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VOLUME V
CONTROL EQUIPMENT OPERATION AND MAINTENANCE - ELECTROSTATIC PRECIPITATORS

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REFERENCE MATERIAL FOR TECHNICAL WORKSHOP ON EVALUATION OF INDUSTRIAL AIR POLLUTION CONTROL EQUIPMENT OPERATION AND MAINTENANCE PRACTICES

Volume V
Operation and Maintenance of
Electrostatic Precipitators

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FOREWORD

The following document is a compilation of selected technical information and publications on the evaluation of industrial air pollution control equipment operation and maintenance practices. The reference manual is intended to be an instructional aid for persons attending workshops sponsored by the U.S. Environmental Protection Agency Regional Offices.

TABLE OF CONTENTS

V-1.

AIR POLLUTION CONTROL EQUIPMENT OPERATION AND MAINTENANCE COURSE

- ELECTROSTATIC PRECIPITATOR -

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Wheelabrator - Frye, Inc.

OPERATION AND MAINTENANCE COURSE
- ELECTROSTATIC PRECIPITATOR -

By H. L. Engelbrecht

1. Abstract

Increasing emphasis on air pollution control focuses the attention of Control Agencies on the performance of the control equipment and the system surrounding it. Continued performance at high collecting efficiency levels requires adequate sizing, suitable design, and good operation and maintenance procedures. Thus, it becomes extremely important to determine if the owner/operator of the air pollution control equipment maintains this equipment and follows these procedures.

The air pollution control equipment never operates by itself; i.e., it is always influenced, restricted, and dependent on the process equipment it serves. Thus, this equipment need also to be operated within given parameters and under specific conditions. Operating and maintenance procedures apply equally.

To understand the operation of an electrostatic precipitator, it is essential to know some basic facts about precipitator theory; for example, influences on the collecting efficiency by changes in process conditions, fuels, etc.

Each precipitator consists of certain components necessary to perform the tasks of charging, transporting, collecting, and removing of the particulates to be collected. Various designs are in use, and the particularities of each design are reviewed.

Common equipment failures are analyzed to examine major causes and to obtain back-up information for preventive maintenance programs.

Although specific maintenance program requirements may vary from process to process and from plant to plant, some basic steps and procedures are common to all. These include safety, inspection program, and definition on inspection and maintenance responsibilities.

Normal precipitator operation includes proper procedures for start-up and shut-down, as well as guidelines for trouble shooting.

In summary, the operation of an electrostatic precipitator requires a planned program of operator's training, equipment know-how, preventive maintenance, adequate spare parts inventory to maintain compliance with the air pollution control emission codes and to prevent enforced limitations of the plant's production schedule.

TABLE OF CONTENTS

2. List of Figures and Tables

3. Reasons for Good Operation and Maintenance Procedures

Electrostatic Precipitators represent a major portion of the investment in an industrial plant. Equipment life and performance have become essential to the operation of the plant. Increasing emphasis on air pollution control focuses the attention of owners and operators on sustained performance at a high level of collecting efficiency. This requires not only an adequately sized precipitator of a suitable design, but equally important, good operation and maintenance procedures.

There are several reasons for proper precipitator maintenance. The most important are:

a. Continuously meeting present emission control codes
b. Prolonging precipitator life
c. Maintaining productivity of process unit served by the precipitator
d. Reduction of operating expenses
e. Better public relations

4. Electrostatic Precipitation Process

Electrostatic precipitators are applied to collect particulate matter after a variety of industrial processes in the power, rock products, metallurgical, and chemical industries. The fundamentals of their operation have been extensively described in the literature. Two of the many publications in this field are referenced (Ref. 1 and 2).

To understand the operation of an electrostatic precipitator, it is essential to know some of the basic precipitator theory.

Electrostatic precipitators are sized on the basis of a formula which gives an exponential relationship between the collecting efficiency, the size of a precipitator, the gas volume, and the precipitator rate parameter.

$$E = 1 - \exp - (W_k \; A/Q)^k \qquad (1)$$

and $$\mathcal{E} = 1 - E \qquad (2)$$

with E = fractional collecting efficiency

$\mathcal{E}$ = penetration

W_k = precipitation rate parameter, ft/sec.

Q = gas volume, ft^3/sec.

A = collecting surface area, ft^2

k = exponent, usually 0.5

The ratio between collecting surface and gas volume is called the "specific collecting surface area" (SCA) and expressed in sq. ft. of collecting surface per 1000 cfm.

$$SCA = \frac{1000}{60} \left(\frac{\ln \mathcal{E}}{W_k}\right)^{1/k} \qquad (3)$$

and $$W_k = \frac{1000}{60} \left(\frac{\ln \mathcal{E}}{SCA}\right)^{1/k} \qquad (4)$$

with W_k = precipitation rate parameter, ft/sec.

SCA = specific collecting surface area, ft^2/1000 cfm

For a given application; for example, flue gas from a power boiler, the collecting efficiency can be plotted as a function of the SCA with W_k considered a constant (Fig. 1 - Line A). A different W_k results in a different line; for example, Line B (Ref. 3).

Experience factors considered in the selection of the precipitator size, i.e., W_k or SCA by the vendor include:

- particle size
- specific dust resistivity
- gas velocity distribution through the precipitator
- gas analysis
- gas moisture content
- electrical sectionalization
- electrode design
- field height
- field length
- number of fields/bus sections
- electrical power supplies

5. Design and Components

Various designs of electrostatic precipitators are in use. A classification according to the method of removing the precipitated dust from the collecting surface is:

1. Dry-process precipitators: dust removal by rapping and/or gravity.

2. Wet-process precipitators: dust removal by water-sprays or overflow systems and gravity.

A classification according to the shape of the collecting surface is:

3. Plate-type precipitators: the collecting surfaces are plates.

4. Pipe-type precipitators: the collecting surfaces are pipes.

A third classification can be made according to the direction of gas flow inside of the precipitator:

5. Horizontal gas flow precipitator
6. Vertical gas flow precipitator

A summary of various classifications as they apply to an industrial single-stage electrostatic precipitator is shown in Fig. 2. One can assume that over 95 percent of all precipitators in use are of the dry-process, plate-type, horizontal gas flow variety. For this reason, the following comments on precipitator components are based on this type.

An electrostatic precipitator has to perform specific operations to collect particulate matter from a gas stream.

- o Charging of particles
- o Transporting the charged particles to the collecting surface
- o Neutralizing the charged particles on the collecting surface
- o Removal of the particles for the collecting surface to the hopper of the precipitator

Each of these tasks requires certain components. For example, charging of particles requires a discharge and high-voltage energizing system. Thus, a precipitator consists of the following basic equipment:

- o Discharge system
- o Collecting surface
- o Rapping systems
- o High-voltage energizing system
- o Precipitator casing
- o Ancillary equipment, such as dust handling systems

There are basic differences between precipitator designs originating from the U.S. and those from Europe. A summary of these differences is given in Table 1; other designs are also in common use, which differ from those.

In general, the discharge system consists of small diameter wires spaced equally between the collecting surface plates. The discharge system is normally connected to the negative pole of the transformer/rectifier and serves as a means to accelerate electrons, which, in turn, ionize gas molecules. These travel towards the grounded collecting surface and charge dust particles entering the space between the electrodes by attachment. Thus, the dust particles migrate to and are precipitated on the collecting surface. The collecting surfaces consist of vertical plates with ribs and/ or stiffeners. They are supported from the top and are mounted in parallel rows, up to 50 ft. high. Spacing between plates is normally 9 to 12 in.

Rapping systems are provided for each electrode system to keep their surfaces free from accumulated dust and to remove the precipitated dust into the dust hopper. Rapping systems act on one or more rows of plates at a time; they are normally single or multiple impact rappers or hammers, impacting at the top or bottom of the collecting surfaces. The discharge system is normally rapped by single impact hammers, or rappers, or multiple impact vibrators at the top or the center.

Electrical timers are provided to adjust the rapping frequency to the requirements of a specific application. Provisions are also made to adjust the rapping intensity.

Electrical energizing systems for electrostatic precipitators have now developed into systems including:

- protective equipment
- thyristors for AC voltage control
- reactors

- o transformer-silicone rectifier combinations in oil-filled tanks, and the
- o necessary electronic control circuitry to control the thyristors to react to the actual conditions inside of the precipitator

The precipitator casing provides the enclosure and the support for all of the internal parts. It is designed for the requirements of the individual unit with respect to gas temperature, negative, or positive pressure, wind, snow, or seismic loads, etc. Adequate openings for inspection and maintenance should be located ahead and after each electrical field, in each individual hopper, and also in each support insulator housing.

Depending on the application and requirements of a specific precipitator installation, ancillary equipment is added to either increase the performance or to protect both operating personnel and precipitator.

Such equipment may consist of additional indicating or recording instrumentation, heating systems for support insulators and/or hoppers, additional rapping systems for the hopper walls or gas distribution systems, key interlock system to prevent access to any hazardous area of the precipitator while the equipment is energized.

Also, classified as ancillaries could be ventilating systems with or without heaters for the insulator housing to prevent condensation. The dust discharge system normally consists of an air lock at the hopper outlet and either a screw conveyor, drag conveyor, pneumatic conveyor, or similar dust transportation system. The air lock can be either a rotary valve, a single-or-double acting flap valve, or a similar device discharging a specific amount of dust from the hopper and preventing any in-or-out leakage of gas or air. The performance of each of these components is essential to the reliability and availability of the electrostatic precipitator.

6. <u>Installation</u>

The installation of an electrostatic precipitator requires a careful review of its future operating conditions; i.e., gas volume, dust load, and required collecting efficiency. The precipitator manufacturer will also want many more data; for example, on fuels, variation of load, gas, and dust analysis, etc. Some of these data will be hard numbers; others will be expected operating ranges.

Together, with other criteria, such as possible space limitations, structural, mechanical, and electrical requirements, they form the basis for the specification of the electrostatic precipitator.

A summary of design factors, which should be included in precipitator design specifications and evaluations, is given by H. J. White (Table 2, Ref. 4).

After the selection process of the submitted proposals has been completed by the vendor and a decision has been made, the vendor will design, fabricate, and ship the precipitator components for assembly and construction in the field. Fabrication and construction are as critical to the performance of the electrostatic precipitator as is proper sizing. It is recommended that the buyer familiarizes himself with the Quality Control procedures and the structural and mechanical standards used by the supplier.

During the erection of the electrostatic precipitator, one subject is of prime importance. This is the alignment between the two electrodes of the electrical field; i.e., between collecting surface plates and discharge wires.

Many problems occurring later in the operation result from mis-alignment of the electrodes. And many other problems not quite apparent during the erection stage; for example, thermal stresses, will also result in alignment problems. Alignment problems can also be the result of lack of clearances of moving parts inside of the precipitator.

After construction of the precipitator is complete, a thorough check-out phase for all components is recommended. This check-out should be supervised by the manufacturer's representative to ensure that all equipment and components are functioning properly. Only after this has been achieved in a manner satisfactorily for both the purchaser and the vendor should the precipitator be judged ready for service.

7. Operation and Performance

The operation and performance of an electrostatic precipitator; i.e., its capability to achieve and maintain a required collecting efficiency and/or dust residual level, depends on a number of factors, which are closely related to the specific advantages and disadvantages of the electrostatic precipitation process.

Main advantages of this process are:

- high collecting efficiency even for small particle sizes
- low pressure drop
- low energy requirements
- adaptability to various types of effluents (wet, dry, corrosive)
- fully automatic operation

There are also inherent disadvantages with this process which, if occurring, can cause a severe reduction in the performance of the precipitator. These disadvantages are either process or design and/or equipment related and some major disadvantages are listed.

Process related

- sensitivity to process changes resulting in changes in gas temperature, gas flow rate, gas analysis, dust load, dust particle size, and dust analysis
- problems caused by dust build-up
- extensive arcing
- back corona
- corrosion

Design and/or equipment related

- dependency on good electrode alignment
- dependency on adequate power levels
- problems caused by dust build-ups
- problems caused by uneven gas velocity distribution, dust distribution and temperature gradients
- reentrainment (hopper, rapper, saltation)
- sneakage
- breakage of electrodes
- failures of mechanical equipment, such as rappers, drives, etc.
- failures of electrical equipment, such as HV transformer-rectifiers and AV controls, rapper/heater controls
- failures or breakdown of insulators
- air inleakage through hoppers, precipitator shell, doors, etc.
- hopper pluggage
- inadequate rapping intensity and/or frequency

Each of these problems will eventually manifest itself with a specific malfunction which can be analyzed and corrected.

A summary of problems associated with electrostatic precipitators was published by Szabo et al (Ref. 5).

Many of these disadvantages or problems of the electrostatic precipitator become apparent at the time of the initial start-up. Others may only become apparent after weeks, months, or even years of operation. Quite often, the problem is further complicated by the simultaneous occurrence of several of these problems.

In general, problems associated with electrostatic precipitators need to be analyzed, if they are process or design related and treated accordingly.

8. Inspection and Maintenance Surveys

Attempts have been made to analyze precipitator malfunctions, and, thus, to predict failures. The principal factors are:

- o design of the precipitator
- o hardware and controls
- o improper erection
- o operating conditions
- o and operating and maintenance practices

A survey by the Industrial Gas Cleaning Institute (IGCI) published April 1971 (Ref. 6) concentrated on:

- o maintenance
- o actual vs. expected maintenance costs
- o operating and maintenance instructions
- o repair and replacement
- o corrosion
- o useful life of precipitator
- o dust removal systems

The results of the survey showed that 59 percent of the respondents reported daily routine inspections; weekly inspections were reported by 9 percent and other (quarterly, yearly) inspections by 27 percent.

Of the precipitators surveyed, 60 percent reported corrosion within three years from start-up, 40 percent of these involved un-insulated precipitators.

The expectancy of useful precipitator life, defined as the period in which the precipitator is amortized, brought the following response:

- o 5.5% indicated 5 years
- o 11% indicated 10 years
- o 11% indicated 12½ years
- o 11% indicated 16 years
- o 33% indicated 20 years
- o 11% indicated 30 years
- o 16.5% indicated 35-40 years

Only 23 percent reported "known" precipitator maintenance costs. Manufacturer's maintenance instructions were considered adequate by 96 percent of the respondents. Repairs and replacement problems in order of severity were stated for:

- o discharge electrode failure (68 percent)
- o rapper malfunctions (40 percent)
- o insulator failures (28 percent)
- o dust build-ups causing shorts (28 percent)
- o hopper plugging (24 percent)
- o transformer-rectifier failures (20 percent)

It is interesting to note that, where dust removal systems were in 100 percent continuous operation, there were no frequent operational problems reported.

A similar study was performed by TVA and reported by J. Grecco (Ref. 7). This study showed outages caused by failures of various components of the precipitators.

Figure 3 shows the major causes for unavailability of nine different precipitators (A to I). The newest survey of four major precipitator user industries was undertaken by the TC-1 Committee of the Air Pollution Control Association (APCA) in the latter part of 1974 (Ref. 8). The study was intended to survey the user's degree of satisfaction with this equipment from an operational and a maintenance viewpoint.

Component failures were grouped by frequency, such as frequent, infrequent, or very seldom. A summary of the results is presented.

COMPONENT FAILURE FREQUENCY (PERCENT)

	Frequent	Infrequent	Very Seldom
o Discharge Electrodes	22.2%	45.3%	28.8%
o Collecting Surfaces	9.9%	15.2%	56.8%
o Rappers or Vibrators	22.2%	35.8%	33.3%
o Support Insulators	8.6%	42.0%	41.6%
o Dust Removal Systems	24.7%	35.8%	30.0%

A summary of the user's opinion on the magnitude of the problem caused by the component failure is given:

COMPONENT	MAGNITUDE OF PROBLEM CAUSED BY FAILURE (PERCENT)		
	Major	Minor	No Problem
o Discharge Electrodes	22.6%	53.1%	21.0%
o Collecting Surfaces	17.3%	32.1%	45.3%
o Rappers or Vibrators	10.3%	53.1%	28.4%
o Support Insulators	9.5%	49.4%	37.9%
o Dust Removal Systems	24.7%	49.0%	17.3%

The causes for these component failures vary from installation to installation. The following comments are based on the above APCA survey.

Discharge electrode failures are typically caused by either fatigue, corrosion, or electrical arcing with the latter being the predominant cause. Corrosion and fatigue failures ranked second and third. The major cause of collecting surface failures is fatigue at the point of suspension; corrosion is the second. Rapping systems using vibrators, either pneumatic or electric, seem to be a higher maintenance item than the impulse type rapper. Support insulator failures are mostly caused by arc-overs due to accumulations of dust or moisture on the surface of the insulator.

Dust removal has always been a major cause of precipitator malfunction; failures are normally due to hopper plugging. Screw conveyor and dust valve problems rank second and third.

9. Plant Inspection and Maintenance Program

Safety

It is obvious that high-voltage electricity can be extremely dangerous. Therefore, all practicial safety measures must be observed even though the system may already incorporate interlocks and other safety devices.

The system should never be adjusted with the high-voltage power on. The rapper circuitry, which is independent of the high-voltage circuitry, is nonetheless also dangerous and must be treated as such.

Spark-rate feedback signals are often taken from the primary of the high-voltage supply and can be 400V. a.c. or more. Fuses on these lines should be removed before maintenance or adjustment is attempted.

Explosive gas mixtures could be created if air is introduced into some systems. If necessary, the system should be purged with an inert gas before introducing air. In all cases, a system should be purged with fresh air before it is entered.

Insulator heaters, hopper heaters, and rapping motors should be shut-off prior to entering the unit. Only authorized personnel should be allowed inside the precipitator. The Key-Interlock System Procedure has to be followed whenever inspection and/or maintenance requires that the precipitator access doors be opened.

Inspection Program

An inspection program should be aimed at providing a minimum of inspection time and produce maximum results in preventive maintenance. But too often internal inspections are either completely neglected or the hot and dusty precipitator gets a rather time-consuming complete inspection. The following is an attempt to shorten the inspection time considerably by providing a list of key points requiring partial inspection. It should be noted, however, that the partial inspection may indicate that a complete inspection is necessary.

Inspection of the electrostatic precipitator should be set up on the following basis by the operator:

Daily (per shift)
Weekly
Quarterly
Annually

The inspection instructions issued by the manufacturer should be followed. Routine daily or weekly inspections should cover the following areas:

I. Control Centers
   Precipitator Control Panels
   Ancillary Control Panels

II. Precipitator
   Dust Removal System
   Gas Distribution Plate Rapper Drives
   Collecting Plate Rapper Drives
   Discharge Wire Rapper Drives
   Transformer-Rectifiers
   Key Interlocks

A more detailed program should be established and followed for quarterly and annual inspections, including inspections inside of the electrostatic precipitator. Such a program should include inspection of:

III. Dust Build-Up in Hoppers

IV. Corrosion
   - around access doors
   - box girders and penthouse areas
   - precipitator housing
   - sidewalls
   - top and bottom corners

V. Rapping systems
   - wear

VI. Gas Distribution Plates and Interior Baffles

VII. Discharge electrodes
   - establish failure pattern, causes

VIII. Collecting Surfaces

IX. Insulators

X. Electrical Instrumentation

- a-c voltage
- a-c current
- d-c voltage
- d-c current
- spark rate meters/indicators

XI. Final Check

As a check on the inspection on the work done, always allow for time to close the precipitator properly and energize it with the normal supply at the maximum possible input, following the manufacturer's instructions.

The voltage on the transformer primary will usually be lower, but the current is considerably higher than during gas load. This check is a good indication as to whether or not a short still exists before the unit is put back in operation. The readings taken during the air-load test should be logged for future reference. Data sheets should be prepared so that a historical record of the precipitator's overall performance can be established.

Inspection and Maintenance Responsibility

Precipitator inspection is performed in a scheduled program, and additionally, whenever the precipitator becomes available for inspection during shut-down periods.

Maintenance is always performed as a continuous task covering components accessible during normal operation (rappers, control panels, drives, etc.)

and during scheduled or unscheduled shut-down periods equipment not normally available for maintenance work.

The objective of inspection is to point out areas or components requiring maintenance work, to repair existing faults or damages, or to point to areas or components where such work may be required in the near future and could be repaired now as preventive maintenance work rather than requiring an additional shut-down of the equipment.

A preventive maintenance schedule should be established for each installation, detailing the precipitator parts to be checked and maintained daily, weekly, monthly, quarterly, semi-annually, annually, and on a situational basis.

All of this work requires skilled personnel to recognize deficiencies during an inspection and to direct the necessary maintenance and/or repair work.

10. Normal Precipitator Operation

Each electrostatic precipitator installation is different not only in design, but also in its application. Therefore, specific check lists for start-up and shut-down of the equipment cannot be established. The following Tables 3, 4, and 5 are only given as examples for steps to be taken during these operations (Ref. 9).

11. Precipitator Inspection and Evaluation

Precipitator inspection and evaluation by Control Agency Personnel starts normally with an unacceptable stack discharge characterized by a high opacity level. This condition necessitates a good look at the precipitator; i.e., both process and hardware. The first, and most of the time best indication of the present state of operation of the precipitator, is to look at the electrical controls and to try to interpret the meter readings in the control cabinets.

