurements should be repeated. If the sum still does not fall within the appropriate range, one or both of the solutions may be exhausted.

Table 6-1. Checking O_2 and CO_2 Measurements

Fuel	Sum of O_2 and CO_2 (%)
Natural Gas	13-19
#2 Oil	15-20
#6 Oil	17-20
Bituminous Coal	18-21
Lignite	18-21
Anthracite Coal	19-21
Refuse	18-22
Wood	18-22

pH Measurement

Two common ways to measure pH include the battery- or line-powered meter and indicator paper. Meters are usually accurate to within ±0.1 pH, while the indicator paper is only accurate to about ±1.0 pH. Intrinsically safe meters are available for use in situations where explosive or ignitable materials may be present; however, they are not necessary. The meter can be kept in a safe location and the sample taken to the meter for analysis.

Usually, the accuracy available with a meter is not necessary for inspections, making indicator paper an acceptable alternative. Indicator paper is adequate whenever the liquid does not contain strong oxidizing agents, is not highly colored, and there is not a high concentration of colloidal matter.

Prior to each set of measurements, the pH meter should be calibrated using buffer solutions with pHs of approximately 4, 7 and 10. Indicator paper should also be checked using these three buffer solutions. If the paper has aged, it will no longer work properly.

Use of Grounding Cables

When working with portable instruments in areas where potentially explosive or ignitable materials are present, all metal probes should be grounded to the duct to avoid a static discharge. The most satisfactory technique is to use a stranded cable with a pipe clamp attached to one end and a spring-loaded jaw clamp on the other, as shown in Figure 6-5. The pipe clamp is firmly attached to the probe and the jaw clamp is attached to the duct, usually at a flange or support. Care should be taken to assure a good connection at the duct and that all paint and rust has been penetrated. One way to check the connection would be to measure the resistance between the probe and the duct using an explosion-proof ohmmeter. If the resistance is less than 3 ohms, the connection is good. Guidance on when to use grounding cables is provided by the following list:

- When the moisture content of the gas stream is low.
- When the gas stream velocity across the probe is high.
- When the gas stream contains a relatively high mass concentration of small-sized particles.
- When there is the possibility of dust deposits in the bottom of the duct.
- When there is any question about the need for a grounding cable.

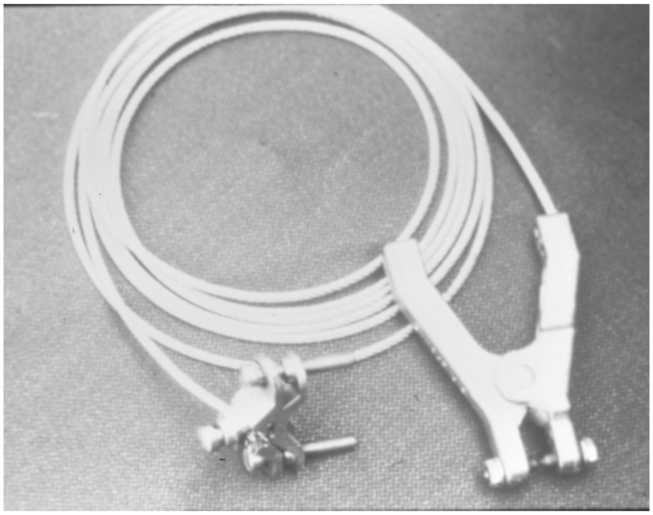


Figure 6-5. Typical grounding cable

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CHAPTER 7

FLOWCHART PREPARATION

Flowcharts are a useful tool when you want to evaluate the performance of an entire system, because they provide a means for organizing and presenting operating data. More specifically, flowcharts can be used for the following purposes:

- Evaluating process operating changes that are affecting control device performance
- Identifying instruments that are not working properly
- Identifying health and safety problems
- Communicating effectively

As discussed later, an expanded block diagram flowchart has been adopted. Major components are shown as simple blocks, rather than using complex sketches resembling the actual equipment. A set of conventional instrument symbols and major equipment symbols have also been adopted, primarily from conventional chemical engineering practice.

Flowchart Symbols

A complete flowchart consists of several symbols representing major and minor pieces of equipment and numerous material flow streams. It is important to be able to differentiate between the various types of material flow streams without sacrificing simplicity and clarity.

Major Components

Symbols for major components are shown in Figure 7-1. A square or rectangle is used to denote major equipment such as the air pollution control devices, tanks and vessels, or process equipment. Fans are denoted using a relatively large circle with a set of tangential lines to indicate the discharge point. A stack is shown as a slightly tapered rectangle. All of these symbols are shaded or filled with crosshatched diagonal lines so that it is easy to pick out the major equipment items from the gas handling ductwork and other streams leaving these units.

The items treated as major equipment depend on the overall complexity of the system being drawn and on individual preferences. These decisions are determined based primarily on the types of data and observations that are possible and the level of detail that is necessary to evaluate the performance of the overall system.

