OHIO EPA'S OPERATION AND MAINTENANCE (O&M) GUIDELINES FOR AIR POLLUTION CONTROL EQUIPMENT

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Prepared for:

Ohio Environmental Protection Agency
1600 WaterMark Drive
Columbus, Ohio 43215

Submitted by:

Environmental Quality Management, Inc.
1310 Kemper Meadow Drive, Suite 100
Cincinnati, Ohio 45240

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SECTION 1.0

INTRODUCTION

1.1 Background

Proper operation and maintenance (O&M) of air pollution control equipment minimizes emissions of air pollutants, reduces equipment malfunctions, and ensures continued compliance with Ohio's air pollution control regulations and permit requirements. Regardless of how well an air pollution control system is designed, poor O&M can lead to the deterioration of its various components and to a decline in its pollutant removal efficiency. Thus, the success of an air pollution abatement program ultimately depends on the proper O&M of the installed air pollution control equipment.

Proper O&M also affects equipment reliability, on-line availability, continuing regulatory compliance, and regulatory agency/source relations. The gradual deterioration in equipment due to lack of timely and proper O&M increases the probability of equipment failure and decreases both the reliability and on-line availability of the equipment. When process operations must be curtailed or shut down to minimize emissions during outages of air pollution control equipment, the plant's productivity suffers. Also, frequent violations of emission limits can result in more inspections, potential fines for noncompliance, and sometimes, mandatory shutdown until emission problems are solved.

This document presents technically sound O&M guidelines for various types of air pollution control equipment commonly used in Ohio. The Ohio Environmental Protection Agency (EPA) and Ohio's local air agencies are making these guidelines available to assist Ohio industry in developing O&M programs. The Ohio EPA and Ohio's local air agencies will also use these guidelines 1) in reviewing preventive maintenance and malfunction abatement plans submitted by regulated entities pursuant to OAC Rule 3745-

15-06(D) and 2) in working with regulated entities with a history of control equipment malfunctions.

This manual focuses on O&M of eight types of air pollution controls (APCs):

1. Mechanical collectors (single and multiple cyclones, and Roto-Clones)
2. Fabric filters (shaker, reverse-air, and pulse-jet units, including dry scrubbers)
3. Electrostatic precipitators (both wet and dry)
4. Carbon adsorbers
5. Incinerators (thermal and catalytic units)
6. Flares
7. Wet scrubbers (spray chambers, venturis, packed-bed units, and tray towers)
8. Condensers (including refrigeration systems)

1.2 Intended Users of the Manual

The manual is designed to be an educational tool for plant and EPA personnel. No attempt is made to tell plant personnel how to operate a plant; rather, the manual provides cause-effect relationships to assist in preventing or locating problems. It will not only serve as a handy O&M reference, but will also provide the necessary information to assist plant personnel in the preparation of their own site-specific O&M manual.

The intended audience consists of the plant environmental engineer, plant O&M personnel, and EPA field personnel. The contents, however, are slanted toward the concerns of the plant environmental engineer, who with the assistance of his/her staff is responsible for long-term control strategies, O&M plans, preparation of bid specifications, and analyses of performance trends. The information presented herein will also enable plant O&M personnel to recognize potential problem areas as well as existing problems, their underlying causes, and their solutions.

The information provided should also help EPA field personnel to determine if the APC is operating within applicable regulations, to judge the effectiveness of the plant's O&M program, and to assess the causes of poor APC performance.

The responsibilities of the plant environmental engineer will generally include proper O&M of the APC, for a wide range of trends analyses related to APC performance, and for background information during the preparation of bid specifications. This manual does not attempt to replace the step-by-step O&M manuals prepared by APC vendors or documents developed by the plant for a site-specific application. Neither does it directly address the development of bid specifications. It does, however, attempt to provide sufficient detail to enable the plant environmental engineer to evaluate the plant's present O&M program and to determine if and where improvements are needed.

Plant O&M personnel should not use this manual for specific instructions on maintenance and repair procedures. Such instructions should be provided by the equipment manufacturer, and minor modifications should be made by plant personnel to fit site-specific needs. This manual presents general operating guidelines that can be used as a background document for determining the completeness of the plant's operating manual, preventive and corrective maintenance procedures, and troubleshooting and inspection procedures.

For Ohio EPA field personnel, the manual provides guidelines for conducting a field inspection of APC systems. Emphasis is on the inspection methodology for evaluating both equipment and performance. Discussions do not include topics covered in detail elsewhere (e.g., equipment design theory, regulatory concerns, and source testing and opacity readings).

1.3 Manual Organization

Section 2 of this manual presents general procedures to follow in the development of an O&M program to minimize APC malfunctions and operating problems that could result in a violation of allowable emission limits. This section also contains recommended management oversight procedures for maintaining awareness of the status of APC O&M.

Sections 3 through 10 present O&M guidelines specific to each of the eight APCs listed above. A brief description of each APC is followed by guidelines on APC monitoring and inspection, major problems and malfunctions, routine maintenance, and operator training. The APC descriptions do not provide "textbook coverage"; such information is readily available in technical literature. Neither are specific instructions for O&M procedures provided because of the unique nature of these control device systems and of the process streams they serve. The intent of this document is to prescribe the basic elements of good operating practice and preventive maintenance programs that can be used as the basis and framework for tailored, installation-specific programs.

SECTION 2.0

DEVELOPMENT OF O&M PROCEDURES FOR AIR POLLUTION CONTROL EQUIPMENT

Generally, one or more individuals at a plant site are responsible for ensuring that the air pollution controls (APCs) are operated and maintained so they meet design removal efficiencies for air pollutants and keep the plant in compliance with established emission limitations.

Unfortunately, most plant O&M personnel do not receive in-depth training on the theory of APC operation, diagnostic analysis, and the problems and malfunctions that may occur over the life of a unit. Plant personnel tend to learn about the operation of a specific unit, and they gain operating experience as a result of day-to-day operating problems. This so-called "on-the-job" training can result in early equipment deterioration or catastrophic failures that could have been avoided.

This section presents the basic elements of an O&M program that can prevent premature APC failure. This program is not all-inclusive; nor does it address all potential failure mechanisms. Nevertheless, it provides the user with enough knowledge to establish a plan of action, to maintain a reasonable spare parts inventory, and to keep the necessary records for analysis and correction of deficiencies in APC operation.

The components of an O&M plan are management, personnel, preventive maintenance, inspection program, specific maintenance procedures, and internal plant audits. The most important of these are management and personnel. Without a properly trained and motivated staff and the full support of plant management, no O&M program can be effective.

2.1 Management and Staff[1]

Personnel operating and servicing the APCs must be familiar with the components of the units, the theory of operation, limitations of the device, and proper procedures for repair and preventive maintenance.

For optimum performance, one person (i.e., a coordinator) should be responsible for APC O&M at small or medium-sized plants, this individual could be the Plant Engineer or Environmental Manager. Except in very large plants, the APC coordinator would have other plant/environmental assignments. All requests for repair and/or investigation of abnormal operation should go through this individual for the coordination of efforts. Upon completion of repairs, final reports also should be transmitted to the originating staff through the APC coordinator. Thus the coordinator will be aware of all maintenance that has been performed, any chronic or acute operating problems that occur, and any work that is in progress.

The coordinator, in consultation with the operation (process) personnel and management, also can arrange for and schedule all required maintenance. He/she can assign priority to repairs and order the necessary repair components, which sometimes can be received and checked out prior to installation. Such coordination does not eliminate the need for specialists (electricians, pipe fitters, welders, etc.), but it does avoid duplication of effort and helps to ensure an efficient operation.

Many APC failures and operating problems are caused by mechanical deficiencies. These are indicated, for example, by changes in differential pressures and temperatures, by opacity readings, and by changes in flow rates. By evaluating process conditions, pressure and temperature readings, inspection reports, and the physical condition of the unit, the coordinator can evaluate the overall condition of the APC and recommend process modifications and/or repairs.

The number of support staff required for proper operation and maintenance of a unit is a function of unit size, design, and operating history. Staff requirements must be assessed periodically to ensure that the right personnel are available for normal levels of maintenance. Additional staff will generally be needed for such activities as a major rebuilding of a unit or structural changes. This additional staff may include plant personnel, outside hourly laborers, or contracted personnel from service companies or APC vendors. In all cases, outside personnel should be supervised by experienced plant personnel. The services of laboratory personnel and computer analysts may also be needed. The coordinator should be responsible for final acceptance and approval of all repairs. Figure 2-1 presents the general concept and staff organizational chart for a centrally coordinated O&M program.

2.2 Training

As with any highly technical process, the O&M staff responsible for APC equipment must have adequate knowledge to operate and repair that equipment.

Many components of APCs are not unique, and special knowledge regarding the components themselves is not required; however, the arrangement and installation of these components are unique in most applications, and special knowledge and care are needed to maintain their optimum performance.

Many plants have a high rate of personnel turnover, and new employees may be assigned to work on an APC who have had no previous contact with such equipment. To provide the necessary technical expertise, management must establish a training program for each employee assigned to APC O&M.

An optimum training program should include the operators, supervisors, and maintenance staff. Changes in operation that affect composition, temperature, oil or moisture content, acid dew point, and the particulate abrasiveness of the gas stream entering the unit can have a detrimental effect on the operation of APC equipment. The process operator has control over many of these variables. An understanding of the cause-and-effect relationship between process conditions and the APC can help to avoid many performance problems. Safety is also an important aspect of any training program. Each person associated with the unit should have complete instructions regarding confined-area entry, first aid, and lock-out/tag-out procedures.

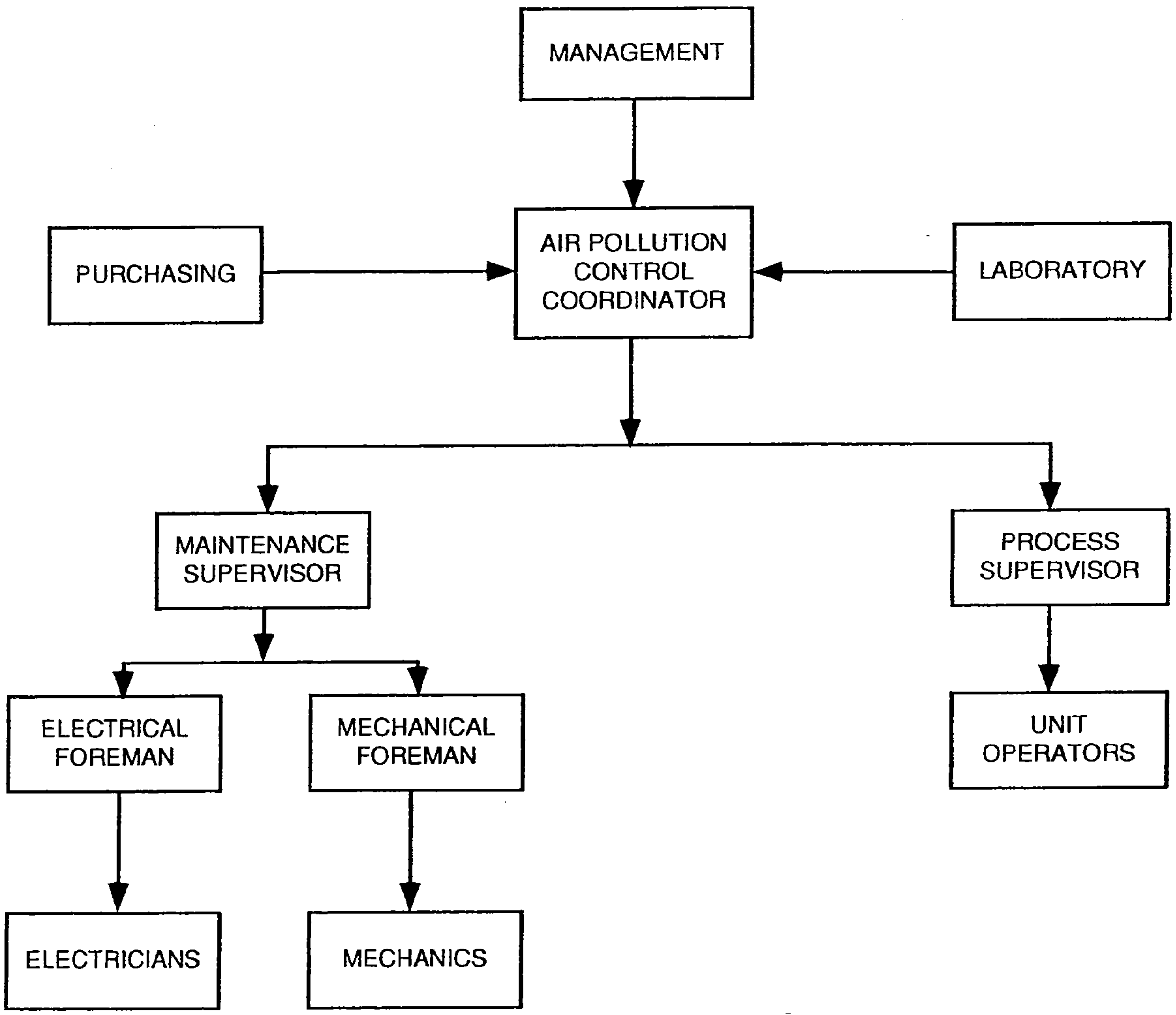


Figure 2-1. Organization chart for centrally coordinated O&M program.

Thus, a typical APC training program should include safety, theory of operation, a physical description of the unit, a review of subsystems, normal operation indicators, abnormal operations (common failure mechanisms), troubleshooting procedures, a preventive maintenance program, and recordkeeping.

The O&M program should emphasize optimum and continuous performance of the unit. The staff should never get the impression that anything less than optimum performance is acceptable. Redundancy is established in the unit solely to provide a margin of safety for achieving compliance during emergency situations. Once a pattern is established that allows a less-than-optimum condition to exist (i.e., reliance on built-in redundancy), less-than-optimum performance becomes the norm and the margin of safety begins to erode.

The training program should be reinforced by the preparation of followup written material. Each plant should prepare and continually update APC operating maintenance manuals for each unit. A generic manual is usually inadequate because each vendor's design philosophy varies. The use of photographs, slides, and drawings aids in the overall understanding of the unit and reduces lost time during repair work.

2.3 Maintenance Manuals

Specific maintenance manuals should be developed for each APC at a source. The basic elements of design and overall operation should be specific to each APC and should incorporate the manufacturer's literature and in-house experience with the particular type of unit. The manual should relate to the physical aspects of the unit. Descriptions should be brief and to the point; long narratives without direct application should be avoided.

Figure 2-2 presents a suggested outline for a typical manual. The manual should begin with such basic concepts as the APC description and operation. These can be followed by a section on component parts, which should include detailed drawings and an explanation of the function of each component.

I. GENERAL DESCRIPTION OF AIR POLLUTION CONTROL
   A. Equipment Components
   B. Auxiliary Equipment (e.g., fan, ash removal system)

II. DESCRIPTION OF OPERATION
   A. Pollutant Collection Mechanisms
   B. Pollutant Removal from APC

III. SAFETY EQUIPMENT
   A. Gas-Monitoring Equipment
   B. Personal Protection Equipment (e.g., hearing protection, protective clothing)

IV. COMPONENT DESCRIPTION
   A. Specific Descriptions of Equipment Components (from vendor)
   B. Details on Materials of Construction, Housing, Valves, Dampers, Motors, Pumps, Fans

V. EXTERNAL INSPECTION AND MAINTENANCE
   A. Housing Components (e.g., gaskets, expansion joints)
   B. Monitoring Equipment
   C. Control Cabinet
   D. Interlocks

VI. INTERNAL INSPECTION AND MAINTENANCE
   A. Internal APC Components (e.g., bags for fabric filter)
   B. Inlet and Outlet Ducts
   C. Hoppers or Sumps

APPENDIX

   A. Inspection and Maintenance Checklist
   B. Layout Details

Figure 2-2. Outline for air pollution control maintenance manual.

The section on external inspection and maintenance includes all supporting equipment, such as cleaning mechanisms, instrumentation, and air compressors (where applicable). The next section should cover procedures for internal inspection and maintenance, as these are extremely critical in maintaining performance. In a fabric filter, for example, periodic checks are necessary to maintain bag integrity, to remove accumulated ash deposits, and to prevent air inleakage. Each of these sections should provide a procedure for evaluating the component. The manual should identify key operating parameters, define normal operation, and identify indicators of possible deviations from normal condition. Fabric filter key operating parameters, for example, include temperature, pressure, cleaning cycle, opacity, or other parameters that can be used to establish the basic operating condition of the unit.

After conditions are evaluated, a procedure must be presented to replace, repair, or isolate each component. If proper procedures are not followed, the corrective action could result in further damage to the unit, excessive emissions, or repeated failure.

2.4 Operating Manuals

Whereas maintenance manuals are designed to facilitate physical repairs to the APC, operating manuals are needed to establish an operating norm or baseline for each unit. Maintenance of the physical structure cannot ensure adequate performance of the unit because gas-stream conditions such as temperature, composition, and volume can cause the APC to malfunction and rapidly decrease collection efficiency.

The operating manual should parallel the maintenance manual in terms of introductory material so that the operators and maintenance personnel have the same basic understanding of the components and their function and of the overall operating theory. Additional information should be provided on the effects of major operating variables such as gas volume, gas temperature, and pressure drop. Figure 2-3 presents a generic outline for an operating manual.

With regard to fuel combustion sources, for example, the manual should discuss the effects of such process variables as burner conditions, burner alignment, and

I. DESCRIPTION OF CONTROL DEVICE
   A. Equipment Components
   B. Auxiliary Equipment (e.g., fans, ash removal system)

II. DESCRIPTION OF OPERATION
   A. Pollution Collection Mechanisms
   B. Pollutant Removal from APC

III. OPERATIONAL FACTORS
   A. Gas Characteristics (e.g, volume, temperature, composition)
   B. Differential Pressure and Other Key Monitoring Parameters
   C. Stack Visuals (e.g., opacity, plume color)

IV. AUXILIARY SYSTEM MALFUNCTION
   (e.g., fan, particulate removal system dampers)
   A. Plugged Hoppers
   B. Fan Noises
   C. Pump and Motor Malfunctions

V. STARTUP
   A. Safety Check
   B. Specific Procedures

VI. SHUTDOWN
   A. Specific Procedures
   B. Differentiate Between Short (Overnight) and Long (Several Days) Shutdowns

Figure 2-3. APC operating manual outline.

pulverizer fineness, which can change the ash particle properties and size distribution. An expected normal range of values and indicator points should be established as reference points for the operator.

Startup and shutdown procedures should be established, and step-by-step instructions should be provided to ensure sequenced outage of equipment to aid in maintenance activities and to eliminate startup problems.

2.5 Spare Parts[1]

An inventory of spare parts should be maintained to replace failed parts as needed. Because all components or subassemblies cannot be stocked, a rational system must be developed that establishes a reasonable inventory of spare parts. Decisions regarding which components to include in the spare parts inventory should be based on the following:

1. Probability of failure
2. Cost of components
3. Replacement time (installation)
4. Whether the part can be stored as an individual component or subassembly (e.g., shaker assembly for fabric filter)
5. In-house technical repair capabilities
6. Available space

The probability of failure can be developed from outside studies, vendor recommendations, and a history of the unit. It is reasonable to assume that components subjected to heat, dust, weather, or wear are the most likely to fail. Components of this type are no different from those in process service, and reasonable judgment must be used in deciding what to stock. Maintenance staff members should be consulted for recommendations concerning some items that should be stocked and the number required. Adjustments can be made as operating experience is gained.

Another factor that enters into decisions regarding a spare parts inventory is the cost of individual components. Maintaining an extensive inventory of high-cost items that have low probability of failure is not justified.

The time required to receive the part from the vendor and the time required to replace the part on the unit also influence whether an item should be stocked. If the lead time for a critical part is a matter of weeks or months, or if a component must be specially built, stocking such items is advantageous.

Many plants have an electronics and mechanical shop whose staff can repair or rebuild components to meet original design specifications. The availability of this service can greatly reduce the need to maintain component parts or subassemblies. In these cases, one replacement can be stocked for installation during the period when repairs are being made. For example, many printed circuit boards can be repaired internally, which reduces the need to stock a complete line of electronic spare parts.

2.6 Work Order Systems[1]

A work order system is a valuable tool that allows the APC coordinator to track unit performance over a period of time. Work order and computer tracking systems are generally designed to ensure that the work has been completed and that charges for labor and parts are correctly assigned for accounting and planning purposes. With minor changes in the work order form and in the computer programs, the work order also can permit continuous updating of failure-frequency records and can indicate whether the maintenance performed has been effective in preventing repeated failures. In general, the work order serves three basic functions:

1. It authorizes and defines the work to be performed.
2. It verifies that maintenance has been performed.
3. It permits the direct impact of cost and parts data to be entered into a computerized data handling system.

To perform these functions effectively, the work order form must be specific, and the data fields must be large enough to handle detailed requests and to provide specific responses. In many computerized systems, the data entry cannot accommodate a narrative request and specific details are thus lost.

Most systems can accommodate simple repair jobs that do not involve multiple repairs, staff requirements, or parts delays. Major repairs, however, become lost in the system as major events because they are subdivided into smaller jobs that the system can handle. Because of this constraint, the tracking system may show a large repair project with many components (e.g., a cleaning system failure or control panel repair) and a common cause as a number of unrelated events.

For diagnostic purposes, the work order system requires a subroutine that links repairs, parts, and location of failure in an event-time profile. The exact location of component failures also must be clearly defined. In effect, it is more important to know the pattern of the failure than its cost.

In summary, the goals of the work order system are as follows:

- To provide systematic screening and authorization of requested work.
- To provide the necessary information for planning and coordination of future work.
- To provide cost information for future planning.
- To instruct management and craftsmen in the performance of repair work.
- To estimate manpower, time, and materials for completing the repair.
- To define the equipment that may need to be replaced, repaired, or redesigned (work order request for analysis of performance of components, special study, or consultation, etc.).

Repairs to the unit may be superficial or cosmetic in nature, or they may be of an urgent nature and require emergency response to prevent damage or failure. In a major facility, numerous work order requests may be submitted as a result of daily inspections or operator analysis. Completing the jobs in a reasonable time requires scheduling the staff and ordering and receiving parts in an organized manner.

For effective implementation of the work order system, the request must be assigned a level of priority regarding completion time. These priority assignments must take into consideration plant and personnel safety, the potential effect on emissions, potential damage to the equipment, and the availability of maintenance personnel, parts, and the boiler, process, or control equipment. Obviously, all jobs cannot be assigned the highest priority. Careful assignment must be made as quickly as possible after requests are received. Figure 2-4 is an example of a five-level priority system.

A work order request that is too detailed will require extra time to complete, and a complex form can lead to superficial entries and erroneous data. The form should concentrate on the key elements required to document the need for repair, the response to the need (e.g., repairs completed), parts used, and manpower expended. Although a multipage form is not recommended, such a form may be used for certain purposes. For example, the first page can be a narrative describing the nature of the problem or repair required and the response to the need. The maintenance staff must indicate the cause of the failure and changes that could prevent recurrence. Simply making a repair to malfunctioning system controls and responding that "the repairs have been made" is inadequate. Unless a detailed analysis is made of the reason for the failure, the event may be repeated several times. Treating the symptom (making the repair or replacing parts) is not sufficient; the cause of the failure must be treated.

In summary, the following is a list of how the key areas of a work order request are addressed.[2]

1. Date - The date is the day the problem was identified or the job was assigned if it originated in the planning, environmental, or engineering sections.

2. Approved by - This indicates who authorized the work to be completed, that the request has been entered into the system, and that it has been assigned a priority and schedule for response. The maintenance supervisor or APC coordinator may approve the request, depending on the staff and

WORKORDER PRIORITY SYSTEM

PRIORITY	ACTION
1	Emergency Repair
2	Urgent repair to be completed during the day
3,4	Work that may be delayed and completed in the future
5	Work that may be delayed until a scheduled outage

Figure 2-4. Example of five-level priority system.

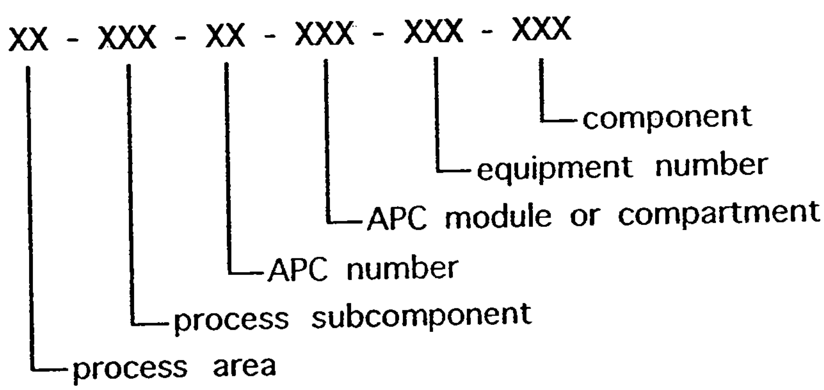
the size of the facility. When emergency repairs are required, the work order may be completed after the fact, and approval is not required.

3. Priority - Priority is assigned according to job urgency on a scale of 1 to 5.

4. Work order number - The work order request number is the tracking control number necessary to retrieve the information from the computer data system.

5. Continuing or related work order numbers - If the job request is a continuation of previous requests or represents a continuing problem area, the related number should be entered.

6. Equipment number - All major equipment in an APC should be assigned an identifying number that associates the repair with the equipment. The numbering system can include the process area, major process component, APC number, APC module compartment, equipment number, and process subcomponent. This numeric identification can be established by using a field or grouped numbers. For example, the following could be used:



If the facility only has one APC and one process, the first five numbers (two groups) may not be required, and the entry is thus simplified. The purpose of the ID system is to enable analysis of the number of events and cost of repair in preselected areas of the APC. Greater detail in the equipment definition will allow more detail in later analyses.

7. Description of work - The request for repair is usually a narrative describing the nature of the failure, the part to be replaced, or the work to be completed. The description must be detailed but brief because only a limited number of characters can be entered into the computerized data system. Additional pages of lengthy instruction regarding procedures may be attached to the request (not for computer entry).

8. Estimated labor - Assignment of personnel and scheduling of outages of certain equipment require the inclusion of an estimate of manhours, the number of in-house staff needed, and whether outside labor is needed. The more complex jobs may be broken down into steps, with different personnel and crafts assigned specific responsibilities. Manpower and procedures in the request should be consistent with procedures and policies established in the O&M manual.

9. Material requirements - In many jobs, maintenance crews will remove components before a detailed analysis of the needed materials can be completed; this can extend an outage while components or parts are ordered and received from vendors or retrieved from the spare parts inventory. Generally, the cause of the failure should be identified at the time the work order request is filled, and specific materials needs should be identified before any removal effort begins. If the job supervisor knows in advance what materials are to be replaced, expended, or removed, efficiency is increased and outage time reduced. Also, if parts are not available, orders may be placed and the parts received prior to the outage. Material requirements are not limited to parts; they also include tools, safety equipment, etc.

10. Action taken - This section of the request is the most important part of the computerized tracking system. It should provide a narrative description of the repair conducted in response to the work order request. The data must be accurate and must clearly respond to the work order request.

11. Materials replaced - An itemized list of components replaced should be provided for tracking purposes. If the component has a preselected ID number (spare parts inventory number), this number should be included.

Actual man-hours expended in the repair efforts can be indicated by work order number on separate time cards and/or job control cards by craft and personnel number.

Copies of work orders for the APC should be retained for future reference. The APC coordinator should review these work orders routinely and make design changes or equipment changes as required to reduce failure or downtime. An equipment log also should be maintained, and the work should be summarized and dated to provide a history of maintenance on the unit.

2.7 Computerized Tracking

2.7.1 Work Orders

If the work completed and parts used in the APC have been entered in the computerized work order system with sufficient detail, maintenance and management personnel can evaluate the effectiveness of APC maintenance.

Preventive maintenance (PM) man-hours and repair man-hours also can be compared to evaluate the effectiveness of the current PM program. The level of detail may allow tracking of the impact of PM on particular subgroups (e.g., fans, hoppers) as changes are made in PM procedures. The effectiveness of the PM program may be further evaluated by comparing the required number of emergency repairs with scheduled repairs over a period of time (i.e., priority 2 versus priority 5, etc.).

The purpose of the computerized tracking system is <u>not</u> to satisfy the needs of the accountants or programmers or to state that the plant has such a system. <u>Rather</u>, the purpose of a computerized tracking system is to provide the necessary information to analyze APC maintenance practices and to reduce component failures and excess emissions. The maintenance staff and APC coordinator must clearly define the kind of data required, the level of detail needed, and the type of analysis required prior to the preparation of the data-handling and report-writing software. Examples of output may be man-hours by department, man-hours by equipment ID, number of repairs, number of events, number of parts, and frequency of events.

2.7.2 APC Operating Parameters

In addition to tracking work orders, the computer can be used to develop correlations between process and APC operating parameters and observed emission profiles. Depending on the type of cycles expected in process operation, the data may be continuously input into the system or it may be entered once or twice a week from operating logs or daily inspection reports.

For example, the key data for tracking performance are pressure differentials, opacity (i.e., 6-minute averages), boiler load (or associated parameter proportional to gasflow volume), flue gas temperature, and fuel quality data (i.e., fuel source, ash, fineness, etc.).

2.8 Procedures for Handling Malfunction

Many malfunctions are of an emergency nature and require prompt action by the maintenance staff to reduce emissions or to prevent damage to the unit. On some units, predictable but unpreventable malfunctions can be identified; for example, such malfunctions for baghouses would include hopper pluggages, bag failure in fabric filters, and cleaning system failure. These problems and corrective actions are discussed in the sections specific to each control device.

An effective O&M program should include established written procedures to be followed when malfunctions occur. Having a predetermined plan of action reduces lost time, increases efficiency, and reduces excessive emissions. The procedures should contain the following basic elements: malfunction anticipated, effect of malfunction on emissions, effect of malfunction on equipment if allowed to continue, required operation-related action, and maintenance requirements or procedure.

REFERENCES FOR SECTION 2

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SECTION 3.0

MECHANICAL COLLECTORS

Proper operation and maintenance (O&M) of mechanical particle control devices is crucial to obtaining their design control efficiency. Routine inspections and scheduled maintenance of a control unit are important facets of typical operations. The upkeep of mechanical collectors will provide the required collection efficiency for regulatory compliance and proper system operation.

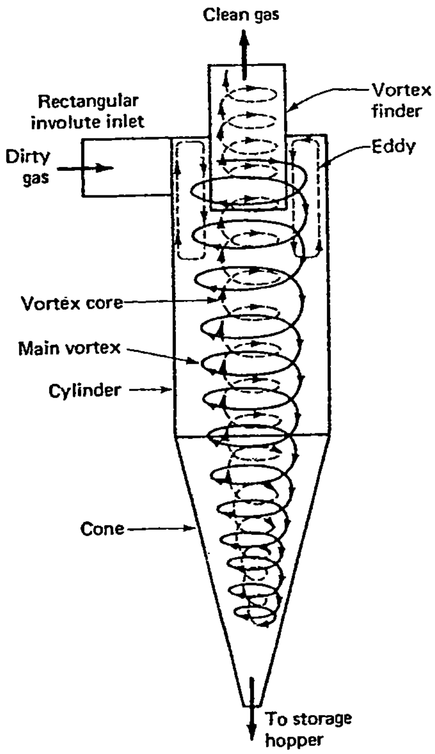
This section discusses the general O&M procedures for cyclones, multicyclones, and Roto-Clones. Roto-Clone is the tradename of a commonly used type of mechanically aided scrubber distributed by American Air Filter. The name is used in this section because it is familiar to potential users of this document. Its inclusion is not intended to be an equipment recommendation.

Mechanical collector O&M procedures included in this section are presented in a general format, and they should be modified to accommodate the specific control unit, configuration, and process specifications.

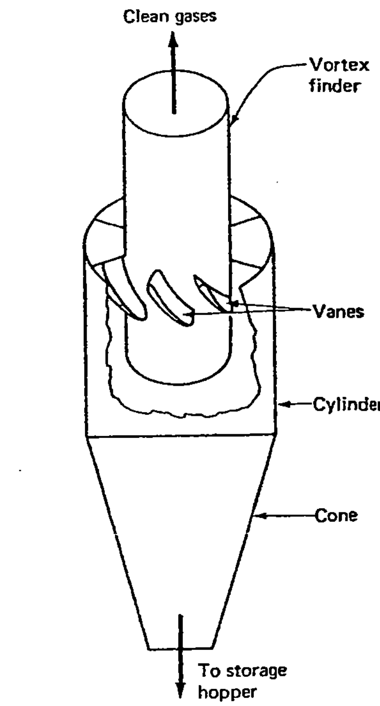
3.1 Description of Mechanical Collectors

Mechanical gas-cleaning devices such as cyclones, multicyclones, and Roto-Clones use centrifugal force as the primary collection parameter (water spray is used with the Roto-Clone). Mechanical collection devices are widely used to collect particles from emission sources having high exit temperatures or sources with emissions containing particulates with a relatively large mean particle diameter (greater than 15 μm).[1]

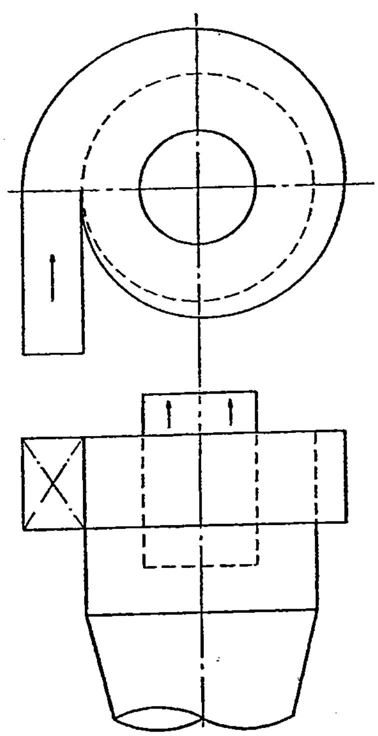
The cyclone (Figure 3-1) is a single gas-cleaning device that uses a centrifugal force generated by a spinning gas stream to separate the particulate matter from the carrier gas. The single cyclone can be made in a number of configurations to allow for



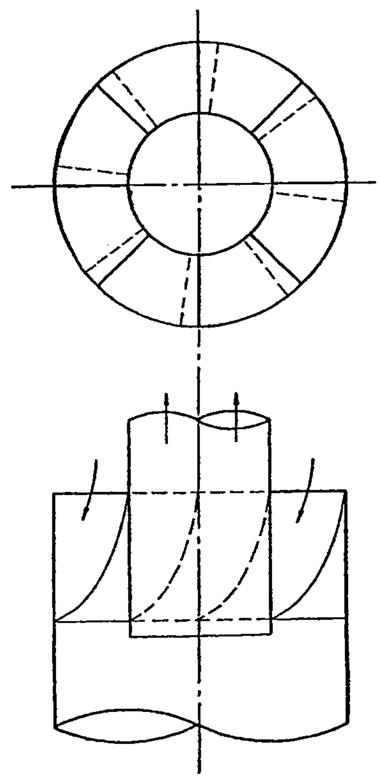
Involute Cyclone Separator



Vane-Axial Centrifugal Separator (Cyclone)



Involute



Axial

Figure 3-1. Cyclone separator schematic.[1,2]

higher collection efficiency or increased volumetric throughput. It can be used as a large single unit (Figure 3-1), in parallel for increased volumetric capacity, in series for increased particle removal efficiency, or in a multiclone configuration (Figure 3-2).[3] Multicyclone tubes are used for handling larger gas volumes. The cyclone tube arrangement is generally square or rectangular, and the tubes are arranged linearly. The number of cyclone rows is kept to a minimum to prevent hopper crossflow and to reduce gas distribution problems.[3] Roto-Clones use a water spray in conjunction with a centrifugal collector to separate and remove particles from the gas stream.

A variety of cyclones are in use, but they generally fall into two major classes--involute and vane axial (Figure 3-1). The difference in these classes is the method by which the gas stream is introduced to the cylindrical shell. The involute cyclone has a rectangular inlet with the inner wall tangent to the cylinder. The inlet is designed to blend gradually with the cylinder over a 180° involute. The vane axial type of cyclone is the one generally incorporated into the design of a multicyclone. The cyclone motion of the gas is imparted to the axially descending dirty gas by a ring of vanes. The centrifugal force resulting from the high rate of spin forces the dust particles to the outer walls of the cylinder and cone.[1]

The cyclone is a relatively simple particle-collection device consisting of several key operating components: the cylindrical body, a tangential inlet through which dirty gas enters, an exit pipe for clean gas discharge, and a conical base equipped with a dust discharge hopper (Figure 3-3). Cyclones are typically operated in a vertical position; however, because the main force of collection is centrifugal and not gravitational, horizontal or inclined arrangements have similar collection efficiencies.[3]

The gasflow patterns within the cyclone are complex. Three main flow patterns carry the particle-laden gas through the collection device. The main vortex carries the separated dust down the walls of the cyclone to the dust hopper. The vortex core is an ascending spiral that rotates in the same direction as the main vortex but carries the cleaned gas from the cyclone or dust hopper inlet to the gas outlet. The radially inward flow is the transition area that feeds the gas from the descending main vortex to the ascending vortex core. The dust collection hopper is the point of final separation of the

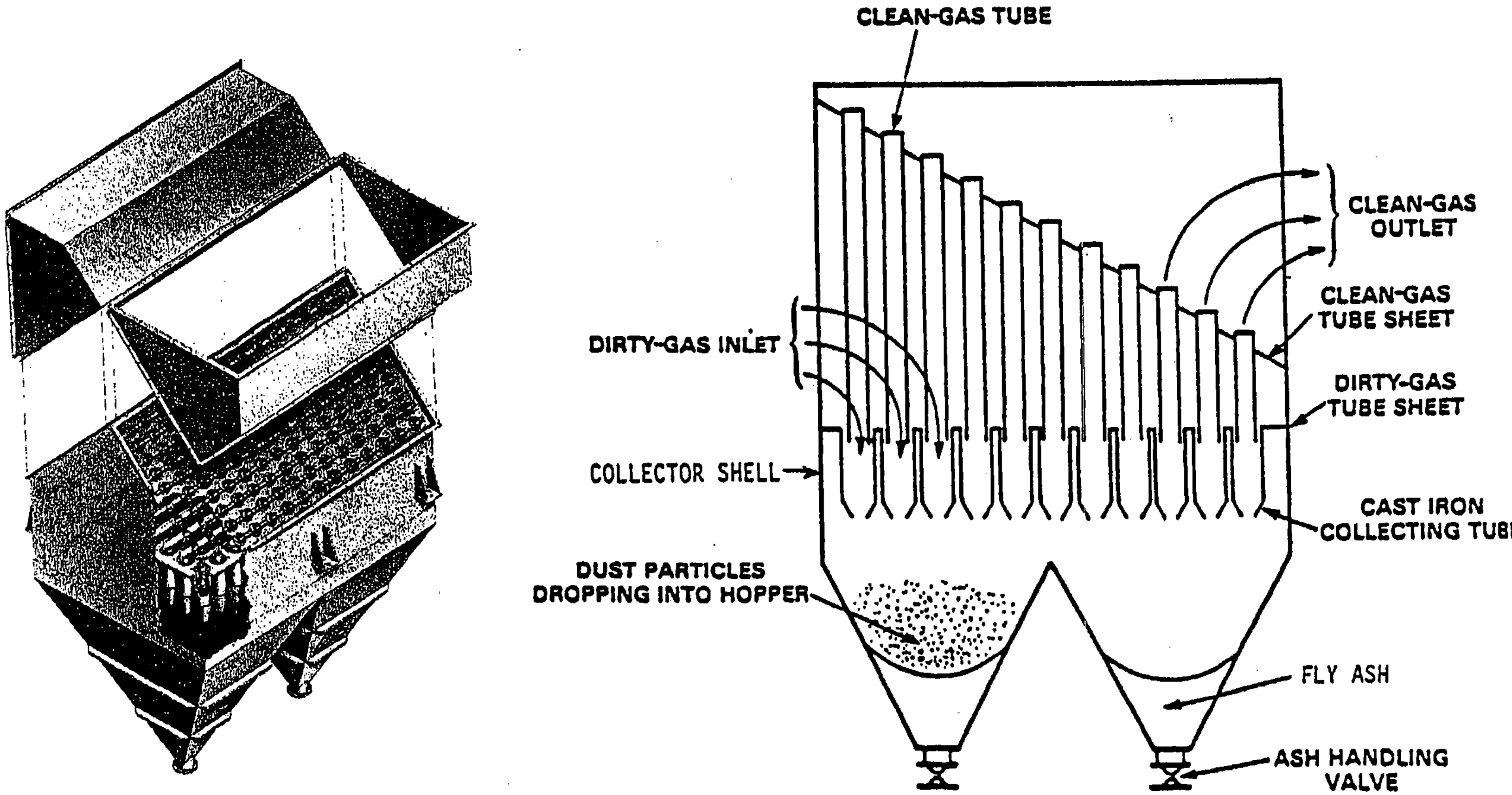


Figure 3-2. Multiclone separator schematic.[1,4]

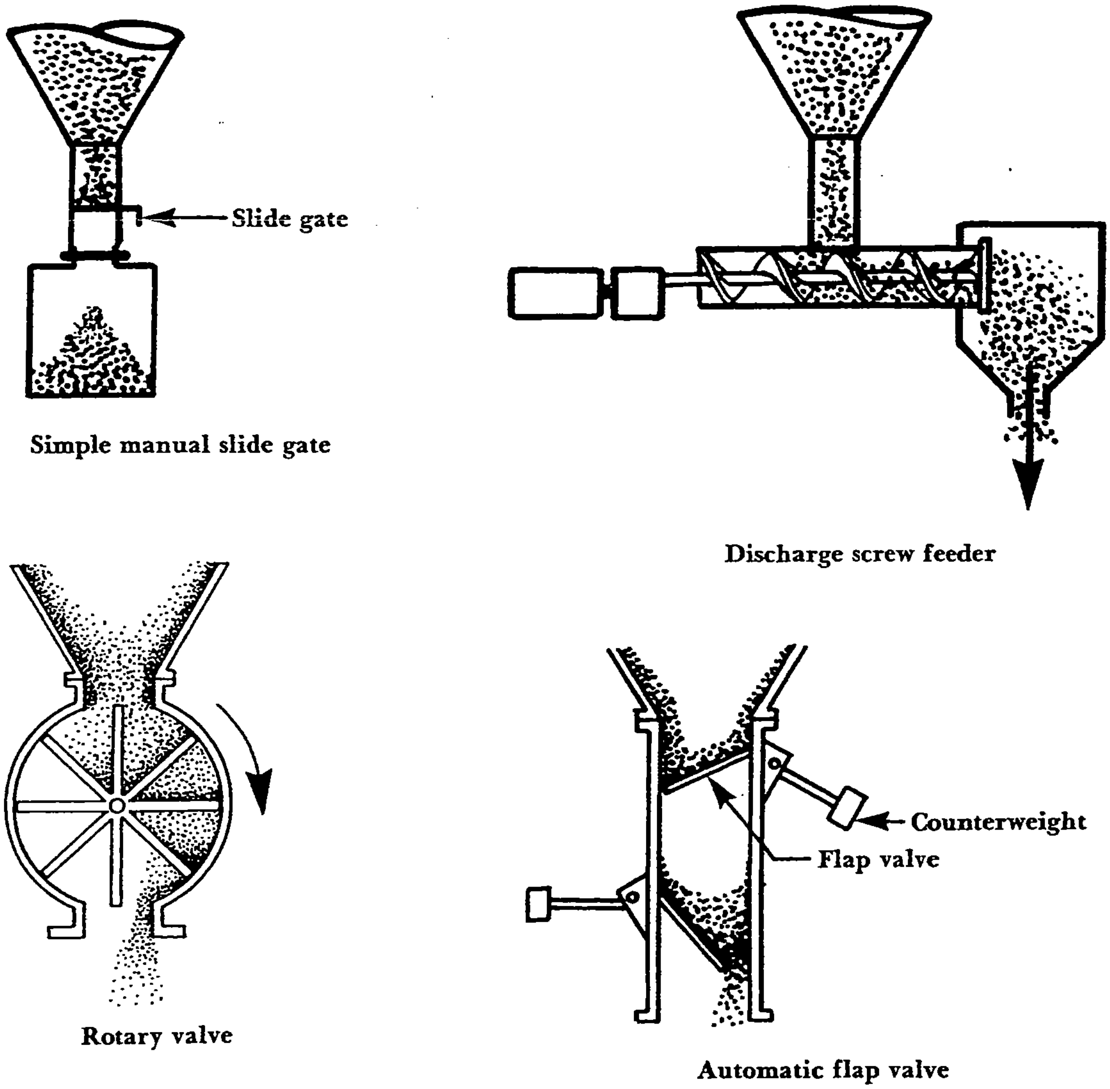


Figure 3-3. Common types of dust hopper mechanisms.[4]

particles from the spiralling gas stream. In this zone, the total gasflow reverses direction and is fed to the ascending spiral flow.[3]

The flow patterns are generated by the creation of a double vortex, which centrifuges the dust particles to the walls. When the particles reach the walls, they are transported down the sides of the walls to the collection hopper, which is isolated from the spinning gases. The downward flow along the cyclone walls must remain smooth and unbroken to minimize particle reentrainment. The flow patterns of the outer vortex depends greatly on the smoothness of the inner walls. Rough surfaces caused by particle abrasion, dents, caking, or corrosion results in a potential turbulent flow regime that tends to promote reentrainment of particles.

As shown in Table 3-1, the collection efficiency of a cyclone also depends on pressure drop, inlet dust loading, velocity, particle size distribution, particle density, and inlet gas stream temperature.[3] For maintenance of the proper collection efficiency of the cyclones or multicyclone, the pressure drop across the unit, inlet gas velocity and inlet gas temperatures should be monitored to assure they are at or near the levels recommended by the manufacturer's design criteria.

TABLE 3-1. PARAMETERS AFFECTING CYCLONE AND MULTICLONE COLLECTION EFFICIENCY

Parameter	Effect on Efficiency
Temperature	Decreases as temperatures increase due to gas viscosity changes.
Inlet loading	Increases with inlet loading.
Pressure drop	Increases with pressure drop up to a certain limit where turbulent flow occurs.
Velocity	Increases with velocity and falls off sharply below 25 ft/s.
Specific gravity	Increases with higher-specific-gravity materials.

Roto-Clones incorporate water spray (with the exception of the Type D Roto-Clone, which is a dry collection unit) with the centrifugal force as the collection mechanisms for particulate matter. Roto-Clones are constructed in a variety of configurations: Type W, wet centrifugal collection (Figure 3-4); Type D, dry centrifugal collection (Figure 3-5); Type N, hydrostatic precipitator (Figure 3-6); and Type R, wet centrifugal collection (Figure 3-7). Each Roto-Clone type has a variety of arrangements to allow for proper particle collection in a given application.

The Type W Roto-Clone can be arranged in two ways (A and D) to facilitate particle collection. Arrangement A, shown in Figure 3-8, is typically applied to light loadings of granular dusts and mists. The dust-laden air enters the Roto-Clone, where it is subjected to a fine water spray. Because the water and dust combination is heavier than air, it impinges on the blades of the impeller and is then directed into the water cone by the blades and the centrifugal force resulting from the rotating impeller. The collected slurry drains from the unit through the sludge chute to the expansion chamber. The clean air is discharged in front of the water cone and pushed through the outlet chamber. The Arrangement D, Type W Roto-Clone, shown in Figure 3-4, is used in situations having a heavy concentration of granular dust. This type of unit is equipped with a centrifugal precleaner that removes a high percentage of the incoming dust from the air stream.[5]

The Type D Roto-Clone (shown in Figure 3-5) is a dry centrifugal dust collector that consists of three major components--the impeller, the housing, and the dust chamber. When the process exhaust stream contains heavy concentrations of abrasive dust, this unit can be operated in conjunction with an air skimmer. The rotating impeller performs three tasks: it pulls the air through the unit at high velocity, it streamlines the air flow, and it concentrates the particles at the periphery by centrifugal force. The housing of the Type D Roto-Clone encloses the impeller and it has two air passages. The primary passage is for cleaned air emerging from the central part of the impeller. The secondary passage, which is reserved for heavily dust-laden air, leads into and through the air-tight dust hopper at the base of the unit. The radial blades are contained hyperbolically to create a converging pattern for all particles. The particles concentrated by the streamline flow are caught by the tips of the blades that bend downward into the secondary air passage and are swept into the dust hopper. The air velocity in the secondary unit is greatly reduced in the dust hopper to allow particle settling.[5]

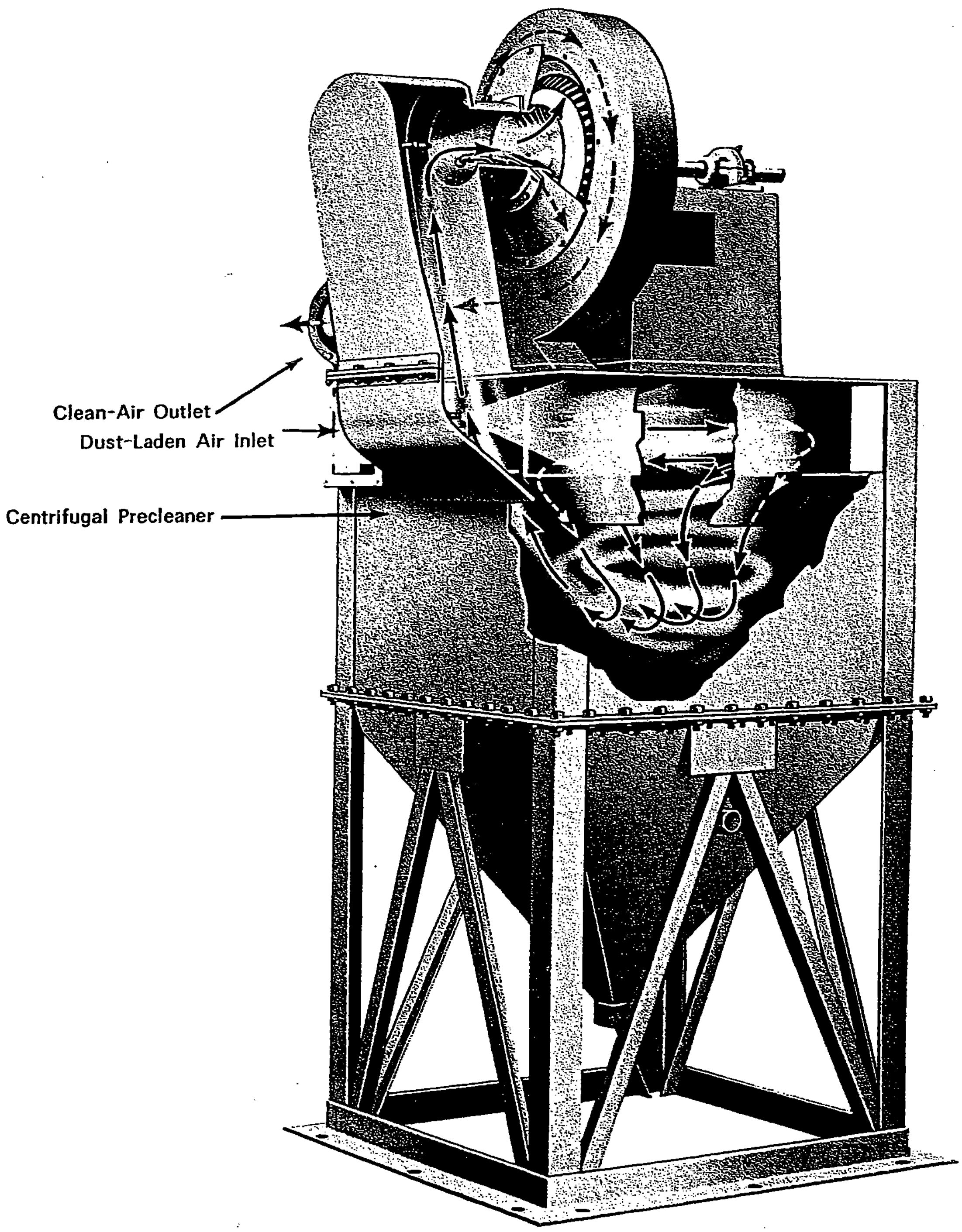


Figure 3-4. Type W Roto-Clone, Arrangement D.[5]
(American Air Filter)

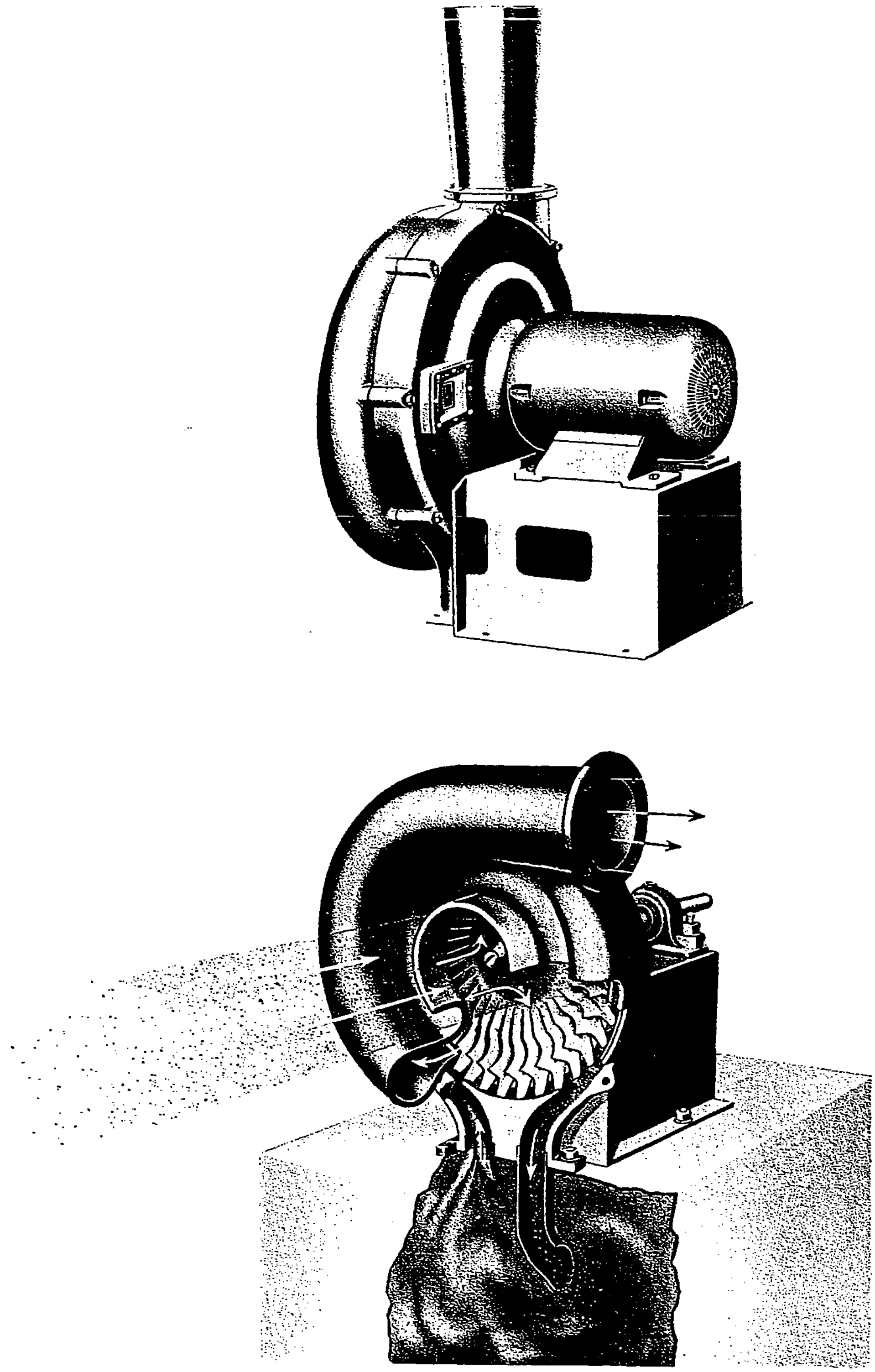


Figure 3-5. Type D Roto-Clone[5]
(American Air Filter)

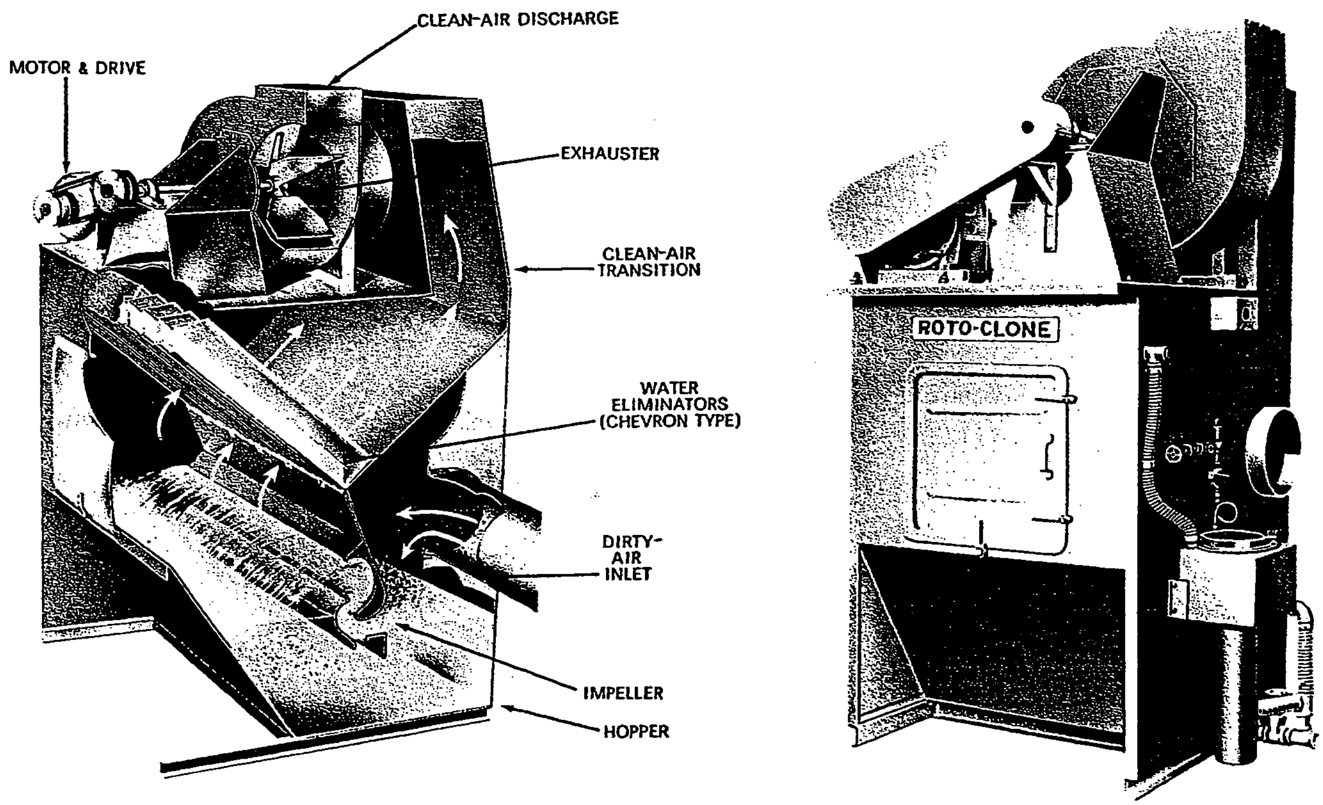


Figure 3-6. Type N Roto-Clone, Arrangement B.[5] (American Air Filter)

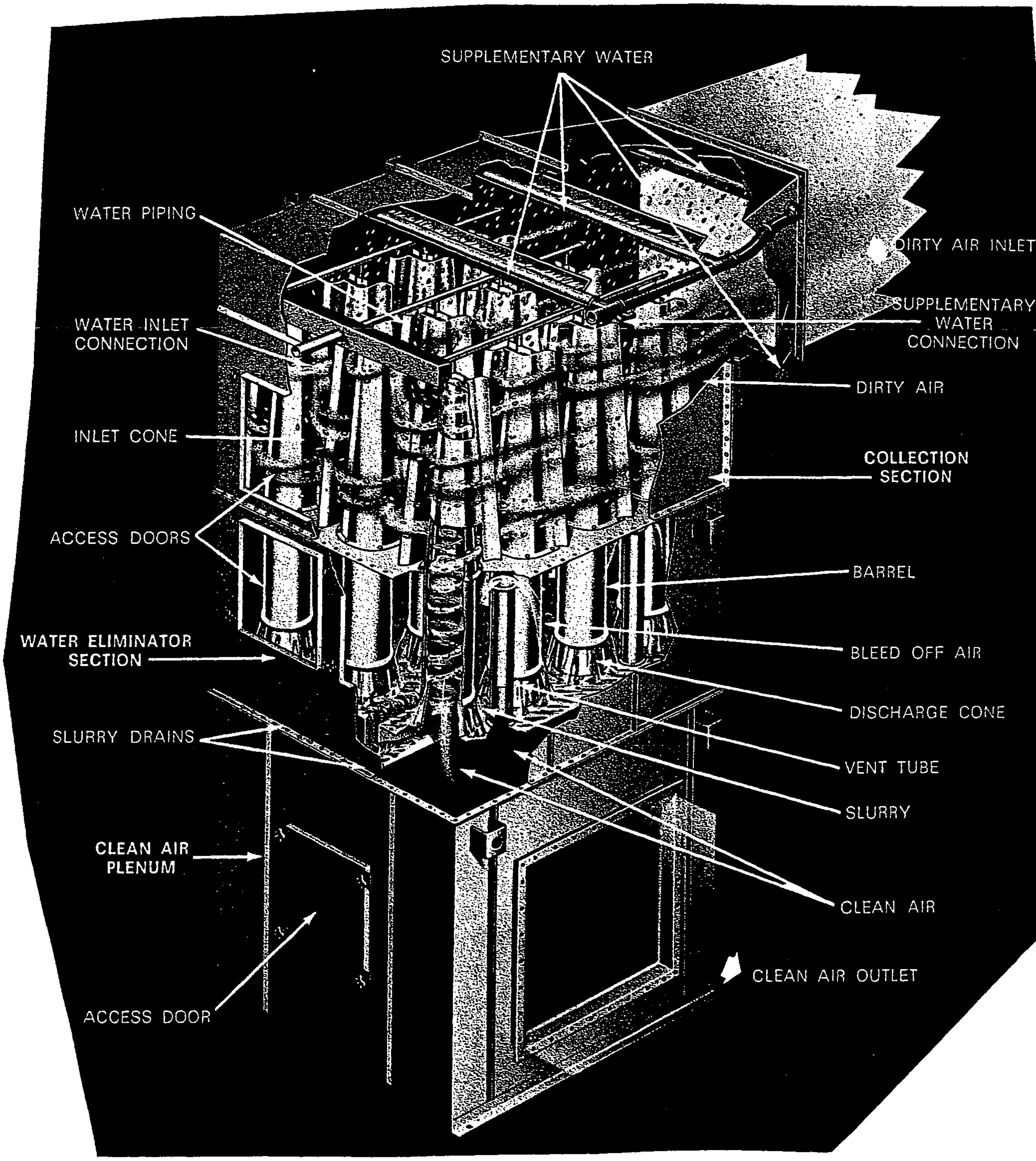


Figure 3-7. Type R Roto-Clone.[5]
(American Air Filter)

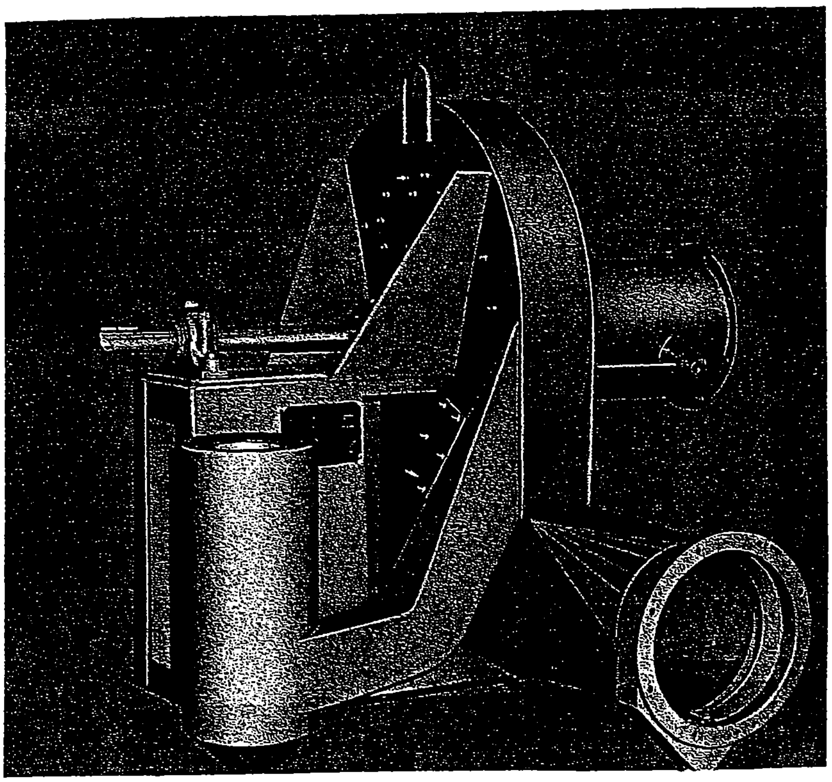


Figure 3-8. Type W Roto-Clone, Arrangement A.[5]
(American Air Filter)

The Type N Roto-Clone can be used in three arrangements. Arrangement B is designed for low cost and manual sludge removal. Arrangement C provides automatic sludge removal. Arrangement D is designed so that the collected material can be sluiced to a process or disposal point. The different arrangements of this unit allow for a variety of sludge-removal techniques, but all collect particles in a similar manner. The particles are separated from the exhaust stream by means of a water curtain created by the flow of gas through a stationary impeller (shown in Figure 3-9). The exhaust gas flowing through the impeller at high velocity carries the water with it in a turbulent sheet. This force causes the particles to penetrate the water droplets and become permanently trapped within them. The particle-laden water droplets are then removed by water eliminators.

Typical operation of the Type N Roto-Clone involves a flange to flange pressure drop of from 5.0 to 12.0 inches w.g. As with the cyclones, the pressure drop across the Roto-Clone is a key parameter in maintaining the proper collection efficiency. The pressure drop depends on two items that require monitoring: 1) inlet gasflow rate, and 2) water flow rate through the impeller. This type of Roto-Clone has a specific standing water level within the unit, which is controlled by an overflow weir within the water level control box.[5]

The Type R Roto-Clone (Figure 3-7) uses wet impingement as the collecting mechanism. Water is introduced into each cone and is carried to the periphery by high-velocity air concentrated with particulate matter entering through two tangential inlets on each cone. The particles impinge against the wetted peripheral surfaces. As the incoming air spins down the inlet cone, the water and a portion of the air is forced between the barrel and outlet cone. Clean air is passed through the center of the outlet cone, and the bleed-off air is passed through a vent tube and into the clean-air plenum.

The typical monitoring parameters for the Roto-Clone particle-collection units are pressure drop, water volume throughput, inlet velocity, and impeller speed. These parameters should be monitored to assure proper operation with respect to manufacturer specifications.

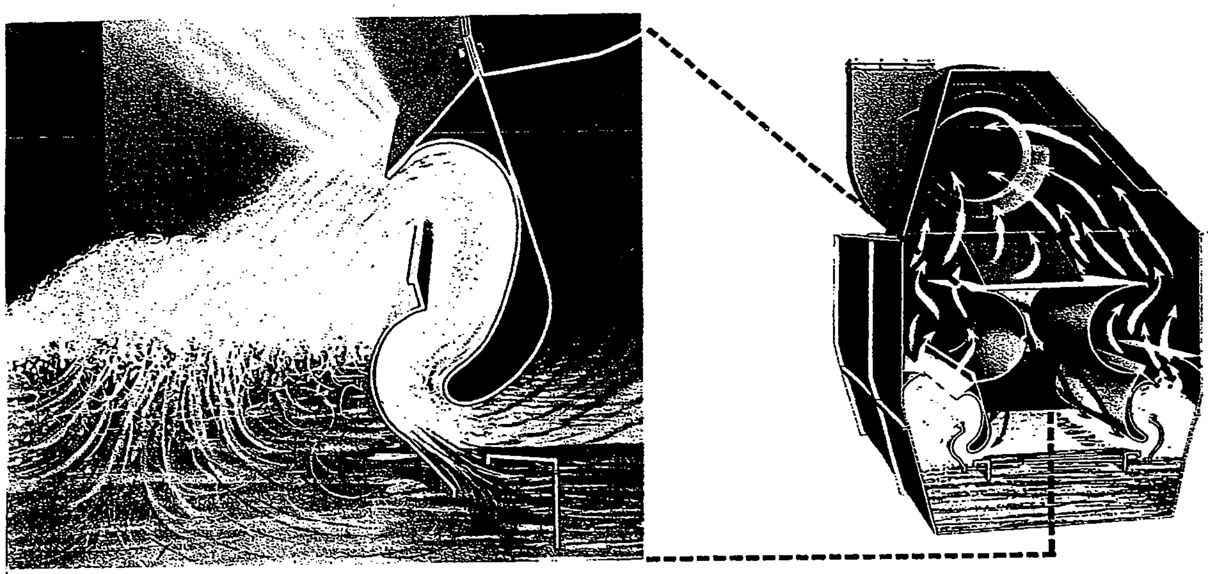


Figure 3-9. Schematic and cut-away view of Type N Roto-Clone water curtain.[5]
(American Air Filter)

3.2 Monitoring Mechanical Collector Operation

Mechanical collection devices require some basic daily monitoring to assure proper operation of the specific unit. Poor monitoring practices could result in decreased collection efficiency and increased particle emissions.

3.2.1 Monitoring Devices for Mechanical Collections

The major parameters affecting cyclone and multicyclone performance are pressure drop across the unit, and gas volume through the unit. In addition, changes in visual emissions at the gas outlet indicate a change in performance. Each device is designed to perform within certain design criteria. The design pressure drop, gas volume, and opacity should be monitored to assure operation within these limits. The pressure drop across the unit can be monitored with a magnehelic pressure gauge or manometer setup. Gas throughput can be monitored by traversing the inlet duct with a pitot tube and manometer as described in USEPA Method 2. An equivalent means of determining inlet gas volume can be used to monitor static and velocity pressures. The opacity should be monitored frequently by certified personnel, as a spot check on the equipment's collection efficiency. If monitoring proves that one or more of the parameters are out of specification, the possibility of malfunctions should be investigated. (These are discussed later in Section 3.3.)