The following general guides when reading these meters should help:

1. When the gas temperature increases, the voltage will increase, and the current will decrease. Arcing can develop. When the gas temperature decreases, the voltage will decrease, and the current will increase.

2. When the moisture content of the gases increases for any given condition, the current and voltage will also tend to increase in value.

3. If reduced voltage exists because of a sparkover, a rise in moisture may allow for an increase in the precipitator voltage level.

4. An increase in the concentration of the particulate will tend to elevate voltages and reduce current flows.

5. A decrease in the particle size will tend to raise voltage while suppressing current flow.

6. A higher gas velocity through the precipitator will tend to raise voltages and depress currents.

7. Air inleakage may cause sparkover in localized areas resulting in reduced voltages.

8. A number of precipitator fields in series will show varying readings with the voltage-current ratio decreasing in the direction of gas flow.

9. If a hopper fills with dust causing a short, the voltage will be drastically reduced, and the current will increase.

10. If a discharge electrode breaks, violent arcing can be observed with the meters swinging between zero and normal.

11. If a transformer-rectifier unit shorts, voltage will be zero at a high current reading.

12. If a discharge system rapper fails, the discharge wires build up with dust; the voltage increases to maintain the same current level.

13. If a plate rapper fails, the voltage decreases to maintain a current level under sparking conditions.

In addition, electrical readings taken at prior plant visits or by plant personnel can be used to evaluate an eventual change in the operation of the electrostatic precipitator. Cunningham (Ref. 11) published voltage-current characteristics (Fig. 4) and information on changes in voltage and current readings at a specific precipitator installation (Fig. 5).

Routine surveillance of the electrostatic precipitator, its connecting ductwork and ancillary equipment, can provide additional input to the general performance level and elimination of problem areas. For example, hoppers of dry collectors must be emptied continuously or periodically to prevent overfilling. Dust levels in a hopper may be determined by sounding, visual inspection (capped ports), or high dust level indicators arranged to alert operating personnel visually or audibly (Ref. 10).

At this point, all mechanical equipment inspection reports should be reviewed for indications of pending problems not taken care of during past outages.

Changes in process conditions need to be evaluated to observe any influences they could have on the precipitator performance.

Troubleshooting charts are normally provided by the precipitator manufacturer. It is best to use these charts since they are tailored to the specific precipitator design and application. A general troubleshooting chart was published by Szabo et al (Ref. 5).

12. Improving Precipitator Operation

In a general sense, any maintenance work done on an electrostatic precipitator should improve its operation or at least maintain its performance at a prior established level. But maintenance work can also be classified as a means of incorporating improvements which will either upgrade the performance, increase the lifetime, or reduce the operating cost of an existing precipitator.

Improvements in precipitator operation can possibly be achieved by:

- changes in the process served by the precipitator
- adding of equipment
- fine tuning

The results of changes in each of the three categories cannot be predicted entirely, but definite estimates can be given based on prior performance.

Changes in the Process

Changes in the process served by the precipitator could result in more favorable conditions of gas volume, temperature, moisture, dust load, or particle size. Because of the wide variety of possible precipitator applications, no qualification is attempted.

Adding of Equipment

Adding of new equipment and/or replacing of obsolete equipment can very definitely improve the performance of the electrostatic precipitator. The obviously most effective addition would be increase the installed collecting surface area by either adding an additional precipitator section in parallel or in series. In series will generally increase the collecting efficiency whereas in parallel allows to handle a larger gas volume at the same or similar collecting efficiency level.

In specific instances, components can be added which will provide a more efficient and trouble-free operation of the precipitator. These are, for example:

- Transformer-rectifiers and controls
- Rapping systems
- Rapper controls
- Gas distribution devices, such as turning vanes, perforated plates, etc.
- Flow control devices, such as dividers, baffles, etc.
- Insulator vent systems
- Insulator heating systems
- Hopper heating systems
- Dust discharge valves

Fine Tuning

Fine tuning of an electrostatic precipitator used to be done either by visual observation of the stack or by optimizing the instrument readings in the control cabinet. Neither method is too accurate, and in addition, they are both extremely time consuming and, thus, impractical for actual use. In addition, when the whole precipitator consisted of maybe two or three fields in series and one or two sections in parallel (for a total of two to six bus sections), a change in the electrical settings or the rapping sequence was easily detectable. With today's precipitators having sometimes six to eight fields in series and four to eight sections in parallel (for a total of 24 to 64 bus sections), the effect of changing the operation of a single bus section is hardly noticeable. This leaves the operator only with the possibility to use real time recording instrumentation such as transmissometers and oscilloscopes with multi-channel recorders.

A transmissometer measures light absorption caused by the dust in the light path with the absorption being a measure of its quantity. The most prominent feature of this device is its capability to produce an instantaneous recording of the dust flow; i.e., immediately recognizing changes in operating conditions causing changes in precipitator performance, rapping spikes, electrical shorts, etc. (Fig. 6).

In addition, a relationship between optical density and dust concentration can be established (Fig. 7, Ref. 11), which allows for instantaneous evaluation of changes in precipitator performance caused by fine tuning of the precipitator; i.e., changing variables such as:

- rapping frequency
- rapping intensity
- electrical power input
- spark rates
- flue gas conditioning
- gas velocity
- gas and dust distribution

Each of these and other parameters will affect the precipitator performance in a different way. The use of the transmissometer allows to optimize these variables and to achieve the highest possible level of collecting efficiency.

An oscilloscope is another valuable tool to fine-tune an electrostatic precipitator by recording the current and voltage levels immediately before and after sparking (Fig. 8).

The oscilloscope will reveal the proper function of the automatic voltage control system and provide a real-time indication of the voltage/current fed into an electrical bus section of the precipitator.

It is obvious that, in addition to the above recommended indicators for the performance of the precipitator, the process related data; for example, fuel rate, gas temperature, etc., need also to be scrutinized when evaluating the performance of the electrostatic precipitator.

13. Conclusion

In conclusion, it can be said that the operation and maintenance of the electrostatic precipitator has to be an item of constant attention to the plant operator, and that the burden of keeping precipitator performance at a high level of collecting efficiency can be eased by careful planning, inspecting, maintaining, and record keeping.

This paper covers some of the problems that may face the maintenance department... Whether these problems actually arise are subject to many variables, including the thought and care given to reliability features in the original design... Success or failure of any given installation will often rest on process effects, frequent comprehensive internal inspections, and correction of repetitive maintenance problems. This care can sometimes result in acceptable performance from a marginal collector (Ref. 12).

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8. APCA TC-1 Particulate Committee, "Electrostatic Precipitator Maintenance Survey", Journal of the Air Pollution Control Association, Pittsburgh, Pennsylvania, November 1976

9. Engelbrecht, H. L., "Plant Engineer's Guide to Electrostatic Precipitator Inspection and Maintenance"
   Plant Engineering, April 1976

10. Smith, E. M., "Preventive Maintenance Helps Prevent Pollution", Pollution Engineering, March/April 1971

11. Cunningham, R. L., "Operational Monitoring and Maintenance of Industrial Electrostatic Precipitators for Optimum Performance"
    I.A.S. Annual Meeting, 1976

12. Katz, J., "Maintenance Program and Procedures to Optimize Electrostatic Precipitators", IEEE Cement Industry Technical Conference, Mexico City, Mexico, May 1974

13. Frenkel, D. I., "Tuning Electrostatic Precipitators", Chemical Engineering, June 19, 1978

15. <u>Literature</u>

The following is a brief sample of books, papers, and articles published during the last few years on subject of precipitator maintenance. Numerous other publications are available for the worker in this field. But most important of all, the information manuals, etc., of the equipment manufacturer should be consulted, and training sessions should be requested from the manufacturer.

Cross, F. L. and Hesketh, H. E., "Handbook for the Operation and Maintenance of Air Pollution Control Equipment"
Technomic Publication
Technomic Publishing Co., Inc.
Westport, Connecticut, 1975

Kester, Bruce E. (Editor)
"Design, Operation, and Maintenance of High Efficiency Particulate Control Equipment"
Specialty Conference sponsored by the Greater St. Louis Section and the Technical Council of the Air Pollution Control Association, St. Louis, Missouri, March 1973

Industrial Gas Cleaning Institute, Inc.
Publication No. E-P 1
"Terminology for Electrostatic Precipitators"
Approved February 1964, revised October 1967 and January 1973

Katz, J., "Maintenance Program and Procedures to Optimize Electrostatic Precipitators"
IEEE Cement Industry Technical Conference
Mexico City, Mexico, May 1974
Published IEEE Transactions on Industry Applications
Vol. 1A-11 November/December 1975

Szabo, MF. et al., "Control of Fine Particulate from Coal-Fired Utility Boilers" Paper No. 77-14.1,
70th Annual Meeting of the Air Pollution Control Association (APCA), Toronto, Ontario, June 1977

Crynack, R. R., "A Review of the Electrical Energization Equipment for Electrostatic Precipitators"
71st Annual Meeting of the Air Pollution Control Association (APCA), Houston, Texas, June 1978

Frenkel, David I., "Tuning Electrostatic Precipitators", Chemical Engineering, Pages 105-110, June 19, 1978

Literature

Steele, C. Jay, "Corrosion Protection Strategy for Pollution Control Equipment", Pollution Engineering, Pages 49-50, March 1978

Schneider, G. G. et al, "Selecting and Specifying Electrostatic Precipitators", Chemical Engineering, Pages 94-108, May 26, 1975

Lane, W. R. and Fletcher, H. R., "Introduction to Electrostatic Precipitator Energization and Control"
71st Annual Meeting of the Air Pollution Control Association (APCA) Houston, Texas, June 1978

Proceedings "Operation and Maintenance of Electrostatic Precipitators" Specialty Conference sponsored by the Michigan Chapter - East Central Section Air Pollution Control Association
Detroit, Michigan, April 1978

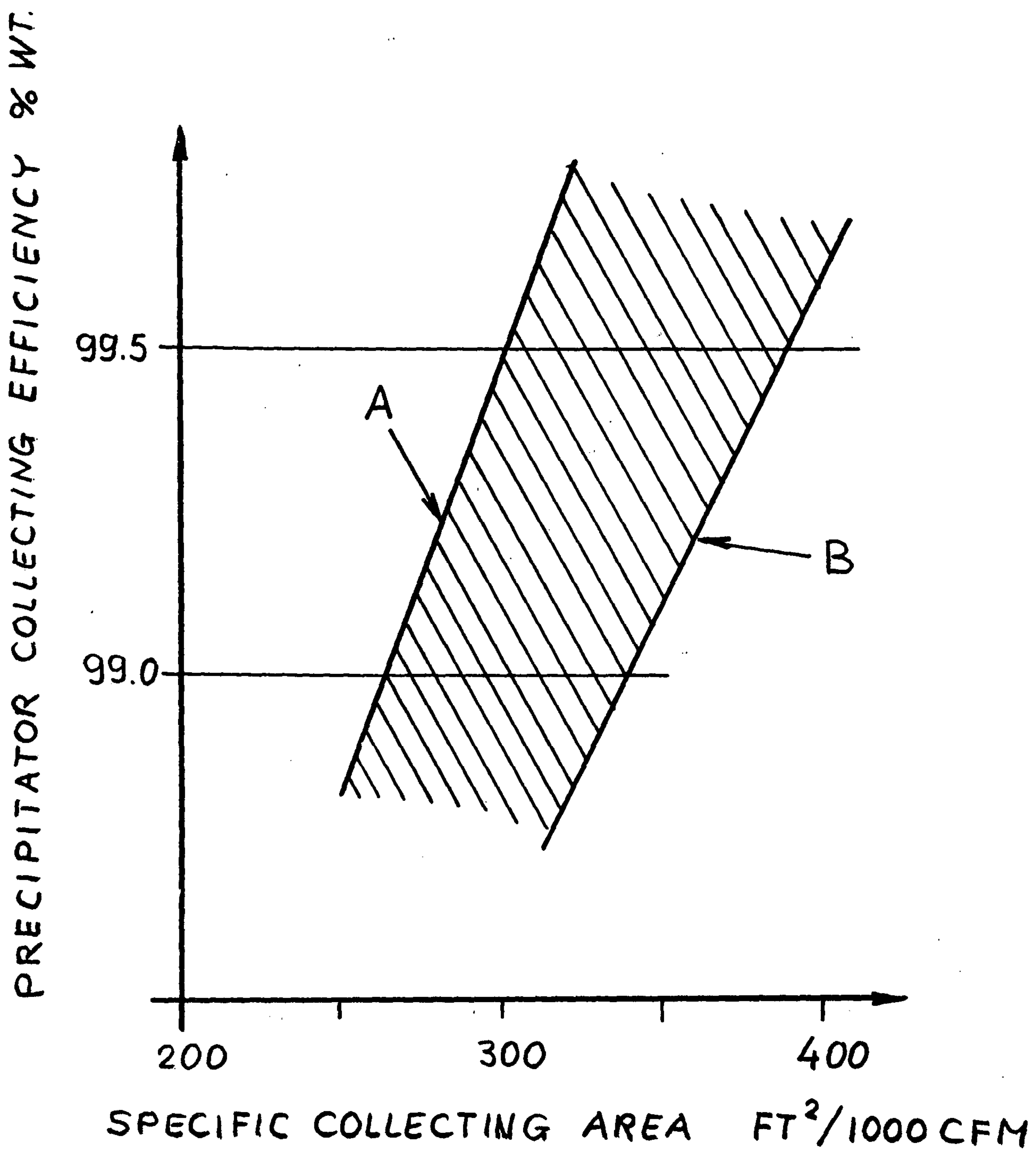


FIG. 1: ELECTROSTATIC PRECIPITATOR COLLECTING EFFICIENCY AS A FUNCTION OF PRECIPITATOR SPECIFIC COLLECTING AREA (SCA).

Reference:

Engelbrecht, H. L., "Hot or Cold Electrostatic Precipitators for Fly Ash from Coal-Fired Boilers"
APCA-Western Pennsylvania Technical Meeting on Coal Utilization
Pittsburgh, Pennsylvania, April 1976 (Reference 3).

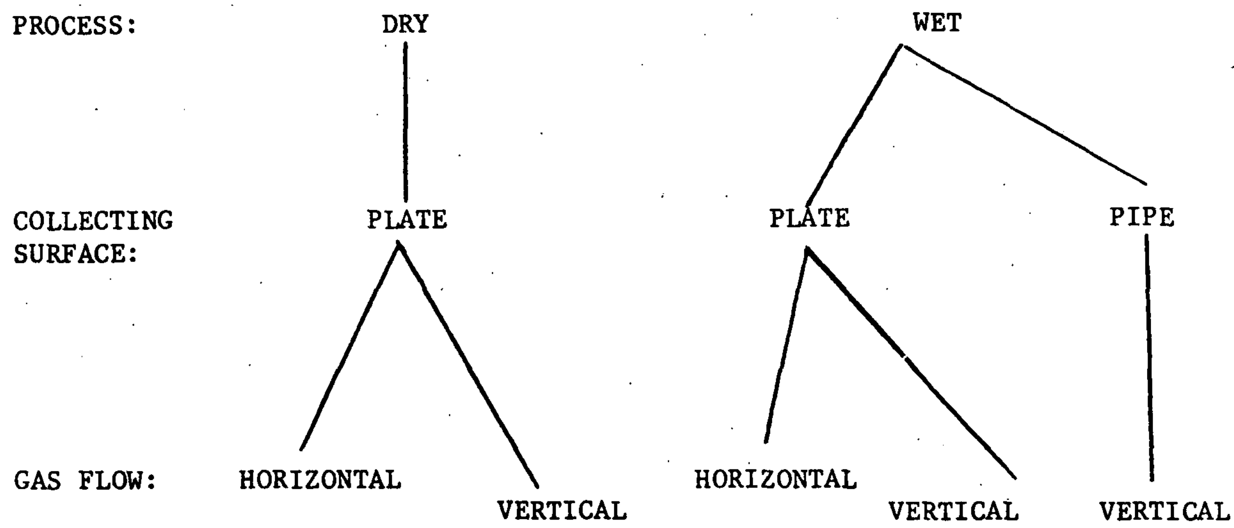


FIG. 2: ELECTROSTATIC PRECIPITATOR CLASSIFICATION LIMITED TO CONVENTIONAL (COTTRELL-TYPE SINGLE STAGE) DESIGNS

TABLE 1: COMPARISON BETWEEN AMERICAN AND EUROPEAN PRECIPITATOR DESIGN

COMPONENT	AMERICAN DESIGN	EUROPEAN DESIGN
1. Discharge System	Straight wires or discharge rods stretching from an upper support frame to a lower guide frame, wires held by weights, wire electrodes larger than the height of the collecting surfaces. Upper frame supported by two insulators.	Discharge wires of short length mounted in wire frames, each frame supported at both ends by structural elements, in turn, supported by four insulators.
2. Collecting Surfaces	Reinforced panels 6-9 ft. long in direction of gas flow, 15 to 36 ft. high.	Collecting surfaces consist of roll-formed panels approximately 18 in. wide, 15 to 50 ft. long, supported by a structural member from the top, interlocked with each other, and tied together at the bottom by a rapper bar.
3. Rapping Systems	Magnetic or pneumatic rappers or vibrators strike the upper support frames of the discharge system. Magnetic or pneumatic rappers or vibrators strike the supporting elements of the collecting surface plates. Rapping impact always from the top.	Each discharge frame rapped by a single hammer, all hammers mounted on a common shaft. Each row of collecting surface panels rapped by a single hammer, all hammers mounted on a common shaft. All drives located on the outside of the precipitator. Rapping impact at or below the center at the trailing edges of the discharge frames and at the bottom trailing edges of the collecting surfaces.

TABLE 2

DESIGN FACTORS WHICH SHOULD BE INCLUDED IN PRECIPITATOR DESIGN SPECIFICATIONS AND EVALUATIONS (REF. 4)

---

1. Corona electrodes: type and method of supporting.
2. Collecting electrodes: type, size, mounting, mechanical, and aerodynamic properties.
3. Rectifier sets: ratings, automatic control system, number, instrumentation, and monitoring provisions.
4. Rappers for corona and collecting electrodes: type, size, range of frequency and intensity settings, number, and arrangement.
5. Hoppers: geometry, size, storage capacity for collected dust, number, and location.
6. Hopper dust removal system: type, capacity, protection against air inleakage and dust blow-back.
7. Heat insulation of shell and hoppers, and precipitator roof protection against weather.
8. Access doors to precipitator for ease of internal inspection and repair.
9. Provisions for obtaining uniform, low-turbulence gas flow through precipitator. This will usually require a high-quality gas flow model study made by experienced people in accord with generally accepted techniques, with full report to precipitator purchaser before field construction.
10. Quality of field construction of precipitator, including adherence to electrode spacing and rigidity requirements.
11. Warranties: performance guarantees, payment schedules, adequate time allowance for performance tests, penalties for non-performance.
12. Support insulators for high-tension frames: type, number, reliability. Air venting, if required.
13. Inlet and outlet gas duct arrangements.
14. Structure and foundation requirements.