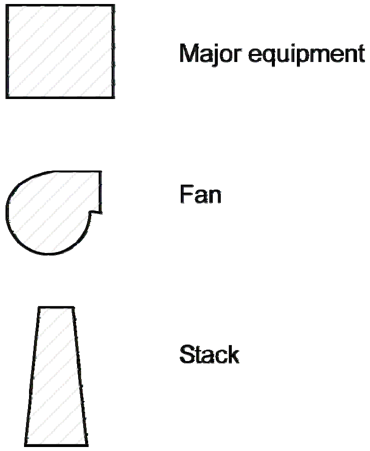

Figure 7-1. Major equipment symbols

Minor Components

A number of relatively small components in air pollution control systems should be shown on the block-diagram-type flowcharts in order to clarify how the system operates. A partial list of these minor equipment components is provided in Table 7-1.

Table 7-1. Minor Components

Fabric Filters	Wet Scrubbers
• Bypass dampers	• Pumps
• Relief dampers	• Nozzles
• Outlet dampers	• Manual valves
• Reverse air fans	• Automatic valves
Carbon Adsorbers and Oxidizers	
• Indirect heat exchangers	
• Fans	

Symbols for the minor components listed in Table 7-1 are shown in Figure 7-2. Note that all of these symbols are relatively simple and quick to draw.

Material Streams

The recommended symbols for the material streams are presented in Figure 7-3. Gas flow streams are shown as two parallel lines spaced slightly apart so that they are larger than other streams. This size difference is important, because it allows the inspector to quickly scan the flowchart and differentiate between gas and liquid material flow streams. Segments of ductwork connecting one major piece of equipment to another are labeled with an alphabetic character. Important liquid and solid material flow streams are shown as solid, single lines. Diamonds with enclosed numbers are used to identify each of these streams.

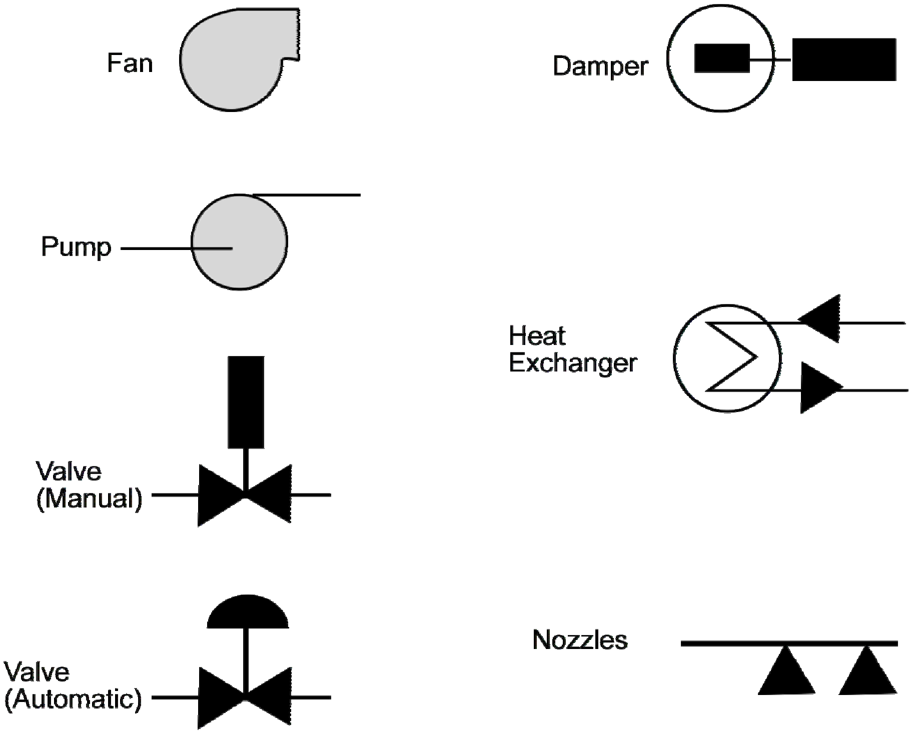

Figure 7-2. Minor component symbols

To avoid cluttering the drawing, some of the liquid and solid material streams for which operating data will not be necessary are unnumbered. These types of streams are often called *utility streams*. They provide necessary materials to the system being shown, and the characteristics of these streams are relatively constant. Typical utility streams for air pollution control equipment systems include make-up water, cooling water, and low-pressure steam. Natural gas, oil, and other fossil fuels can also be treated as utility streams to simplify the drawings. Instead of the numbered diamonds, these utility streams are identified either by using one of the codes listed in Table 7-2 or by a one- or two-word title. The codes or work titles are placed next to a "stretched-S" symbol, which is used to indicate that the source of the utility stream is outside the scope of the drawing.