The monitoring of the Roto-Clone control devices is similar to the monitoring of the cyclones. For units operating as the only piece of control equipment or as the primary control unit, the opacity of the exit gas should be monitored visually. This is a simple method for determining relative collection efficiency and potential unit malfunction. The pressure drop across each unit also should be checked to see if it is within the design specifications. The pressure drop not only dictates collection efficiency but also relates to the fan requirements and, in turn, the operating cost. The pressure drop can be monitored with a magnehelic gauge or manometer attached to the unit. The monitoring of pressure drop and opacity is important in troubleshooting the mechanical collectors. The water level and/or throughput also should be monitored on the wet collection units.

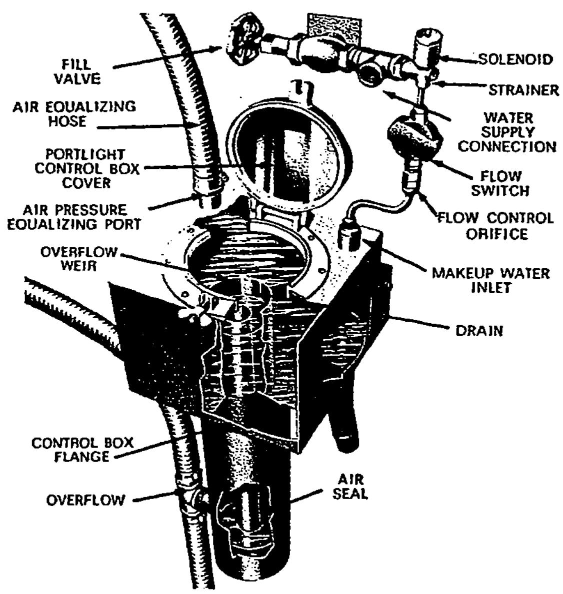


Figure 3-10. Type N Roto-Clone water level control box.[5] (American Air Filter)

This can be done with a level control box, as shown on the Type N Roto-Clone in Figure 3-10.

3.3 Inspection and Maintenance Procedures for Mechanical Collectors

This section describes the frequency of and procedures for maintaining cyclones, multiclones, and Roto-Clones in general. These procedures must be adjusted to individual system installations.

3.3.1 Cyclones

In addition to the continuous monitoring of pressure drop and spot visual opacity inspections, weekly inspections of each unit should be performed and logged on an Inspection Form (Figure 3-11) to assure proper operation. A well-planned maintenance program will assure satisfactory operation of all collection components, including ductwork, fan, collector, and exhauster.

The inspection of single cyclones should consist of a general visual inspection of primary and ancillary components. During the inspection, the inspector should attempt to identify any disruptions in the cone, cylinder, inlet duct, vortex finder, axial vanes, hopper, hopper discharge, and all connecting hardware and welds. These disruptions could consist of dents, holes, broken seals, worn seals, or any other type of deterioration that could result in decreased collection efficiency due to flow disruption.

In boiler applications, the hopper should be inspected to assure that no combustion is occurring. This would cause distortion (plate separation) and allow air leakage into the system. If system shutdown is possible, the interior should be inspected periodically for particle accumulation on the cyclone wall or deterioration due to particle abrasion. The interior of the cyclone should also be inspected to assure that moist particulate matter has not caked on the interior collection surface.

Maintenance of the cyclone can consist of routine items such as painting to protect the unit from corrosion, sandblasting the interior to retain wall smoothness, and replacing fan components. Cyclone components with dents or holes should be replaced immediately, and a stock of spare parts should be on hand or readily available from the

WEEKLY CYCLONE OR MULTICLONE INSPECTION FORM	
Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (print):
Control ID:	Signature of Inspector:
INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS
1) CLONE - Holes - Dents - Deterioration	
2) CYLINDER	
3) INLET	
4) VORTEX FINDER	
5) AXIAL VANES	
6) HOPPER - Seal leaks - Combustion	
7) HOPPER DISCHARGE	
8) FAN	

Pressure Drop ______________________ in. w.g.

Inlet Velocity ______________________ fps

Interior Check (optional)? (Yes/No) ______________________

Noticeable Deterioration? (Yes/No) ______________________

% Opacity ______________________

Figure 3-11. Example weekly cyclone inspection form.

manufacturer. All maintenance should be performed in accordance with site safety procedures.

The following are some typical cyclone component replacement parts.

- Inlet duct
- Vortex finder
- Cylinder
- Cone
- Vane
- Hopper release mechanism
- Hopper
- Fan drive belt

These items should be replaced on an as-needed basis, based on the results of the weekly inspections. The maintenance should be scheduled and recorded on a report form similar in format to that shown in Figure 3-12.

3.3.2 Roto-Clones

Inspection and maintenance of Roto-Clone particle control units depend on the specific type of unit and its arrangement. Generally, several major collection components, in addition to the inlet ductwork and exhaust mechanism, must be inspected and maintained on a routine basis. Each control unit should be inspected weekly in accordance with site safety procedures and recorded on a form similar to the one shown in Figure 3-13. Typical components that should be inspected are as follows:

- The bearings on the Roto-Clone should be inspected to assure proper lubrication. The pillow block on the Roto-Clone shaft should be flushed and refilled with the proper quantity of grease every six months. The ounces of grease required for each pillow is dictated by the manufacturer.

- The spray nozzles should be inspected to assure proper water delivery.

- The inlet to the Roto-Clone should be inspected by opening the inspection door to the units. Accumulation of material in the inlet at the borderline of the wet and dry section should be noted and removed during inspection or scheduled for maintenance. The cleanout of accumulated material should be scheduled so that the accumulation does not exceed 1/10 of the total cross section area.

MAINTENANCE REPORT FORM

Department	Unit	System	Subsystem	Component	Subcomponent

Originator: ____________ Date: ________ Time: ________

Assigned To:

1	Mechanical
2	Electrical
3	Instrumentation

Priority:

1	Emergency
2	Same Day
3	Routine

Unit Status:

1	Normal
2	Derated
3	Down

Problem Description: ____________

Foreman: ____________ Date: ________

Cause of Problem: ____________

Job Status:

1	Repairable
	Hold for:
2	Tools
3	Parts
4	Outage

Work Done: ____________

Supervisor: ____________ Completion Date: ________

Materials Used: ____________

Labor Requirements: ____________

Figure 3-12. Example of maintenance report form.

WEEKLY ROTO-CLONE INSPECTION FORM	
Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (print):
ROTO-CLONE ID:	Signature of Inspector:
INSPECTION ITEMS	COMMENTS/CORRECTIVE ACTIONS
1) BEARINGS - Greased?	
2) NOZZLES & STRAINER - Proper water delivery?	
3) ROTO-CLONE INLET - Quantity of accumulated material	
4) PRECLEANER INLET	
5) ROTO-CLONE IMPELLER	
6) SLUDGE DRAIN	
7) EMERGENCY OVERFLOW	
8) FLAT SPRAY NOZZLE - Parallel to blade edges?	

Pressure Drop Check ______________________ in. w.g.

Water Pressure Check ______________________ in. w.g.

Opacity ______________________ %

Interior Duckwork Check (optional)? (Yes/No) ______________________

Noticeable Deterioration? (Yes/No) ______________________

Figure 3-13. Example weekly Roto-Clone inspection form.

- If a precleaner is installed with the unit, the borderlines of the dry and wet zones to the inlet should be inspected for particle deposition. This deposit should be removed during scheduled maintenance, based upon the inspection. The particle deposit should not exceed a level more than 1/4 the area of the precleaner inlet.

- The Roto-Clone impeller should be inspected for accumulations of foreign material or obstructions in the blade hooks. The buildup of particles on the hooks disrupts the collection mechanism of the unit. The removal of the material can be performed by manual scraping or high-velocity water spray through the access door in back of the unit and from the front side of the impeller.

- The flat spray of the flushing nozzle, located at the impeller, should be parallel to the blade edges. The spray should be in operation during the inspection to assure proper positioning.

- The grating in the bottom of the Roto-Clone hopper and the sludge drain pipe should be kept clean. Removal of any particle accumulation should occur during routine maintenance.

- An emergency overflow is provided on the side of the hopper to drain off the water in case the hopper drain pipe becomes clogged. This should be inspected periodically so that the stoppage can be cleaned out immediately. If an overflow has been provided with an open funnel discharge connection to the disposal line, the hopper drain should be cleared at the first opportunity.

3.3.3 Multicyclones[6]

This section describes the procedures for evaluating the operating condition of a multicyclone collector to determine points of collector bypass, gasket leaks, collection-tube wear, pluggage, or flow maldistribution.

Inspection of Multicyclone--

The following is a general step-by-step procedure for inspecting multicyclones. This procedure should be tailored to the individual collector unit but a complete inspection should be performed at least once per year or whenever the process is shut down for repairs.

- For internal inspection of the collector, the process must be taken off line prior to the inspection in accordance with site lockout tag-out procedures.

- The collector should be purged, and particulate should be removed from the collector hoppers to aid in cooling (where applicable) and to prevent its resuspension into the gas stream.

- Because of thermal draft when controlling hot gas streams, a certain amount of natural draft is expected during the cool-down period. After the cooling period, the I.D. fan dampers should be closed to reduce the draft to the collector and the suspension of particles from surfaces.

- All access doors to the collector should be opened, and the gasket material should be checked for burnt areas, hardness, or breakage. The gaskets should be soft and make continuous contact with the door seat. Deficiencies should be noted, and checks should be made of each door during smoke testing to determine if leaks occur.

- After being equipped with appropriate safety equipment (i.e., hard hat, safety glasses and shields, dust respirator, gloves, coveralls, steel-toed shoes, etc.), the facility's inspector should enter each section of the collector, perform the following tasks, and take appropriate notes:

  a) Look for dust patterns on collector walls, joints, seams, and the lower tube sheet between tubes. A shiny area may indicate the location of outside air inleakage into the hopper area or plenum. Dust patterns should be noted, which indicate gasflow patterns or particle stratification.

  b) Inspect all seal-welded seams, nuts, and bolts on the inlet, outlet, and hoppers for integrity and any evidence of air inleakage.

  c) Make note of the number and location of tubes that are loosened from the dirty-gas tube sheet, which can indicate areas of flue gas leakage from the inlet plenum into the collection hopper.

  d) Make note of the location of areas of particle buildup inside the hopper, which may indicate an area of cool gas inleakage.

  e) Make note of the number and location of worn or chipped tubes or tubes that are uneven at the dust discharge opening.

  f) Note the number and location of tubes that contain scale or hardened fly ash on the internal collection tube surfaces.

g) Note the number and location of collector-tube dust outlet plugs.

h) Note the number and location of fallen-pressure recovery turning vanes in the collector tubes.

i) Note the location and severity of particle buildup on the dirty-gas tube sheet in the dirty-gas plenum.

j) Note the location of any particulate buildup and pluggage of the inlet turning vanes or ramps.

k) Inspect the inlet turning vanes for wear, and note the location and number of each.

l) Inspect the leading-edge side (gas inlet side) of the gas outlet tubes for abrasive damage and wear. Note the number and location of penetration points.

When a visual inspection of the collector has been completed, it should be completely cleaned to remove any hardened material. Depending on the extent of tube scaling and material buildup, the cleaning may be done with chipping hammers, scrapers, wire brushes, or other mechanical devices. Final cleaning may include sandblasting and water-washing. The purpose of the final cleaning is to aid in the visual inspection of the collector for penetration during pressurization and smoke testing. Sandblasting tends to remove protective coatings (paint, epoxy, etc.), and these coatings will have to be reapplied after the testing.

Washing should be done with a high-pressure water jet with sufficient velocity to dislodge hardened scale. It should begin at the highest point in the collector, that allows water and sludge to drain through the unit and out of the hopper. The hopper valves should be opened or cycled to prevent containment of material in the hopper.

The clean-gas tube sheet area should be washed first. Particular care should be taken to remove scale or deposits in each of the exits of the outlet gas tubes. Removal of scale is important because a positive seal is required between the plug and tube wall in subsequent steps involving pluggage of the collector.

The second wash area includes the dirty-gas inlet, the bottom of the clean-gas tube sheet, the inlet turning vanes, and the dirty-gas tube sheet. The third wash area includes the underside of the dirty-gas tube sheet, the collector tubes, and the hopper. The inside of each collector tube should be scraped and hand-cleaned to ensure complete removal of scale and deposits that could interfere with collector-tube plug sealing.

After washing is completed, all doors should be opened and the collector allowed to dry. A final check of the clean collector should be made to determine major penetration points or openings in the tube sheets.

Flue Gas Bypass or Penetration Evaluation--

This section describes methods that may be used to determine if flue gas is bypassing the clean-gas tube sheet, if flue gas is penetrating the dirty-gas tube sheet into the hopper, or if ambient air is leaking into the hopper or into the inlet gas plenum.

Penetration occurs through the tube sheet, around gaskets, and through welds when a pressure differential exists across the opening. In normal operation, this difference in pressure is equivalent to the collector static pressure drop. Because access to the openings is internal to the collector, they can not be directly observed or measured. To overcome this deficiency, the following procedure has been developed for visually observing the penetration points by use of a smoke test. Although this method is time-consuming and man-power intensive, it is the only positive means of determining the location of gas bypasses.

Pressurization is accomplished by use of the boiler forced-draft fan. Major areas to be pressurized are the inlet gas plenum and dust hopper (Figures 3-14 and 3-15). Pressurization of Area 1 allows penetration to be observed through the dirty-gas tube sheet, clean-gas tube sheet, and collector body. Pressurization of Area 2 allows penetration to be observed through hopper doors, ash valves, and the hopper shell.

The gas openings through the turning vanes and gas outlet tubes must be sealed before pressurization can be accomplished. Each collector-tube dust outlet and gas outlet tube must be sealed with a pneumatic sewer plug or an inflatable rubber plug.

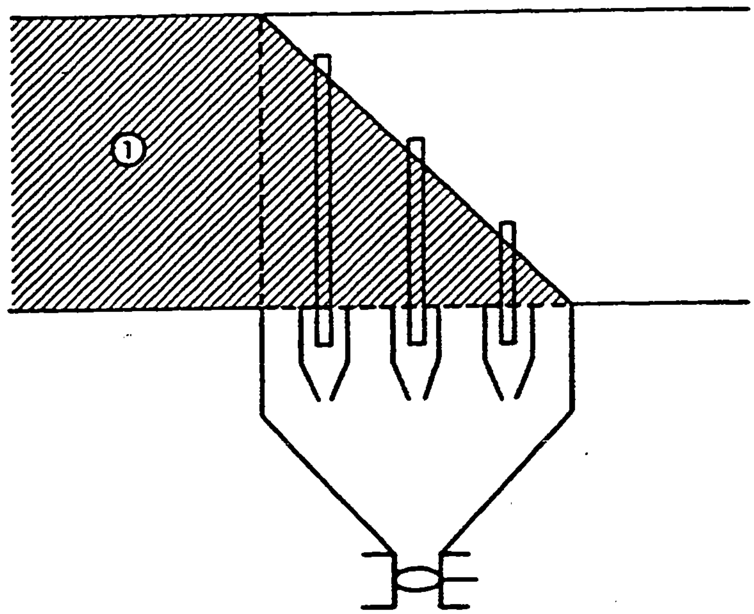


Figure 3-14. Inlet gas plenum.[6]

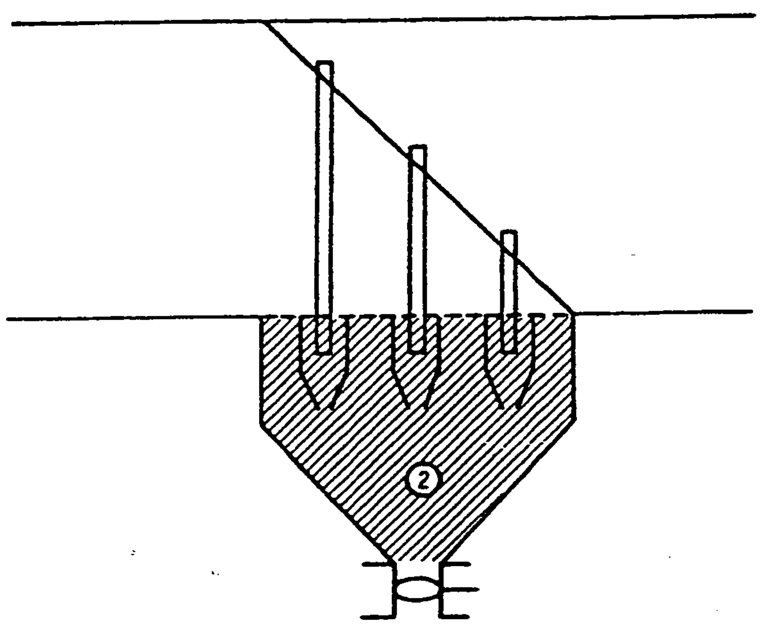


Figure 3-15. Dust hopper.[6]

The pneumatic plug consists of a rubber washer between two metal plates. Normal diameter of the rubber washer is increased by compressing the rubber between the washers with a large wing nut. The metal plug is available in various sizes depending on the diameter of the collector tube dust outlet. Selection of a plug with the proper diameter is important to ensure that the system is completely sealed.

Pluggage of both gas outlet tubes and dust discharge openings can also be accomplished with an inflatable rubber sphere. The plug is inserted in a tube, and compressed air is then used to inflate it. Each inflatable plug is equipped with a pneumatic check valve and fitting for an air check. The fitting is a conventional outside-thread valve that allows the attachment of a flexible rubber hose extension. Each plug is attached to a large metal chain to keep it from being lost down the gas outlet tube when it is deflated. The chain is used to hold the plug in position during installation.

Plugs may be purchased in various sizes (4, 5, or 6 inches in diameter) and may be over-inflated to accommodate intermediate sizes. A 4-inch diameter may be extended to 6 inches without rupturing the plug. With both plugs in place, the inlet side of the collector (Area 1) can be pressurized with the forced-draft fan. When several of the dust discharge tube plugs are removed, the forced-draft fan can be used to pressurize both Areas 1 and 2.

After the collector has been washed and allowed to dry out, metal diaphragms or pneumatic plugs should be installed in the dust outlet of each collector tube. If diaphragms are used, the lower edge of the rubber washer should be even with the bottom edge of the tube. When the diaphragm is compressed, the assembly must be held in position until a secure seal is achieved. Because many dust outlet tubes are tapered, the assembly may tend to move upward during expansion. The tightness of each tube should be checked by pulling downward on the tightening wing nuts.

If expandable plugs are used, they should be inserted half-way into the tube opening and inflated to create a tight seal. The amount of compressed air used during inflation should be limited to prevent plug rupture.

In an inclined clean-gas tube sheet of conventional design, access to the clean-gas tube outlets is relatively easy. Plugs should be installed in the upper rows, first, then installed downward towards the clean-gas outlet. Either inflatable plugs or diaphragms may be used, depending on the tube edge configuration.

If gas outlet envelopes are used to direct the cleaned flue gas, the gas outlet tube exit may not be accessible for direct plug insertion. Because of the narrow passage and depth of the envelope, diaphragm plugs cannot be inserted and tightened by hand.

The limited space also makes the placement of inflatable plugs difficult and time-consuming. Adding to this difficulty, the plug is attached to the mechanical arm by friction fitting it into the arm yoke, which allows the arm to be detached with minimum effort after plug placement. Figures 3-16 and 3-17 are drawings of the mechanical arm used to put the plugs in the proper place. Rubber air extension tubes must be used to allow inflation of the plugs from outside the envelope area. Extensions may be purchased in various lengths (2, 3, or 4 feet) and used in combination as required (Figure 3-18).

Plugs should be placed in the front tubes first, then installed toward the rear of the envelope. Inflated plugs in the front rows may be used as a fulcrum to aid in the positioning of tubes in the rear rows. Considerable manual dexterity is required to place the plugs in the openings. The work area (e.g., tube openings) must be lighted from above the envelope opening and above the personnel installing the plugs. During placement, the tube opening is typically in the shadows of the plug and mechanical arm. Experience indicates that placement is best achieved by feel and estimating distance rather than by visual attempts.

Because the placement of the plug is by feel, bumping and/or scraping of the plug against the envelope wall is likely, and this motion frequently results in losing the plug from the yoke. Retrieval of the plug may be difficult if the attached ring is lost over the end of the placement arm. The loss of the plugs can be prevented by placing the inflation line on top of the arm and placing tension on the line pulling the plug against the yoke.

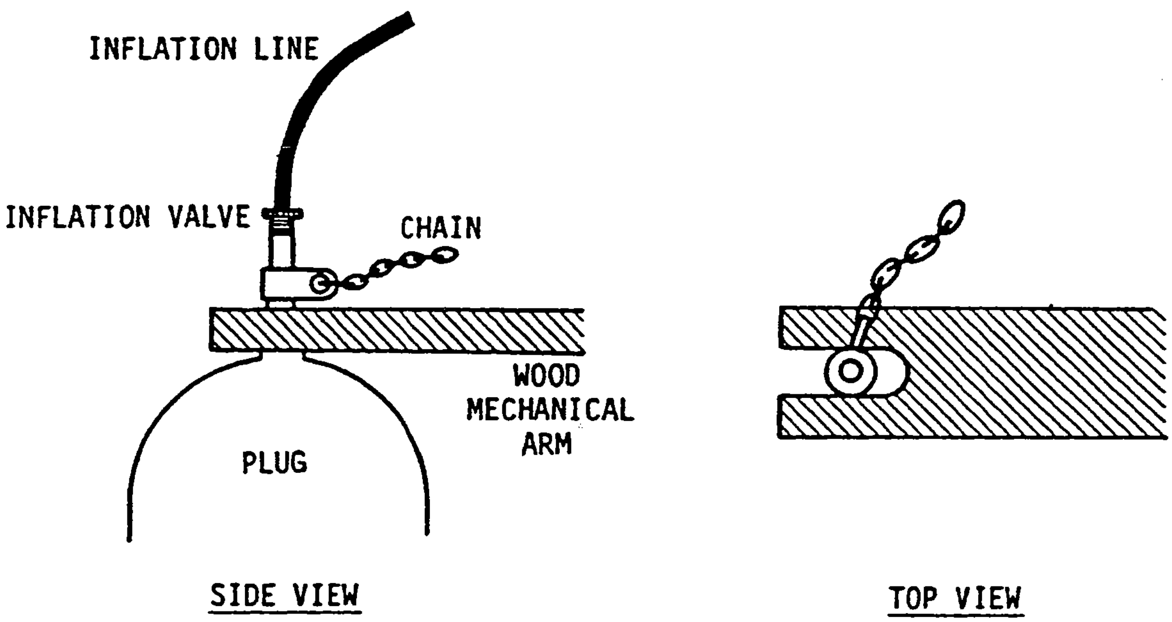


Figure 3-16. Enlarged view of plug, chain, and mechanical placement arm.[6]

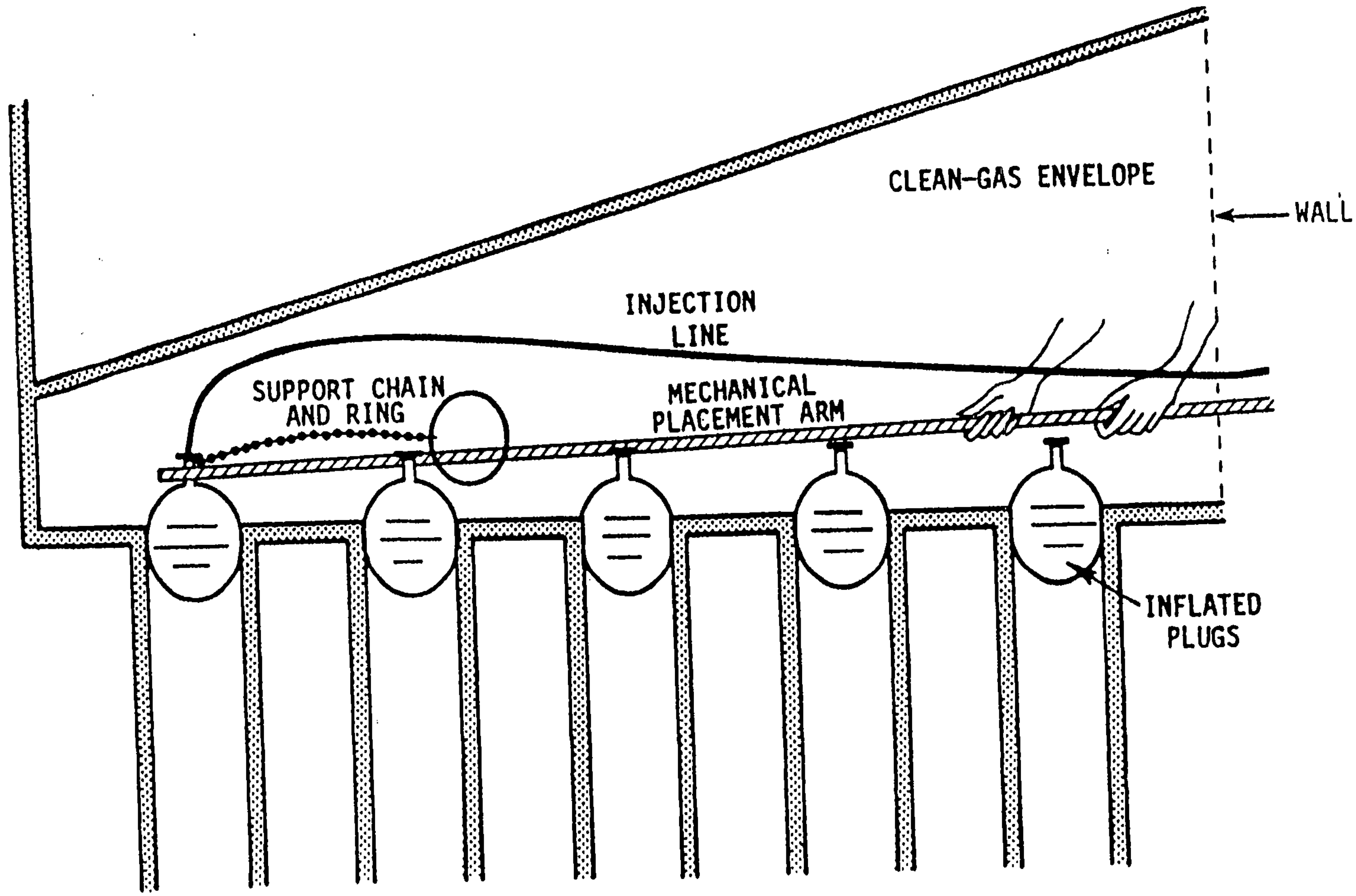


Figure 3-17. Diagram of mechanical placement arm with inflation lines removed for clarity.[6]

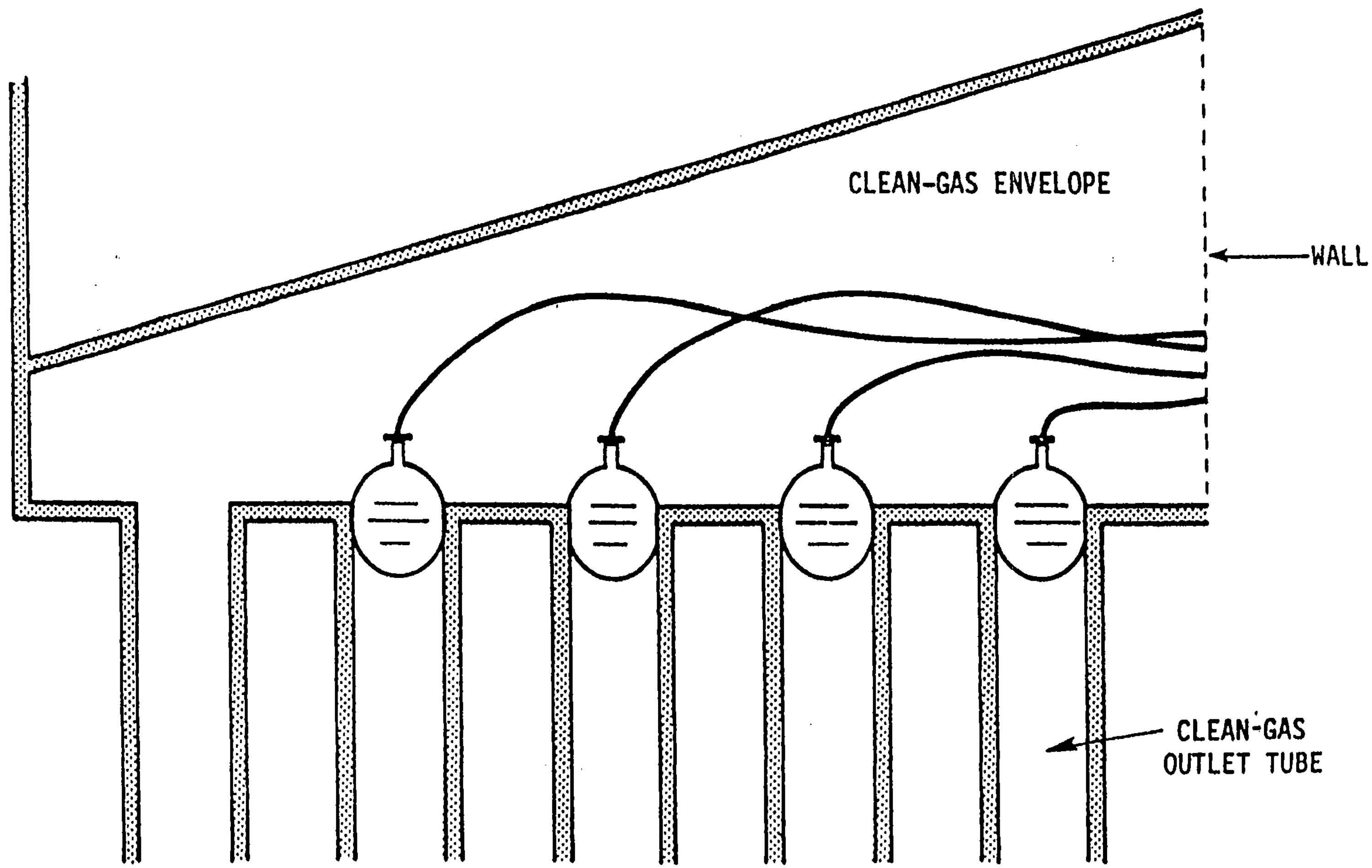


Figure 3-18. Placement of plugs in clean-gas outlet tubes.[6]

If the uninflated plug drops down in the gas outlet tube, the metal ring will prevent its loss. The plug must be retrieved, however, and placed in position for complete sealing. Considerable effort is required to place the plug in the farthest outlet position because of the cantilever position of the mechanical placement arm.

Because of the limited work space and the difficulty in plug placement, this task may require many man-hours. During this period, compressed air may leak from defective inflation valves and allow deflation. After all tube plugs have been installed, the envelopes should be visually checked for dropped or defective plugs. All dropped or defective plugs should be repaired and/or replaced.

At this point, all plugs should have been placed and the collector should be available for pressure testing.

Pressure-Testing of Dirty- and Clean-Gas Tube Sheets--

The following procedure should be used to determine gas leakage through the tube sheets and around collector-tube seal gaskets:

1) Close the collector I.D. fan damper.

2) Close the dirty-gas plenum access doors.

3) Start the forced-draft (F.D.) fan with dampers full open.

4) Measure the fan static pressure on the collector inlet with a magnehelic gauge or manometer. The pressure should be greater than or equal to the anticipated collector static pressure drop.

5) Check ceiling plugs (gas outlet tubes and collector dust discharge) for leaks and/or removal due to F.D. fan pressure.

6) Stop F.D. fan and replace or reinflate improperly placed plugs (determined from Step 5).

7) Place ignited smoke bombs into the dirty-gas plenum. Multiple bombs may be required, depending on collector size and/or plenum configuration. An effort should be made to place the bombs on the dirty-gas tube sheet and not on the inlet duct to the collector. For complete detection of penetration points, the density of smoke near the tube sheet openings must be at a maximum. The diffusion of the aerosol smoke in the plenum is relatively

slow, and unless a complete coverage is obtained, major penetration points may be overlooked.

8) Start F.D. fan and maintain required forced-draft static pressure.

9) From the outlet gas plenum, inspect all seams, flanges, and gas outlet tube welds and seals for penetration of aerosol smoke, which indicates gas bypass points. Note location and describe type of penetration point (weld, gasket, etc.).

10) Check the underside of the dirty-gas tube sheet for gas bypass through welds, flanges, and collection-tube seal gaskets. Note location and describe all penetration points.

11) Stop F.D. fan and remove several clean-gas outlet tube plugs to allow the smoke in the dirty-gas plenum to dissipate.

Pressure Testing of Hopper and Ash Valve--

The following procedure should be used to pressure-test the hopper and ash valves for evidence of inleakage:

1) Reinstall plugs in clean-gas outlet tubes removed in the previous procedure.

2) Remove half of the plugs from the bottom of the collection tubes to allow the hopper to be pressurized by the F.D. fan.

3) Close hopper doors and insert an ignited smoke bomb into each hopper apex through an inspection port or a rod-out hole.

4) Reseal inspection ports or rod-out holes.

5) Start F.D. fan and maintain required forced-draft static pressure.

6) Observe all hopper seams, welds, hopper doors, inspection ports, and ash valves for visual evidence of gas penetration. Note areas of leakage and describe the penetration point.

7) Stop F.D. fan and open access door to allow smoke to dissipate.

8) Deflate and remove all sealing plugs from the collector.

Preparation of Inspection Report--

A final report identifying scale, buildup, plugging areas, and inleakage points should be prepared. This report should include a narrative on the particular deficiency and a location chart of the tube sheet.

Although all scale and pluggage problems are eliminated by collector washout, these problems should be documented for future reference. Figure 3-19 shows an example location chart.

Repair of Collector Penetration Points--

The following repairs should be made to penetration points in the collector:

- Tube sheet weld seams - Clean, brush, and weld penetration points.
- Tube sheet gasket - Clean and brush affected area and seal openings with high-temperature caulk, epoxy, or castable joint compound. The original seal gasket is typically composed of asbestos, and replacement is almost impossible without disassembly of the collector.
- Collection-tube gasket - Remove collection tube, clean and brush setting surface, and replace gasket. If tube sheet is scored or wrapped, castable cements, epoxies, or other compounds may be used to enhance the seal.
- Collector shell - Clean, brush, and weld penetration points.
- Hopper doors - Replace sealing gasket and/or replace warped doors and door joint.
- Ash valve - Replace valve flange gasket and/or repair ash valve to ensure positive seal.
- Clean-gas outlet tubes - Weld patches on penetration points or replace clean-gas outlet tubes as necessary. Install deflector plates on tubes to prevent damage.

Replacement of Worn or Failed Components--

The following repairs should be made to return the collector to proper operating condition:

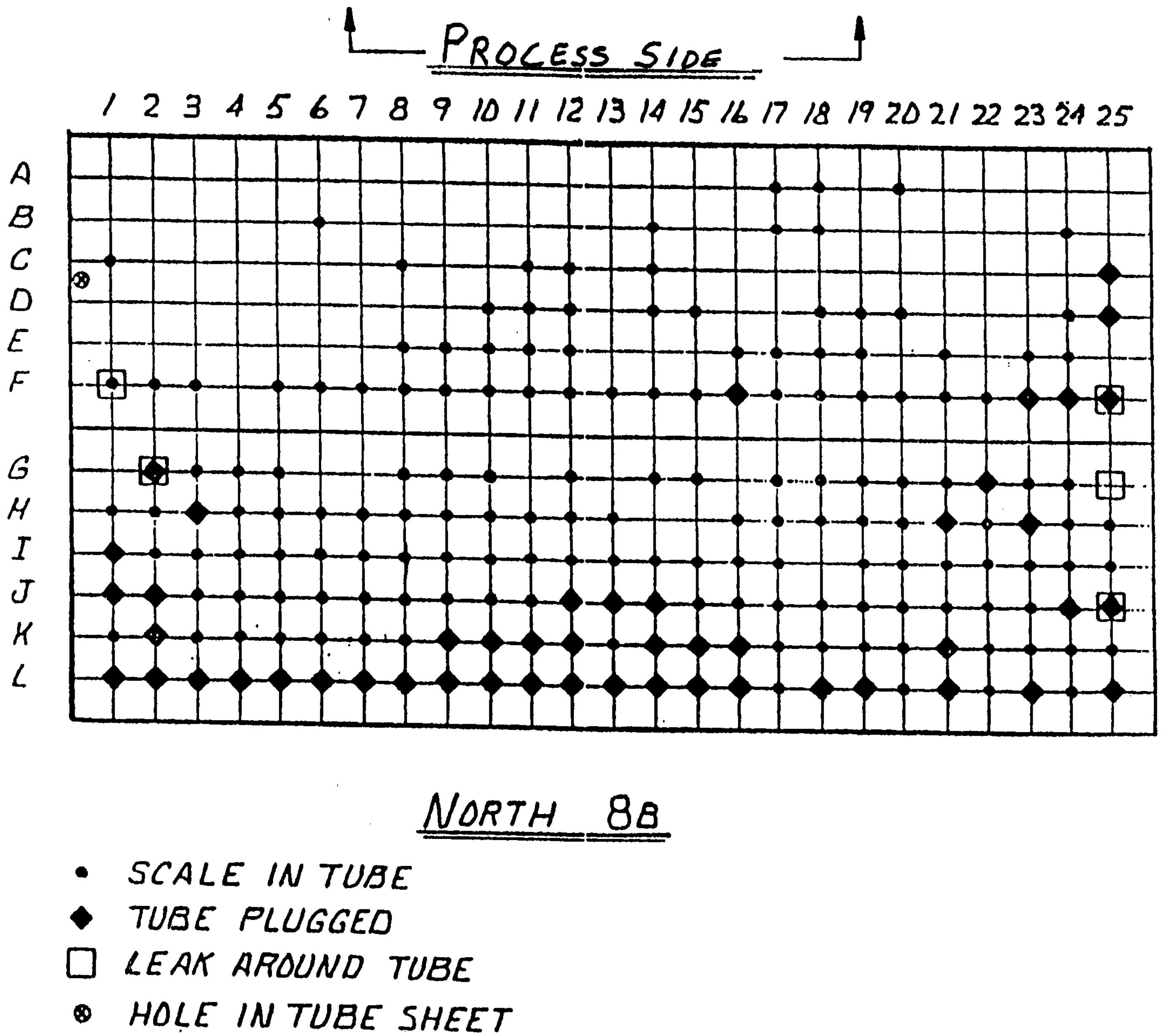


Figure 3-19. Example location chart.[6]

- Replace worn collection tubes that show wall penetration or distorted dust outlet tubes.
- Replace worn inlet turning vanes.
- Replace worn pressure monitoring devices.

3.4 Major Problems or Malfunctions of Mechanical Collectors

Several operating conditions and/or malfunctions can reduce collector performance. These conditions and parameters are discussed in this section, along with a cause and/or potential solution to the problem.

3.4.1 Cyclones

A decrease in cyclone particle collection can be noted during routine inspections of exit gas opacity and unit components. If a decrease in efficiency is noted, a number of parameters can be checked to correct the problem. Some of the key items for malfunction correction are listed in Table 3-2.

3.4.2 Roto-Clones

Roto-Clone particle collection units all have similar malfunctions and problems, even though they vary in types and arrangements. The general problems and possible corrections for these units are discussed in this section.

An excessive quantity of water in the exhaust could be attributed to one or a combination of several of the following:

- Incorrect impeller rotation. (The proper rotation for the collection impeller is counterclockwise.)
- Improperly sized cone spray or auxiliary nozzles and incorrect spray patterns (i.e., flat spray at 7 o'clock and parallel to blades and cone spray centered at the wheel).
- Sharp inlet elbows. (These can seriously reduce air volume and may result in water carryover.)

- Bent blade tips and obstructions in impeller, such as rags, excessive paint, collected material buildup, etc.
- Plugged or obstructed drain pipes.
- Incorrect outlet piping location. (The bottom of the outlet pipe should never be above the bottom of the Roto-Clone scroll.)
- Improper gasketing of water cone.
- Worn, torn, or cracked gaskets.

TABLE 3-2. PROBLEMS AND MALFUNCTIONS IN CYCLONE PARTICLE COLLECTION

Problem	Possible Malfunction	Corrective Action
Fluctuation in pressure drop	Fluctuation of inlet velocity	Correct velocity to design specifications. Adjust fan.
	Particle accumulation	Pressure-wash interior. Decrease moisture content. Adjust particle inlet distribution.
	Particle abrasion to cylinder cone or vortex finder	Coat interior with abrasion-resistant material. Replace worn component.
	Particle reentrainment	Check hopper for leaks.
Flow disruption	Dent in cone/cylinder	Repair or replace component.
	Hole in cone/cylinder	Repair or replace component.
	Particle maldistribution	Eliminate flow disturbances (i.e. bends or turns in ductwork) immediately before inlet. Pressure wash interior and inlet.
	Vane wear	Replace worn vanes.
	Air inleakage	Seal leaks in hopper and/or connecting ductwork.

Excessive particle concentration in the outlet gas (increased opacity) can be attributed to one or more of the following:

- Equipment is running dry or with insufficient water supply due to clogged spray nozzles or strainer or low water pressure. Most Roto-Clone types require a minimum nozzle pressure of 40 lb.
- Impeller blade hooks are obstructed.
- Precleaner spray nozzle is misaligned. A flat spray must discharge in a vertical plane.

3.4.3 Multicyclone[6]

Several operating conditions and/or malfunctions can reduce multicyclone performance. Most of these conditions result in disturbance of the cyclone vortex, pluggage of gas passages, or interference with dust discharge from the cyclone tube. The following discussion identifies the major failure mechanisms and their effect on multicyclone collector efficiency.

Gas and Particulate Maldistribution--

For each cyclone tube to receive the same amount of particle loading, the distribution of gasflow must be uniform, both horizontally and vertically, across the multicyclone inlet. Proper duct inlet design often requires the use of turning vanes. Sharp dust turns or improperly joined ducts may result in particle stratification at the outer radius of the turn, which increases abrasion. In many systems, duct expansion causes the gas stream to decelerate at the entrance to the collector. Stagnation or low velocity can result in dust buildup on the approach to the inlet turning vanes of the collector tube. Reduction in gas velocity can also cause particle fallout if the velocity is decreased below transport velocity. Continued deposition and dust hardening can occur when the system periodically passes through either the moisture or acid dew point. This situation can create obstructions to flow at the entrance to individual cyclone tubes.

Minor deposition generally occurs in almost all multicyclones as a result of secondary flows and operation at lower than design gas volumes during process variations and/or startup and shutdown periods. Heavy deposition generally does not occur in well-designed systems and is limited by particle reentrainment from the deposit area.

Heavy deposits that harden or are located in low-velocity areas, however, may eventually change the flow pattern in the collector. Although these deposits might not affect the pressure drop across the unit, they would increase particle penetration.

Maldistribution can also aggravate abrasion and/or pluggage of the turning vane which, in turn, may cause increased penetration and increased maintenance. If maldistribution is suspected, based on visual inspection of the collector, velocity profiles and particulate concentrations should be obtained at the multicyclone entrance. The flow patterns in Figure 3-20 indicate particle stratification at the inlet to the collector. Gasflow is generally from the upper right downward. The gas then makes a turn from the lower left to right into the entrance of the multicyclone. As a result of their inertia, particles are concentrated on the outer radius of the turn. Upon entering the collector, particles are concentrated in the lowest area of the gas stream. This flow distribution results in the first row of tubes receiving the greatest particle mass and the largest particles. Finer particles in the upper portion of the gas stream are concentrated in the back of the collector.

Gas Volume and Pressure Drop--

The potential collection efficiency of the collector is a function of the gas volume handled by each cyclone tube. Passage of the gas through the turning vane and subsequent change in gas direction require energy to be expended. Energy is stored as kinetic energy in the gas stream. The expenditure of energy that manifests itself as static pressure drop must be provided by the collector I.D. fan.

For the collector to achieve maximum separation efficiency, the inlet gas velocity must be at the maximum design value for the specified tube diameter (i.e., maximum gas volume passing through a fixed area inlet). Because the gas volume and static pressure drop are proportional for a given collector, pressure drop is considered an indicator of the proper operating point for the collector. Operation above the design pressure drop may

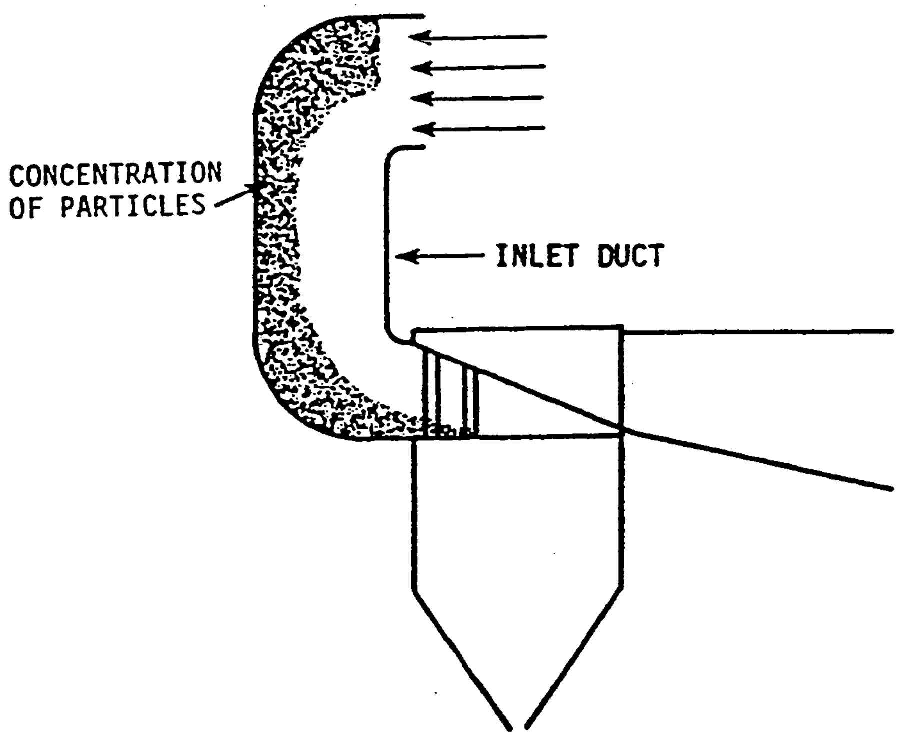


Figure 3-20. Inlet duct of multicyclone, indicating particle stratification.[6]

increase turbulence and decrease collector efficiency. Conditions that could cause high gas volumes include operation at high excess air and ambient air inleakage in the duct preceding the collector. High excess air does not generally occur in utility boiler operations, but it is common in industrial boiler applications.

To yield maximum efficiency, the collector must operate at the design gas volume. The design volume is generally at the maximum process rating and gas temperature. When the process is operated at reduced capacity, it usually generates less than the required flue-gas volume and the collection efficiency decreases. The reduction in efficiency can be significant when the process is operated at 20 to 50 percent below the design gas volume.

The actual operating conditions should be reviewed and a corresponding adjustment in gas volume (e.g., reducing excess air, repairing duct inleakage) should be made to permit the collector to operate within the design limits. This review may result in the expansion of the number of tubes in the collector or the removal of tubes (tube sheet opening repaired) to obtain optimum operating conditions.

Inlet Turning Vane Wear--

The inlet turning vane or ramp is designed to impart a tangential motion to the inlet gas stream of the collector. This tangential motion transforms into a vortex in the collection tube. Impaction of particles on the turning vane surface causes abrasion and metal wear over the life of the collection tube. Severe damage results in disturbance of the vortex and increased gas turbulence and limits collection efficiency.

Three materials are typically used to form the inlet turning vane: mild steel, gray iron, and white iron. The relative life of each material in an abrasive environment is a function of the Brinell hardness of the material. Nominal Brinell hardness of gray iron is about 180 and white iron, about 400. The relative life of white iron compared with that of gray iron is about 200 percent.

Severe abrasive damage generally lowers the effective pressure drop across the collector. The change in pressure drop occurs over months or years and is generally not noticeable. If this change is not referenced to a baseline pressure drop, it may not be discernible. As the wear becomes more acute, inlet vane structural failure can occur that allows complete bypass of particles through the inlet turning vane. Because the abrasive damage does not occur uniformly over the tube matrix, bypass may occur through a few tubes without any significant change in operating parameters.

Periodic internal inspection of the collector is required to determine vane condition and to remove eroded components. Tube sheet location failure records should be maintained to determine if repeat failures are occurring at the same locations. Repeated failures could be indicative of particle stratification and/or gas maldistribution.

Inlet Ramp Pluggage--

Material buildup on the turning vane or ramp may occur as a result of particle fallout, or it may develop as a scale. The scale may develop in boiler applications as sulfuric acid condenses on the cool metal surfaces at low boiler-load conditions. Fly ash combines with the acid and forms a hard scale when the boiler load and flue gas temperature increase. The deposits can generally be found on the ramp, tube sheet, ductwork, and clean-gas outlet tubes.

The initial effect of inlet ramp fouling on collection efficiency is similar to turning vane wear in that the vortex is weak or it fails to form. An improperly developed vortex results in turbulence and short-circuiting of the gas volume to the gas outlet tube without particle separation. Also, because about 90 percent of the tube pressure drop is generated by creation of the vortex, a low resistance path occurs through a partially plugged inlet. This can result in flow disturbance across the tube sheet and increased cross-hopper flow.

Complete pluggage of the inlet ramp results in loss of the collection tube and increased flow to the remaining tubes, which causes a marginal increase in static pressure drop across the collector. In a typical 200-tube collector, complete pluggage of 25 percent of the tubes would only increase the pressure drop from 3.5 to 4.0 in. H_2O at the design gas volume.

As with inlet vane wear, the changes in static pressure drop may not be identifiable before complete failure. Frequent interval inspections are necessary to determine the magnitude and extent of tube plugging. Correction may include periodic washing of the collector, mechanical cleaning, or changes in process operation (e.g., operating levels, material inputs, etc.).

Collection Tube Wear--

Contact of abrasive particles with the walls of the collection tube results in erosion and eventual failure of the collector tube. Normal wear occurs at the bottom of the cast-iron tube. As the metal thins, holes may appear along the bottom of the tube, or the dust outlet may become elliptical or egg-shaped. These conditions result in a poorly formed gas vortex and an increase in surface roughness and turbulence. Erosion of the dust outlet opening increases particle reentrainment and decreases cyclone collection efficiency. When abrasive particulate matter is being collected, annual inspection of the collection tubes is recommended.

Collection Tube Scale--

For mechanical collectors controlling combustion gases, scaling in the collection tube as a result of acid dew point condensation increases surface roughness and particle reentrainment in the outlet gas vortex. Whether scaling is periodically scoured off by the particulate in the vortex or develops into complete pluggage depends on operating temperatures, and concentrations of gaseous pollutants in the flue gas stream.

Gas Outlet Tube Pluggage--

Scaling of the collector may also occur in the gas outlet tube. Because the cross-sectional area of the outlet tube is less than that of the collection tube, a thick scale may close the tube completely. Also, the removal of larger abrasive particles in the collection tube limits the self-cleaning scouring effect in the outlet gas stream. Because the outlet gas stream may receive infiltrated ambient air that leaks into the ash hopper, the gas may be at a substantially lower temperature than the inlet flue gas. This reduced temperature may cause localized sulfuric acid condensation at low process loads. Increased static pressure drop across individual tubes results in downward flow from the dirty-gas plenum into the hopper, and as a result of cross hopper ventilation, gas flows upward into the tubes with low static resistance.

Dust Outlet Tube Pluggage--

Severe scaling of the cyclone collection tube may result in complete closure of the dust outlet opening at the bottom of the tube. When the outlet is plugged, particles may begin to build up in the tube. The turning vanes can become so restricted that there is no flow through the tube. As with inlet turning vane pluggage, the loss of the collection tube reduces the size of the collector and increases the gas volume through the remaining tubes. If complete closure of the gas passage does not occur, the opening becomes a bypass through the tube sheet (flow entering through the inlet vanes and exiting through the gas outlet tube) and particles are discharged with the gas.

Air Inleakage--

Air inleakage into the flue gas stream or into the collector as a result of the system being under negative pressure can result in abnormal collector operation. Air inleakage can also limit operation, depending on the point of inleakage. Inleakages can be classified into three types: 1) inleakage into inlet plenum and entrance ducts, 2) inleakage in the outlet plenum, and 3) inleakage into the collector hopper. Inleakage into the hopper appears to have the most detrimental effect on collector performance.

Total air inleakage into exhaust streams with less than 21 percent oxygen (e.g., combustion sources) may be determined by simultaneous measurement of flue gas oxygen and the temperature of the flue gas before and after the collector. Sampling locations should be selected to provide representative gas-stream conditions with minimum gas-stream stratification. Multipoint samples (traverses) should be used to ensure the collection of a representative sample. An increase in oxygen content with a simultaneous decrease in gas-stream temperature is indicative of ambient air infiltration. Because of radiation and convective heat loss through duct and collector walls, a decrease in gas-stream temperature may be noted even when there is no inleakage (increase in flue gas oxygen content). For example, if 30,000 scfm of air inleakage occurs in a gas stream containing 100,000 scfm at 6 percent oxygen, the final gas stream of 130,000 scfm will contain 9.46 percent oxygen.

Points of inleakage can also be noted during internal inspection by identifying gas jets or clean metal areas and in dust deposits on duct and collector walls.

Inleakage into Inlet Plenum--

When air entering the inlet plenum is colder than flue gases containing acid gases, it can severely lower the flue gas temperature below the acid dew point. This depression in dew point may be confined to wall areas, or it may be more general, depending on the location of the opening and amount of mixing in the gas stream. In most cases, the infiltrated air stratifies along the wall and causes condensation and/or corrosion damage. Large amounts of air combined with operation of the process at high excess air levels can result in gas volumes that exceed those of the collector design. It can also lead to lower collection efficiency.

Inleakage Into Outlet Plenum--

The effects of leakage in the outlet gas plenum are similar to those associated with inlet plenum leakage. The increased gas volume, however, does not have an effect on collector performance. Inleakage at this location increases the gas volume that must be handled by the fan, which increases the horsepower requirements of the fan.

Air Inleakage into Particulate Hopper--

In some applications, the fan is located downstream of the multicyclone. This location places the collector and ductwork under negative atmospheric pressure. In a well-operated unit, the dirty-gas stream may be operated at a negative pressure of 5 to 15 in. H_20 while the clean side is operating at a negative pressure of 9 to 19 in. H_20 (4-inch pressure drop).

At this negative pressure, any opening in the flue gas stream obviously results in significant air inleakage into the system. The hopper is generally operating at a negative pressure that is very close to the collector outlet pressure, as most of the collector pressure drop is developed across the turning vanes.

Inleakage may occur in the hopper area. Such inleakage creates a gasflow from the hopper through the dust outlet of the collector tubes and into the gas outlet tubes. Depending on the condition of the hopper seals, this flow may account for 10 to 20 percent of the collector gas volume. The upward flow of gas through the narrow dust discharge opening at the bottom of the collection tube increases the reentrainment of fine particles at the dust outlet and reduces collector efficiency. As shown in Table 3-3, the following are the major points of hopper inleakage: gaskets between shell flanges, poorly constructed field welds, joint between hopper and shell, gasket between ash hopper and ash valve, ash valve, manhole door gaskets, doorframe gasket, and inspection port.

TABLE 3-3. CHECKLIST OF MAJOR POINTS OF HOPPER INLEAKAGE

Hopper Inleakage

- Gaskets between shell flanges
- Field welds
- Joint between hopper and shell
- Gasket between ash hopper and ash valve
- Ash valve
- Manhole door gaskets
- Doorframe gasket
- Inspection port

Major inleakage may be determined audibly as the inleaking gas passes through the openings. Noise in the process area can mask these sounds, however, and many small leaks may not be detectable. Hopper leaks may be identified more effectively by plugging the gas outlet tubes of the collector and pressurizing the inlet plenum and hopper through the use of the forced-draft fan. Leaks may be visually located by use of a white smoke bomb placed in the hopper. Insulation may prevent identification of weld breaks in the hopper wall, or it may diffuse the smoke over a wider surface before it is emitted into the air.

Flue Gas Inleakage Into Particulate Hopper--

The dirty-gas tube sheet, which separates the inlet gas plenum from the particulate hopper, is the point where the cyclone tubes are attached. Normal flow is through the cyclone inlet turning vanes, which creates the vortex. The gas then flows out through the gas outlet tube. Because most of the multicyclone pressure drop is generated at the turning vane and the hopper operates near the outlet plenum pressure, a substantial pressure differential is present across the tube sheet. Any openings between the inlet plenum and hopper form an orifice that allows high-velocity gas to penetrate. The gas, which contains substantial amounts of uncollected particulate matter, bypasses the cyclone tubes and enters the hopper area.

Bypass and hopper inleakage have similar effects on multicyclone efficiency. The flow of gas in the hopper creates cross-hopper ventilation and upward gasflow into the dust outlet tubes. Upward velocity prevents the discharge of fine particles from the tube and reentrains particles from the particulate collection hopper.

The most common areas of dirty-gas tube sheet penetration are around the gaskets or 0-rings sealing the cyclone tube to the tube sheet or around tube-sheet welds and/or section joints. Figure 3-21 shows the location of the sealing gasket in a typical tube attachment. Openings may also occur where the tube sheet is attached to the collector wall.

The dirty-gas tube sheet can become distorted because of thermal stress and vibration (as during startup and shutdown) and prevent the gaskets from providing positive seals. The number and severity of such bypasses may increase when collector operating practices are changed. For example, a change from base-load operation to peaking or cyclic operation may create severe bypass problems.

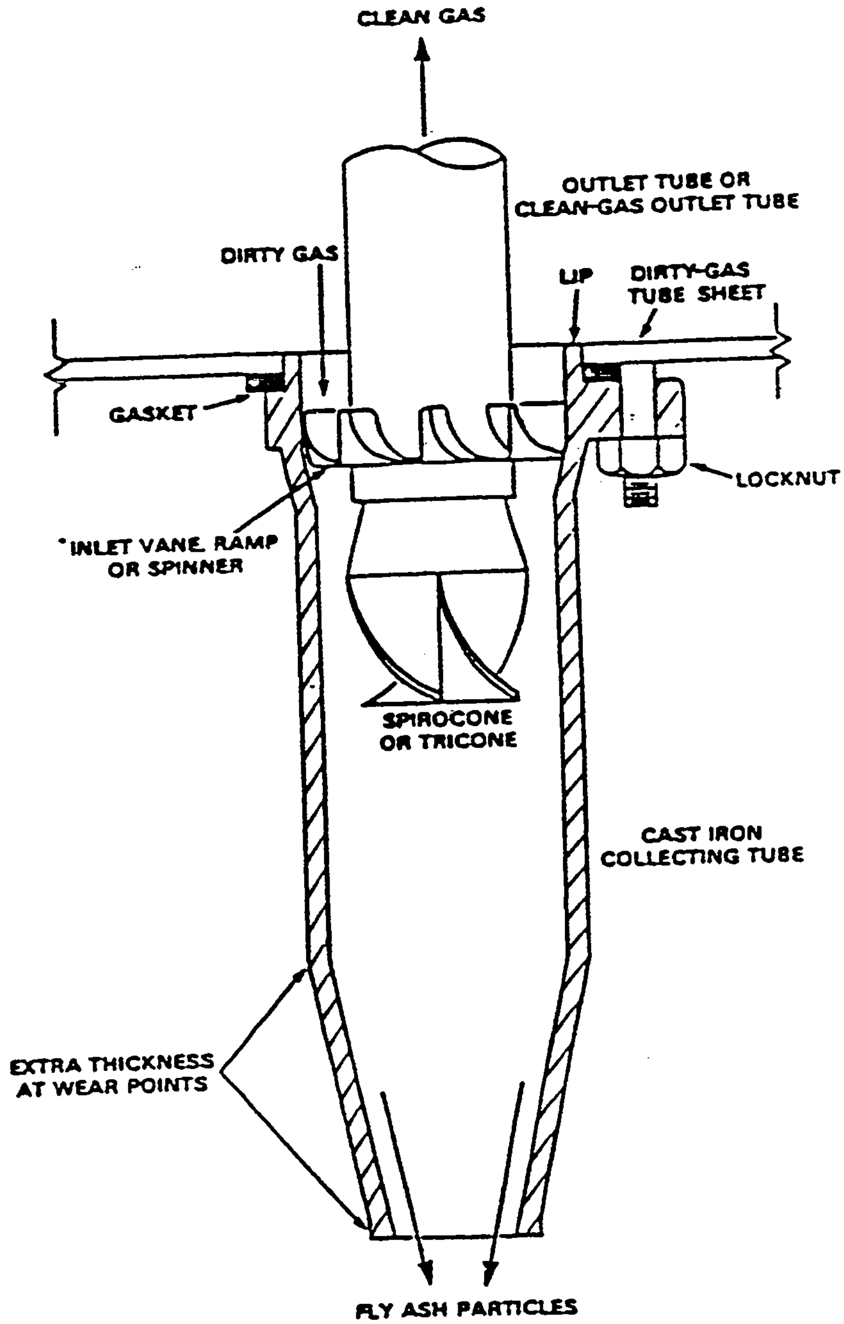


Figure 3-21. Cross section of collection tube showing gasket seal.[6]

On-line measurements may be unable to determine this form of bypass. Visual identification is possible, however, during an internal inspection or through smoke testing.

Collector Bypass--

Penetration of flue gas from the inlet plenum to the clean-gas plenum is defined as collector bypass. Any opening in the clean-gas tube sheet or clean-gas tube forms an orifice through which particles may pass.

Major areas of bypass are the gasket seal between the gas outlet tube and the tube sheet, the weld or press joint between the gas outlet tube and the tube sheet, and the weld or joints between the tube-sheet sections or wall. Figures 3-22 through 3-24 show several examples of these penetration points.

Penetration may also occur through holes on the leading edge of the gas outlet tube in the dirty-gas plenum (Figure 3-25). The tubes are exposed to the dirty gas. Abrasion damage occurs as the gas is directed to the collection-tube turning vanes. In most cases the pressure drop across the penetration point is equivalent to the collector pressure drop (3 to 4 in. H_2O). As a result, substantial gas bypass occurs through the orifice.

Because most bypass occurs internally, it is difficult to determine the points of inleakage while the collector is on line. A visual inspection of the tube sheet, outlet tubes, gaskets, and welds can identify major penetration points and allow corrections to be made. Many penetration points, however, are hidden and can only be identified under a static pressure differential. For these leaks to be found, the collector must be sealed and pressurized, and the penetration must be observed visually by use of a white aerosol smoke.

Hopper Crossflow--

Because of space limitations, multicyclone collectors are designed with multiple rows of collection tubes in the direction of gasflow. For maximum efficiency, the design must ensure that all collection tubes receive an equal volume of flue gas. As gas is passed through the initial leading row of tubes, the total gas volume is reduced and the

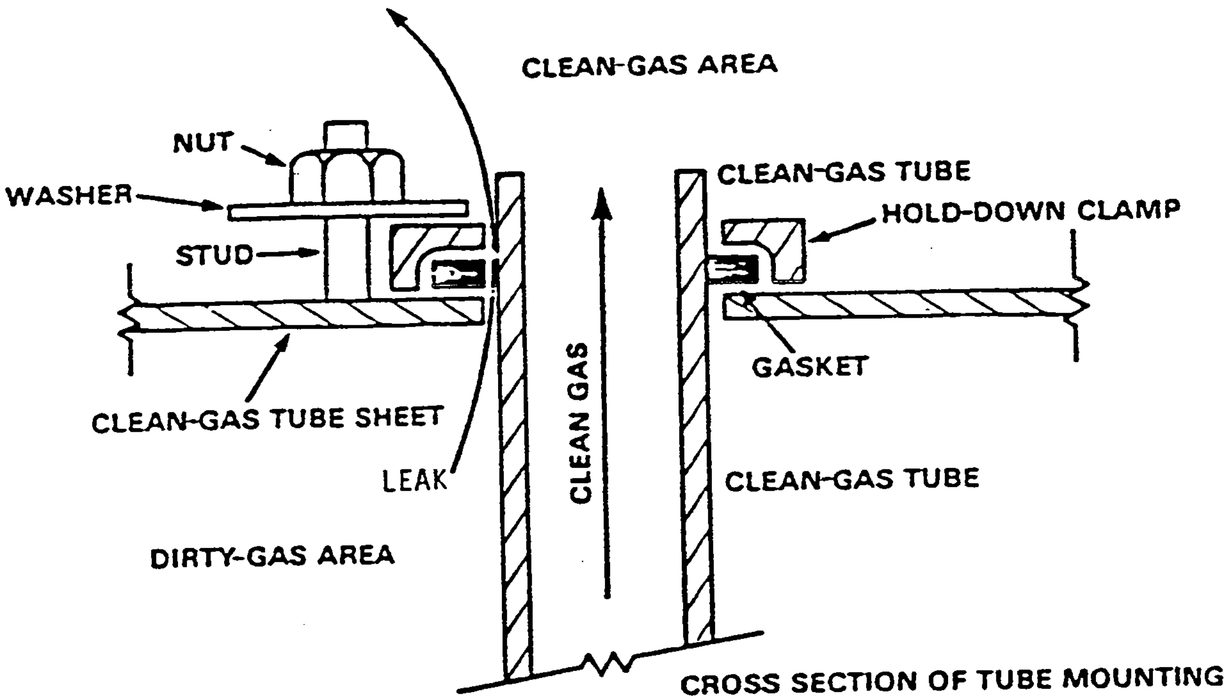


Figure 3-22. Example of gasket leaks.[6]

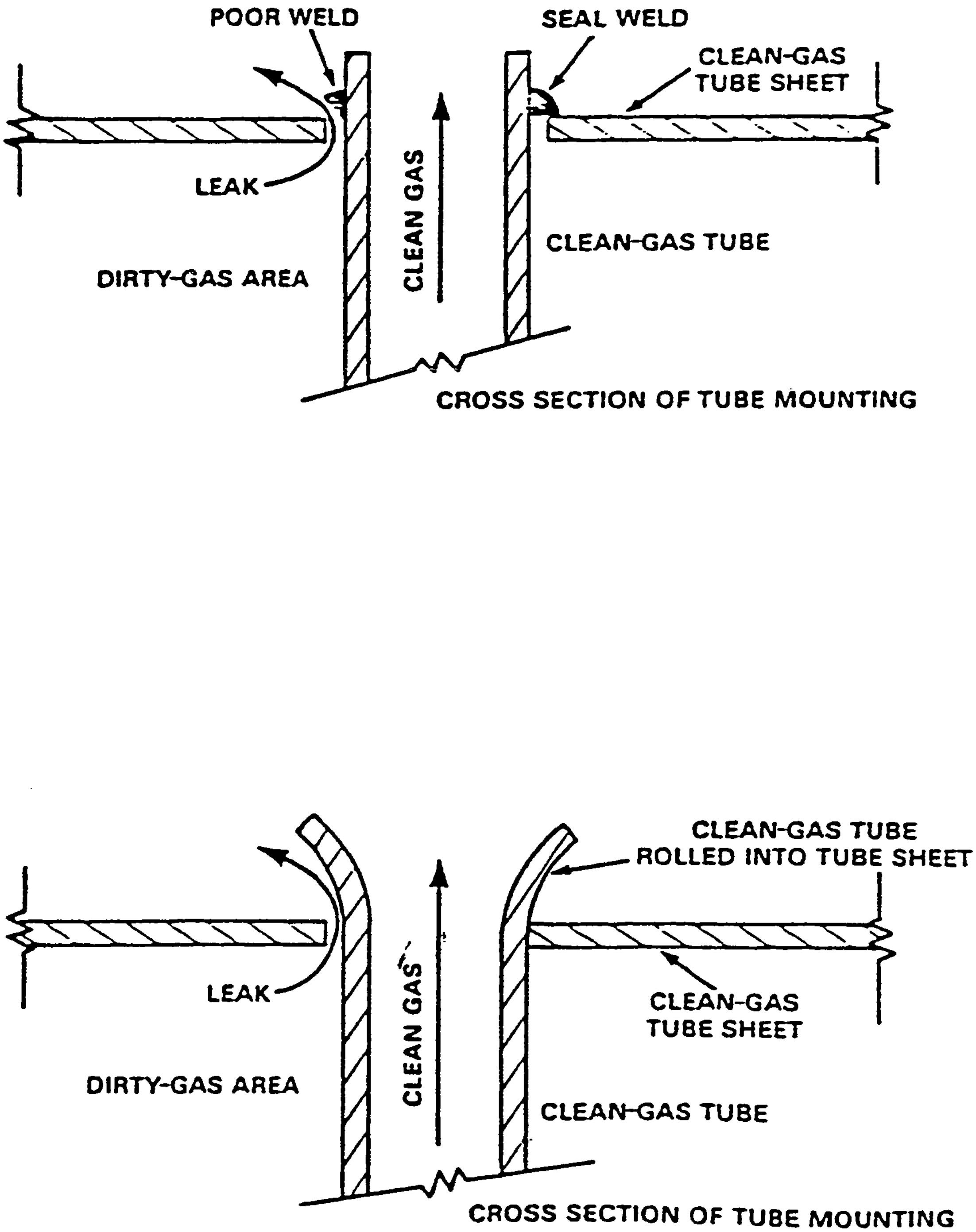


Figure 3-23. Example of clean-gas outlet tube and clean-gas tube sheet leaks.[6]

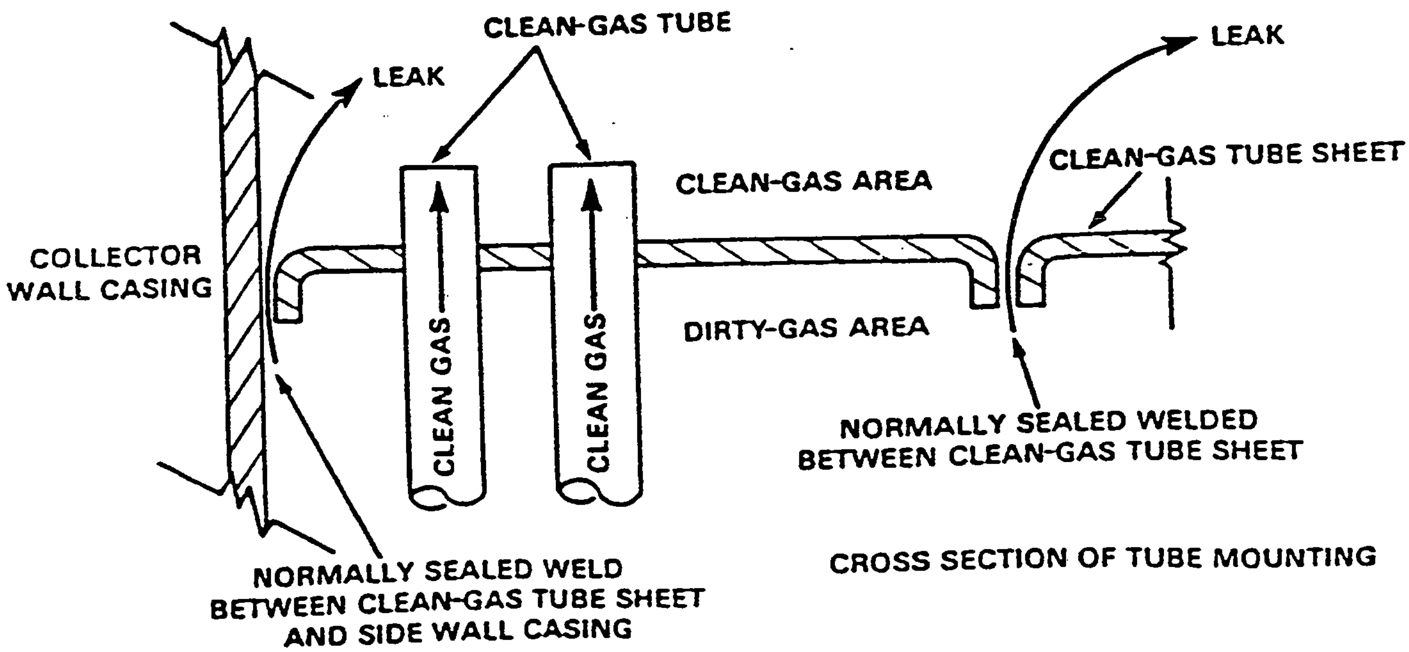


Figure 3-24. Example of leaks between tube sheet sections[6]

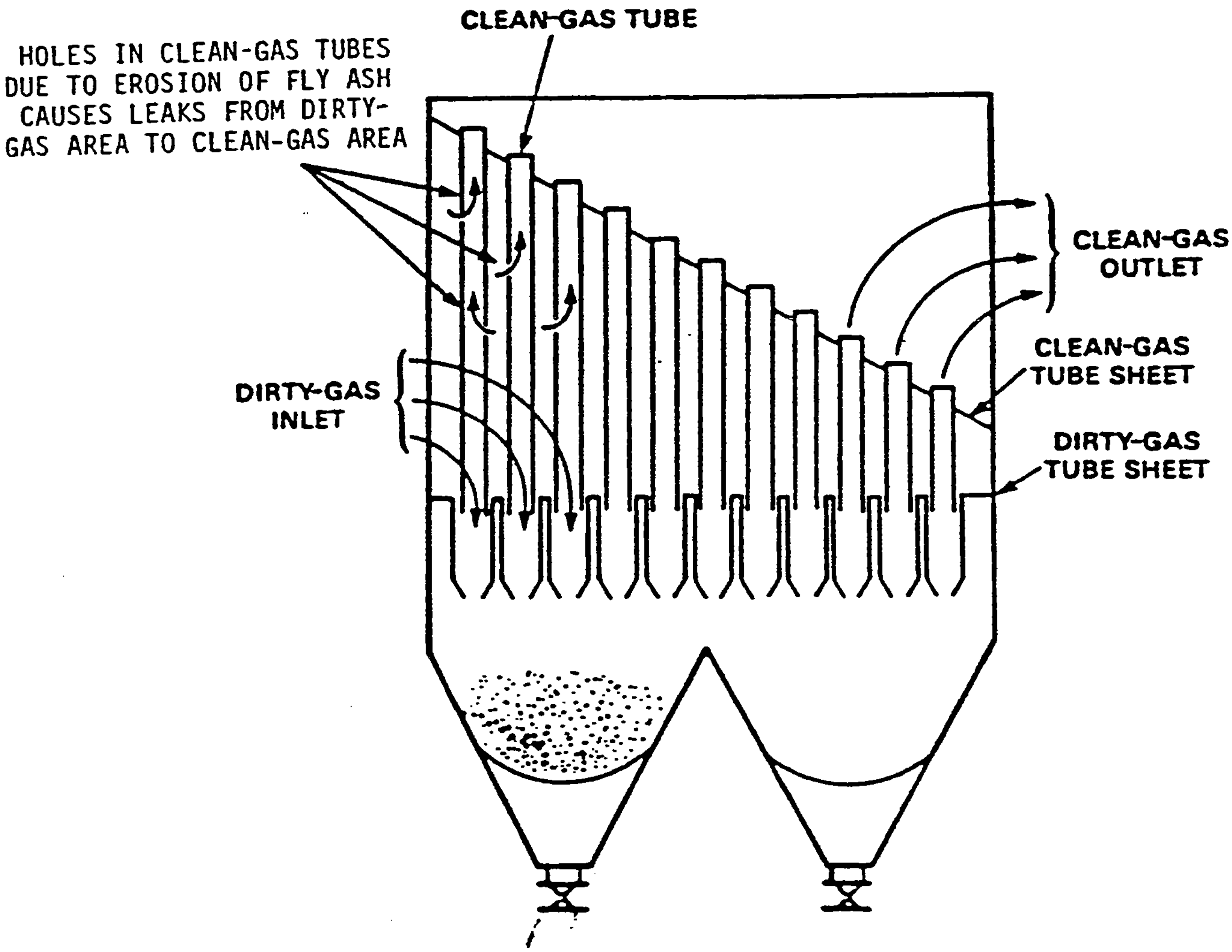


Figure 3-25. Collector bypass through holes in gas outlet tubes.[6]

gas velocity in the plenum is reduced. In many designs, the clean-gas tube sheet is inclined to maintain uniform velocity.