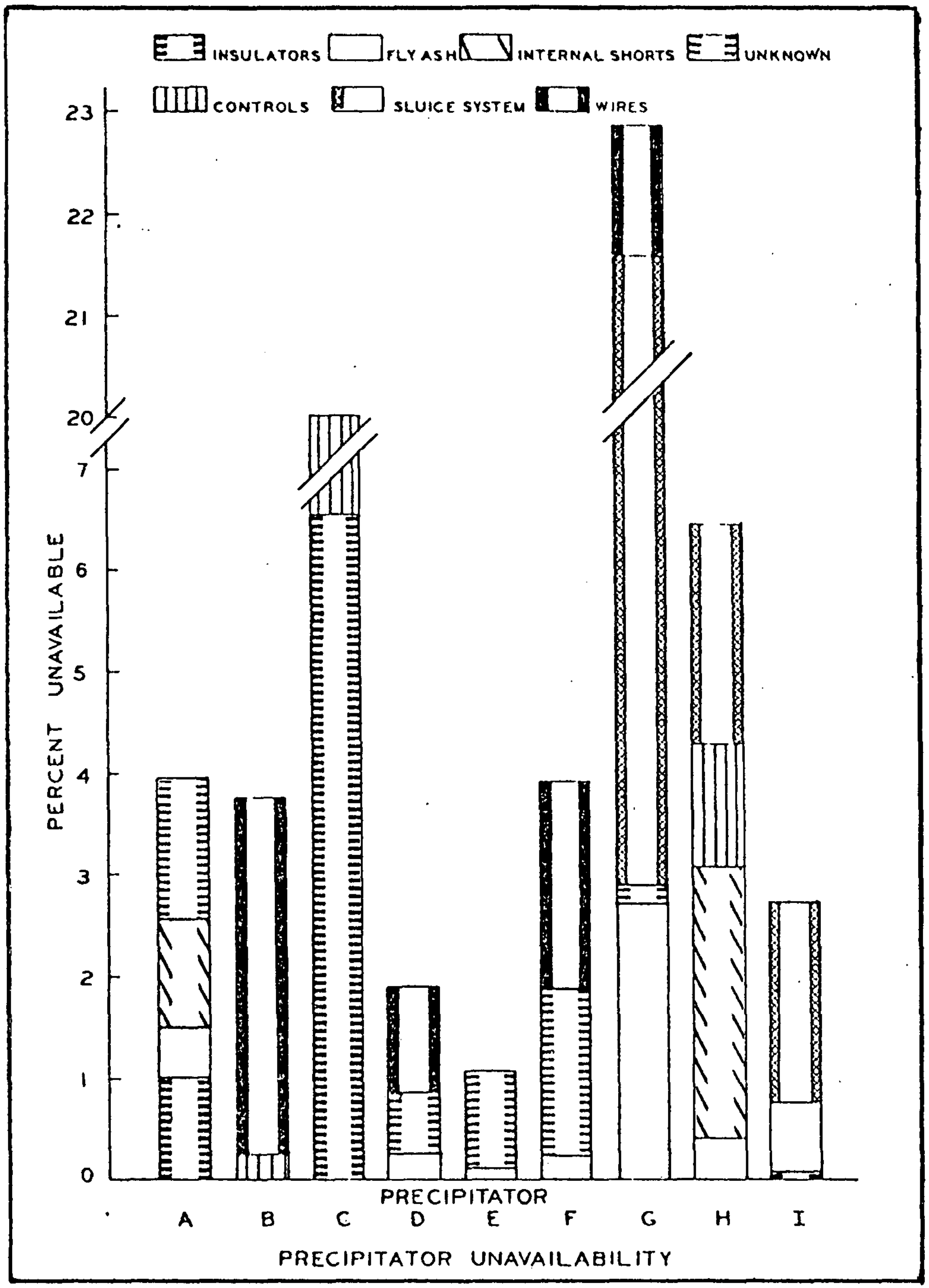


FIG. 3: PRECIPITATOR UNAVAILABILITY

Grecco, J., "Electrostatic Precipitators - An Operator's View"
Specialty Conference: Design, Operation, and Maintenance of
High Efficiency Particulate Control Equipment
St. Louis, Missouri, March 1973

TABLE 3: PRECIPITATOR START-UP CHECKLIST (REF. 9)

PRECIPITATOR START-UP CHECKLIST

1. Check line voltage for proper phase and magnitude.
2. Inspect transformer-rectifier tanks for signs of oil leaks or physical damage. Check oil tank gauge. Refill if necessary (follow manufacturer's instructions).
3. Check hopper discharge valves and dust handling equipment.
4. Inspect exhaut fan.
5. Follow key-interlock procedures for opening precipitator access doors. Inspect interior of precipitator. Remove any foreign materials (tools, rags, cleaning materials, etc.) from inside the unit.
6. Disconnect high-voltage conductor at support insulator and check resistance between discharge system and ground. Reading should be 100 megohms or greater.
7. Inspect all rapper drivers for proper position (follow manufacturer's instructions).
8. Check rotation and alignment of all gear motors and drives that have been serviced.
9. Inspect access doors for operation and alignment. Lock them. Return door keys to their proper location in key-interlock transfer blocks.
10. Check condition of all explosion-relief devices (if applicable).
11. Inspect precipitator control cabinets for evidence of loose connections.
12. Complete procedure outlined in the key-interlock instructions to return all keys to operating position.
13. Preheat support insulators at least 2 hours before energizing the precipitator. Start insulator vent system (if applicable).
14. Activate dust-discharge and dust-handling systems.
15. Start collecting surface and discharge-electrode rapping systems. Operation should be continuous during start-up.
16. Activate gas distribution plate rapping system (if applicable).
17. Turn on high-voltage current as soon as gas flow has been started to the precipitator (by activating exhaust fan, dampers, or slide gates) and the temperature of the precipitator's internal parts exceeds dewpoint of the gas. (High voltage, however, should not be activated if there is a possibility of combustible gases being present in the precipitator).
18. Set precipitator operating control on "automatic".
19. Turn off insulator heaters or set on "automatic".
20. Turn off continuous rapping and set on "automatic".

PRECIPITATOR SHORT-TIME SHUT-DOWN CHECKLIST

1. Turn on insulator heating system and de-energize high-voltage system.
2. Keep rapping systems for collecting-surface plates, discharge wires, and gas-distribution plates activated unless precipitator is to be entered. (If entry is planned, follow key-interlock system procedures to open precipitator access doors.)
3. Keep dust discharge system operating continuously.
4. Operate exhaust fan at reduced flow rate.

TABLE 4: PRECIPITATOR SHORT-TIME SHUT-DOWN CHECKLIST (REF. 9)

PRECIPITATOR SHUT-DOWN CHECKLIST

1. Activate insulator heating system. Leave on for at least 6 to 8 hours after precipitator is de-energized (do not turn on heating system if maintenance or inspection work is to be done in insulator compartments).
2. Keep rapping systems for collecting surface plates, discharge wires, and gas-distribution plates on for several hours to help clean precipitator as thoroughly as possible.
3. Turn off exhaust fan.
4. Follow key-interlock system procedures to open precipitator access doors.
5. Ground all high-voltage components securely. Warning signs should be used on all switches (follow manufacturer's instructions).
6. Clean precipitator manually.
7. Discharge all dust from hopper if downtime is to be extensive.
8. Seal flues to other precipitators, stack, or any crossover flues to prevent gases from other sources from entering precipitator (such gases can condense and cause extensive corrosion).

TABLE 5: PRECIPITATOR SHUT-DOWN CHECKLIST (REF. 9)

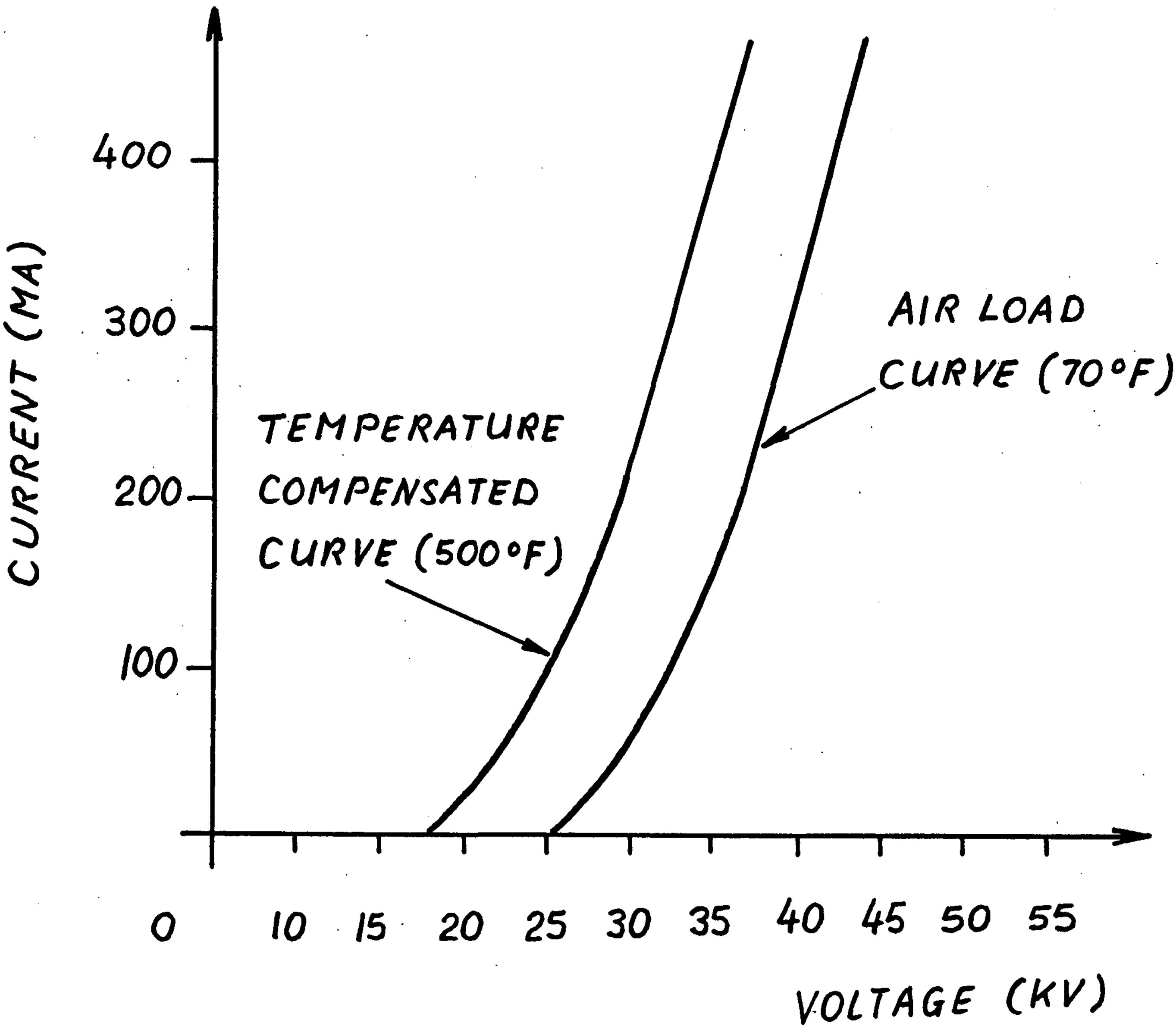


FIG. 4: VOLTAGE-CURRENT CHARACTERISTICS (Inlet Section)

Reference:
Cunningham, R. L., "Operational Monitoring and Maintenance of Industrial Electrostatic Precipitators for Optimum Performance", IAS Annual Meeting, 1976 (Reference 11)

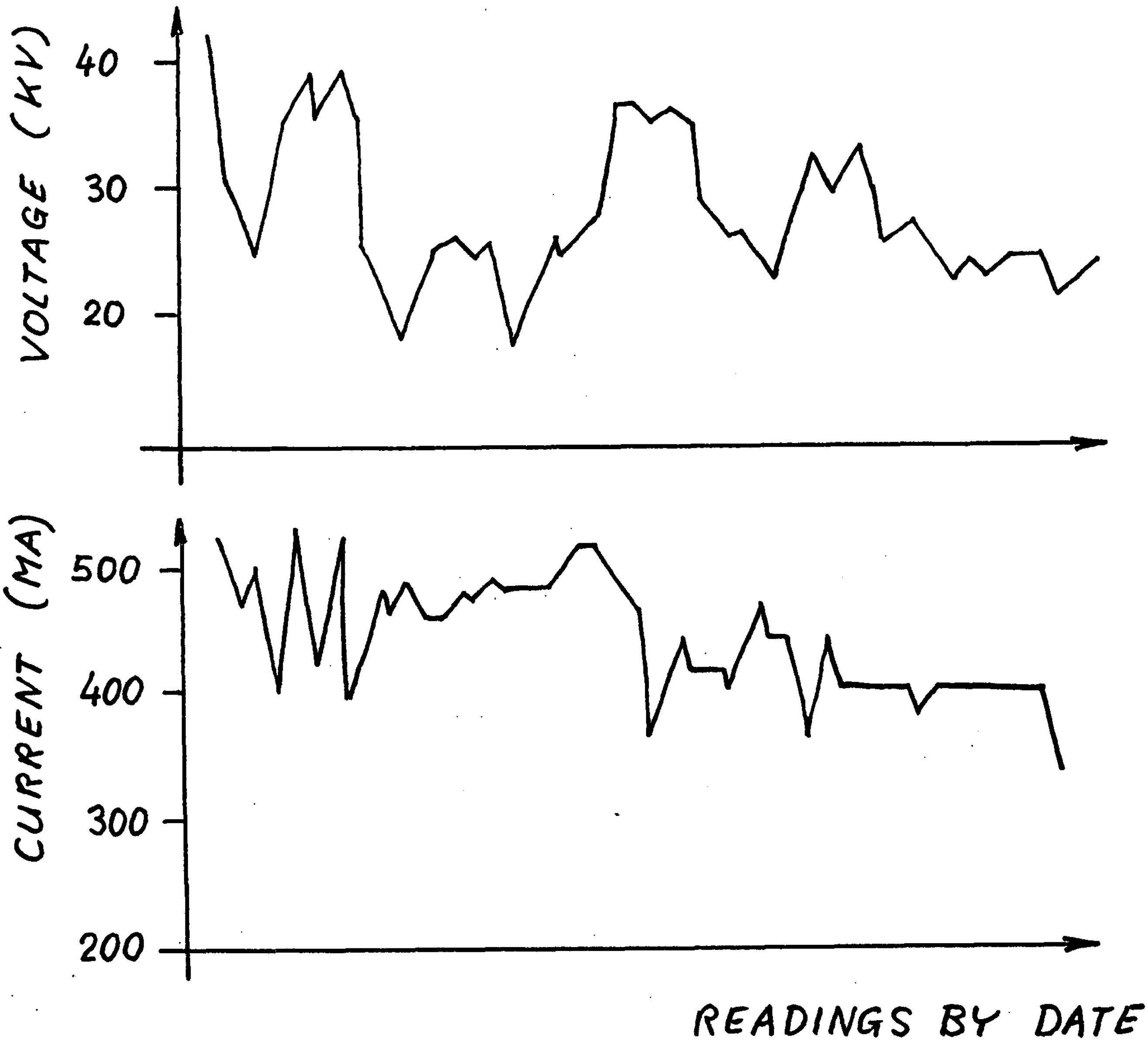
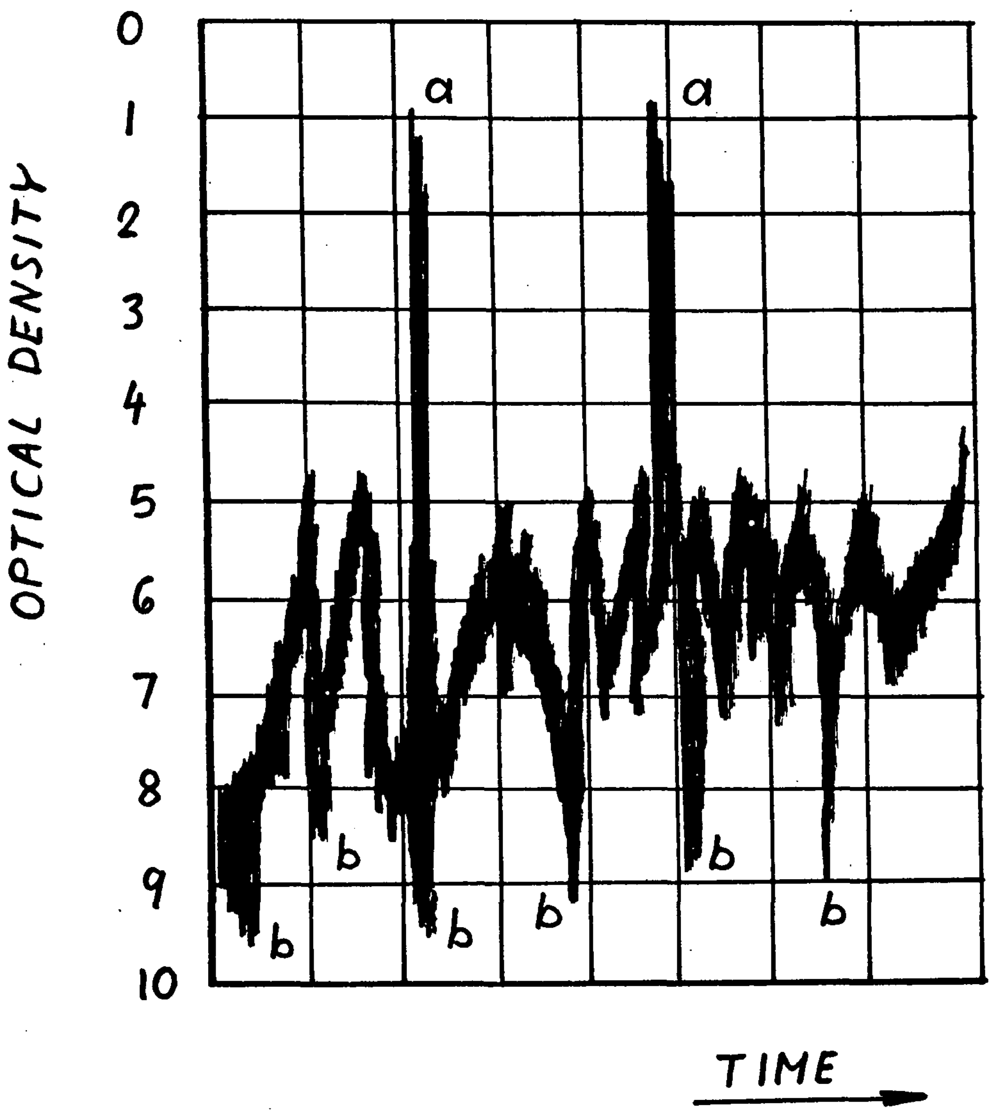


FIG. 5: CHANGES IN VOLTAGE AND CURRENT READINGS OVER TIME

Reference:
Cunningham, R. L., "Operational Monitoring and Maintenance of Industrial Electrostatic Precipitators for Optimum Performance", IAS Annual Meeting, 1976 (Reference 11)



a - Zero Emission Scan
b - Emissions Spikes

FIG. 6: OPTICAL DENSITY PRINT-OUT

Reference:
Frenkel, D. I., "Tuning Electrostatic Precipitators", Chemical Engineering, June 19, 1978 (Reference 13)