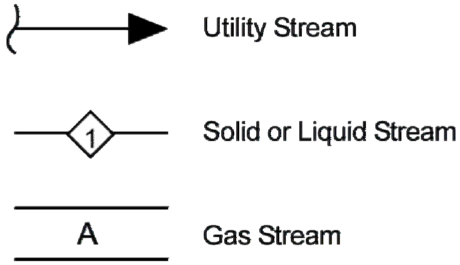

Figure 7-3. Material stream symbols

Table 7-2. Codes for Utility Streams			
Cal	- Compressed calibration gas	HS	- High pressure steam
CA	- Compressed air	IA	- Instrument air
CD	- Condensate	LS	- Low pressure steam
CW	- City (or plant) fresh water	Oil	- No. 2 or No. 6 oil
Gas	- Natural Gas		

Instruments

The presence of an instrument or a sampling port is indicated by a small circle connected to a stream line by a short dashed line, as shown in Figure 7-4. The type of instrument is indicated using the symbols listed in Table 7-3.

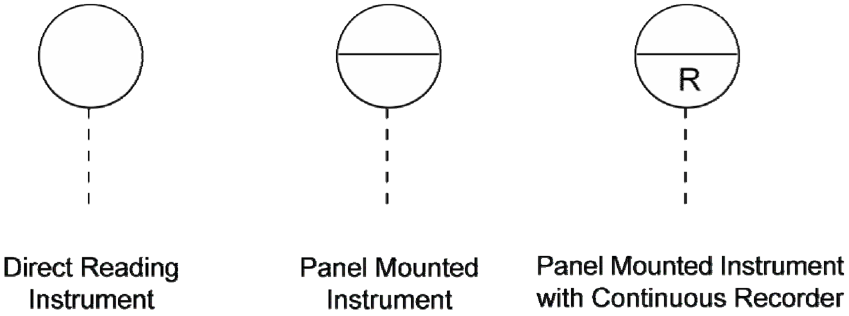

Figure 7-4. Instrument symbols

Table 7-3. Instrument Codes			
A	- Motor current	pH	- Liquid or slurry pH
CEM	- Continuous emission monitor	ΔP	- Static pressure drop
Den	- Density	SP	- Gas static pressure
F	- Flow	SSP	- Stack sampling port
L	- Liquid level	T	- Temperature
LEL	- Lower explosive limit	V	- Vacuum gauge
MP	- Measurement port	VOC	- Low concentration VOC monitor
Op	- Opacity	W	- Weight
P	Gas or liquid pressure		

Instruments such as manometers and dial-type thermometers can only be read at the gauge itself. These indicating gauges are simply denoted by the instrument circle and the instrument code. Instruments with panel-mounted gauges, usually in the control room, are indicated using a line horizontally bisecting the instrument circle. In this case, the instrument code is placed directly above the line. When the instrument indications are recorded on a continuous strip chart or with a data acquisition system, the letter "R" is placed below the line.

Materials of Construction

The materials of construction are relevant whenever there has been or may be a serious corrosion problem that could affect either system performance or safety. It is impractical to specify the exact types of material and protective coatings on each vulnerable component because there are several hundred combinations of materials and coatings in common use. However, the general type of material in certain selected portions of the system may be important. For example, it would be helpful to know that a stack discharging high concentrations of sulfuric acid vapor is composed of carbon steel because this material is easily attacked by sulfuric acid. The stack platform and access ladders could be vulnerable to failure as the corrosion problem gets progressively worse. A small set of symbols is presented in Table 7-4 for identifying materials of construction. These symbols should be placed next to the major equipment item or the gas handling ductwork segment.

Table 7-4. Codes for Construction Materials

CS	- Carbon steel	RL	- Rubber lined
FRP	- Fiberglass reinforced plastic	SS	- Stainless steel
N	- Nickel alloy	WD	- Wood

Emission Points

The stack or emission discharge point is obviously important because of visible emission observations and because of the presence of continuous emission monitors and stack sampling ports in some systems. The emission points, which should be subject to Method 9 or Method 22 visible emission observations, are identified by a set of inverted triangles immediately above the source as shown in Figure 7-5. These are numbered whenever there is any possibility of confusing different sources within a single industrial complex. The numbers used in the triangles should correspond with the emission point identification numbers used in the inspector's working files. Typical identification numbers E_1, E_2, ... E_n are used for enclosed emission points such as stacks and F_1, F_2... F_n are used for fugitive emission points such as storage piles and material handling operations.

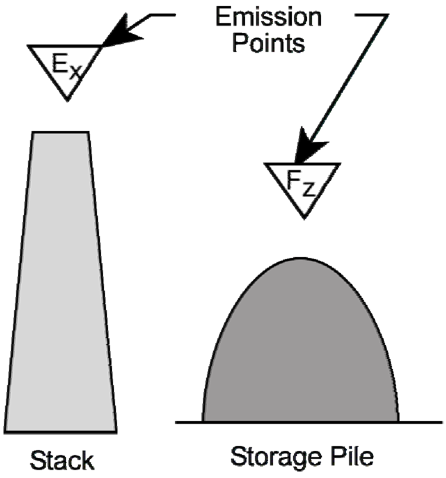

Figure 7-5. Identification of emission points

Flowchart Diagrams

Flowcharts can serve many purposes; and, as a result, many levels of sophistication in flowchart preparation exist. Some of the most complex are design-oriented piping and instrumentation drawings, termed *P&I drawings*, which show every major component, valve, and pipe within the system. Even a drawing for a relatively simple system or part of a system can have more than 500 separate items shown on it. Conversely, a simple block diagram used as a field sketch may have only 3 to 5 symbols on the drawing.