In theory, this should maintain uniform flow to each row of tubes. In practice, however, the gas incurs greater total pressure loss when it passes through the rows of clean-gas tubes between the first and last row. As a result, less gas flows into the inlets of the rear rows of tubes. Because there is less flow to these tubes and because the gas outlet tubes are shorter, pressure drop decreases substantially across these tubes. This reduction in pressure drop offers a point of minimum gas resistance that allows gas to flow down through the dust outlet of the leading tubes and through the hopper. The gas then enters the dust discharge of the rear tubes (Figure 3-26). The gasflow exiting the front-tube dust discharge theoretically increases the efficiency (similar to hopper evacuation), but this is negated by dust entrainment in the hopper and penetration of dust into the rear clean-gas tubes via the cyclone dust discharge.

The effects of cross-hopper ventilation may be increased if other abnormal operating conditions occur, such as hopper inleakage, plugged turning vanes, plugged gas outlet tubes, plugged cyclone dust discharge, or dirty-gas tube-sheet bypass.

The potential for cross-hopper flow increases with the number of cyclone rows in the direction of gasflow because of increased pressure differential between tube rows. For prevention of this flow, many facilities use collectors with multiple hoppers having positive seals between hoppers (i.e., baffles) or a single hopper with a baffle (Figure 3-27). The baffle in a single hopper must extend into the apex of the hopper, and the ash level is used to maintain a seal between sections.

3.5 Operator Training

Training in the proper procedures for inspecting, maintaining, operating, and troubleshooting mechanical particle-collection devices is a key parameter for productive facility management. Management must establish a training frequency for APC equipment inspection, maintenance, and operation that allows new employees to become

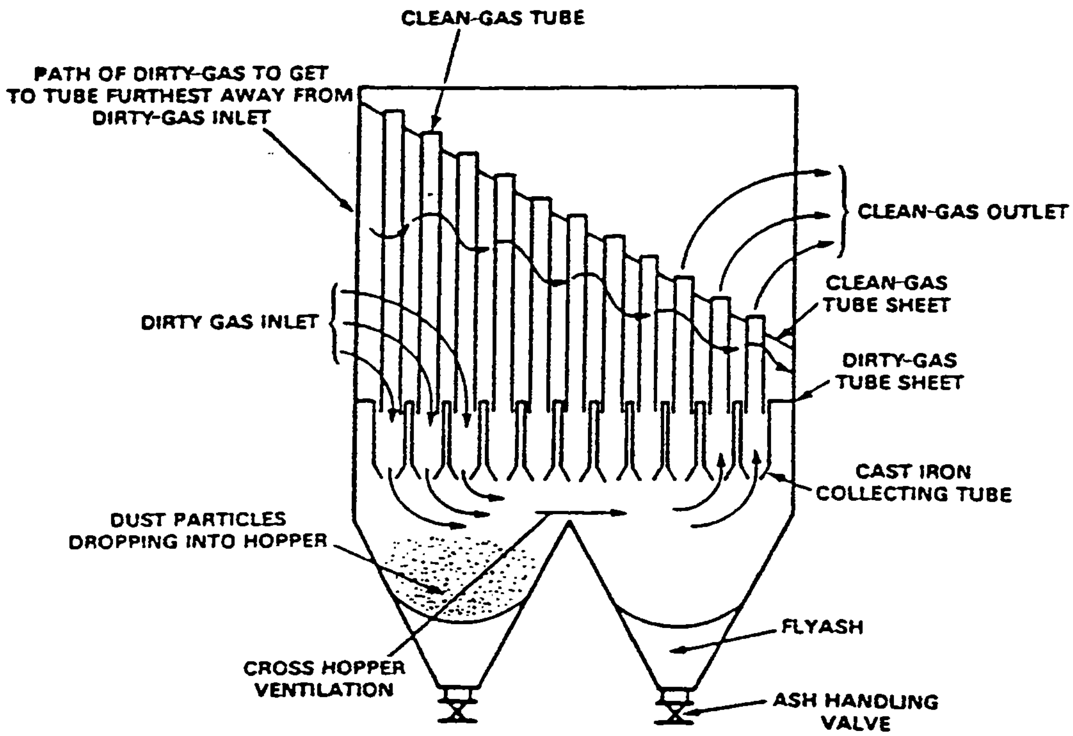
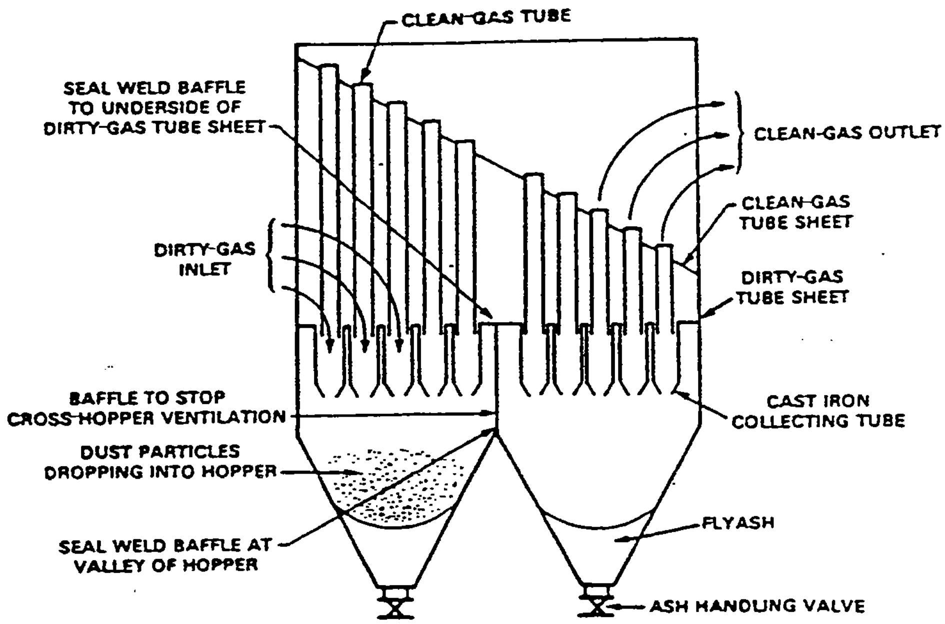
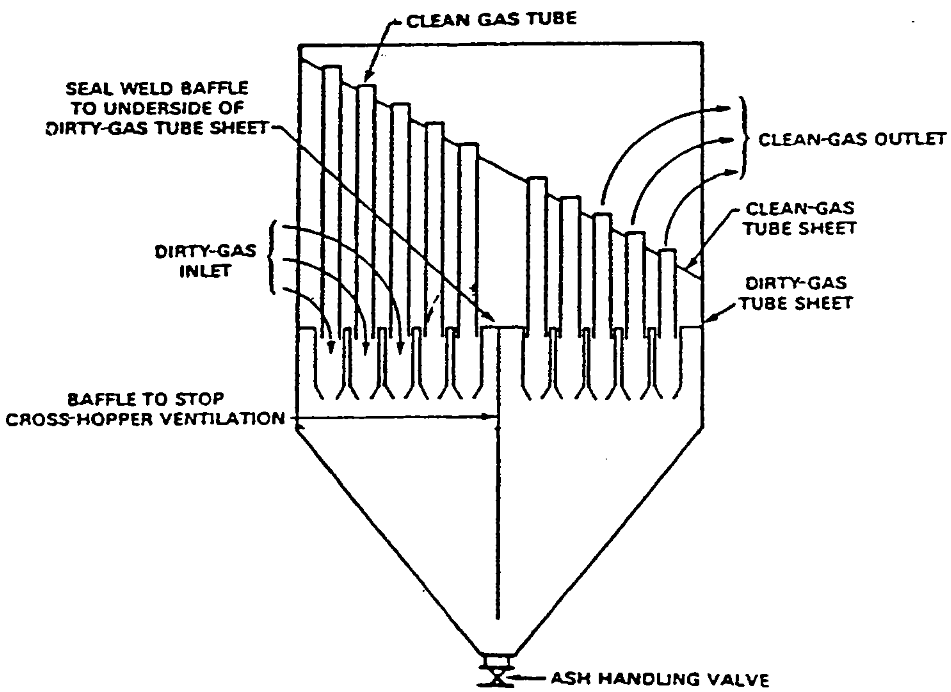


Figure 3-26. Poor distribution and hopper crossflow.[6]



MULTIPLE HOPPERS WITH BAFFLE



BAFFLE IN SINGLE HOPPER

Figure 3-27. Methods to reduce hopper crossflow.[6]

accustomed to the proper operating procedures and seasoned employees to stay current with these procedures.

Training in proper startup, shutdown, inspection, maintenance, and operation should be provided by the equipment manufacturer for newly installed units. For existing units, process engineers should be knowledgeable in the workings of each unit. After startup training, regular training courses should be held by in-house personnel or through the use of outside expertise. A set of users manuals discussing the procedures should be kept available for quick reference. Each training session should include specific written instructions and practical experience on safety, inspection procedures, system monitoring equipment and procedures, routine maintenance procedures, and recordkeeping.

Training should also include opacity verification in accordance to U.S. EPA Reference Method 9. This method requires semiannual recertification in method procedures. This time schedule would also provide a good benchmark for equipment training as well.

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SECTION 4.0

FABRIC FILTERS

This section provides industrial users of fabric filters with guidance and procedures for the proper operation and maintenance of this equipment so as to comply with applicable emission standards. It will also assist Agency personnel who are responsible for making inspections at facilities that use fabric filters to have a better recognition and clearer understanding of the indicators of efficient and reliable equipment operation.

4.1 General Description

Fabric filters are widely used as a control technology for particulate matter (PM). This technology removes PM entrained in the flue gas streams of industrial process ventilation or fuel combustion units by passing the dust-laden gas stream through a porous fabric.

Fabric filters (often referred to as "baghouses", which are actually the structures that house the fabric filter systems) typically consist of one or more compartments containing long cylindrical fabric bags. The compartments in this type of fabric filter system generally contain multiple rows of bags. Another kind of fabric filter is commonly referred to as a cartridge filter. Cartridge filters serve the same function as the bags in standard fabric filter systems, but self-contained cartridges (rather than bags) are used for PM capture.

Fabric filters are very efficient PM-collection devices. They typically achieve efficiencies greater than 99 to 99.9 percent for particle sizes ranging from submicrometer (10^{-6} m) to several hundred micrometers.[1] Because of their high efficiencies, fabric filters are usually considered the best available control technology (BACT) for PM emissions. They are often used for control of toxic particulate emissions.

Fabric filters can be used in series with gas pretreatment equipment for simultaneous control of PM, sulfur dioxide (SO_2) from coal-fired boilers, and corrosive acid gases. The two most common fabric filter methods used for SO_2 and acid gas control are dry sorbent injection and spray drying. In the first technique, a dry powder, sodium-based compound is injected into the flue gas upstream of the fabric filter. The powder collects on the bags as a particulate; SO_2 and acidic materials are removed by reaction with the powder in the suspended state and as the gas is filtered through the sorbent-coated bags. In the spray-drying technique, a lime-based alkaline solution is atomized into the flue gas stream ahead of the fabric filter. The solution evaporates and reacts with the SO_2 and the acidic materials. The dry reaction products are removed as particulate. Figure 4-1 depicts a typical dry scrubbing/fabric filter system.

4.1.1 Filtering Mechanism

The particle collection surface consists of the filtering medium (fabric) and a structural support. Chemically treated or untreated felt fabric or woven cloth of natural or synthetic fibers is used in standard bag designs. Cartridge filter designs use the same material, only they are configured in self-contained cartridges.

Two main phenomena comprise the manner in which particles are collected on the filter. With an unused or recently cleaned filter bag, particles are collected primarily by impaction or direct interception onto the fibers of the fabric itself. A layer of particles continues to build up on the fabric surface. Continued PM filtration builds a dust cake on the fabric surface, which, in turn, increases PM capture. This dust layer (dust cake) replaces the fabric as the filtering medium and is actually more efficient than the uncoated fabric.

Eventually, the dust cake buildup reaches a thickness that increases the pressure drop across the filter above the design set point. When this occurs, it must be removed by some means. The fabric cleaning cycle will remove most of the dust cake. After a few cleaning cycles, a steady-state dust cake forms and remains on the fabric surface, and this residual dust cake forms the basis for particle collection when the filter is put back in service.

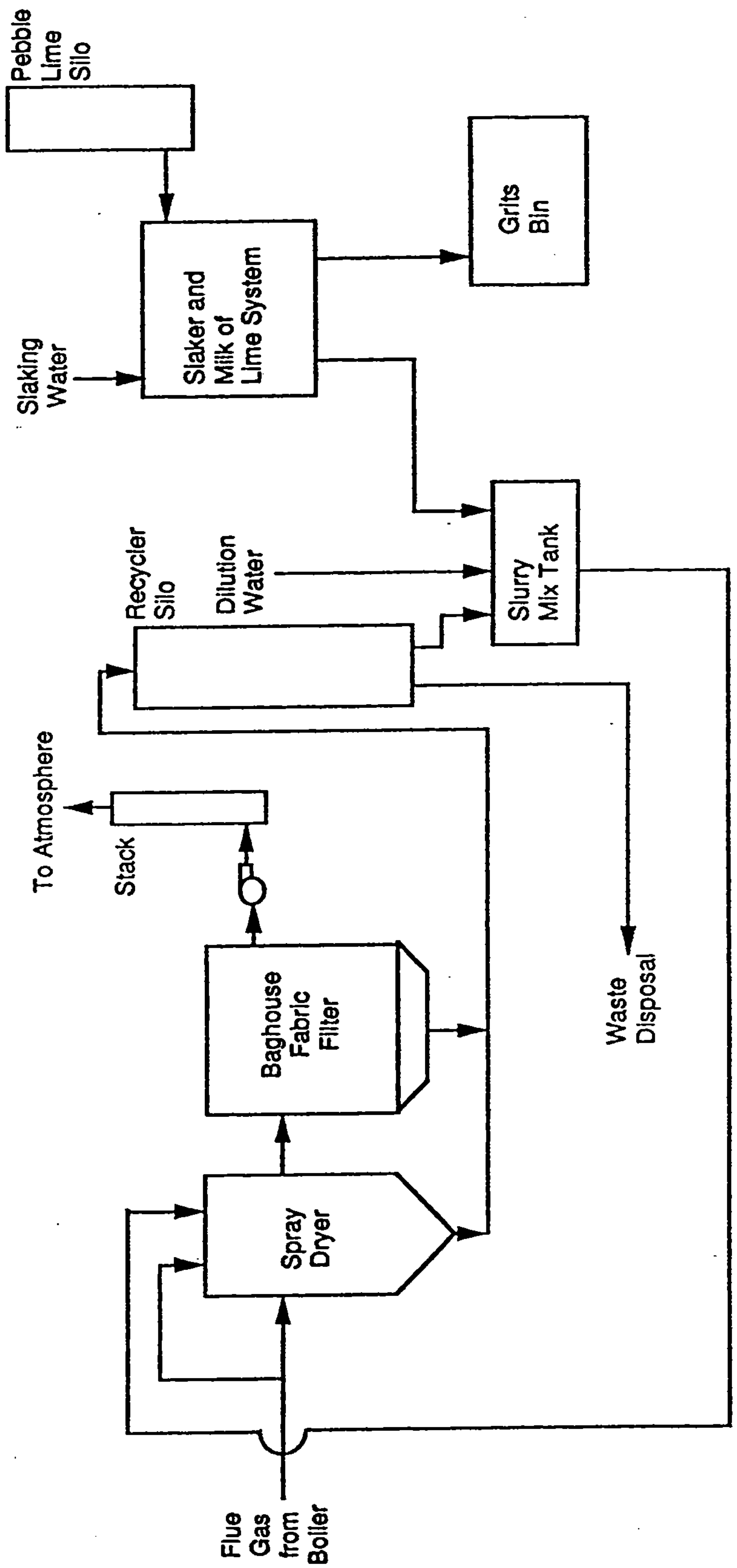


Figure 4-1. Typical dry scrubbing system.[2]

4.1.2 *Types of Fabric Filters*

Fabric filters are classified by several methods, the most common of which are location of system fan, direction of dirty gas flow, and fabric cleaning mechanism. Each is described in the subsections that follow.

Location of System Fan--

Particulate-laden air is either pushed through or pulled through the fabric filter. Figure 4-2 shows the different fabric filter fan arrangements. The control device is referred to as a positive-pressure fabric filter, when the dirty gas stream is pushed through the system and as a negative-pressure fabric filter when the dirty gas is pulled through the system.

In positive-pressure fabric filter designs, the system fan is situated upstream of the collector. These designs are generally used for extremely high airflows, but this type of fabric filter presents inherent operational and maintenance concerns. Because the fan is located on the dirty side of the collector, PM present in the gas stream can attack the fan and cause premature damage to the fan blades and bearing assembly.

In negative-pressure designs, the system fan is located downstream of the collector. Negative-pressure baghouses must be structurally reinforced to compensate for the suction applied by the induced draft fan and to prevent the infiltration of outside air into the system. Fan reliability is better in these baghouses because the fan handles a clean gas stream.

Direction of Dirty Gas Flow--

The two flow directions of dirty gas and the subsequent PM collection are known as interior and exterior filtration. In interior filtration, PM is collected on the interior surface of the filter bag or cartridge. In exterior filtration, PM is collected on the exterior surface of the filter bag or cartridge.

Figure 4-3 depicts an interior filtration system. The particulate-laden gas stream enters the collector and is directed inside the bag by diffuser vanes and a cell plate (also

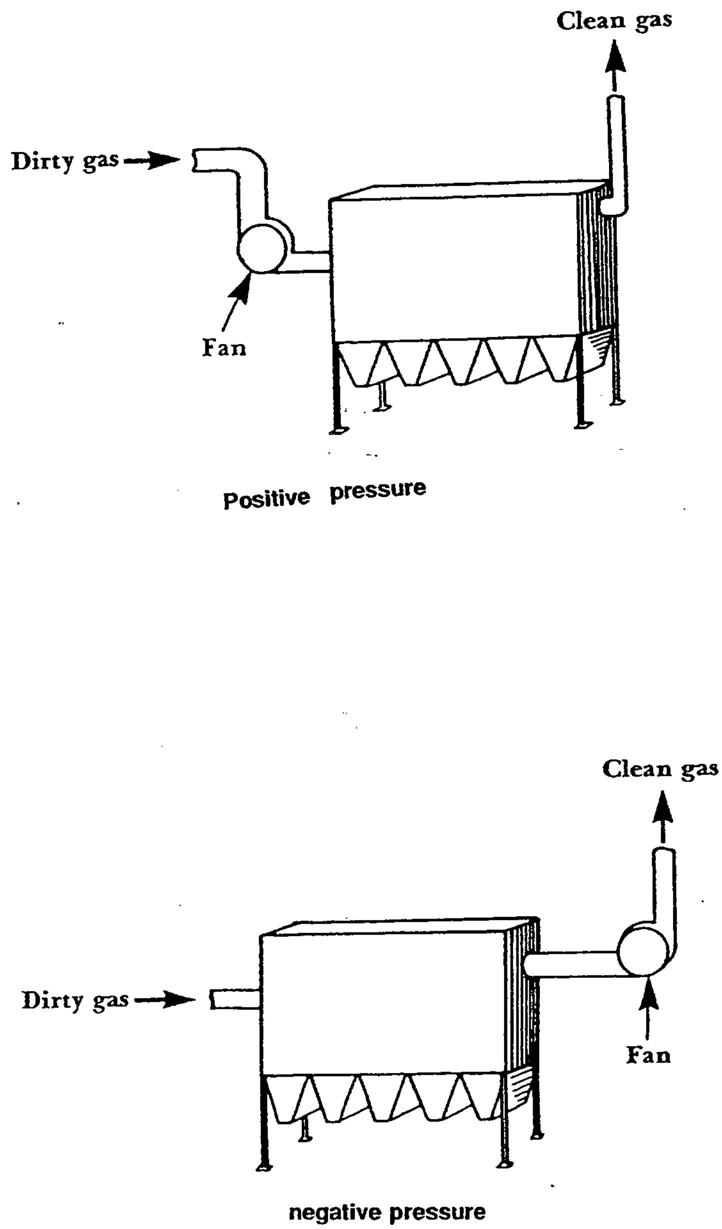


Figure 4-2. Positive and negative pressure fabric filters.[3]

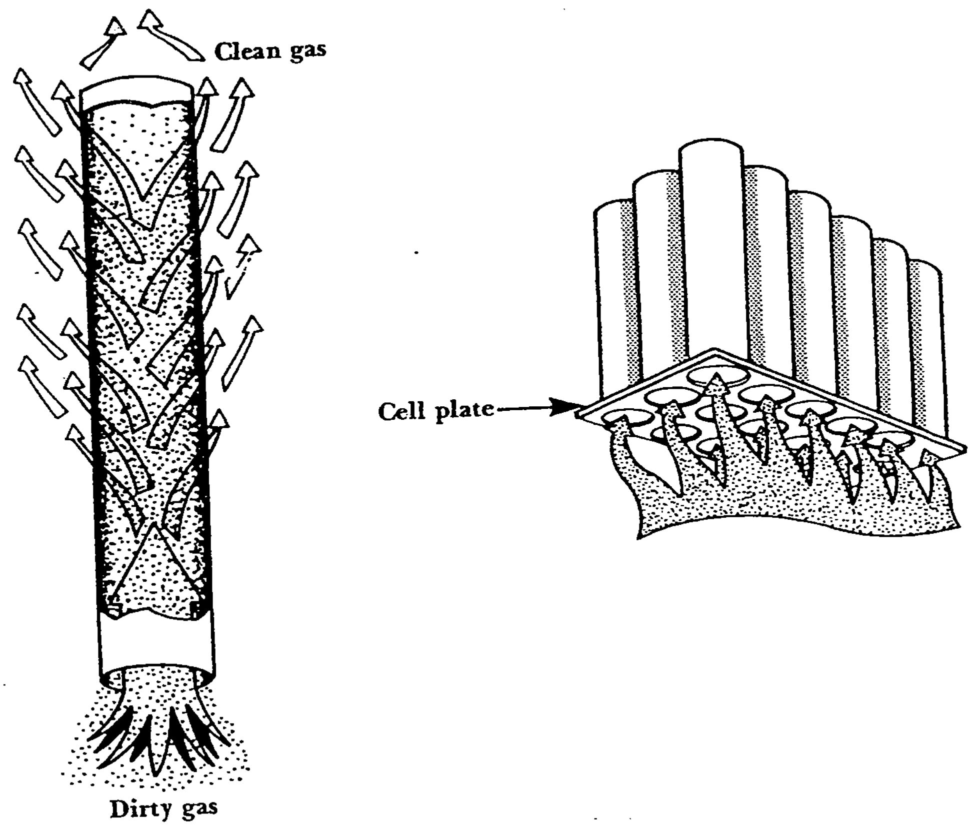


Figure 4-3. Interior filtration (particles collected on the inside of the bag).[3]

referred to as a tube sheet) that separates the bag inlet (dirty side) from the bag outlet (clean side); clean gas then passes through the bag (inside out).

Figure 4-4 depicts an exterior filtration system, in which dust is collected on the outside of the bags. Particulate-laden gases enter the collector and pass through the bags (outside in). Clean gas enters the interior of the bag and passes through the top of the bag. A cell plate separates the bag outlet section (clean side) from the bag inlet section (dirty side). Because the gas stream is pushed from outside to inside in this method, internal bag support is needed to prevent bag collapse. Internal cages or rings are commonly sewn into the bag fabric.

Fabric Cleaning Mechanism--

The fabric cleaning mechanism is also a distinguishing feature among fabric filter designs. The shaking, reverse-air, and pulse-jet cleaning methods are the most common.

Shaking, a low-energy method that gently shakes dust-laden bags to remove the dust cake, is used in interior filtration systems. The primary kinds of shaking motions are horizontal, vertical, and sonic vibration (Figure 4-5).

In shaker-type fabric filters (Figure 4-6), the filter bags are sealed at the top and hung by hook or clasp. The bags are open at the bottom and are attached to the stationary cell plate. Particulate-laden gas enters the bag below the cell plate and passes through the bag interior. The mechanical shaker system normally consists of a motor and cam/crankshaft assembly connected to the bag support frame. The rotary movement of the cam or crankshaft causes the bags to move or shake from the top. As a result, the bag flexes and cracks the dust cake, which then falls into collection hoppers. Other, less-popular shaker fabric filter designs create bag vibration by use of sound waves generated by a sonic horn blast.

Bag cleaning can be done by bag, row, or compartment. The flow of dirty gas to the bags being cleaned is stopped before cleaning is begun to prevent dust reentrainment and to promote efficient dust cake release.

Reverse-air cleaning is also a low-energy cleaning mechanism. Cleaning is accomplished by stopping the dirty gas flow to a bag, bag section, or fabric filter

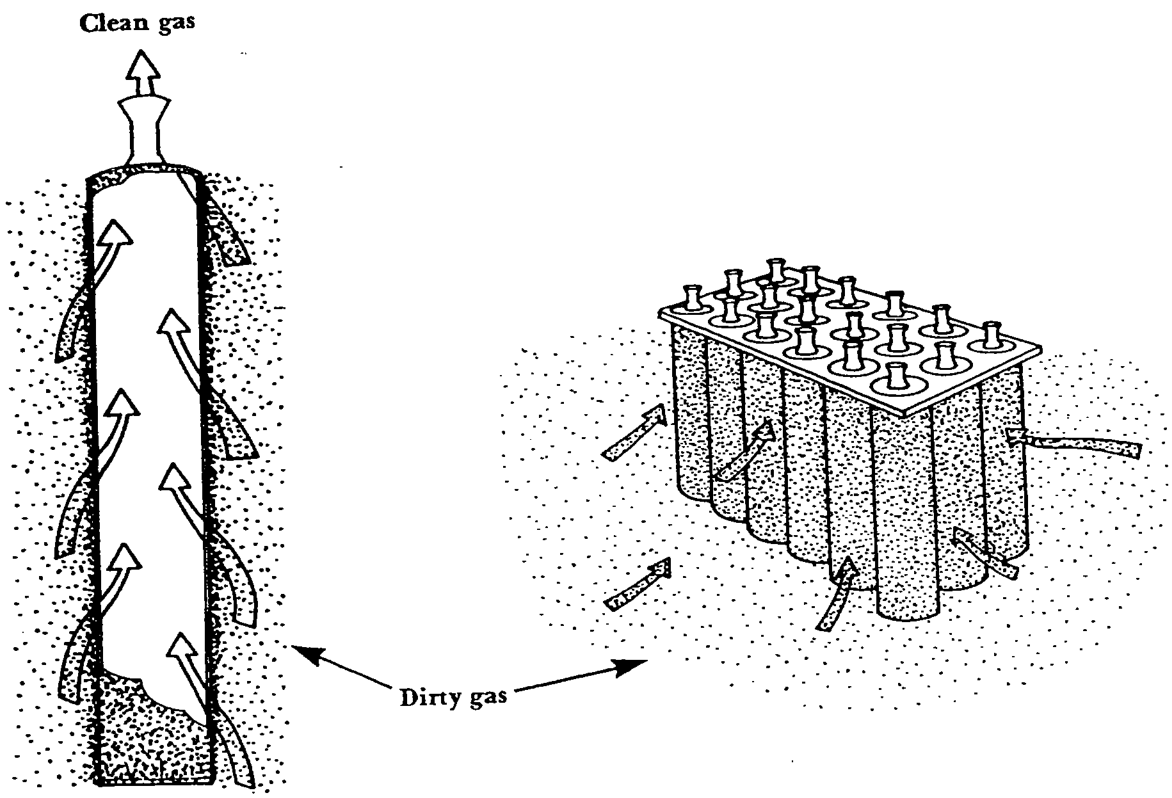


Figure 4-4. Exterior filtration (particles collected on the outside of the bag).[3]

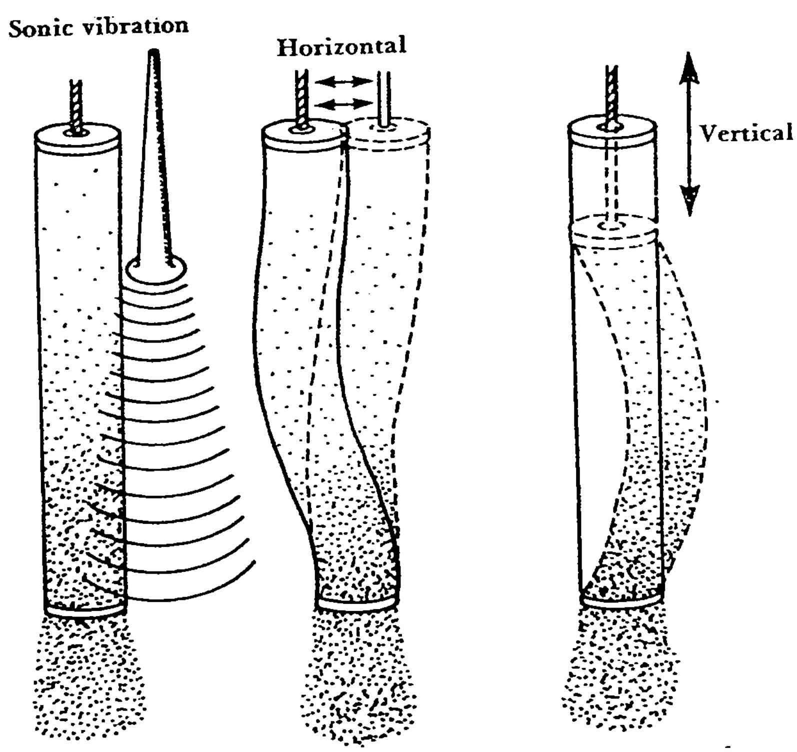


Figure 4-5. Shaking cleaning mechanisms.[3]

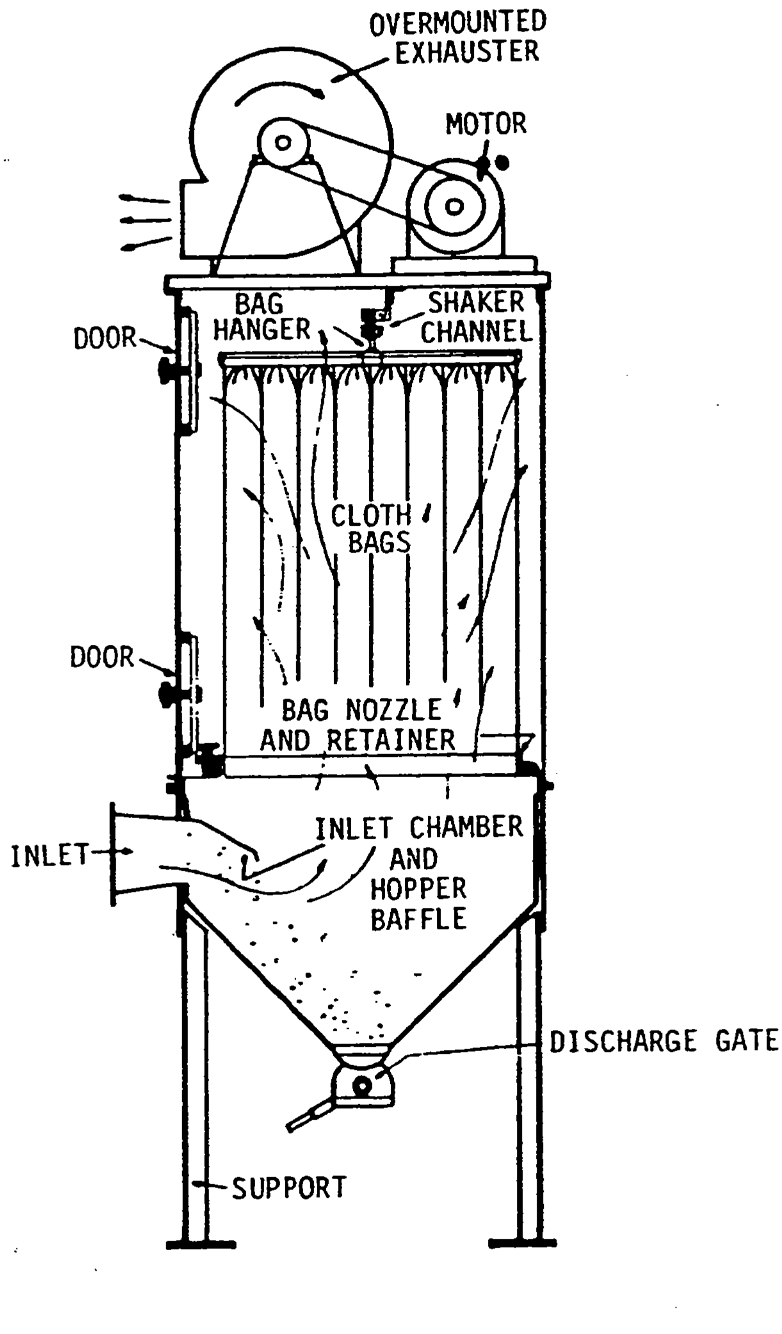


Figure 4-6. Small shaker-type fabric filters (Flakt, Inc.).[4]

compartment and allowing a low-pressure air stream to enter in the opposite direction (Figure 4-7). The reverse air-flow collapses the bags and breaks the dust cake. Reverse-air units are most applicable to interior filtration systems, but they can also be used in exterior filtration systems if internal bag support is provided. Figure 4-8 shows an example of a reverse-air fabric filter.

As in shaker-type fabric filters, the filter bags in reverse-air units are sealed at the top and hung by hook or clasp. The bags are open at the bottom and are attached to the stationary cell plate.

Pulse-jet (or pressure-jet) bag cleaning is the most popular method used in current fabric filter designs. Figure 4-9 shows a pulse-jet fabric filter. Pulse-jet cleaning is used exclusively for exterior filtration fabric filter models and cartridge filter systems. Bags in a pulse-jet system are supported by cages and are suspended from an upper cell plate.

The pulse-jet cleaning technique uses a high-pressure jet of compressed air directed through the top of the bags to the interior of the filter bags. Compressed air for cleaning is supplied through a manifold-solenoid assembly into blow pipes. A bag cup and venturi are installed at the top of the bags to improve the effect of the air blast and also protect the bag top from wear.

The compressed air jet travels down and back up the bag; the standing wave causes the bag to flex and expand (Figure 4-10) and then breaks the dust cake. Pulse-jet units generally use compressed air systems that will feed a common header arrangement that injects air into bags based on a per-compartment cleaning cycle (Figure 4-11).

4.1.3 Auxiliary Equipment

Fabric filter systems include auxiliary equipment such as structural housing (the baghouses) and insulation, dust hoppers, and a system fan.

Most fabric filters consist of two or more separate bag compartments. Baghouse shells are of rigid metal construction. In high-temperature or acidic gas stream applications, the baghouse structure is insulated to prevent moisture or acid condensation in the unit, which can cause corrosion and premature deterioration of the equipment.

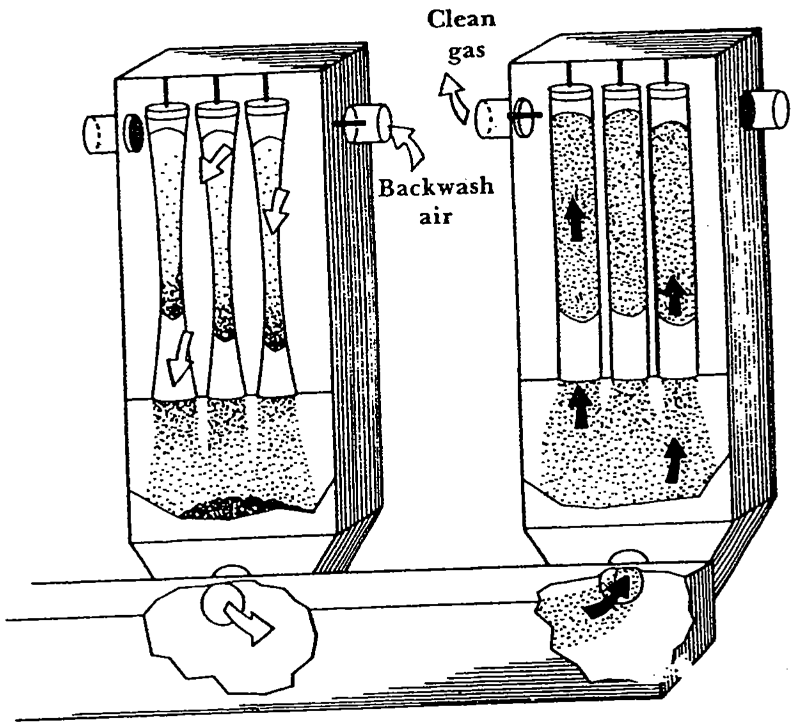


Figure 4-7. Reverse-air cleaning.[3]

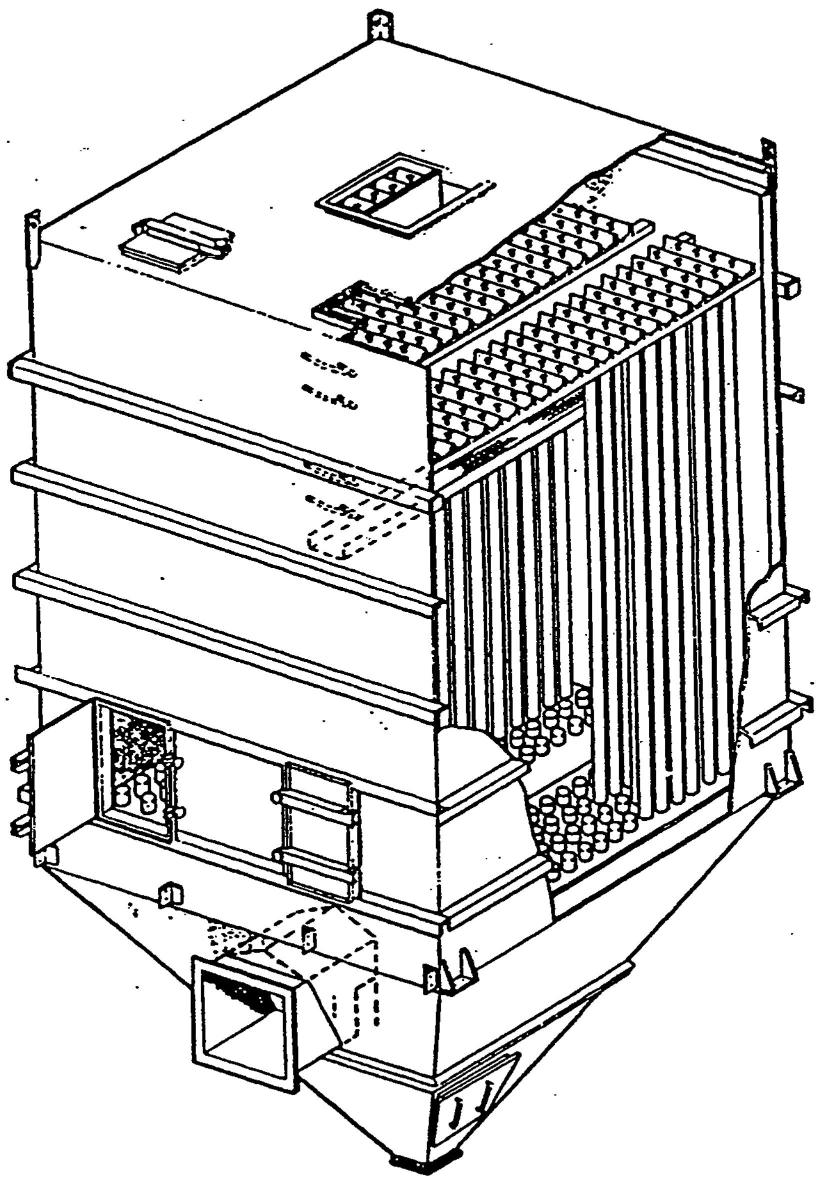


Figure 4-8. Reverse-air fabric filter (MicroPul Corporation).[4]

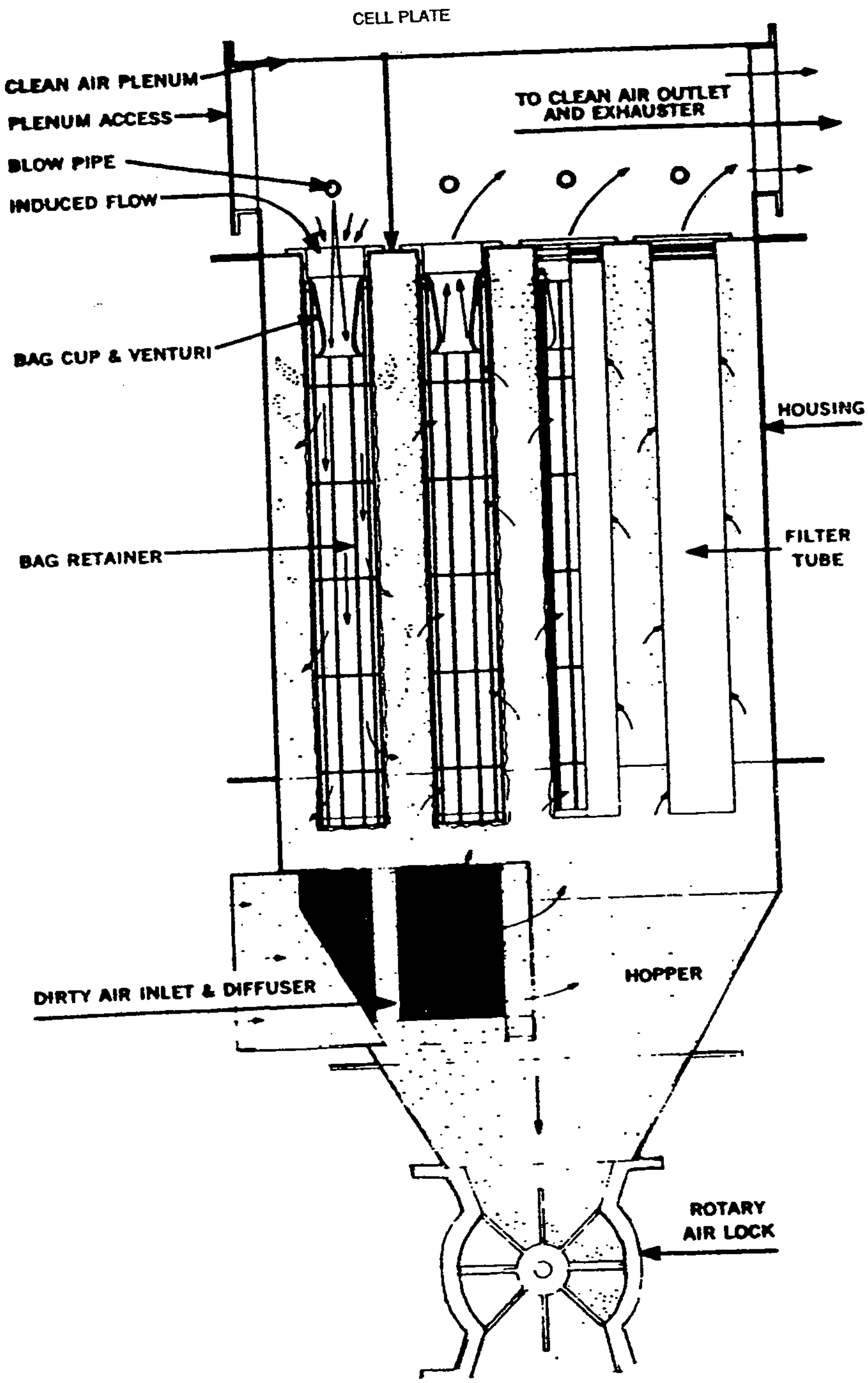


Figure 4-9. Example of a pulse-jet fabric filter (George A. Rolfes Company).[4]

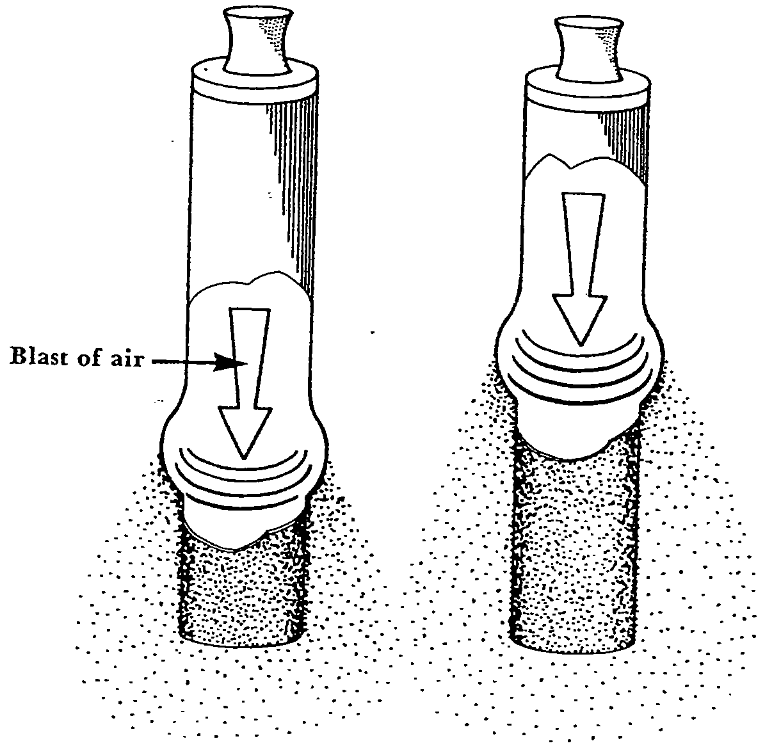


Figure 4-10. Pulse jet cleaning.[3]

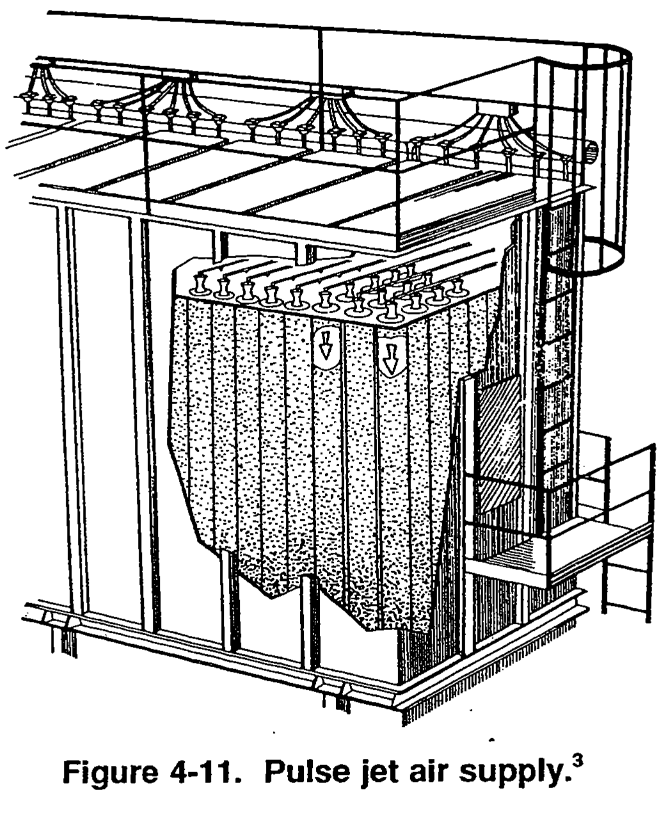


Figure 4-11. Pulse jet air supply.[3]

Hoppers are installed below the bag compartments to collect the dust that is removed from the bags. Hoppers in medium and large fabric filter systems are emptied automatically, either by pneumatic or mechanical systems, at a remote dust accumulation point. Dust collection hoppers in small fabric filter systems are generally emptied into 55-gal drums for disposal.

Hoppers are normally designed with about a 60-degree slope to allow free dust flow to the hopper's bottom opening. Additional hopper/dust flow modifications include strike plates, poke holes, vibrators, and rappers. Hoppers also have access doors for easier cleaning, internal inspections, and maintenance. Figure 4-12 shows a hopper in a fabric filter system.

The hopper's discharge system normally consists of a discharge valve at the hopper bottom, which empties into a dust-conveying system. The most common hopper discharge valves are trickle valves (gravity and motorized), rotary airlock valves, and automatic slide gates. Hoppers in many small fabric filter systems do not have a discharge valve; instead, they empty directly through a chute into a drum. Some small systems have manual slide gates. Figure 4-13 shows a trickle valve and rotary airlock valve.

The two main types of dust-conveying systems are mechanical screw and pneumatic systems (Figure 4-14). Screw conveying systems consist of a revolving screw feeder located at the hopper bottom. Pneumatic conveyors use compressed air to blow the dust discharged from hopper valves. Pneumatic conveying systems almost always include hopper discharge valves. Screw conveying systems, however, do not necessarily require hopper discharge valves.

4.1.4 Key Operating Parameters

Efficient operation and effective life of fabric filter systems can be promoted by proper monitoring of selected key parameters followed by appropriate corrective action. Some parameters are monitored on a continuous basis, whereas others are monitored periodically. The following operating parameters are good indicators of efficient fabric filter operation:

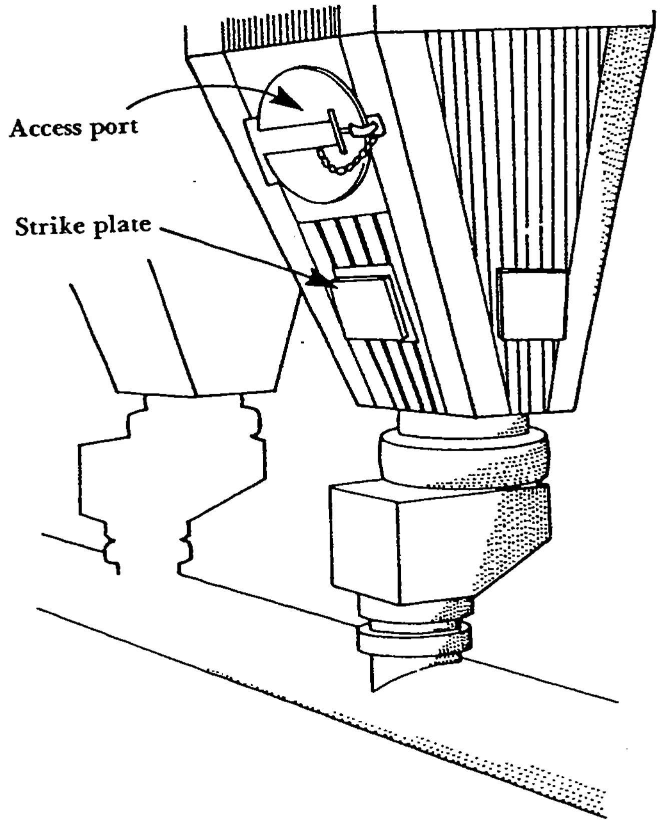


Figure 4-12. Hopper on fabric filter system.[3]

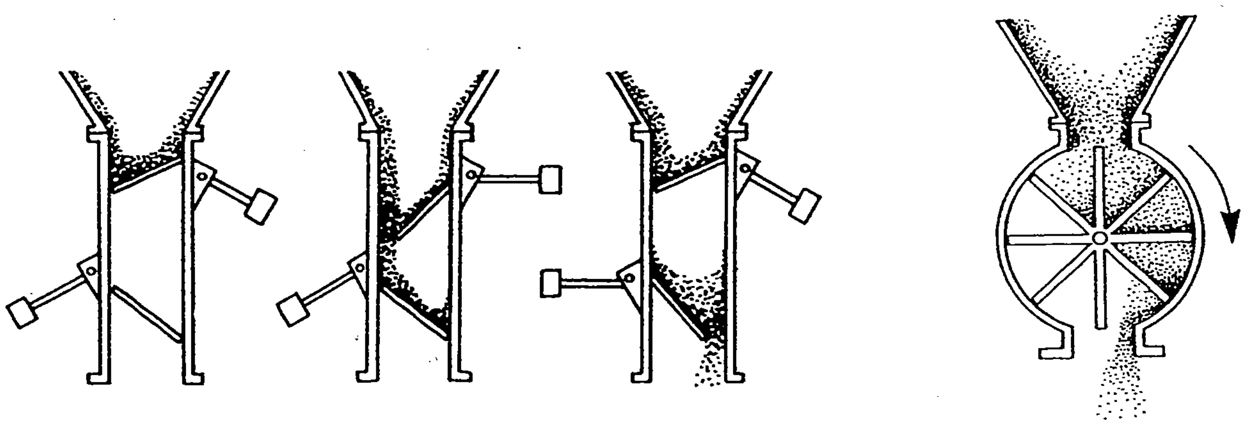
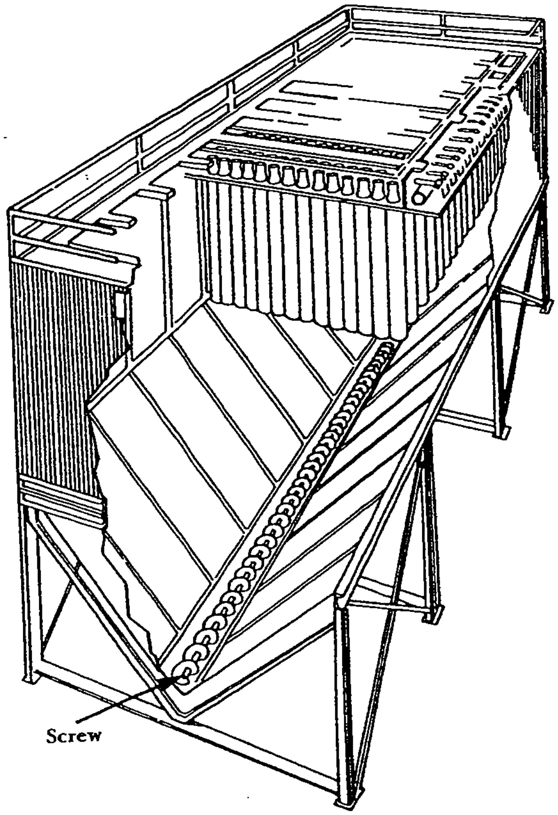
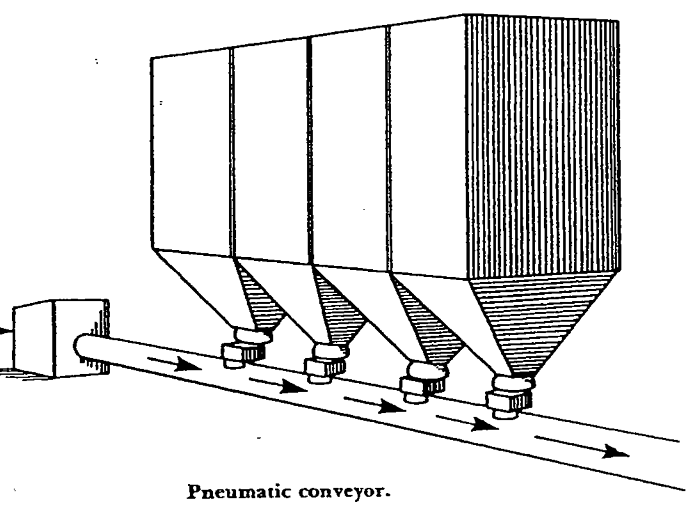


Figure 4-13. Trickle valve discharge device and rotary air lock.[3]



Screw conveyor.



Pneumatic conveyor.

Figure 4-14. Screw and pneumatic conveyors.[3]

Pressure drop (entire system or individual compartments)
System gasflow rate
Gas temperature
Bag tension
Dust removal
Opacity of baghouse exhaust

Pressure Drop--

Pressure drop is often the only parameter monitored in a fabric filter system.[5] Each system is designed to operate within a defined pressure-drop range. Proper fabric filter operation is indicated if pressure drop is fairly steady during operation and gradually increases as the dust cake builds on the bags. After the bag cleaning cycle, the pressure drop decreases instantaneously.

Pressure drop can be measured across an entire fabric filter system or for individual compartments. Pressure drop measurements can indicate permeability of filter cloth, extent of dust deposit before cleaning, cleaning efficiency, and plugging or blinding of the filter fabric.[4]

System Gas Flow Rate--

Because fabric filter pressure drop is a function of velocity, pressure drop values can only be compared for system diagnostic purposes at the same volume flow. Noting and recording system gasflow is also useful in detecting potential inleakage of outside air.

A change in system gas volume (and velocity) will affect the unit's air-to-cloth (A-C) ratio, required cleaning energy and effectiveness, bag life, and PM collection efficiency.[4] Higher gas volumes lead to higher A-C ratios and gas velocities. These, in turn, will shorten bag life as a result of more frequent cleaning, higher particle velocity through the fabric (increased abrasion), greater bag blinding potential, and a higher pressure drop--all of which are factors that limit fabric filter efficiency.[4]

Gas Temperature--

Monitoring of gas temperature (inlet and outlet) can provide information about fabric filter performance and indicate possible reasons for decreased performance or process problems. An acceptable temperature range is normally determined by the manufacturer during the design of the fabric filter unit. An increase in temperature difference between the inlet and outlet may indicate excessive inleakage of outside air into the fabric filter housing.

Inlet temperature monitoring is important for minimizing bag damage due to exposure to temperatures outside the acceptable range. The exposure of the fabric filter to temperatures above the maximum exposure limit can cause immediate bag failure due to complete tensile strength loss and permanent elongation from melting. Short excursions above the upper temperature limit can weaken bags.[4]

Minimum inlet temperature limits are directly related to the acid dewpoint of the gas stream. Operation of a fabric filter below the minimum inlet temperature can allow moisture and/or acid condensation and result in bag blinding or chemical attack of the fabric.

Bag Tension--

Proper bag tension is an important factor for improving bag life and minimizing PM emissions. A bag should be tight enough to prevent excessive fiber-to-fiber and bag-to bag contact and abrasion, but not tight enough to cause the bag to exceed its tensile strength during cleaning.[4] Figure 4-15 presents an example of a properly tensioned bag.

Dust Removal --

Excessive dust buildup in the fabric filter hopper can adversely affect system performance. If the level of dust in the hopper increases substantially, dust can become reentrained in the gas stream and overload the bags, increase their cleaning frequency, and shorten their effective life.

Hopper dust levels are affected by several things, including the proper operation of the hopper discharge valve (if applicable) and dust viscosity. A malfunctioning discharge valve will increase dust levels by not evacuating any previously collected dust. Sticky or tacky dust may cling to hopper walls or bridge across the top of the hopper and thereby prevent the use of the whole hopper volume.

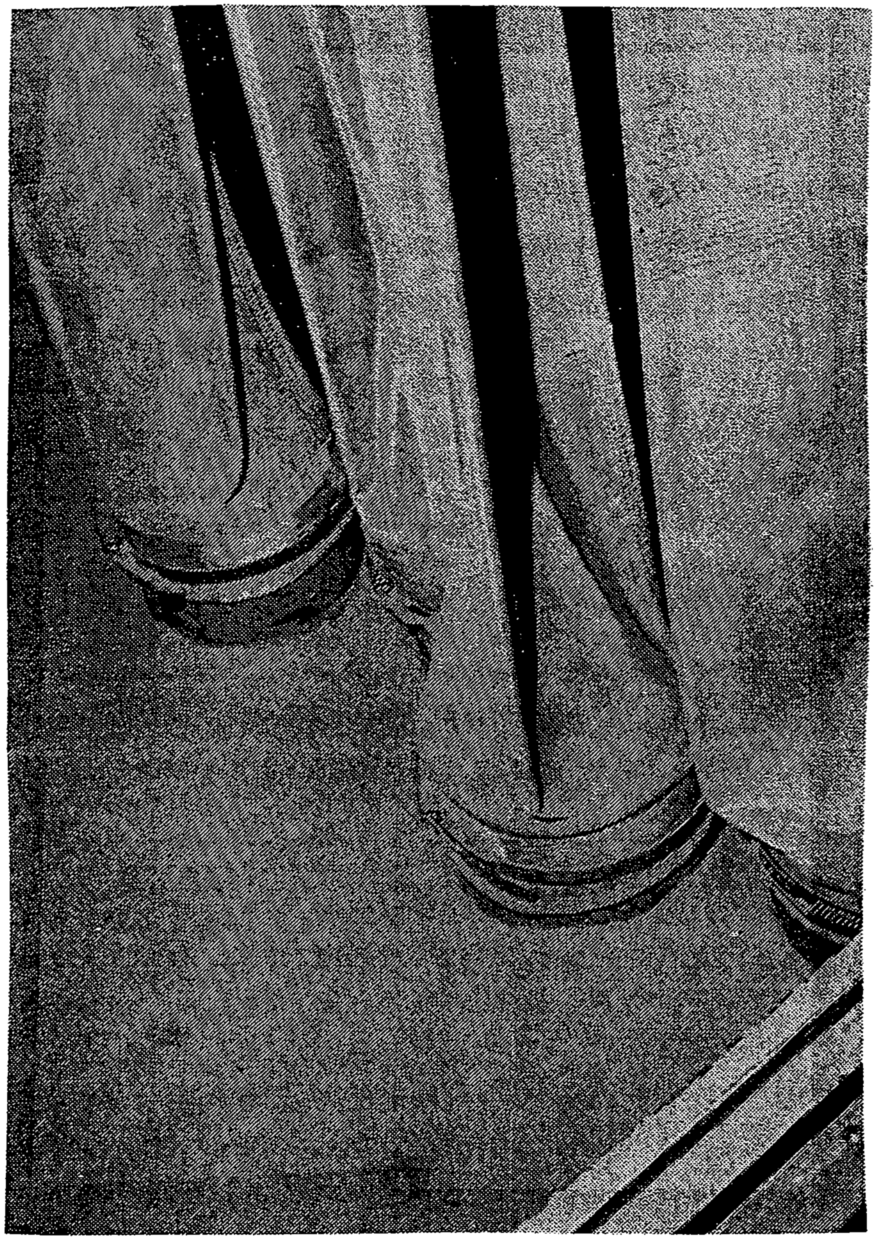


Figure 4-15. Example of a properly tensioned bag that is collapsed during reverse-air cleaning.[4]
(PEI Associates, Inc.)

Opacity of Fabric Filter Exhaust--

In excess of 5 percent opacity in visible emissions from a fabric filter stack may indicate a decrease in collector performance that warrants investigation. Although there is no standard mass emission-percentage opacity relationship, sources could develop a site-specific correlation of mass particulate emissions to percentage opacity to provide a relative indication of fabric filter performance with respect to permitted emission limits.

Frequent or continuous monitoring of opacity (by human observer or instrument) can be used to develop curves for tracking decreased fabric filter performance versus length of equipment service life.

4.2 Monitoring Fabric Filter Operation

4.2.1 Monitoring Systems

Routine monitoring of the key operating parameters identified in Subsection 4.1.4 will improve the performance of a fabric filter and increase its effective service life. The readings of some of the instrumentation described in the following subsections (e.g., thermocouples, differential pressure gauges, and opacity transmissometers) can be electronically recorded for permanent records.

Pressure Drop--

Static pressure gauges such as magnehelic gauges or manometers can be installed at the inlet and outlet of the fabric filter to determine the unit's pressure drop. In multicompartment fabric filters, the pressure drop across each compartment can be measured along with the overall pressure drop. Static pressure indicators used for this purpose must withstand high temperature and dust loadings. Over time the pressure-sensing lines can become clogged with dust or damaged by moisture or corrosion, and the gauge can become unreadable. Provisions for cleaning the pressure taps are required to prevent premature instrument failure due to clogging.

Portable pressure meters can be used as an alternative to differential pressure gauges. Hand-held static pressure gauges inserted through pressure taps provide a simple method of taking pressure readings. This technique is less expensive and reduces potential problems of meter moisture or corrosion damage and clogging; however, the readings are not continuous.

Pressure indicators can be installed on pulse-jet fabric filters to measure compressed air header pressure. This type of instrument can be used to signal when the header pressure drops below a set point that may indicate inefficient bag cleaning.[4]

System Gasflow Rate--

A pitot tube traverse is normally used to measure total gas volume. Measurement of inlet and outlet gas flow is important for comparative purposes. Use of the pitot tube method relies upon the procedures specified by U.S. EPA Reference Methods 1 and 2. The pitot tube traverse samples the gas velocity in multiple areas of the duct; the gas volume is calculated by taking the average velocity and the duct cross-sectional area.

Most facilities do not measure gas volume. Other indicators may be used to estimate the gas volume or to indicate changes from a baseline measurement. The alternate parameters include fan operating voltage or amperage, production rate, or gas condition (e.g., percent O_2, CO_2).[4]

Gas Temperature--

Inlet and outlet gas temperatures can be measured by simple thermocouples. The thermocouples can be permanently installed in the duct, or they can be portable and inserted during inspections. Permanent thermocouples can be connected to continuous recorders with digital, analog, or strip-chart display.[4] It may be necessary to have separate thermocouples to measure inlet conditions in compartmental units.[4]

Bag Tension--

Bag tension is an operating parameter that generally cannot be monitored on a frequent basis. Either the entire fabric filter or individual compartments must be off-line to inspect for adequate bag tension. Monitoring of this parameter is described later in this section.

Dust Removal--

Hopper level indicator and alarm systems can be used to monitor the dust level in fabric filter hoppers. When dust levels exceed the level of the detector, an alarm is triggered to prompt corrective action. The level detector should be installed high enough in the hopper to account for normal dust levels, but low enough to allow adequate response time to clear the hopper before the dust buildup reaches the tube sheet and becomes reentrained or blocks the filter inlet.[4]

The two types of level indicators are most commonly used are a capacitance-type probe and a radioactive detector.[4] The former is inserted into the hopper. As dust builds up around the probe, a change in capacitance occurs and sets off an alarm signal. The radioactive type uses a beam that is received by a detector on the opposite side of the hopper. When the dust level interrupts this beam, an alarm signal is tripped.