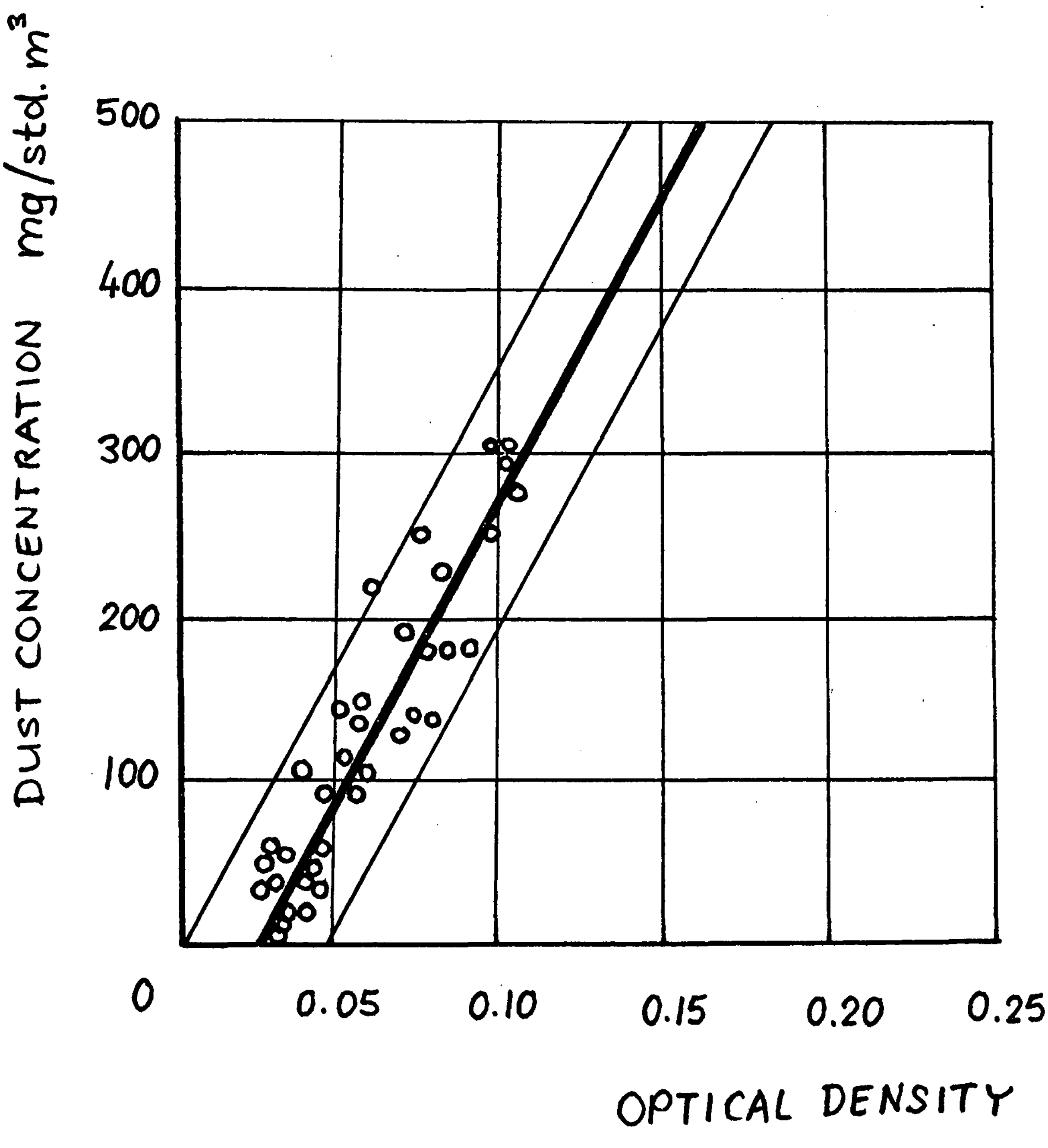
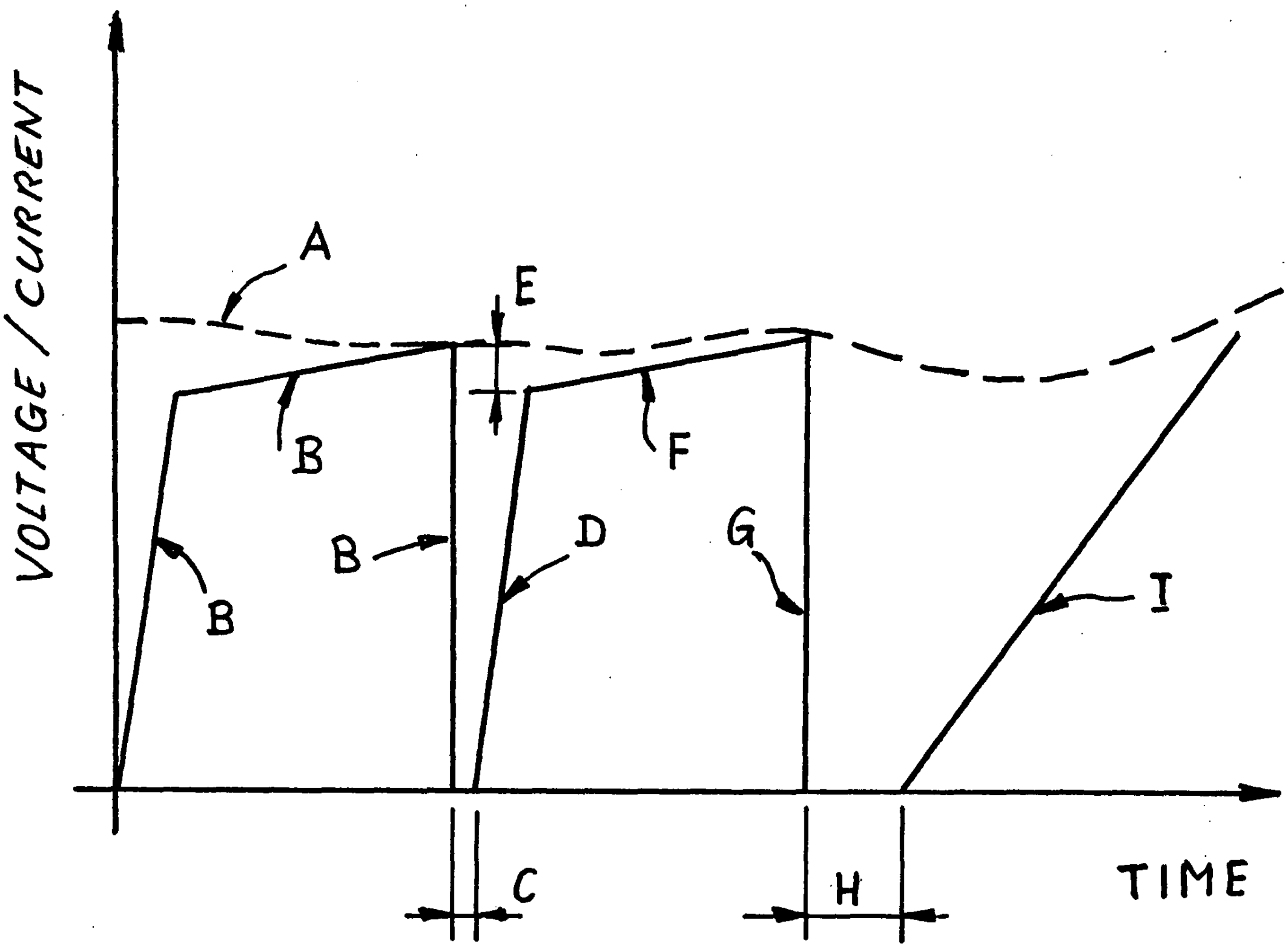


FIG. 7: RELATIONSHIP BETWEEN OPTICAL DENSITY AND DUST CONCENTRATION FOR A LIGNITE-FIRED BOILER

Reference:
Frenkel, D. I., "Tuning Electrostatic Precipitators", Chemical Engineering, June 19, 1978 (Reference 13)



A - Varying Sparkover Level

B - Envelope of Precipitator Current Pulses

C - Spark Quench

D - Fast Ramp

E - Setback

F - Slow Ramp

G - Rapid Turn-Off

H - Arc Quench

I - Soft Start

FIG. 8: ELECTRICAL POWER LEVELS OF AN ELECTROSTATIC PRECIPITATOR IN AN ARCING MODE OF OPERATION

Chemical Engineering

Selecting and Specifying Electrostatic Precipitators

Industrial electrostatic precipitators are complex devices. There are many added-cost features that will pay off in better operation and lower maintenance, but are likely to be omitted in the low-bid specification. Also, proper erection and inspection procedures are vital if you expect to receive trouble-free service and high efficiencies.

GILBERT G. SCHNEIDER, THEODORE I. HORZELLA, JACK COOPER and PHILIP J. STRIEGL, Enviro Energy Corp.

There are many details that you must be aware of if you want to select and specify precipitators intelligently.

For example, inclusion of many specialized design-features will enable the precipitator to be erected easily and to be operated and maintained with the fewest problems. But since most precipitators are bought on a bid basis, these features are likely to be omitted (to provide for the lowest cost), unless you have specified that they must be included.

Careful attention to detail during the erection of the precipitator will pay dividends during startup, and in later operation. Here, again, you must know which problems must be avoided.

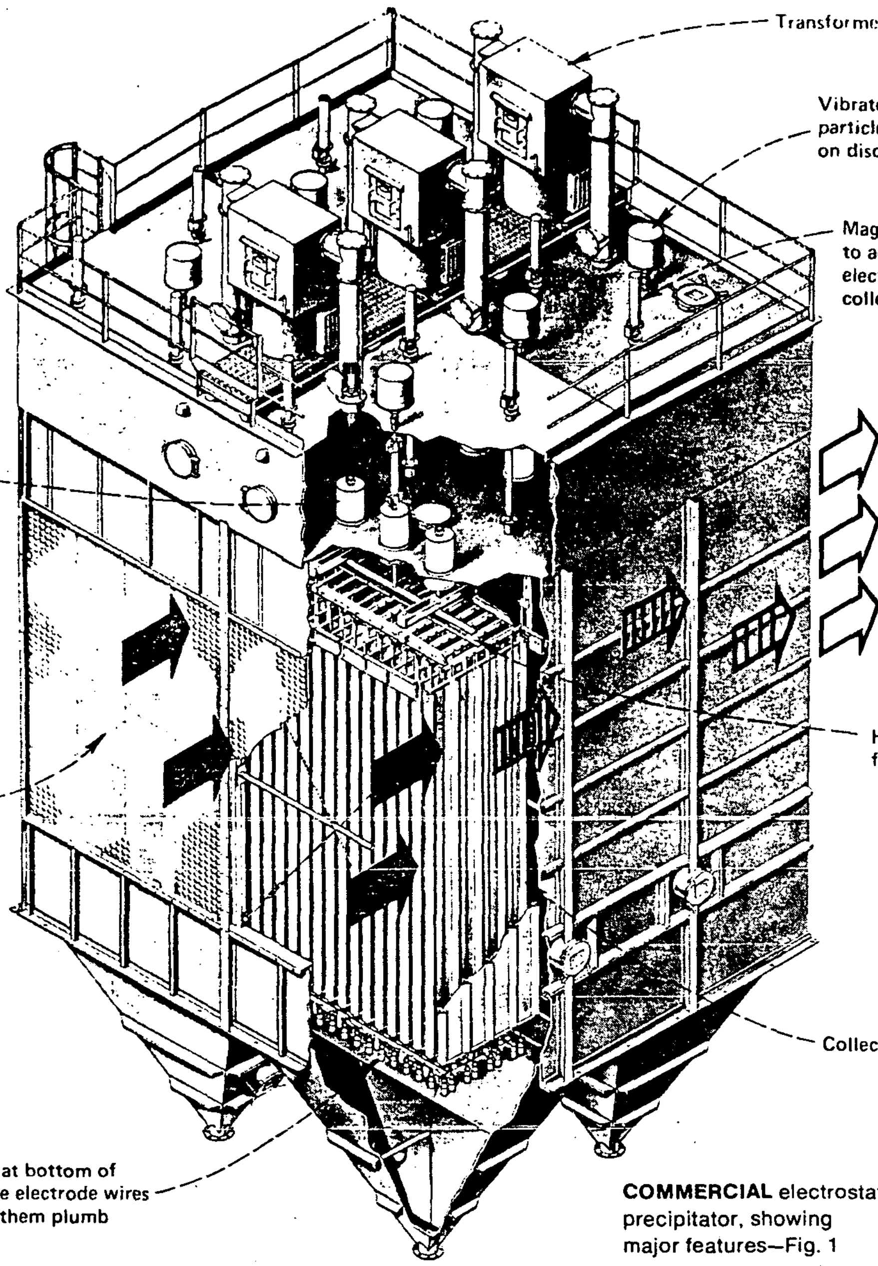
One of the things that complicates the purchase of electrostatic precipitators is that there is much "art" involved in the selection of the equipment by the vendor. This selection relies more on experience with previously sold precipitators than on solid engineering data and calculations. Depending on the supplier's experience bank, it is perfectly reasonable for an engineer to receive vendors' bids that, for the same gas flow, vary in size by factors of two or more.

In the design of this type of equipment, it should be noted that size increases directly with gas volume for a constant efficiency but increases exponentially as efficiency requirements rise. That is, costs increase exponentially with increase of efficiency.

Before we go into details of the precipitators, let us discuss the particulate-containing gases that will be going through them.

Particle Size of the Pollutant

Particulate air-pollution-control problems involve particles under 100 microns (μm) in size. Although the particles are not spherical, the particle size is expressed as



COMMERCIAL electrostatic precipitator, showing major features—Fig. 1

the diameter of an equivalent sphere that would follow the settling rate of Stokes' law.

Particles are often described, depending on their size or nature, as:

- Dust—Particles from 0.1 to 100 microns (μm).
- Mist—Liquid droplets suspended in a gas.
- Fume—Solid particles or liquid droplets that are formed by condensation from a vapor.

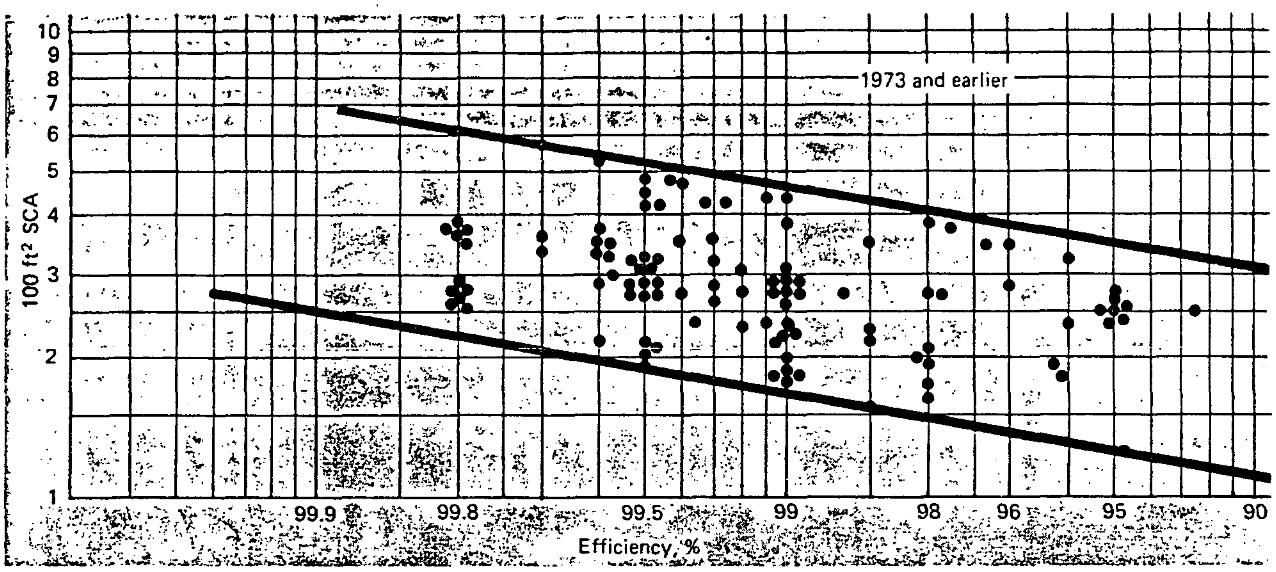
In most industrial applications, particle size interests us only insofar as it affects the capability of the air-pollution-control equipment. With the electrostatic precipitator, as with other industrial air-pollution-control devices, the larger particles are easier to collect (except when the particle is large but extremely fluffy).

There is a basic difference between the electrostatic precipitation principle and the mechanical methods (used in centrifugal separation, wet scrubbing and gas filtration). In the precipitator, the electrical forces are applied only to the suspended particles. In the mechanical methods, the complete gas stream is subject to externally applied forces, resulting in a much higher consumption of energy for the collection process. The size of the precipitator will be affected by the particle size, but the energy consumption for the collection process will remain almost constant.

Properties of the Particles

Certain physical and chemical properties of the particles are important because they affect the properties of the agglomerates that result when the particles reach a collecting surface.

For example: Mists will form liquid droplets that flow by gravity into the hopper. Some metallurgical fumes, such as zinc and lead oxides, form low-bulk-density layers that will break (during rapping of the collection



VARIATION in size (SCA) supplied for any specified efficiency (coal-fired boilers)—Fig. 2

plates) into fluffy agglomerates, which float in the gas stream. Other fine dusts, such as cement, form a relatively dense agglomerate that quickly falls into the hopper during rapping. Finally there are dusts, such as those produced in no-contact (low odor) kraft recovery boilers, which are very tacky and difficult to remove by rapping; special attention must be given to a proper rapper system to minimize operational problems.

The electrical conductivity of the particle is most important. (However, in the field of electrostatic precipitation, the reciprocal property, "resistivity," is used for the sake of numerical convenience.) Nonconductive or high-resistive particles, as they deposit on the surface of the collecting electrode, form an electrical insulating layer that prevents the movement of ions to ground. Thus the flow of current from the discharge electrode to the collecting electrode is reduced, and the voltage differential is increased until sparking occurs. A resistivity of the particles above 2×10^{11} ohm-cm is generally considered the limit for proper electrostatic precipitation.*

Excessive conductivity (or low resistivity) of particles, such as carbon black and other carbonaceous materials, causes the particles to immediately lose their charge as they contact the collecting electrode. Thus the particles are not retained on the collecting electrode surface, but rather reenter the gas stream.

Conditioning To Modify Particle Resistivity

As White points out in "Industrial Electrostatic Precipitation," "adaptation of conditioning methods to practical situations requires a broad knowledge of the basic principles and contingent factors to obtain useful results."

Conditioning to modify particle resistivity may consist of:

- Addition of chemicals, or water vapor, to the gas stream.
- Modification of the material producing the dust.
- Change of the gas temperature.

More often than not, a combination of these methods will be chosen.

Addition of chemicals (or water vapor), even in very small amounts, has shown remarkable effect on the resistivity of the particles. Ammonia, sulfuric acid, sodium chloride, sulfur trioxide, and other substances, added in trace amounts, have improved the operation of some precipitators from an unacceptable performance to one that meets air-pollution-control requirements.

In most cases, the conditioning chemical is adsorbed on the surface of the particles. However, several cases of conditioning of weak basic particles by using both strong acids and water vapor suggests that the acid is adsorbed on the particle surface, and that water vapor is then absorbed. A similar situation occurs when conditioning weak-acid particles with a strong base and water vapor.

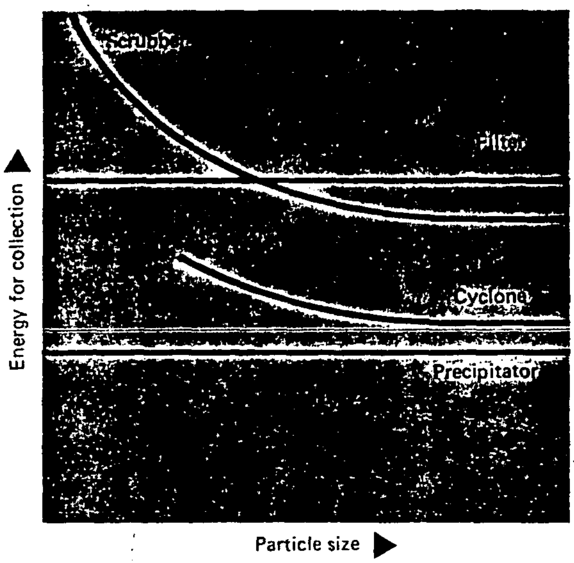
Gas Flow

Gas flow is critical in the design and operation of an electrostatic precipitator. The basic principle on which the precipitator works—the migration of minute particles to the collecting electrode—involves a finite length of time. If the gas velocity in any of the passages around the collecting electrodes exceeds the design gas velocity, some particles will not have adequate time to reach the collecting electrode.

After the particles have been deposited on the collecting electrodes, they are made to fall into the hoppers by rapping the electrodes. During this operation, good gas-flow patterns are critical to avoid reentrainment of particles in the gas stream. This reentrainment is possibly the most devastating effect caused by poor gas-flow.

At times, excessive gas velocity—due to unbalanced gas flow—may cause reentrainment from the hoppers. Uneven gas flow may result from part of the gas moving

*The resistivity of various dust particles, under operating variables such as gas temperature, gas moisture, and chemical composition of the gas, is presented in tabular and graphical form in "Industrial Electrostatic Precipitation," by H. J. White, Addison-Wesley, Reading, Mass., 1963. Because the resistivity is affected by so many variables, we do not attempt to give such information in this article.



ENERGY consumption of dust collectors—Fig. 3

through the hopper space rather than between the collecting plates. This gas "sneakby" through the hoppers will result in very poor performance. With today's requirements of efficiencies above 99%, a 1% sneakby would make it impossible to meet the required efficiency. Baffles in the hoppers, when properly designed and installed, will usually correct such gas-flow imbalance.

Modification of the materials that produce the dust has been successfully applied to coal-fired boilers. Coal that contained natural conditioning agents (such as sulfates) was mixed with low-sulfur coal of high resistivity. The resulting mixture produced a dust that could be effectively collected in an electrostatic precipitator.

Changing the temperature of the particulate-containing gas is a widely accepted practice. In general, temperature in the 200 to 400° F of range will produce high-resistivity dust when natural conditioning agents are absent. (This is typical of low-sulfur-coal-fired boilers.)

One answer is to locate the precipitator ahead of the heat exchanger that heats incoming air (and, consequently cools the hot gas). The gas-flow upstream of the air heater (at about 700° F) represents about 1.5 times the volume of gas flow downstream of the air heater (at about 300°F). It would appear that a larger precipitator would be required to handle the gases at higher temperature (higher volume). However, in actual practice (with low-sulfur coals), because of the high-resistivity problems in the 200 to 400°F range, it is the smaller gas volume that requires the larger precipitator.

It should be kept in mind, though, that the "hot" precipitator (upstream of the air heater) may not necessarily be the universal answer for low-sulfur coal. Some low-sulfur coals contain other impurities that may have a conditioning effect, thus making the "cold" precipitator (downstream of the air heater) the more economical selection.

This should warn prospective users of precipitators that dusts from untested sources should be tried out in a pilot precipitator or, if feasible, in a full-scale existing installation. Such test work will support a final decision on a "hot" or "cold" precipitator.

The best precipitator will function no better than the gas-flow distribution allows. The flue design, both upstream and downstream of the precipitator, has a direct effect on gas distribution. Transitions and turning vanes must be designed in accord with principles developed in wind-tunnel tests. Diffusion plates or screens at the precipitator inlet will convert a flow of great turbulence into a multitude of small turbulences immediately downstream of each opening of the plate. These small turbulences will promptly fade out, causing a nonturbulent flow through the precipitator. Diffusion devices are usually perforated plates that are provided with rappers to dislodge any dust buildup.

Selection of the Precipitator

Precipitators are selected using the Deutsch equation or some of its modifications, and applying numerous experience factors.

$$\eta = 100\,[1 - e^{-wA/V}]$$

Where:

η = collection efficiency, %; w = migration velocity, cm/s; A = area of the collecting electrodes, ft²; V = gas flow, thousand ft³/min; e = base of natural logarithms.

The units in the above equation are used by U.S. manufacturers of precipitators to express the migration velocity in whole numbers. The above equation is used to calculate the collecting area (A) when the gas flow (V) and the collection efficiency required (η) are known. The equipment designer will select a migration velocity (w) from his experience file. This migration velocity will vary, depending on operating conditions, source of the dust, and temperature and chemical composition of the gases. The ranges of such variations are too large for us to present meaningful data for the chemical engineer.