Flowcharts for air pollution control studies should be relatively simple. Generally, you need more equipment detail than shown on a simple block diagram, but far less information than provided by the standard P&I drawing. The flowcharts should not be so cluttered with system design details that it is difficult to include operating conditions that help to identify health and safety risks and performance problems. Since these are primarily working drawings, they must be small enough to be carried easily while walking around the facility. Also, the flowcharts should not require a lot of time to prepare or to revise.

Examples

An example flowchart for a relatively complicated air pollution source, a waste solvent incinerator, is shown in Figure 7-6. The process equipment in this example consists of a starved air modular incinerator with primary and secondary chambers. The air pollution control system consists of a venturi scrubber followed by a mist eliminator.

The primary and secondary chambers of the waste solvent incinerator have been shown separately because data from each chamber is important to the inspection. However, many components of the incinerator and wet scrubber systems have not been shown because their operating conditions are not central to the potential air pollution emission problems or health and safety problems.

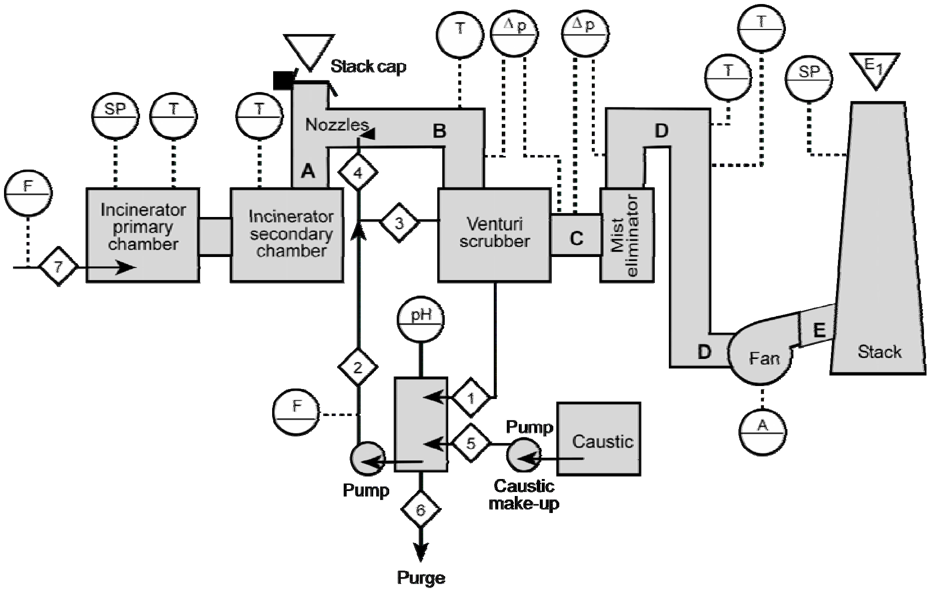

Figure 7-6. Flowchart of a waste solvent system

Another flowchart example is shown in Figure 7-7. This is a simple wet scrubber system serving a recycle operation in a hot mix asphalt plant. Most of the plant is not shown since the scrubber only controls the particulate emissions from the mixing of hot, new aggregate with cold, aged recycled asphalt pavement. The duct labeled as Section C serves as the emission discharge point. The liquid recycle pond is shown using an irregular shape and with a slightly different form of cross hatching so that it is easy to differentiate between the pond and the major equipment items.

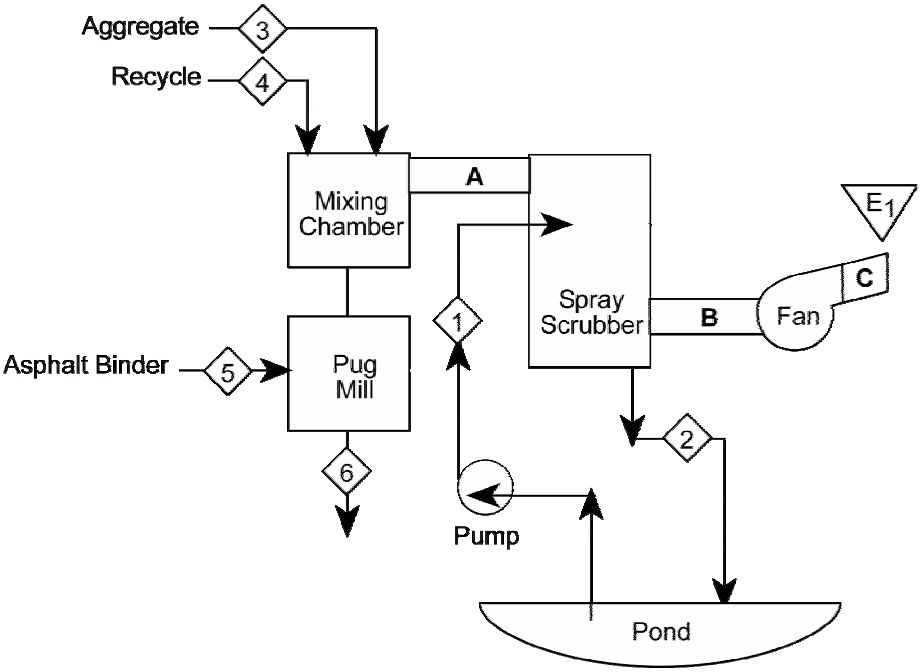

Figure 7-7. Flowchart of an asphalt plant mixing chamber

It should be noted that the symbols for the major pieces of equipment and the symbols for other parts of the system should be located in logical positions. For example, the pond in Figure 7-7 is placed near the bottom of the sketch, and the stack is in a relatively high location.