Hopper dust level can also be monitored by indirect methods. On pneumatic dust-conveying systems, the operator can check for a plugged hopper by checking the amount of vacuum drawn on a hopper as dust is removed. On mechanical screw conveying systems, the current drawn by the conveyor motor can be used as an indicator of normal dust removal. A third method involves the use of a thermocouple inserted into the hopper. A clogged hopper with dust buildup will coat the thermocouple and reduce the temperature.

Opacity of Fabric Filter Exhaust--

Opacity of fabric filter outlet gas streams can be measured by human observation or by a continuous recording instrument. Plant personnel who are certified to make U.S. EPA Reference Method 9 (Appendix A, 40 CFR 60) observations can used to spot- check stack opacity, or they can be used on a defined schedule to observe opacity for longer periods.

Opacity monitors are continuous instruments that measure and record stack opacity levels. Opacity can be measured and recorded on a real-time basis and over selected averaging times. Most current opacity monitor designs are double-pass transmissometers (the light beam passes through the gas stream and is reflected back across the duct to a transceiver). Regardless of the design, opacity monitors must meet the instrument operating requirements specified in Performance Specification 1, Appendix B, 40 CFR 60.

4.2.2 Equipment Inspections

Two general classes of inspections are performed on fabric filter equipment. One class is routine in nature and performed in support of general maintenance activities. Routine inspection and maintenance procedures are discussed in Section 4.3. The second class of inspection, referred to as a diagnostic inspection, is performed to determine the cause of detectable operating problems. These inspections are described in Section 4.4.

4.3 Inspection and Maintenance Procedures for Fabric Filter

The inspection frequency and action items for fabric filters are usually specific to each manufacturer and equipment design; however, some equipment is common to most designs and requires routine inspection. The following are the major elements that should be evaluated during the inspection of the fabric filter system:[4,6]

- Parameter monitors--Includes opacity or broken bag detectors; manometers for determining pressure drop across fabric, compartments, or entire collector; indicators for cleaning sequence, cycle time, compartments off line, temperature, volume flow, air-to-cloth ratio, moisture, pulse-jet header pressure, and reverse-air flow.

- Baghouse exterior--Includes cleaning system operation; cleaning method; overall condition of exterior housing, including structural members, access doors, and gaskets; reverse-air fan operation; and shaker mechanism. External inspection will reveal visual evidence of corrosion; warping of panels; faulty or missing gaskets; loose bolts; and noise, odor, or elevated temperatures, which are indicators of worn bearings, overstressed fan belts, and electric motor problems.

- Fabric filter interior (if feasible)--Condition of bags, i.e., tears, pinholes, and sagging (inadequate tension). A sagging or slack bag can result in the bag folding over the bottom thimble connection and creating a pocket in which accumulated dust can rapidly abrade and tear the fabric. Slackness also prevents effective cleaning action with both reverse-flow or mechanical shaking systems. Dust seepage or bleeding and/or pinhole leaks are evidenced by dust deposits on the clean side of the fabric. Staining and stiffening of the dirty fabric indicates excessive caking caused by moisture condensation or chemical reactions. The latter condition leads to fabric blinding and excessive pressure loss as well as to fabric failure. More than a 1/4-inch dust layer on floor plates or isolated piles of dust suggest excess seepage and/or torn or missing bags. Inspection of the inlet plenum, including bag interior, will reveal any excess dust buildup on bags and distribution plates. As a "rule-of-thumb" for smaller fabric filters, if the amount of dust on a bag after cleaning is more than twice the weight of a new (unused) bag, insufficient cleaning is indicated. The condition of solenoid valves, poppet valves, mechanical linkages, and bag clamps is also indicated.[4,7]

Table 4-1 summarizes the items that should be included as part of regular fabric filter inspections. Most major system components should be inspected routinely and any needed maintenance performed.

4.3.1 Routine Preventive Maintenance Inspections[4]

This section presents suggested procedures for performing routine preventive maintenance inspections of typical pulse-jet, reverse-air, and shaker type fabric filters.

Pulse-Jet Fabric Filters--

Evaluation of Plume Characteristics. An average opacity should be predetermined. Most pulse-jet collectors operate with less than 5 percent opacity, so values approaching 5 percent <u>may</u> suggest operating problems. If puffs are observed, the timing should be noted so that it is possible to identify the row being cleaned just before the puff.

Filtration System. The pressure drop across the collector should be noted. If there is a gauge, its proper operation should first be confirmed by observing meter response during the pulsing cycle. If the condition of the gauge or its connecting lines is questionable, one line at a time should be disconnected to identify any plugged or crimped lines (disconnecting lines may not be possible if a differential pressure transducer is connected to the gauge lines).

TABLE 4-1. GENERAL ITEMS INCLUDED IN ROUTINE FABRIC FILTER INSPECTIONS[4,6,8-12]

- Inspect filter media (bags, cartridge) for blinding, leakage, wear, slack, bag tension, loose bag clamps or thimbles, broken hooks, cages, or discoloration. (weekly)
- Inspect and maintain system instruments (pressure, opacity). (monthly)
- Inspect the overall collector and compartment housings, hooding, and connecting ductwork for leakage, corrosion, or dust accumulation. (semi-annually)
- Inspect all solenoid-operated pneumatic damper actuators, airlocks, and valves for proper seating, dust accumulation, leakage, synchronization, and operation. (weekly)
- Inspect hopper discharge for possible bridging of dust. (daily)
- Measure the pressure drop of the bag. Compare frequency of cleaning with that recommended by the manufacturer. (weekly)
- Inspect fan bolts (for tightness), bearings (for vibration), and temperature. Inspect for erosion or dust buildup in the housing and on the wheel. Check alignment of fan impeller with V-belt drive or coupling and driver. Check sheave for signs of V-belt wear. (semi-annually)
- Inspect all bearings on fans, motors, dampers, etc. for lubrication and free rotation. (monthly)
- Inspect foundation bolts on collector, motor, fan, etc. for tightness. Also inspect bolts on collector housing and structural members. (annually)
- Inspect access door(s) for leaks due to faulty gaskets or warping of door(s) and/or frame(s). (quarterly)

In the absence of a properly operating gauge, portable instruments should be used to measure the static pressure drop at isolated ports installed specifically for this purpose. It is important for measurements at the inlet and the outlet to be made separately so that plugged tap holes and lines can be identified.

Checking the operation of the cleaning system should include noting the air reservoir pressure. The ends of the reservoir and the connections to each of the diaphragm valves should be checked for air leakage. Because these valves are normally activated on a frequent basis, it is usually possible to observe a complete cleaning cycle. Each valve should generate a crisp thud when activated. Absence of this sound could indicate air leakage into the blow pipe (Figure 4-16). If too many of these valves are out of service, the air-to-cloth ratios are probably high, which can cause excessive emissions through the fabric filter or inadequate pollutant capture. Even if all diaphragm valves are working properly, reduced cleaning effectiveness can result from the low compressed-air pressures.

If the compressed-air pressures are too high, especially for units designed with a high air-to-cloth ratio, the intense cleaning action could result in some seepage of dust through the bag fabric when the bag is pushed into the support cage immediately after cleaning. This will cause a momentary puff of 5 to 10 percent opacity.

Holes and tears can lead to puffs or 5 to 30 percent opacity during the cleaning cycle. During the pulse, the material bridged over these areas is removed and the particulate matter is allowed to leak through (Figure 4-17). As soon as the pulse dissipates, material tends to bridge over the holes again and the area eventually heals. As the holes and tears increase in size, the duration of the puff also increases. Continuous emissions result when the holes and tears become too large to bridge over.

The discharge of solids from the filter hopper should be observed if this can be done safely and conveniently. Solids are usually discharged on a fairly continuous basis (following each pulsing of a row).

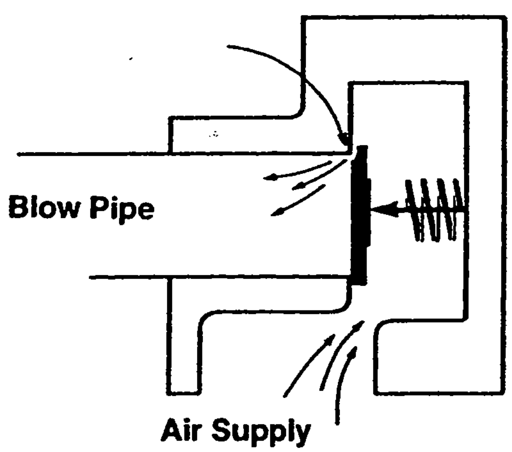


Figure 4-16. Cleaning valve problems (air inleakage into blow pipe). [Illustration reproduced from "The Maintenance of Exhaust Systems in the Hot Mix Plant (IS-52A)" published by the National Asphalt Pavement Association.][4]

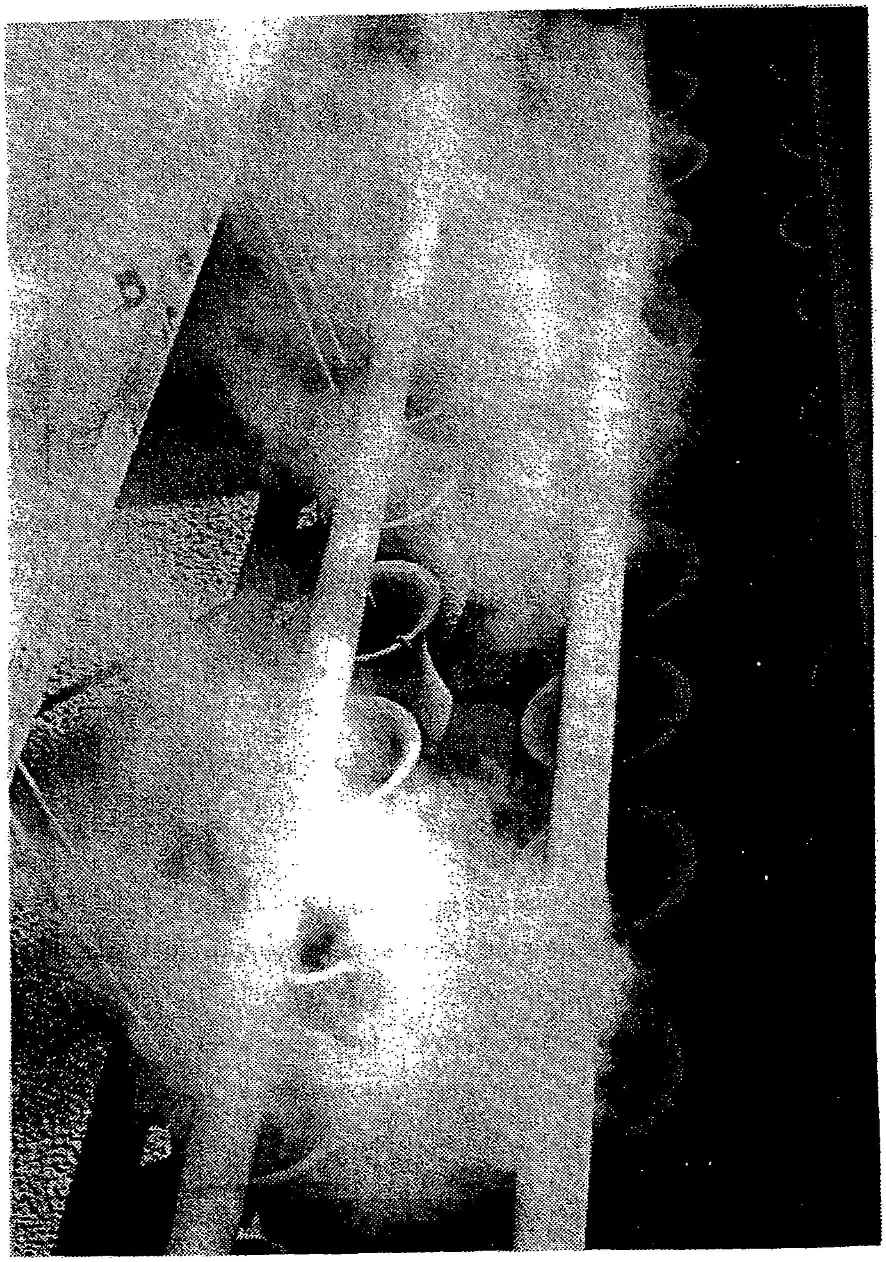


Figure 4-17. Pinhole leaks in bags can be determined by watching for emissions immediately after the cleaning pulse is fired, as shown in this photo. (PEI Associates, Inc.)[4]

Compressed-Air System. The compressed-air system should be inspected to determine whether it contains any water or rust deposits that could cause the system to malfunction. One quick method of checking whether the system has water or rust deposits is to open carefully the valve on the blowdown system and to observe whether any water or other material is being expelled through the valve. Also, if the system has oil traps, the traps can be visually inspected to determine if they are retaining any water or other material.

Reverse-Air and Shaker Fabric Filters--

Evaluation of Plume Characteristics. An average opacity should be predetermined. Most reverse-air and shaker collectors operate with less than 5 percent opacity. Values approaching this opacity may suggest operating problems. A drop in opacity when a specific compartment has been isolated for cleaning usually indicates holes or tears in bags in that compartment. Shaker collectors often have opacity spikes immediately following the cleaning cycle. Both conditions warrant further evaluation.

Filtration System. The pressure drop across the collector should be noted. If there is a gauge, its proper operation should first be confirmed. If the condition of the gauge or its connecting lines is questionable, one line at a time should be disconnected to identify any plugged or crimped lines (disconnecting lines may not be possible if a differential pressure transducer is connected to the gauge lines).

If a properly operating gauge is not available, the static pressure drop should be measured with portable instruments. These measurements should be made at isolated ports installed specifically for the use of portable instruments. It is important to make the measurements at the inlet and the outlet separately so that plugged tap holes and lines can be identified. Care must be exercised during the rodding of tap holes, because on some designs it is possible to poke a hole in the bag adjacent to the tap hole.

The pressure drop across each compartment should be determined during the cleaning cycle. In shaker collectors, the pressure drop should be zero during the cleaning of a compartment. Nonzero values indicate damper leakage problems. In reverse-air collectors, backflow will cause a measurable pressure drop with a polarity opposite that of the filtering cycle. If no gauge is available and the unit operates at an elevated gas temperature, the gas temperature should be measured. Measurement can be made at a point on the inlet duct to the collector or at one of the tap holes (if direct access to the interior of the collector is possible).

The rate of solids discharge also should be checked, if this can be done safely and conveniently. Solids are usually discharged only at the beginning of the cleaning cycle in each compartment.

Air leakage through access hatches, solids discharge valves, hopper flanges, and fan isolation sleeves should be checked by listening for the sound of inrushing air.

Table 4-2 lists recommended inspection items and provides a maintenance schedule for major fabric filter system components.

4.3.2 Daily Inspection and Maintenance

At least twice per 8-hour shift, stack opacity and system pressure drop should be checked. Sudden changes in these values, as well as those for gas temperature and volume flow, may indicate immediate problems.[4]

Daily checks of the fabric filter include pressure drop and opacity readings, the operation of dust removal and discharge system, system fan operation, and an external check of the baghouse structural integrity and bag-cleaning system. If continuous pressure drop and opacity recorders are used, patterns for these two key operating parameters can be developed. Other factors that can be checked on a daily basis are gas temperature and volume. Fan voltage and/or current monitoring can be used as an indicator of abnormal gas volume flow.[4]

Figures 4-18, 4-19, and 4-20 provide example daily inspection forms for shaker, reverse-air, and pulse-jet fabric filters, respectively. The plant employee performing the inspection should fill out these forms and note any problems identified. The completed form should be submitted to the plant's maintenance and engineering departments for recordkeeping. Upon receipt of the form, the maintenance department supervisor should sign it to acknowledge the maintenance activities noted on the form. Figure 4-21 is an

TABLE 4-2. TYPICAL MAINTENANCE INSPECTION SCHEDULE FOR A FABRIC FILTER SYSTEM[4,6,8-12]

Inspection Frequency	Component	Procedure
Daily	Stack Opacity Monitor or Human Observation	Check exhaust for visible emissions.
	Differential Pressure System/Manometer	Check and record fabric pressure loss and fan static pressure. Watch for trends. Check for clogging.
	Reverse-Air/Compressed-Air System	Check for air leakage (low pressure). Check valves.
	Gas Temperature and Volume	Check and record information.
	Collector	Observe all indicators on control panel and listen to system for properly operating subsystems. Check integrity of external structural. Check counterflow audible air infiltration into fan, baghouse (solids discharge valve, access doors, shell), and ductwork.
	Shaker Mechanism	Check for proper operation.
	Rotating Equipment and Drives	Check for signs of jamming, leakage, broken parts, wear, etc.
	System Fan	Check for bolt tension and wear, and lubrication.
	Dust-Removal System	Check to ensure that dust is being removed from the system.
Weekly	Filter Bags	Check for tears, holes, abrasion, proper fastening, bag tension, dust accumulation on surface or increases in folds.
	Damper Valves	Check all isolation, bypass, and cleaning damper valves for synchronization and proper operation. Lubricate as needed.
	Cell Plate	Clean surface, check for warping and leaks.
	Cleaning System	Check cleaning sequence and cycle times for proper valve and timer operation. Check compressed air lines, including oilers and filters. Inspect shaker mechanisms for proper operation. Inspect isolation dampers.

(continued)

Table 4-2. (continued)

Inspection Frequency	Component	Procedure
	Hoppers	Check for bridging or plugging. Inspect screw conveyor for proper operation and lubrication. Inspect compressed-air system for pneumatic units. Check discharge valves for proper function.
	Rotating Equipment and Drives	Lubricate.
	Opacity, Pressure, and Temperature Instruments	Clean and check for proper operation/calibrate.
Monthly	Shaker Mechanism	Inspect for loose bolts, integrity.
	Fan(s)	Check for corrosion and material buildup; check bearings and shaft for wear and V-belt drives and chains for tension and wear.
	Monitor(s)	Check accuracy and calibrate all indicating equipment.
Quarterly	Inlet Plenum	Check baffle plate for wear; if appreciable wear is evident, replace. Check for dust deposits. Check for clean-side dust deposits.
	Access Doors and Airlock	Check all gaskets for wear and proper alignment.
	Shaker Mechanism Tube type (tube hooks suspended from a tubular assembly)	Inspect nylon bushings in shaker bars and clevis (hanger) assembly for wear.
	Channel shakers (tube hooks suspended from a channel bar assembly)	Inspect drill bushings in tie bars, shaker bars, and connecting rods for wear.
Semiannually	Motors, Fans, etc.	Lubricate all electric motors, speed reducers, exhaust and reverse-air fans, and similar equipment.
Annually	Collector	Check all bolts and welds. Inspect entire collector thoroughly; clean and touch up paint where necessary.
	Filter Bags	Conduct ultraviolet light/fluorescent dye tests to check for bag and seal integrity.

DAILY FABRIC FILTER INSPECTION FORM	
Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (Print):
Fabric Filter ID:	Signature of Inspector:
INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS
1) Shaker Mechanism (external) - motor operating - proper sequence - signs of jamming, broken parts, leakage, wear, deterioration - appearance of bearings, belts, drive rod, shaft OK	
2) Check collector structure for external signs of wear, corrosion, cracked welds, loose belts	
3) Check all system motors and fans, and other rotating equipment and drives - signs of jamming, leakage, broken parts, wear, deterioration	
4) Check dust removal system - proper operation of discharge valve and dust conveying system	
5) Listen for hissing sounds indicating system air infiltration	
6) Check pressure gauges for clogging	
Stack Opacity Reading (Attached Method 9 observation sheet if applicable) _____%	
Gas Temperature inlet __________°F outlet __________°F	
Pressure drop __________ in. w.g.	

Figure 4-18. Example of daily inspection form for shaker fabric filter.

DAILY REVERSE-AIR FABRIC FILTER INSPECTION FORM	
Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (Print):
Fabric Filter ID:	Signature of Inspector:
INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS
1) Reverse air system - damper valves operational - indications of air leakage	
2) Check collector structure for external signs of wear, corrosion, cracked welds, loose belts	
3) Check all system motors and fans, and other rotating equipment and drives - signs of jamming, leakage, broken parts, wear, deterioration	
4) Check dust removal system - proper operation of discharge valve and dust conveying system	
5) Listen for hissing sounds indicating system air infiltration	
6) Check pressure gauges for clogging	
Stack Opacity Reading (Attached Method 9 observation sheet if applicable) _____%	
Gas Temperature inlet __________°F outlet __________°F	
Pressure drop __________ in. w.g.	

Figure 4-19. Example of daily inspection form for reverse-air fabric filter.

DAILY PULSE-JET FABRIC FILTER INSPECTION FORM	
Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (Print):
Fabric Filter ID:	Signature of Inspector:
INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS
1) Compressed air system - damper valves operational - indications of air leakage - air compressor operational	
2) Check collector structure for external signs of wear, corrosion, cracked welds, loose belts	
3) Check all system motors and fans, and other rotating equipment and drives - signs of jamming, leakage, broken parts, wear, deterioration	
4) Check dust removal system - proper operation of discharge valve and dust conveying system	
5) Listen for hissing sounds indicating system air infiltration	
6) Check pressure gauges for clogging	
Stack Opacity Reading (Attached Method 9 observation sheet if applicable) _____% Gas Temperature inlet __________°F outlet __________°F Pressure drop __________ in. w.g.	

Figure 4-20. Example of daily inspection form for pulse-jet fabric filter.

MAINTENANCE REPORT FORM

Department	Unit	System	Subsystem	Component	Subcomponent

Originator: ____________ Date: ________ Time: ________

Assigned To:

1	Mechanical
2	Electrical
3	Instrumentation

Priority:

1	Emergency
2	Same Day
3	Routine

Unit Status:

1	Normal
2	Derated
3	Down

Problem Description: ____________

Foreman: ____________ Date: ________

Job Status:

1	Repairable
	Hold for:
2	Tools
3	Parts
4	Outage

Cause of Problem: ____________

Work Done: ____________

Supervisor: ____________ Completion Date: ________

Materials Used: ____________

Labor Requirements: ____________

Figure 4-21. Example of maintenance report form.[4]

example of a maintenance report form that can be used to initiate and document the results of any maintenance activities.

4.3.3 Weekly Inspection and Maintenance

The extent of weekly inspection and maintenance depends on access to the equipment; i.e., the unit must be off-line. Lubrication of all rotating equipment, drives, and other moving parts should be scheduled at least weekly. Pressure-sensing lines and temperature probes should be cleaned, checked for proper operation, and calibrated (if necessary). Cell plates should be cleaned and inspected for warping and signs of leaks around the structure walls. Figures 4-22, 4-23, and 4-24 are example weekly inspection forms for shaker, reverse-air, and pulse-jet fabric filters, respectively. Figure 4-25 is an example filter bag identification form that can be used when performing internal inspections of the fabric filter system for bag problems. The plant employee performing the inspection should fill out these forms and note any problems identified. The completed form should be submitted to the plant's maintenance and engineering departments for recordkeeping. Upon receipt of the maintenance form (Figure 4-21), the maintenance department supervisor should sign it to acknowledge the maintenance activities noted on the form.

Shaker Fabric Filters--

The operation and tight seal of isolation dampers should be inspected. The shaker mechanism should be inspected for proper operation (e.g., unrestricted movement). The shaking intensity should be checked for uniformity throughout compartments. Filter bags should be checked for bag tension, fallen or torn bags, presence of any dust deposits on the clean side of the cell plate, holes, abrasion and bag-to-bag contact, proper bag fastening at both ends, and dust accumulation on bag surface or in bag creases and folds.[4]

Reverse-Air Fabric Filters--

The operation and tight seal of isolation and reverse-air dampers should be inspected. Filter bags should be checked for bag tension, fallen or torn bags, presence

WEEKLY SHAKER FABRIC FILTER INSPECTION FORM	
Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (Print):
Fabric Filter ID:	Signature of Inspector:
INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS
1) Check cell plate for warping, signs of leakage, or cracks.	
2) Dust Hopper - check for bridging or plugging - check operation of discharge valves - screw conveyor motor operating - pneumatic blower compressor/fan motor operating	
3) Check for operation of instrumentation - opacity (Yes/No) - pressure (Yes/No) - temperature (Yes/No)	
4) Check all isolation valves, bypass valves, and cleaning system valves for operability, seat tightness, and proper synchronization	
5) Cleaning system - check sequence and cycle times for proper valve and timer operation - check for unrestrictive movement of shaker system - check for uniform shaking intensity	
6) Filter bags (check and replace/adjust as needed) - bag tension - proper fastening to cell plate - fallen or torn bags - holes in bag - abrasion, bag-to-bag contact - dust accumulation in bag creases, folds, on surface (Attach bag location form)	
7) Lubricate all rotating equipment, drives, and other moving parts	
8) Lubricate damper valves	
Stack Opacity Reading (Attached Method 9 observation sheet if applicable) _____%	
Gas Temperature inlet _________°F	outlet _________°F
Pressure drop _________ in. w.g.	

Figure 4-22. Example of weekly inspection form for shaker fabric filter.

WEEKLY REVERSE-AIR FABRIC FILTER INSPECTION FORM	
Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (Print):
Fabric Filter ID:	Signature of Inspector:
INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS
1) Check cell plate for warping, signs of leakage, or cracks.	
2) Dust Hopper - check for bridging or plugging - check operation of discharge valves - screw conveyor motor operating - pneumatic blower compressor/fan motor operating	
3) Check for operation of instrumentation - opacity (Yes/No) - pressure (Yes/No) - temperature (Yes/No)	
4) Check all isolation valves, bypass valves, and cleaning system valves for operability, seat tightness, and proper synchronization	
5) Cleaning system - check sequence and cycle times for proper valve and timer operation - check for unrestrictive movement of shaker system - check for uniform shaking intensity	
6) Filter bags (check and replace/adjust as needed) - bag tension - proper fastening to cell plate - fallen or torn bags - holes in bag - abrasion, bag-to-bag contact - dust accumulation in bag creases, folds, on surface (Attach bag location form)	
7) Lubricate all rotating equipment, drives, and other moving parts	
8) Lubricate damper valves	

Stack Opacity Reading (Attached Method 9 observation sheet if applicable) _____%

Gas Temperature inlet __________°F outlet __________°F

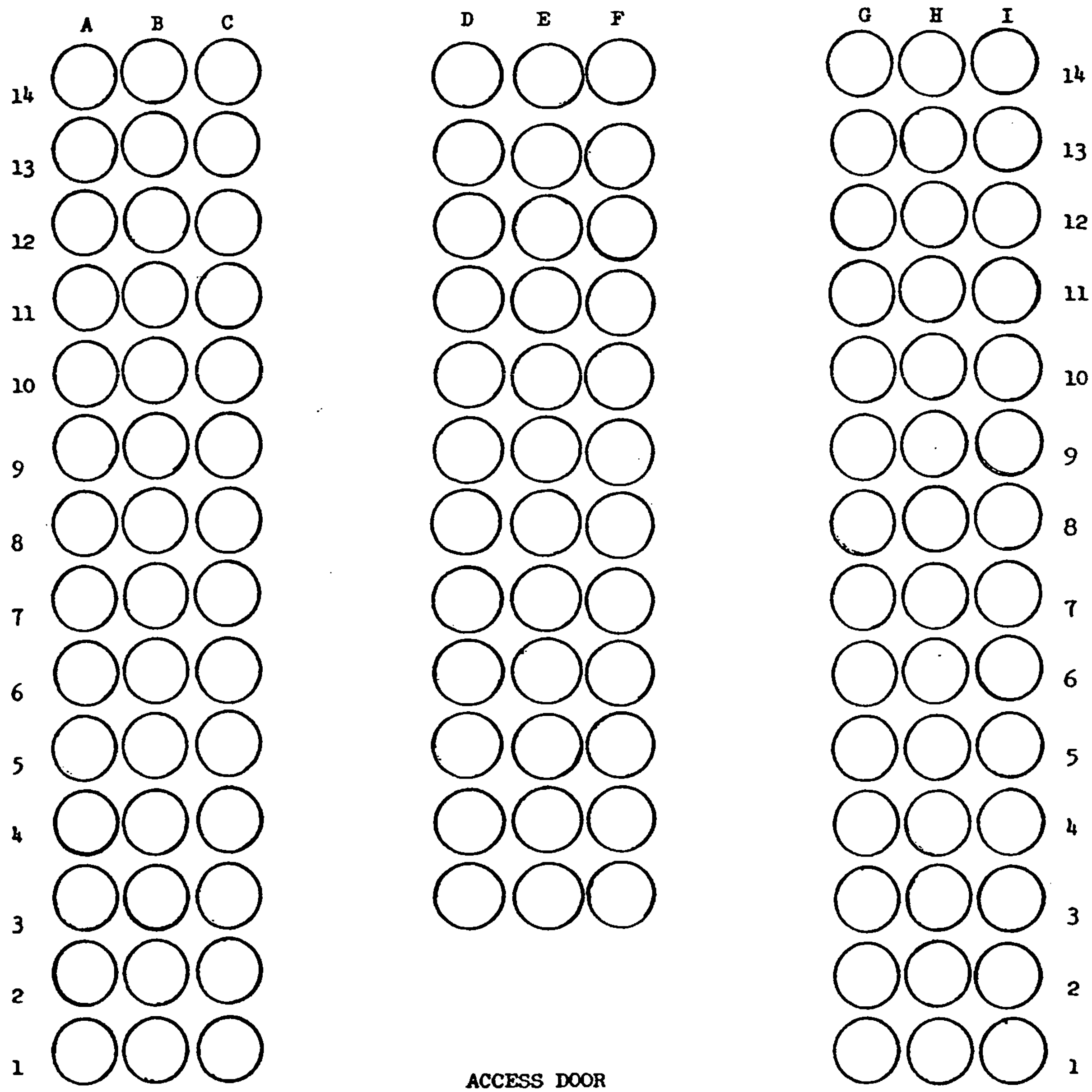
Pressure drop __________ in. w.g.

Figure 4-23. Example of weekly inspection form for reverse air fabric filter.

WEEKLY PULSE-JET FABRIC FILTER INSPECTION FORM	
Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (Print):
Fabric Filter ID:	Signature of Inspector:
INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS
1) Check cell plate for warping, signs of leakage, or cracks.	
2) Dust Hopper - check for bridging or plugging - check operation of discharge valves - screw conveyor motor operating - pneumatic blower compressor/fan motor operating	
3) Check for operation of instrumentation - opacity (Yes/No) - pressure (Yes/No) - temperature (Yes/No)	
4) Check all isolation valves, bypass valves, and cleaning system valves for operability, seat tightness, and proper synchronization	
5) Cleaning system - check sequence and cycle times for proper valve and timer operation - check for unrestrictive movement of shaker system - check for uniform shaking intensity	
6) Filter bags (check and replace/adjust as needed) - bag tension - proper fastening to cell plate - fallen or torn bags - holes in bag - abrasion, bag-to-bag contact - dust accumulation in bag creases, folds, on surface (Attach bag location form)	
7) Lubricate all rotating equipment, drives, and other moving parts	
8) Lubricate damper valves	
Stack Opacity Reading (Attached Method 9 observation sheet if applicable) _____%	
Gas Temperature inlet _________°F	outlet _________°F
Pressure drop _________ in. w.g.	

Figure 4-24. Example of weekly inspection form for pulse-jet fabric filter.

BAG FAILURE LOCATION RECORD



MODULE NO. ____________

DATE__________________

REPLACE - R
PATCH - P

CAP-OFF - C
RETENSION - T

Figure 4-25. Bag failure location record.

of any dust deposits on the clean side of the cell plate, holes, abrasion and bag-to-bag contact, proper bag fastening at both ends, and dust accumulation on bag surface or in bag creases and folds.[4]

Pulse-Jet Fabric Filters--

On the dirty side of the cell plate, filter bags should be inspected for a thin, uniform, exterior deposit of dust. Bags should be checked for abrasion or wear from bag-to-bag contact and for proper bag fastening at both ends. On the clean side of the cell plate, each row of bags should be checked for leakage or holes, the presence of which is indicated by dust deposits on the underside of the compressed-air blowpipes or on the cell plate itself. The cleaning system should be activated (the inspector should use hearing protection). The blowpipes should remain secure during operation, and each row of bags should fire at the same time. Misaligned blowpipes should be adjusted to prevent damage to the upper part of the bags. The compressed air system should be checked for leaks and evidence of oil or water entrainment. Moisture or oil accumulation should be drained from the system.[4]

4.3.4 Long-Term Inspection and Maintenance

Long-term inspection and maintenance procedures (i.e., frequence of application is less than weekly) are likely to be more equipment-specific than common daily and weekly inspection procedures.[4] Long-term procedures generally involve overall integrity checks of major system components. Examples of equipment that can be checked monthly, quarterly, semiannually, and annually were shown earlier in Table 4-2. Long-term inspection forms for fabric filters should be process and fabric filter specific. They can be developed, on a site specific basis, using the format of the daily and weekly inspection forms.

4.4 Equipment Problems and Corrective Measures

4.4.1 Common Equipment Malfunctions[13]

Common Malfunctions--

Regardless of the cleaning mechanism involved, most fabric filter maintenance focuses on the bags and moving mechanical parts, especially parts on the dirty side of the filters. High-maintenance items also vary according to the application. Commonly observed malfunctions are discussed here.

The highest-maintenance item in fabric filter systems is the bag. The most common problems are tears or pinholes, blinding (cake buildup), and bleeding (seepage). These problems can be diagnosed and subsequently minimized with frequent inspections and preventive maintenance. These actions, however, will not eliminate bag failure. Variations in fabric quality, sewing techniques, quality control, and gas flow distribution within the system also contribute to bag failure. During the first several months of operation, a small number of bag failures may result from manufacturing or installation defects. Under normal operating conditions, however, a sudden increase in frequency of failure indicates that the bags have reached or are nearing the end of their operating life.

Visible stack emissions usually indicate bag failure. Where a stack monitor is used, increases in opacity readings are further indicators. In either case, three methods can be used to identify leaking bags: 1) inspection of bags for holes, 2) elimination of bags with excessive dust accumulation, and 3) use of a bag leak detection device.

Valves used to isolate individual bag chambers in a shaker type fabric filter often experience sealing problems. A slight flow and pressurization in the isolated compartment are indicative of a poor bag seal. This condition can be determined by observing the shaking process and noting whether the bags are inflated.

4.4.2 Diagnostic Equipment Inspections[4]

This subsection presents a suggested procedure for performing diagnostic inspections of typical pulse-jet, reverse-air, and shaker type fabric filters when certain problems arise.

Pulse-Jet Systems

High Opacity (continuous or puffs). On top-load type designs, the clean side of several compartments should be checked, provided they can be safely isolated and no pollutant capture problems will occur at the source origin. Even slight dust deposits can be a sign of major problems. Most of the dust in the clean-side plenum is reentrained as a result of the relatively high gas velocities. Dust near one or more of the bag outlets may suggest inadequate sealing on the cell plate. Bag holes or tears may disperse dust throughout the top side of the cell plate and make it difficult to identify the bag with the hole. Fluorescent dye tests may be used later to identify the problem.

High Pressure Drop, High Opacity, or Process Fugitive Emissions. In a top-access system, the possibility of fabric blinding can be checked from the top access hatch. Oil and water in the compressed air line are sometimes partially responsible for the blinding that removes part of the fabric area from service.

In conventional pulse-jet collectors, the possibility for blinding can only be checked at the dirty-side access hatch. The photograph in Figure 4-26 shows easily removable dust. A crusty cake is sometimes evidence of excessive moisture or sticky deposits on the bags.

Continuously High Opacity, Frequent Bag Failures (primarily at bottom). Premature bag failure at the bottom can occur in both types of pulse-jet collectors if the support cages are slightly warped and the bags rub at the bottom. This can be checked from a dirty-side access hatch, or sometimes from below (as shown in Figure 4-27). <u>Only the operator (using extreme caution) should open the hatches at the tops of hopper areas, as hot solids can flow rapidly out of these hatches.</u>

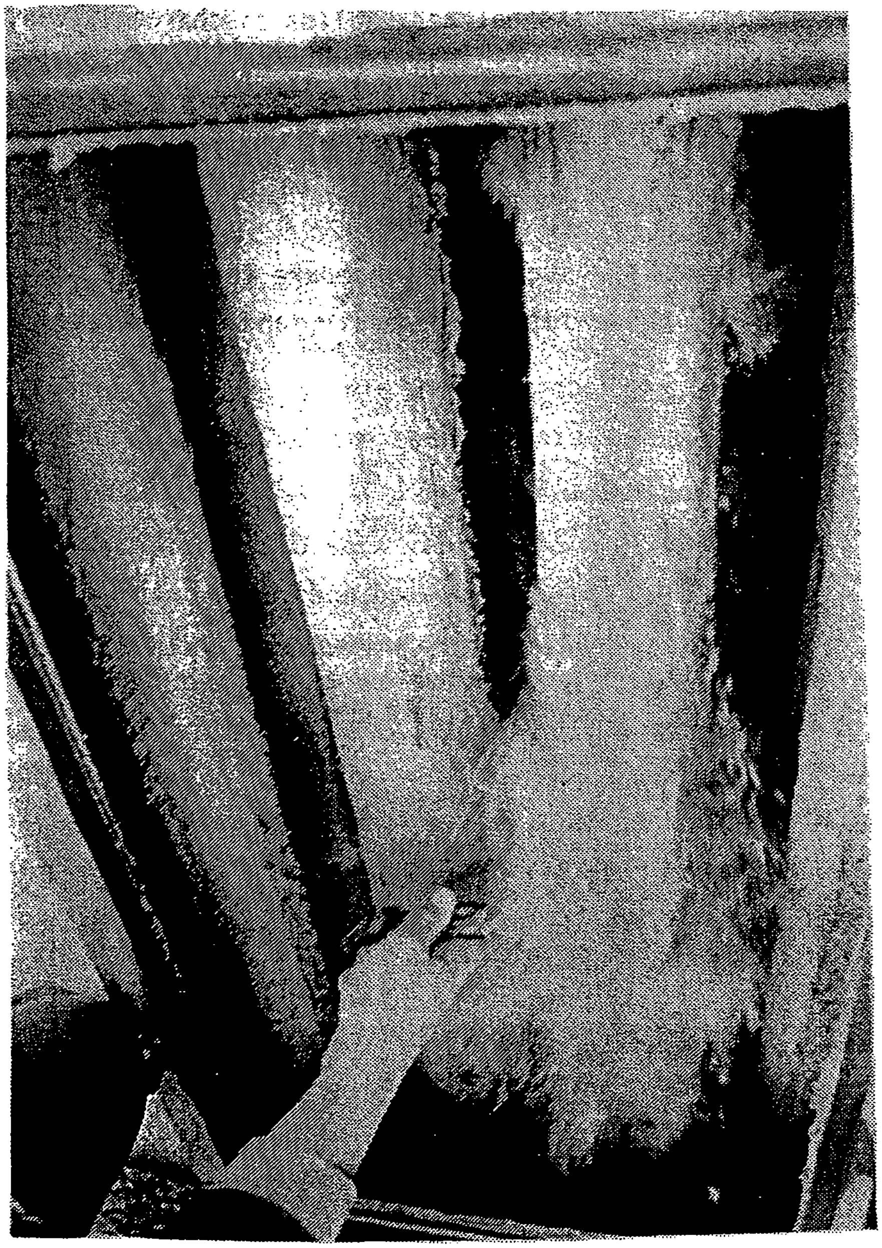


Figure 4-26. Knocking dust off bags to see how easily removable it is (In this case, the material was dry and easily removable, but the cleaning mechanism was not working.)[4]

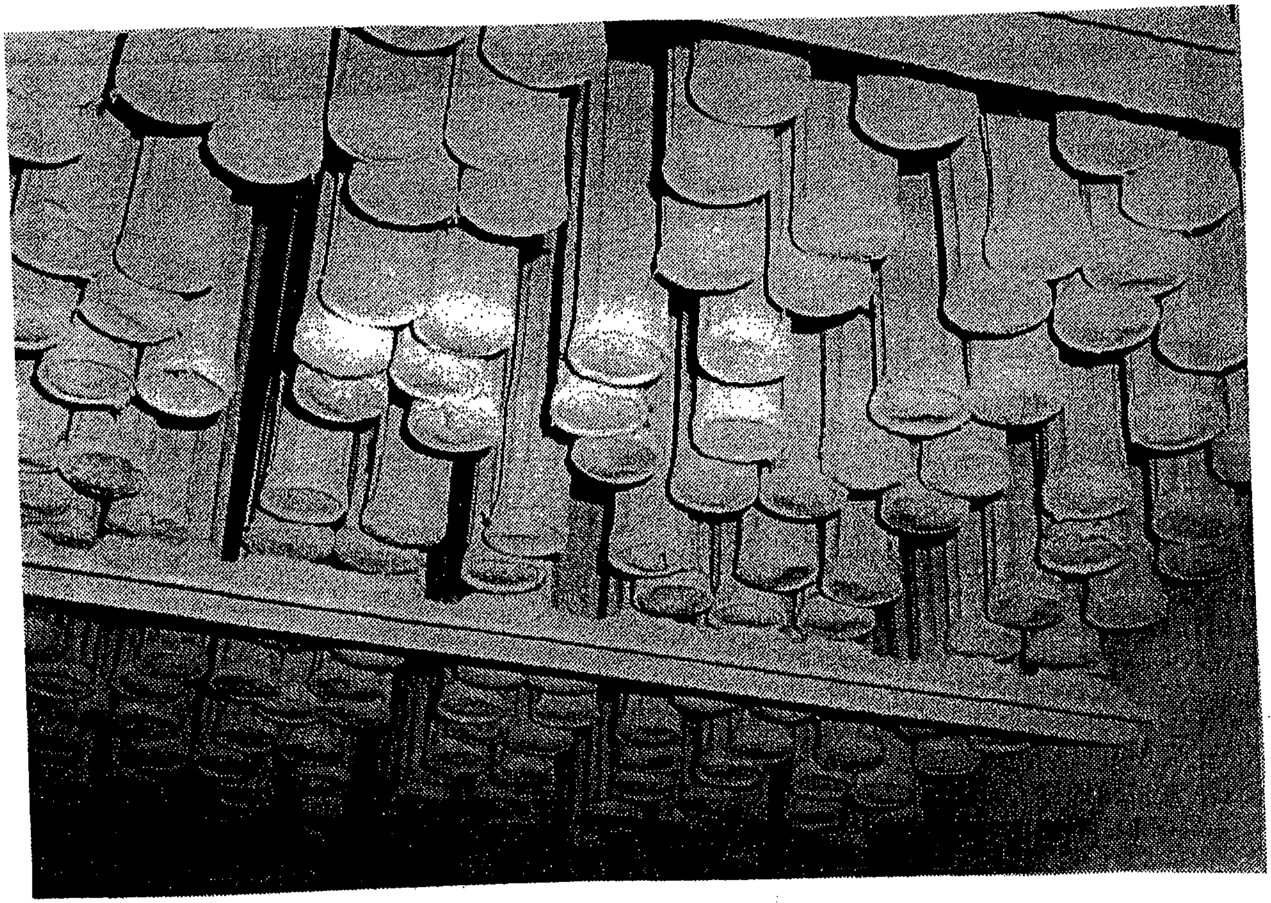


Figure 4-27. Bag-to-bag contact in a pulse-jet fabric filter resulting from poor alignment of cages during installation.[4]

The bag failure charts for the fabric filter should be examined. A distinct spatial pattern may indicate the damage due to abrasion (inlet gas blasting, inlet swirling, or rubbing against internal supports). The date of the bag removal and the elevation of the apparent damage (T-top, M-middle, B-bottom) helps to identify many common modes of failure. By using such charts, operators have been able to minimize both excess emission incidents and bag replacement costs. A rapid increase in the rate of failure often suggests significant deterioration of fabric strength due to chemical attack or high temperature excursions.

When bags are removed from service, a simple rip test should be performed. If the cloth can be ripped by inserting a screw driver and pulling, the bag damage probably resulted from chemical attack, high temperature excursions, moisture attack, or routine fabric exhaustion. Most fabrics damaged by abrasion-related problems cannot be ripped even near the site of the damage.

High Opacity and Distinct Pattern to Bag Holes and Tears. Bag and cage assemblies should be carefully inspected on removal. Often the point of bag failure is next to a sharp point on the support cage. Premature failure may also be caused by cages that do not provide enough support for the fabric.

If all the bags have failed at the top, the compressed-air nozzles may be misaligned (see Figure 4-28). This can cause the pulse to be directed at a narrow area in the top of the bag.

Reverse-Air and Shaker Type Fabric Filters--

Suspected Air Leakage, Low Gas Temperature, or Low Pressure Drop. The O_2 and CO_2 levels at the inlet and outlet of combustion source fabric filters should be checked. The measurement point on the inlet must be between the solids discharge valve and the tube sheet, so that potential inleakage at this point can also be taken into account. There should not be more than a 1 percent rise in the O_2 levels going from the inlet to the outlet (e.g., 6% O_2 in and 7% O_2 out).

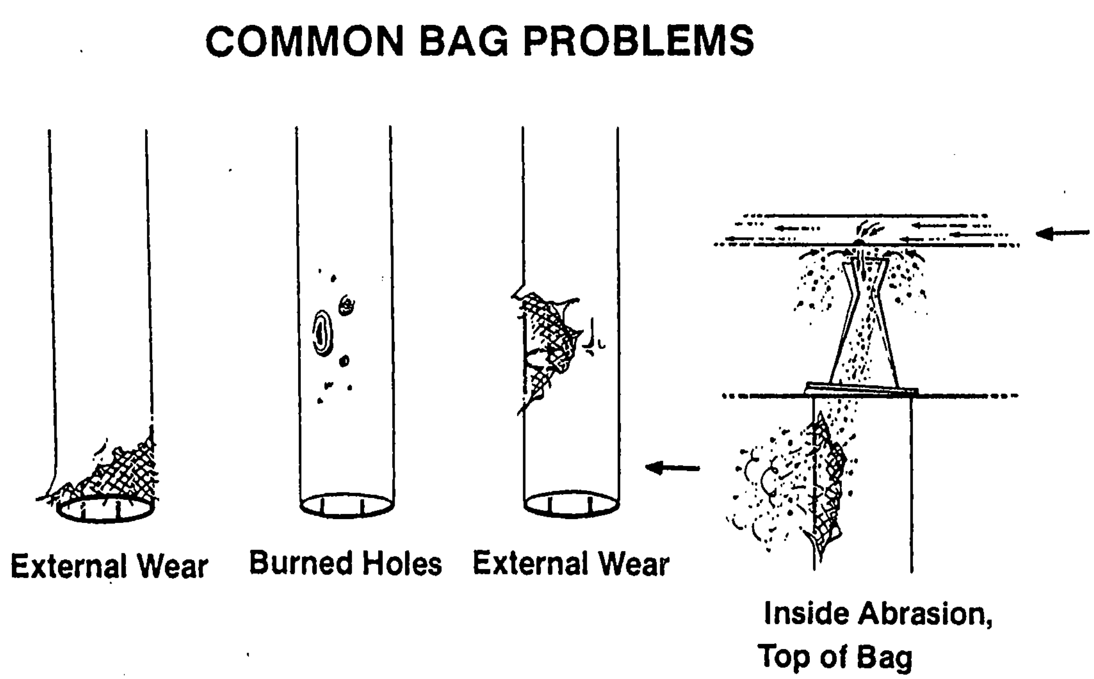


Figure 4-28. Common bag problems with pulse-jet fabric filters, including abrasion at the top of the bags caused by misalignment of compressed air nozzles (National Asphalt Pavement Association).[4]

Continuously High Opacity (During Most of Operating Period) or Pressure Drop Much Greater or Lower than Baseline. The presence and nature of the clean-side deposits should be checked by viewing conditions from the access hatch. Note that the operator must isolate the compartment before attempting to do the internal inspection. All safety procedures must be carefully followed prior to entry.

The presence of snap-ring leakage is often indicated by enlarged craters in the clean-side deposits around the poorly sealed bags. Holes and tears can sometimes be located by the shape of dust deposits next to the holes (see Figure 4-29). Poor bag tension is readily apparent from the access hatch. Improper discharge of material from the bags can often be confirmed by noting that the bags close to the hatch are full of material one or more bag diameters up from the bottom (see Figure 4-30). Deposits on the bags should also be noted.

Anything more than a trace of material on the clean-side tube sheet indicates that emissions from this compartment are probably substantially above the baseline levels.

If the bag failure charts show a distinct spatial pattern, the damage may be due to abrasion (inlet gas blasting, inlet swirling, and/or rubbing against internal supports). Including the date of the bag removal and the elevation of the apparent damage (T-top, M-middle, B-bottom) makes it possible to identify many common modes of failure. Using such charts, operators have been able to minimize both excess emission incidents and bag replacement costs. A rapid increase in the rate of failure often suggests significant deterioration of fabric strength. A simple rip test should be preformed on a bag recently removed from service. If the cloth can be ripped by inserting a screw driver and pulling, the bag damage probably resulted from chemical attack, high temperature excursions, moisture attack, or routine fabric exhaustion. Most fabrics damaged by abrasion-related problems cannot be ripped even near the site of the damage.

The compressed-air system should be inspected for proper installation and to ensure that it has the aftercoolers, automatic condensate traps, and filters for proper operation.[6] The inspector also should determine whether any water or rust deposits are in the compressed-air system that could cause the system to malfunction. One quick method for checking the presence of water or rust deposits is to open the valve on the

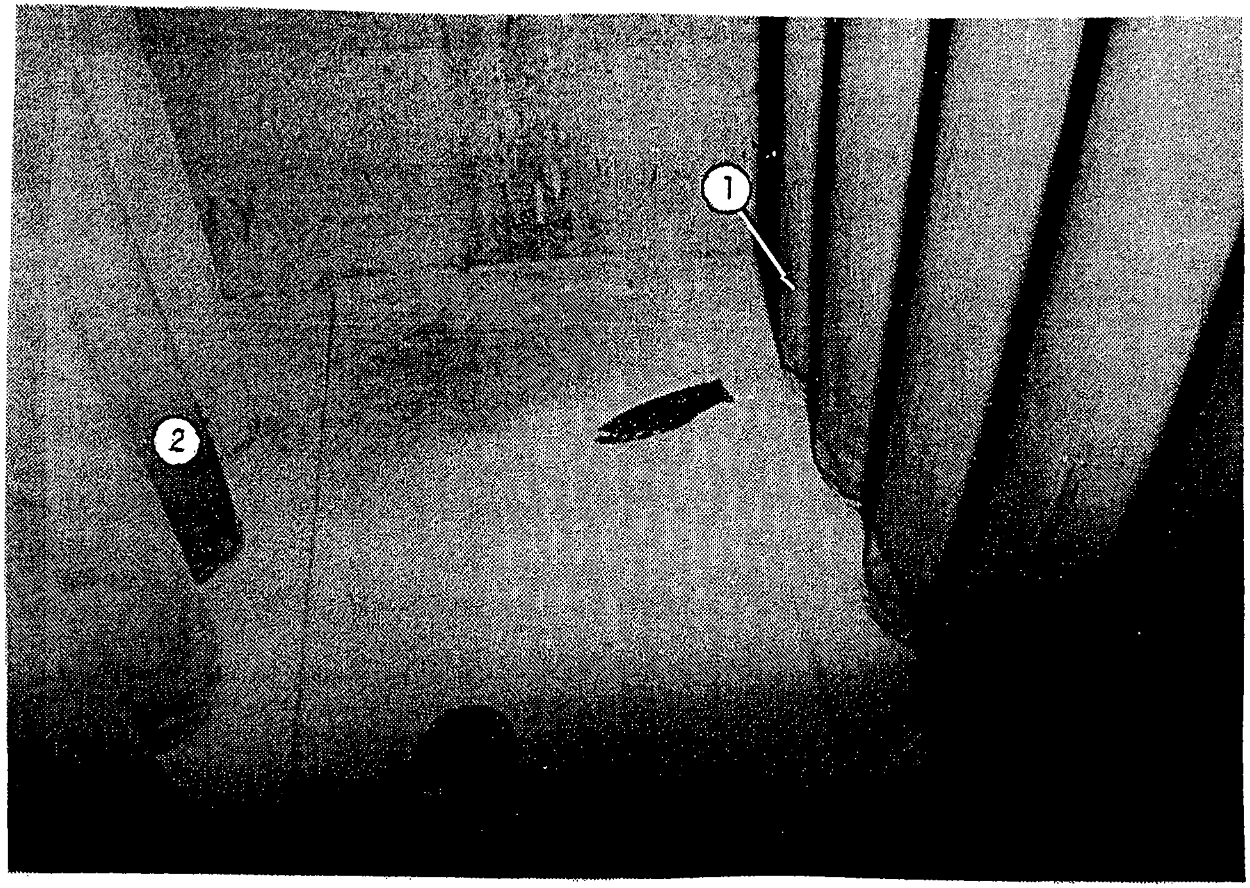


Figure 4-29. Pinhole leak (1) forms a dust jet on the floor near a shaker-type filter. [Note that the darkened bag (2) is being abraded by dust from the pinhole leak and it too will ultimately fail.]
PEI Associates, Inc.[4]

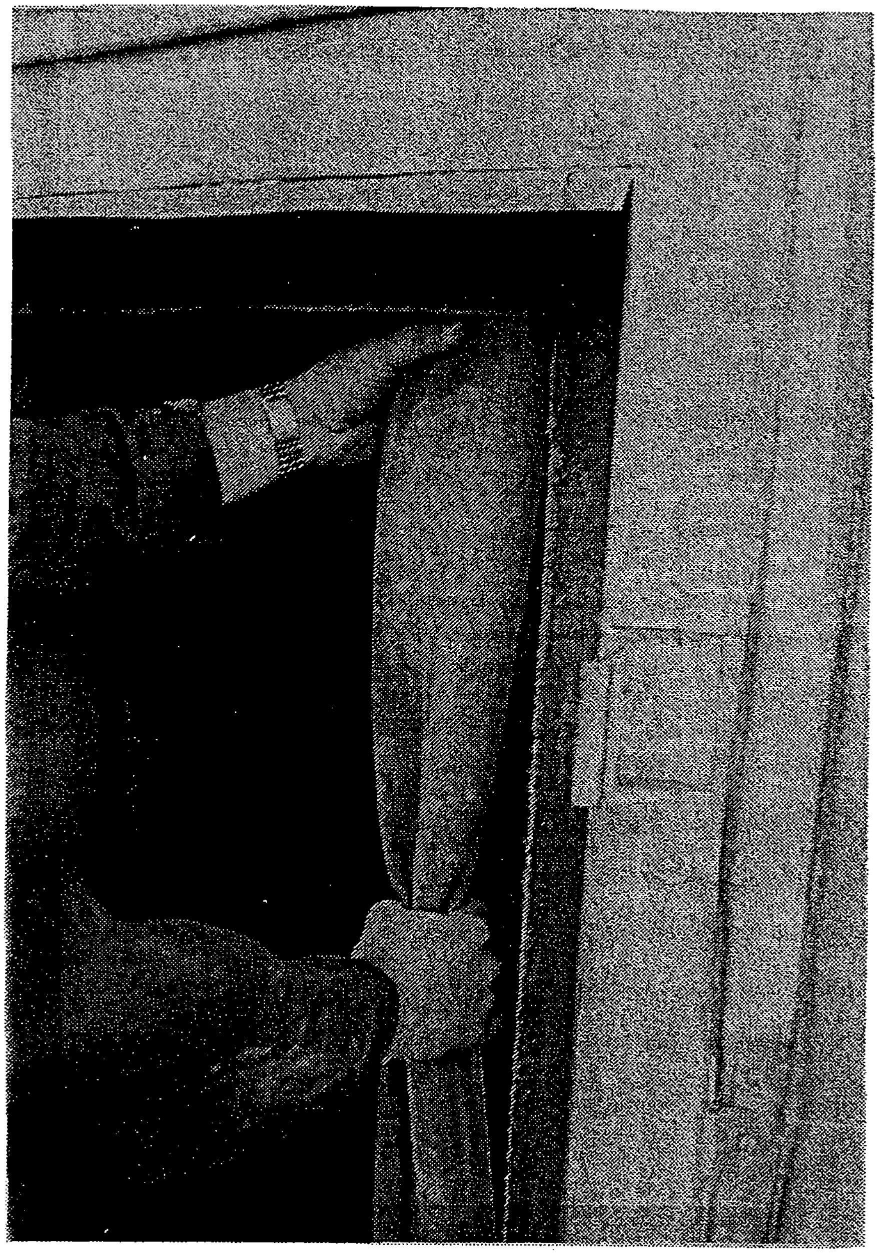


Figure 4-30. Checking for excessive build-up and poorly tensioned bags in a reverse-air fabric filter. This bag passed both tests. (PEI Associates, Inc.)[4]

blowdown system carefully and note whether any water or other material is being expelled through the valve. If the system has oil traps, the traps also can be visually inspected to determine if they are retaining any water or other material.

4.4.3 Corrective Measures and Troubleshooting

Table 4-3 lists the procedures for troubleshooting and correcting common baghouse problems.

Fabric filter equipment suppliers generally specify an inventory of spare parts and replacement equipment when installing a new system. A facility should contact its supplier for a list of specific recommended equipment. The most important item to maintain in inventory stock is a full set of replacement bags. Table 4-4 presents a typical inventory of replacement parts that should be kept on site in the absence of a manufacturer's specific recommendations.

4.5 Operator Training

As for any piece of equipment, proper maintenance of a fabric filter depends on the support of facility management and its willingness to provide its employees with the proper training. Efficient operation of a fabric filter, promoted by adequate inspection and maintenance procedures, is as important as the productive operation of any piece of process equipment. Management and employees must take a proactive approach to its operation to prevent production-stopping equipment malfunctions or failures.

The training and motivation of employees assigned to monitor and maintain a fabric filter are critical factors. These duties should not be assigned to inexperienced personnel that do not understand how a fabric filter works or the purpose behind assigned maintenance tasks.

When a new system is commissioned, training should be provided by the fabric filter manufacturer. The manufacturer's startup services will generally include introductory training for facility operators and maintenance personnel. The field service engineer involved in startup procedures will instruct plant personnel in methods that will ensure proper assembly and operation of the system components, will check and reset system

TABLE 4-3. FABRIC FILTER TROUBLESHOOTING AND DIAGNOSTIC GUIDE 13

The following chart lists the most common problems found in a fabric filter air pollution control system and offers general solutions. In some instances, the solution is to consult the manufacturer. This may not be necessary in plants that have sufficient engineering know-how available.

When the information applies to a specific type of fabric filter, the following code is used:

JP....................Jet-pulse
S.....................Shaker
RA....................Reverse-air

Symptom	Cause	Remedy
High system pressure drop	System undersized	Consult manufacturer. Install double bags. Add more compartments or modules.
	Bag cleaning mechanism not adjusted properly	Increase cleaning frequency. Clean for longer duration. Clean more vigorously (must check with manufacturer before implementing).
	Compressed-air pressure too low (JP)	Increase pressure. Decrease duration and/or frequency. Check air dryer, and clean if necessary. Check for obstruction in piping.
	Repressuring pressure too low (RA)	Speed up repressuring fan. Check for leaks. Check damper valve seals.
	Shaking not vigorous (S)	Increase shaker speed (check with manufacturer).
	Isolation damper valves not closing (S, RA, JP)	Check linkage. Check seals. Check air supply of pneumatic operations.

(continued)

Table 4-3. (continued)

Symptom	Cause	Remedy
	Isolation damper valves not opening (S, RA, JP)	Check linkage. Check air supply on pneumatic operations.
	Bag tension too loose (S, RA)	Tighten bags.
	Pulsing valves failed (JP)	Check diaphragm valves. Check solenoid valves.
	Air volume greater than design	Damper system to design point. Install fan amperage controls.
	Cleaning timer failure	Check to see of timer is indexing to all contacts. Check output on all terminals.
	Not capable of removing dust from bags	Check for condensation on bags. Send sample of dust to manufacturer. Send bag to lab for analysis for blinding. Dryclean or replace bags. Reduce air flow.
	Excessive reentrainment of dust	Continuously empty hopper. Clean rows of bags randomly instead of sequentially (JP).
	Incorrect pressure reading	Clean out pressure taps. Check hoses for leaks. Check for proper fluid in manometer. Check diaphragm in gauge.
Low fan motor amperage/low air volume	High baghouse pressure	See "high system pressure drop."
	Fan and motor sheaves reversed	Check drawings and reverse sheaves.
	Ducts plugged with dust	Clean out ducts and check duct velocities.
	Fan damper closed	Open damper and lock in position.
	System static pressure too high	Measure static on both sides and compare with design pressure.

(continued)

Table 4-3. (continued)

Symptom	Cause	Remedy
	Fan not operating per design	Check fan inlet configuration and be sure even airflow exists .
	Belts slipping	Check tension and adjust.
Dust escaping at source	Low air volume	See above causes and remedies under "low-fan motor amperage/low air volume."
	Ducts leaking	Patch leaks so air does not bypass source.
	Improper duct flow balancing	Adjust blast gates in branch ducts.
	Improper hood design	Close open areas around dust source. Check for cross drafts that overcome suction. Check for dust being thrown away from hood by belt, etc.
Dirty discharge at stack	Bags leaking	Replace bags. Tie off bags and replace at a late date. Isolate leaking compartment if possible without upsetting system.
	Bag clamps not sealing	Check and tighten clamps. Smooth out cloth under clamp and reclamp.
	Failure of seals in joints at clean/dirty air connection	Caulk and tighten clamps. Smooth out cloth under clamp and reclamp.
	Insufficient filter cake	Allow more dust to build up on bags by cleaning less frequently. Use a precoating of dust on bags (S, RA).
	Bags too porous	Send bag in for permeability test and review with manufacturer.
Excessive fan wear	Fan handling too much dust	Check bags.

(continued)

Table 4-3. (continued)

Symptom	Cause	Remedy
Excessive fan vibration	Improper fan	Check with fan manufacturer to see if fan is correct for application.
	Fan speed too high	Check with manufacturer.
	Buildup of dust on blades	Clean off and check to see if fan is handling too much dust. Do not allow any water in fan (check drain, look for condensation, etc.).
	Wrong fan wheel for application	Check with manufacturer.
	Sheaves not balanced	Have sheaves dynamically balanced.
	Bearings worn	Replace bearings.
High compressed air consumption (JP)	Cleaning cycle too frequent	Reduce cleaning cycle if possible.
	Pulse too long	Reduce duration. (After initial shock all other compressed air is wasted.)
	Pressure too high	Reduce supply pressure if possible.
	Damper valves not sealing	Check linkage. Check seals.
	Diaphragm valve failure	Check diaphragms and springs. Check solenoid valve.
Reduced compressed-air pressure (JP)	Compressed air consumption too high	Reduce supply pressure if possible.
	Restrictions in piping	Check piping.
	Dryer plugged	Replace desiccant or bypass dryer if allowed.
	Supply line too small	Consult design.
	Compressor worn	Replace rings.
Premature bag failure: decomposition	Bag material improper for chemical composition of gas or dust	Analyze gas and dust and check with manufacturer. Treat gas stream with neutralizer before it enters the system.

(continued)

Table 4-3. (continued)

Symptom	Cause	Remedy
	Operating below acid dew point	Increase gas temperature. Bypass upon startup.
Moisture in system	System not purged after shutdown	Keep fan running for 5 to 10 minutes after process is shut down.
	Wall temperature below dew point	Raise gas temperature. Insulate unit. Lower dew point by keeping moisture out of system.
	Cold spots at structural members	Fully insulate structural members.
	Compressed air introducing water (JP)	Check automatic drains . Install aftercooler. Install dryer.
	Repressuring air causing condensation (RA, JP)	Preheat repressuring air. Use process gas as a source of repressuring air.
High screw conveyor wear	Screw conveyor under-sized	Measure hourly collection of dust and consult manufacturer.
	Conveyor speed too high	Slow down speed.
High air-lock wear	Air lock undersized	Measure hourly collection of dust and consult manufacturer.
	Thermal expansion	Consult manufacturer to see if design allowed for thermal expansion.
	Speed too high	Slow the speed down.
Material bridging in hopper	Moisture in baghouse	Check moisture dew point of exhaust gas. Add hopper heaters.
	Dust being stored in hopper	Remove dust continuously.
	Hopper slope insufficient	Rework or replace hoppers.
	Conveyor opening too small	Use a wide-flared trough.
Frequent screw conveyor/airlock failure	Equipment undersized	Consult manufacturer.
	Screw conveyor misaligned	Align conveyor.

(continued)

Table 4-3. (continued)

Symptom	Cause	Remedy
	Overloading components	Check sizing to see that each component is capable of handling a 100% delivery from the previous component.
High pneumatic conveyor wear	Pneumatic blower too fast	Slow down blower.
	Piping undersized	Review design and slow down blower or increase pipe size.
	Elbow radius too short	Replace with long radius elbows.
Pneumatic conveyor pipes plugging	Overloading pneumatic conveyor	Review design.
	Slug loading of dust	Check tackiness of dust.
	Moisture in dust	Check gas stream dew point.
Fan motor overloading	Air volume too high	Check ducts and structure for leaks.
	Motor not sized for cold start	Damper fan at startup. Reduce fan speed. Provide heat faster. Replace motor.
Air volume too high	Ducts leaking	Patch leaks.
	Insufficient static pressure	Close damper valve. Slow down fan.
Reduced compressed air consumption (RP, PP)	Pulsing valves not working	Check diaphragms. Check springs. Check solenoid valves.
	Timer failed	Check terminal outputs.
High bag failure: wearing out	Baffle plate worn out	Replace baffle plate.
	Too much dust	Install primary collector.
	Cleaning cycle too frequent	Slow down cleaning.
	Inlet air not properly baffled from bags	Consult manufacturer.
	Shaking too violent (S)	Slow down shaking mechanism (consult manufacturer).
	Repressuring pressure too high (RA)	Reduce pressure.

(continued)

Table 4-3. (continued)

Symptom	Cause	Remedy
	Pulsing pressure too high (JP)	Reduce pressure.
	Cages have barbs (JP)	Remove and smooth out barbs.
High bag failure: burning	Stratification of hot and cold gases	Force turbulence in duct with baffles.
	Sparks entering baghouse	Install spark arrestor.
	Thermocouple failed	Replace and determine cause of failure.
	Failure of cooling device	Review design and work with manufacturer.

TABLE 4-4. TYPICAL INVENTORY OF REPLACEMENT PARTS FOR FABRIC FILTERS[13]

Bags (complete set of replacement) and accessories: clamps, nuts, bolts, hangers

Bag retainers (pulse-jet)

Cleaning mechanism

- Shaker: bearings, hangers, crankshaft, connecting rod, motor belts
- Pulse-jet: venturis, solenoid and diaphragm valves, tubing

Timing mechanism

Screw conveyor: belts, hanger bearings, coupling bolts

Airlocks: bearing and seals

Pneumatic system components (see manufacturer's recommendations)

Damper valves: solenoids, seals, cylinders

Magnehelic gauges

Gasketing, caulking, lubricants, special tools

Electrical switches, relays, fuses

instrumentation and controls, will check for the proper operation of the dust discharging system, and will perform simple troubleshooting.

Following startup training, regular training courses should be held by in-house personnel or through the use of outside expertise. The set of manuals typically delivered as part of a new fabric filter installation will include manufacturer-recommended maintenance procedures. At a minimum, annual in-house training should include a review of these documents and confirmation of the original operating parameters. Training should include written instructions and practical experience sessions on safety, inspection procedures, system monitoring equipment and procedures, routine maintenanceprocedures, and recordkeeping. For plant personnel involved in taking fabric filter opacity readings, U.S. EPA Reference Method 9 requires a semiannual recertification in method procedures.

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SECTION 5.0

ELECTROSTATIC PRECIPITATORS

Electrostatic precipitators (ESPs) are widely used for controlling particulate emissions from boilers and industrial process sources. To ensure continued operation of the ESPs at the maximum emission control efficiency levels, source specific routine and preventive O&M measures must be identified and implemented. This section provides O&M guidelines for ESPs. A brief description of different types of ESPs is followed by identification of key operating parameters that impact the operation of ESPs. Major operating problems and malfunctions are discussed followed by routine maintenance needs and procedures. Recommendations for operator training and frequency are included.

The information presented in this section has been extracted from the published reports and references presented at the end of this section. These sources also contain additional information regarding operation and maintenance of ESPs.

5.1 Description

5.1.1 Theory of Operation and ESP Types

An electrostatic precipitator uses electrical forces to capture particles in an incoming gas. The particles are given an electrical charge by forcing them to pass through a corona, a region in which gaseous ions flow. The electrical field that forces the charged particles to the walls comes from electrodes maintained at high voltage in the center of the flow path. Figure 5-1 illustrates the basic processes involved in electrostatic precipitation.