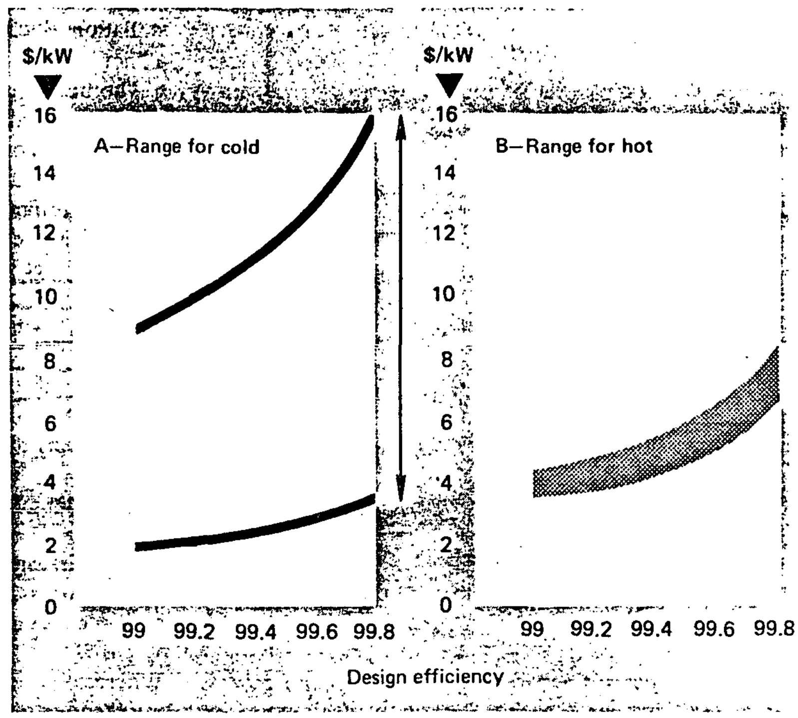
The migration velocity (w) is the average rate at which particles are charged, and conveyed to the collecting electrode (where they lose their electrical charge and are removed into the hoppers). Those particles that are not collected, or which are reentrained into the gas stream, are factored-in in this migration velocity. At the present state of the art, these factors are determined by experience.

"Experience" factors, such as particle size, particle agglomeration, gas velocity, gas temperature, gas composition, and chemical and physical properties of the particles, are all grouped into this so-called migration velocity.

Also included as experience factors are design peculiarities typical to the specific application, such as configuration of the ductwork, use of distribution plates, the type of process producing the particulates, and many other subjective-judgment elements the designer wishes to incorporate.

It is easy to understand that today's precipitator design is strongly tinted by the experience, and subjective decisions, of the individual selecting the equipment.

Attempts to quantify the experience factors and to incorporate them in computer programs are underway by numerous engineers and scientists. The precipitator in-



USER'S cost of erected precipitators of various design efficiencies. Variation in particle resistivity makes for a much wider cost range for cold precipitators—Fig. 4

dustry, however, has been very slow in employing the computer in this important task; hence, the selection of equipment is made today in basically the same manner as in the early 1940s. Most of the computer studies have come from outside the electrostatic-precipitator industry. The greatest difficulty in applying the resources of electronic data processing to the selection of precipitators is the lack of complete field-test results covering all of the variables that affect the basic concept of migration velocity. The designers of electrostatic precipitators use the following parameters as guidelines in equipment selection:

Dry Precipitators—Face velocity (velocity of the gas across the precipitator) is kept in the range from 1 to 15 ft/s, depending on the dust source.

Aspect ratio (collecting-plate total depth divided by collecting-plate height) is kept above about 1.0.

The electrical system is arranged in bus sections, each bus section representing any portion of the precipitator that can be independently energized.

The number of fields (number of bus sections arranged in the direction of gas flow) are calculated thusly: As a rule of thumb, manufacturers will use 1 field for up to 90% collection efficiency, 2 fields for up to 97%, 3 fields for up to 99% and 4 or more fields for efficiencies above 99%.

The number of cells (number of bus sections arranged in parallel) are established so that if any field is shorted out, the overall precipitator efficiency will not fall below the specifications.

Often, more than one cell will be energized from a common high-voltage electrical set (or source). However, more than one field in any one cell should not be energized from the same high-voltage electrical set, since a short would affect more than one field in the same cell, causing a substantial reduction in collection efficiency. In general, one high-voltage electrical set is used for up to 25,000 ft^2 of collecting surface. About 55mA are supplied per 1,000 ft^2 of collecting surface.

Wet Precipitator—The wet precipitator is ideally suited for removing acid mists or other materials that can be collected as a liquid solution or suspension. The wet precipitator is also useful for either high- or very-low-resistivity dusts, provided that the process is not affected by such wet collection of the dust. There are cases where the dust can be removed from the collecting surface only by wet washing of the surface, and here the wet precipitator is the only answer—unless alternate methods of collection (such as fabric filters) are used.

The wet precipitator may be designed similarly to a dry one, but furnished with water sprays for continuously, or periodically, washing the collecting surfaces and the discharge electrodes. More often, though, the wet precipitator is designed as a series of pipes in parallel, each containing a single discharge-electrode in its center. Gases flow vertically through each pipe, and the collected mist flows down the pipe surface. Intermittent washing or flushing is usually required. As in the dry precipitator, the basic design parameters vary with each application.

BASIC STRUCTURAL CONSIDERATIONS

Structural engineering and design considerations are frequently overlooked by the engineer who specifies and buys electrostatic precipitators. Such details are perhaps as important as the design of performance parameters if the machine is to operate reliably for its expected life. It is often presumed that the manufacturer's experience and engineering capability should be accepted at face value. Consequently, evaluations of proposals are based essentially upon migration velocities, face velocities, quantity of collecting surface, electrical supply, sectionalization, number of rappers, and the like.

Of course these criteria are extremely important in comparing competitive designs. And, in most cases, the manufacturer's structural engineering capability is sufficient. Still, it is prudent to evaluate the structural design—at least, beyond the details of casing thickness, design pressure and temperature, and construction materials (which are the items usually included in proposals).

Hence, to provide a more complete picture before final evaluation, you should thoroughly examine (a) the supplier's standard fabrication and erection dimensional-tolerance system; (b) his procedures for qualifying his subcontractors; (c) his quality-control and inspection procedures in the shops and in the field; (d) the caliber of the individuals designated as construction supervision or advisers and service engineers, and (e) even the workload in his organization to assess the level of competence that will be applied to your precipitator.

This section of our article is not intended as a construction or design manual for electrostatic precipitators. Each manufacturer has his standards, design philosophy and "track record." Certainly, we do not wish to evaluate here the relative merits of the designs offered. Rather, what follows is an attempt to provide the user's buyers, engineers and operators with a guide that will enable them to examine and discuss the equipment with the manufacturers more knowledgeably. Assurance that the electrostatic precipitator will be designed and erected so that it will operate both reliably, and as intended, should be based upon considerably more than merely pages of legalistic terms, conditions and warranties. (It is now generally accepted that low price and "paper" guarantees do not generate the best investment in pollution-control equipment.)

In the competitive atmosphere of a "bid business," a manufacturer will generally propose only the equipment and features that he believes necessary and sufficient to meet the contract requirements. Although he will strive to point out his "features" at sales presentations, he will rarely offer designs that, in his judgment, will make his price noncompetitive. He will try to avoid increases in proposal and engineering costs that will be caused by deviations from his standards, which, after all, were developed largely as a result of commercial aspects and his knowledge of operating experience.

Therefore, a plant engineer must either carefully express his needs in the specification, recognizing the impact on his cost or, alternatively, evaluate proposals with extreme care.

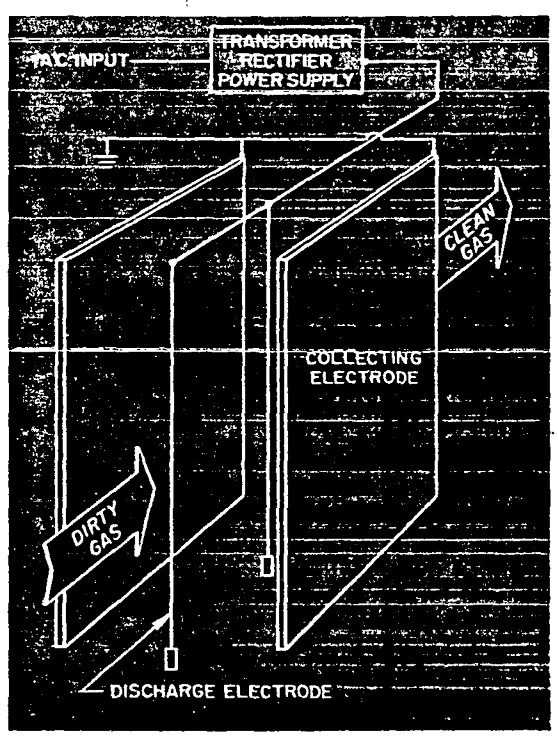
Catastrophic structural failures have been rare (although they have occurred). What one must be wary of, usually, is the subtle structural problem. One such problem might be lack of provision for expansion, possibly stemming from a temperature assumption that allows no margin (causing excessive deflection of the substructure or the interior precipitator beams and columns). There are many other such problems, even insufficient attention to fabrication and erection tolerances (which will result in misalignment and other operating difficulties after the precipitator is onstream).

Under the pressure of plant operation, with the natural reluctance to shut down units because of high cost, the true causes of malfunction are extremely difficult to ascertain, and repairs are expensive in both time and money. Even more disturbing is that the symptoms are often the result of several deficiencies that overlap and tend to mask each other. Fortunes have been spent by manufacturers and plants in making corrections and modifications in one shutdown after another, frequently without any benefit.

Problem prevention usually requires no more than a professional attention to detail, proceeding from a knowledgeable understanding of functional requirements, in logically following the design, fabrication and erection phases of the precipitator. The cost of this review will be far less than that of even a few days of forced shutdown.

The Support Structure

Use of standard AISC (American Institute of Steel Construction) allowable stresses and deflections for



Basics of Electrostatic Precipitators

Particles in the dirty gas entering a precipitator are charged by the discharge electrode. The particles then migrate to the collecting electrodes (collecting plates), where they adhere and lose their charge. The particles are generally dislodged from the collecting plates by vibrators or rappers that are attached to the plates, and fall into hoppers below the plates. In some cases, however, it is necessary to wash the particles off; liquid particles may drip off by themselves.

structural-steel design may not provide a rigid enough "platform" to support the multiple columns of a precipitator. Some deflection is inevitable, but it is the relative deflections between support points that must be examined for the effects on internal alignment.

In an attempt to minimize these relative deflections, manufacturers generally place high restrictions on the allowable deflections, frequently leading to the need for massive structural girders. Additional structural columns to grade should be studied as an alternative (to reduce the support of the precipitator by members in flexure).

Because the casing expands in the plan view with increasing temperature, it is necessary to provide for sliding at the support points, with resulting frictional forces. This friction causes torsion on the structural member (since the sliding takes place across its top flange), and consequent bending in the precipitator columns. Also, the vertical loads will be eccentric to the steel member in either the hot or cold position (or both), depending upon the detail dimensioning. Most designers will offset the precipitator columns relative to the steel for half the calculated expansion.

The hoppers (with insulation and lagging), moving with the casing, must clear the flanges of the support girders in both the cold and hot positions. To provide the space required, in view of the large girders (usually needing rather wide flanges), the precipitator columns are extended—in effect raising the casing in relation to the steel. The bending moments caused by friction forces at the base are thus increased and the columns must be checked carefully. Errors occur here frequently because of poor coordination between designers of the precipitator and those who design the structural steel.

To reduce the frictional resistance, Lubrite (or other friction-reducing plates) are interposed between the structural steel and the precipitator-column base. When these are used in the design, one should carefully check allowable bearing-pressures and dimensional details in the hot and cold positions. Installation must be supervised to assure that the sliding surfaces are horizontal.

Fabrication and erection tolerances usually dictate that "shim packs" be installed between the precipitator base and the structure, thereby allowing for vertical adjustment of the casing. Logically, the base of the precipitator should be detailed "high" in the event that the structural tolerance is on the "plus" side at erection—otherwise, shims would be of no value.

Perhaps some adjustable "jackbolt" provision could be made so that shims could be fitted after the loads have been applied rather than as they are commonly used today—that is, as a tool to overcome tolerances "to a level" after erection of the steel.

To control expansion movements, most precipitators are anchored to the structure at one column base, with all others allowed to grow radially from the one point. If all the column bases are bolted to the steel, it is necessary to make provision for movement by using slotted holes. Considering fabrication and erection tolerances and the possibility of overtightened bolts, many designs incorporate shear-bar guides and stops at a limited number of columns along the two lines that radiate from the anchor column parallel to the structural steel.

These bars both control the expansion and transmit lateral shear at the base (from wind or seismic loads, which may be in excess of frictional loads). These shear bars must be located accurately and must be deep enough to allow for the maximum shim pack. Therefore, they should be placed after the casing is installed. Admittedly, access to the shear bars at this time is somewhat difficult and, occasionally, an erector may place the shear bars prematurely. This is another reason for careful field quality-inspection.

Casings

Functionally, the precipitator casing both houses and supports the collecting surfaces and discharge systems, forming a gastight enclosure between the inlet and outlet plenums or flue connections. Therefore, the casing is subjected to, and must be designed for:

- Static or dead loads of all components, including any equipment located on the roof, superstructure weights, hoppers, and dust loads.
- Roof live-loads and snow-loads.
- Loads and movements imposed by connecting flues.
- Wind and seismic loads.
- Internal gas pressure (or vacuum).
- Dynamic loading imposed by vibrators and rappers.

Additionally, the casing will be subjected to the elevated temperature of the flue gas: hence, the design must provide for the casing's overall expansion. Superimposed upon this expansion relative to the surrounding structure, there are also the differential expansions between components, and the consideration of thermal gradients in specific members as the stresses and deformations are influenced by end-restraints (connections).

The structural components of the casing are:

Upper Beams—These beams support the collecting surfaces and discharge systems, transformer and other electrical equipment on the roof, as well as the roof casing itself, and part of the superstructure and other loads. Because these beams are somewhat shielded from the gas stream, they are subjected to temperature differentials between bottom and top, particularly during the transient states of startup and shutdown.

Columns That Support the Upper Beams—These columns are subjected to lateral loads: i.e., pressure from wind that is transmitted through the casings, seismic forces, and flue loads. Since the columns form part of the heated enclosure, the bases must be permitted to "slide" relative to the cold steel substructure. Therefore, any friction loading results in additional column stresses.

In multicell or multichamber precipitators, interior columns are required to reasonably limit the spans of the beams. In the direction of gas flow, an interior partition ties the columns together, acting as a diaphragm. Frequently, this partition is a double wall having insulation between two panels to provide a heat break in the event one chamber is shut down. Certain designs employ bracing in lieu of panels. Placed at ninety degrees to the gas flow, the columns are either designed to be self-supporting for the full height, or use K-bracing of one form or another.

Some casings are developed as horizontal panels, with the "columns" formed by massive vertical "stiffeners."

Lower Beams—A series of lower beams (and baffles) tie the columns together, supporting hoppers in most cases.

Casing—The casing consists of stiffened panels designed to transmit pressure and wind loads to the columns. Also, external loads exerted by plenums and flues (or stub stacks) may be transmitted through the stiffeners of the casing sheets.

Roof—The casing roof consists of secondary members and a cover plate that supports the discharge system (through electrical insulators), transformer-rectifier sets, control panels, etc.

Stresses in the Structure

We must readily appreciate the possibilities of thermal stresses in a structure of the foregoing type, resulting from differential heating and cooling of the elements.

Aside from the potential for structural failure, particularly at connections, excessive deformation of the casing structure may cause misalignment of the discharge and collecting systems. If such deformation is purely elastic, internal inspection of the precipitator in the cold condition will reveal nothing. Therefore, the best protection is a rigorous and thoroughly understood design analysis, paying particular attention to deflections and thermal stresses.

It would be well to become aware of the manufacturer's design criteria prior to award of the contract, and to include a review of all stress analysis in parallel with the approval of drawings during the engineering phase of the contract.

The increased allowable stresses for A-36 steel over A-7 has tended to "lighten" structures. However, the modulus of elasticity (governing deflections) has not increased and, therefore, deflections are greater in many modern designs. As the temperature increases, the modulus decreases, so that deflections in the hot condition should be carefully examined.

Fortunately, most precipitators operate at gas temperatures below 800°F, so the phenomenon of creep rarely needs be considered. However, because of (1) marked reductions in allowable stresses, (2) the possibility of graphitization, and (3) decreased oxidation corrosion resistance in carbon steel (A-36) at temperatures in excess of about 750°F, manufacturers look to other steels for construction.

Because of availability and cost, there is a tendency in the direction of certain proprietary materials such as Corten or Mayari R as opposed to "pedigreed" alloys; i.e., those recognized by the ASME codes as acceptable for elevated temperatures.

We would recommend to the plant engineer that he carefully discuss these materials with the metallurgists employed by the suppliers. In our opinion, there is little or no structural improvement made through the use of these materials (in place of A-36) up to gas temperatures of 800°F. Actually, designs to higher stress levels, a reason for selecting Corten A, again may result in greater deflections of members.

The primary benefit of using these proprietary steels may lie in some increased resistance to certain corrosive media at low temperatures and during shutdown. Note that although the gas temperature may wisely be used as a design temperature, the metal temperatures of main structural members should be about 50 deg lower.

Inspection and maintenance of both collecting and (most particularly) discharge sytems, is (in many designs) via key-interlocked doors through the roof casing (usually one door per dust-plate section). The operator has to crawl under casing stiffeners and over and around suspension hardware. The floor of the crawl space is usually the discharge-electrode support system, with the implications of scraped shins and sore knees. Specifying minimum clearances will eliminate the competitive tendency among manufacturers to reduce casing, rapper shaft, and suspension hardware costs by providing uncomfortably low headroom. Walkways and access doors between fields are a worthwhile investment for inspection, cleaning and general maintenance of the precipitator internals.

Miscellaneous

Pains must be taken during erection of casing, collecting and discharge systems to assure alignment. However, because of the effects on deflections of the structure, final alignment should be checked after all the loads have been imposed on the precipitator. These loads must include attachment of both the inlet and outlet flues, which often impose significant forces and moments on the casing. Frequently, the precipitator erection is "completed" by one contractor, with another installing the flues at a later date. Normal fabrication tolerances may require considerable "jacking" of the materials in order to make welded connections. This process may seriously impair alignment of internals.

It is preferable that alignment be rechecked after a short period of initial operation, allowing the system a sort of "shakedown run" through a few temperature cycles, because of the possibility that some weld connections may yield plastically.

Designs that separately support inlet and outlet plenums to relieve the casing of the loads must include supports that compensate for expansion of the precipitator relative to those supports. Pressure loads on the plenum faces may transmit torsional loads onto precipitator columns, depending upon the connection design.

Roofs, Penthouses and Superstructures

Insulator-Compartment Designs—Some designs provide separate insulator compartments, with the roof casing covered by insulation, and with a walking-surface deck plate. This deck plate will be cold relative to the casing. It must be adequately supported, either through rigid insulation or metal framing, and sloped for drainage (so as to prevent water and ice accumulation).

Clearances must be provided for the movements of insulator compartments, rapper-shaft sleeves and any other equipment or equipment supports that will move as the casing and precipitator structure expands.

Designs for any of the deck plate's metallic supports that are attached to the casing must be examined for expansion provision. The criticality increases with higher gas temperatures and larger precipitator size. The exposed deck plate must be maintained watertight to prevent damage to insulation.

Penthouse—Penthouse designs extend the casing over the precipitator to form single large insulator compartments, eliminating the need for bus ducts.

The operating temperature of the penthouse is controlled by radiation and convection from the precipitator roof, conduction through the casing, and the flow of pressurizing air required to purge insulators. Heat losses depend upon the method of insulation. Frequently, the insulation is attached to the underside of the penthouse roof and to the inside of the walls so that the roof is cold steel, presenting a walking surface.

The structure is then required to absorb the expansion differential between the precipitator and the penthouse, with reactions transmitted into the casing, with a potential for causing distortion and misalignment.

Rapper shafts extending through the height of the penthouse, with rappers mounted above the roof, must be protected against any forces that may cause misalignment or binding.

If pressure testing of the precipitator shell along with the flue system is desired, it is important that the penthouse design-pressure be specified. Frequently, penthouses are designed of thinner materials than the precipitator casing. At best, pressure tests of precipitators are difficult and costly because of the many penetrations that must be temporarily sealed.

Weather Enclosures—Superstructures, or weather enclosures, may be provided to protect personnel and equipment; this will be money well spent, since it will assure maintenance inspections on a routine basis. These structures are cold, so connections to the precipitator must transmit vertical and lateral loads while also allowing for differential expansion.

Under weather enclosures, the precipitator roof is an insulated walking surface but the surface need not be weathertight (i.e., a sealed deck plate is not necessary). However, in some monolithic castable designs that fail to provide for differential movements in the casing, the penetrations and the castable do not last very long. Fissures, and the ultimate development of rubble, allow radiation and connection from the casing, which will make the area extremely uncomfortable for maintenance personnel.

Weather enclosures must be properly ventilated for both the comfort of personnel and the protection of electrical equipment and controls that are located on the precipitator roof. Undersized roof vents or gravity ridges may be less costly than liberally sized louvered blowers located along the walls; but in the long run, the operating difference will be appreciated.