Applications

The following problems illustrate how flowcharts can be helpful during the inspection of air pollution control systems. They serve as a tool for organizing relevant data and determining what needs further investigation. Follow these steps when evaluating the overall system:

1. Determine whether the operating data are consistent and logical.
2. Compare the current data to the baseline data.
3. Determine specific areas that may need emphasis during the inspection.
4. Determine potential health and safety problems that may be encountered during the inspection.

Example Problem 1

A regulatory agency is conducting an inspection of a soil remediation unit at a hazardous waste site. This site is an abandoned chemical plant where several nonvolatile carcinogens are present in old lagoons. The plant uses a rotary kiln for destruction of the carcinogens and two side-by-side pulse jet fabric filters for control of particulate matter generated in the kiln. Based on the current data shown in Figure 7-8 and the baseline data shown in Table 7-5, determine the following:

A. Are the operating data for the system consistent and logical?
B. Do any important discrepancies exist between the current and baseline data?
C. What areas of the facility should be emphasized during the inspection?
D. What health and safety issues should be considered during the inspection?

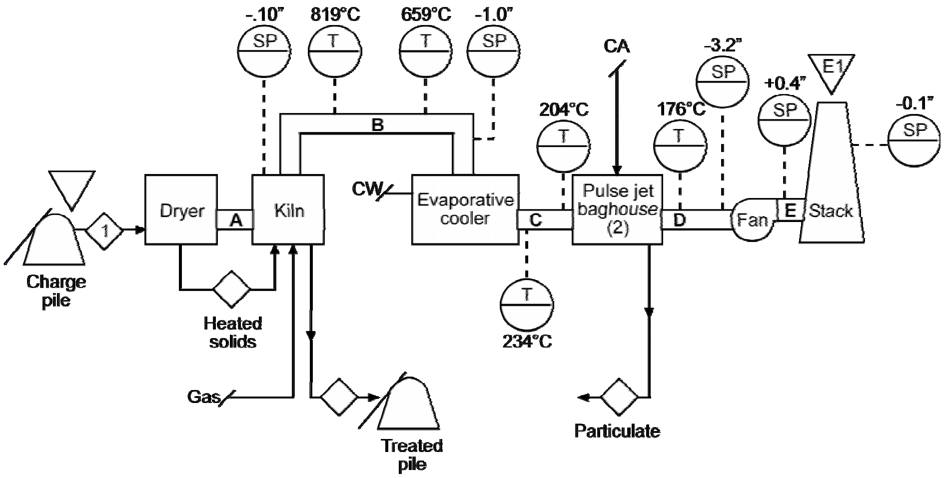

Figure 7-8. Flowchart of a hazardous waste incinerator and pulse jet baghouse system

Table 7-5. Baseline Data for the Hazardous Waste Incinerator

Location	Temperature (°C)	Static Pressure (in. H_2O)
Kiln hood	810	-0.1
Evaporative cooler inlet	785	-1.0
Evaporative cooler outlet	240	No Data
Baghouse inlet	195	No Data
Baghouse outlet	190	-5.1
Duct E	No Data	-1.5
Stack	No Data	-1.0

Solution:

Part A

Determine if the operating data for the system are consistent and logical. There should be logical trends in the gas temperatures, gas static pressures, gas oxygen concentrations and other parameters along the direction of gas flow. For this example, the gas temperature and static pressure data are listed in Tables 7-6 and 7-7 in the direction of gas flow.

Table 7-6. Gas Temperature Profile for the Hazardous Waste Incinerator (°C)

	Current	Baseline
Kiln hood	819	810
Evaporative cooler inlet	659	785
Evaporative cooler outlet	234	240
Baghouse inlet	204	195
Baghouse outlet	176	190

Table 7-7. Gas Static Pressure Profile for the Hazardous Waste Incinerator (in. H_2O)

	Current	Baseline
Kiln hood	-0.10	-0.10
Evaporative cooler inlet	-1.0	-1.0
Evaporative cooler outlet	No Data	No Data
Baghouse inlet	No Data	No Data
Baghouse outlet	-3.2	-5.1
Duct E	+0.4	-1.5
Stack	-0.1	-1.0

The gas temperature and static pressure trends through the system are both logical. The gas temperatures are at a maximum at the discharge of the kiln and decrease throughout the system. The gas temperature at the fan outlet is not provided for this example. Note that sometimes gas temperature at the fan outlet is *higher* than that at the fan inlet due to compression that occurs as the gas moves through the fan. The static pressures become progressively more negative as the gas approaches the fan. After the fan, the static pressure of the system significantly increases, as expected. Since the set of plant instruments provides consistent and logical profiles through the system, they are probably relatively accurate.