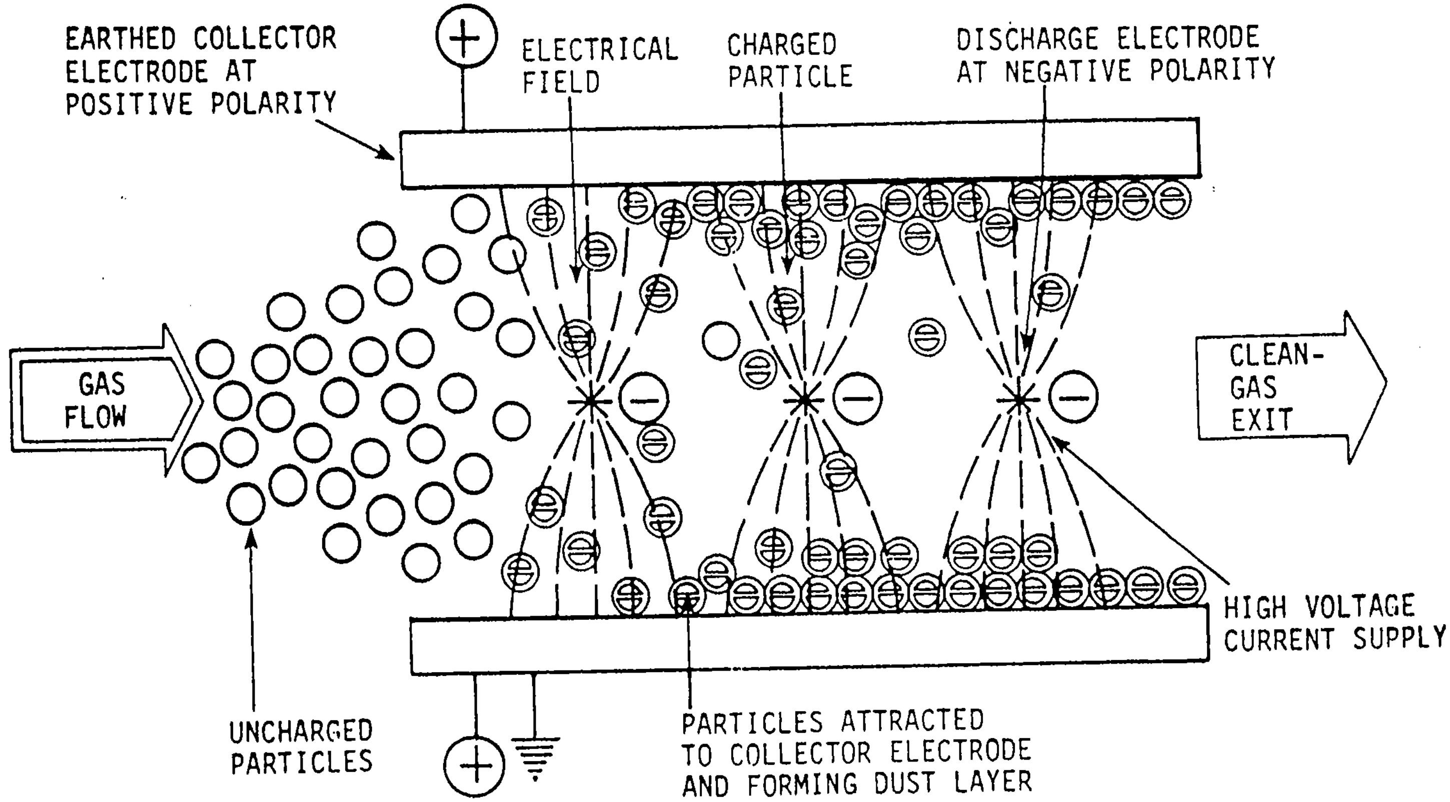

Figure 5-1. Basic processes involved in electrostatic precipitation (Lodge Cottrell)

In a full size ESP, several auxiliaries and support systems are required to effectively implement the electrostatic precipitation principle. Electrical equipment for producing high-voltage supply is necessary for the ESP. A high-voltage transformer (to step up the line voltage) and a rectifier (to convert AC voltage to DC) provide the power necessary for the precipitation process.

The particulate matter collected on the collection plates must be removed by use of a rapping mechanism (or water flushing in case of a wet ESP). The particulate-laden gas stream must travel through the ESP unit at acceptable velocities for effective collection of particulate matter and a fan and ductwork system must be designed and configured to ensure a steady flow of gas through the system.

Figure 5-2 shows an ESP and its main components.

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

5.1.2 ESP Types

Various types of ESP designs are used for a wide range of particulate application. The primary ESP types used in industrial emission control applications are:

- Plate-wire precipitator
- Flat-plate precipitator
- Tubular precipitator, and
- Wet precipitator

Plate-Wire Precipitator--

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

The plate-wire ESP allows many flow lanes to operate in parallel, and each lane can be quite tall. As a result, this type of precipitator is well-suited for handling large

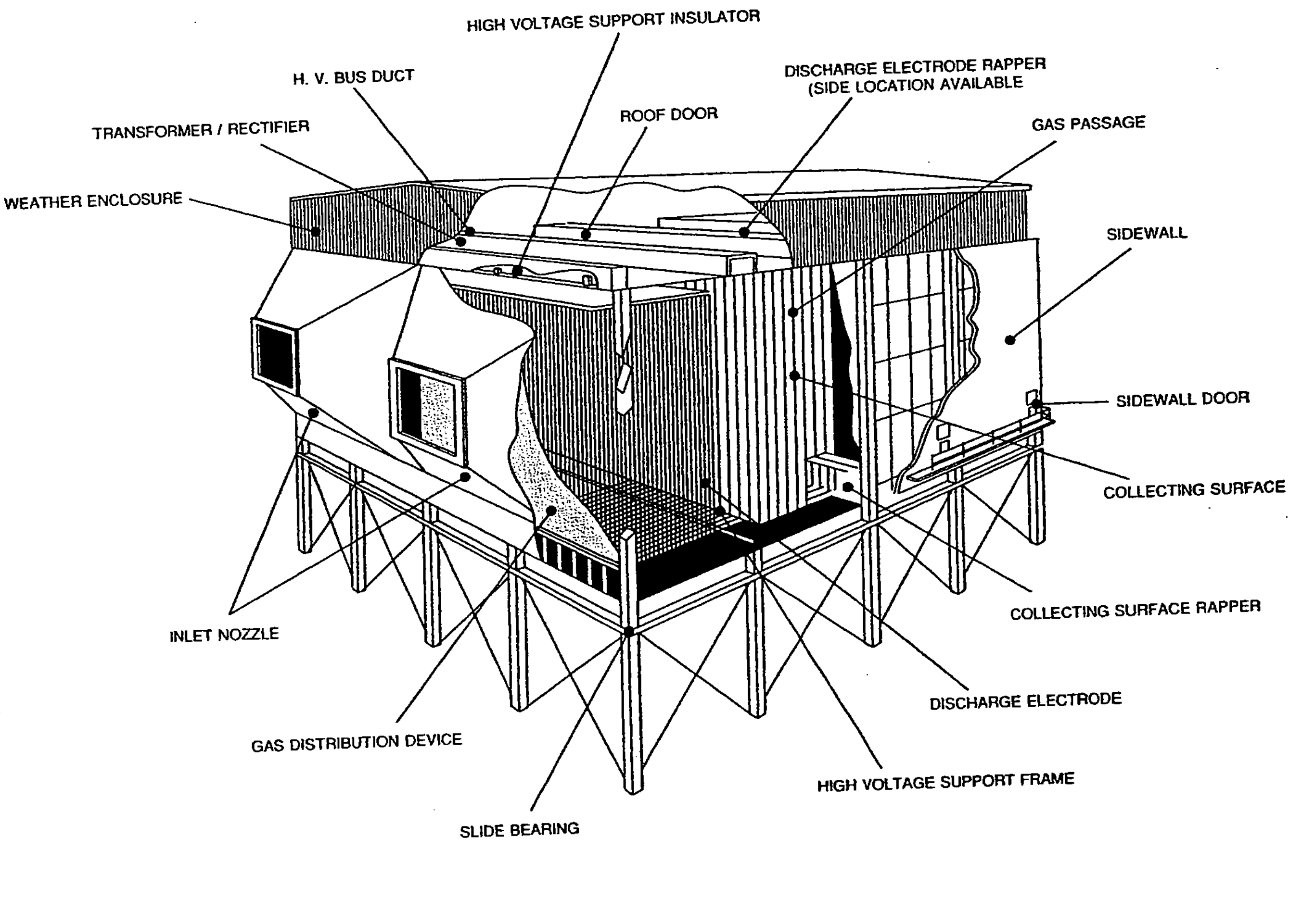

Figure 5-2. Electrostatic precipitator components (Industrial Gas Cleaning Institute).

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

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

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

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

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

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

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

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

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

Flat-Plate Precipitators--

A significant number of smaller precipitators (100,000-200,000 acfm) use flat plates instead of wires for the high-voltage electrodes. The flat plates (United McGill Corp. patents) increase the average electric field that can be used to collect the particles, and they provide an increased surface area for the collection of particles. Corona cannot be generated on flat plates by themselves, so corona-generating electrodes are placed ahead of and sometimes behind the flat-plate collecting zones. These electrodes may be sharp-pointed needles attached to the edges of the plates or independent corona wires. Unlike plate-wire or tubular ESPs, this design operates equally well with either negative or positive polarity. The manufacturer has chosen to use positive polarity to reduce ozone generation. A flat-plate ESP operates with little or no corona current flowing through the collected dust, except directly under the corona needles or wires. This has two consequences. The first is that the unit is somewhat less susceptible to back corona than conventional units are because no back corona is generated in the collected dust, and particles charged with both polarities of ions have large collection surfaces available. The second consequence is that the lack of current in the collected layer causes an electrical force that tends to remove the layer from the collecting surface; this can lead to high rapping losses.

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

Tubular Precipitators--

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

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

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

Wet ESPs--

The major differences in the types of wet ESP's available today are as follows: the shape of the collector, whether treatment of the gas stream is vertical or horizontal, whether incoming gas is preconditioned with water sprays, and whether the entire ESP is operated wet. Figures 5-3 through 5-6 show four different types of wet ESPs. Casing can be constructed of steel or FRP, and discharge electrodes can be carbon steel or special alloys, depending on the corrosiveness of the gas stream.

In circular-plate wet ESPs, the circular plates are irrigated continuously; this provides the electrical ground for attracting the particles and also removes them from the plate. It can generally handle flow rates of 30,000 to 100,000 cfm. Preconditioning sprays remove a significant amount of particulate by impaction. Pressure drop through these units usually ranges from 1 to 3 inches of water.

Rectangular flat-plate units operate in basically the same manner as the circular-plate wet ESPs. Water sprays precondition the incoming gas and provide some initial particulate removal. Because the water sprays are located over the top of the

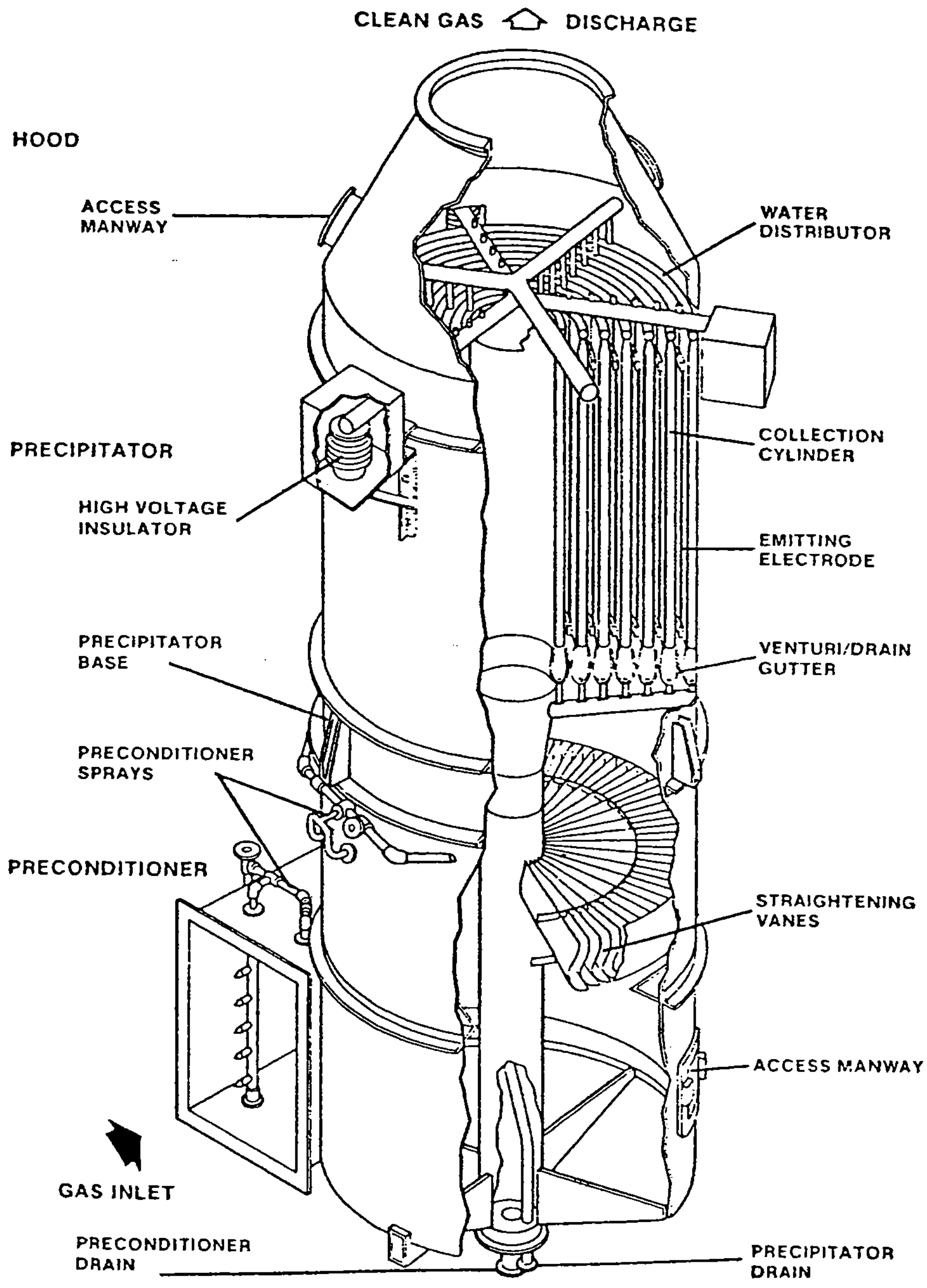

Figure 5-3. Concentric-plate wet ESP (Fluid Ionics, Inc.).

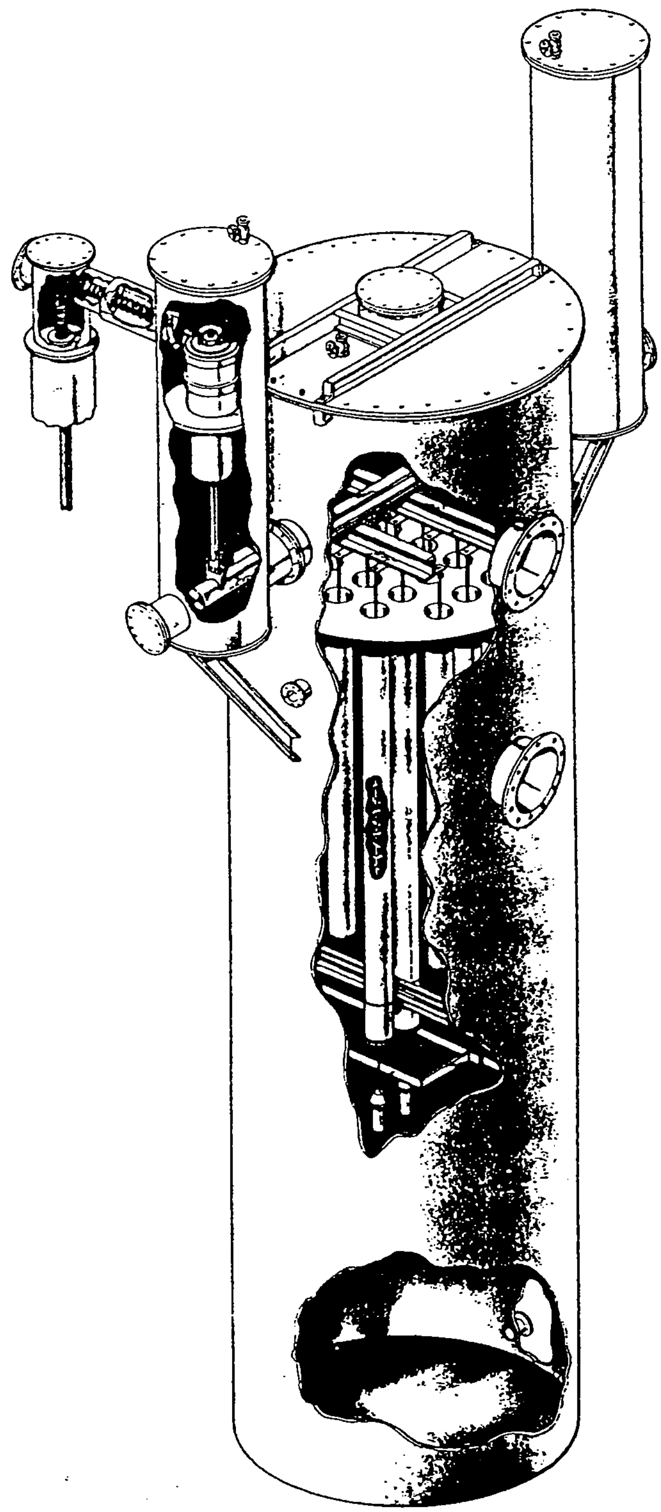

Figure 5-4. Circular-plate wet ESP (Detarring Operations) (Environmental Elements, Inc.)

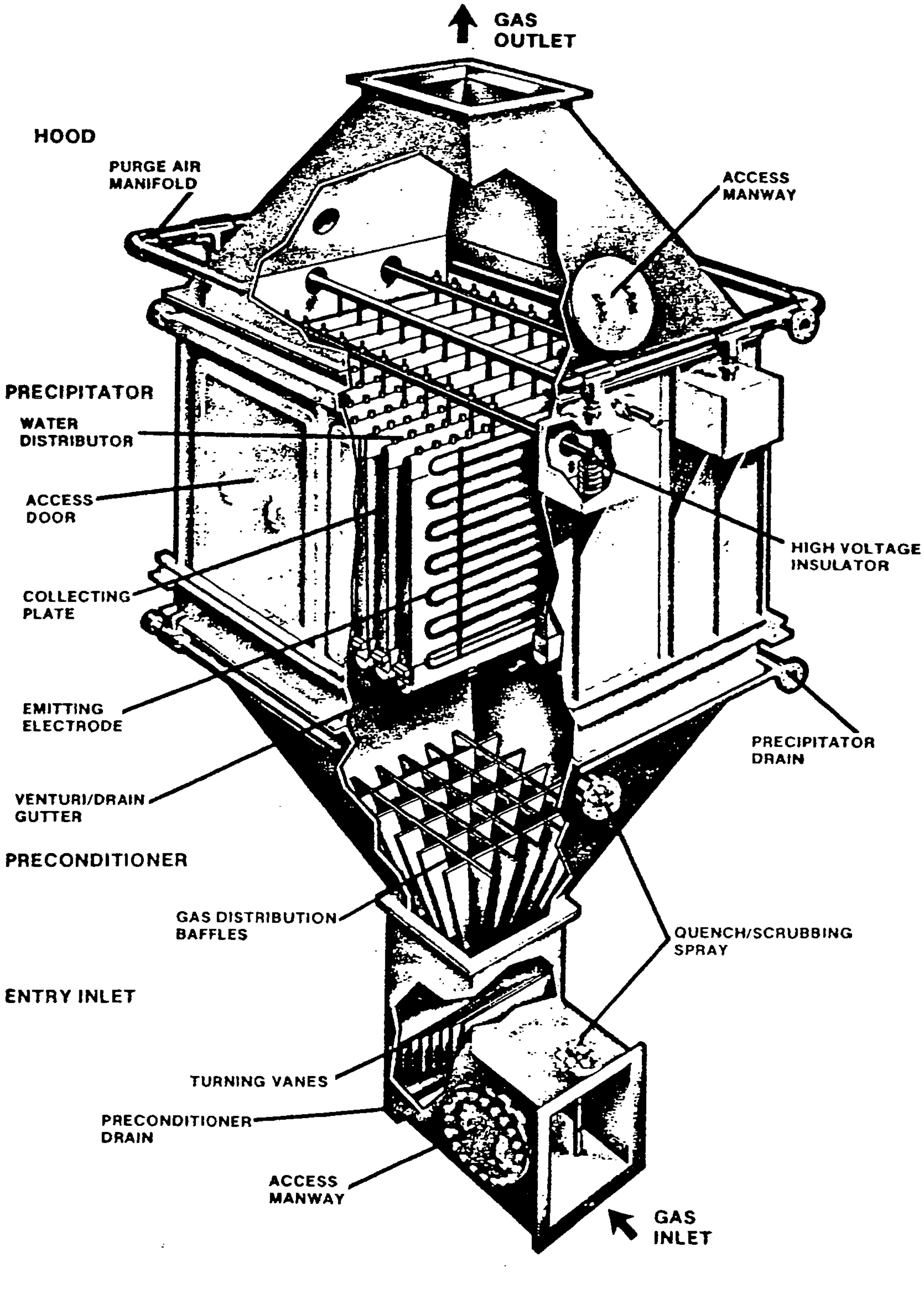

Figure 5-5. Flat-plate-type wet ESP (Fluid Ionics, Inc.)

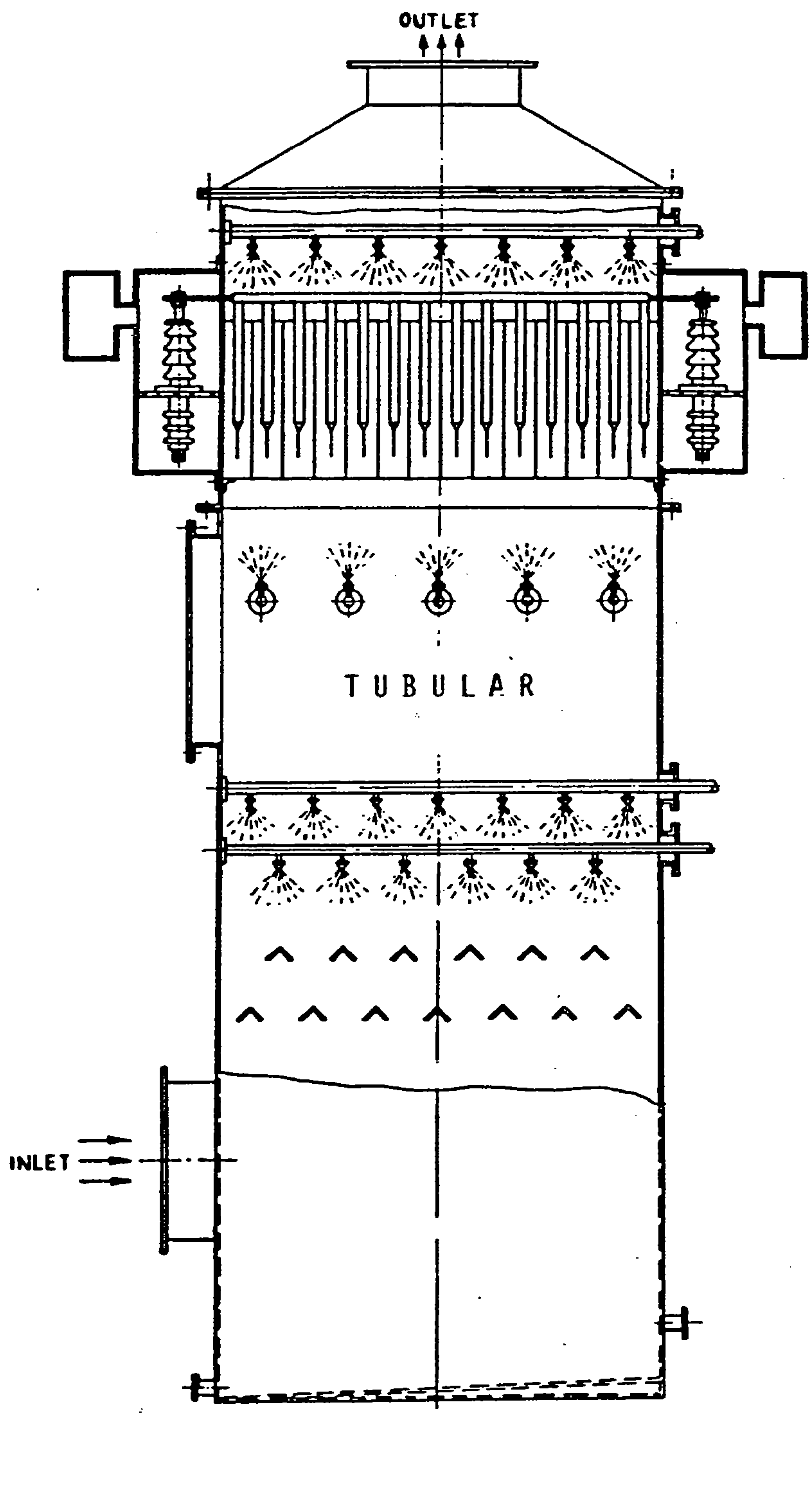

Figure 5-6. Tubular wet ESP (Beltran)

electrostatic fields and the collection plates are continuously irrigated, the collected particulates flow downward into a trough that is sloped to a drain for treatment. The last section of this type of wet ESP is sometimes operated dry to remove entrained water droplets from the gas stream.

The preconditioner liquor and the ESP liquor are generally treated separately so that the cleanest liquor can be returned to the ESP after treatment.

5.1.3 ESP System Components

The emission control performance of an ESP depends upon the design and operating status of its system components. The primary system areas that are common to different ESP types are:

- ° Sectionalization and energization
- ° Rapping techniques
- ° High voltage frame insulators
- ° Hoppers and solids discharge equipment
- ° Gas distribution
- ° Instrumentation

Sectionalization and Energization--

High efficiency precipitators have more than one electrical field. Two or more fields are normally provided in the direction of the gas flow. For large incinerators, the gas flow can be split into two or more chambers each of which has several fields in series. The sectionalization of the precipitators improves both precipitator performance and reliability.

One of the underlying reasons for sectionalization is the significant particle concentration gradient and dust layer thickness gradients between the inlet and outlet of the precipitator. At the inlet of the precipitator, the dust layer accumulates rapidly since 60 to 80 percent of the mass is collected rapidly. This makes this field more prone to electrical sparking due to the nonuniformities in the dust layer electrical fields. Also, the fine particles which are initially charged in the inlet field but not collected create a space charge in the interelectrode zone. This space charge inhibits current flow from the discharge electrodes and collection plates. By sectionalizing the precipitator, the inherent electrical disturbances in the inlet field do not affect the downstream fields.

Another reason for sectionalization is the differences in electrical sparking which are normally moderate-to-frequent in the inlet fields and low-to-negligible in the outlet fields. The automatic voltage controllers used on precipitators are designed to quench the electrical spark by reducing the applied voltage to zero for milliseconds. Then the voltage is increased in several steps to a voltage close to the one at which sparking occurred. When sparking rates increase in a field, the net effect is to lower the peak voltages and to lower the applied time of the electrical power. By using a number of independent power supplies, the electrical disturbances in one field are isolated.

Rapping Techniques--

For dry type electrostatic precipitators, there are two major approaches to rapping: (1) external roof-mounted rappers, and (2) internal rotating hammer rappers. The external rappers are connected to groups of collection plates or an individual high voltage frame by means of rapper shafts, insulators, and shaft seals. The advantage of these roof-mounted rappers is that there is access to the rapper during operation and the intensities can be adjusted for variations in dust layer resistivity. The disadvantage is that the large number of rapper shaft components can attenuate rapping energy and become bound to the hot or cold decks.

The internal rotating hammer rappers have individual rappers for each collection plate. Due to the greater rapping forces possible, these can be used for moderately high resistivity dusts. The disadvantages of these rappers are the inability to adjust the frequency and intensity in various portions of the precipitator and the inaccessibility for maintenance. Also, the internal rotating hammer rappers can be vulnerable to maintenance problems such as shearing of the hammer bolts, distortion of the hammer anvils, bowing of the support shafts, and failure of the linkages.

High Voltage Frame Insulators--

In both wet and dry types of electrostatic precipitators, there are two different types of high voltage frame insulators: high voltage frame support insulators and bus line post insulators. The frames are supported at the top by means of a set of cylindrical or post insulators.

There are either 2 or 4 cylindrical high voltage frame support insulators per frame depending on the manufacturer's design approach. They are usually 1 inch thick and rest on a gasket to reduce the risk of cracking. The high voltage frame is suspended from the top cover on the cylindrical insulator. There are a set of holes or nozzles through the cover to allow heated purge air to flow downward into the precipitator and thereby reduce dust and moisture build-up on the interior surfaces. For further insulator protection, tubular heaters are often mounted near the external bases of the insulators.

The post type insulators are kept clean and dry using a heated purge air flow into the insulator compartment or penthouse. Typical temperatures are 150 to 200 degrees Fahrenheit.

There are insulators at the bottom of the precipitator to stabilize the high voltage frames. These insulators are necessary to maintain proper collection plate-to-discharge electrodes even during times of gas flow rate and gas pressure variations. The anti-sway insulators must be mounted so that they allow free movement of the lower high voltage frame assemblies during thermal expansion and contraction. Also, they must be oriented to minimize dust accumulation. In their location directly above the hoppers, it is not possible to supply a dry, heated air stream for protection against moisture and solids build-up.

Hoppers and Solids Discharge Equipment--

For dry type electrostatic precipitators, proper design of the hopper and solids discharge equipment is especially important. These units handle high mass loading and some of the reaction products are hygroscopic and prone to bridging. Hopper heaters and thermal insulation are important to avoid the hopper overflow conditions which could cause an undervoltage trip of a field and which could possibly cause serious collection plate-to-discharge electrode alignment problems.

Hopper insulation generally consists of 2 to 4 inches of mineral wood insulation mounted one or more inches away from the side of the hopper wall. The insulation includes a weather proof outer lagging and air stops at regular intervals to prevent any chimney effect convective cooling. Hopper heaters located on the bottom one-third of the hopper are used to reduce the possibility of solids bridging.

Electrostatic precipitator hoppers normally have a hopper center baffle to reduce gas sneakage around the fields. This baffle should extend well into the bottom area of the hopper. However, there should be some clearance around the entry to the discharge valve throat so that the baffle does not inadvertently contribute to the solids bridging problems.

Precipitator hoppers often include capacitance or nuclear level detectors, electrical vibrators, poke holes, and strike plates.

Gas Distribution--

One of the most important steps in ensuring adequate gas distribution is to allow sufficient space for gradual inlet and outlet transition sections. Units with very sharp duct turns before and after the transition are also prone to gas distribution problems.

Proper gas distribution is achieved by the use of one or more perforated gas distribution screens at the inlet and outlet of the precipitator. These are generally hung from the top and cleaned by means of externally mounted rappers. Location of the gas distribution screens (and ductwork turning vanes) is usually based on either 1/16th scale flow models or gas distribution computer models.

ESP Instrumentation--

The principal instruments used to monitor electrostatic precipitator performance are generally included on the primary control cabinet for each transformer-rectifier set. Table 5-1 summarizes the types of instruments often used.

5.2 Monitoring ESP Operation

For a continued optimum performance of ESPs, several key parameters must be monitored regularly and necessary corrective actions must be taken to rectify any deviations from acceptable parameter ranges.

TABLE 5-1. ELECTROSTATIC PRECIPITATOR SYSTEM INSTRUMENTS

Parameter Measured	Process/Equipment Controlled	Portable Instrument Port or Sampling Tap
Inlet gas temperature	Precipitator trip	Yes
Outlet gas temperature	-	Yes
Inlet static pressure	Induced draft fan	Yes
Combustibles monitor	Precipitator trip	-
T/R set electrical meters for each field:		
Primary voltage	Undervoltage trip	-
Primary current	Overcurrent trip	-
Secondary voltage	-	-
Secondary current	Overcurrent trip	-
Spark rate	Spark rate limit	-
Rapper frequency	-	-
Penthouse air temperature	Purge air fan	-
Penthouse static pressure	-	-

Performance monitoring includes measurement of key operating parameters by both continuous and intermittent methods, comparison of these parameters with baseline and/or design values, and the establishment of recordkeeping practices. These monitoring data are useful in performance evaluation and problem diagnosis.

5.2.1 Key Operating Parameters and Their Measurement

The typical ESP parameters that must be monitored are: gas volume and gas velocity through the ESP; temperature, moisture, and chemical composition of the gas; particle size distribution and concentration; resistivity of the particulate; and power input. Many of these factors are interrelated.

Gas Volume and Temperature--

According to predictive equations and models, a decrease in gas volume results in an increase in collection efficiency and vice versa. A decrease in gas volume results in an increase of the specific collection area or SCA (ft^2 of plate area/1000 acfm), a decrease in gas velocity through the ESP, an increase in the treatment time (during which the particulate is subjected to the electric field charging and collecting mechanisms), and hence, improved performance. A decrease in velocity may also reduce rapping reentrainment and enhance the collection of the fine particles in the 0.1 to 1.0 µm range, which are exceptionally difficult for most ESPs to collect.

For industrial applications, the ESP is normally designed for maximum expected flow and it will generally not be exceeded. The facility should not perform any major source modifications without evaluating their impacts on the flow rate.

Monitoring the temperature of the gas stream can provide useful information about the performance of an ESP and can provide useful clues for diagnosing both ESP performance and process operating conditions. The effect of temperature is most important as it relates to the resistivity of the particulate and is an indicator of excessive inleakage into the gas stream.

Temperature can also affect gas properties to such an extent that they will change the relative levels of voltage and current and the density and viscosity of the gas stream, which affect particle migration parameters.

Lastly, comparison of inlet and outlet temperatures may be useful in the diagnosis of excessive inleakage into the ESP. Even the best constructed and insulated ESP will experience some temperature drop, which can range from 1° to 2°F on smaller ESPs or up to 25°F on very large ESPs. In any case, some acceptable difference or maximum differential should be set, and when exceeded, this should be an indicator of improper operation or a maintenance problem that must be corrected.

Chemical Composition and Moisture--

The chemical composition of both the particulate entering the ESP and the flue gas can affect ESP performance, although in somewhat different ways. In many process applications, either the gas composition or key indicators of gas composition are usually available on a continuous or real-time basis. Chemical composition of the particulate matter, however, is often not available except on an intermittent, grab-sample basis.

The chemical composition of the particulate matter influences ESP performance. Specifically, it greatly influences the range of resistivity with which the ESP will have to operate. The presence of certain compounds such as alkalies, calcium, or other components can be used to predict resistivity problems. In addition, chemical composition can change with particle size, which may change ESP performance at the inlet, mid, and outlet sections and further complicate prediction of ESP performance on a day-to-day basis.

The presence of water vapor and/or acid gases may prove useful as resistivity modifiers or conditioners, and they may be necessary for proper ESP performance. On the other hand, they may cause a sticky particulate that is difficult to remove.

Particle Concentrations and Size Distribution--

Electrostatic precipitators can be designed for a wide range of mass loadings to provide satisfactory performance when combined with other operating and design parameters. Within limitations, changes in the mass loading do not seriously affect an ESPs performance, although some changes in outlet concentration can occur. However, any source modifications must be evaluated for their impact on the mass loading and ESP performance.

Particle size distribution is usually determined through the use of cascade impactors. Various types of cascade impactors are available with different particle cut sizes and for different loadings. The cascade impactor is usually placed on a standard sampling probe and inserted into the gas stream for isokinetic sampling of the particulate. After sampling is completed, each stage of the impactor is weighed in the lab and compared against its initial weight to determine distribution.

Power Input--

The power input to the ESP can be a useful parameter in monitoring ESP performance. The value of power input for each field and for the total ESP indicates how much work is being done to collect the particulate. In most situations, the use of power input as a monitoring parameter can help in the evaluation of ESP performance, but some caution must be exercised.

The transformer/rectifiers (T-R's) of most modern ESPs are equipped with primary voltage and current meters on the low-voltage (a.c.) side of the transformer and secondary voltage and current meters on the high-voltage rectified (d.c.) side of the transformer. The terms primary and secondary refer to the side of the transformer that is being monitored; the input side is the primary side of the transformer. Older models may have only primary meters and, perhaps, secondary current meters. When both voltage and current meters are available on the T-R control cabinet, the power input can be estimated. Each T-R meter reading must be recorded.

When only the primary meters are available, the values for a.c. voltage and current are recorded and multiplied; however, when secondary meters are available, d.c. kilovolts and milliamps also should be recorded and multiplied. When both primary meters and secondary meters are available, the products of voltage and current should be compared. These values represent the number of watts being drawn by the ESP; in all cases, the secondary power output (in watts) is less than the primary power input to the T-R. The primary and secondary meter values should not be multiplied; however, this is done occasionally to aid in the evaluation of the ESP performance (e.g., primary voltage to secondary current).

The power inputs calculated for each T-R set and for the ESP do not represent the true power entering the T-R or the effective power entering the ESP; however, they are sufficiently accurate for the purpose of monitoring and evaluating ESP performance. These values indicate just how well each of the sections is working when compared with the actual voltage and current characteristics. The ratio of secondary power (obtained from the product of the secondary meter readings) to the primary power input will usually range from 0.5 to 0.9; the overall average for most ESPs is between 0.70 and 0.75. In general, as the operating current approaches the rated current of the T-R it appears to be more efficient in its utilization of power. This is due to a number of factors, including semiconductor controlled rectifier (SCR) conduction time, resistance of the dust layer, and capacitance of the ESP. The actual voltage and current readings that are used to calculate power will be controlled by the gas composition, dust composition, gas temperature, and physical arrangement within the ESP. Thus, as one moves from inlet fields towards outlet fields, the apparent secondary power/primary power ratio increases in most ESPs because the ESPs tend to operate to their rated current output. When ESPs only have primary voltage and current meters, the power input may be estimated by obtaining the multiplication product.

5.2.2 Parameter Monitoring

Parameter monitoring usually plays a key role in an overall operation and maintenance plan, particularly one that stresses preventive maintenance. Such monitoring also forms the basis for a recordkeeping program that places emphasis on diagnostics. Typically, daily operating data are reduced to the data on a few key parameters that are monitored. Acceptable ranges may be established for various parameters (by use of baseline test data) that require further data analysis or perhaps some other action if the values fall outside a given range. Care must be taken not to rely on just one parameter as an indicator, as other factors, both design- and operation-related, usually must be considered. Typical parameters that can be monitored daily include opacity, corona power input sparking, fan operation, gas temperature, process operating rates, and conditioning systems (if used).

Many sources use opacity levels as the first indicator of performance changes. In general, opacity is relatively easy to monitor daily or continuously and is a good indicator and tool for this purpose. If used in conjunction with mass/opacity correlations, it can help in the scheduling of maintenance and in the reduction or optimization of ESP power input. It is not wise to rely on opacity data alone, however, as such reliance can cause one to overlook problems that can affect long-term performance (e.g., hopper pluggage may not significantly increase opacity at reduced load, but it may misalign the affected fields and reduce their performance at full load or in other difficult operating situations).

Another useful parameter that can be monitored daily is the corona power input to the ESP, which can be thought of as a measure of the work done to remove the particulate. Corona power input can be obtained by multiplying the voltage and current values of either the primary or secondary side of the transformer. As noted earlier, the apparent power input on the primary and secondary side will differ because of circuitry and the metering of these values. Values from the secondary meters are preferred. As a general rule, performance improves as the total power input increases. This is normally the case when resistivity is normal to moderately high, assuming most other factors are "normal" and components are in a state of good repair. One should not rely solely on power input, however. The pattern or trends in power input throughout the ESP are important in a performance evaluation. Also, in some cases, although the apparent power input is high, the performance is poor. For example, when dust resistivity is low or very high or when spark rates are very high, corrective measures will usually lower power input, but will also substantially improve performance.

Some ESPs are relatively insensitive to power input changes. This condition is usually limited to high-efficiency ESPs that are generously sized and sectionalized. The normal power input of some of these ESPs may be reduced by one-half to two-thirds without causing any substantial change in performance. The emissions from the ESPs are caused primarily by rapping reentrainment and gas sneakage, both of which are relatively unaffected by the level of power input. In this case, power reduction for energy conservation is probably a useful option.

Varying corona power input affects power density (watts/square foot of plate area). This may be tracked two ways: 1) by obtaining an overall value for the ESP, or 2) by checking the power density in each field from inlet to outlet of the ESP. Power density should increase from inlet to outlet as the particulate matter is removed from the gas stream (the maximum value is usually less than 4 watts/ft^2). Power density accounts for the differences or normalizes the values for power input in each field that are caused by different field size. Most normally operating ESPs will show an overall power density of 1 to 2 watts/ft^2; values of 0.10 to 0.50 watt/ft^2 are more common for high-resistivity dusts.

The gas volume passing through the ESP is important to the actual SCA, the superficial velocity, and the treatment time. Normal gas flow to the ESP can be monitored daily using gas temperature, fan operation, and normal process operation as indicators. The temperature of the gas stream, the excess-air values (for combustion sources), and the production rate all influence the gas volume entering the ESP. If gas volume is known or estimated, the specific corona power (watts/1000 acfm) can be calculated. This value tends to account for changes in performance due to different loads and power input because removal efficiency generally increases as the specific corona power increases. The same cautionary remarks that apply to overall power input also apply to specific corona power. The values obtained for specific corona power input may be misleading if other factors are not considered.

5.3 ESP Malfunctions

Other than changes in process conditions, the most common malfunction associated with ESP performance is from broken discharge wires and plugged hoppers. A detailed list of the causes and effects of malfunctions, categorized according to functioning component, is given in the following pages. In some cases, solutions to the problems are provided. Table 5-2 provides a summary of common ESP malfunctions.

Discharge Electrodes--

In a weighted wire design, a broken wire may swing freely and cause shorting between discharge and collector electrodes, usually immobilizing an entire field. Wire breakage results from electrical, mechanical, or chemical problems.

<u>Electrical</u>

Electric erosion (arcing) is the principal cause of failure.

Minimum clearance between electrodes results in repeated sparkover, causing local heating and vaporization of metal. The tension from the suspension weights causes ultimate failure.

Breakage can occur on shroud as well as wire and usually occurs on the lower portion of wire.

<u>Mechanical</u>

Excessive rapping breaks wire.

Crimps and bends are sources of fatigue with rapping and vibration.

TABLE 5-2. SUMMARY OF MALFUNCTIONS ASSOCIATED WITH ELECTROSTATIC PRECIPITATORS

Malfunction	Cause	Effect on ESP Efficiency	Corrective Action	Preventive Measures
Poor electrode alignment	Poor design Ash buildup on frame hoppers Poor gas flow	Can drastically affect performance and lower efficiency	Realign electrodes Correct gas flow	Check hoppers frequently for proper operation
Broken electrodes	Wire not rapped clean, causes an arc which embrittles and burns through the wire. Clinkered wire. Causes: a) poor flow area, distribution through unit is uneven; b) excess free carbon due to excess combustion air or fan capacity insufficient for demand required; c) wires not properly centered; d) ash buildup resulting in bent frame, (same as c); e) clinker bridges the plates and wire shorts out; f) ash buildup, pushes bottle weight up causing sag in the wire; g) J hooks have improper clearances to the hanging wire; h) bottle weight hangs up during cooling, causing a buckled wire; i) ash buildup on bottle weight to the frame forms a clinker and burns off the wire.	Reduction in efficiency due to reduced power input, bus section unavailability	Replace electrode	Inspect hoppers Check electrodes frequently for wear Inspect rappers frequently Check flow distribution
Distorted or skewed electrode plates	Solids buildup in hoppers Gas flow irregularities High temperatures	Reduced efficiency	Repair or replace plates Correct gas flow	Check hoppers frequently for proper operation; Check electrode plates during outages
Vibrating or swinging electrodes	Uneven gas flow Broken electrodes	Decreases in efficiency due to reduced power input	Repair electrodes	Check electrodes frequently for wear
Inadequate level of power input (voltage too low)	High dust resistivity Excessive particulate on electrodes Unusually fine particle size Inadequate power supply Inadequate sectionalization Improper rectifier and control operation Misalignment of electrodes	Reduction in efficiency	Clean electrodes, gas conditioning or alterations in temperature to reduce resistivity; Increase sectionalization	Check range of voltages frequently to make sure it is correct continuous resistivity measurements
Back corona	Particulate accumulated on electrodes causing excessive sparking, requiring reduction in voltage charge	Reduction in efficiency	Same as above	Same as above

(continued)

TABLE 5-2 (continued)

Malfunction	Cause	Effect on ESP Efficiency	Corrective Action	Preventive Measures
Broken or cracked insulator or flower pot bushing leakage	Ash buildup during operation causes leakage to ground Moisture gathered during shut-down or low load operation	Reduction in efficiency	Clean or replace insulators and bushings	Check frequently Clean and dry as needed; Check for adequate pressurization on top housing
Air leaks in through hoppers	From dust conveyor	Lower efficiency; dust reentrained through ESP	Seal leaks	Identify early by increase in ash concentration at bottom of exit to ESP
Air leaks in through ESP shell	Flange expansion	Same as above, also causes intense sparking		
Gas bypass around ESP: - dead passage above plates - around high tension frame	Poor design - improper isolation of active portion of ESP	Only small percentage drop in efficiency unless severe	Baffling to direct gas into active ESP section	Identify early by measurement of gas flow in suspected areas
Corrosion	Temperature goes below dewpoint	Negligible until precipitation causes interior plugs or plates to be eaten away; air leaks may develop, causing significant drops in performance	Maintain flue gas temperature above dewpoint	Energize precipitator after process system has been on line for ample period to raise flue gas temperature above acid dewpoint
Hopper pluggage	Wires, plates, insulators fouled because of low temperatures Inadequate hopper insulation Improper maintenance Boiler leaks causing excess moisture Ash conveying system malfunction: gasket leakage, blow malfunction, or solenoid valves Misadjustment of hopper vibrators Material dropped into hopper from bottle weights Solenoid, timer malfunction Suction blower filter not changed	Reduction in efficiency	Provide proper flow of ash	Frequent checks for adequate operation of hoppers Provide heater and/or thermal insulation to avoid moisture condensation

(continued)

TABLE 5-2 (continued)

Malfunction	Cause	Effect on ESP Efficiency	Corrective Action	Preventive Measures
Inadequate rapping, vibrators fail	Solids buildup Poor design Rappers misadjusted	Resulting buildup on electrodes may reduce efficiency	Adjust rappers	Frequent checks for adequate operation of rappers
Too intense rapping	Poor design Rappers misadjusted Improper rapping force	Reentrains ash, reduces efficiency	Same as above	Same as above Reduce vibrating or impact force
Control failures	Power failure in primary system Transformer or rectifier failure: a) insulation breakdown in transformer b) arcing in transformer between high voltage switch contacts c) leaks or shorts in high voltage structure d) insulating field contamination	Reduced efficiency	Find source of failure and repair or replace	Pay close attention to daily reading of control room instrumentation to spot deviations from normal readings
Sparking	Inspection door ajar System leaks Plugging of hoppers Dirty insulators	Reduced efficiency	Close inspection doors; repair leaks; unplug hoppers; clean insulators	Regular preventive maintenance will alleviate these problems

Poor electrical alignment causes the wire frame to oscillate, fatiguing wires and increasing sparking.

Swinging wire frames can often be detected by listening for the regular snap of the arc-over.

Chemical

Acid gases corrode wires. Material flakes off during rapping, thus exposing new surfaces to additional corrosion attack.

Wire buildup is not usually due to insufficient rapping but to some other factor, such as process change. Uniform buildup can have the effect of creating a larger diameter wire and requiring higher voltage to initiate ground current. A sudden failure or rash of failures can occur from process changes or extreme malfunction in the ESP.

In a rigid frame design, one broken wire does not result in the failure of the entire bus section. High "G" forces in rapping rigid wire frames can lead to premature mechanical failure near the impact point, at connection to support members, sharp bends, and welded connections. High resistivity dusts are very tenacious and need high rapping forces. These conditions require an ESP designed for high resistivity dust.

Rappers (Vibrators/Impulse)--

Impulse electric or pneumatic rappers are more successful in difficult rapping applications than are electric vibrators.

Pneumatic rappers are beneficial in warm, high-moisture ambient environments. If the temperature falls below freezing, however, pneumatic is not recommended because the entrapped moisture in the air lines may freeze unless adequate air dryers are installed.

Rappers (Mechanical Failures)--

Failures occur in the transmission hardware at the interface of a high-strength alloy and mild steel components.

Poor quality of welds from rapper to support frame may result in cracks. Good welding practice is to preheat and postheat.

Rapper binds due to misalignment during installation.

Rapper rod seizure occurs from dust accumulation.

Collector Electrodes--

Plate corrosion results from gas temperature going below dew point and allowing condensation to occur on lower portion of plate. Air leakage into hopper also produces condensation and corrosion on electrodes.

Mechanical failure at supports can occur from poor construction or assembly and overrapping.

Dust Removal System--

Plugging is the main problem and could result from moisture condensation, with its associated dust agglomeration and caking within the hopper. Dust buildup will eventually contact high-voltage electrode frame and short cut high-voltage bus sections, misaligning electrodes, and form clinkers by ash fusion from the high-voltage current. Hoppers and heaters should be operated continuously to avoid buildup.

Housing and Casing--

Air leaks and infiltration (causing corrosion) can occur at expansion joints, slip joints, and inlet/outlet ducts. Should acid/gas temperature go below dew point, condensation can also result in corrosion.

Coupons of aluminum, corten, and stainless steel are often placed inside the unit to study the corrosion resistance of these materials. Coatings such as coal tar epoxy are used to eliminate corrosion.

Insulators--

Dust and/or moisture accumulation on the insulator surface could lead to electrical arc-over as evidenced by tracking. Excessive arc-over could result in insulator cracking or breakage. Filtered and heated purge air prevents fouling of the insulators, bus bars, and bus ducts.

5.3.1 Troubleshooting Procedures

Guidelines for troubleshooting and correcting ESP malfunctions are provided in Tables 5-2 and 5-3. These charts may be used as diagnostic aids to troubleshoot specific symptoms. A supplementary approach to evaluate operational problems is to interpret abnormal electrical meter readings from the ESP control cabinet. Table 5-3 provides guidance for troubleshooting and correcting ESP electrical malfunctions and Table 5-4 shows how gas parameters and electrical failure impact ESP meter readings.

5.4 Electrostatic Precipitator Operation and Maintenance

Proper operation and maintenance of an ESP requires familiarity with procedures for equipment startup, shutdown, inspection, recognition of common malfunctions, and troubleshooting. Discussion of the cause and effect relationship and the impact on performance is discussed in this section.

5.4.1 Pre-Startup Inspection

The inspection performed before startup is critical to the performance of an ESP. The precipitator may not be operational for one of three reasons:

New installation requiring shakedown and debugging.

Process shutdown resulting in ESP shutdown.

ESP shutdown for maintenance.

Regardless of the reason for shutdown, an opportunity exists while the unit is down to perform a thorough inspection. This inspection should be performed at least annually. An example of a checklist for visual and mechanical inspection during shutdown is provided in Figure 5-7.

5.4.2 Routine Startup

After the precipitator has been thoroughly inspected, the unit should be buttoned up (following all safety procedures). An outline procedure for routine startup is given

TABLE 5-3. TYPICAL TROUBLESHOOTING CHART FOR ELECTROSTATIC PRECIPITATOR ELECTRICAL PROBLEMS

Symptom	Cause	Remedy
No primary voltage No primary current No precipitator current Vent fan on Alarm energized	Overload condition	Check overload relay settings Check wiring components
	Misadjustment of current limit control	Check adjustment of current limit control setting
	Overdrive of SCR's	Check signal from firing circuit module
No primary voltage No primary current No precipitator current Vent fan off Alarm energized	Relay panel fuse blown	Replace
	Circuit breaker tripped	Reset circuit breaker
	Loss of supply power	Check supply to control unit
Control unit trips out on overcurrent when sparking occurs at high currents	Circuit breaker defective or incorrectly sized	Check circuit breaker
	Overload circuit incorrectly set	Reset overload circuit
	Short circuit condition in primary	Check primary power wiring
High primary current No precipitator current	Transformer or rectifier short	Check transformer and rectifiers
No primary voltage No primary current No precipitator current Vent fan on Alarm not energized	SCR and/or diode failure	Replace
	No firing pulse from firing circuit and/or amplifier	Check signal from firing circuit and/or amplifier
Same as above, even after replacing components or subpanels, changing wires, or repair	SCRs being fired out of phase	Reverse input wires
Low primary voltage High secondary current	Short circuit in secondary circuit or precipitator	Check wiring and components in H.V. circuit and pipe and guard. Check precipitator for: Interior dust buildup Full hoppers Broken wires Ground switch left on Ground jumper left on Foreign material on H.V. frame or wires Broken insulators

(continued)

TABLE 5-3. (continued)

Symptom	Cause	Remedy
Abnormally low precipitator current and primary voltage with no sparking	Misadjustment of current and/or voltage limit controls	Check settings of current and voltage limit controls
	Misadjustment of firing circuit control	Turn to maximum (clockwise) and check setting of current and voltage limit controls
Spark meter reads high -- off scale Low primary voltage and current No spark rate indication	Continuous conduction of spark counting circuit	Deenergize, allow integrating capacitor to discharge, and reenergize
	Spark counter counting 60 cycles peak	Readjust
	Failure	Replace
Spark meter reads high; primary voltage and current very unstable	Misadjustment of PC-501	Readjust
	Loss of limiting control	Replace
Neither spark rate, current, nor voltage at maximum	Misadjustment of PC-501	Readjust setting
	Failure	Replace
	Failure of signal circuits	Check signal circuits
No spark rate indication; voltmeter and ammeter unstable, indicating sparking	Failure of spark meter	Replace spark meter
	Failure of integrating capacitor	Replace capacitor
	Spark counter sensitivity too low	Readjust
No response to current limit adjustment; however, does respond to other adjustments	Controlling on spark rate or voltage limit	None needed if unit is operating at maximum spark rate or voltage adjustment. Reset voltage or spark rate if neither is at maximum.
	Failure	Replace
	Current signal defective	Check signal circuit
No response to voltage limit adjustment; however, does respond to current adjustment	Controlling on current limit or spark rate	None needed if unit is operating at maximum current or spark rate. Reset current and spark rate adjustment if neither is at maximum
	Voltage signal defective	Check voltage signal circuit
	Failure	Replace

(continued)

TABLE 5-3. (continued)

Symptom	Cause	Remedy
No response to spark rate adjustment; however, does respond to other adjustment	Controller on voltage or current	None needed if unit is operating at maximum voltage or current. Reset voltage and current adjustment if neither is at maximum
	Failure	Replace
Precipitator current low with respect to primary current	Surge arrestors shorted	Reset or replace surge arrestors
	H.V. rectifiers failed	Replace H.V. rectifiers
Low or no voltage across ground return resistors	H.V. transformer failed	Replace H.V. transformer
	Ground or partial ground in the ground return circuit	Repair ground return circuit

TABLE 5-4. GUIDE FOR INTERPRETING ABNORMAL METER READINGS

1. Increasing gas temperature results in a corresponding voltage increase and current decrease (arcing can develop). Conversely, decreasing gas temperature will result in voltage diminution and current increase.
2. An increase in moisture content at given process conditions results in a relatively small increase in current and voltage levels.
3. Excessive sparkover may result from additional moisture and is indicated by a voltage increase.
4. Grain loading increase somewhat elevates voltages and reduces current.
5. A particle size decrease causes a voltage rise and diminished current.
6. Gas velocity (flow rate) increase tends to increase voltages and depress current.
7. Air leakage may cause additional sparkover and reduced voltage.
8. During normal operation for individual power supplies, the voltage/current ratio decreases in the direction of gas flow.
9. Hopper overflow results in shorting, drastically reduced voltage, and current increase.
10. Broken, swinging discharge electrode wires result in violent arcing and extreme and erratic meter behavior.
11. A T/R short results in zero voltage and high current.
12. Buildup on wires is accompanied by a voltage increase to maintain the same current level.
13. Buildup on plates is accompanied by a voltage decrease to maintain the same current level.

ESP PREOPERATION AND INSPECTION CHECKLIST

Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (print):
ESP ID:	Signature of Inspector:

INSPECTION ITEM	CHECKED YES	NO	COMMENTS/CORRECTIVE ACTIONS:
DISCHARGE ELECTRODES			
Upper Support Frame	______	______	
Lower Support Frame	______	______	
Hanger Supports	______	______	
Antiswing Supports	______	______	
Weights	______	______	
Wires	______	______	
Alignment	______	______	
Corrosion	______	______	
Buildup	______	______	
COLLECTOR ELECTRODE			
Warpage	______	______	
Support	______	______	
Spacers	______	______	
Guides	______	______	
Alignment	______	______	
Corrosion	______	______	
Buildup	______	______	
GAS SNEAKAGE BAFFLES	______	______	

Figure 5-7. Preoperation and inspection checklist for electrostatic precipitator. (continued)

ESP PREOPERATION AND INSPECTION CHECKLIST

Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (print):
ESP ID:	Signature of Inspector:

INSPECTION ITEM	CHECKED YES	CHECKED NO	COMMENTS/CORRECTIVE ACTIONS
RAPPERS(COLLECTOR/DISCHARGE)			
Mechanical/Electrical Connections	______	______	
Buildup	______	______	
Corrosion			
TR SET			
Surge Arrestor Gap	______	______	
Transformer Liquid Level	______	______	
Ground Connections	______	______	
High Tension Bus Duct	______	______	
Conduits	______	______	
Full Wave Switch Box	______	______	
Alarm Connections	______	______	
Ground Switch Operation	______	______	
High Voltage Connections	______	______	
Register Board			

Figure 5-7. Preoperation and inspection checklist for electrostatic precipitator. (continued)

ESP PREOPERATION AND INSPECTION CHECKLIST

Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (print):
ESP ID:	Signature of Inspector:

INSPECTION ITEM	CHECKED YES	CHECKED NO	COMMENTS/CORRECTIVE ACTIONS
INSULATOR COMPARTMENT			
Filter Compartment	______	______	
Dusts/Insulation			
Flow	______	______	
Temperature	______	______	
Motor	______	______	
Pressure	______	______	
Heater	______	______	
BLOWER			
Current	______	______	
Voltage	______	______	
RPM	______	______	
Static Pressure	______	______	
Belt Tension	______	______	
Bearing Lubrication	______	______	
Damper	______	______	

Figure 5-7. Preoperation and inspection checklist for electrostatic precipitator. (continued)

ESP PREOPERATION AND INSPECTION CHECKLIST

Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (print):
ESP ID:	Signature of Inspector:

INSPECTION ITEM	CHECKED YES	CHECKED NO	COMMENTS/CORRECTIVE ACTIONS
DUCTS (INLET/OUT/STACK)			
Leakage	_______	_______	
Joints	_______	_______	
Gasketing	_______	_______	
Dampers	_______	_______	
Comments/Corrective Actions			

Figure 5-7. Preoperation and inspection checklist for electrostatic precipitator.

below. Power on/off buttons with green and red lights are usually provided for components.

1. Follow key interlock procedures for closing access doors.

2. Preheat insulator compartments for several hours before energizing system.

3. Activate dust handling system (air lock, screw conveyors, etc.).

4. Operate discharge and collector electrode rapping system.

5. Operate gas distribution baffle plate vibrators.

6. Turn on high voltage (manual mode) for one section only and bring up input voltage slowly (10 percent increments) to rated voltage or rated current while recording panel meter readings. This procedure is commonly referred to as an airload test. The test establishes reference readings and checks operation of electrical equipment, clearances, etc. After these readings are recorded, turn down high voltage on the field and similarly perform an airload test on the next field. If excessive sparking or d.c. readings are obtained, another internal inspection may be necessary.

7. If system operates satisfactorily, turn off T/R sets.

8. Open bypass dampers.

9. Start blower.

10. If possible, preheat the ESP by pulling hot, clean air through the system, thus avoiding condensation of moisture and contaminant gases. Buildup of condensed material on electrodes is difficult to remove. Energize one field only to minimize the effect.

11. Allow contaminant gases to pass through the unit.

12. Record data from monitoring instrumentation (fan motor amperage and voltage; temperatures; a.c. voltage/current; d.c. voltage/current; spark rate).

5.4.3 Routine Inspection and Maintenance During Operation

During routing operation, an inspection procedure that includes a recording of ESP operation data should be used. Samples of a routine daily and weekly inspection form for an ESP are provided in Figures 5-8 and 5-9, respectively. Only visual inspection of

DAILY ESP INSPECTION FORM	
Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (print):
ESP ID:	Signature of Inspector:

T/R CONTROL SET NO.	PRIMARY VOLTS	PRIMARY AMPS	SECONDARY AMPS 1	SECONDARY AMPS 2	SECONDARY KVOLTS 1	SECONDARY KVOLTS 2	SPARKS PER MINUTE	COMMENTS/CORRECTIVE ACTIONS

HV Bus Duct Noise?	YES / NO
Localized Sparking?	YES / NO
Transformer-Rectifier Readings OK?	YES / NO
Precipitator Hopper Levels OK?	YES / NO
Rapper and Vibrator Controller Operating?	YES / NO

Gas Temperature _____°F

Opacity __________%

Figure 5-8. Example daily ESP inspection form.

WEEKLY ESP INSPECTION FORM	
Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (print):
ESP ID:	Signature of Inspector:

INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS
Check HV Transformer Oil Level and Temperature	
Inspect T/R Control and Purge Air Filters	
Check Access Door Air Inleakage	
Check Purge Air and Heater System Operation	
Rapper System Settings Check	
Vibrator System Settings Check	

Rapper/Vibrator Setting Record	Field 1	Field 2	Field 3	Field 4	COMMENTS/CORRECTIVE ACTION
Rapper Settings - Previous Intensity Frequency					
Rapper Settings - New Intensity Frequency					
Vibrator Settings - Previous Intensity Frequency					
Vibratory Settings - New Intensity Frequency					

Figure 5-9. Example weekly ESP inspection form.

the unit is possible, and therefore only instrumented operational parameters can be obtained. Inspection forms for longer periods of time (e.g., quarterly and annually) are more ESP manufacturer and process specific and should be developed on a site and ESP specific basis. A tailor-made checklist can be prepared by the user based on vendor recommendations and process specific gas parameters. An example maintenance report form is presented as Figure 5-10 to report items requiring maintenance attention and the completed maintenance activities.

5.4.4 Routine Shutdown

An ESP is shut down primarily because of routine or emergency process shutdown, routine ESP maintenance, or emergency ESP malfunction. In these situations, the ESP should continue to be operated until it is purged with clean air. The following steps are then taken:

1. Stop blower.
2. If possible, isolate ESP by closing inlet/outlet dampers.
3. Shut down T/R set.
4. Continue to operate rapping and dust removal system until wires and plates are believed to be clean; then shut down rappers and dust removal system (make sure that hoppers are clean).
5. Open access doors following interlock procedure.

   Note: Hopper access doors should be opened with care because hot dust may be packed against them.
6. Use ground hooks to remove extraneous electric charge buildup.
7. Allow system to cool and dust to settle before entering.
8. Allow insulator compartment vent system to operate.

MAINTENANCE REPORT FORM

Department	Unit	System	Subsystem	Component	Subcomponent

Originator: ____________ Date: ________ Time: ________

Assigned To:

1	Mechanical
2	Electrical
3	Instrumentation

Priority:

1	Emergency
2	Same Day
3	Routine

Unit Status:

1	Normal
2	Derated
3	Down

Problem Description: ____________

Foreman: ____________ Date: ________

Job Status:

1	Repairable
	Hold for:
2	Tools
3	Parts
4	Outage

Cause of Problem: ____________

Work Done: ____________

Supervisor: ____________ Completion Date: ________

Materials Used: ____________

Labor Requirements: ____________

Figure 5-10. Example maintenance report form.

5.4.5 Maintenance During Shutdown

When the ESP can be entered, internal inspection can be commenced (Figure 5-7). It is advisable to leave the insulator compartment vent heaters on during shutdown to prevent moisture from condensing on the high-voltage insulators. Generally, the high-maintenance items are:

Discharge electrode breakage
Plugged hoppers
Insufficient rapping
Insulator bushing failure
Electrical component breakdown

5.4.6 Wet Electrostatic Precipitator Operation and Maintenance

As one would expect, the WEP has a high potential for corrosion and scaling and requires a water treatment system. If the wash liquor is to be recycled through the WEP, which in most cases is necessary to save on water consumption, the same water treatment methods used with scrubbers must be applied. Concentration of suspended and dissolved solids must be maintained, in addition to pH control. The clarification of solids must be sufficient to minimize spray nozzle plugging and buildup of recycled materials on the internal members of the precipitator. If condensible materials are being collected, a means for removing them must be provided (such as skimming devices or methods for sludge removal).

The dissolved solids concentration must be maintained at a steady and acceptable level, either by the right amount of purging, by chemical treatment, or both.

Pre-Startup Inspection--

Before starting up the WEP, a thorough inspection of the system is required. The procedure and checklist to follow is provided in Figure 5-7, with the exception of items applying to the water cleaning system.

<u>Water Cleaning System</u>

Turn on water cleaning system and check all pipe connections for leaks.

Check for adequate water flow.

Check individual water line pressure.

Check angles and direction of nozzle spray. Correct nozzle positioning is necessary to obtain coverage of precipitator internals.

Inspect drain system to ensure that wastewater drains freely.

Check for adequate clearance between piping and high voltage system.

WEP inspection checklists can be compiled using Figures 5-7 through 5-9 and equipment supplier maintenance documents.

Routine Startup--

Follow procedure in Section 5.4.2, except replace Items 3, 4, and 5 with activation of spray system.

Routine Inspection and Maintenance During Operation--

Only visual inspection of the external components of the system is possible during operation. Therefore, only instrumented operational parameters can be observed, along with inspection of electromechanical equipment and structural components. A routine daily and weekly inspection checklist for a WEP can be made from Figures 5-8 and 5-9. Since actual inspection and maintenance practices are quite specific to the particular system used, a tailormade checklist should be prepared by the user and vendor.

Common Malfunctions--

Scaling, buildup, and corrosion are commonplace in WEP's. These conditions are prevalent not only within the liquor recirculating system, but also in the electrostatic precipitator housing. Liquor clarification and chemical treatment are critical to WEP performance. Thorough familiarity with scrubber and dry ESP troubleshooting procedures are necessary in order to properly diagnose WEP malfunction and poor performance.

5.5 Operator Training

Proper training of ESP operating staff is necessary to ensure that the system operates at its peak performance level. An ESP system consists of several electrical and mechanical components. The operator must understand the function of each component and should be able to diagnose impacts of any abnormal changes in the operating parameters of the individual system components.

The operators will normally receive initial training from the ESP manufacturer. A manufacturer's representative is on site during the start up of the system to ensure that the system parameters are defined for the source being controlled. Minor and major adjustments will be done during the startup phase and the ESP operator should accompany the vendor representative during this phase.

The operator should also renew the equipment manual provided by the system supplier and highlight key sections of the manual. A ready reference chart of the key parameters and their normal accepted ranges should be prepared to identify any potential problems.

Operator training should be performed when the ESP is initially installed and periodically (e.g., semiannually) for new operators. The operator training should address ESP failure modes and malfunction diagnosis topics. This should include:

- ° Special operating problems
- ° Process startup and shutdown
- ° Wire breakage
- ° Plate alignment
- ° Hopper overflow
- ° Dust handling system

Understanding of the operating parameters of the process discharging to the ESP is also important and the operator should be familiar with the process parameters and their impact on the operator of the ESP system. The operator should be aware of the process upset conditions and necessary ESP remedial measures.

REFERENCES FOR SECTION 5

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2. LVW Associates, Inc. Engineering Handbook for Hazardous Waste Incineration (Draft No. 2). Prepared for the U.S. Environmental Protection Agency, Cincinnati, Ohio. May 31, 1990.

3. U.S. Environmental Protection Agency. Operation and Maintenance Manual for Electrostatic Precipitators. EPA/625/1-85/017. September 1988.

4. U.S. Environmental Protection Agency. Management and Technical Procedures for Operating and Maintenance of Air Pollution Control Equipment. EPA 905/2-79-001. June 1979.

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SECTION 6.0

CARBON ADSORBERS

This section provides guidance on proper operation and maintenance (O&M) of carbon adsorption systems (CASs) used as air pollution control devices to comply with applicable emission standards. It is also intended to assist Agency personnel responsible for making inspections at facilities that use CASs in the recognition and understanding of the indicators of efficient and reliable equipment operation.

6.1 General Description

Adsorption is a surface phenomenon in which volatile organic compounds (VOCs) are selectively adsorbed on the surface of such materials as activated carbon, silica gel, or alumina. Because it is the most widely used adsorbent, activated carbon is the focus of this section. Adsorption systems using silica gel or alumina are less likely to be found in air pollution control and, thus, are not discussed in this manual.

6.1.1 Principles of Adsorption

It is well established that the molecular forces at the surface of a liquid are in a state of imbalance or unsaturation. The same is true of the surface of a solid where the molecules or ions may not have all their forces satisfied by union with other particles. Because of this unsaturation, solid and liquid surfaces tend to satisfy their residual forces by attracting to and retaining on their surfaces gases or dissolved substances with which they come in contact. This phenomenon of concentration of a substance on the surface of a solid (or liquid) is called adsorption. The substance thus attracted to a surface is said to be the adsorbed phase or adsorbate, and the substance to which it is attached is the adsorbent. "Adsorption" should be carefully distinguished from "absorption". In the latter process, a substance is not only retained on a surface, but also passes through the surface to become distributed throughout the phase. Where doubt exists as to whether a process is true adsorption or absorption, the noncommittal term "sorption" is sometimes used.

The study of adsorption of various gases (or vapors) on solid surfaces has revealed that the forces operating in adsorption are not the same in all cases. Two types of adsorption are generally recognized, namely, "physical" (van der Waals adsorption) and "chemical" (activated adsorption).

Physical adsorption is the result of the intermolecular forces of attraction between molecules of the solid and of the substance adsorbed. For example, when the intermolecular attractive forces between a solid and a gas (or vapor) are greater than those existing between molecules of the gas itself, the gas will condense on the surface of the solid. The adsorbed substance neither penetrates within the crystal lattice of the solid nor dissolves in it; it remains entirely upon the surface. Should the solid be highly porous and contain many fine capillaries, however, the adsorbed substance will penetrate these interstices if it "wets" the solid. At equilibrium, the partial pressure of the adsorbed substance equals that of the contacting gas phase. Lowering the pressure of the gas phase or raising the temperature will readily remove the adsorbed gas or desorb it in unchanged form. Physical adsorption is characterized by the fact that the adsorption equilibrium is established rapidly and is reversible.

Chemisorption, or activated adsorption, is the result of chemical interaction between the solid and the adsorbed substance. The strength of the chemical bond may vary considerably, and identifiable chemical compounds may not form. Nevertheless, the adhesive force is generally much greater than that found in physical adsorption. The process is frequently irreversible; and, on desorption, the original substance will often be found to have undergone a chemical change.[1]

6.1.2 Activated Carbon

Activated carbon is composed largely of neutral carbon atoms with no electrical gradients between molecules. Thus, carbon does not attract polar molecules in preference to nonpolar molecules. Carbon is effective in adsorbing organic compounds from a humid gas stream because it does not show a higher affinity for the polar water molecules.

Activated carbon is made by a two-step process. In the first, material from various sources (e.g., coconut shells, petroleum products, wood, and coal) is carbonized by heating it in the absence of air until all organic compounds except the carbon are volatilized. High-temperature steam, air , or carbon dioxide is then used to make the carbon porous or activated. Depending on the extent of this process and the original source, the carbon can be made to fit the use for which it is desired.

After activation, the external surface of a carbon particle is a few square meters per gram; however, the available surface area within the pores is hundreds of square meters per gram. The pore structure of activated carbon consists of progressively smaller pore sizes. Diffusion of the adsorbate gas into the larger pores occurs fairly rapidly, but as the pore diameters become smaller, the diffusing molecules strike the walls and stick for short periods of time. This diffusion process continues until the molecules reach a location where they no longer have sufficient energy to escape the forces that hold them to the pore wall. This usually occurs where the pore diameter is not more than twice the diameter of the adsorbate molecule (critical diameter).