Hoppers

Whether suspended from the casing or supported directly on the substructure that is interposed between the casing and the steel, hoppers are required for both collection and temporary storage of the dust. The simplest and most common hopper is pyramidal, converging to a round or square discharge. Frequently, the hoppers are baffled at the division between two dust-plate sections to prevent gas bypassing the treater.

In certain applications, where the dust is to be removed by screw conveyors, the pyramid converges to an elongated opening along the length of the conveyor. In others, where the dust agglomerates in a sticky fashion (e.g., salt cake) and has a tendency to build up on any sloping surface, the hoppers are eliminated and the casing is extended down to form a flat-bottomed box under the precipitator. The dust is removed by drag conveyors that cover the entire bottom plate.

For many applications, however, hoppers slopes will shed the dust (provided the angles are steep enough). The valley angle (the angle between the corner of the hopper and a horizontal plane) should be checked as the governing minimum slope. Although valley angles as low as 52 deg have been used successfully, for some processes, 60 deg is an often-specified minimum.

Hoppers must be kept clean and dry. Therefore, although many designs do not require vibrators (they are both costly and require maintenance), it may be prudent to examine past experience in operating plants of the same or similar process and install mounting provision for vibrators anyway (to avoid later costly removal of insulation and lagging if operation shows the need for vibrators).

Moisture-laden dust that hits cold steel hoppers, has a tendency to stick. Therefore, insulation of hoppers is vital. However, this is sometimes not sufficient, and additional heating of the hoppers may be advisable, albeit expensive.

Installing hopper heating after operation is a costly construction affair involving building of scaffolding, and removal and replacement of the insulation and lagging. Therefore, in marginal cases, provision might be made in the design of the hopper and insulation to allow for future installation of strip heaters. Other common methods of hopper heating are attachment of mineral-insulated heating cables or by installing steam tracing. These devices are best applied at initial erection.

The discharge of the hopper should be as large as practical and the inner surfaces free of all projections and rough welds. Internal ladder rungs, attached by welding to hopper walls, in addition to presenting projections for dust buildup, provide a hazard to personnel in the event of weld failure caused by corrosion or external vibrators.

When a baffle extends too far down into a hopper, there is a danger of its acting as a "choke," causing bridging between the baffle and one or both sides of the hopper. Stopping the baffle a liberal distance (say 2 ft) clear of the sloping hopper wall should not, usually, allow gas bypassing. A gas sweep under a baffle of this type, considering the pressure drop of the turn, is possibly (and even probably) a symptom of poor gas distribution to the precipitator (that is, a downward jet at the entrance).

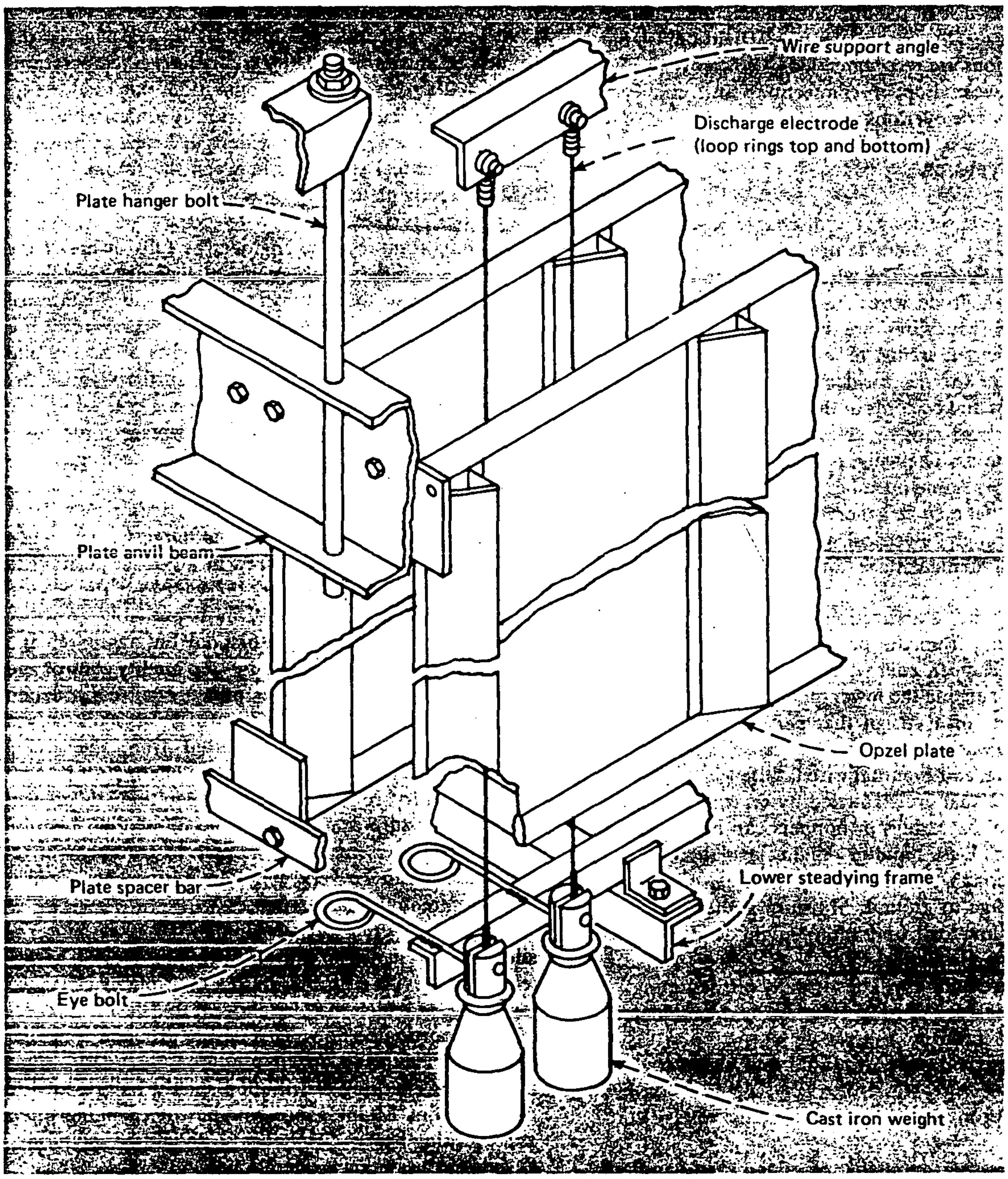
Access to hoppers should be via external, key-interlocked doors. Bolt-on doors through baffles should be avoided because of the dangerous possibility of dust accumulation on the far side of the door. Liberal "pokehole" ports should be provided to allow for clearing blockage at the discharge.

Overfilling of hoppers is a cause of precipitator problems. Dust buildup is capable of lifting discharge systems, shorting out sections, and frequently causing electrode breakage.

Level alarms are extremely valuable, provided they are kept in working order. Too often, because they are located near the top of the hoppers (even so high as to place them above the bottom of the structural steel supporting the precipitator), they are inaccessible for periodic inspection and maintenance. Also, the temperature of the atmosphere in this confined area may be sufficient to cause the alarm mechanism to fail; this is a point for critical review of details prior to installation of the instrument.

Hopper capacity should be carefully checked to provide a reasonable time for minor maintenance of the dust-removal system.

With certain types of dust, either those that are pyrophoric or contain high levels of carbon, the danger of fire increases if hoppers are allowed to overfill and smolder, up to the levels where a spark from the precipitator may ignite the mixture. The smoldering material, itself forming clinkers, may structurally damage the hopper without actually breaking out in flame. Poorly placed (or faulty) level alarms cannot be the primary cause of the damage, but the preventive alarm function is one that is certainly



DETAIL of wire-weight system precipitator electrode construction—Fig. 5

well worthwhile designing and maintaining properly.

Anywhere from 60% to 70% of the dust will be removed by way of the inlet hoppers. However, in the event of inlet-field failure, the dust load will be transferred to the next hopper downstream, and so forth. This point is particularly important in sizing both discharge systems and conveyors. As for conveyor selection, the Conveyor Equipment Mfrs. Assn. places a manual at the disposal of the plant engineer. Just a few points are worth mentioning here. There is no better assurance of performance than a liberally sized, low-speed conveyor, that normally operates at 15-45% of the trough loading, depending upon the dust. The loading should be based upon the lowest anticipated dust density.

Alignment of the conveyors is important, and to a great extent it will depend upon the alignment of hopper connections. Because of the difficulty in erecting multiple hoppers to close alignment tolerances, field-adjustable flange connections are recommended. Also, provision for expansion between hopper connections and conveyor troughs must not be overlooked.

Discharge Systems

There are two basic designs of discharge-electrode systems offered today by manufacturers.

Wire-Weight System—The wire-weight system consists of individual electrode wires suspended from an upper support-frame. The wires are best shrouded in some fashion to prevent arcing to exposed, sharp, ground edges, or where the electrical clearance is reduced by passing the tops and bottoms of the collecting dust plates. The wires are held taut by suitable weights suspended from their bottoms. The weights in turn are spaced by a guide frame. The frame must be stabilized against swinging, an action that may be generated mechanically by the gas stream, through "electrical wind," by an improperly functioning automatic voltage-control, or some combination of these.

Commonly, the stabilization is accomplished by trusses extending from the upper support-frame to the guide frame. Rapper energy, transmitted through the trusses, aids in keeping the lower guide-frames clean.

Guide frames of a design that permits dust buildup high enough to raise the weights may cause slackening of the wires, arcing, and eventual wire failure.

Guide frames that are stabilized by ceramic, or other, insulators from the casings or hoppers can be a maintenance problem. Dust buildup on the insulators during operation, although resistive in some cases, presents a source of leakage to ground. Moisture gathered during shutdown (or low-load operation) might lead to complete failure of an insulator.

Electrode wire failure will be virtually nil, assuming:

- Reasonable care, during erection, in alignment of the casings and surfaces.
- A well-designed support, guide and stabilizer system.
- Reliable, properly adjusted automatic voltage-controls.
- Good operating maintenance of the dust-handling system.

Unfortunately, there are many precipitators in which the foregoing preconditions have not been met; repeated wire failure (really the symptom, not the problem) has been the culprit in the eyes of the operators.

Rigid Wire Frame—The rigid wire frame was furnished by U.S. suppliers prior to 1950 and then virtually abandoned (in favor of the wire-weight design) because of its many reliability and operating problems. Recently, U.S. licensees of foreign manufacturers have reintroduced frame electrodes to this country, and there are quite a few modern installations both in operation and on order (as there are wire-weight designs in European plants).

The rigid frame requires a high degree of quality control, both in fabrication and erection, and is intrinsically more costly. Replacement or repair is an expensive, time-consuming undertaking. It is about the same as attempting to replace a dust-collecting plate.

At lower temperatures, up to 400°F, warpage of the frames is uncommon, but for operating temperatures above 400°F, or with cyclical operation, potential deformation of the frames becomes seriously undesirable.

The rigid frame employs wider gas lanes, or ducts, to provide electrical clearance between the frame and the dust-collecting plate. This leads to larger casings to house the required surface areas.

It is important that the engineer be fully aware of the differences and the requirements of each design philosophy in detail, so that he avoids incorrect evaluations of one versus another.

The erection sequence usually consists of casings and hoppers first, followed by collecting surfaces and, then, discharge systems. If the casings are not erected to true dimensions, plumbed vertically, and square cornered in the plan view, attempts will often be made to compensate during the installation of collecting surfaces, i.e., using guides that should be free of frictional loads as "jacks," and so forth. Then, the discharge system, which should hang freely, is stabilized in an offset position to maintain, as best as possible, the wire-to-plate centers. This kind of construction will most probably prove an operating headache from the first day on; again, this is a vital reason for in-depth, step-by-step quality control and inspection, *regardless* of the pressure of construction schedules.

Discharge systems are supported from the casing through standoff electrical insulators. These must be kept in a clean, dry condition during operation, to prevent dust- or moisture-coatings from accumulating, because such coatings present a leakage path to ground. Wet accumulations can be very common during shutdown as the moisture in the gas condenses.

Warmed, filtered pressurizing-air supplies must be adequately designed to prevent such a problem. The system must provide distribution to a multiplicity of insulators, none of which may be allowed to "starve" because of disproportionate flow. This design problem is similar to that of balancing an air-conditioning system. Some method for checking distribution should be provided to the operators. Maintenance routines of changing filters and checking heater elements also should be established as soon as the system is operational.

Most commonly used electrical insulators lose dielectric strength as temperature increases. Although the maximum temperature varies with the insulating material, 400°F is a probable limit. Therefore, it is necessary that electrical insulators be isolated thermally from hot gases. The purge-air system normally suffices, but insulators mounted on hot casing-steel may be affected by conduction, at least for several inches along the length. Fortunately, most electrical insulators retain structural strength under higher temperatures and also act somewhat as thermal insulators, so that, if the electrical path is long enough, the effect of the conducted heat is limited to a short distance up the insulator.

Collecting Surfaces

The keys to any successful collecting surface configuration are:

Dust-Plate Trueness—It is important to ensure trueness of the individual dust plate, i.e., it must be free of kinks or excessive "oil canning." This trueness will depend upon care in fabrication, the packaging for shipment, and how the surfaces are stored and handled in the field. Most manufacturers will supply complete procedural details if requested to do so.

Dust-plate bundles should be stored on edge, on closely-spaced, level dunnage that has been positioned to take the loads directly from the shipping frames on the bundles. If stored for long periods, bundles should be protected from weather.

Most damage occurs during unpackaging and raising. Supervisory experience is the best guide. Although many foremen are thoroughly competent, having been involved in the erection of other precipitators, it is wise not to leave this operation solely to the devices of the workmen. Removing a damaged dust plate after the unit is "buttoned up" is difficult and costly. Close inspection as dust plates are installed will pay dividends.

The effect of wind on deformation of surfaces during raising is minimized by dust-plate packaging designs that permit installation of entire bundles into the casing shell prior to their being opened.

Depending upon orientation of the gas inlet, high winds passing through during construction—in the direction of gas flow—may damage plates, and this may go unnoticed if inspection is not constant.

Ruggedness of the Support System (and Its Dimensional Tolerances)—This system supports the dust plates and, in many designs, must transmit rapper energy to them. Be aware that a manufacturer's "standard" design may not be sufficiently rugged for all types of rappers. The design must allow for alignment adjustment at erection and should also allow for readjustment, if necessary, after shakedown operation. Particular attention should be paid to the effects of vibration and impact loading (notch sensitivity) at all welded points.

Alignment—Sufficient, adequate spacers must be provided to maintain alignment, while also allowing for possible temperature variation between dust plates (and, of course, temperature differentials between the casings and dust plates).

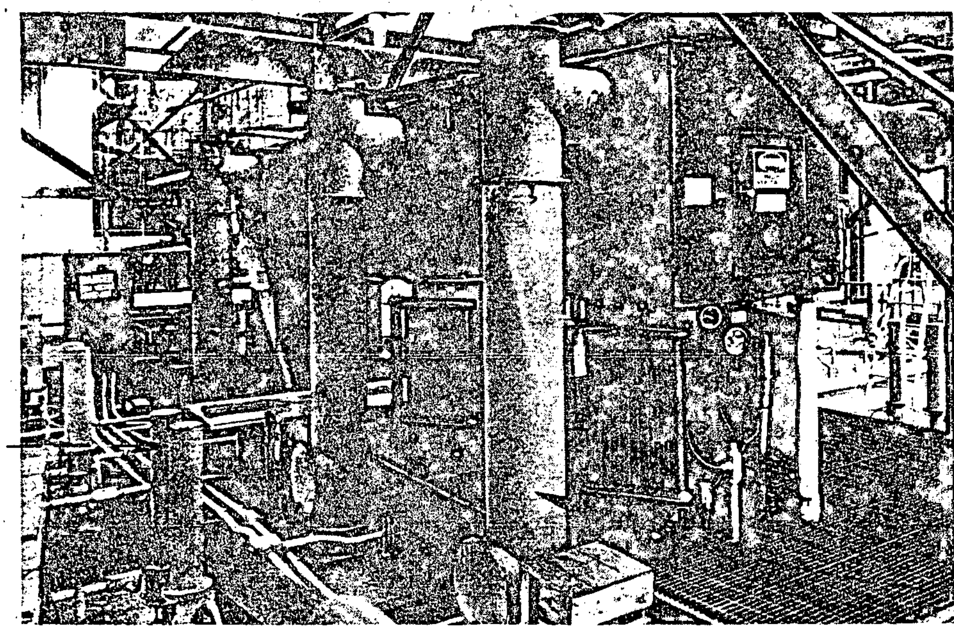
Often, the surfaces are guided at the bottom by using interior plates whose primary function is to provide a gas baffle. Such baffle plates may be somewhat thin, and may expand more than exterior casings; hence they frequently distort (or buckle). If this happens, the collecting surfaces may be pulled out of alignment through the guides.

TYPICAL transformer-rectifier (T-R) set for powering precipitator—Fig. 6

Rapper Anvils—Rapper anvils that are attached to either dust-plate supports or rapper header beams require particular attention because of the duty to which they are subjected. Since alignment is extremely critical, designs that permit bending of flanges, or other local deformations, must be questioned.

Alignment Tolerances—Beware of "tolerances" given on drawings to govern alignment unless there are full explanations of:

- How materials may be installed to those tolerances.



T-R SET, rappers and other items of precipitator equipment mounted on the roof—Fig. 7

- How inspection and checking is intended. Inspection by "eyeballing" is always somewhat subjective.
- How adjustment is provided to meet the requirements.

Baffles—The baffles between the extreme outer dust plates and the casings are necessary to prevent bypassing of untreated gases, because there are no discharge electrodes in this space.

Many designs call for such baffles to be installed after the surfaces are in and aligned. Unless there are walkways between fields (and the baffles are thus made accessible), such installation is almost impossible because of workspace limitations. Erectors often add these baffles to the casing plates while they are still on the ground, or before the dust plates are installed. The result is frequently a less-than-desirable closing of the space. Even inspection is difficult. Therefore this feature is best discussed with the manufacturer during the design stage.

Rappers

Rappers are used to remove dust from the collecting and discharge surfaces, and their effectiveness and reliability are vital. The types generally furnished are:

- Electromagnetic impulse, either single or multiple.
- Electric vibrators.
- Pneumatic impulse.
- Various mechanical hammers. These are usually associated with foreign designs but are sometimes furnished by others for special applications.

Each manufacturer has developed rapper applications for compatibility with his suspension system and rapper schedule (number of surfaces per rapper), based upon his experience and tests. Generally, pneumatic rappers will impart more energy than either electromagnetic rappers or electric vibrators, and will remove tenacious dusts more readily. However, it is important to be certain that all the hardware in the system is designed to withstand such high-energy forces. Changing from electrical vibrators to pneumatic rappers (in an attempt to improve operation) without also "beefing up" the hardware has led to structural failure.

Mechanical hammers are frequently very effective. But moving parts in the dirty gas stream become a maintenance problem. Any repairs will require shutdown of a chamber or system.

In the final installation, it is important that there is no binding of rapper shafts against casings so that the energy is directed where it belongs—to the surfaces to be cleaned. The design of rapper shafts through penthouses should be examined thoroughly with regard to the expansion differential between the penthouse and the casing.

Rapper controls should be readily adjustable for intensity, sequence and cycle time. Optimizing these for best rapper performance with the aid of a dust density meter in the outlet or stack) is a good practice.

It is prudent to check—at least once a week, but preferably once a day—that all rappers and the controls are in working order. A manual control that allows operation of one rapper at a time, coupled with an indicator panel in the main control room that monitors the automatic control, is an excellent feature. (Indicators that simply monitor power to a rapper may not tell the full story of the operation.)

Equipment on the Roof

The first-cost economics of locating automatic voltage-controls and rapper controls on the precipitator roof, or "operating floor," are attractive. However, the reliability of control elements that are subjected to the hot and generally dusty atmosphere makes it well worth evaluating the additional wiring and conduit cost that results from locating the controls in the main air-conditioned control room.

In engineering a precipitator, manufacturers may not provide a detailed layout of all of the components on the roof, thereby leaving conduit or piping runs to a contractor's judgment.

Frequently, the problems of close spacing of equipment, and of access to doors and cabinets, do not become evident until after erection. Further, the contractor tends to install the lowest-cost system possible in keeping with his specifications. This may result in an overall layout that is not conducive to good maintenance. The best protection is a concise specification and a detailed drawing study.

Although infrequent, transformer-rectifier (T-R) sets do sometimes fail. The methods of removal and replacement should be thoroughly understood and agreed upon. Again, although the first cost may be higher, transformer rectifiers located on a separate platform—with good access for removal—could be a sound investment. A spare T-R set, in storage on the platform, would make for minimum downtime after a failure.

A kilovoltmeter in the control panel of the T-R set is more indicative of what is happening in the precipitator than is a voltmeter on the transformer's primary side. When a kV meter is not provided, T-R sets may be equipped originally with provision for attaching such a meter for checking and test purposes.