Part B

Compare the current data to the baseline data to determine if any important discrepancies exist.

Step 1. Use Table 7-6 to compare the current temperature data to the baseline data.

a. Evaluate the destruction efficiency of the rotary kiln using the kiln outlet temperature data.

   The primary function of this portable plant is to incinerate the contaminated soil. It is apparent from the flowchart that the most useful single parameter for evaluating the destruction efficiency of the rotary kiln system is the kiln outlet temperature monitored by the temperature gauge on the left side of duct B. The present value of 819°C compares well with the baseline data obtained during the trial burn tests in which the unit demonstrated good performance. Accordingly, it appears that the unit is presently in compliance.

b. Evaluate the temperature data for Duct B.

   The 160°C temperature drop (from 819°C to 659°C) in the short duct between the kiln and the evaporative cooler is relatively new. The baseline data indicate that the previous temperature drop was 25°C. The significantly higher temperature drop currently occurring across this section indicates that significant air infiltration is probably happening. This air infiltration could reduce the amount of combustion gas being pulled from the kiln, resulting in fugitive emissions. A check for fugitive emissions should be included in the scope of the inspection.

c. Evaluate the temperature data for the evaporative cooler.

   The evaporative cooler is important because it protects the Nomex® bags used in the downstream pulse jet baghouses from excessive temperatures. It is clear from the flowchart that currently there is a gas temperature drop of 425°C across the evaporative cooler. This fact combined with an observed outlet gas temperature of 234°C demonstrates that this unit is operating as intended. It is not necessary to climb to the top of the unit to check the spray nozzles.

d. Evaluate the temperature data for the baghouse.

The data indicate a severe temperature drop across the baghouse (28°C). This is most likely due to air infiltration, and this should be evaluated during the field inspection.

Step 2. Use Table 7-7 to compare the current pressure drop data to the baseline data.

a . Evaluate the static pressure data at the kiln.

The baseline data and the current data are in agreement.

b. Evaluate the static pressure drop from the evaporative cooler inlet to the baghouse outlet.

The baseline static pressure drop is 4.1 in. H_2O and the current pressure drop is 2.2 in. H_2O. Pressure drops across evaporative coolers tend to remain constant. However, the pressure drop across baghouses can vary due to changes in dust concentration or because of a malfunction. A decrease in pressure drop may result in a pulse jet baghouse if there is air infiltration in the area between the upper tube sheet and the collector outlet. Since the temperature data indicate a possible air infiltration problem, this area should be checked visually during the field inspection.

c. Evaluate the static pressure data from the baghouse exit to the stack.

The static pressure increase created by the fan (3.6 in. H_2O) is similar for the baseline and current conditions. The static pressure drop from the fan exit to the stack is also in agreement.

Part C

The areas that should be emphasized during the filed inspection as follows:

- Check for air infiltration in Duct B.
- Check for fugitive emissions from the rotary kiln.
- Investigate reasons for the temperature drop across the pulse jet baghouse.
- Check for air infiltration across the pulse jet baghouse.

Part D

Determine what health and safety issues should be considered during the performance evaluation.

The pulse jet baghouse should be one of the main areas evaluated during the field portion of the inspection. However, this work must be conducted carefully in order to minimize safety hazards. The roof of the unit should be avoided because it is an uninsulated metal surface at 176°C (349°F). The soles of safety shoes could begin to melt and cause a fall.

Furthermore, there is a slight possibility of falling through the roof of the baghouse. The gas temperature drop of 28°C across the baghouse indicates severe air infiltration that may be caused by corrosion. If so, the roof may have been weakened. Corrosion is very likely in this process due to the formation of hydrochloric acid and water vapor in the kiln.

The waste being burned in this portable plant includes several suspected carcinogens. This should be noted on the flowchart to serve as a reminder to stay out of areas where inhalation problems or skin absorption hazards could exist.

Example Problem 2

A company is routinely evaluating the performance of a venturi scrubber serving a hazardous waste incinerator. They are using an Enhanced Monitoring Protocol that is based on the static pressure drop gauge across the venturi. Answer the following questions based on the data shown in Figure 7-9.