The purpose of a carbon adsorber is to transfer the adsorbate from the gas stream to the carbon, where it can more easily be recovered or disposed of. Therefore, at some point the adsorbate must be removed from the carbon. This process is called desorption or regeneration. Desorption is accomplished by shifting or reversing the equilibrium established during the adsorption process. There are three ways to shift the equilibrium: 1) increasing the temperature, which is usually done by the use of steam; 2) reducing the pressure of the atmosphere surrounding the carbon; and 3) reducing the concentration of the adsorbate in the gas stream to a value less than the concentration within the carbon. In most air pollution control applications, desorption is accomplished by increasing the temperature, whether by use of an in situ regeneration system or at a regeneration facility after the carbon has been replaced. After desorption, adsorbate remaining in the carbon is called the "heel." The heel will reduce the working capacity of the carbon for subsequent use, depending upon the total amount of residual adsorbate.[2]

6.1.3 Full-Scale Adsorption Systems

Carbon adsorption is used for pollution control and/or solvent recovery in a variety of industries. It is usually a batch operation, and it can involve multiple beds. Five types of adsorption equipment are used in collecting gases: 1) fixed regenerative beds, 2) disposable/rechargeable canisters, 3) traveling-bed adsorbers, 4) fluidized-bed adsorbers, and 5) chromatographic baghouses. Of these five, the first two are the most common.[3] In this document, the fixed regenerative bed is discussed in the most detail.

The practical application of the adsorption process to a full-size carbon bed is illustrated in Figure 6-1. In this figure, VOC-laden air (SLA) flows from left to right. As shown, the bed has three zones, labeled saturated, mass transfer, and fresh. The saturated zone, which is located at the entrance to the bed, represents the carbon that has already adsorbed its working capacity of adsorbate. Because the saturated carbon is at thermodynamic equilibrium with the incoming vent stream, no net mass transfer occurs in this zone. The mass transfer zone (MTZ) is the section of the carbon bed where the adsorbate is removed from the carrier stream. The carbon in this zone is at various degrees of saturation, but it is still able to adsorb some adsorbate. In a typical system, the mass transfer occurs within a section approximately 3 inches in depth. The fresh zone is downstream of the mass transfer zone and represents the region of the bed where no new adsorbate has passed since the last regeneration. This zone still has available all its working capacity (i.e., equilibrium capacity minus the heel).

During operation, the mass transfer zone moves down the bed in the direction of flow. Breakthrough occurs when the mass transfer zone first reaches the bed outlet. The breakthrough point is characterized by the beginning of a sharp increase in the outlet concentration. The available adsorption time for a specific bed before breakthrough occurs is a function of the amount of carbon present, its working capacity, and the concentration and mass flow rate of adsorbate.

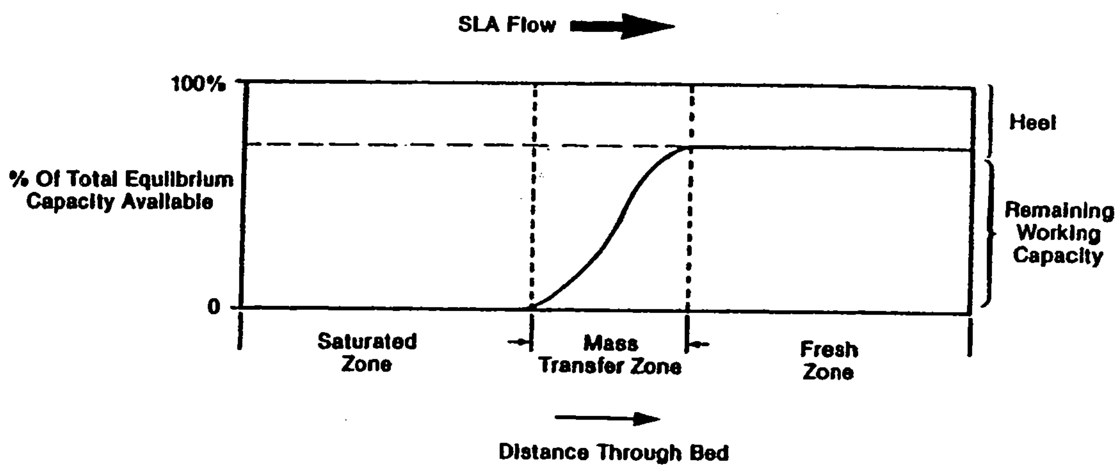

Figure 6-1. Available working capacity in a working bed as a function of distance through bed.[2]

Theoretically, the concentration in the last zone should be zero; however, a small amount of adsorbate is typically present as a result of two factors:

1. A small amount of SLA may pass through the adsorber without actually contacting the carbon.

2. Because of the low concentration of adsorbate in the vent stream in the last few inches of the bed, the heel remaining from the previous cycle will slowly desorb.

The breakthrough curve, which is the outlet concentration as a function of time, is a mirror image of the concentration profile in the mass transfer zone. As the mass transfer zone reaches the end of the bed, the outlet concentration rises. This will continue until the outlet equals the inlet concentration.[2]

Fixed Regeneration Bed Systems--

Figure 6-2 presents a process flow diagram for a typical two bed carbon adsorber system. The adsorber system can be broken down into three separate sections: pretreatment, carbon adsorber, and recovery/waste treatment. The vent stream containing the adsorbate enters the adsorption system via the pretreatment section. If the temperature of the vent stream is above the maximum specified in the design, it is reduced within the pretreatment section (usually with a heat exchanger). In addition, a filter is included in the pretreatment section to remove any particulate present in the vent stream.

From the pretreatment section, the vent stream enters the adsorber. Figure 6-2 depicts a two-bed adsorber system. At least two adsorber beds are needed to provide continuous emission control so that one remains on line while the other is regenerated. Adsorber systems with three or more beds are operated similarly. During operation, the organic-laden vent stream passes through the on-line bed for a predetermined time or until breakthrough occurs. The on-line bed is then taken off line for regeneration (desorption) and the other bed is brought on line.

Regeneration of the off-line bed is usually accomplished by passing steam through the bed countercurrent to the direction of vent stream flow. The steam that is

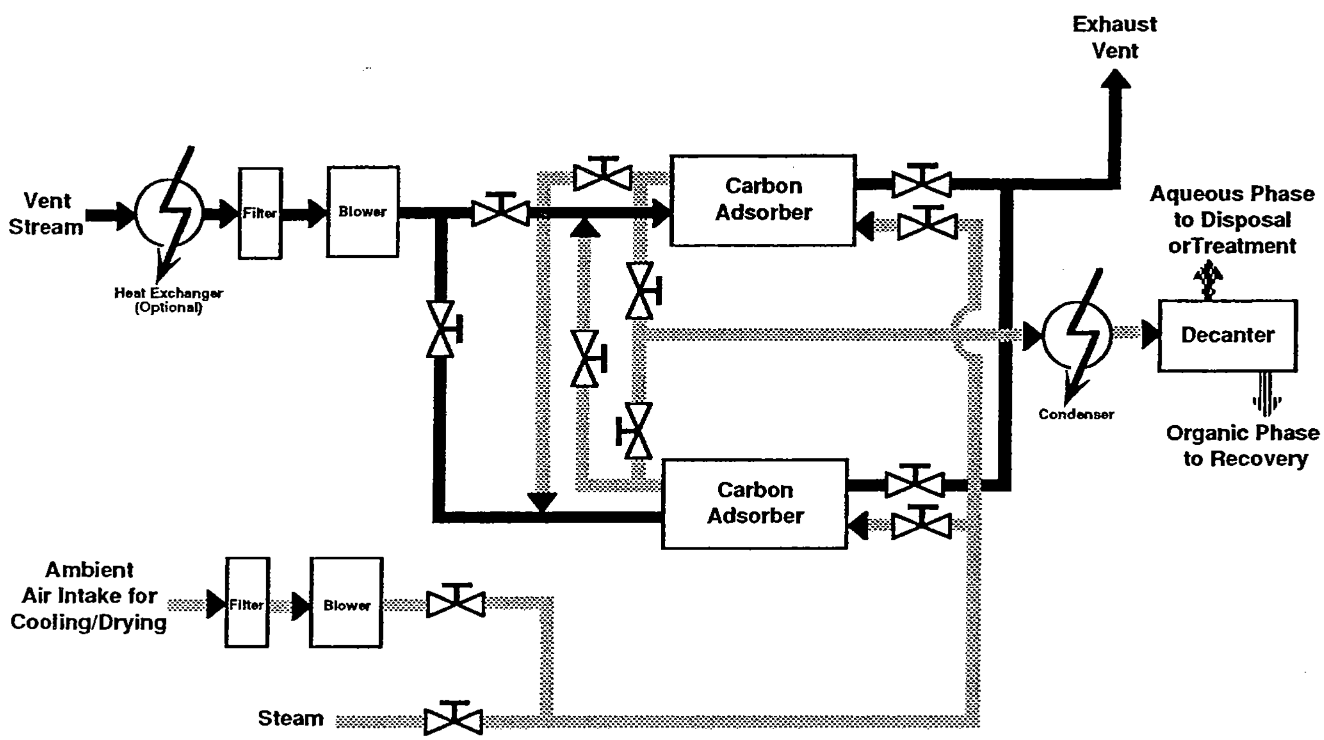

Figure 6-2. Carbon adsorber system process flow diagram.[2]

injected into the bed serves several purposes: 1) it provides the energy to raise and hold the bed at an elevated temperature, 2) it provides the energy required to desorb the adsorbate from the carbon, and 3) it carries the desorbed adsorbate from the bed. The steam is condensed and then decanted.

Two liquid phases are present in the decanter, the aqueous phase and organic phase. The aqueous phase is either disposed of or, if the level of organics is high, treated prior to disposal. The organic phase is generally recovered for reuse. After the desorption step, heated air is sometimes used to dry the bed. This is not required in most cases, however, because removing water from the carbon usually has little effect on the adsorption process. In fact, the moisture left on the bed can be beneficial because it acts as a heat sink during the adsorption process.

Finally, the regenerated bed is cooled by passing ambient air through it. In a well-designed system, both cooling and drying are performed with the airflow countercurrent to the direction of flow when the adsorber is on line. The air exiting the regenerating bed is directed through the on-line bed to remove any trace adsorbate.

Full Scale System Design Considerations--

Both the physical system design and the system control and operation during adsorption and desorption are important to achieving high removal efficiencies on a continuous basis.

The design of full-scale carbon adsorption systems begins with a determination of the inlet stream characteristics. Characteristics that may be important include:

- Specific compound(s) present
- Flow rate and temperature (range and average)
- Adsorbate concentration (range and average)
- Relative humidity

Any commercial activated carbon should be capable of acceptable performance if the design of the system is based on that particular carbon. Selecting a carbon with a majority of micropores that are smaller than approximately twice the diameter of the adsorbate molecules will result in the greatest adsorptive forces.[2] Under certain conditions, however, the carbon adsorption process may not be suitable for some VOCs. Compounds with one or more of the following physical/chemical properties may not readily adsorb or remain adsorbed to carbon especially at low gas stream concentrations, elevated temperatures, or high relative humidities:

- Molecular weight < 50 g/g-mol
- Boiling point, at atmospheric pressure, < 20°C
- Index of refraction (as a measure of the compound's degree of polarity) ≤ 1.40.

Light-molecular-weight polar compounds with relatively low boiling points may exhibit extremely low adsorption capacities at low concentrations (e.g., vinyl chloride, methylene chloride, ethylene bromide, and formaldehyde). At concentrations in the low parts per million range or less, the mass transfer zone of these compounds can quickly move through the carbon bed and result in hastened breakthrough. In addition, other compounds in the gas stream with a higher affinity for carbon adsorption will often dislodge (desorb) these compounds. As more strongly adsorbed compounds displace the less strongly adsorbed ones, they push them through the bed, which creates a wave front of the lower-molecular-weight compounds at the front of the MTZ. Therefore, rapid breakthrough of these compounds may result in high carbon replacement/regeneration cost.[4]

When the carbon has been selected, the required bed area is calculated based on the desired superficial velocity. For a specified flow rate, the bed area determines the superficial velocity of the vent stream through the bed. The lower limit of superficial velocity is 20 ft/min to insure proper air distribution. The upper limit is usually 100 ft/min. This upper limit is to keep bed pressure drops within the discharge head capacities of the types of fans used in these applications and to avoid excessively high system power costs. Typical superficial velocities are based on vendor experience and the results of pilot-scale testing; they will usually be between 50 and 100 ft/min.

Generally, bed depths of carbon adsorbers range from 1.5 to 3.0 feet. A bed depth of at least 1.5 feet is used to insure that the bed is substantially deeper than the MTZ, which is normally 3 inches deep. If the MTZ is longer than the bed, breakthrough will occur almost immediately. The maximum bed depth of 3 feet is based on keeping system pressure drop within reasonable limits.

Steaming requirements are set as part of the initial system design. The longer the bed steaming time, the greater the amount of adsorbate removed and the smaller the amount of removable heel remaining. As previously discussed, the working capacity of a carbon bed, which is the amount of adsorbate the bed can remove during an adsorption cycle, is the difference between the heel and the equilibrium capacity. Therefore, the longer the bed is steamed, the greater the available working capacity.

In well-designed systems, the bed is steamed countercurrently to the direction of flow during adsorption. This will help minimize the adsorbate emitted at the adsorber outlet prior to breakthrough. After steaming, the concentration of adsorbate (i.e., the amount of heel that remains) is lower at the end of the bed where the steam enters. When the adsorber is brought on line, the lower amount of heel where the SLA exits the bed means less adsorbate is available to desorb. Also, having more working capacity available at the bed exit helps prevent momentary increases in outlet concentration as a result of changes in inlet conditions caused by process upsets.

Another consideration in adsorber design is fouling. Fouling occurs when compounds that will not desorb from the bed are present in the vent stream. These compounds can be solid particles, high-molecular-weight compounds, or compounds that chemically react on the surface of the carbon (such as some ketones). Regardless of the source, bed fouling gradually reduces the carbon adsorption capacity.

Two methods can be used to compensate for fouling. One is to increase the volume of carbon beyond the minimum required to achieve the desired adsorption time. The second is to gradually increase the amount of steam used to regenerate the bed. Increasing the steam used in regeneration reduces the heel, which helps maintain sufficient working capacity. A combination of these methods can also be used.

Figure 6-3 shows a typical adsorption/desorption cycling arrangement for a two-bed adsorber system. For the purpose of discussion, the times shown on the figure correspond to operational aspects of the system. The sequence begins with Bed 1 coming on line as Bed 2 goes off line at t_0. For the example shown, adsorption lasts 90 minutes, the steaming time is fixed at 30 minutes, and the cooling/drying time is also 30 minutes. The off-line bed is on standby for 30 minutes. In this example, this 30 minutes allows the operator to compensate any daily variations in vent stream conditions and bed fouling without having to leave a bed on line after breakthrough. It is important that a bed not be left on line after breakthrough because that will significantly reduce the overall removal efficiency during that cycle.

Two types of trigger mechanisms are used to control the adsorption/desorption cycles: continuous monitors and timers. Continuous monitors take a bed off line when a specified outlet concentration is reached. Timers cycle the bed at a specified time. A combination of both mechanisms may also be used. One advantage to using continuous monitors is that they allow the beds to remain on line until breakthrough; thus, their full capacity is used during each cycle. This is not the case for a timer-based system because properly guarding against breakthrough requires that allowances be made for variations in the breakthrough time due to changes in the inlet stream characteristics.[2]

Although continuous monitors allow for the use of more of the available adsorption capacity than timers do, timers can be used as the trigger mechanism in many situations. They are especially appropriate for adsorbates that do not foul the bed or where inlet stream characteristics are very stable. If a timer is used, continuous monitors or a periodic sampling program should be used to adjust the adsorption times as necessary. Deviations in operating conditions do not affect properly designed systems that use timers unless the conditions exceed the range of the design specifications. When this is allowed to occur, a bed may be kept on line after breakthrough. This would significantly reduce removal efficiency.

A final and important consideration in system design is prevention of channeling. Channeling occurs when a portion of the SLA bypasses the bed or a certain section of

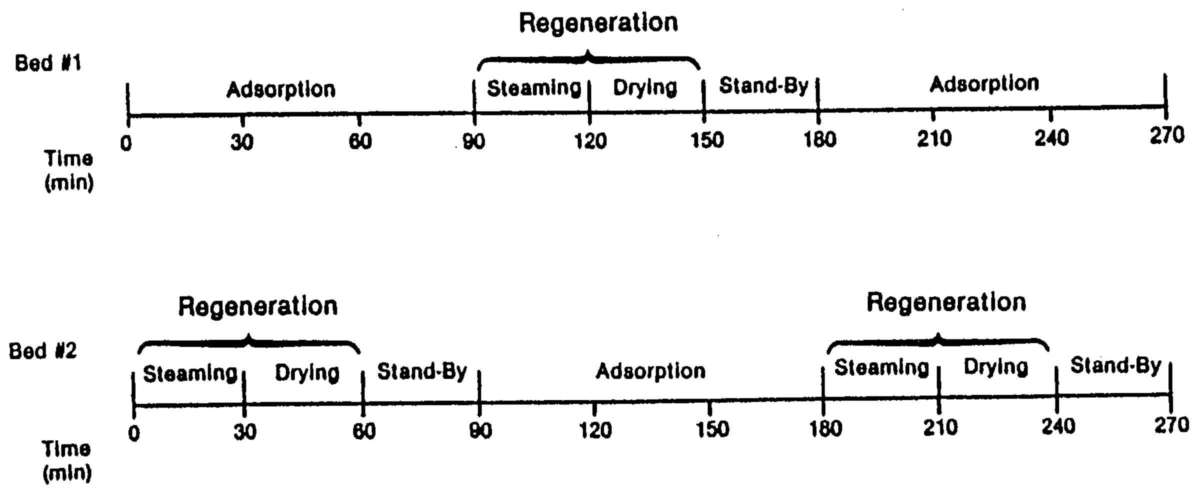

Figure 6-3. Adsorption/desorption cycles in a two-bed system.[2]

the bed receives a greater portion of the flow than other sections do. The inlet of the vessel must be designed to achieve proper distribution of the SLA so that it does not impinge on a portion of the bed at high velocity. The potential for channeling can be minimized by the use of distribution baffles. It is also important to achieve proper distribution of the regeneration steam. If steam is not well distributed, the steam flow can also cause channels to form in the bed. Poor steam distribution can also result in some portion of the bed not being properly regenerated.

Proper design can minimize the potential for channeling. Maintenance of the distribution baffles and steam distribution system, however, should be performed during scheduled system shutdowns or whenever an increase is detected in the adsorber outlet VOC concentration which is significant enough to result in a removal efficiency below the minimum design level.[2]

Disposable/Rechargeable Canisters--

For very small vent flows, flows of an intermittent or infrequent nature, and effluents with very low sorbate concentration, utilization of disposable canisters of carbon or other sorbent may be an economical and desirable control approach. Disposable paper and fiber cartridges have been developed that contain the sorbent as a fine powder dispersed in and on an inert carrier of paper, organic or inorganic textiles, and plastic filaments. Paper can contain 50 to 75 percent carbon by weight, and cellulose filters with up to 80 percent activated carbon are available. Such elements, however, are rarely used by industry. A more frequently used element is a replaceable and disposable canister filled with granular sorbent held in a permanent container in the vent line and operated until the sorbent approaches saturation. The canister is then manually removed much like a cartridge filter and disposed of as solid waste (landfill, solid waste incinerator, etc.). Consideration should be given to the disposal method and the possible release of the sorbate as a further environmental pollutant.

For emission control in remote locations, such as breathing losses from a storage tank containing volatile solvents or hydrocarbons, 55-gal steel drums of granular carbon are available from several sources. These drums are specially fitted with inlet and outlet nozzles. Such a drum installed on the vent of a benzene storage tank continuously venting 0.1 ft^3/min of vapor containing 13.5 percent benzene by volume would have a useful life of 2 weeks. When saturated, the spent carbon is replaced with fresh carbon. The spent carbon can be handled as combustible solid waste, but often arrangements can be made to return it to the carbon manufacturer for regeneration.[5]

Traveling Bed Adsorbers--

Continuous countercurrent column adsorbers have been designed and used with limited operation. Both downward-traveling packed-column units and tray units have been used. In both, freshly regenerated adsorbent is elevated and added at the top of the column at a rate that maintains a constant height of solids. A mechanism is provided at the bottom for steady removal of saturated sorbent, which is then regenerated in another vessel before the adsorbent returns to the top. Gas to be treated enters at the bottom and passes up the column being purified and leaves at the top. In a traveling packed-bed unit, all the bed rests on a bottom support grill or grate and the gas passes upward through the voids in the granular bed of solids. With the tray design, solids are fluidized on each tray by the gas rising through sieve-plate holes in the tray. The solids slowly travel across the tray to a downcomer that conducts the solids to the tray below, and the design much resembles that of a plate-type absorption column.[5]

Fluidized-Bed Adsorbers--

Unless bed staging is practiced, a single-stage fluidized bed adsorber would not appear to be a desirable adsorption mechanism at first glance. All sorbent particles in such a bed are well back-mixed, and a typical "adsorption wave" does not occur in the bed. Because all particles are in equilibrium with the outlet gas, low outlet pollutant concentrations can be attained only if all the bed particles are kept relatively unsaturated. This makes the adsorptive capacity of the bed low, and the concept would be unattractive were it not for the ease with which adsorbent particles can be removed, externally regenerated, and returned to the bed on a continuous basis. An advantage of the fluidized bed is the ability to obtain high heat transfer rates with cooling tubes submerged in the bed to remove the heat of adsorption. It also has merit in a situation where frequent sorbent regeneration is needed. In addition, it might have application for adsorption of organics from a very moist gas stream where frequent carbon regeneration is needed to remove adsorbed water.[5]

Chromatographic Baghouses--

In this approach, granular adsorbent is continuously introduced at a controlled rate into the gas stream to be treated, and the gas stream conveys the suspended adsorbent through a contact area of adequate length and residence time to provide appreciable contact and adsorption before entering a conventional fabric filter. The sorbent is filtered from the gas stream on the surface of the bags and further adsorption may occur as additional gas passes through the collected cake of sorbent. Periodically, the sorbent is removed from the bags in the conventional manner. Because the flow of sorbent and gas is concurrent, the exit concentration of pollutant is controlled by the ratio of sorbent to gas used, and to a lesser extent by the contact time provided. Such a system cannot completely saturate the sorbent and reach extremely low outlet pollutant concentrations. With suitable sorbents, however, the spent solids removed from the baghouse can be regenerated and recirculated.[5]

6.1.4 Auxiliary Equipment

No adsorber system could operate without adequate auxiliary equipment and components to collect, transport, and filter vapor-laden airstreams being delivered to the adsorber. These components must be properly designed to provide proper service to the adsorber. The ducts and piping must be sized properly for required air velocities to optimize the efficiency of the adsorber. If the air velocity is too high, the stationary-bed adsorber may become a fluidized-bed adsorber, or low flows may create severe channeling through the beds. The fan is the catalyst for forcing the gas stream into and out of the unit, so it is important that careful attention be given to the design and sizing of this equipment.[6]

Because there are several adsorber configurations, the location of a filter can vary. It can be placed before the inlet airstream (in a stationary bed) to reduce possible contamination to the adsorbent, or it can be placed after the fluidized-bed adsorber to reduce particulate emissions. The filter efficiency can be monitored by measuring the pressure drop across the filter with either a manometer or a pressure gauge that will read from 1 to 20 inches water column.

Some adsorber systems require compressed-air systems for valve and damper operation. For best results, the air supply should be kept contaminant-free through the use of a filter installed close to the adsorber. The compressed-air supply should be equipped with an in-line filter, a pressure regulator, and a lubricator.

Following adsorption, several devices are installed in series for recovery of the contaminant after regeneration. Condensers and separators are examples of recovery devices. The condenser is installed just after the system for removal of the heat from the vapors. There are two basic types of condensers: surface condensers and contact condensers. In a surface condenser the coolant does not contact the vapors or condensate. Most surface condensers are of shell-and-tube configurations. Water flows through the tubes and vapors condense on the shell side. In contact condensers, the coolant vapors and condensate are intimately mixed. These condensers are more flexible, simpler, and considerably less expensive to install. Sizing these condensers is also more straightforward.

Separators (decanters) are installed after the condenser to separate the contaminant from the water. Separators work on the principle of gravitational forces, where the heavier material to be separated is removed from the bottom of the canister and the lighter material is removed through a line located at the top of the canister. Water separators are more effective with single solvent applications and when the solvent is immiscible in water.[1]

Foul condensate from the decanter or water separator may still contain recoverable solvent or water-soluble compounds. To meet regulatory effluent standards and/or to further recover solvent may require the use of air- or steam-stripping of the foul condensate. In such cases, the stripping offgases may need to be controlled, typically by carbon adsorbers or by thermal or catalytic incinerators.

6.1.5 Key Operating Parameters

Key operating parameters for carbon adsorbers include:

- Operating temperature
- Inlet and outlet adsorbate concentration
- Gas stream relative humidity
- Gas volumetric flow rate
- Steaming conditions

In addition, changes from the initial design operating conditions should be considered, including adsorbate type(s) and steaming conditions for regenerable carbon adsorbers.

Temperature--

The operating temperature of an adsorber can be affected in three ways: 1) changes in the inlet stream temperature, 2) exothermic chemical reactions taking place inside the adsorber, or 3)failure of the cooling step after regeneration. Changes in the inlet stream's temperature lead to changes in the adsorber operating temperature. Changes in the inlet solvent loading can change the rate of heat generation because of the heat of adsorption. Heat can also be generated within the system by chemical reactions taking place on the bed. Ketones in particular have been identified by several studies as particularly reactive compounds. The problem is usually not serious, however, unless the concentration of adsorbate is extremely high, the gasflow rate through the carbon is relatively low, and the carbon is dry and contains no heel.

Each of these possible scenarios results in a variation in the temperature at which the adsorption process takes place. Therefore, the effect of temperature on breakthrough must be evaluated. The relationship between carbon capacity and temperature indicates that as the temperature within the bed increases, the adsorptive capacity of the carbon decreases. Thus, as the temperature increases, the working capacity of the carbon also decreases. A shift in this direction has no effect on the achievable removal efficiency, but it does require a change in the cycle time to compensate for the shift.

Changes in operating temperature should not cause an increase in the baseline outlet concentration prior to breakthrough because the outlet concentration at the beginning of the cycle is primarily a function of the heel remaining in the last few inches of the bed. The amount of heel is established by the bed steaming conditions during desorption. Only if the temperature of the carbon in the adsorber rises to values close to those during steaming is there a chance the removable heel will desorb and subsequently decrease the achievable removal efficiency.

Temperature fluctuations in the inlet stream can essentially be eliminated by installation of a heat exchanger upstream of the carbon adsorber. A properly designed system will not permit the inlet temperature to exceed the maximum design temperature.[2]

Inlet and Outlet Adsorbate Concentration--

The concentration of organics in the inlet stream may vary because of process changes. Short-term variations are those that occur within a given cycle, whereas long-term variations may last over several cycles. Changes can occur as equipment or product lines are either brought on or taken off line.

For the purpose of this discussion, the flow rate through the bed is assumed to remain constant. Therefore, when the concentration increases, the loading rate to the adsorber increases.

Increasing the concentration will increase the working capacity of the carbon. The working capacity increase, however, will not be large enough to offset the increase in mass loading completely. Therefore, the net effect will be a decreased working capacity. The effect of variations in inlet concentration on the outlet concentration prior to breakthrough should be negligible. As stated previously, the outlet concentration is a function of the heel that remains in the last few inches of the bed after regeneration. Because the inlet stream reaches equilibrium with the carbon within the mass transfer zone, the amount of heel at the adsorber outlet is independent of inlet concentration. Thus, short-term variations in the inlet concentration will not increase the baseline outlet concentration.[2]

An increase in outlet concentration generally indicates breakthrough and that it is time to regenerate or replace (in nonregenerative systems) the carbon bed. A detected increase of hydrocarbons above a setpoint using a continuous hydrocarbon monitor can be used to start the regeneration cycle.

Gas Stream Relative Humidity--

With relatively high inlet concentrations, relative humidity does not significantly affect working capacity. Because this is generally the case for adsorbate concentrations greater than 1,000 ppm, only a slight change should occur in the breakthrough time associated with variations in relative humidity in this case.

Below adsorbate concentrations of 1,000 ppm, water begins to compete with adsorbate for the available adsorption sites, and the bed working capacity for that adsorbate is then affected. In this case, some type of dehumidification system upstream of the bed or dilution with ambient air may be required. Relative humidity has no effect on the amount of heel that is retained within the carbon pores.

High relative humidities are present in most operating systems, regardless of the vent stream conditions because of the water remaining on the bed after steaming. The working capacity gained by reducing the humidity is small. In this case, reducing steam humidity would probably not be cost-effective. In addition, the water content in the bed provides a heat sink valuable in controlling bed temperature.[2]

Volumetric Flow Rate--

The superficial bed velocity for a system changes as the volumetric flow to the system changes. The primary effect is to change the depth of the mass transfer zone within the bed. As the superficial velocity increases, the depth of the mass transfer zone also increases, as the individual carbon pellets are exposed to the adsorbate for a shorter period and the quantity removed at a given point decreases. The effect of a deeper mass-transfer zone is that the time prior to breakthrough is shortened by increases in volumetric flow rate.[2]

Steaming Conditions--

As previously discussed, steaming requirements are determined as part of the initial system design. Variables that must be considered are the steaming temperature, duration, and rate. Because steam temperature is generally fixed for a given plant, the effect of temperature is not discussed. The amount of steam required is determined by the required working capacity. Once the initial design is set, if the amount of steam used per desorption cycle remains constant, the available working capacity will also remain constant, assuming no fouling or other degradation of the carbon bed.

In actual application, however, the carbon's total adsorption capacity gradually decreases over time due to fouling. If the operator desires to maintain the same breakthrough time, steam use per desorption cycle must be gradually increased. At some point the amount of steam required per desorption cycle becomes so great that either insufficient time remains to complete desorption before breakthrough of the on-line bed or the cost of steam becomes too great. At this point the carbon must be replaced.

Although the amount of steam is important in the desorption process, duration is also a consideration. To remove the adsorbate, sufficient time at the steaming temperature is required to allow for diffusion of the adsorbate out of the pores and out of the carbon particles. Without sufficient time, increasing the flow of steam will not remove the adsorbate from deep within the pores of the carbon.[2]

6.2 Monitoring Carbon Adsorption System Operation

System monitoring may include measurement and recording of key operating parameters as well as discharge monitoring for solvent breakthrough. Monitoring of operating parameters may include:

- Operating temperatures
- Outlet VOC concentrations
- Gas flow rate
- Steaming conditions
- Pressure drop

6.2.1 Monitoring Systems

Instrumentation for measuring any or all of these parameters may range from simple to complex. The most recent plant installations may have the capability to generate daily reports of plant operations, such as overall performance, alarm conditions, efficiency, and energy consumption. In some cases, these data may be transmitted via modem to offsite locations for purposes of troubleshooting or detailed diagnosis.

Operating Temperatures--

Inlet gas temperatures and the temperature of the carbon bed can be measured by simple thermocouples. The thermocouples can be permanently installed in the duct, or they can be portable and inserted during inspections. Permanent thermocouples can be connected to continuous recorders with digital, analog, or strip-chart display.

Outlet VOC Concentration--

Outlet VOC concentration monitoring can demonstrate whether breakthrough occurs. Although not an exact test, it is probable that a system that goes through several cycles of full-load operation without reaching breakthrough is operating at adequate adsorption efficiencies. Determination of the presence or absence of breakthrough requires continuous measurement of VOC concentrations in the 0- to 500-ppm range. Several types of instruments are currently available for measuring solvents at these low levels, including:

- Flame ionization detectors (FIDs)
- Photoionization detectors (PIDs)
- Diffusion sensors.

These systems each have some advantages and disadvantages. They require calibration for the solvent being measured if exact measurements are required, but they can also be used without calibration to indicate relative concentration levels. If the output of a suitable detector is connected to a recorder, the adsorber discharge concentration can be monitored over several cycles to determine if breakthrough occurs. For a facility operating at normal production rates, the absence of breakthrough may be taken as evidence that the adsorption system is operating satisfactorily. For successful testing, an inspector must become familiar with the use of the instrumentation, the required safety considerations, and its application to carbon adsorption systems.[7]

When these monitors are used, care must be taken to ascertain that all VOC compounds can be detected by the instrument. For example, vinyl chloride exhibits an ionization potential of 9.995 eV. Therefore, if a PID is used to monitor breakthrough, the ultraviolet ionization source (bulb) must be of equal or greater potential. Use of a bulb with lesser potential will not ionize vinyl chloride or other VOCs with ionization potentials equal to or greater than vinyl chloride (i.e., the instrument will be blind to these compounds).

Gas Flow Rate--

Of particular concern are gas flow and distribution. Excessive airflow will reduce carbon efficiencies and allow volatiles to escape to the atmosphere. Inadequate airflow or incorrect damper adjustment may cause uneven airflow distribution to systems with multiple beds in parallel. This may promote uneven adsorbtion between beds and eventual premature breakthrough from the bed(s) receiving the greatest airflow.

A pitot tube traverse is normally used to measure total gas volume. Use of the pitot tube method relies upon the procedures specified in U.S. EPA Reference Methods 1 and 2. The pitot tube traverse samples gas velocity and the duct cross-sectional area.

Most facilities do not measure gas volume. Other indicators may be used to estimate the gas volume or to indicate changes from a baseline measurement. The alternate parameters include fan operating voltage or amperage, production rate, or gas condition (e.g., percent O_2, CO_2).

Steaming Conditions--

Steaming conditions can be monitored by measuring steam temperature and pressure with a thermocouple and magnehelic gauge, respectively, and observing the duration of the carbon regeneration cycle. These parameters can be compared to design values to aid in determining if beds are being fully regenerated.

Pressure Drop--

The pressure drop across a carbon adsorber can be used as an indicator of proper gas flow, carbon bed plugging, or carbon bed channeling.

Static pressure gauges such as magnehelic gauge or manometer can be installed at the inlet and outlet of the carbon adsorber to determine the unit's pressure drop. Portable pressure meters can be used as an alternative to differential pressure gauges. Hand-held static pressure gauges inserted through pressure taps provide a simple method of taking pressure readings. This technique is less expensive and reduces potential problems of meter moisture or corrosion damage and clogging; however, the readings are not continuous.

6.3 Routine Inspection and Maintenance Procedures

Effective air pollution control with carbon adsorption must be accompanied by a routine maintenance program. The program should provide for scheduled inspections of all equipment components, as well as all necessary monitoring of operating parameters to ensure correct operation and optimum performance of the control equipment.

Routine maintenance of air pollution control equipment can also be important because equipment failure can be expensive in terms of lost production, lost solvents, degradation of air resources, and potential effects on employee health. Each component must operate properly to ensure steady, efficient output and the desired results from the system.

Establishing an equipment maintenance program need not be elaborate or complicated. The work involved in routine inspection and servicing may largely be performed by shop personnel operating the control equipment. Of course, extensive repairs or rebuilding should be accomplished by skilled and trained maintenance personnel. System components of the carbon adsorber that require routine maintenance fall into four major categories: 1) air handling, 2) adsorbing, 3) stripping, and 4) reclaiming.

The function of the air-handling apparatus is to collect, transport, and deliver particulate-free, solvent-laden air to the adsorber. Any leaks in the ductwork on the suction side of the fan will introduce excessive ambient air into the system and result in a reduction of VOC concentration and poor adsorber efficiency. Air-duct leakage on the pressure side of the fan will discharge unwanted VOC vapors into the work place. Leakage checks should be performed periodically, especially at flexible connections, at joints in the ductwork, on the fan and filter housing, and around the adsorber bed dampers. Accurate collection velocity data should be established by routinely checking the capture velocity at the source with a vane-type velocity meter or a thermal anemometer. Correct operation of flow-indicating devices within the ducts can be verified by mechanically stopping flow to the duct or by turning off the fan motor.

Ventilation system imbalance may also occur from time to time and may require periodic adjustments to dampers to rebalance the system. The particulate filter bag installed in-line ahead of the adsorber beds should be equipped with a differential pressure gauge to indicate dirty or stopped-up filter media. The bag should be changed or cleaned when the differential pressure increases by 1 inch (water) or more.

Maintenance inspections on the adsorption-cycle equipment are somewhat more complex than for the air-handling apparatus. The integrity of the activated carbon must be maintained to ensure efficient removal of VOC vapors from the airstream. As the carbon particles erode with time and the capillaries become plugged with contaminants and polymers, the granules gradually lose their ability to adsorb and retain VOC molecules. Carbon adsorbability and retentivity should be tested regularly by opening up the bed and extracting carbon samples from the top, center, and bottom layers. Laboratory analysis will reveal the effectiveness of the carbon bed. Most manufacturers of activated charcoal will perform adsorbability and retentivity tests for their customers. If the carbon fails these tests, all the adsorbent should be removed from the system and regenerated or replaced.

Maintenance requirements on the desorption-cycle equipment primarily involves the steam supply, valving, and timer controls. Steam pressure on the carbon tanks should be regulated to minimize steam stripping pressure (3 to 10 psi on perchloroethylene [PCE]). Lower steam pressure will require too much run time to strip the beds adequately, whereas pressure that is too high will tend to fluidize the bed and create excessive erosion of the carbon granules. Steam traps must be operative or water will be carried into the carbon beds and retard proper stripping action. Periodically, the steam pressure relief valves located in the supply line and in the main carbon tanks should be checked for correct pressure settings by increasing steam pressure until the valves "pop off." Steam leaks around gaskets and operating dampers should be corrected by replacing the gaskets and seals. Gasket materials that are in contact with the solvent vapors must withstand the chemical properties of that particular solvent. Often the gasket material supplied with the system may not be suitable for the VOC presented to the adsorber, and a substitute material may be required. Leaks around the carbon tanks may create additional problems of corrosion around the leak. Boiler feedwater treatment may require some modification if "carryover" chemicals are introduced into the carbon beds and create corrosion problems.

The apparatus used to reclaim the VOC requires little maintenance. The automatic cooling-water valve should be checked for proper opening and closing operation. Automatic mechanical valve shafts and other mechanisms should be lightly oiled. The condenser may eventually become inefficient because of excessive buildup of solubles from the cooling water. Acidizing of the water jacket or tubes may be required to renew condenser efficiency. Inadequate separation of water and VOC in the decanter may indicate a plugged vent line. All vent lines and drain lines must be unrestricted for correct operation of the system.

In general, normal maintenance procedures should be followed in routine cleaning of electrical contacts; lubrication of all bearings, compressed-air components, and air cylinder shafts; replacement of obviously broken or worn parts; and housekeeping practices around the adsorber. In the final analysis, common sense is the best maintenance tool available in view of the fact that a large percentage of carbon adsorber equipment failures can be traced to neglect, improper operation, or just plain abuse.[1]

Figures 6-4 and 6-5 present example daily and weekly inspection forms for carbon adsorbers. These forms should be tailored to specific carbon adsorption systems and applications. Inspection forms for longer periods (i.e., monthly, quarterly, and annually) are not included because they are highly specific to the carbon adsorbtion system design and to the process being controlled. Figure 6-6 shows an example maintenance report form.

DAILY CARBON ADSORBER INSPECTION FORM	
Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (print):
Carbon Adsorber ID:	Signature of Inspector:
INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS
System Motors and Fans Operating? Drive Belts OK?	
Visible Liquid Leaks Pumps Carbon Adsorber	
System Gas Leak?	

Outlet VOC concentration ____________ ppm   Steam Pressure ____________ in WG

Temperatures: Gas ____________ °F   Adsorber ____________ °F   Steam ____________ °F

Pressures: Inlet _________ in WG   Outlet ____________ in WG

Carbon Regeneration time ______________ min.

Regeneration set point ____________ hrs or ________________ VOC ppm

Figure 6-4. Example daily carbon adsorber inspection form.

WEEKLY CARBON ADSORBER INSPECTION FORM	
Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (print):
Carbon Adsorber ID:	Signature of Inspector:
INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS
Bearings Greased?	
Ductwork Condition? Corrosion Air Leaks	
Check Pressure Gauges for Clogging	
Calibrate VOC Instrument	
Time between regeneration cycles ________ hrs Time for regeneration cycle ________ min VOC concentration after regeneration ____________ ppm VOC concentration just before regeneration ________ ppm	

Figure 6-5. Example weekly carbon adsorber inspection form.

MAINTENANCE REPORT FORM

Department	Unit	System	Subsystem	Component	Subcomponent

Originator: ____________________ Date: __________ Time: __________

Assigned To:

1	Mechanical
2	Electrical
3	Instrumentation

Priority:

1	Emergency
2	Same Day
3	Routine

Unit Status:

1	Normal
2	Derated
3	Down

Problem Description: ____

____

____

____

Foreman: ____________________ Date: __________

Job Status:

1	Repairable
	Hold for:
2	Tools
3	Parts
4	Outage

Cause of Problem: ____

____

____

Work Done: ____

____

____

Supervisor: ____________________ Completion Date: __________

Materials Used: ____

____

____

Labor Requirements: ____

____

Figure 6-6. Example maintenance report form.

6.4 Equipment Problems and Troubleshooting

6.4.1 Troubleshooting

An overall system material balance, taken over a reasonable time period, is one of the best techniques for determining overall system efficiency and to detect system problems and malfunctions. To use a material balance, the plant must maintain accurate records of VOC-containing materials entering the process and of the recovered solvent. Recovered VOCs returned to the process is considered as part of the VOC entering the system. The VOC concentration of all materials entering the process must be known. Figure 6-7 shows a form for performing a VOC material balance.

Most of the information can be assembled from shipping data and from component data available from raw-material suppliers. The information needed to complete the material balance is the quantity of recovered VOC. This information is only available directly from the source through the use of totalizing flowmeters that measure VOC from the recovery systems. Nonregenerative installations do not have these flowmeters installed; therefore, the material balance procedure will not be applicable to every carbon bed installation.

A third efficiency evaluation procedure can be used for systems that use instruments (such as flowmeters) to provide data that can be used to calculate steam-to-recovered-VOC ratios. If one assumes a constant VOC input into the system and a constant length of adsorption cycles, a decrease in the ratio of VOC to steam is indicative of a decrease in collection efficiency. This technique is readily used on systems recovering immiscible VOCs and having flowmeters on both the VOC and water streams following the decanter. Although the techniques will alert maintenance/inspection personnel to a malfunction of some type in the carbon-bed system, it is unfortunately of little aid in diagnosing the problem.

Several types of visual inspections can also be used to help evaluate or troubleshoot a carbon adsorption system. The first visual check that can be made is to

CARBON BED ADSORPTION SYSTEM MATERIAL BALANCE

Inventory Period: From ____________ to ____________.

INPUT

(a) Solvent containing materials:
# of materials x (# solvent/# material) = # solvent.
1.
2.
3.
4.
5.
6. Total solvent in raw materials (in #) (=1 + 2 + 3 + 4 + 5) ______

(b) Purchased solvent
7.
8.
9.
10.
11. Total purchased solvent (in #) (=7 + 8 + 9 + 10) ______

RECOVERED SOLVENT

12. Total solvent from recovery system ______
13. Solvent sold ______
14. Recycled solvent (=12-13) ______

% OVERALL EFFICIENCY

$$100 \times \frac{(12)}{(6) + (11) + (14)} = \quad \%$$

Note: If the solvent-recovery system returns more than one solvent stream, a separate sheet should be prepared for each solvent stream. Overall efficiency is the average of the efficiencies for each stream.

Figure 6-7. Overall material balance for facilities using solvent recovery systems.[2]

determine if the proper bed is on the adsorption or desorption cycle according to the mode selection of the control panel.

If the system operates on timed cycles, a check should be made to determine if the bed actually changes at the predetermined time (the cycle duration). At this time, the inspector may also inquire as to the rationale for the cycle duration. Sometimes operating conditions no longer coincide with design specifications and cycle times have not been adjusted accordingly to insure adequate system performance.

The concentration setting of the organic analyzer being used to monitor the carbon adsorber outlet concentrations should be checked to see if it is within reasonable limits. If possible, the zero setting of the device (as described in the operating manual) should also be checked.

6.4.2 Equipment Problems

Bed Fouling--

Bed fouling gradually decreases working capacity by tying up the active adsorption sites in the micropores or blocking the pores that allow adsorbate molecules to enter. Because the capacity of the system is decreased, the time prior to breakthrough is shortened. This has no effect on an adsorber's removal efficiency until the shortened length of the adsorption cycle begins to conflict with the regeneration time. At this point the carbon should be replaced.

Fouling will not affect the outlet concentration prior to breakthrough because fouling has no effect on the amount of heel left in the bed.

Fouling gradually reduces bed working capacity. In some cases, the steam flow and/or temperature can be increased to reduce the heel and thus increase the working capacity as the bed ages. At some point, however, increasing the steam flow will have little beneficial effect on working capacity. Therefore, even if the system is well designed and operated, eventually insufficient time will remain to regenerate the off-line bed before the on-line bed reaches breakthrough. At this point, the carbon must be replaced.

Though fouling of the carbon bed has no effect on the efficiency of an adsorber system, it does reduce bed life, which in turn increases the annual operating cost of the system. The fouling rate is affected by numerous factors, but the adsorbate characteristics can be considered the most important (e.g., particulates and adsorbates that polymerize on the carbon).[2]

Channeling--

A carbon adsorber system should be designed with adequate flow baffles and proper steam distribution to prevent channeling. If channeling does occur, it will cause elevation of the outlet concentration over a cycle or a gradual increase during the cycle. In systems with VOC monitors, these increases will be readily apparent. If the amount of channeling is small, the system still may be able to retain the required removal efficiency. If significant channeling occurs, adsorber removal efficiency will be significantly degraded.

In a well-designed system, channeling need not occur. From the perspective of the ability of a carbon adsorber to meet a specific regulatory removal requirement, channeling is actually a malfunction of the system rather than a factor causing inherent variability in short-term efficiency.[2]

Changes in the Adsorbate--

The concentration and type of organic are key factors in the design of a carbon adsorption system. The adsorption characteristics of each compound are assessed by using data on their physical properties such as polarity, refractive index, boiling point, molecular weight, and solubility in water. Nonpolar compounds (compounds with high refractive indices) tend to be adsorbed more readily. High vapor pressure/low boiling point adsorbates and low-molecular-weight compounds adsorb less readily. Compounds with molecular weights greater than 142 adsorb readily but are difficult to desorb.

If the adsorbate is water-soluble, water left as condensate in the bed after steaming and cooling can contain adsorbate. When the adsorber is brought on line, the water and adsorbate will evaporate from the bed during the first part of the adsorption cycle, which will slightly increase the initial outlet concentration for a brief time until the concentration rapidly falls to a normal baseline value.

The properties and adsorption characteristics affect both the design and operating conditions. If the feed stream is changed, the adsorber system must be reevaluated. If it can accommodate the new feed, achievable removal efficiency will not be affected even though on-line adsorption time and steaming requirements may need to be changed. If timers are used as the trigger mechanisms, the new working capacity of the beds must be determined. Based on this working capacity and a maximum inlet loading, the appropriate new adsorption time can be determined so that the timers can be reset for the new operating conditions.[2]

6.5 Operator Training

Similar to any piece of equipment, a carbon adsorption system will not receive proper maintenance without facility management support and the willingness to provide its employees with proper training. Efficient operation of a carbon adsorber, promoted by adequate inspection and maintenance procedures, is as important as the productive operation of any piece of process equipment. Management and employees must take a proactive approach to operation to prevent production-stopping equipment malfunctions or failures.

The training and motivation of employees assigned to monitor and maintain the system are critical factors. These duties should not be assigned to inexperienced personnel that do not understand how a carbon adsorption system works or the purpose behind assigned maintenance tasks.

System training should be provided by the manufacturer when a new system is commissioned. The manufacturer's startup services will generally include introductory training for facility operators and maintenance personnel. The field service engineer involved in startup procedures will instruct plant personnel in methods for ensuring proper assembly and operation of the system components, checking and resetting system instrumentation and controls, checking for the proper operation of any continuous emission monitoring system, and performing simple troubleshooting.

After startup training, regular training courses should be held by in-house personnel or through the use of outside expertise. The set of manuals typically delivered as part of a new installation will include manufacturer-recommended maintenance procedures. Annual in-house training should, at a minimum, include a review of these documents and confirmation of the original operating parameters. Training should include written instructions and practical experience sessions on safety, inspection procedures, system monitoring equipment and procedures, routine maintenance procedures, and recordkeeping.

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SECTION 7.0

THERMAL FUME AND CATALYTIC INCINERATORS

This section provides operators with guidance and procedures to properly operate and maintain thermal and catalytic incinerators. This section is also designed to assist regulatory personnel responsible for inspections at facilities using thermal incineration systems. This information is intended to improve recognition and understanding of failure mechanisms and improve reliability of control systems.

7.1 Thermal Fume Incinerators

7.1.1 General Description

Thermal incineration systems are generally used to destroy combustible gases or vapors that are present in gas streams. These vapors can be present in low concentrations (lean) or high concentrations (rich) in an air/oxygen or inert gas atmosphere. The design and operation of the devices are critically dependent on the pollutant concentration, type of pollutant, presence of other gases, level of oxygen, and stability of the processes served by the system.

In general, fume incinerators can achieve destruction efficiencies of $\geq$ 99 percent. Special units have been designed to achieve removal efficiencies of 99.99%. The destruction efficiency for an individual pollutant species is controlled by peak combustion temperature and time of exposure (i.e., residence time). Failure to achieve the designed removals are related to the degree of mixing (i.e., turbulence), carrier gas composition, and flame stability. Overall, the destruction efficiency follows the 3 T's of classical combustion theory: time, temperature, and turbulence.

A fume incinerator consists of an oxidation chamber, auxiliary fuel source and burner, preheat system, heat recovery system, combustion control system, and safety devices.

Typically the oxidation chamber consists of a steel shell lined with a refractory material which is either cast, blanket, or brick. Refractory is typically 4 to 8 inches thick and designed to retain heat and protect the shell from thermal stress and corrosive gases. Typical combustion temperatures are ≥ 2000°F and shell temperatures are 180° to 400°F. Refractory materials are specified based on flue gas composition [i.e., moisture, acid gases (SO_2, HCl, HF, etc.)] and peak temperature.

Burners are used to increase carrier gas temperature to the desired combustion temperature to achieve the designed destruction efficiency. The burner also serves as a pilot for positive ignition and as a preheater for system start-up. Burner fuels may be natural gas, propane, diesel fuel, No. 2 oil, or byproduct gases/fuels. Depending on the composition of the carrier gas and fumes to be oxidized, the oxygen used for combustion may be provided by the carrier gas, ambient air, or oxygen enrichment. For flame stability, a premix burner design is typically used with fuel and air premixed in the burner. When elevated levels of water vapor are present in the carrier gas, ambient combustion air is required to provide flame stability.

Figure 7-1 is a generalized cross section of a combustion chamber. This representation employs a burner at one end of the chamber. Alternative designs also use tangentially fired burners and tangential fume inlets to increase residence time and improve mixing.

In order to reduce fuel requirements, heat exchangers are used to recover heat from the stack exhaust and/or preheat process exhaust streams. A typical arrangement is provided in Figure 7-2. Limits on preheat temperature may be imposed to prevent preignition of fumes in the heat exchanger.

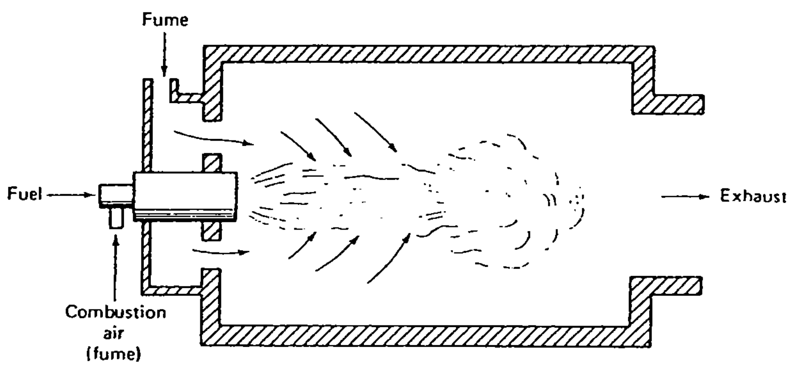

Figure 7-1. Combustion chamber.

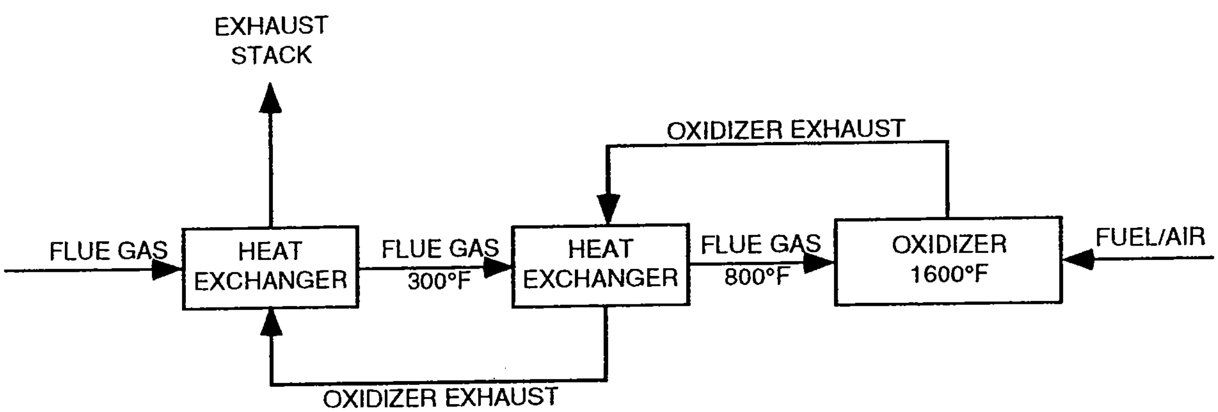

Figure 7-2. Arrangement of heat exchangers.

7.1.2 Key Operating Parameters

The key operating parameters of any thermal oxidation (incineration) system are primarily the temperature to which the pollutant is exposed and the time of exposure. Figure 7-3 shows the typical relationship between destruction efficiency and time/temperature. As can be seen, as residence time is increased the temperature required for a given pollutant destruction efficiency is decreased. The exact relationship is specific for each hydrocarbon species and combination of species.

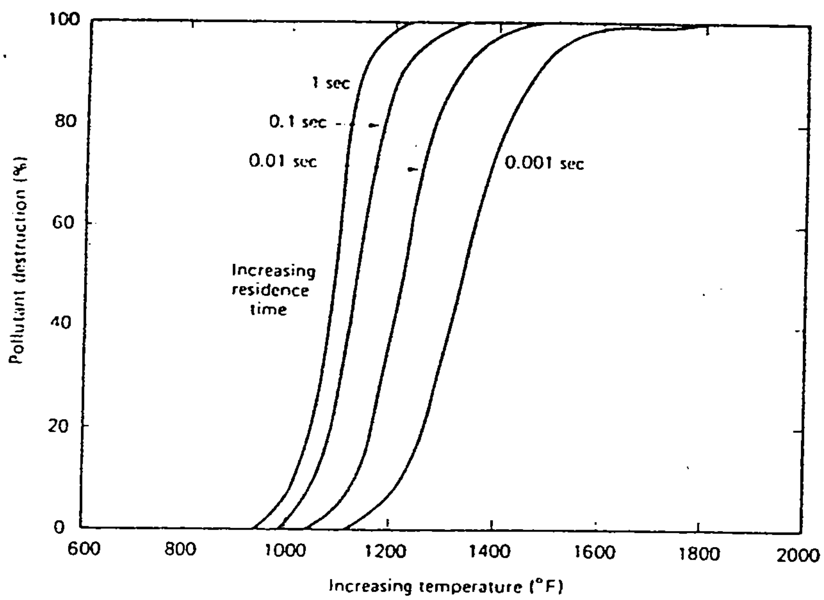

Figure 7-3. Coupled effects of temperature and time on rate of pollutant oxidation.[2]

Residence time of the incinerator is typically specified by the regulatory agency or by the vendor to ensure adequate destruction of the pollutant. The value is defined by the physical dimensions of the chamber, combustion temperature, primary gas volume, and the fuel rate necessary to reach combustion temperature.

Another important operating parameter is the gas volume rate through the combustion chamber. This parameter is expressed in actual cubic feet per minute (acfm) and is the sum of the primary gas volume and the products of combustion produced by oxidation of fuel and pollutants. In systems where oxygen in the primary gas is not sufficient for combustion and air is supplied from the ambient environment, the total gas volume may be estimated by adding the products of combustion of fuels and pollutants to carrier gas volume. In addition, most incinerators are operated with excess oxygen. This additional oxygen and the associated nitrogen (from air) must be considered in the total gas volume calculations. When oxygen is supplied from the primary gas volume, the calculation of total combustion gas volumes requires a detailed combustion calculation. The methodology for these calculations are described in detail in combustion textbooks and are not presented in this document.

The temperature that may be achieved by combustion of a given fuel is dependant on the mass of the flue gas products and primary gas (m), specific heat of the gases (C_p), and the heat released by combustion (Q). For most combustion calculations the specific heat of the flue gas products is 0.26 Btu/lb °F, but if the primary gas stream contains a significant percentage of water vapor, it may be higher (e.g., 0.30 Btu/lb °F). The mass of the combustion gas stream may be estimated using standard stoichiometric combustion constants for the fuels. The weight of the primary gas stream may be estimated by carrier gas composition. If the stream is primarily air, the weight is 0.075 lb/dscf. The weight of moisture in the carrier gas must be included at a weight of 0.046 lb/wscf.

The equation for expected temperature increase is

$$\Delta T = \frac{Q}{mCp}$$

where Q = Heat input Btu/min

m = Mass of final gas stream, lb/min

Cp = Average specific heat for final gas stream, Btu/lb °F

ΔT = Temperature rise, °F.

7.1.3 Monitoring

Monitoring fume incinerator performance can be done by measurement of hydrocarbon and carbon monoxide outlet concentrations or by monitoring operating variables such as incinerator temperature, fuel rate to the incinerator, and fan current. Table 7-1 summarizes the equipment that can be used to monitor these parameters.

Monitoring of Gas Concentrations--

Direct monitoring of the outlet hydrocarbon concentration is costly, technically difficult, and is not necessarily required if other parameters are monitored (see below). The monitoring of this parameter, however, provides a direct indication that the incinerator is effectively destroying the hydrocarbons fed into the system. The measurement can be accomplished using a total hydrocarbon (THC) analyzer or a gas chromatograph (GC), which identifies individual hydrocarbon (HC) species. In complex gas systems, the destruction of multiple species is not equal at a given temperature. There is also the possibility of creation of species by recombination and/or incomplete combustion.

TABLE 7-1. METHODS OF MONITORING INCINERATOR PERFORMANCE

Method	Instrument	Variable	Usage
Outlet gas concentrations	FID	THC	Primary
	GC	HC species	Primary
	NDIR	CO	Secondary
Operating parameters	Thermocouple	Temperature	Primary
	Ammeter	Fan current	Secondary
	Flow meter	Fuel rate	Secondary

The use of a total hydrocarbon analyzer provides an indication of the relative overall destruction efficiency of the system. When the composition of the process gas stream changes, the response of the analyzer may be affected. For example, when multiple processes are captured for destruction and when process units cycle in and out of the system, both the rate and species may change. This may result in an increase or decrease in the measured outlet concentration. This change may be a true change in HC weight due to thermal destruction efficiency or simply a change in response of the instrument. Interpretation of the monitor output may be difficult and require a baseline and/or range of normal operation conditions to be determined to permit a comparison of measured values.

The use of a GC may be appropriate to target a major species present in the input gas stream that is considered difficult to thermally degrade. This species can be the surrogate for monitoring the overall performance of the system. Because of the number of possible products of incomplete combustion, tracking of all species may not be technically feasible.

For most HC species the last product of incomplete combustion is carbon monoxide (CO). This species is considered difficult to oxidize and is a stable compound. If sufficient oxygen, temperature, and turbulence are provided to complete combustion to CO_2, a low level of CO may be expected (i.e., $\leq$ 30 ppm). CO may be monitored using a nondispersive infrared analyzer which is a good indicator of overall system performance.

Monitoring of Temperatures and Gas Flows--

Monitoring of the temperature and gas flow operating parameters provides an indication to insure that the incinerator achieves the required destruction efficiency. For example, if a stack test determines that a removal efficiency of 99 percent is achieved at 1500°F and at a residence time of 0.75 seconds, monitoring of the combustion temperature and/or residence time may be appropriate. In general, residence time is not a measured variable and must be calculated from other measured variables (i.e., volume of the combustion chamber and gas flow rate). For most systems, continuous monitoring of the combustion temperature with a thermocouple is considered adequate to demonstrate performance.

There are several conditions, however, when temperature may be misleading:

1. If primary gas volume exceeds design values, residence time may decrease.

2. If the system becomes self fueling and required oxygen exceeds the oxygen that is available, products of incomplete combustion (HC, CO, etc.) are produced and primary fuel may be reduced to a minimum.

Both of these conditions may be identified by monitoring of operating variables such as primary fan current or fuel rates.

7.1.4 Thermal Incinerator Inspection and Maintenance

A thermal oxidizer system has few moving parts and therefore has low maintenance requirements. As with all mechanical systems, alignment and lubrication of bearings is necessary to prevent failure. Lubrication of mechanical linkages, slides, and other metal moving parts is required.

Filters and strainers for liquid fuels should be changed periodically to ensure even fuel flow. Parallel (duplicate) piping of strainers and filters is required for online service.

Prefilters used to prevent particulate matter entry to the oxidizer must be changed on a regular schedule to prevent draft losses and capacity limitation. Burner tips should be inspected and cleaned to ensure proper fuel mixing and efficient combustion.

Inspection of thermal incinerators requires regular observation of monitoring devices (i.e., thermocouples, gas monitors, recorders, etc.). Most incinerators will have continuously recorded inlet and outlet incinerator temperature and auxiliary fuel input. Fuel pressure and fan current are also generally available using a magnehelic gauge and ammeter, respectively. Where heat recovery is used, inlet and outlet heat exchanges temperatures are monitored using thermocouples. Ideally, outlet carbon monoxide and oxygen will also be continuously monitored. Set points on each monitor are used to notify operator of incinerator malfunction between inspections (e.g., high and low temperature, high CO levels). A review of strip charts should be conducted once per shift to determine if operating conditions are typical of normal conditions and to note any trends. Figure 7-4 is an inspection checklist that can be used during the shift inspection. Figure 7-5 shows an example maintenance report form.

A more detailed physical inspection of the system should be made on a quarterly basis. This should include external and internal system components including refractory, heat exchangers and electrical systems. Figure 7-6 shows an example quarterly inspection form. This form should be modified for each incinerator based on incinerator design, process application, and applicable regulatory requirements.

7.1.5 Common Problems or Malfunctions of Thermal Incinerators

The categories of potential problems may be divided into operational, startup, and long-term maintenance. Each may have an effect on reliability, destruction efficiency, or cost of operation. The following is a brief discussion of problems typically encountered in a fume incineration system.

SHIFT/DAILY INCINERATOR INSPECTION FORM	
Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (Print):
Incinerator ID:	Signature of Inspector:
INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS
1) Temperature alarms during shift: - High CO - Low	
2) Gas monitor alarms? - High CO - Low oxygen	
3) Fan operation - Abnormal sounds?	
4) Strip charts operational? Check paper and ink.	

Flue gas to incinerator	Range _________°F	Reading _________°F
Combustion temperature	Range _________°F	Reading _________°F
Flue gas CO monitor	Range _________°F	Reading _________°F
Flue gas oxygen monitor	Range _________°F	Reading _________°F
Fan Current	______ amps	
Fuel rate	______scfm	

Heat Exchangers (for heat recovery)		IN	OUT	PRESSURE DROP
#1	Process gas	______°F	______°F	______ in. H_2O
	Combustion gas	______°F	______°F	______ in. H_2O
#2	Process gas	______°F	______°F	______ in. H_2O
	Combustion gas	______°F	______°F	______ in. H_2O

Figure 7-4. Example shift/daily incinerator inspection form.

MAINTENANCE REPORT FORM

Department	Unit	System	Subsystem	Component	Subcomponent

Originator: ____________ Date: ________ Time: ________

Assigned To:

1	Mechanical
2	Electrical
3	Instrumentation

Priority:

1	Emergency
2	Same Day
3	Routine

Unit Status:

1	Normal
2	Derated
3	Down

Problem Description: ____________

Foreman: ____________ Date: ________

Job Status:

1	Repairable
	Hold for:
2	Tools
3	Parts
4	Outage

Cause of Problem: ____________

Work Done: ____________

Supervisor: ____________ Completion Date: ________

Materials Used: ____________

Labor Requirements: ____________

Figure 7-5. Example maintenance report form.

QUARTERLY INCINERATOR INSPECTION FORM	
Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (Print):
Incinerator ID:	Signature of Inspector:
INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS
Refractory condition? (cracks, spalling, corrosion)	
Burner condition? (warpage, corrosion, fouling)	
Heat exchanger(s) and combustion chamber condition? (fouling, corrosion, leaks)	
Pressure seals condition? (check packing glands)	
Shell condition? (thermal shock, welds condition)	
Check auxiliary fuel piping train and note condition.	
Check interlocks, electrically operated valves, shutoff dampers, gauges, continuous recorders and thermocouples for proper operation. (calibrate where applicable)	

Figure 7-6. Example quarterly incinerator inspection form.

Startup and Shutdown Procedures and Problems--

The most critical period in the operation of a fume incinerator is the period during startup from a cold or hot condition. Insurance companies and the National Fire Protection Association (NFPA) have established guidelines (procedures) to ensure fire/explosion protection during a system startup. These guidelines have been adopted by most manufacturers and have a history of preventing catastrophic failure of the thermal treatment system. It is important to remember that the fume that is being incinerated is a fuel/air mixture capable of releasing heat when ignited. Depending on the mixture, oxygen, temperature, and ignition source, spontaneous and explosive oxidation can occur.

In general, the procedures summarized in Figure 7-7 should be followed for startup, operation, and shutdown of a thermal treatment source. Each step must be completed and verified prior to moving to the next step. Each device should be interlocked electrically, which requires clearance before the next step can occur. Override of a specific item is not recommended without a full understanding of the potential risk, effect, and cause of the failure. For example, if a flame sensor will not allow continued firing of the burner, manual override may be used intermittently to verify failure of the sensors. Bypass of the interlock is not allowed for continuous operation for obvious reasons. The flame sensor is installed expressly for the purpose of detecting a flame out condition in which raw fuel may be injected into a hot combustion chamber without an ignition source. When this occurs, an explosive gas mixture can be created.

Not all systems are fully automatic. Smaller systems may be semiautomatic or manual in the startup sequence. The automatic system requires only the initiation of the firing sequence and a preset program is initiated, which follows the NFPA startup sequence. This program also shuts down the system if a fault is detected. Depending on program sophistication, the system may list faults, go to back up systems, call for operator action, or restart of the system.

1. Prepurge

   a. Power on to control system
   b. Fan motor on
   c. Airflow verified
   d. Fuel valves closed

2. Purge

   a. Airflow to maximum rate
   b. Purge timer starts (length of time set to allow furnace to be purged of any combustible fumes; eight complete air changes considered sufficient)

3. Ignitor sequence

   a. Airflow to light-off rate
   b. Auxiliary fuel pressure verified as sufficient; temperature verified, if required
   c. Ignitor electric spark mechanism starts
   d. Ignitor timer starts
   e. Ignitor fuel valve opens, fuel is ignited in furnace by sparking mechanism
   f. Ignitor flame sensed by flame scanner
   g. Ignitor timer ends time cycle, shuts off sparking mechanism (if no flame sensed by flame scanner, ignitor fuel valve immediately closes, and postpurge cycle starts)

4. Main burner sequence

   a. Main burner fuel-control valve verified in light-off position
   b. Atomizing fluid (air or stream) valve opens (needed only on certain oil-fired units)
   c. Burner timer starts cycle
   d. Main burner fuel shut off valves open--allowing fuel to main burner
   e. Main flame ignites from ignitor flame

Figure 7-7. Startup, operation, and shutdown summary procedures for thermal incinerator. (continued)

f. Burner timer ends time cycle, ignitor fuel valve closes (if main flame not sensed by flame scanner, fuel shutoff valves immediately close, and postpurge cycle starts)
g. Interlocks verifying light-off positions on fan and control valves are now by-passed, allowing fuel and air rates to be adjusted

h. Main burner is now in service subject to the following conditions:

(1) Fan on
(2) Airflow proven
(3) Flame detected
(4) Fuel pressure adequate
(5) Furnace temperature not high

5. Normal operation

a. Fuel and airflow are now adjusted to provide optimum furnace temperature for incinerator; this may be done manually or automatically; on refractory-lined units, warm-up must be done gradually to prevent thermal shock to the refractory
b. Once the incinerator reaches its operating temperature, fumes can be introduced into the furnace
c. Proper incinerator operation is maintained by controlling incinerator outlet temperature and fume, auxiliary fuel, and airflow rates

6. Normal shutdown

Normal shutdown is accomplished by closing the fume flow valves, then the auxiliary fuel valves; the systems then proceed to the postpurge cycle

7. Postpurge

a. Fan adjusted to maximum flow rate
b. Postpurge timer starts time cycle
c. Keeps air flowing until five complete air changes have occurred in the furnace
d. Postpurge time ends cycle, fan turned off, incinerator is shut down

Figure 7-7. Startup, operation, and shutdown summary procedures for thermal incinerator.

The semiautomatic system is the most common operating protocol. This requires the operator to initiate steps in the procedure after verification of system interlock clearances. These steps are generally verified through indicator lights or alarms.

For a completely manual system, the start sequence is initiated and confirmed by the operator. If the established sequence is not followed, explosion or failure can occur.

Burner Fouling--

Burning of a dirty fuel oil containing high levels of ash, water, or metals can generate a slag or deposit on the burner surfaces that impairs fuel/air mixing. If a dirty fuel is used, frequent inspection and cleaning are recommended. If the carrier gas volume is used for combustion air, precleaning (filters) may be required to prevent burner fouling. This may also be required if the source of ambient air is in a dirty environment. Special care should be taken if the fume is composed of organic vapors that may polymerize on surfaces (i.e., styrene, cellusolve, etc.).

Preignition--

When a heat exchanger is used to preheat the process gases prior to the oxidizer, a danger of preignition is present. For maximum heat recovery and minimum fuel usage, process gases are heated using the exhaust gases from the oxidizer. Typically the tendency is to recover as much heat as possible and reduce the heat lost to the stack. This may allow a preheat of 1000° to 1200°F depending on combustion temperature in the oxidizer. When oxygen is present in the carrier gas and organic vapors are rich, the spontaneous ignition temperature may be exceeded. If this occurs combustion is initiated in the tube and shell heat exchanger, which thermally stresses the tubes. Failure of the tubes allows passage of fumes from the fume side to the flue gas side, effectively bypassing the oxidizer. Most heat exchangers have a leakage rate of one percent or less and thermal stress can increase the leakage rate substantially. Preignition cannot generally be detected by thermal methods, but can be identified as a decrease in carrier gas oxygen content between heat exchanger inlet and oxidizer. For typical protection, preheat of the carrier gases should be limited to 800°F.