Gas Distribution, Gas Proportioning, and Flues

Uniform gas distribution, with the gases entering perpendicularly to the face of the precipitator, is important to proper operation. High velocity jets may either cause erosion of dust from collecting surfaces or permit volumes of gas to move through the machine relatively untreated.

Flow-model studies (and the distribution devices installed—most often one or more perforated plates) are not always effective in developing the desired distribution. However, flow-model studies will generally not be conducted unless specified by the customer although they are at least qualitative indicators of what is going on. Unfortunately, most flow devices installed are fixed by design, so changes or adjustments require costly shutdowns.

The velocity of the gas entering the precipitator is so low, and the areas are so broad, that a pitot-tube traverse to check velocity is impractical. Instead, the most commonly used tool is the hot-wire anemometer. It would be worthwhile to allow a period in the construction schedule of two weeks to one month to allow for conducting tests and making adjustments before operation. Most programs have a time schedule that precludes this step as a luxury. If these adjustments are neglected, an equivalent period may have to be spent in making the changes after startup.

There are devices such as the "Konitest" that may be used effectively, but they require that specially designed hardware be installed initially in order to make them practical. Attention must be paid to flue designs to avoid both the close coupling that makes distribution more difficult, and surfaces that may allow for gross dust accumulation. Of what value is a flow-model study if the dust builds up for several feet on the bottom of a flue?

Any distribution device must be kept clean through adequate rapping.

Multiple-chamber precipitators require some means for gas proportioning. These are most commonly louver dampers at the outlet. Guillotine shutoff dampers at the inlet should not be used for proportioning since they tend to destroy proper gas distribution to a chamber.

During the initial layout phase of a project, attention must be given to the adequate location of test ports for both inlet and outlet sampling. After locating the ports in a section of the flue where a reasonably uniform velocity profile may be expected, it is advisable to provide proper platforms and weather protection for the test crews.

ECONOMICS

Installed Cost

The installed costs of electrostatic precipitators vary considerably, depending upon construction location, whether they are new or retrofitted, and on the season of the year. The fob. cost, however, is more-or-less predictable—it is basically a function of the area of collecting surface provided.

After the collecting-surface area has been determined (as described on p. 97), the packaging configuration is established. The package is then subjected to various constraints, such as the length-to-height ratio (L/H), the contact time, the number of fields, the gas velocity, etc. If the relationships between the quantity of gas and the package meet the criteria of past experience, that particular geometry will be priced and offered to the customer. The specific geometry is also affected by a supplier's standard modules for length, height and width.

Variations in Installed Cost

The limitations of the selection criteria as influenced by suppliers' experience, plus variations in packaging geometry, result in installed costs that vary by several hundred percent for similar applications.

Electrostatic precipitation is a mature technology wherein the fundamental principles have not changed. The changes presently occurring are in the refinement of application, such as attempts to maximize corona power, improve gas distribution, optimize rapping techniques and prevent reentrainment.

The fundamental change that has taken place in the recent past is that the technology is being required to operate at its boundary conditions, which results in exponential changes in costs. For example, older performance curves that related efficiency with cost were relatively flat and predictable in the efficiency range for which most precipitators were bought (90 to 98%). But these curves became asymptotic as the efficiency passed 99%. In these days of EPA and state regulations, one seldom sees precipitator specifications calling for less than 99% efficiency, and this is the area where prior knowledge is practically nonexistent both for performance and for cost data. This requirement imposes a need to completely understand the effects of independent variables on electrostatic precipitator efficiency.

Cost Effectiveness of Efficiency Models

The current state of the art in predicting efficiencies from the independent variables may show a 1% difference between the predicted and observed values. This is a good statistical fit, but that 1% difference at 96-97% efficiency level translates into an almost 10% difference in the precipitator's fob. cost. The same 1% difference in fit about the 99% efficiency point can result in a 25% differential in cost.

Thus, to be cost effective, there must be significant improvement in the currently used efficiency models. The current sizings generally contain a plethora of contingency and safety factors to ensure compliance with the customer's requirements. This is because the penalties for being wrong are so high that they can bankrupt a small company and seriously damage the profitability of even the very large companies. These factors have resulted in a marked tendency toward overkill in precipitator design, and most users have had to fund for significant added costs for pollution control over what they had expected.

Cost Effectiveness of Precipitator Geometry

The specific geometry of the enclosure for the collecting surface that has been specified by the efficiency model, affects the installed cost.

One precipitator supplier can produce a relatively small precipitator in 35 different "standard" combinations, to meet various application criteria. The selection of the least-cost configuration in conjunction with an improved efficiency model is necessary to provide a truly cost-effective precipitator to the users.

Operating Costs

The variables that have an effect on installed cost also can affect operating costs. The major electrical requirements are a function of the design power-density (watts per square foot of collecting surface). Power requirements range from 0.00019 kW/actual cfm to 0.00040 kW/acfm, according to a recent study of TVA installations. Additional operating costs can be incurred, depending upon the specific installation requirements. Typical requirements are as follows:

- Rapper system—1 kVA/rapper panel.
- Control and signal power—0.25 kVA/T-R control panel.
- Insulator-compartment vent system—4 kVA/compartment.

These are generally ignored in cost comparisons, as they are not significant when compared to the corona power requirements. Another general guideline is that the annual operating costs are 10% of the installed cost.

Maintenance Costs

Costs of maintaining a precipitator are influenced by relative size, efficiency requirements and design parameters. A review of TVA's costs shows a range of $0.01 to $0.03/actual cfm of gas treated. Typical items of maintenance are rappers, rapper anvils, electrode wires, ash-handling-system parts, curtains and electrical controls. #

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Reprints of this 15-page report on precipitators will be available shortly. Check No 227 on the reprint order form in the back of this or any subsequent issue. Price: $2.

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ELECTROSTATIC PRECIPITATORS IN INDUSTRY

by

Robert L. Bump

Research-Cottrell, Inc.

Electrostatic precipitators in industry

Here is an overview of the subject, touching on theory, design, sizing, controls, component reliability, efficiency, the upgrading of old equipment and the retrofitting of new, and the conditioning of gases.

Robert L. Bump, Research-Cottrell, Inc.

☐ For over half a century, electrostatic precipitation has been the method of choice to control particulate emissions at industrial installations ranging from cement plants and pulp and paper mills to oil refineries and coke ovens. In most cases, the particulates to be collected are by-products of combustion. In others, they are dust, fibers or other small solids from a production process.

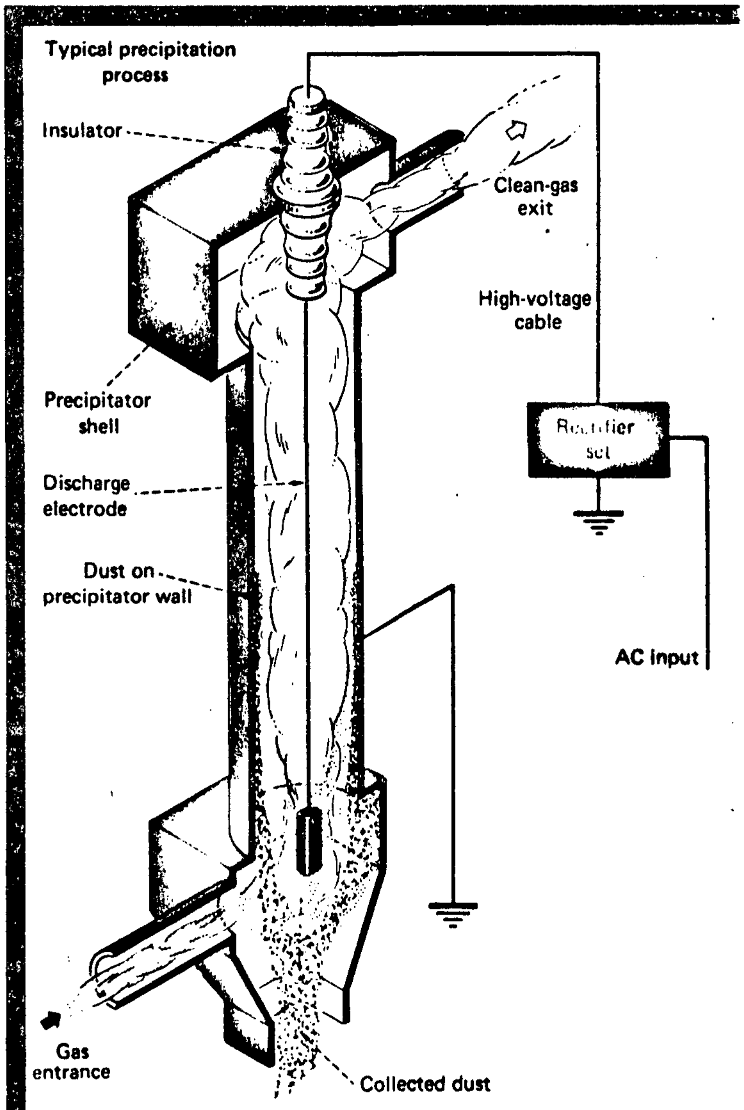
In the past decade, precipitator design—spurred by increasingly stringent emission regulations—has advanced at an especially rapid rate. Efficiencies and availability records not considered possible a few years ago are now routinely achieved. Although the geometrically accelerating cost curves associated with higher and higher purity standards are well known, the cost of precipitators has not risen exponentially as might have been expected. Why not? This article explores some of the reasons.

General precipitator design

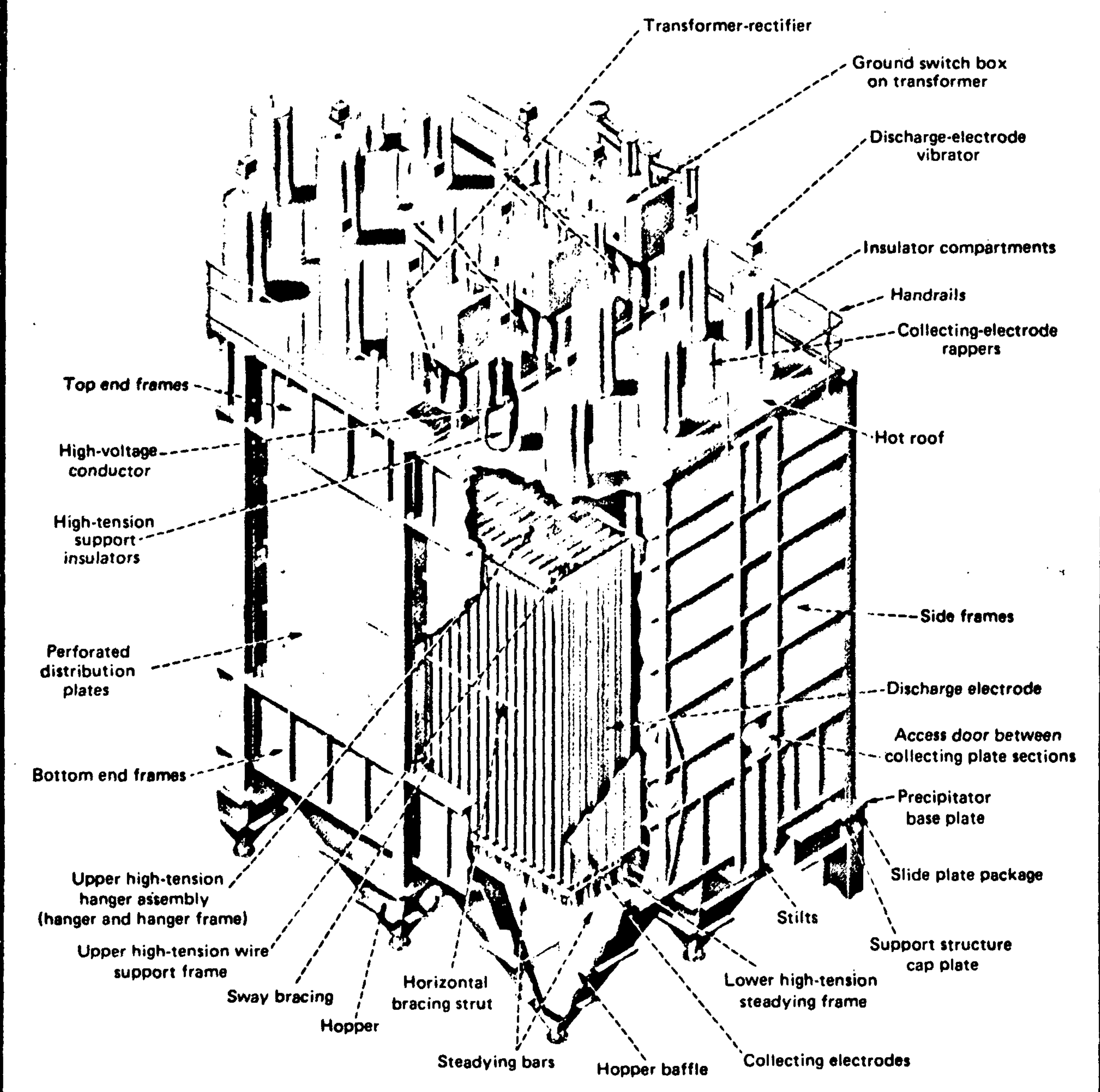
A modern precipitator system, whether it was created to treat flue gas from a heat source or to deal with particulates spilling from process streams, is likely to be far superior to any unit that could have been built 10 or 20 years ago. Among the factors underlying this superiority are these: far-more-sophisticated mathematical techniques for predicting precipitator performance; superior construction materials; computerized data banks of technical information based on 50 years or more of experience in building industrial precipitators; availability of high-quality auxiliaries such as flues, dampers and handling systems; design improvements growing both out of experience with earlier precipitators and out of accelerating research programs.

Precipitator theory

Electrostatic precipitation is a physical process by which a particulate suspended in a gas stream is charged electrically and, under the influence of the



How a precipitator removes particulates from gases that pass through it Fig. 1



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electrical field, separated from the gas stream. The system that does this (Fig. 1) consists of a positively charged (grounded) collecting surface placed in juxtaposition to a negatively charged emitting electrode. A high-voltage dc charge is imposed on the emitting electrode, setting up an electrical field between the emitter and the grounded surface. The dust particles pass between the electrodes, where they are negatively charged and diverted to the oppositely charged collecting surface.

Periodically, the collected particles must be removed from the collecting surface. This is done by vibrating or rapping the surface to dislodge the dust. The dislodged dust drops below the electrical-treatment zone and is collected for ultimate disposal.

A commercial precipitator (Fig. 2) comprises symmetrical sections of collecting surfaces, discharge electrodes, suitable rapping devices, dust hoppers, and an enveloping casing and the necessary electrical energizing sets.

Mathematics and design

One major source of improvement in precipitator design is in the sophistication of the mathematical tech-

Type of process	Fuel analysis°
Size or production rate of process	Dust analysis
Gas volume	Particle size
Temperature	Resistivity
Gas analysis	Efficiency required
Type of fuel°	Space limitations

° For particulate control on power boilers

niques employed to predict the exact size of a precipitator to handle a specific task. When emission standards were less stringent, larger margins of error were tolerable. Now that standards have risen to impose efficiencies of 99% or more, there is less room for error.

Major advances in precipitator design techniques have resulted in precipitators more precisely "tailored"—and therefore more efficient in operation—to a specific installation. The Deutsch equation, once the definitive tool for precipitator sizing, is no longer adequate to meet current demands for efficiencies well in excess of 98%. A modified Deutsch equation, now in use, factors in many of the newer practical considerations inadequately expressed in earlier theoretical approaches to sizing.

Too conservative a design produces unacceptably high equipment costs. Too "lean" a design means unacceptable operating and maintenance costs—not to mention stiff fines for out-of-compliance operation.

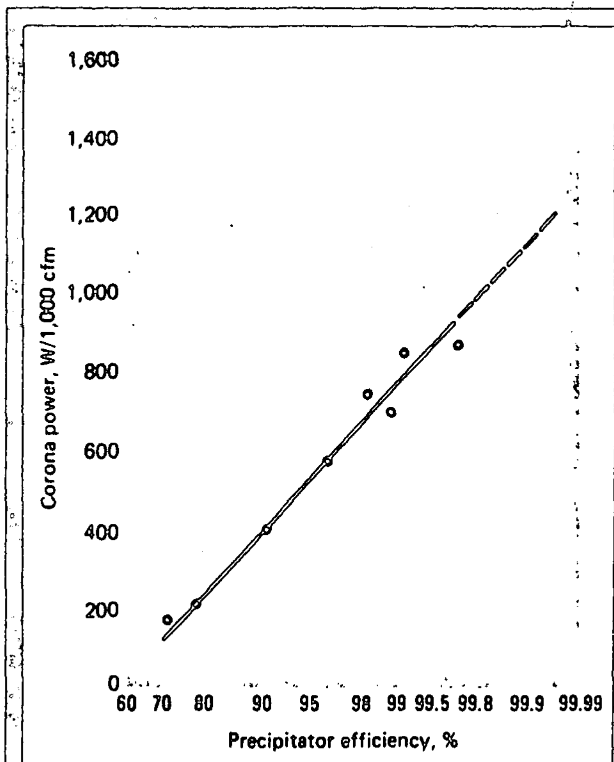
Sizing

The primary factors in precipitator sizing have been *face velocity* (the speed at which the gas travels through the precipitator), *migration velocity* (the speed at which the dust particle travels toward the plate under the influence of the electrical field) and *aspect ratio* (the ratio of precipitator height to its length).

In recent years, however, a more sophisticated approach to sizing has evolved. Extensive investigation of the relationship of process and operating variables to predicted performance, combined with a wealth of actual field experience correlating operational versus predicted performance, has been pulled together to create a central computerized bank of essential information.

From this data bank, which considers type of process, detailed particulate analysis, temperature, particle size and dust resistivity, a precipitator sizing program has been developed that generates a variety of acceptable options. If, for example, several process variations are possible (e.g., variety of fuels in a power boiler), the program considers all of them—in contrast to the old, often inadequate method of selecting a migration velocity for a single operating condition.

The modern result is a properly sized unit with less guesswork and more certainty of predictable and proper performance than ever before. Equally important, a way of mathematically modeling the effects of other alternatives is also easily available.



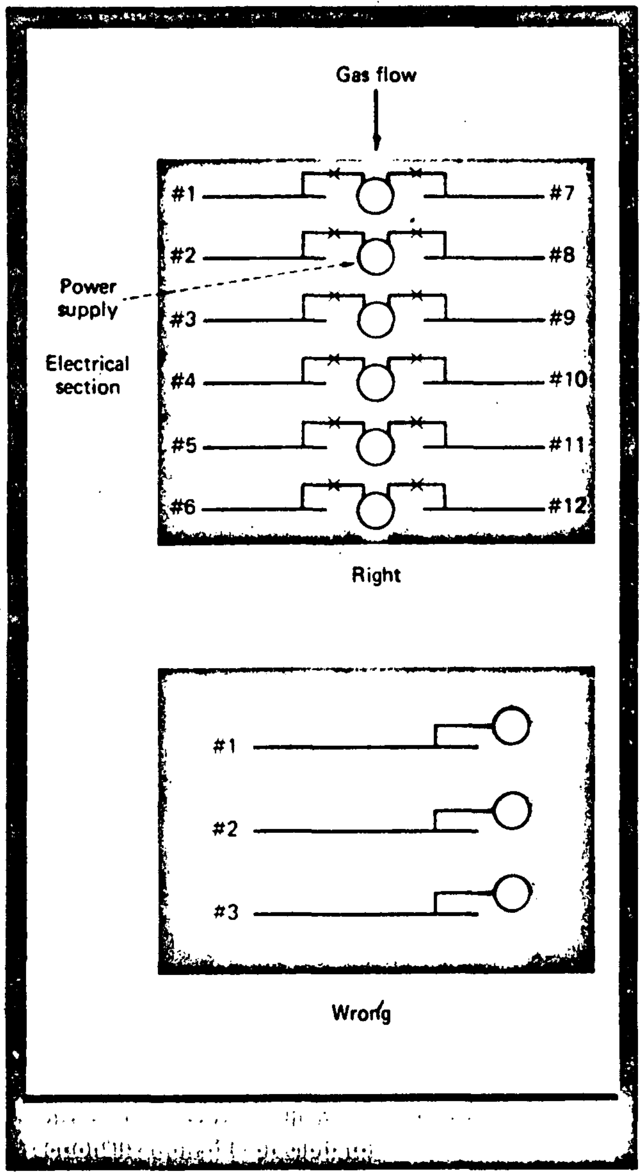
To obtain such a mathematical model, however, the purchaser must furnish detailed process information. Table I lists the minimum data required to size a precipitator. Without these data, assumptions would have to be made that might not clearly identify the pertinent points affecting the proper equipment selection. Also to be considered are operating and maintenance procedures, including specific schedules for process downtime and process-equipment inspection and reconditioning. These factors can influence original design parameters relating to cost and reliability.

Electrical sectionalization

In order to ensure optimization of power input and to afford the highest percentage of onstream reliability, the modern precipitator is divided into a substantially greater number of independent electrical sections than was previously done.

The efficiency of a precipitator is a direct function of the power input (Fig. 3). Any condition that adversely affects power input should be avoided in the basic design of the precipitator. Proper alignment and stability of the high-voltage system is essential.