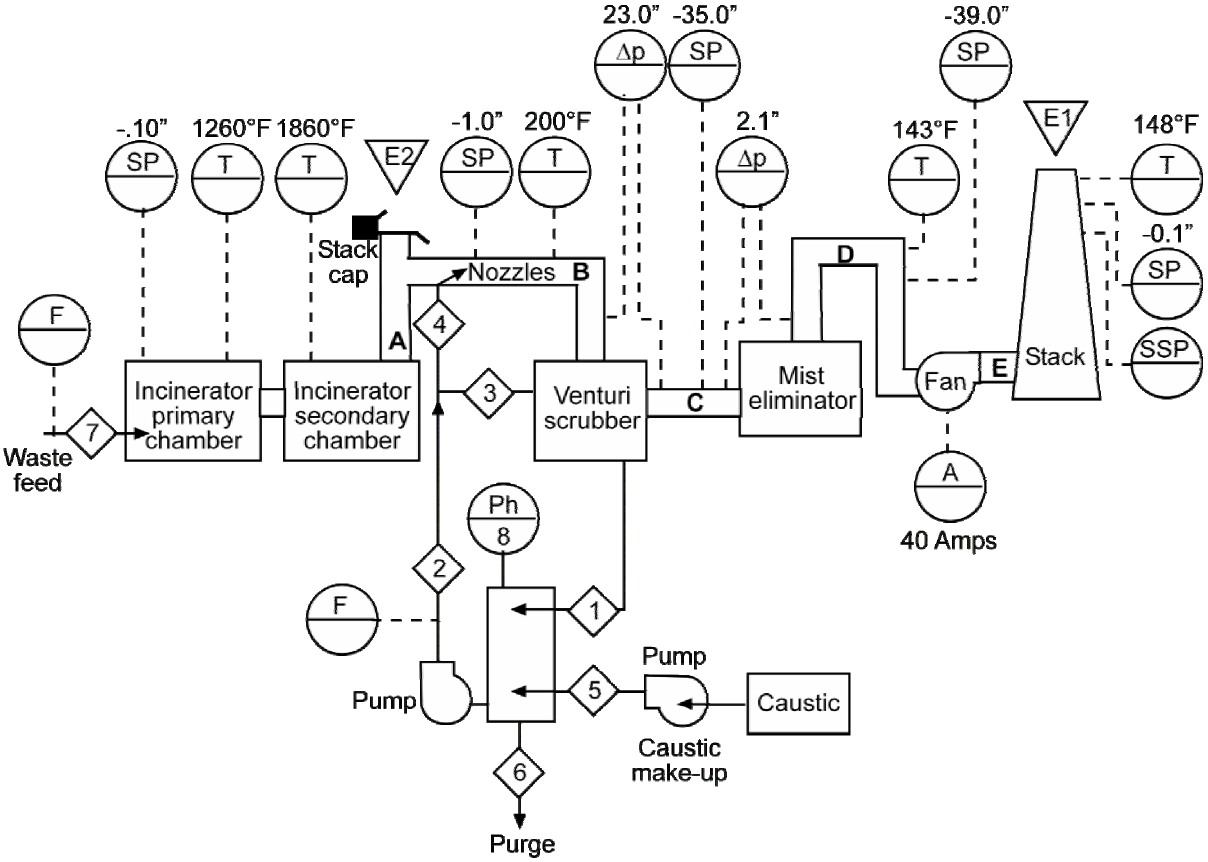

Figure 7-9. Flowchart of a hazardous waste incinerator and venturi scrubber system

A. Is there any reason to believe that the venturi scrubber pressure drop gauge is malfunctioning?
B. Is there any reason to be concerned about fugitive emissions from the emergency bypass stack?

The current data and the corresponding baseline data are provided in Tables 7-8 and 7-9.

Table 7-8. Static Pressures and Static Pressure Drops (in. H_2O)

	Current	**Baseline**
Static Pressures		
Incinerator primary chamber	-0.10	-0.12
Duct B	-1.0	-1.10
Mist eliminator inlet	-35.0	-38.0
Fan Inlet (Duct D)	-39.0	-40.0
Stack	-0.1	-0.1
Static Pressure Drop		
Venturi scrubber	23.0	36.0
Mist eliminator	2.1	1.6

Table 7-9. Gas Temperatures (°F)

	Current	**Baseline**
Incinerator secondary chamber	1860	1835
Duct B	200	197
Fan Inlet	143	142
Stack	148	147

Solution:

Part A

First, evaluate the quality of data before attempting to evaluate the system. There should be logical trends for the static pressures, gas temperatures, and other relevant parameters.

The static pressure and pressure drop data have been combined into a single graph (Figure 7-10), which can be used to evaluate the static pressures along the entire gas flow path. It is apparent that the current static pressure drop for the venturi scrubber does not make sense. The current mist eliminator inlet static pressure and fan inlet static pressure data suggest that the static pressure drop across the venturi scrubber should be higher than indicated by the gauge. It is quite possible that the venturi scrubber pressure drop gauge is malfunctioning and that the actual static pressure drop is relatively similar to the baseline value of 36 in. H_2O.

Part B

There is no reason to suspect fugitive emissions from the emergency bypass stack. The static pressures upstream and downstream of the bypass stack are negative. Accordingly, ambient air could leak into the stack if it were poorly sealed; however, untreated gases could not escape.