Thermal Expansion--

A rapid increase in either flue gas or carrier gas temperature can result in thermal stress of the heat exchangers, which increases leakage and results in fume bypass. Preheat of the system must conform to the manufacturer's recommended heat up schedule to prevent thermal failure of the heat exchanger. Thermal expansion must also be considered in the preheat of the oxidizer if castable or monolithic refractory is used. Rapid heat up and cycling will increase refractory failure.

Inleakage--

Inleakage of ambient air into a rich gas stream can result in dilution of the pollutants. If this dilution places the concentration of the fume in the explosive range, catastrophic failure can occur (i.e., concentration of combustibles greater than lower explosive limit and less than upper explosive limit). Periodic integrity verification of the gas transport system is recommended to reduce inleakage.

When inleakage occurs in a lean system, the ability to capture emissions at the process source is decreased. This limits the capacity of the system because of tramp air.

Heat Exchanger (HEX) Fouling--

Fouling of the preheat system reduces the heat transfer rates from the exhaust gas to the preheated media. This causes a decrease in the preheat temperature and an increase in the stack temperatures. Fouling can occur from failure of the prefilters in the air pollution control equipment used to prepare the carrier gas stream for incineration. Certain pollutants may also present problems when exposed to elevated temperatures. These pollutants polymerize or pyrolize under exposure to heat. Limits must be imposed on preheat or preheat eliminated to minimize fouling.

Refractory Failure--

Refractory failure is typically associated with thermal stress. Rapid or frequent cycling of heat rates results in expansion and contraction which stresses materials. Block and castable refractories are more prone to this failure mechanism. Cracks and shock damage (spalling) should be repaired using castable (plastic) materials.

Corrosion of the refractory may occur if the carrier gases contain chlorine, sulfur or fluorides. Oxidation of these gases can have a detrimental effect on refractory and/or metal components of the system. A shutdown purge is designed to remove corrosive gases before the gases can condense on the surfaces.

Draft Restrictions--

Draft loss (pressure drop) across the incinerator system can occur as a result of fouling of the prefilters, heat exchangers, or ducts. Draft losses are considered in the equipment specification and dictate fan selection for the design. Increases in draft losses, decrease the available gas volume which can be treated. Operation at higher than optimal combustion temperatures can also increase draft losses due to an increase in fuel combustion products.

Temperature of Combustion--

The temperature of combustion of the oxidizer is dictated by the total carrier gas volume, fuel fired, and fume incinerated. Because all of these are variable, a feed back system is necessary to limit fuel rates to achieve the desired combustion temperature. Typically a thermocouple is placed at the outlet of the oxidizer to measure the average combustion temperature. This sensor is connected to a programmable controller that sets fuel flow to maintain the desired combustion temperature. Due to the location of the thermocouple, a high failure rate is expected and dual sensors are recommended. Because a portion of the flue gas heat input is supplied by the pollutants in the gas stream, a minimum fuel flow setting must be maintained to prevent extinguishing of the ignition source and provide positive feedback control.

Slaging/Fouling--

Because of the elevated temperature in the oxidizer, the potential exists for fouling of the chamber with foreign materials. Dust and dirt not removed in prefilter systems or air pollution control equipment may become liquid and adhere to refractory surfaces. These deposits (slags) may increase refractory failure and change combustion characteristics of the chamber.

Flame Safety--

Flame safety is an important aspect of all combustion processes. Failure to detect flame out may result in the continued introduction of fuel or fume into a hot combustion chamber in which ignition has ceased. A rich gas mixture is produced, which then spontaneously combusts with violence. The resulting explosion can destroy the incinerator and adjacent process equipment.

All components of the flame safety system must be inspected frequently and spare parts accessible for replacement. Under no circumstances should the flame safety be bypassed or disabled during normal operation. Disabling interlocks and safeties should only be used as part of troubleshooting or fault detection by trained service personnel.

Self- Fueling System/Run Away Combustion--

The most serious failure mechanism that may occur for a fume incineration system is a self fueling scenario. Self fueling is a term applied to a condition in which the heat release necessary to achieve a set combustion temperature is supplied solely by pollutants in the carrier gas. Under these conditions the auxiliary fuel system is reduced to minimum fire or pilot condition. Without the benefit of auxiliary fuel modulation control, the upper limit of the combustion temperature is removed. If oxygen for combustion is supplied by ambient air with the auxiliary fuel system, the combustion process can proceed in an air starved mode in which increased levels of incomplete combustion, CO, and fume may be exhausted from the oxidizer. As fume concentration continues to increase, heat release rates exceed set points and temperatures exceed design limits.

In a high concentration event, total control of the process is lost and failure of the system occurs. The term run-away is descriptive of the event. Short event increases in the concentration may be noted as spikes on the temperature recorder. Thermal mass of the refractory and heat exchangers tend to prevent these events from being of concern. A gradual increase in fume concentration, which forces the auxiliary fuel rate to minimum is a potential concern. When fuel rates approach the minimum and the control function is in danger of being lost, operator intervention is required.

The only possible mechanism that can be employed to stop a self fueling condition is to reduce the input of fume (fuel) to the oxidizer. This is usually accomplished by diverting the carrier gas stream to the atmosphere or a standby flare. If this scenario is a real possibility, procedures and bypass contingencies should be installed as part of the design.

In general, self fueling occurs only in rich gas streams where an increase in pollutant rates can occur rapidly. These are usually associated with release events from process sources such as reactor vessels or other pressure sources. Lean systems typically have sufficient dilution air to accept a moderate increase in fume concentration.

Table 7-2 summarizes the failure mechanisms, associated symptoms, and possible corrective actions.

7.2 Catalytic Incinerator

7.2.1 General Description

Catalytic incinerators are special types of thermal incinerators in which hydrocarbons are exposed to media, which increase the kinetic rate. This media is defined as a catalyst and is usually in the form of a solid matrix or pellet. The effects of a catalyst are as follows:

TABLE 7-2. SUMMARY OF FAILURE MECHANISMS, SYMPTOMS, AND CORRECTIVE ACTIONS FOR THERMAL FUME INCINERATORS

Failure mechanism	Symptoms	Corrective actions
Burner fouling	High CO Insufficient combustion air Flame instability Flame out	Clean burner tips Prefilter ambient air Filter process stream Cease using process combustion air Improve fuel source
Preignition in heat exchanger	Decrease in carrier gas O_2 Leakage from fume side to flue gas side (bypass) Unexplained increase in outlet HC concentration	Reduce preheat temperature Retube heat exchanger
Thermal expansion (heat exchanger)	Tube failure Inleakage and bypass to flue gas side	Retube Conform to manufacturer's recommended preheat schedule Limit maximum temperatures
Thermal expansion (oxidizer)	Refractory failure Shell failure due to heat stress	Repair refractory Limit maximum temperature and preheat rates Limit thermal cycling
Inleakage (rich system)	Decreased concentration of fume below UEL Potential for explosion	Periodic integrity check of transport system UEL monitors
Inleakage (lean system)	Decreased concentrations of fume below 25 percent of LEL Reduced capture volume at source	Periodic integrity check of transport system LEL monitor
Inleakage (heat exchanger)	Increased stack HC concentration Tube failure	Retube HEX Limit temperature excursions

Failure mechanism	Symptoms	Corrective actions
HEX fouling	Decreased preheat temperature (i.e., ΔT decreased) Increased stack temperature	Prefilter carrier gases Reduce heat exchanger temperature Eliminate preheat heat exchangers Clean heat exchangers
Refractory failure	Cracks Spalling Crumbing	Reduce cycling Limit peak temperature Post shutdown purge to remove corrosive gases
Draft control	Increased pressure drop Decreased capacity Decreased capture capacity	Reduce fouling Reduce combustion temperature Reduce transport air inleakage
Temperature control	Irregular combustion temperature	Feed back temperature control system Dual temperature sensors
Slaging	Deposits in oxidizer Refractory failure Increased draft losses	Prefilter carrier gases Prefilter ambient combustion air
Flame safety	Flame out due to interlock protection Irregular flame	Inspect and replace sensor Relocate sensor's position
Self fueling	Increased temperature with no auxiliary fuel control	Vent to bypass Vent to flare

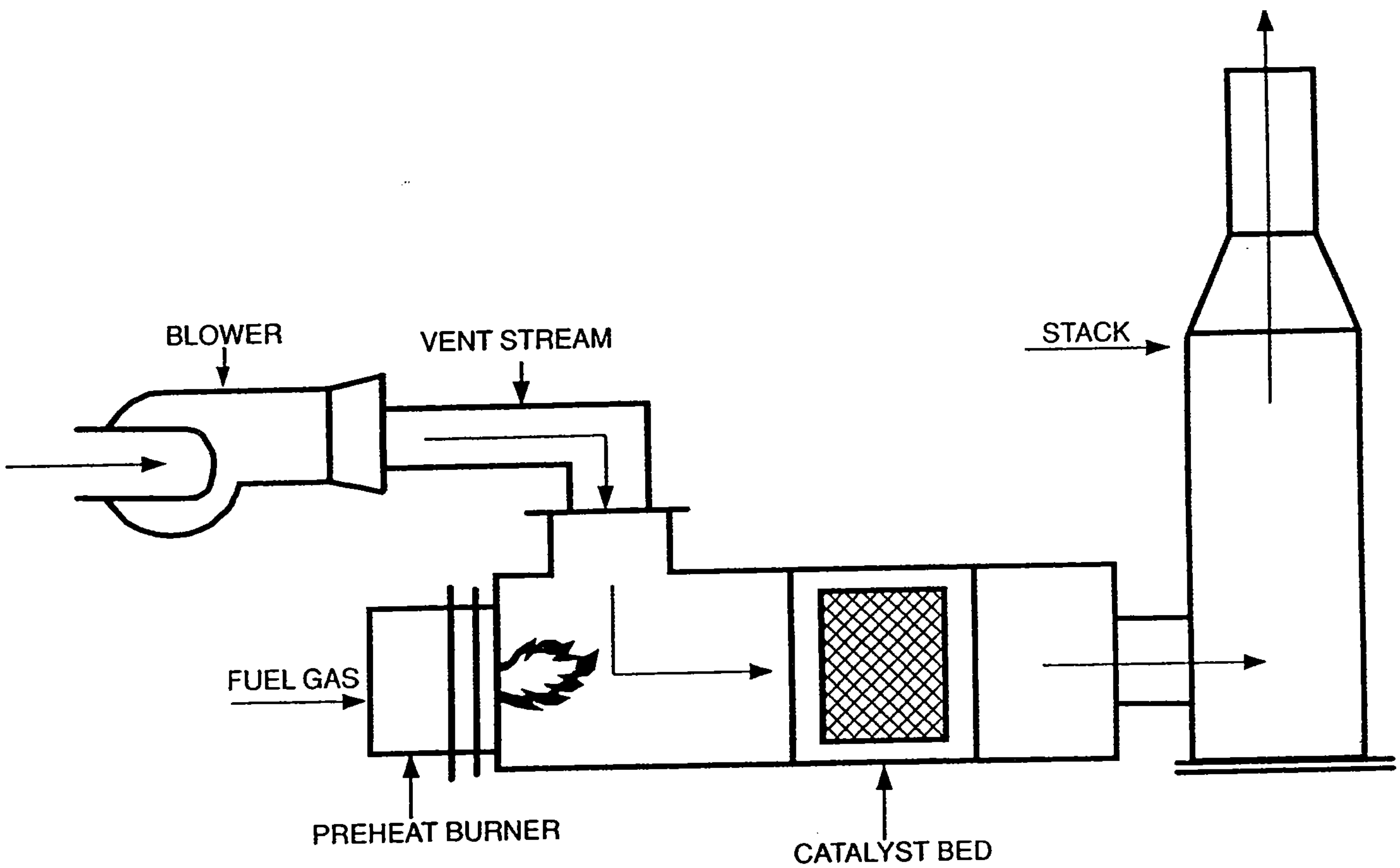

Figure 7-8. Schematic of catalytic incinerator without any heat recovery.

1. It increases the reaction rate (i.e., oxidation)

2. It allows the reaction to occur at lower temperatures.

In general, a catalytic incinerator consists of a preheater, catalyst bed, auxiliary air system and heat recovery section. Figure 7-8 is a schematic of a system where no heat recovery is used and Figure 7-9 is a schematic of a system where heat recovery is used to preheat the carrier gas (fume).

7.2.2 Theory of Operation

Fumes containing hydrocarbons and oxidant (i.e., oxygen in air or enriched oxygen) are preheated to the minimum activation temperature necessary to initiate oxidation in the presence of a catalyst. The fume is then passed through a matrix or bed constructed of a ceramic material. An active catalyst is impregnated on the surface of the material, which forms the active sites for the reaction to occur.

The most active catalyst is a platinum metal, but oxides of vanadium, nickel, cobalt, copper, and chromium may also be used. Several of these are deactivated (poisoned) by metals or halogens, and the selection of catalyst type must be determined by the composition of the gas stream to be incinerated. Typical catalyst poisons include antimony, arsenic, iron oxide, zinc, phosphorous and sulfur.

Catalysts do not alter the position of the equilibrium reaction, but accelerate the reaction, thereby lowering the operating temperature. Because the catalyst forms a site for completion of the reaction, it is not consumed.

Catalysts used for VOC control are typically platinum or palladium. Typical destruction efficiencies are between 90 and 98 percent, but can be designed for up to 99.99 percent. The degree of destruction is controlled by the following parameters:

a. Inlet temperature of the gases entering the bed, °F.

b. Specific volume of the catalyst, ft^3/scfm.

c. Type of catalyst metal and volume used.

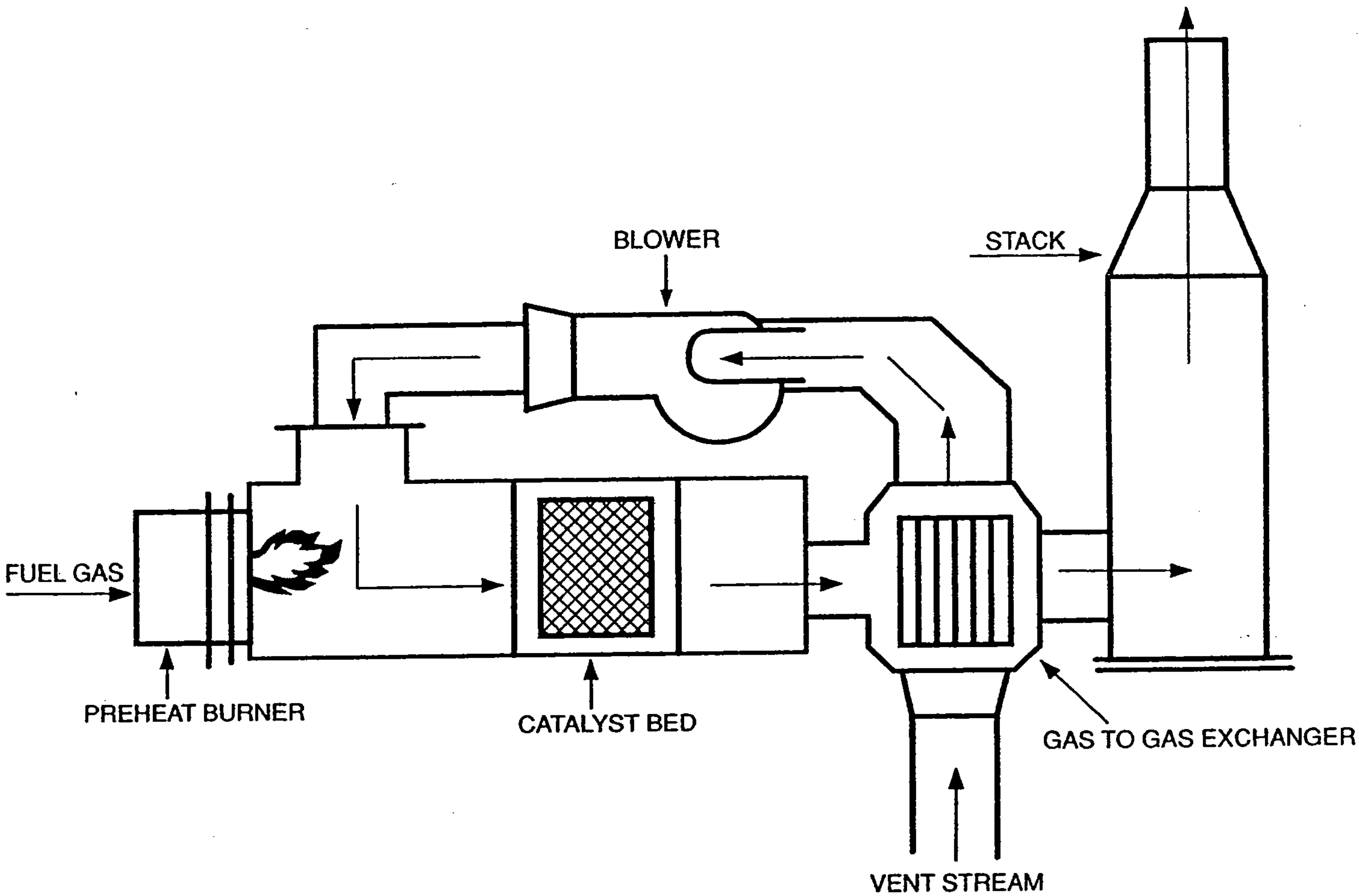

Figure 7-9. Schematic of a catalytic incinerator using heat recovery.

Certain hydrocarbon species are more difficult to destroy, and higher temperatures and/or increased catalyst volumes are required to achieve effective removal. In general, alcohols are easily oxidized and alkanes and chlorinated compounds are more difficult. Table 7-3 compares the relative destructibility of various compound groups.

TABLE 7-3. RELATIVE DEGREE OF DESTRUCTIBILITY OF ORGANIC COMPOUND CLASSES

Compound class	Relative destructibility
Alcohols	Highest
Cellosolves/dioxane	
Aldehydes	
Aromatics	to
Ketones	
Acetates	
Alkanes	
Chlorinated hydrocarbons	Lowest

Because the oxidation temperature of a catalyst system is lower than comparable thermal systems, the formation of oxides of nitrogen are reduced. In addition, the heat required to complete the reactions is also reduced, which reduces the cost of auxiliary fuels.

Systems require preheating to reach the minimum temperatures at which catalytic oxidation occurs. Once this minimum temperature is achieved, heat liberated from the oxidation of the pollutant may be sufficient to support the reaction without auxiliary fuel. This is particularly true when heat recovery is used to preheat the inlet fume gas stream.

From a macroscopic view, the steps in a catalytic reaction are:

1. Transfer of reactants to, and products from, the outer catalyst surface.

2. Diffusion of reactants and products within the pore of the catalyst.

3. Active adsorption of reactants and the desorption of the products on the active centers of the catalyst.

4. Reaction(s) on active centers on the catalyst surface.

In addition, thermal activity occurs, which heats the catalyst and flue gas streams. These activities are:

1. Heat transfer to or from active centers to the catalyst particle surface.

2. Heat transfer to and from reactants and products within the catalyst particle.

3. Heat transfer to and from moving streams in the reactor.

4. Heat transfer from one catalyst particle to another within the reactor.

5. Heat transfer to or from the walls of the reactor.

Because the reactions are temperature dependent, a classic VOC conversion curve is produced as temperature is increased. Figure 7-10 is a typical curve for a VOC. Individual curves for specific VOC species may have a different slope.

To prevent thermal degrading (deactivation) of the catalyst, the concentration of VOC in the treated gas stream must be limited. In general, when the carrier gas is air (20.9% O_2), the heat value of the gas stream must be less than 10 Btu/scf. If the carrier gas is an inert gas (N_2, etc.), the heat value may be increased to 15 Btu/scf.

The space velocity (superficial velocity) through the catalyst bed is a limiting factor in the degree of destruction. This is comparable to residence time in a thermal treatment unit. Volume of treated gas, dilution air, and combustion gases from the preheat are used to calculate this velocity. For example, if the primary gas volume is 20,000 scfm and dilution air is 5000 scfm, the total volume is 25,000 scfm. For most noble metal catalysts the velocity to achieve 95 percent destruction is between 30,000 and 40,000 h^{-1}, and 10,000 and 15,000 h^{-1} for base metal catalysts. Therefore, the volume of the bed should be:

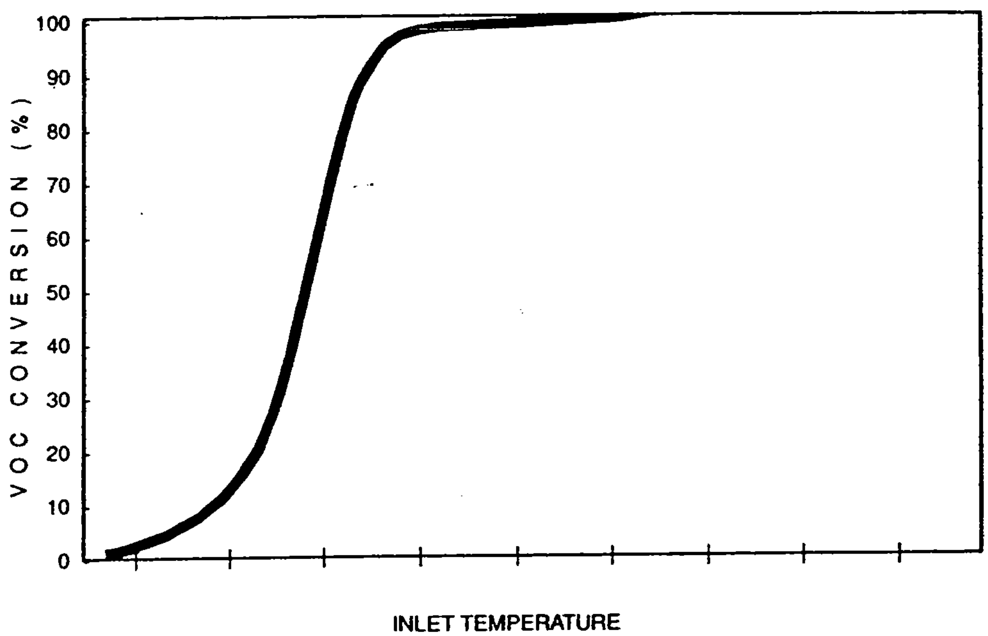

Figure 7-10. Relationship of percent conversion to temperature.

$$V_{bed} = \left(60 \ \frac{min}{h}\right)\left(25{,}000 \ \frac{ft^3}{min}\right)\left(\frac{h}{30{,}000}\right)$$

$$V_{bed} = 50 \ ft^3 \ \textit{for a noble metal catalyst}$$

7.2.3 Monitoring

The monitoring of catalytic incinerator performance (VOC destruction) is similar to that discussed under thermal systems in Section 7.1.3. There are certain specific concerns which are applicable to the catalyst system because of the potential for catalyst fouling and/or failure.

Monitoring of Gas Concentrations--

Direct monitoring of the outlet hydrocarbon concentration is costly, technically difficult, and is not necessarily required if other parameters are monitored (see below). The monitoring of this parameter, however, provides a direct indication that the incinerator is effectively destroying the hydrocarbons fed into the system. The measurement can be accomplished using a total hydrocarbon (THC) analyzer or a gas chromatograph (GC), which identifies individual hydrocarbon (HC) species. In complex gas systems, the destruction of multiple species is not equal at a given temperature. There is also the possibility of creation of species by recombination and/or incomplete combustion.

The use of a total hydrocarbon analyzer provides an indication of the relative overall destruction efficiency of the system. When the composition of the process gas stream changes, the response of the analyzer may be affected. For example, when multiple processes are captured for destruction and when process units cycle in and out of the system, both the rate and species may change. This may result in an increase or decrease in the measured outlet concentration. This change may be a true change in HC weight due to thermal destruction efficiency or simply a change in response of the instrument. Interpretation of the monitor output may be difficult and require a baseline and/or range of normal operation conditions to be determined to permit a comparison of measured values.

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The use of a GC may be appropriate to target a major species present in the input gas stream that is considered difficult to thermally degrade. This species can be the surrogate for monitoring the overall performance of the system. Because of the number of possible products of incomplete combustion, tracking of all species may not be technically feasible.

For most HC species the last product of incomplete combustion is carbon monoxide (CO). This species is considered difficult to oxidize and is a stable compound. If sufficient oxygen, temperature, and turbulence are provided to complete combustion to CO_2, a low level of CO may be expected (i.e., $\leq$ 30 ppm). CO may be monitored using a nondispersive infrared analyzer which is a good indicator of overall system performance.

Monitoring of the Temperature and Gas Flow--

Monitoring of the temperature and gas flow operating parameters provides an indication to insure that the incinerator achieves the required destruction efficiency. For example, if a stack test determines that a removal efficiency of 99 percent is achieved at 700°F, monitoring of the catalyst bed temperature and/or residence time may be appropriate. In general, residence time is not a measured variable and must be calculated from other measured variables (i.e., volume of the combustion chamber and gas flow rate). For most systems, continuous monitoring of the combustion temperature with a thermocouple is considered adequate to demonstrate performance.

There are several conditions, however, when temperature may be misleading:

1. If primary gas volume exceeds design values, residence time may decrease.
2. If the inlet concentration of pollutant decreases significantly and does not provide fuel for oxidation heating of the catalyst bed.
3. If the catalyst becomes poisoned.

7.2.4 Catalytic Incinerator Inspection and Maintenance

A catalytic incineration system has few moving parts and therefore has low maintenance requirements when properly operated. As with all mechanical systems, alignment and lubrication of bearings is necessary to prevent failure. Lubrication of mechanical linkages, slides, and other metal moving parts is required.

Filters and strainers for liquid fuels should be changed periodically to ensure even fuel flow. Parallel (duplicate) piping of strainers and filters is required for online service.

Prefilters used to prevent particulate matter entry to the oxidizer must be changed on a regular schedule to prevent draft losses and capacity limitation. Burner tips should be inspected and cleaned to ensure proper fuel mixing and efficient combustion.

Inspection of catalytic incinerators requires regular observation of monitoring devices (i.e., thermocouples, gas monitors, recorders, etc.). Most incinerators will have continuously recorded inlet and outlet incinerator temperature and auxiliary fuel input. Ideally, outlet carbon monoxide and oxygen will also be continuously recorded. Set points on each monitor are used to notify operator of incinerator malfunction between inspections.

A review of strip charts should be conducted once per operating shift to determine if operating conditions are typical of normal conditions and to note any trends. A more detailed physical inspection of the system should be made on at least a quarterly basis. This should include external and internal system components including refractory, heat exchangers, and electrical systems. Figures 7-11 and 7-12 are example inspection checklists for catalytic incineration systems on a per shift and quarterly frequency, respectively. Figure 7-5 shows an example maintenance report form that can be used for catalytic incinerator maintenance.

7.2.5 Common Problems or Malfunctions of Catalytic Incinerators

Many of the problems and malfunctions associated with catalytic incinerators are the same as to those associated with thermal fume incinerators discussed in Section 7.1.3 and are not repeated in this subsection. The following discussion of problems and malfunctions, therefore, focuses on problems and malfunctions that are only associated with catalytic incinerators.

Temperature of Oxidation--

The temperature of catalyst in the oxidizer is dictated by the total carrier gas volume, auxiliary fuel fired, and fume incinerated. Because all of these are variable, a feed back system is necessary to limit fuel rates to limit catalyst temperature. Typically a thermocouple is placed at the outlet of the catalyst bed to measure the average bed temperature. This sensor is connected to a programmable controller that sets auxiliary fuel flow to maintain the desired bed temperature. Because of the location of the thermocouple, a high failure rate is expected and dual sensors are recommended. Because a major portion of the flue gas heat input is supplied by the pollutants in the gas stream, a minimum fuel flow setting may not control bed temperature and higher temperatures may occur that may damage the catalyst.

SHIFT INCINERATOR INSPECTION FORM			
Facility Name:	Date of Inspection:		
Facility Location:	Time of Inspection:		
Process:	Name of Inspector (Print):		
Incinerator ID:	Signature of Inspector:		
INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS		
1) Temperature alarms during shift: - High - Low			
2) Gas monitor alarms? - High CO - Low oxygen			
3) Fan operation - Abnormal sounds?			
4) Strip charts operational? Check paper and ink.			
Flue gas to incinerator	Range ________°F	Reading ________°F	
Combustion temperature	Range ________°F	Reading ________°F	
Catalyst temperature	Range ________°F	Reading ________°F	
Flue gas CO monitor	Range ________°F	Reading ________°F	
Flue gas oxygen monitor	Range ________°F	Reading ________°F	
Fan Current	______ amps		
Fuel rate	______scfm		
Heat Exchangers (for heat recovery)	IN	OUT	PRESSURE DROP
#1 Process gas	______°F	______°F	______ in. H_2O
Combustion gas	______°F	______°F	______ in. H_2O
#2 Process gas	______°F	______°F	______ in. H_2O
Combustion gas	______°F	______°F	______ in. H_2O

Figure 7-11. Example shift catalytic incinerator inspection form.

QUARTERLY CATALYTIC INCINERATOR INSPECTION FORM	
Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (Print):
Incinerator ID:	Signature of Inspector:
INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS
Refractory condition? (cracks, spalling, corrosion)	
Burner condition? (warpage, corrosion, fouling)	
Heat exchanger(s) and combustion chamber condition? (fouling, corrosion, leaks)	
Pressure seals condition? (check packing glands)	
Shell condition? (thermal shock, welds condition)	
Check auxiliary fuel piping train and note condition.	
Check interlocks, electrically operated valves, shutoff dampers, gauges, continuous recorders and thermocouples for proper operation. (calibrate where applicable)	
Catalyst cleaned (follow suppliers instructions) Date of last cleaning ____________	

Figure 7-12. Example quarterly catalytic incinerator inspection form.

Slaging/Fouling --

Because of the lower temperature in the bed oxidizer as compared to thermal units, the potential for fouling the chamber with foreign materials is reduced. Dusts and dirt not removed in prefilter systems or air pollution control equipment may, however, adhere to catalyst surfaces. These deposits (slags) may increase catalyst failure and reduce the destruction characteristics of the catalyst bed.

Auxiliary Burner Flame Safety--

Flame safety is an important aspect of all combustion processes. Failure to detect flame out may result in the continued introduction of fuel or fume into a hot combustion chamber in which ignition has ceased. A rich gas mixture is produced that spontaneously combusts with violence. The resulting explosion can destroy the incinerator and adjacent process equipment.

All components of the flame safety system must be inspected frequently and spare parts should be accessible for replacement. Under no circumstances should the flame safety be bypassed or disabled during normal operation. Only trained service personnel should be involved with disabling interlocks and safeties as part of troubleshooting or fault detection.

Catalyst Poisoning--

The most serious limitation to catalytic combustion systems is the destruction or deactivation of the catalyst due to poisoning by contaminants. This effect falls into two categories: irreversible and reversible.

Irreversible Catalyst Failure--

This failure mechanism is caused by coating or attachment of a poison to the noble metal used in the catalyst bed. Typical poisons are phosphorus, bismuth, lead, arsenic, antimony, mercury, iron oxides, tin, and silicon. Several of these elements are present in ambient air or process streams. Fumes having organic components containing these elements are not candidates for application of catalytic incineration systems. An engineering feasibility study is typically conducted to determine if the potential exists for incineration of these elements. Process changes between the design and operation of the incinerator may result in inclusion of forbidden substances. If poisoning occurs, the catalyst must be removed and returned to the supplier for remanufacture. Current research has been conducted to produce poison resistant catalyst for phosphorus and silicon applications.

High temperature can sinter the catalyst and reduce the active surface area. When this occurs the bed is destroyed and must be replaced.

Reversible Catalyst Failure--

Reversible catalyst poisoning occurs when compounds coat the bed surfaces, which temporarily blind the pores or oxidation sites. Typical reversible poisons are sulfur (reduced states), halogens, and carbon particles. These can be removed by oxidation through increasing bed temperature. Activation can also be restored by washing the bed to remove solid particles using detergents, acids, or caustic.

Low Oxygen--

A decrease in oxygen content of the fume may result in insufficient oxygen to complete the reaction. This condition can result in the formation of complex products of incomplete combustion.

Insufficient Preheat--

A minimum temperature of the bed is necessary to initiate catalytic oxidation. The preheat is typically established to provide the minimum temperature necessary to activate the catalytic reaction. The efficiency of reaction is also temperature dependent and a set temperature must be maintained to achieve design efficiency.

Poor Mixing--

Inadequate mixing of fume, preheat combustion gases and dilution air (oxygen) can result in stratifications in the bed which impede uniform oxidation and result in local heating of bed sections. Turbulence and mixing are equally important in catalytic as well as thermal systems.

Low Pollutant Concentration--

In general, the efficiency of the reaction increases with fume concentration. At low fume concentrations destruction efficiency may decrease by 30 to 40 percent. Application of a catalytic system to variable flow and pollutant rates may be unsuccessful. Engineering feasibility studies should be completed to determine the typical range of concentrations. If low fume rates are encountered, injection of fuel gas (propane, natural gas, etc.) may be required to maintain bed temperatures.

Poor Gas Distribution--

Partial fouling of the catalyst bed and/or poor gas distribution can result in local exceedance of face velocity. This can produce local heating and/or failure. Since bed temperature is measured as the average gas temperature exiting the system, it is important that minimum stratification occur and deviation from the average be minimized.

High Face Velocity--

Increased treatment volume decreases the specific volume of the catalyst bed and decreases efficiency. Limits on total gas volume are imposed to assure optimum destruction efficiency. High velocity can also erode the bed and decrease useful service life.

Table 7-4 summarizes the failure mechanisms, symptoms, and corrective actions associated with catalytic incinerators. The reader is also referred to Table 7-2 which contains failure mechanisms for thermal fume incinerators which are also applicable to catalytic incinerators.

7.3 Spare Parts

Spare parts should be maintained to replace fuses, sensors, relays, and key controllers in the flame safety circuits and monitoring instruments. Replacement burners and refractory should also be kept onsite. Experience based maintenance and

TABLE 7-4. SUMMARY OF FAILURE MECHANISMS, SYMPTOMS, AND CORRECTIVE ACTIONS FOR CATALYTIC INCINERATORS

Failure mechanism	Symptoms	Corrective actions
Catalyst failure (thermal)	Sintered surface Deactivation Low bed temperature	Replace bed
Catalyst failure (poison/reversible)	Deactivation	Increase bed temperature to burn out contaminant Prefilter carrier gases Use clean auxiliary fuels (n.g., propane) Change process streams; isolate poison
Catalyst failure (poison/irreversible)	Deactivation	Replace bed Isolate poison from process stream
Low oxygen	High CO Elevated PIC Low bed temperature	Increase dilution air Monitor fume O_2
Low preheat	High CO Elevated PIC Low bed temperature	Install auxiliary fuel burners Install feed back temperature control system Monitor preheat temperature
Poor mixing	High CO Bed failure	Increase turbulence or premix dilution air
Low pollutant concentration	Low destruction efficiency High CO/PIC Low bed temperature	Inject fuel HC to fume Increase temperature Replace with direct fired unit
Poor gas distribution	Low destruction efficiency High CO/PCC Local bed failure (thermal)	Improve gas flow distribution Improve mixing
High velocity	Bed erosion Low efficiency	Reduce gas volume Reduce temperature air inleakage Increase bed volume

Note: See Table 7-2 which contains failure mechanisms, symptoms, and corrective actions for thermal fume incinerators that are also applicable to catalytic incinerators.

parts replacement histories should be used to determine future needs. Each system is unique and a general maintenance program is only a starting point.

7.4 Operator Training

Similar to any piece of equipment, thermal and catalytic fume incinerators will not receive proper maintenance without facility management support and the willingness to provide its employees with proper training. Efficient operation of a fume incinerator, promoted by adequate inspection and maintenance procedures, is as important as productive operation of any process equipment. Management and employees must take a proactive approach to the operation of a fume incinerator in order to prevent production-stopping equipment malfunctions or failures.

The training and motivation of employees assigned to monitor and maintain a fume incinerator are critical factors. These duties should not be assigned to inexperienced personnel that do not understand how an incinerator works or the purpose behind assigned maintenance tasks.

System training should be received from the incinerator manufacturer when a new system is commissioned. The manufacturer's start-up services will generally include introductory training for facility operators and maintenance personnel. The field service engineer involved in startup procedures will instruct plant personnel in the methods to ensure proper assembly and operation of the system components, check and reset system instrumentation and control, check for the proper operation of interlocks and temperature systems, and perform simple troubleshooting.

Following startup training, regular training courses should be held by in-house personnel or through the use of outside expertise. The set of manuals typically delivered as part of a new incinerator installation will include manufacturer-recommended maintenance procedures. Annual in-house training should at a minimum include a review of these documents and confirmation of the original operating parameters. Training should include written instructions and practical experience sessions on safety, inspection procedures, system monitoring equipment and procedures, routine maintenance procedures, and recordkeeping. For plant personnel involved in taking incinerator opacity readings, U.S. EPA Reference Method 9 requires a semi-annual recertification in method procedures.

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SECTION 8.0

FLARES

This section provides readers with guidance and procedures for the proper operation and maintenance of flares. Flaring is a direct combustion control process that is used for the destruction of combustible gases, normally, volatile organic compounds (VOC). Typically flares are used to control emissions from intermittent sources or emergency relief vents; however, flares are receiving increasing use on continuous operating sources. Flares are capable of achieving high levels of VOC destruction (e.g., greater than 95 percent) if proper attention is paid to combustion process controls.

8.1 General Description

Flare systems are basically gaseous fuel burners designed to burn efficiently and smokeless. A gas flaring system converts combustible pollutants to nontoxic combustion products. Flare systems are broadly categorized in two ways: 1) enclosed ground flares, and 2) elevated flares. Elevated flares can be further subdivided according to the method of flaretip gas mixing (steam-, air-, non-, and pressure-assisted). Elevated flares mainly are designed to eliminate potential ground-level fire hazards. Ground level flares must be completely enclosed for obvious safety reasons.

Flares can present safety and operational problems. Some of the problems associated with operations of a flare system include:

- Thermal radiation: Heat given off to the surrounding area may be unacceptable.
- Light: Luminescence from the flame may be a nuisance if the plant is located in an urban area.
- Noise: Mixing at the flare tip is done by jet venturis which can cause excess noise levels in nearby neighborhoods.

- Smoke: Incomplete combustion can result in toxic or obnoxious emissions.
- Energy consumption: Flares waste energy in two ways: first, by keeping the pilot flame constantly lit and, secondly, by the potential recovery value of the waste gas being flared.

Enclosed Ground Flares--

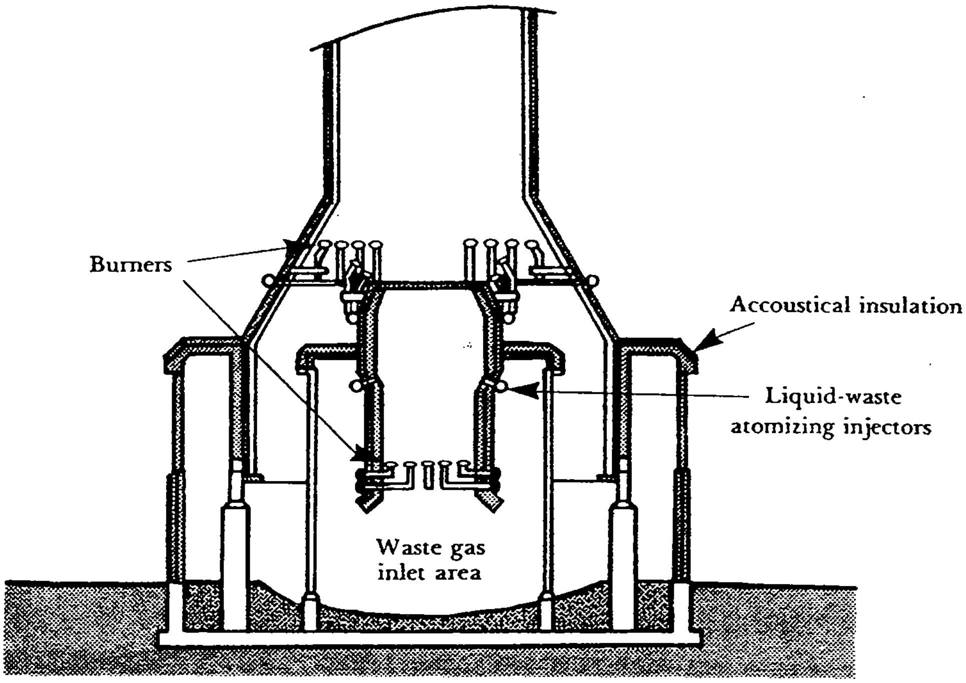
Ground level flares locate the flare tip and combustion zone at ground level. This type still requires an elevated stack for release of effluent gases.

In enclosed ground flare systems the burner heads are enclosed within a refractory shell that is internally insulated. Figure 8-1 illustrates a typical enclosed ground flare. The shell reduces noise, luminosity and heat radiation, and it provides protection from wind. Enclosed flares generally have less capacity than open flares and are normally used for low volume, constant flow vent streams. Reliable and efficient operations can be obtained over a wide range of inlet conditions. More stable combustion can be achieved with lower Btu content gases with enclosed flares than with open flare designs. Enclosed flares are typically found at landfills, and in industrial settings that are densely populated.

Elevated Systems--

A typical elevated flare is composed of a system which first collects the waste gases and passes them through a knockout drum to remove any liquids. Water seals or other safety devices are placed between the knockout drum and the flare stack to prevent a flashback of flames into the collection system. The flare stack is essentially a hollow pipe. The diameter of the flare stack determines the volume of waste gases that can be handled. At the top of the stack is the flare tip which is comprised of the burners and a system to mix the air and fuel.

In elevated systems, combustion takes place at the top of the discharge stack. The gases are vented through an elevated stack from a gas collection system. The flare is unconstricted and is subject to wind driven flame blowout. Elevating the flare can prevent potentially dangerous ground conditions especially where the open flame poses



Source: Straitz, 1980.

Figure 8-1. Ground flare.

a safety hazard. Further, products of combustion can be dispersed above working areas to reduce the effects of noise, smoke, odors, etc.

As with all combustion processes the VOC control efficiency is controlled by flame temperature, residence time in the combustion zone, and turbulent mixing of gaseous components. Combustion is complete if all (most) of the VOC are converted to carbon dioxide and water. Incomplete combustion results in unwanted by-products (e.g., smoke, CO, products of incomplete combustion-PICs) are generated. However, with proper design and good operation and maintenance, undesirable combustion products can be minimized.

The various flare designs differ primarily in their method of mixing. Elevated flares are the most common type used in industry.

Steam Assisted--

These units are the predominant design used in industry. They are mostly used in heavy industry. To ensure an adequate supply of air and good mixing this type of flare injects steam into the combustion zone. The steam promotes turbulence for mixing and induces air into the flare. These units are often designed to handle a turn down ratio of 1000:1 and have flow rates in excess of 30,000 m^3/hour and as low as 30 m^3/hour. Figure 8-2 shows a flare tip from a steam-assisted flare unit.

Air Assisted--

These units are common in facilities where steam may not be available. A forced air fan located at the base of the elevated stack is used to provide combustion air. Typically these flares are small because it is not economical to move large volumes of combustion air. The amount of combustion air is varied by changing fan speeds and, in some systems, by varying the diameter of the air nozzles.

Non-Assisted--

The non-assisted unit is a burner head without any provision for enhancing the mixing of air into the flame. These devices are restricted to low heat content and low carbon/hydrogen ratio gas streams that burn readily without forming smoke. These units

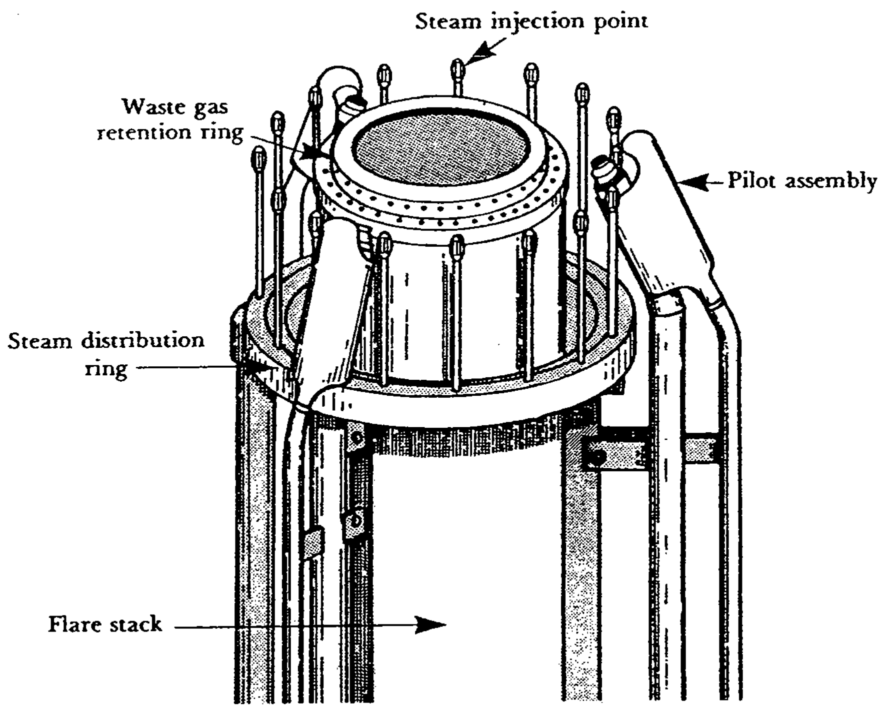


Figure 8-2. Steam-assisted flare tip.

require less air for complete combustion, have lower combustion temperatures and are less likely to cause cracking.

Pressure-Assisted Flares--

Pressure-assisted flares use a high pressure drop burner tip to enhance atomization and fuel-to-air mixing. These units typically have multiple burner heads that are often located at ground level. Each head is staged to operate according to a specific inlet gas volume and back pressure setting.

Auxiliary Equipment--

The major components of all flare systems are the relief, safety and depressurization valves, pressure control valves, condenser, water seals, stack, gas pilots, and the burner gas management system.

Process Description--

Figure 8-3 shows the basic elements of a steam-assisted elevated flare system. The vent stream is sent to the flare through the collection header. The vent stream entering the header can vary widely in volumetric flow rate, moisture content, VOC concentration, and heat value. The knock-out drum removes water or hydrocarbon droplets that could create problems in the flare combustion zone. Vent streams are also typically routed through a water seal before going to the flare. This presents possible flame flashbacks, caused when the vent stream flow rate to the flare is too low and the flame front pulls down into the stack.

Purge gas (N_2, CO_2, or natural gas) also helps to prevent flashback in the flare stack caused by low vent stream flow. The total volumetric flow to the flame must be carefully controlled to prevent low flow flashback problems and to avoid a detached flame (a space between the stack and flame with incomplete combustion) caused by an excessively high flow rate. A gas barrier or a stack seal is sometimes used just below the flare tip to impede the flow of air into the flare gas network.

The VOC stream enters at the base of the flame where it is heated by already burning fuel and pilot burners at the flare tip. Fuel flows into the combustion zone, where

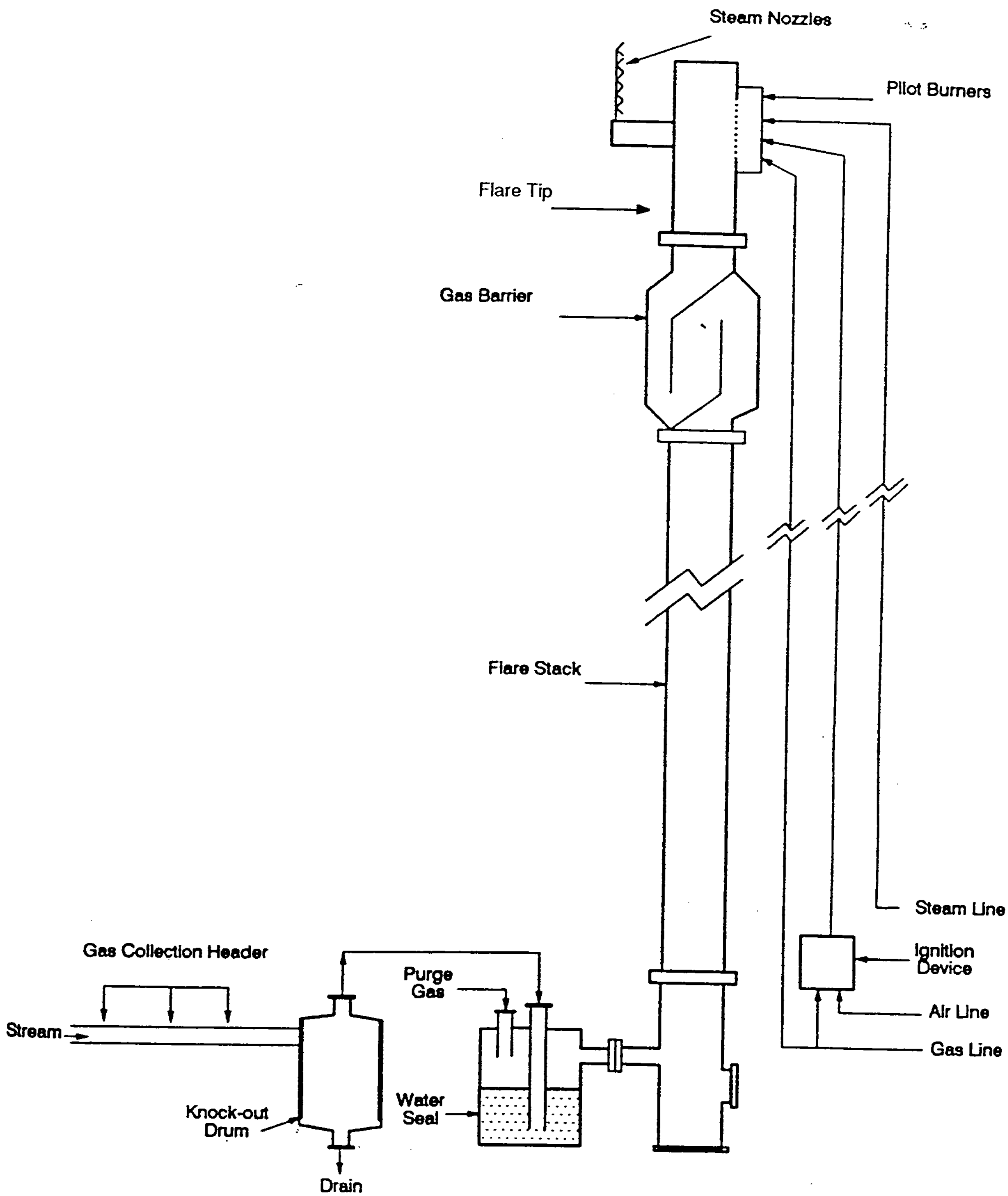


Figure 8-3. Steam assisted elevated flare system.[13]

the exterior of the microscopic gas pockets is oxidized. The rate of reaction is limited by the mixing of the fuel and oxygen from the air. If the gas pocket has sufficient oxygen and residence time in the flame zone, it can be completely burned. A diffusion flame receives its combustion oxygen by diffusion of air into the flame from the surrounding atmosphere. The high volume of flue gas flow in a flare requires more combustion air at a faster rate than simple gas diffusion can supply. Thus, this flare design adds high velocity steam injection nozzles to increase gas turbulence in the flame boundary zones, drawing in more combustion air and improving combustion efficiency. This steam injection promotes smokeless flare operation by minimizing the cracking reaction that forms soot.

Key Combustion Parameters--

The major factors affecting flare combustion efficiency are:

- Vent gas flammability
- Auto ignition temperature
- Gas heating value
- Gas density
- Flame zone mixing

The flammability limits of flared sources influence ignition stability and flare extinction. The flammability limits are stoichiometrically controlled by the gas composition and the oxygen demand (i.e., the gas must be between its upper and lower flammability limits in order to burn). When flammability limits are narrow, the flame may be starved for oxygen and cracking will occur. Cracking is the formation of soot, and if the soot is cooled below its ignition temperature smoking occurs.

The auto ignition temperature is the temperature at which the fuel/air mixture will flame. Flame stability is necessary to ensure that safe burning is occurring. Flame instability may occur when the gas discharge velocity exceeds the flame velocity or when the gas velocity falls below the burning velocity. Blow out occurs in the former condition and flash back occurs in the latter.

The heating value required to maintain endogenous conditions varies with burner design. Large flames require higher heating value fuel than would be required for combustion in a focused burner. The lowest heating value needed to sustain a flame is approximately 200 Btu/scf.

The density of the gas also affects the stability of the flame. Buoyant gases are easier to mix, have a rapid flame speed, and burn better. By design most flares have a low gas exit velocity. Thus, the gas density mix establishes the operating pressures and the purge gas required to prevent flash back.

Flame zone mixing plays a major role in combustion efficiency. Good mixing or high turbulence assumes that the fuel-to-air ratio is maintained in proper proportion and under conditions that prompt ignition and maintain combustion. The management of fuel-to-air ratios is accomplished by:

- underfeed - Raw fuel is under the flame, fuel and air flow same direction
- cross feed - Raw fuel is sprayed into the flame to maintain ignition
- vortex - Air is supplied to the flame from above the fuel
- overfeed - Air is mixed with the fuel near the flame

8.2 Monitoring Flare Operation

The key operating parameters to be monitored to assure proper gas flow through the system and appropriate conditions for thermal destruction of the combustible pollutants are:

- Flame presence
- Pressure and pressure differentials of system components (e.g., knockout drums, seals, fuel gas, steam, and blower)
- Temperatures at flare inlet and outlet and combustion zone
- Liquid levels in water seals and knockout drum
- Exit gas velocity

8.2.1 Monitoring Devices

Flame Presence--

Visual inspection is one method of determining whether a flame is present; however, if the flare is operating smokelessly, visual inspection would be difficult. An inexpensive heat sensing device, such as an ultra-violet beam sensor or a thermocouple, is recommended for use at the pilot light to indicate continuous presence of a flame.

Automatic ignition panels (e.g., electric arc ignition systems) sense the presence of a flame with either visual or thermal sensors and reignite the pilot light when flameouts occur.

Pressure--

The measurement of certain pressures and pressure differentials is needed for safe and efficient operations. Knockout drums, water seals, operating equipment and piping are designed for a specified system pressure. The maximum allowable working pressure is typically 10 percent higher than the normal operating pressure. For a flare control system, pressure indicating gauges should be monitored at least once per shift and located at:

- suction side of compressor or blower
- knockout drums (condenser) front and back
- fuel gas to pilots
- steam, air, and purge gas lines
- water seal (front and back)

Pressure measuring instruments take various forms depending on the magnitude of the pressure and the accuracy desired. Manometers that may contain a wide variety of fluids are commonly used. Differential diaphragm gauges using magnetic linkage are also available for low pressure systems. Pressure measuring devices should be located in positions that avoid errors caused by impacts, eddies, fluid hammers, etc. For differential pressure readings, it is preferable to use a differential pressure device rather than take the difference between the readings of two instruments.

The pressure level of flare system components depends on the type of pressure relief valve employed and the pressure levels of the equipment connected to the flare system. Over pressurizing flares cause a discharge of vapors and liquids, flame out, and/or a build up of back pressure. Excessive back pressure causes upstream process failure and unsafe conditions. The principal types of pressure relief valves are: conventional, balanced bellow, piston and pilot operated.

Conventional pressure relief valves are those where the disk of the valve is held tightly against an inlet nozzle by means of a spring. This type of valve is least expensive, but is limited to a back pressure that is 10 percent of the maximum allowable working pressure. The other types of pressure relief systems do not depend on back pressure for performance. However, to ensure that these safety devices work properly at their maximum capacity, the back pressure should not exceed 50 percent of the relief valve set pressure. Relieving excess pressure via the pressure relief valves should be kept to a minimum. These valves are not self-venting and will leak continuously once operated.

Special attention should be focused on maintaining the proper operating pressures at the water seal which is used to prevent flash back. Cooling of gases by the liquid seal will create a partial vacuum in the cooler disengagement portion of the seal drum creating a siphon effect which drains the water seal and creates an unsafe condition.

Temperature--

Heat exchange rates (where applicable), heat balance, partial pressures and destruction efficiencies are all controlled by temperature. Continuous temperature monitors (thermocouples) should be installed in the following locations.

- inlet stream to flare
- outlet stream from flare
- flame center
- pilot center

Liquid Levels--

Flame arrestors and water seals are intended to prevent fires, once started, from spreading throughout the flare system. Under normal operating conditions one of the most important conditions is the stability of the liquid seal. This seal affects the flash back protection and flame stability at low flow rates. Stability of the liquid seal is affected by the ratio of the inlet or outlet gas areas, dispersion of the gas into the seal liquid, temperature of the gas inlet stream and maintenance of the liquid level by means of alarms and control devices. There are two types of seals: pipe and drum. Pipe seals usually consist of a loop in the flare inlet line or a trap built into the face of the flare. Pipe seals provided limited space for removal of water or condensed hydrocarbons. Seal drums are larger, more expensive, and contain more liquid. Hence drums are generally less susceptible to pulsation and have a lower likelihood of the seal being blown by over pressurization. Liquid levels should be checked at least once per shift. In addition, high or low level alarms (as applicable) and level controls for the accumulating liquids (water and hydrocarbons) are necessary to prevent accumulation of flammable liquids (condensates) or to maintain the integrity of the liquid seals.

Exit Gas Velocity--

It is recommended that the exit gas velocity of the flared stream be determined by a flow indicator in the vent stream of the affected facility. This should be performed at a point closest to the flare and before the stream is joined with any other vent stream.

8.3 Inspection and Maintenance Procedures for Flares

8.3.1 Inspection

Flare systems are typically custom designed units consisting of common equipment. Because of the nature of the materials handled and the conditions under which components operate, the flare system is subject to corrosion, erosion, thermal stress, cracking, spalling and plugging. Most of the maintenance costs and problems, however, arise from instrumentation and process control devices. Daily, monthly and annual inspections are recommended.

On a daily basis, the auxiliary fuel, pressure seals, knockout drum, and monitoring and electrical devices should be physically inspected to verify that they are clean, functioning and calibrated. Pressure seals should be tight and intact. Gas jets should be free of corrosion and cleaned of deposits and blockages. Valves and electrical devices should be checked for proper position and condition. Such things as dirty contacts, moisture leaks, deteriorating insulation and plugged drains should all be repaired. Pressure gauges, thermometer and/or thermocouples and level indicators should all be inspected for physical integrity and calibrated as necessary. Figure 8-4 presents an example daily inspection form.

DAILY FLARE INSPECTION FORM		
Facility Name:	Date of Inspection:	
Facility Location:	Time of Inspection:	
Process:	Name of Inspector (Print):	
Flare ID:	Signature of Inspector:	
INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS	
1) Temperature strip charts functioning properly? - inlet - outlet - combustion chamber		
2) Flame monitor		
3) Pressure gauges		
4) Positions of valves and dampers?		
5) Check liquid level indicators for signs of clogged drains. (knockout drum, water seals)		
6) Pressure seals		
Temperatures	Range	Current
Flare inlet	______ °F	______ °F
outlet	______ °F	______ °F
combustion chamber	______ °F	______ °F
Differential Pressures Knockout Drum ______ in. WG Blower ______ in. WG Seal No. 1 ______ in. WG Seal No. 2 ______ in. WG Seal No. 3 ______ in. WG		
Fuel Gas Pressure ______ in. WG	Steam Pressure ______ in. WG	
Exit Gas Velocity ______ ft/min	Opacity ______ %	

Figure 8-4. Example daily flare inspection form.

On a monthly basis moving parts such as fans and blowers, solenoids, check valves and dampers should be lubricated and cleaned of any foreign matter that may interfere with operation. Figure 8-5 presents an example form for monthly inspections.

Annually or during each equipment shut down, structural components including anchors, straps, foundations and guy wires, should be inspected for integrity. Refractory lining should be checked for cracks and spalling. The outer shell of the stack and flare system components should be checked for cracks and fatigue caused by over pressurization or temperature stress. Flares are typically utilized in harsh environments and corrosion/erosion problems should be carefully monitored and attended whenever found.

As always, inspection forms should be tailored to system specific components (e.g., electric arc ignition system) and operational and regulatory requirements. All maintenance activities and inspections should be recorded and studied for trends and variances from design and/or normal operating conditions. Figure 8-6 shows an example maintenance report form.

8.3.2 Routine Maintenance

Most of the problems that occur with flares have a direct impact on emission rates. Flares are not immune to physical problems caused by overloading. Excessive flow rates may cause explosions, uncontrolled fire, and ventilation of toxic or obnoxious gases. Hence routine maintenance to assure that safety devices are intact and that process controllers are functioning properly is critical. Fouling and plugging is the deposition of foreign material on the exterior and/or interior of nozzles, valves, monitors, controllers and burner heads. Cleaning of deposits is generally performed only during major shutdowns.

8.3.3 Spare Parts

Generally flares are moderate maintenance systems. A facility should maintain a ready supply of antifouling agents, gauges, valves, floats, and gasket material.

MONTHLY FLARE INSPECTION FORM	
Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (Print):
Flare ID:	Signature of Inspector:
INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS
1) Inspect, lubricate, and clean: - Fans and blowers - Solenoids - Check valves - Dampers	
2) Calibrate: - Temperature monitors - Pressure gauges - Level indicators	
3) System exterior observations (e.g., rust, connections, leaks) - Ducts - Knockout drum - Seals - Flare tip - Fuel line - Steam lines - Fan housing - Fan motor	

Figure 8-5. Example monthly flare inspection form.

MAINTENANCE REPORT FORM

Department	Unit	System	Subsystem	Component	Subcomponent

Originator: ____________ Date: ________ Time: ________

Assigned To:

1	Mechanical
2	Electrical
3	Instrumentation

Priority:

1	Emergency
2	Same Day
3	Routine

Unit Status:

1	Normal
2	Derated
3	Down

Problem Description: ____

Foreman: ____________ Date: ________

Cause of Problem: ____

Job Status:

1	Repairable
	Hold for:
2	Tools
3	Parts
4	Outage

Work Done: ____

Supervisor: ____________ Completion Date: ________

Materials Used: ____

Labor Requirements: ____

Figure 8-6. Example maintenance report form.

8.4 Malfunctions

Operational failures and malfunctions include both equipment and personnel induced accidents. A brief discussion on problems associated with flares is provided in Table 8-1 to alert readers of issues that may cause safety problems and/or excessive emissions.

8.5 Operator Training

Similar to any piece of equipment, a flare will not receive proper maintenance without management's support and the willingness to provide its employees with proper training. Efficient operation of a flare, promoted by adequate inspection and maintenance procedures, is important. Management and employees must be cognizant of proper procedures necessary to prevent equipment malfunctions or failures.

System training should be received from the manufacturer when a new system is commissioned. The manufacturer's start-up services will generally include introductory training for facility operators and maintenance personnel. The field service engineer involved in startup procedures will instruct plant personnel in the methods to ensure proper assembly and operation of the system components and instrumentation and controls. Training should also include procedures to perform simple troubleshooting.

Following start-up training, regular courses should be held by in-house personnel or through the use of outside expertise. The set of manuals typically delivered as part of a new installation will include manufacturer-recommended maintenance procedures. Annual in-house training should at a minimum include a review of these documents and confirmation of the original parameters. Training should include written instructions and practical experience sessions on safety, inspection procedures, system monitoring equipment and procedures, routine maintenance procedures, and recordkeeping.

TABLE 8-1. MALFUNCTION MECHANISMS, SYMPTOMS AND CORRECTIONS

Mechanism	Symptom	Correction
Over pressurization	Relief valves open, compressor overheating, condenser out jet temperature low, condenser flooded, flame out, leaks	Set valves and dampers to correct position. Clean condensate removal system.
Cross and open connections	Back fire, soot/smoke, open valves, leaks, submerged pipes	Verify connection and valve position.
Burner fouling	Flame out, flame instability, soot/smoke	Clean burner tips more frequently.
Improper flame temperature	Soot/smoke, flame instability, flame color change	Adjust fuel/air mixtures ratio. Verify flame heat content.
Refractory failure	Cracks, spalling, crumbling, hot spots on shell, paint blisters	Ramp up to operating temperature. Properly limit peak temperatures. Limit heat/cool cycles. Protect from corrosion.
Self fueling	Increased temperature, maximum turn down, extended flame length, unusual noise	Purge with inert gas. Flood knockout drum.
Internal explosion/ flashback	Vibration, noise, vacuum in seal line, pulsation in knock out drum, relief valves open, metal incandescence	Water seals not maintained. Adjust fuel/air ratio. Increase refractory thickness. Erect wind shields. Increase exit velocity.
External burning	Flame flickering, extended flame front	Lower exit velocity.
Secondary fire	Submerged stack drain, large pilot gas consumption	Adjust condenser, adjust pilot.

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SECTION 9.0

WET SCRUBBERS

This section provides the reader with guidance on proper operation and maintenance of wet scrubber systems used as air pollution control devices. Wet scrubber systems include spray chambers, venturis, packed bed and tray towers, absorbers and water assisted mechanical collectors (e.g., Roto-Clones). Water assisted mechanical collectors are discussed in Section 3.

9.1 General Description

Wet scrubbers can be used to separate particulate and gases from other gas streams. They are used in situations where:[1]

1. Soluble gases are present.
2. The contaminant cannot be removed easily in a dry form.
3. Soluble or wettable particulates are present.
4. The contaminant will undergo some subsequent wet process (such as recovery, wet separation or settling, or neutralization).
5. The pollution control system must be compact.
6. The contaminants are most safely handled wet rather than dry (where the dry particulate may ignite or explode).

There are many different types of scrubbers. The type of scrubber selected is based on factors such as the gas temperature, pollutants to be removed, space available, and desired efficiency. Some types of scrubbers are mainly designed to remove particulate pollutants (e.g., venturi scrubbers) and others are designed to mostly remove gaseous pollutants or soluble particulates (e.g., packed towers and tray towers). Spray chambers are often added ahead of other scrubbers to condition the gas by saturating the gas stream, by cooling the gas stream via evaporative cooling, or by removing larger particulates. Examples of various categories of scrubbers and related types of scrubbers are presented in Table 9-1. Figures 9-1 through 9-4 show representative schematics of a spray chamber, fixed and variable throat venturi scrubbers, and packed tower, respectively.

Wet scrubbing is a two-step process, the first step being the capture of the gas stream contaminants in the liquid and the second step being separation of the scrubbing liquid droplets from the gas stream after it leaves the scrubber. This step is important in the ultimate collection of pollutants because poor liquid separation will cause reentrainment of the droplets containing the pollutant.

There are four basic types of liquid entrainment separators or "demisters": mesh-pad, chevron, centrifugal, and cyclonic. The mesh-pad and chevron types utilize inertial impaction of the liquid droplets to cause their agglomeration and removal. The centrifugal and cyclonic types utilize centrifugal inertia to collect the liquid droplets. Figure 9-5 shows schematics of the generic types of entrainment separators.

A wet scrubber system could contain more than one different type of scrubber. A typical air pollution control system for a hazardous waste incinerator, for example, might contain a spray chamber or quench chamber to cool and saturate the exhaust gases as they leave the incinerator. A venturi scrubber would follow the spray chamber to remove most of the particulate before the gas stream enters a packed column for gaseous contaminant removal (e.g., hydrogen chloride or chlorine gas). Liquid entrainment separators would follow both the venturi and packed column to remove the water droplets and their contained pollutants before going to the next air pollution control stage. In most of these type of systems, an induced draft fan follows the air pollution controls to pull the gases through the control system and force the cleaned exhaust gases through the stack. This type of scrubber control system is shown schematically in Figure 9-6.

9.1.1 Pollutant Collection

Pollution collection mechanisms are briefly discussed in this section. More detailed discussions of wet scrubber collection mechanisms and system design are readily available in most textbooks on air pollution control.

TABLE 9-1. MAJOR TYPES OF WET SCRUBBERS[a,b]

General Category of Scrubbers	Particle Capture Mechanism[c]	Liquid Collection Mechanism	Specific Types of Scrubbers
Preformed-spray	Impaction	Droplets	Spray towers Cyclonic spray towers Vane-type cyclonic towers Multiple-tube cyclones
Packed-bed scrubbers	Impaction	Sheets, droplets (moving bed scrubbers)	Standard packed-bed scrubbers Fiber-bed scrubbers Moving-bed scrubbers Cross-flow scrubbers Grid-packed scrubbers
Tray-type scrubbers	Impaction Brownian diffusion	Droplets, jets, and sheets	Perforated-plate Impingement-plate scrubbers Horizontal impingement-plate (baffle) scrubbers
Mechanically aided scrubbers	Impaction	Droplets and sheets	Wet fans
Venturi and orifice scrubbers (gas atomized scrubbers)	Inertial impaction Brownian diffusion	Droplets	Standard venturi scrubbers Variable-throat venturi scrubbers: flooded disc, plumb bob, movable blade, radial flow, variable rod Orifice scrubbers

[a] List not intended to be all inclusive.
[b] Reference 2.
[c] Absorption is the capture mechanism for gaseous pollutants.

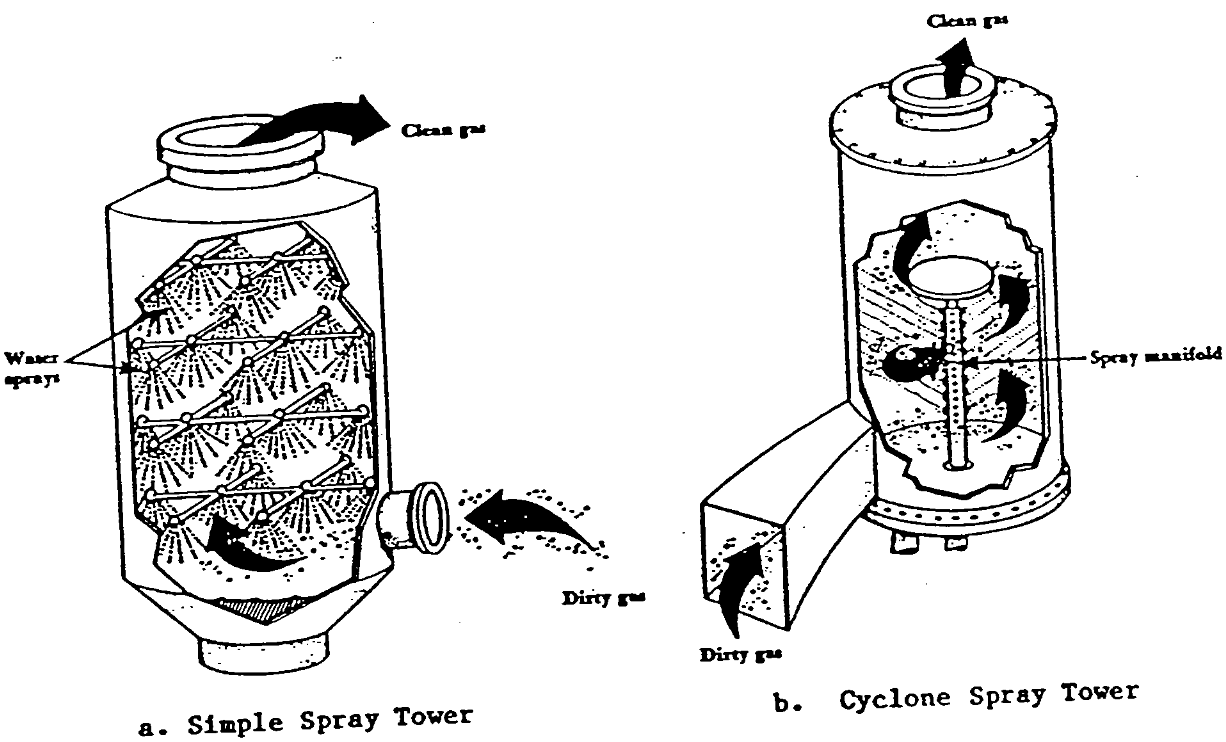


Figure 9-1. Preformed spray scrubbers[3].

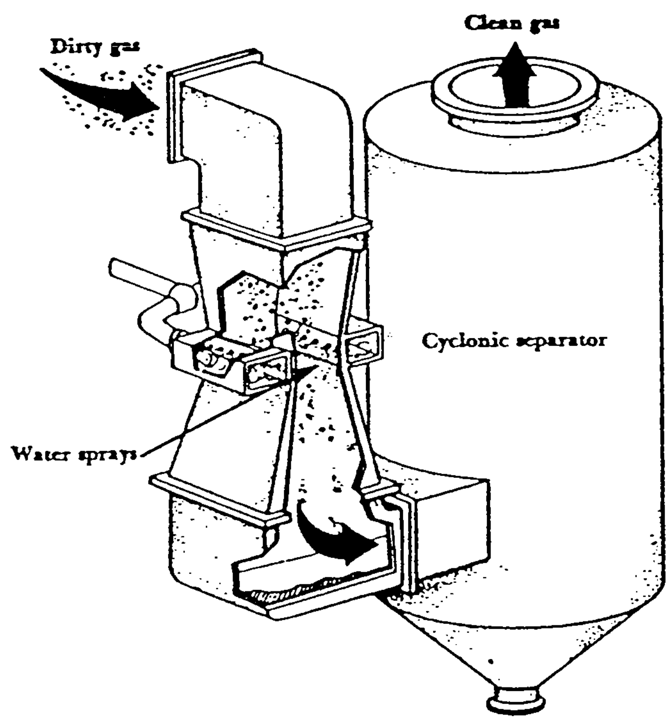


Figure 9-2. Fixed throat venturi scrubber[3].

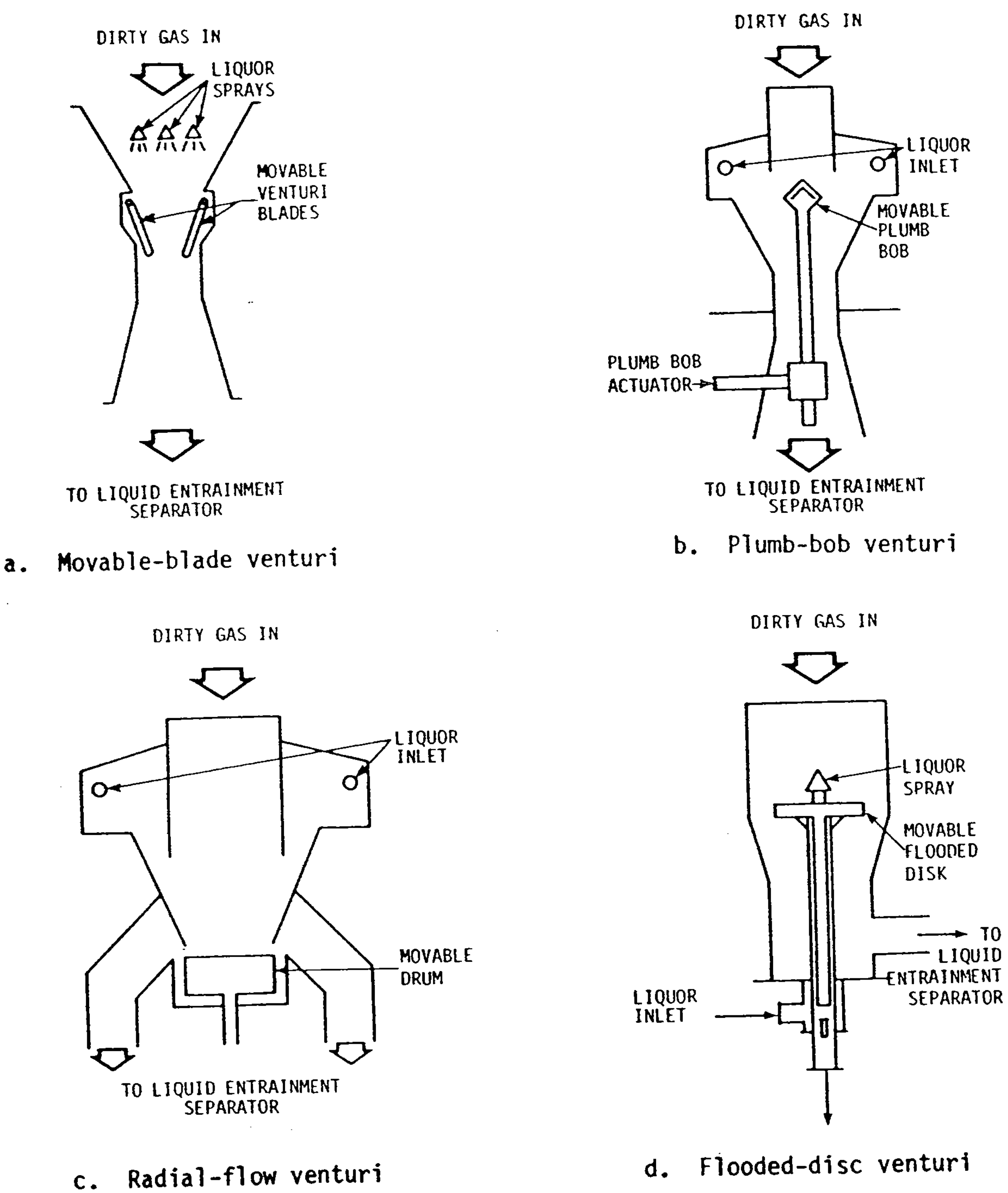


Figure 9-3. Throat sections of variable throat venturi scrubbers (Industrial Gas Cleaning Institute, Inc.).

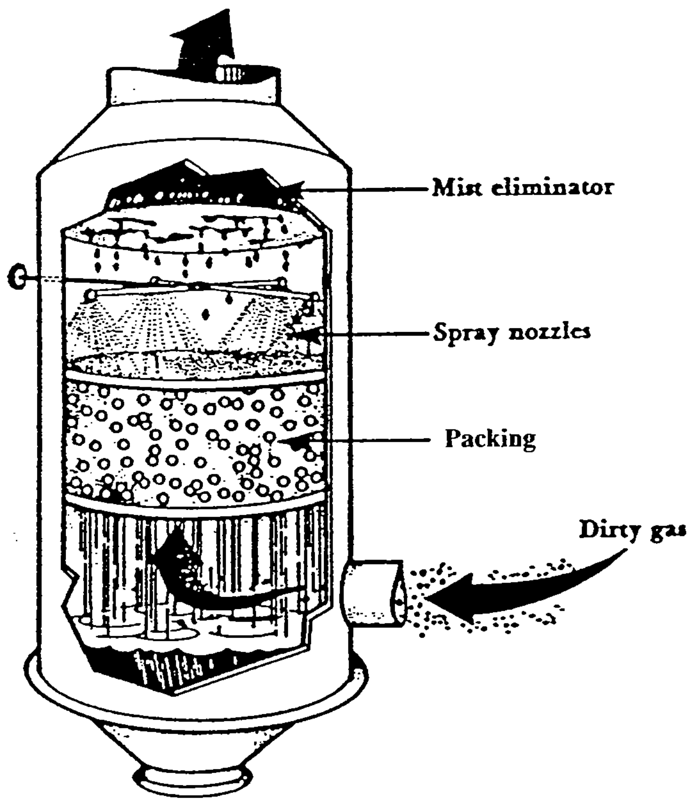
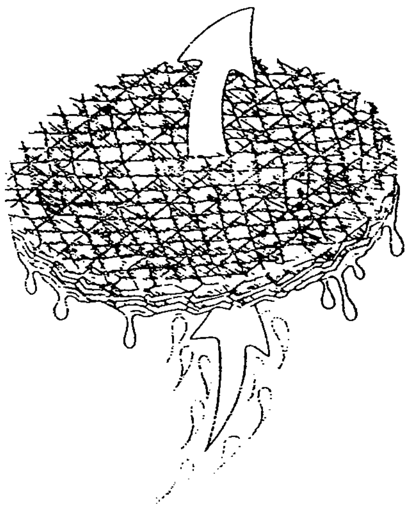
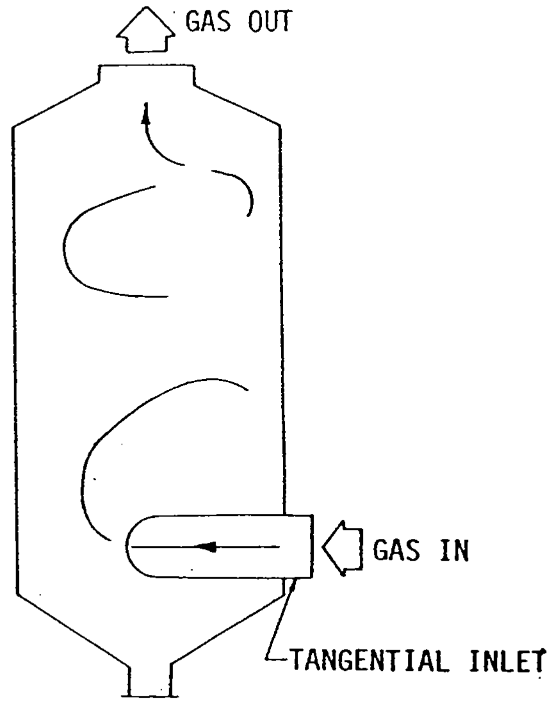


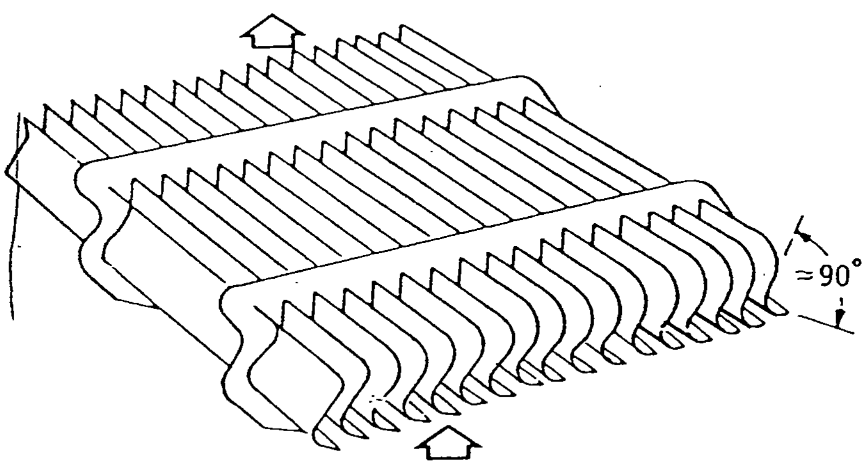
Figure 9-4. Packed bed scrubber[3].



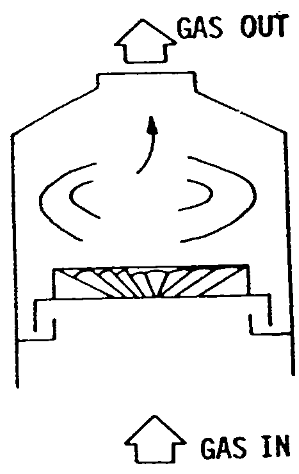
WIRE MESH



CENTRIFUGAL MIST COLLECTOR



CHEVRON MIST ELIMINATOR



CYCLONIC MIST COLLECTOR

Figure 9-5. Liquid entrainment separators (Industrial Gas Cleaning Institute, Inc.).

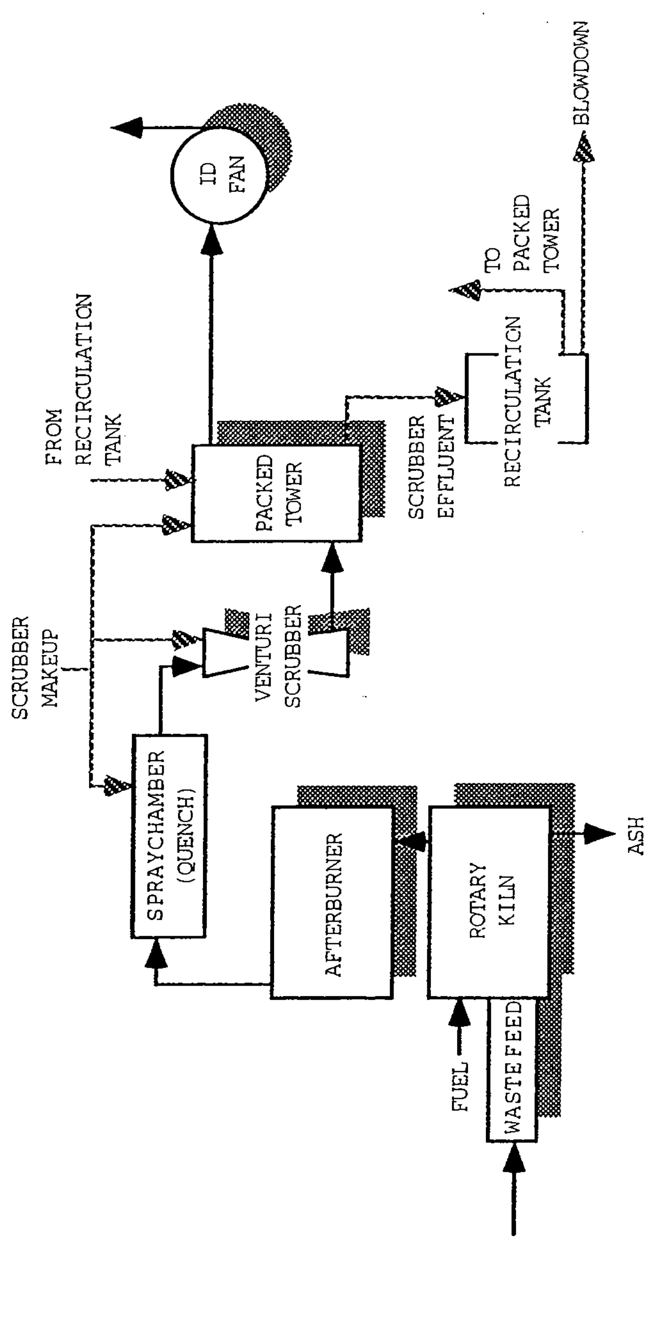


Figure 9-6. Schematic diagram of a wet scrubber air pollution control system controlling a hazardous waste incinerator.

Particulate--

All of the fundamental mechanisms employed to collect particulate in wet scrubbers are very particle size dependent. The two most commonly used mechanisms are impaction and Brownian diffusion. Impaction is a very effective means of capture for particles larger than 0.5 microns and Brownian diffusion is the primary capture mechanism for the very small particles in the less than 0.1 micron range. In the 0.1 to 0.5 micron range, both collection mechanisms can be active, but neither is especially effective.

Impaction occurs as a particle laden gas stream flows around an obstacle (e.g., a water droplet) and the particles remain on a straight trajectory and collide with the obstacle due to their inertia. Impaction is highly dependent on the particle diameter and is directly proportional to the differences in the relative velocities of the particle and the target.

The trajectories of very small particles are affected by the impacts of gas molecules. The random movement due to these collisions is termed Brownian diffusion. During this random movement, the particle may get close enough to a water droplet to be captured. The rate of Brownian diffusion is inversely proportional to the particle size diameter. As particle size decreases, Brownian diffusion increases. It also increases as the gas temperature increases due to the increased kinetic energy of the gas molecule striking the small particles.

Due to the combined action of impaction and Brownian diffusion, penetration of particulate matter in gas atomized scrubbers is low for particles greater than 1.0 microns and less than 0.10 microns.[4] However, there is a peak in the penetration curve (penetration = 1 - collection efficiency/100) at approximately 0.2 to 0.5 microns. Gas atomized scrubbers and other air pollution control devices using impaction and Brownian diffusion are least effective in the 0.2 to 0.5 micron size range.

Scrubbing systems for installations requiring very high particulate removal efficiencies in the submicron particle size range can utilize flux force/condensation mechanisms to aid capture.[4] These are inherently simultaneous mechanisms which facilitate both impaction and Brownian diffusion. Flux force/condensation conditions are initiated by removing the sensible heat from the gas stream downstream of a quench (i.e., supersaturating the gas stream using water sprays) so that a portion of the gas stream water vapor condenses on the particles to be removed, and creates a bigger particle that is easier to remove from the gas stream.

Gases and Vapors--

Gas and vapor collection in wet scrubber air pollution control devices is achieved by absorption. The process of absorption refers to the contacting of a mixture of gases with a liquid so that part of one or more of the constituents of the gas will dissolve in the liquid.

The gaseous air contaminants most commonly controlled by absorption include sulfur dioxide, hydrogen sulfide, hydrogen chloride, chlorine, ammonia, oxides of nitrogen, and light hydrocarbons.[5] The necessary condition for absorption is the solubility of these pollutants in the absorbing liquid. The rate of transfer of the soluble constituents from the gas to the liquid phase is determined by diffusional processes occurring on each side of the gas-liquid interface. Consider, for example, the process taking place when a mixture of air and gaseous hydrogen chloride (HCl) is brought into contact with water. The HCl is soluble in water, and those molecules that come into contact with the water surface dissolve immediately. However, the HCl molecules are initially dispersed throughout the gas phase, and they can only reach the water surface by diffusion through the air, which is substantially insoluble in the water. When the HCl at the water surface has dissolved, it is distributed throughout the water phase by a second diffusional process. Consequently, the rate of absorption is determined by the rates of diffusion in both the gas and liquid phases.[1]

Equilibrium is another important factor to be considered in controlling the operation of absorption systems.[1] The rate at which the pollutant will diffuse into an absorbent liquid will depend on the departure from equilibrium that is maintained. The rate at which equilibrium is established is then essentially dependent on the rate of diffusion of the pollutant through the nonabsorbed gas and through the absorbing liquid. The rate at which the pollutant mass is transferred from one phase to another depends also on a so-called mass transfer, or rate coefficient, which equates the quantity of mass being transferred with the driving force. As can be expected, this transfer process ceases upon the attainment of equilibrium.

In gas absorption operations the equilibrium of interest is that between a nonvolatile absorbing liquid (solvent) and a solute gas (usually the pollutant). The solute is ordinarily removed from its mixture in a relatively large amount of a carrier gas (air) that does not dissolve in the absorbing liquid. Temperature, pressure, and the concentration of solute in one phase are independently variable.

9.1.2 Key Operating Parameters

The scrubbing system is composed of exhaust hoods and ducts handling airborne contaminants. Gas pretreatment equipment may be required for coarse particulate removal and for cooling before the contaminants enter the scrubber vessel. The contaminant-laden droplets are removed by the entrainment separators. The clean gas is then passed through an induced-draft fan and up the stack. Forced-draft fans upstream of the scrubber are also used. The key operating parameters affecting the pollutant collection are:[3]

Velocity/gas flow rate
Liquid-to-gas ratio
Pressure drop
Temperature
Particle size distribution (particulate)

Velocity/Gas Flow Rate--

The collection efficiency of most scrubbers depends on the velocity of the gas stream through the liquid-contacting section of the scrubber vessel. For particulates, the relative velocity between washing liquids (droplets) and particulates is critical to contaminant collection. In the case of high-energy venturi scrubbers, a velocity of 40,000 ft/min can be delivered.[3] Fine droplet size and high density lead to increased removal efficiency.

When a high-temperature gas stream enters the scrubber, the volumetric flow rate diminishes accordingly (based on the temperature of the scrubber liquid) because the gas is being cooled by the scrubber liquors. When the system flow rate decreases, the resulting relative velocity may not be sufficient to collect the desired amount of particulate and emissions will increase.

For a packed tower or tray tower, low or no gas flow might indicate plugged packing in the absorber, fan problems, duct leaks, or an increase in liquid flow to the tower. Increased gas flow might indicate a low liquid flow rate, packing failure, or a sudden opening of a system damper.

Liquid-to-Gas Ratio--

The liquid-to-gas flow rate (L/G) is a calculated value, reflecting the liquid recycling rate (gal/min) for every 1000 ft^3 of gas cleaned. Typical values range from 2 to 40 gallons of liquid per 1,000 ft of inlet gas; and are a function of inlet gas temperature, inlet solids content, and method of water introduction. High L/G ratios are used for high-temperature gas streams and high-grain loadings. Should the L/G ratio fall below the design value, collection efficiency will diminish. Table 9-2 presents typical liquid-to-gas ratios for various types of wet scrubbers.

High L/G ratios are required for high temperature gas streams to prevent pollutant reentrainment. When the L/G ratio is not sufficient to saturate the gas stream, pollutant laden droplets reentering the scrubber from recycled liquors will evaporate (evaporative cooling) and leave the previously captured particulate reentrained in the gas stream. Should this occur, pretreatment with clean liquor (for quenching) may be required. The quenching stage saturates the gas stream to minimize evaporation in the scrubbing stage.

Pressure Drop--

The pressure drop across a scrubber includes the energy loss across the liquid gas contacting section and entrainment separator, with the former accounting for most of the pressure loss. A low pressure drop scrubber ranges from 2 to 10 in. H_2O; medium, from 10 to 30 in. H_2O; and high, 30 and above. The higher the pressure drop, the greater the particulate collection efficiency for both particle size and concentration. Table 9-3 presents typical pressure drops for various types of wet scrubbers.

TABLE 9-2. TYPICAL LIQUID-TO-GAS RATIOS FOR WET SCRUBBERS[2]

Scrubber Type	Liquid-to-Gas Ratio, gal/1000 ft^3
Venturi	5 - 8
Cyclonic spray tower	5 - 10
Spray tower	10 - 20
Impingement plate	3 - 5
Packed bed	1 - 4

TABLE 9-3. TYPICAL SCRUBBER PRESSURE DROPS[2]

Scrubber Type	Pressure Drop, inches water
Venturi	10 - 70
Centrifugal (cyclonic) spray	1 - 3
Spray tower	1 - 2
Impingement plate	1 - 10
Packed bed	1 - 10
Wet fan	4 - 10
Self-induced spray (orifice)	2 - 20
Irrigated filter (filter bed scrubber)	0.2 - 3

For tray and packed towers, an increase in pressure drop might indicate plugging or an increase in gas or liquid flow rates. A decrease in pressure drop might indicate a decrease in gas or liquid flow, channeling through the scrubber due to poor liquid distribution or partial plugging, or a damaged packing support plate allowing the packing to fall to the bottom of the scrubber.

Temperature--

Wet scrubber inlet and outlet temperatures are key parameters that should be monitored when controlling gas streams with elevated temperatures.

An increase in temperature could indicate a failure of the cooling equipment (e.g., quench chamber, dilution air) which would result in decreased pollutant collection efficiency and perhaps damage to the scrubber.

Particle Size Distribution--

Performance of a scrubber controlling particulate emissions depends on the gas stream particle size distribution. Efficient collection of submicron contaminants challenges the application of any type of control equipment. High-energy venturi scrubbers are designed for submicron contaminant collection. Changes in process equipment or operation can change the particle size distribution and, in turn, impact collection efficiency.

9.2 Monitoring Wet Scrubber Operation

Proper instrumentation is vital to the monitoring of scrubber performance. Many installations require instrumentation with associated alarms and interlocks to protect valuable components from malfunctions such as loss of water pressure or a process temperature runaway.

9.2.1 Pressure Drop

Every major scrubber system should include a continuous monitor to measure static pressure drop across the scrubber. Static pressure drop can be measured with a differential pressure gauge or manometer. Care must be taken in the design of the tubing and fittings to prevent plugging and to allow easy cleaning, and tubing materials should be selected to withstand the service expected. For example, certain plastics can melt when exposed to high temperatures; some plastics become excessively brittle at low temperatures; and polypropylene tubing is degraded under continuous exposure to sunlight.

9.2.2 *Temperature*

For sources that generate hot gases, the gas temperatures must be monitored if the scrubber contains materials that cannot withstand high temperatures. A high-temperature alarm and/or an interlock system is usually installed to shut down the process or to bypass the scrubber system. Where gas temperatures vary widely, it is sometimes necessary to install temperature feedback instrumentation that controls the water flow rates to the presaturator.

9.2.3 *Liquid Flow Rate*

Liquid flow rates are important because the liquid-to-gas ratio has a direct impact on the driving forces for particulate collection and absorption in wet scrubbers. Also, very low liquid flowrates could aggravate problems with poor liquid distribution in plate tower absorbers. Low liquid flowrates in packed towers could cause some packing wetting problems.

Water flow rates can be measured by in-line flow meters or doppler type indirect flow meters. A less expensive and less accurate method of flow measurement is the use of a pump pressure gauge calibrated to indicate flow rates. Open-channel type flow-measuring devices such as the Parshall flume are sometimes useful, although the preferred measuring point for liquor flow is between the pump outlet and the scrubber spray nozzles. The recirculation pump discharge pressure can be used as an indirect indication of liquid flow.

Alarm systems can also be included to indicate low water levels in orifice-type scrubbers. In systems that include presaturators, water flow through the scrubber and the presaturator should be measured individually.

9.2.4 *Other Monitoring Equipment*

Scrubber instrumentation often includes liquor pH indicators, fan ammeters, and fan vibration sensors. The pH meters are needed when pH of the scrubbing liquor must be closely controlled. Maintaining clean, accurately calibrated probes, although often difficult, is essential to the success of pH control. Fan ammeters and tachometers can be used in conjunction with the manufacturer's fan performance curves to provide an estimate of gas flow through the scrubber system, or these instruments can be used to provide a quick comparison of the system's performance with previous performance. It is helpful in all scrubber systems to provide small ports in the ducting before and after the fans, the scrubber vessels, and the presaturators. These ports should be 1/4" to 1" O.D. ports which can be used to periodically measure static pressure, gas temperature, gas flow rate, and/or gas oxygen concentration. Liquor sampling taps should also be included so that the pH and liquor solids levels can be routinely checked.

9.3 Inspection and Maintenance Procedures for Wet Scrubbers

9.3.1 Inspections

Inspection guidelines are given below, including guideline procedures for routine startup, inspection and maintenance during operation, and routine shutdown.

Pre-Startup Inspection--

Whether the scrubber has recently been installed or has undergone internal service and maintenance, before it is started up it must be thoroughly inspected. A checklist for preoperation inspection is provided in Figure 9-7. This checklist is to be used as a guideline only, and should be tailored for each specific system. The inspection survey during shutdown should include internal and external observations from the ducts up through the stack. If possible, as part of the pre-startup inspection before the unit is put into service, it is advisable to operate pumps and other components to observe their performance.

Routine Startup--

Proper startup procedures are critical to assure all components and instruments are operational and to prevent damage to the control system. After the scrubber has been thoroughly inspected, the following general startup procedure should be followed:[6]

PRE-STARTUP SCRUBBER INSPECTION CHECKLIST			
Facility Name:	Date of Inspection:		
Facility Location:	Time of Inspection:		
Process:	Name of Inspector (Print):		
Scrubber ID:	Signature of Inspector:		

INSPECTION ITEM	CHECKED		COMMENTS/CORRECTIVE ACTIONS
	YES	NO	
Ducts			
Warpage	___	___	
Corrosion	___	___	
Abrasion	___	___	
Gasketing	___	___	
Slip Joint	___	___	
Solids Buildup	___	___	
Gas Pretreatment Equipment			
Nozzles	___	___	
Solids Buildup	___	___	
Gasketing	___	___	
Corrosion	___	___	
Valve Operation	___	___	
Sump Sludge	___	___	
Scrubber			
Nozzles	___	___	
- Clogging	___	___	
- Wearing	___	___	
- Abrasion	___	___	
Abrasion	___	___	
Buildup	___	___	
Corrosion	___	___	
Piping	___	___	
- Scaling	___	___	
- Rusting	___	___	
- Riggings	___	___	
- Leakage	___	___	
Sump Sludge	___	___	

Figure 9-7. Preoperation inspection checklist for scrubbers.

INSPECTION ITEM	CHECKED YES	CHECKED NO	COMMENTS/CORRECTIVE ACTIONS
<u>Mist Eliminator</u>			
Nozzles	___	___	
- Clogging	___	___	
- Wearing	___	___	
- Abrasion	___	___	
Piping	___	___	
- Rusting	___	___	
- Pitting	___	___	
- Leakage	___	___	
Valve Operation	___	___	
Corrosion	___	___	
	___	___	
<u>Mist Eliminator Media</u>			
Buildup	___	___	
Cleaned	___	___	
Replaced	___	___	
<u>Liquor Treatment</u>			
pH Control	___	___	
- Calibration Check	___	___	
- Probe Buildup	___	___	
Caustic Hold Tank	___	___	
Sludge Buildup	___	___	
Valve Operation	___	___	
Piping Leakage	___	___	

Figure 9-7. Preoperation inspection checklist for scrubbers (continued).

1. Close all drain valves.

2. Fill vessels to normal level.

3. Activate circuit breakers for all controls and components.

4. Open pump suction valves.

5. Start pumps.

6. Open discharge valves slowly.

7. Open isolation dampers.

8. Start fan (if fan has an inlet control damper, it should normally be closed until fan reaches speed).

9. Record data from monitoring instrumentation.

10. Note changes in monitoring data as gases pass through system.

Routine Inspection and Maintenance During Operation--

During normal operation, the scrubber should be inspected on a daily and monthly basis. Example daily and monthly inspection forms for an operational scrubber are presented in Figure 9-8 and 9-9, respectively. A tailormade operational checklist should be prepared for each specific type of equipment based on the manufacturer's recommendation, knowledge of the controlled process, and internal administrative requirements. Figure 9-10 presents an example maintenance report form.

Routine Shutdown--

Proper shutdown procedures should be followed to avoid equipment damage and release of process pollutants to the atmosphere. A general procedure for scheduled shutdown is outlined below:

1. Stop blower.

2. Isolate scrubber vessel by closing dampers.

3. Shut down makeup water.

<table>
<tr><th colspan="2">DAILY SCRUBBER INSPECTION FORM</th></tr>
<tr><td>Facility Name:</td><td>Date of Inspection:</td></tr>
<tr><td>Facility Location:</td><td>Time of Inspection:</td></tr>
<tr><td>Process:</td><td>Name of Inspector (Print):</td></tr>
<tr><td>Scrubber ID:</td><td>Signature of Inspector:</td></tr>
<tr><td>INSPECTION ITEM</td><td>COMMENTS/CORRECTIVE ACTIONS</td></tr>
<tr><td>1) Gas pretreatment equipment
(if applicable)

- Leaks
- Abnormal sounds
- Pressure drop normal?</td><td></td></tr>
<tr><td>2) Scrubber and mist eliminator

- Leaks
- Abnormal sounds
- Pressure drop normal?</td><td></td></tr>
<tr><td>3) Liquor treatment

- Leaks
- Abnormal sounds</td><td></td></tr>
<tr><td colspan="2">Pressures:

Pressure drop across scrubber _____ in. WG
Scrubbing liquid pressure _____ psi</td></tr>
<tr><td>Scrubber liquid flow _____ gpm</td><td>Quench liquid flow _____ gpm
(if applicable)</td></tr>
<tr><td>Temperatures:

Gas into system _____ °F
Liquid from scrubber _____ °F</td><td>Gas into scrubber _____ °F
Gas from scrubber _____ °F</td></tr>
<tr><td colspan="2">Fan amps _____ Pump amps _____

Opacity _____ %</td></tr>
</table>

Figure 9-8. Example daily inspection form.

MONTHLY SCRUBBER INSPECTION FORM	
Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (Print):
Scrubber ID:	Signature of Inspector:
INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS
1) Gas Pretreatment Equipment Piping Leakage Valve Operation Pump/Lub.	
2) Scrubber Piping Leakage Valve Operation Level Control Pump/Lub.	
3) Mist Eliminator Piping Leakage Valve Operation Pump/Lub.	
4) Liquor Treatment Piping Leakage Valve Operation Level Control Pump/Lub.	
5) Fans, Ducts, Pipes - Abrasion - Corrosion - Solids Buildup	
6) Check sensors, alarm systems, and bypass devices for proper operation	

Figure 9-9. Example monthly inspection form.

MAINTENANCE REPORT FORM

Department	Unit	System	Subsystem	Component	Subcomponent

Originator: ____________________ Date: __________ Time: __________

Assigned To:

1	Mechanical
2	Electrical
3	Instrumentation

Priority:

1	Emergency
2	Same Day
3	Routine

Unit Status:

1	Normal
2	Derated
3	Down

Problem Description: ____

____

____

____

Foreman: ____________________ Date: __________

Job Status:

1	Repairable
	Hold for:
2	Tools
3	Parts
4	Outage

Cause of Problem: ____

____

____

Work Done: ____

____

____

Supervisor: ____________________ Completion Date: __________

Materials Used: ____

____

____

Labor Requirements: ____

____

Figure 9-10. Example maintenance report form.

4. Allow system to cool.

5. Continue to blow down at normal rate until liquid levels reach pump inlet, and then shut pumps off.

6. Stop all other pumps.

7. Deactivate all circuit breakers.

8. Open access door and use necessary safety procedures for inspection.

9.3.2 Preventive Maintenance

Preventive maintenance is an important tool in assuring the continuous operation of scrubber systems. Preventive maintenance programs for scrubbers should include periodic inspection of equipment, replacement of worn parts, periodic cleaning of components prone to plugging, maintenance of an adequate spare parts inventory, and recording of all maintenance performed on scrubber equipment.

All instrumentation such as differential pressure gauges, scrubbing liquor flow meters, pump pressure gauges, and fan ammeters should be observed at least once per work shift. All equipment should be inspected regularly at regular intervals, determined by the severity of service and the likelihood of component failure. Failure-prone items include nozzles and pumps handling slurries, forced-draft fans handling particulate-laden gases, induced-draft fans downstream of inadequate liquid entrainment separators, wear plates, pH probes, and bearings. These items should be inspected as often as once per shift depending on the likelihood of failure. Such components as ductwork and induced-draft fans handling clean, dry gases should be inspected monthly.

All worn parts and malfunctioning equipment should be serviced as they are discovered to prevent deterioration of system performance and to prevent damage to equipment. An inventory of spare parts must be maintained in stock for replacement of nozzles, bearings, pump seals, liners for pumps with replaceable liners, pump impellers, wear plates for fan wheels with wear plates, pH probes, and valve parts. Records should be made of all maintenance performed and all parts replaced. This information is useful in planning subsequent preventive maintenance schedules and in determining the type and number of replacement parts needed.

9.3.3 Spare Parts

Scrubber manufacturers supply a list of recommended spare parts. Spare parts for auxiliary equipment, such as pumps, fans, piping, dampers, valves, and instrumentation, are also required. Table 9-4 shows the spare parts inventory guidelines.

TABLE 9-4. REPLACEMENT PARTS FOR SCRUBBERS

Motor (fan, pump, seals, bearings, impeller)
Mist eliminator media (full set)
Gauges (temperature, pressure)
pH probe and required reagent
Piping and valves
Nozzles
Packing
Wear plates

9.4 Common Problems or Malfunctions of Scrubbers

Wet scrubbers can provide continuous reliable service when they are operated properly and maintained regularly. Poor operation and maintenance leads to component failure. Most scrubber failures result from abrasion, corrosion, solids buildup, and wear of rotating parts.

The troubleshooting chart present in Table 9-5 gives guidelines for causes and remedies of symptoms noted during inspections. Although there is some discussion of pumps in this chart, it is by no means exhaustive. Fans are not mentioned because of the extensive scope of troubleshooting guides from manufacturers. The probable cause of fan noise, low or high flow rates, and static pressure are too numerous to itemize.Common failure modes for individual components are further discussed below.

TABLE 9-5. TYPICAL TROUBLESHOOTING CHART FOR SCRUBBERS[3]

Symptom	Cause	Remedy
Low pressure drop (scrubber section)	Low airflow rate	Check blower
	Low liquid flow rate	Check pump/nozzles
	Eroded cleaning section	Inspect/repair
	Meters plugged	Clean lines
High pressure drop (scrubber section)	High airflow rate	Check blower
	Plugging in ducts or scrubber	Inspect/clean ducts
Low pressure drop (mist eliminator)	Low airflow rate	Check blower
	Low liquid flow rate	Check pump/nozzles
	Media dislocated	Inspect/repair
High pressure drop (mist eliminator)	High airflow rate	Check blower
	High liquid flow rate	Check pump/nozzles
	Clogging	Inspect/clean
	Flooding	Inspect/drain
High temperature in stack	Insufficient wash liquor	Check pump/nozzle
	Liquid temperature too hot	Check sump temperature
Pump leaks Pump pressure increase	Worn packing or seals	Replace
	Nozzle plugging	Reduce nozzles
	Valves closed	Open valves
Pump flow rate/pressure diminished	Impeller wear	Replace
	Nozzle abraded	Replace
	Speed too low	Check motor
	Defective packing	Replace
	Obstruction in piping	Check pipes, strainer, and impeller
Pump noise/heat	Misalignment	Check/repair
	Bearing damage	Replace
	Cavitation	Check/repair
Corrosion	Inadequate neutralization	Check pH control
Erosion	Incompatible materials	Replace materials
	High recycled solids content	Wastewater system
Scaling	Improper chemical treatment	Change treatment
Pipe plugging	High solids content	Cleaning
	Abrupt expansion/contraction/ bends	Change pipe fittings

9.4.1 Nozzle Plugging

Nozzle plugging is one of the most common malfunctions in scrubbers. Plugged nozzles reduce the liquid-to-gas ratio or cause maldistribution of the liquid. Nozzle plugging results from improper nozzle selection, excessive solids in scrubbing liquors, poor pump operation, and poor sump design. Remedies for nozzle plugging include replacement with nozzles of a different type, frequent cleaning, and reduction of liquor solids content by increasing liquor blowdown and makeup water rates. Because presaturator nozzles are especially prone to plugging, the quench water should be limited to fresh water or very dilute liquors. Many quench nozzles cannot tolerate greater than 2 percent solids in the liquid.[7] Nozzle plugging can be detected by observing the liquid spray pattern the nozzles produce. If the nozzles are not accessible while the pumps are operating, they should be checked during scrubber shutdowns for evidence of caking over the nozzle openings. A decrease in water flow rate during scrubber operation is an additional symptom of nozzle plugging.

9.4.2 Solids Buildup

Solids buildup is another problem common to wet scrubbers and one that is often difficult to control. The two types of solids buildup are sedimentation and chemical scaling. Sedimentation occurs when a layer of particles becomes attached to a surface or settles in areas of low turbulence. Sedimentation can lead to plugging of pipes and ducts or buildup on internal parts. Chemical scaling results from a chemical reaction of two or more species to form a precipitate on the surfaces of scrubber components.

Solids buildup may occur in piping, sumps, scrubber packing, instrumentation lines, or ductwork, and may lead to reduced scrubber efficiency and major equipment failure. Most scrubbers using open pipes cannot reliably tolerate liquor slurries of over 15 percent solids by weight. It is usually best to maintain solids content at less than 6 to 8 percent.[7] Techniques to control scaling include increasing the liquid-to-gas ratio, controlling pH, providing greater residence time in the holding tank, and adding other chemical agents such as dispersants. Solids buildup can be detected by inspection of accessible components and by inspection of the inner surfaces of piping, tubing, and ductwork at removable fittings and hatches.

9.4.3 Corrosion

Corrosion problems arise frequently in wet scrubbers, especially when the gases being cleaned contain acid-forming compounds or soluble electrolytic compounds. The combustion of fossil fuels, especially coal, coke, and residual fuel oil, yields oxides of sulfur, which can produce sulfuric acid in scrubbing liquors. Metals-refining processes, such as copper and lead smelting, can also produce oxides of sulfur. Combustion of polyvinyl chloride plastics, commonly found in incinerator feeds, can produce hydrochloric acid in scrubbing liquors. Rotary aggregate dryers and similar process equipment can produce chlorides or fluorides, depending on the composition of the aggregate. The phosphate fertilizer industry and the feldspar industry are especially troublesome sources of fluorides. Acids and electrolytes in general are corrosive to mild steels, chlorides are corrosive to many stainless steels, and fluorides are harmful to nearly all stainless steels except certain specially formulated (and expensive) high-nickel alloys.[8] Recirculation of scrubbing liquors increases the concentrations of any corrosive agents they contain.

Prevention of corrosion is best handled through proper choice of materials of construction and through pH control. When a pH control system is to be the principal defense against corrosion, regular maintenance at frequent intervals is necessary, especially at the pH electrodes. Another common operating problem occurs when scrubber liquor blowdown rates are reduced to limit the emission of pollutants into surface waters. Reducing or eliminating blowdown can so greatly increase the acid and electrolyte concentrations in the liquor that otherwise acceptable materials of construction become ineffective against corrosion.

9.4.4 Abrasion

Abrasion can occur where gases or scrubbing liquors containing high concentrations of abrasive particulates are in the turbulent mode or are subjected to a sudden change in flow direction. Typical wear areas in scrubbing systems include venturi throats, walls of centrifugal mist collectors near the inlet duct, and elbows in the ductwork.[7] Solutions to abrasion wear include the use of precleaning devices and the use of large-radius turns in ductwork.

9.4.5 Wear of Rotating Equipment

Rotating equipment including fans, pumps, and clarifiers must receive special attention in scrubber service because of potential abrasion, plugging, and corrosion. Key wear areas in these components include the bearings and any components rotating in the fluid stream.[9]

Fan wear is a common problem. Forced-draft fans often suffer abrasion because of exposure to particulate-laden gases. Wear problems in forced-draft fans can be addressed by the use of special wear-resistant alloys, by reduction of fan rotation speeds (by installing a larger fan), or by moving the fan to an induced-draft location on the clean air side of the scrubber system. Induced-draft fans can undergo corrosion or solids buildup on the blades if mist is carried over from the liquid entrainment separator. Induced-draft fan problems can be addressed by use of corrosion-resistant materials or by improving liquid entrainment separation.

Pump wear is also a common problem in scrubber systems. Pump housings, impellers, and seals are subject to abrasion and corrosion by scrubber slurries. Rubber linings and special-alloy pump materials are often used to reduce abrasion and corrosion of the housings or impellers. Installation of a water flush in the seals can help reduce wear of the seals.[9]

9.5 Operator Training

Similar to any piece of equipment, a wet scrubber will not receive proper maintenance without facility management support and the willingness to provide its employees with proper training. Efficient operation of a wet scrubber, promoted by adequate inspection and maintenance procedures, is as important as the operation of process equipment. Management and employees must take a proactive approach to the operation of a wet scrubber in order to prevent production-stopping equipment malfunctions or failures.

The training and motivation of employees assigned to monitor and maintain a wet scrubber are critical factors. These duties should not be assigned to inexperienced personnel that do not understand how a scrubber works or the purpose behind assigned maintenance tasks.

System training should be received from the scrubber manufacturer when a new system is commissioned. The manufacturer's start-up services will generally include introductory training for facility operators and maintenance personnel. The field service engineer involved in startup procedures will instruct plant personnel in the methods to ensure proper assembly and operation of the system components, check and reset system instrumentation and controls, check for the proper operation of the scrubber liquid conditioning system, and perform simple troubleshooting.

Following start-up training, regular training courses should be held by in-house personnel or through the use of outside expertise. The set of manuals typically delivered as part of a new scrubber installation will include manufacturer-recommended maintenance procedures. Annual in-house training should at a minimum include a review of these documents and confirmation of the original operating parameters. Training should include written instructions and practical experience sessions on safety, inspection procedures, system monitoring equipment and procedures, routine maintenance procedures, and recordkeeping. For plant personnel involved in taking opacity readings, U.S. EPA Reference Method 9 requires a semi-annual recertification in method procedures.

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SECTION 10.0

CONDENSERS

This section provides readers with guidance and procedures for the proper operation and maintenance of condensers used as air pollution control devices. This method of control is generally used in conjunction with other air pollution controls. Also, as an air pollution control technique, it is generally limited to gas streams with components that have a boiling point greater than 100°F (long-chain hydrocarbons).

10.1 General Description

Condensers are devices designed to separate one or more components of a vapor mixture by reducing the gaseous vapor to its liquid form. If sufficient heat is removed and pressure is increased all gases will become a liquid. The change from gas phase to liquid phase is accomplished by 1) increasing pressure and holding temperature constant, 2) reducing temperature and holding pressure constant, or 3) increasing pressure and reducing temperatures concurrently. Condensation occurs when the partial pressure of the gas equals its vapor pressure.

High-pressure, low-temperature, ultra-high-efficiency systems are costly to build and operate. The most common approach to air pollution control is to build a system that operates at the same pressure as the emission source and removes heat. Condensation techniques work best on gas streams that have contaminants with a low vapor pressure at moderately high temperatures. These techniques can be used on contaminants with high vapor pressure; however, economics generally discourage this application. Two different mechanical processes are in common use as air pollution control systems. The most common of the two is the surface condenser; the other is the direct-contact condenser. Figure 10-1 is a simplified diagram of a typical refrigerated surface condenser system. Figure 10-2 is a simplified diagram of a direct-contact condenser.

Surface condensers use common heat exchange concepts in which the refrigerant is separated from the vapors by a containment device. Some of the applicable types of condensers include shell-and-tube, double-pipe, spiral-plate, flat-plate, air-cooled, water-cooled, and extended-surface. Condensing can be accomplished either in the shell or in the tubes. In typical air pollution control scenarios the emission stream will contain large volumes of gases (air) that are not condensable within the operating range of the system. Hence, capture of the condensate is usually accomplished within the shell. Condensers may be either vertical or horizontal in layout.

Direct-contact condensers cool the vapor mixture by spraying cool liquids directly into the gas stream. Contact condensers are simpler, less expensive, and have fewer parts. They are, however, much larger and typically create a large volume of dilute liquid wastes. These systems also scrub particulate matter from the gas stream, and this dual capability allows designers to use them as a primary system for removal of particulate matter and as a preconditioner in front of fine particulate matter removal systems (electrostatic precipitators, fabric filters, etc.).

10.1.1 Design Overview

The design and operation of a condenser are greatly affected by the number and chemical and physical properties of the contaminants, the moisture and particulate content of the flare gas, gasflow rates, condensation temperatures, and required removal efficiency. The simplest form of condenser requires that the designer determine the condensation temperature, select a coolant, and size the condenser. In the most complex form, chemical engineering principles for gas dehumidification are required.

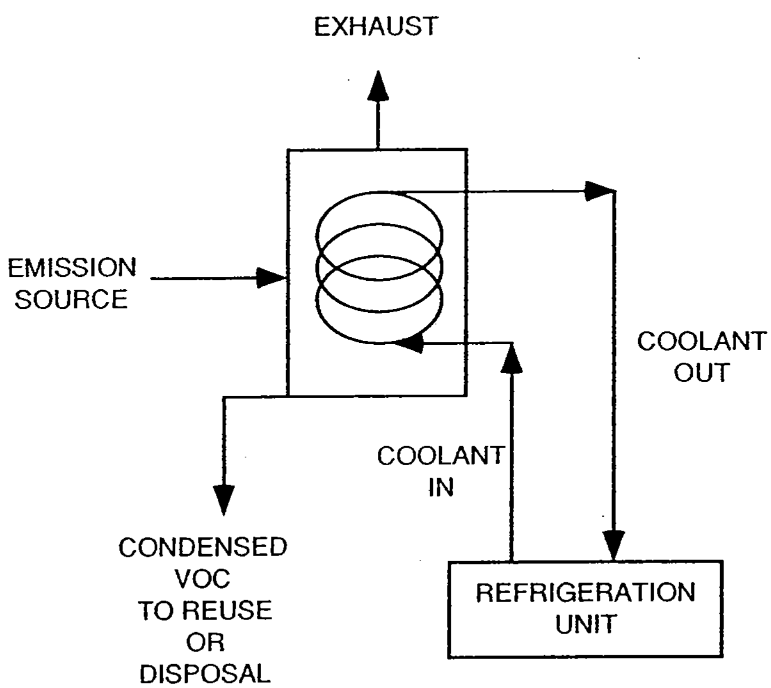

Figure 10-1. Typical configuration of a refrigerated surface contact VOC condenser system.

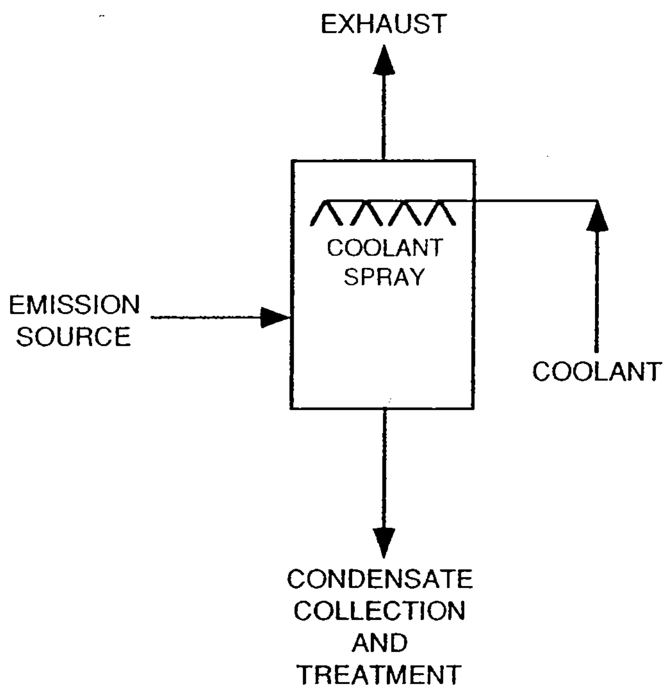

Figure 10-2. Typical configuration of a direct-contact condenser system.

Condensation Temperature--

Multicomponent gas mixtures are cooled by convection with the heat-transfer surface giving up its sensible heat until the gas becomes saturated with one or more of its condensable components. The temperature at which saturatization is achieved is known as the dew point. The dew point can be predicted from the temperature-vapor pressure curve for the component and its mole fraction in the vapor. The equation for this prediction is:

$$Y_i P = (P_i)_g \tag{1}$$

where Y_i = The mole fraction of component "i" in the vapor

P = The absolute gas pressure

$(P_i)_g$ = The partial pressure component "i" in the vapor.

Once condensation starts, the gas temperatures will only drop when latent heat and sensible heat have been removed in sufficient quantities to permit the gas to remain saturated with component "i". Because component "i" must diffuse heat to the transfer surface, the process is both heat- and mass-transfer-controlled. In systems with multiple condensable fractions, each fraction will condense as the gas becomes saturated with the fraction fulfilling the equivalent partial pressure relationship.

To determine the temperature that must be achieved for a specified emission level of component "i," one uses the following equations:

$$P = P_1 + P_2 + P_3 + P_{i+1} \ldots \tag{2}$$

$$V_i = Y_i \tag{3}$$

$$Y_i P = P_i \qquad (4)$$

$$P_i = \frac{n_i RT}{V} \qquad (5)$$

$$\frac{P_i}{P} = \frac{n_i(RT/V)}{n(RT/V)} = \frac{n_i}{n} = x_i \qquad (6)$$

where n_i = Number of moles of the "i" fraction

n = Number of moles of the gas in the volume (V)

R = Ideal gas constant (0.082 l-atm k^{-1} mol^{-1})

T = Absolute temperature (°K)

x_i = Mole fraction of component "i"

V_i = The allowable volumetric fraction of component "i" in the emission

Y_i = The allowable mole fraction of "i" in the emission

P = The absolute total pressure of the gas

P_i = The allowable vapor pressure of component "i" in the emission

The required gas temperature is determined when the fraction "i" vapor pressure is equal to P_i on its vapor-pressure temperature curve. Figure 10-3 is a generalized example of a vapor-pressure volume temperature curve for a substance that contracts upon freezing (e.g., carbon dioxide). As shown on the figure the solid, liquid, and vapor phases appear as surfaces. One must recognize that two phases are present during any phase change and that in the transition from gas phase to liquid phase the change in volume is usually great.

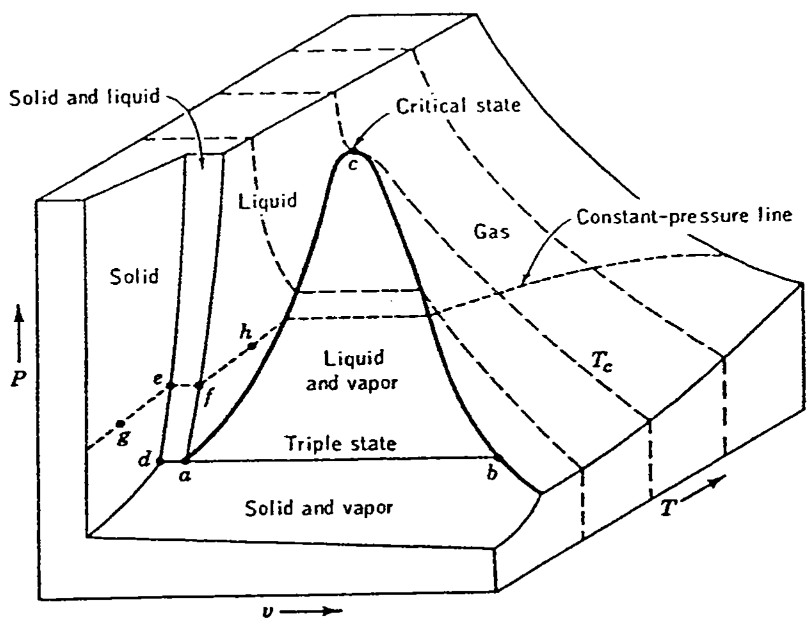

Figure 10-3. A pressure vs. volume vs. temperature surface for a substance that contracts on freezing.

As discussed, condenser removal efficiency depends on the concentration and nature of the emission stream. For example, compounds with high boiling points (i.e., low volatility) condense more readily than those with low boiling points. Table 10-1 lists common hydrocarbons and their boiling points. The temperature necessary to achieve a given removal efficiency or outlet concentration depends on the outlet vapor pressure of the "i" constituent at the vapor-liquid equilibrium.

TABLE 10-1. COMMON HYDROCARBONS AND THEIR BOILING POINTS

Name	Formula	Boiling point, °F
Alkanes (C_nH_{2n+2})		
Methane	CH_4	-258
Propane	C_3H_8	-44
Pentane	C_5H_{10}	31
Hexane	C_6H_{14}	155
Octane	C_8H_{18}	258
Alkenes (C_nH_{2n})		
Ethylene	C_2H_4	-152
Propylene	C_3H_6	-53
Butene	C_4H_8	21
Pentene	C_5H_{10}	86
Aromatics		
Benzene	C_6H_6	176
Toluene	C_7H_8	231
Ethylbenzene	C_8H_{10}	277
Naphathalene	$C_{10}H_8$	424

When the partial pressure is known, condensation temperature can be identified by consulting the vapor pressure-temperature chart for the gas. Vapor pressure-temperature charts have been compiled for many common organic constituents. For specific charts, the reader is referred to Perry's Chemical Engineers Handbook or Lange's Handbook of Chemistry, both published by McGraw-Hill.

Selecting Coolant--

Coolant selection is based on the condensation temperature. Ideally, the refrigerant will have 1) convenient evaporation and condensation pressures, 2) high critical and low freezing temperatures, 3) high latent heat of evaporation and high vapor-specific heat, 4) low viscosity and high film heat conductivity, and 5) chemical inertness. It will also be nonflammable, detectable by simple tests, and low in cost. Table 10-2 identifies several common refrigerants and their freezing-point temperatures. It is customary to use a refrigerant that has a freezing point that is not less than 10 degrees lower than what is theoretically calculated.

Condenser Sizing--

Condenser sizing must account for both heat and mass transfer. The calculation requires individual heat-transfer coefficients of the gas components, the coolants, and the specific heat exchanger. The heat exchange design process is extremely complex. It must account for temperature differentials, mass rate of flow, materials of construction, surface area, scale and corrosion buildup, emissity of surfaces, gas density, thermal conductivity, specific heat density, viscosity, velocity, coefficient of thermal expansion, and pressures. A conservative number for the overall heat transfer coefficient is 20 Btu/h per ft^2 per °F. This number represents an inefficient design, and its use will establish a surface area that is larger than a high-efficiency system would need. The equations and procedures required to estimate the surface area needed to condense a specified amount of vapor(s) can be found in most heat transfer textbooks and are not repeated in this document.

10.1.2 Key Operating Parameters

The basic operating parameters include the exhaust gas concentration of the most volatile fraction of concern, the exhaust gas temperature, and the inlet and outlet

TABLE 10-2. FREEZING POINT FOR IDENTIFIED REFRIGERANT

Refrigerant	Temperature, °F
Water	32
6% NaCl	25.5
8% NaCl	22.9
18% NaCl	6.7
6% CaCl	28
8% CaCl	24
18% CaCl	4.7
24% CaCl	-14.1
30% CaCl	-46
Ammonia	-107.8
Carbon dioxide	-110
Ethyl alcohol	-174
10% Glycerin	30.2
40% Glycerin	1.0
60% Glycerin	-31
Freon 11	-60
Freon 12	-90
Freon 13	-30

temperatures of the coolant. In addition, system pressures are key system operating parameters that can indicate proper flue gas flow and coolant flows to identify system plugging problems. Also, if a contact system is used, the nozzle operating pressure and the flow rates of the coolant are needed to assure good spray distribution patterns and to avoid short-circuiting.

10.2 Monitoring Condenser Operation

Routine monitoring and recording of the key operating parameters identified in Subsection 10.1.2 and preventative maintenance activities based on this monitoring will improve operations, extend service life, and minimize malfunctions. Historically, condensers have not included automatic recording thermocouples, pressure gauges, or flow-meters.

10.2.1 Monitoring Devices

Monitoring devices are generally limited to three basic functions, pressure, temperatures, and safety.

Pressure--

The measurements of certain pressures and pressure differentials are needed for safe and efficient operations because a drop in pressure corresponds to an increase in velocity and a decrease in heat transfer and condensate capture rates. The pressure gauge is used to measure pressure drop across nozzles, tubes, etc.

Pressure-measuring instruments take various forms, depending on the magnitude of the pressure and the accuracy desired. Manometers that may contain a wide variety of fluids are commonly used. Differential diaphragm gauges that use magnetic linkage are also available for low-pressure systems. Pressure-measuring devices should be located in positions that avoid errors caused by impacts, eddies, fluid hammers, etc. For differential pressure readings, using a differential pressure device is preferable to taking the difference between the readings of two instruments. Several problems can cause faulty pressure readings. Plugging and fouling of the tubing is the most common problem. Also, differential pressure transmitters are sensitive devices that can be damaged by excessive shock and vibration.

Static pressures are measured by use of manometers and/or pressure gauges. The most common problems with these devices are as follows:

- Fouling and plugging.
- Trapped air which gives false readings.
- Tap elevation is above or below the base of the gauge.
- Located too close to curves, obstructions, valves, etc.

Temperature--

Heat exchange rates, heat balances, partial pressures, and recovery efficiencies are all controlled by temperature. A means of recording, indicating, and controlling temperature are needed in the design, fabrication, operation, and testing of condensers. Temperature monitors should be installed in the following locations:

- Gas stream inlet (wet and dry bulb)
- Gas stream outlet (wet and dry bulb)
- Condensate pool
- Coolant inlet
- Coolant outlet

In the past, temperatures generally have not been continuously recorded. Continuous temperature data, however, can be used as an indicator of proper system heat transfer and gas flow rate.

Monitoring of temperature is essential to good performance. Hence, potential thermocouple problems must be identified because the temperature reading is the primary measurement used for control purposes. Measuring temperature requires care to be taken 1) to be certain the instrument indicates the correct temperature, and 2) to interpret the readings correctly.

The amount of variation from true temperature of the gas depends on the temperature and velocity of the gas, the ambient temperature, the size of the sensing element, and the physical construction of the sensing element. The temperature of a fluid (liquid or gas) flowing under pressure in the pipes is usually measured by inserting a glass thermometer, an electrical resistance thermometer, or a thermocouple into a well that projects into the fluid. The well must have the mechanical strength and rigidity to withstand the hydrostatic pressure. It must also be resistive to corrosion and erosion.

It is often desirable to know the temperature in different portions of the condensers to determine if safe conditions exist, or if conditions are uniform or unbalanced among tubes and also to determine differential measurements between inlet and outlets. These measurements are usually taken by thermocouples peened to the structure. These devices are subject to error because of thermal conduction in the wires and the specific conductance of the gas. Erosion and corrosion are major concerns.

Safety--

Conditions that could result in explosive mixtures of fuel and/or unsafe emissions of toxic gases are avoided by the installation of monitors capable of detecting combustible and toxic vapors in the exhaust gas. Continuous monitoring could be conducted to determine if an explosive atmosphere exists or if unacceptably high toxic air pollutants are being omitted. This monitoring could be done with direct reading instruments such as:

- Combustible gas indicator
- Flame ionization detector with gas chromatography
- Infrared spectrophotometer

Direct-reading instruments were developed as early warning devices for use in industrial settings where leaks or an accident could release a high concentration of a known chemical into the ambient air. All direct-reading instruments have inherent limitations:

- Accuracy is a function of calibration.
- Sensitivity varies by temperature, number of components, moisture content, particle content, and interferants.
- Response time varies by compound.
- Optical components get dusty and misaligned.
- Plugging and fouling of probes are common.

Because condensers are seldom the final control device prior to atmospheric discharge, safety monitoring is not commonly practiced.

10.3 Inspections and Maintenance of Condensers

10.3.1 Inspection and Maintenance Items

Within the constraints of the hardware, operation and performance enhancements are designed to control air emissions, to extend service life, to minimize malfunctions, to control operating costs, and to ensure safety. Daily inspections should be performed while the unit is operating. This inspection should include visual checks for the following:

Vibrations--

Vibrations can produce severe mechanical damage; therefore, operation should not be continued when vibration is evident. Vibration may indicate excessive flow rates, bypassing, vapor locks, erosion, pluggage, impaction, broken supports, worn impellers, open valves, etc.

Leakage--

Leakage may occur in several areas, depending on the type of condenser. The inspector should be looking for leaks in the coolant system, primary containment shell, and vapor ducts leading into and out of the condenser. If a contact system is used, the inspector also should look for evidence of windblown mist and capture-system overflow.

Pressure Drop--

Excessive pressure drop indicates fouling and plugging. Fouling and plugging can be so severe that thermal stress and mechanical damage may occur. Plugging and fouling increases noncondensable gas volumes, which in turn overload the vent control system or discharge unacceptable quantities of fraction "i" emissions.

Excessive Exhaust Temperature--

The systems performance is largely determined by changes in outlet gas temperatures. Increases in the exhaust temperature indicate that removal efficiencies are decreasing and emissions are increasing.

Lower Condensate Rate--

Changes in the rate of condensate collection may indicate a process upset condition. Careful review is needed to ensure that the proper rate units are monitored (e.g., weight per unit time, weight per unit manufactured, gallons per compressor kWh).

Exterior Corrosion--

Condensers often differ in materials of construction. They also may handle a wide variety of substances, including corrosive liquids and gases. Thus, special precautions may be necessary if any individual parts create a galvanic action that could dissolve tubing, fins, connectors, collectors, straps, grounding devices, etc.

Safe Working Temperature and Pressures--

The maximum allowable working temperature and pressure are indicated on the condenser's name plate. Condensers are designed to operate at specified temperatures. Variation in temperature and pressure and the rate of change may cause differential expansion, warping, increased brittleness, decreased emission transmissibility, leakage, gasket failure, increased flow rates, increased emissions, etc.

Proper Coolant Flow Rate and Temperatures--

Coolant flow rates determine if the system is operating efficiently. When coupled with low front end temperatures, excessive flow rates may cause freezing conditions, which in turn may cause compressor burnout, unwanted condensate formation, and/or excessive pressure.

10.3.2 Inspection Frequency

Typically, condenser operators make periodic inspections to ensure proper operation and to identify potential problems. Clearly, the manufacturer's recommended preventive maintenance schedule should be followed. Inspection activities are somewhat limited because of the simplicity of the process.

Daily inspections should be conducted for vibration, leaks, broken gauges and monitors, proper calibration and span for monitors, and safe working pressures and temperatures.

Weekly inspections should be conducted on all moving parts (e.g., pumps, fans, motors, and valves).

Monthly inspections of ductwork, dampers, and structural components should be conducted for corrosion, erosion, settling, and misalignments.

In addition, an interior inspection should be conducted at least annually or whenever the equipment is shut down. Figures 10-4 through 10-6 are example inspection forms for a condenser unit. Figure 10-7 is an example maintenance report form.

10.3.3 Spare Parts

Generally, condensers are low maintenance systems. A facility should maintain a ready inventory of expendable items and tools for the system, as recommended by the manufacturer. Experience indicates that broken pressure gauges, thermometers, and transducers are the most frequently needed replacement parts.

DAILY CONDENSER INSPECTION FORM		
Facility Name:	Date of Inspection:	
Facility Location:	Time of Inspection:	
Process:	Name of Inspector (Print):	
Condenser ID:	Signature of Inspector:	
INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS	
1) Leaks - Ducts - Pipes - Seals - Bonnets		
2) Monitor conditions (check strip charts if applicable) - Temperature - Pressure - Flue gas velocity (if applicable) - LEL monitor (if applicable) - VOC monitor (if applicable)		
3) Drains for condensate - Free flowing - Normal appearance		
4) Exterior appearance - Rust - Hangers and anchors in place - Other		
	Inlet	Outlet
Temperatures, °F Coolant Gas Pressures, in. W.G. Coolant Gas	 ______ ______ ______ ______	 ______ ______ ______ ______
LEL or VOC Monitor _______%	Gas Flow Rate ______ ft/min	

Figure 10-4. Example daily condenser inspection form.

WEEKLY CONDENSER INSPECTION FORM	
Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (Print):
Condenser ID:	Signature of Inspector:
INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS
1) Pumps and valves - Leaks - Packing - Visual appearance	
2) Fans - Abnormal noise or vibration - Housing condition	
3) Compressors - Leaks - Seals - Abnormal noise or vibration	
4) Condenser - Abnormal noise or vibration - Leaks - Temperatures and pressures in normal range	
5) Drains and drain cocks - Fouling - Free flowing	

Figure 10-5. Example weekly condenser inspection form.

MONTHLY AND ANNUAL CONDENSER INSPECTION FORM	
Facility Name:	Date of Inspection:
Facility Location:	Time of Inspection:
Process:	Name of Inspector (Print):
Condenser ID:	Signature of Inspector:
INSPECTION ITEM	COMMENTS/CORRECTIVE ACTIONS
1) Component conditions (rust, cracks, leaks) - Foundation - Fire suppression system - Galvanic protection system - Hangers and grounding straps	
2) Thermocouples, pressure gauges - Calibrate if applicable - Check strip charts and daily logs/forms for trends - Check for proper operation	
3) Other - Abnormal noise or vibration from condensers, fans, pumps, and compressors - Leaks	
Annually or During Shutdown	
1) Inspect internals for fouling, plugging, or corrosion. Clear or replace if necessary. - Tubes - Shell	
2) Pressure test condenser (coolant side) - Results	

Figure 10-6. Example monthly and annual condenser inspection form.

MAINTENANCE REPORT FORM

Department	Unit	System	Subsystem	Component	Subcomponent

Originator: ____________________ Date: __________ Time: ____________

Assigned To:

1	Mechanical
2	Electrical
3	Instrumentation

Priority:

1	Emergency
2	Same Day
3	Routine

Unit Status:

1	Normal
2	Derated
3	Down

Problem Description: ____

Foreman: ____________________ Date: __________

Job Status:

1	Repairable
	Hold for:
2	Tools
3	Parts
4	Outage

Cause of Problem: ____

Work Done: ____

Supervisor: ____________________ Completion Date: ____________

Materials Used: ____

Labor Requirements: ____

Figure 10-7. Example maintenance report form.

10.4 Problems and Malfunctions for Condensers

Most of the problems that occur with condensers have a direct impact on emission rates. Condensers, however, are relatively immune to physical problems caused by overloading.

Excessive flow rates, however, may increase erosion and cause entrainment of liquids and particulate matter in the gas stream. Evidence or erosion first shows up in the monitoring devices that protrude into the liquid or gas stream. Exceeding design temperatures or thermal shock episodes cause differential expansion and contraction that may cause leakage and/or structural damage. Tightening of bolts and connectors should be confirmed if the temperature records indicate that temperature ranges have been exceeded.

Fouling and plugging results from the deposition of foreign material on the exterior and/or interior of tubes, pipes, valves, and monitors. Evidence of fouling is indicated when pressures increase or decrease, performance decreases, hot/cold spots occur, and short-circuiting of flow pattern are noted. Deposits are generally cleaned only during a major shutdown. Typically, shutdowns are scheduled when operating costs exceed the costs of downtime for repair or when emission standards are violated. Corrective measures include chemical flushes and mechanical scraping.

10.5 Operator Training

As with any piece of equipment, management's support and the willingness to provide its employees with proper training are essential to the proper maintenance of a condenser. Efficient operation of a condenser, promoted by adequate inspection and maintenance procedures, is important. Management and employees must be cognizant of proper procedures for preventing equipment malfunctions or failures.

Training should be provided by the manufacturer when a new system is commissioned. The manufacturer's startup services generally include introductory training for facility operators and maintenance personnel. The field service engineer involved in startup procedures will instruct plant personnel in the methods to ensure the proper assembly and operation of the system components. Instructions will also typically include how to check and reset system instrumentation and controls, how to check for the proper operation of the dust-discharging system, and how to perform simple troubleshooting.

Following startup training, regular training courses should be held by in-house personnel or through the use of outside expertise. The set of manuals typically delivered as part of a new installation will include manufacturer-recommended maintenance procedures. Annual in-house training should at least include a review of these documents and confirmation of the original operating parameters. Training should include written instructions and practical experience sessions on safety, inspection procedures, equipment and procedures for system monitoring, routine maintenance procedures, and recordkeeping.

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