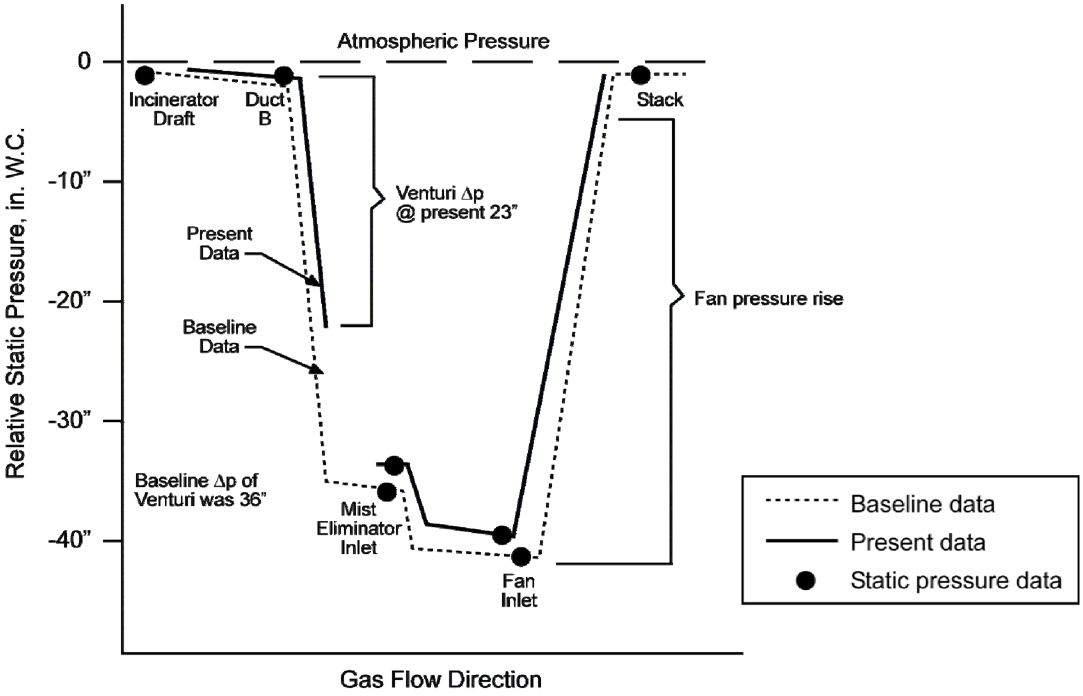

Figure 7-10. Static pressure profiles

Review Problems

Use the figure shown below to answer Questions 1-3.

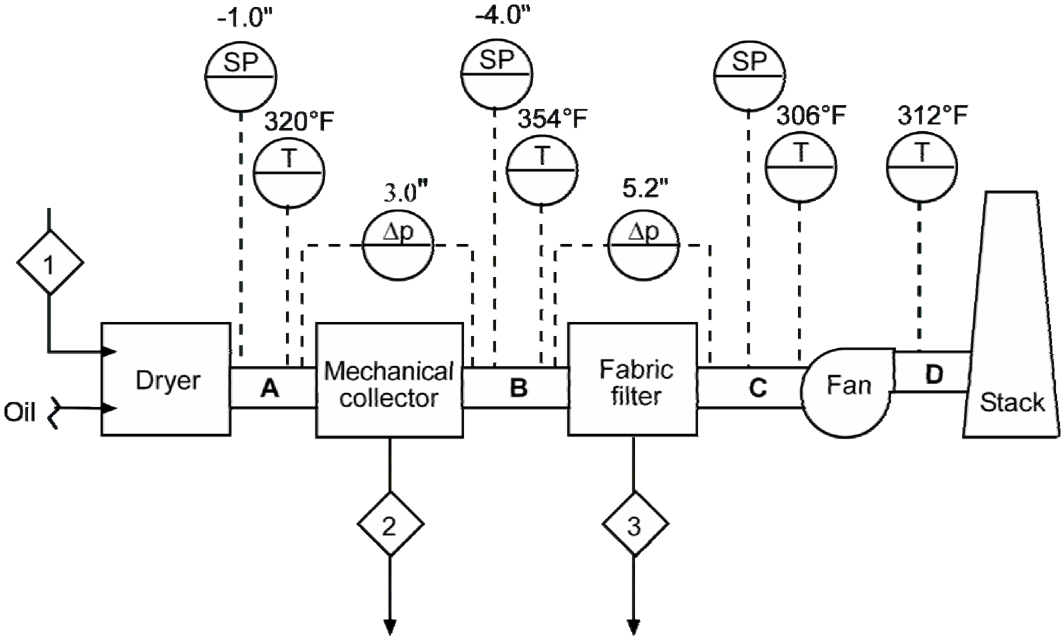

Figure 7-11. Example flowchart

1. Which static pressure reading appears to be illogical according to the flowchart?

    a. Duct A
    b. Duct B
    c. Duct D
    d. They all appear logical.

2. Estimate the static pressure at the inlet to the fan.

    a. +0.7 in. H_2O
    b. -1.7 in. H_2O
    c. -9.2 in. H_2O
    d. None of the above

3. The temperature in Duct A was checked by plant personnel and determined to be correct. Which of the other temperature readings appears to be illogical according to the flowchart?

    a. Duct B
    b. Duct C
    c. Duct D
    d. They all appear logical.