Theoretically, the most efficient precipitator would be one in which each individual discharge electrode has its own power supply in order to maximize power input. This is highly impractical. However, it is both practical and advisable to have the precipitator divided into a number of separately energized electrical sections that can be individually isolated. This practice not only allows to some extent for variations and stratification in temperature, dust loadings and so forth, but



it renders a smaller section of the precipitator vulnerable to external malfunctions such as dust-removal problems. When such problems occur, one section can generally be shut down for dust removal while other sections remain onstream.

For example, today a typical 99%-efficient precipitator (Fig. 4) on a 350,000-lb/h boiler would have six separate electrical sections in series and two in parallel, each with its own power supply. Ten years ago, such an approach would not even have been considered. There would have been three large sections.

In addition, it is common practice to provide some redundancy so that outage of one or more sections does not adversely impact on efficiency.

Automated controls

A relatively new field of development is the application of sophisticated electronic measuring and control devices to precipitator control circuitry. Power is now held at an optimum level automatically and dependably, despite wide variations in gas and dust conditions.

Component reliability

Keeping the precipitator on-line requires increased reliability in the components used. To this end, research and testing is directed constantly toward upgrading existing components and developing new hardware. This includes such areas as plate and discharge-electrode designs, suspension systems, rapping processes and mechanics.

A major impetus for research in all these areas is matching component life to maintenance schedules or turnaround so that unscheduled shutdowns due to component breakdown can be avoided.

In addition, "fall-out" benefits are being realized. During one study on rapping systems, for example, cracking was noticed between rods and frames. Investigation revealed that a solid rapper rod acted as a heat sink during welding to the rapper frame and upset welding heat balance. Subsequent tests on welding techniques suggested a better way—hollow rapper rods at the welded end. Now the welded surfaces of both rod and frame respond equally to welding heat cycles. New welds exhibit 85% more resistance to cracking than those made with solid rods.

Factors affecting efficiency

In addition to the accumulation of data on precipitator sizing and design, there has been a substantial accumulation of data on operation procedures and firing practices that can cause the precipitator to lose efficiency.

Gas volume—A precipitator is a volumetric device. For example, any increase in boiler load that results in excessive flow through the precipitator will cause a loss of efficiency. A precipitator designed for 3 ft/s face velocity and an efficiency of 99% will drop to 96.5% if the velocity increases to 4 ft/s, a 33% load increase.

Temperature—A change in operating temperature may also have an effect on precipitator efficiency. Particle resistivity varies greatly in the temperature range of 200 to 400°F. Ignoring the effects of temperature on gas volume, the impact of temperature on efficiency would be, assuming 99% guarantee at 325°F (on a fly-ash application):

Temperature, °F	Efficiency, %
200	99.9+
325	99
400	99.5

Obviously, there is benefit to be derived in operating below or above the 300 to 350°F level.

Fuel—Any significant change in the type of fuel being fired will have an effect on the precipitator's performance. For example, a change from a 2%-sulfur bituminous coal to a 0.5%-sulfur, subbituminous Western coal can result in a design efficiency of 99.5% dropping to 90% or less. Other chemical constituents, such as sodium oxide, in the ash can have an effect on performance by reducing bulk resistivity.

The unit should be designed for the worst expected fuel.

Inlet loading—Since a precipitator is designed to remove a certain percentage (by weight) of the entering material, all things being equal, an increase of 50% at the inlet will result in the same increase at the outlet. Therefore, if an operating change involves an increase in percentage of dust, a corresponding increase at the outlet—resulting in greater opacity—can be expected.

Carbon—Variations in firing practice or coal pulverization that affect the quantity of combustible in the fly ash also impact on precipitator performance. Carbonaceous materials readily take on an electrical charge in a precipitator, but lose their charge quickly and are readily reentrained. Not only is the carbon particle very conductive, it is large and light compared with the other constituents making up fly ash.

These are the major variables to be considered if a deterioration in performance is to be avoided.

Age as a factor in performance

The question is often asked whether or not precipitator performance deteriorates with age. The answer, based on available operating experience, is "No;" however, there are two basic factors involved.

First, operating conditions that affect gas volume, temperature, gas and dust composition and so forth cannot be changed. Second, the precipitator must be maintained properly to the extent that the internals remain in good alignment and are adequately cleaned by the rapping system.

Meeting new clean-air standards

Assuming that precipitator performance has not deteriorated, there is still a major problem facing chemical plant operators. That is the ever-increasing stringency of clean-air codes, both new and revised, whether on the local, state or federal level. Collection efficiency requirements in the range of 99% and more are becoming the norm. Few precipitators installed before 1970 are rated this high.

To meet the new requirements, the plant operator has two choices. He can either upgrade existing equipment, or replace it with new collection equipment.

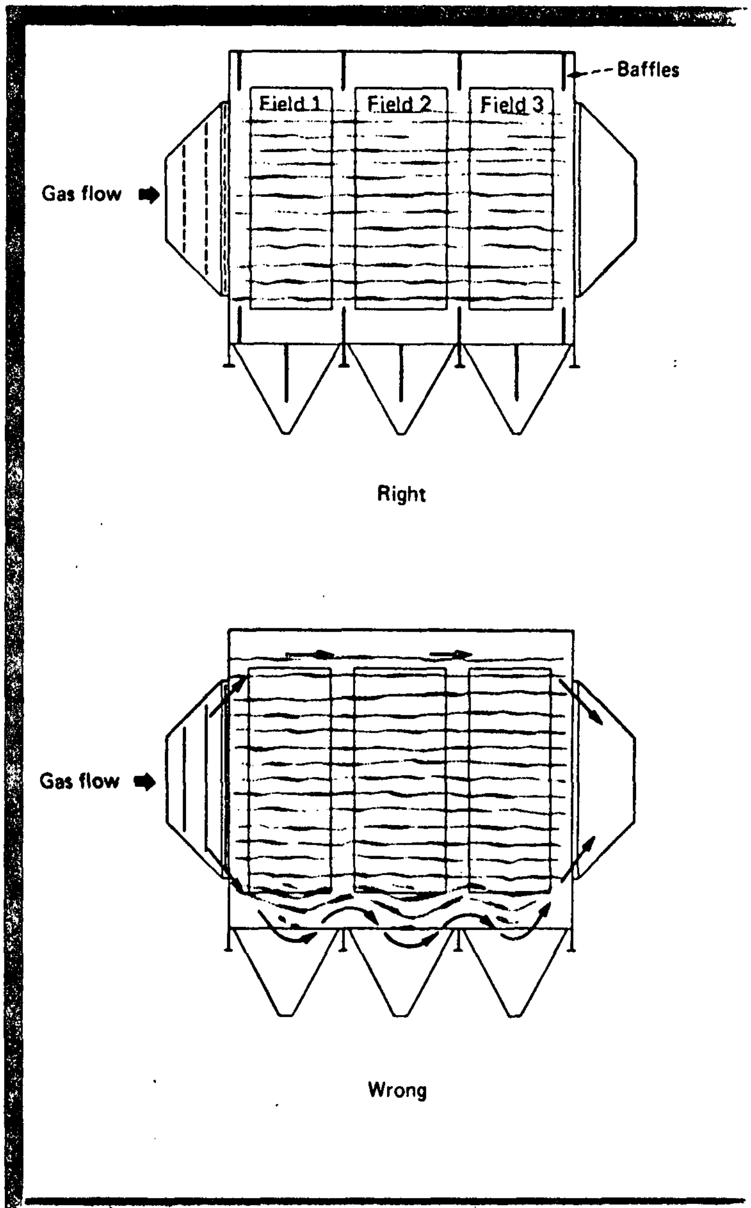
Upgrading existing equipment

Nothing short of additional equipment will yield 99% performance where 90% is installed. However, there are some areas where improvement can be obtained.

Gas distribution—Before efficiency requirements went to the 99% level, good gas distribution was not as critical as it is now. Therefore, it may be possible to improve the efficiency of older units by improving the flow pattern.

Ash conditioning—As mentioned earlier, a fuel change can result in a low or high resistivity situation, which can be controlled by injecting trace chemicals into the gas stream to make the dust precipitable. Such conditioning can have a markedly beneficial effect on collection efficiency.

Energization—Older precipitators are generally equipped with fewer electrical energizing sets than current practice dictates and may not be as responsive to varying operating conditions. To this extent, efficiency may be improved by increased electrical sectionalization.



Proper design prevents gas leakage

New equipment

The decision to install new collection equipment in series with existing equipment, or to replace the existing equipment entirely, is affected by several considerations. These include space, efficiency of the existing collection devices, their condition, pressure drop as related to possible need for a new fan and other operation considerations, and, of course, cost.

For example, assume an old, low-efficiency mechanical collector in poor condition is taking space where a new electrostatic precipitator can go. If the mechanical collector is left in place, the induced-draft fan cannot handle the pressure drop across the new equipment. In this instance, the mechanical collector should be removed and replaced with the new equipment.

In another example, a 5-yr-old precipitator is in good condition and operating at 95% efficiency. A new clean-air code calls for 99% efficiency. Since there is space downstream of the existing precipitator, the most feasible—and economical—solution is to add a new, small precipitator in series with the existing one.

Retrofitting alternatives

In some instances an existing precipitator can be made longer and higher so as to meet new requirements. However, this approach requires both a lengthy outage and the space necessary to do the modification.

Another sometimes viable approach is to "double-deck" a new precipitator over an existing unit. An alternative to this approach, assuming space is available, is to duct from the old precipitator to the new one and then double back to the existing stack.

When the precipitator is located on a building top, additional problems occur. In most cases, the building cannot support the weight of additional or new (that is, larger) equipment. This can be resolved by putting up a new support structure that penetrates the building roof and runs down to grade. An alternative solution is to, where possible, locate the new unit at grade and duct down to it.

Loss of efficiency occurs when gas bypasses the electrostatic zone in a precipitator. This can occur between the end plates and the shell, over the top of the electrical fields or in the hoppers (Fig. 5) if proper design care isn't taken.

As good flow control in a precipitator is achieved, there is a marked increase in collection efficiency. Precipitators have gone, for example, from 96% to 99.5% efficiency simply by corrections in flow control alone. Proper use of perforated plates, turning vanes and baffles is essential.

Complete and accurate information on fuel analysis and ash chemical composition is essential. The preferred data are discrete analyses, rather than merely an indication of expected ranges of constituents. With these data, the sizing program can determine the worst-case combination of constituents.

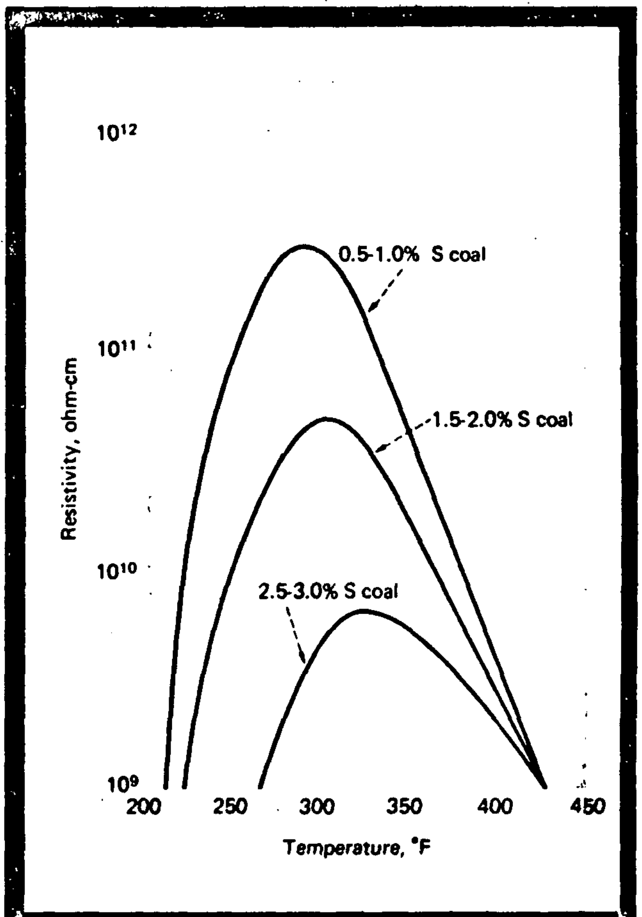
Work has also been done on cold-side sizing. Analysis of performance data on cold-side units and pilot precipitator work has indicated that there is significant deviation from the performance predicted by the commonly used Deutsch-Anderson equation at efficiency levels in excess of 98%. This led to the development of a modified equation.

In a typical example, use of the original equation would have resulted in a precipitator about 15% smaller. In addition, the program requires an identification of the boiler type, coal, mass mean particle size,* and sulfur and sodium oxide contents of the ash. Based on these inputs, the necessary collection area is indicated.

Obviously, as improvements in sizing technique develop, improvements in other design areas are necessary if precipitator efficiency is to be increased and maintained.

Gas flow distribution—Higher efficiencies demand more and more emphasis on the need for uniform gas flow. Detailed laboratory model studies are often employed to develop the most economical configuration for a new precipitator or to identify flow problems in existing installations. In many instances, a redistribution of gas flow through the precipitator can increase collection efficiency by several percentage points.

*Diameter of a particle of average mass



Component reliability—The need for continuous on-line availability has required constant attention to the development of precipitator component reliability without extensive increase in equipment costs.

As a matter of fact, developments in precipitator design have advanced to the point where buyers dealing with established, reputable suppliers can be assured that they are purchasing the system and component reliability they need.

Precipitator placement—Long-range studies of precipitators in flue-gas streams indicate that gas temperature can affect precipitator performance. In certain applications, precipitators have shown that high operating temperatures are not only feasible, but economically desirable. Hot-side application can eliminate the uncertainty about dust resistivity that can result in dew-point corrosion, poor precipitator performance and low efficiency.

Ash conditioning—Either moisture or chemical treatment of flue gas can alter the electrical properties of dust particles and enhance their "precipitability." This permits greater flexibility in the choice of fuel, and more-efficient particulate collection over a wide range of operating conditions.

The first precipitator installations were cold-side operations with flue-gas temperatures seldom exceeding 300°F. In these installations, the electrical resistivity of the ash is established by a surface-conduction mechanism sensitive to the presence of minute quantities of sulfur trioxide, sodium oxide and other hydrophilic species, as well as to the partial pressure of water vapor in the system. The quantities and interreactions of these substances are not readily predictable. Therefore, low-temperature resistivity is variable and unpredictable.

However, in recent years many installations have been made ahead of the air preheater where temperatures are in the 650 to 850°F range. In these operations, resistivity is established by bulk chemical analysis of the ash, since conduction proceeds via a volume-conduction mechanism. It has been found that the predictability of fly-ash resistivity is not only much more reliable at elevated temperatures, it is virtually certain to be within a predictable range at 650 to 850°F.

Fig. 6 shows the effect of temperature on resistivity for a given low-sulfur fuel.

Because of the accompanying decrease in gas density at the higher temperatures, requirements in the corona starting potential in hot-side precipitators is greatly reduced. In addition, the elevated temperatures have been found to reduce sparkover level. The net result is a more efficient use of the electrical power input to the precipitator.

The final area of significant difference between hot- and cold-side operation is in the physical properties of the fly ash as related first to removal from the electrodes by rapping and then to removal from the precipitator dust hopper. Experience has shown that fly ash from a cold-side, high-resistivity operation is more adhesive than hot-side ash. To keep the electrodes relatively clear of this insulating layer usually requires more intense and more frequent rapping. This, in turn, limits gas velocity to about 4 ft/s to prevent excessive reentrainment of the fly ash.

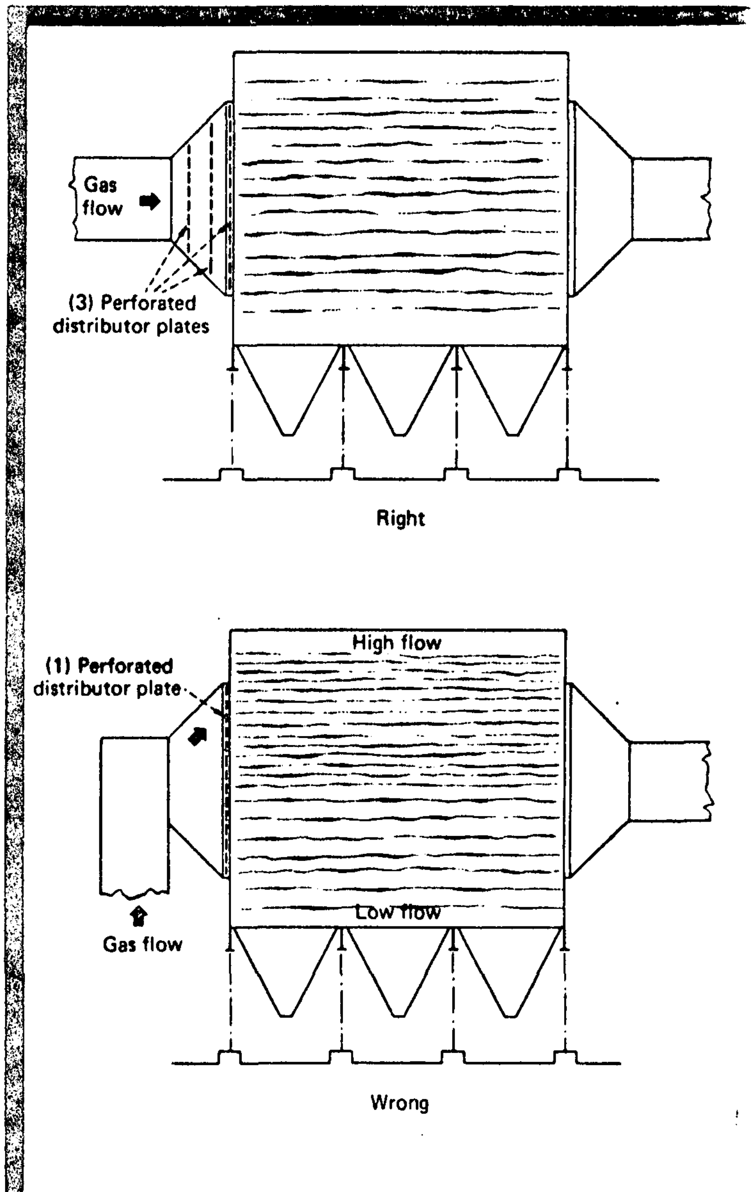
Conversely, at elevated temperatures it is commonplace today to use gas velocities in the 5 to 5.5 ft/s range.

Removal of collected ash from hoppers has sometimes been a difficult and troublesome chore on cold-side installations. Hopper plugging not only reduces precipitator efficiency but, also, can cause serious damage to the internals. This may include distortion of lower high-tension framework, bowing discharge electrodes and accelerating failures. Moreover, ash buildup in the hoppers increases possibility of dust reentrainment and loss of efficiency.

Since the fly ash in high-temperature operations is almost fluid, and the gas temperature is far above the dew point, there have been essentially no problems reported with ash handling.

Ash conditioning

To combat fuel-supply uncertainties and shortages, many plants are burning lower-sulfur fuels. These low-sulfur fuels may generate more ash and gas per Btu, and the ash has an electrical resistivity several orders of magnitude greater than that from higher-sulfur coals.



[illegible] precipitator efficiency

This, too, will affect precipitator operating efficiency. For precipitators to perform at the required degree of efficiency, these ash particles can be treated chemically to enhance their charge retention.

To accomplish this, small quantities of SO_3 are injected into the flue gas. This reduces the electrical resistivity of the fly ash, making the dust more amenable to collection in the precipitator.

By improving the electrical operation, the gas-conditioning system can significantly improve precipitator performance and minimize the need to enlarge the precipitator for low-sulfur fuels.

Such a system can also be used as an "efficiency" backup system on high-sulfur-fuel operations at a reduced capital expenditure.

There are several types of commercial SO_3 gas-conditioning systems: direct injection or evaporation of liquid SO_3; catalytic conversion of SO_3; vaporization of

Economic comparison of SO_3 gas-conditioning processes — **Table II**

Process	Capital investment, thousand dollars		Operating costs*			
			¢/lb SO_3		¢/kWh	
	250 MW	500 MW	250 MW	500 MW	250 MW	500 MW
Molten sulfur	373	565	4.70	3.76	0.008	0.006
Liquid SO_2	320	512	8.56	7.73	0.0146	0.0132
Liquid SO_3	281	441	8.92	8.00	0.0152	0.0136
Sulfuric-acid evaporation	650	1,020	7.38	6.16	0.0123	0.0103

*Based on conditioning of a low-sulfur Western-coal flue gas to an optimum resistivity level estimated at 55 ppm SO_3.

sulfuric acid; and sulfur burning followed by the catalytic conversion of SO_2 to SO_3.

SO_3 injection—The simplest system to design and build is a liquid-SO_3 conditioning system. Liquid SO_3 is readily available in commercial quantities and is clear, colorless, stable, not particularly corrosive, and has a fairly low vapor-pressure. However, it is highly toxic and requires reasonable safeguards. SO_3 is highly hygroscopic and, when dispersed in air, immediately forms an extremely dangerous sulfuric acid mist.

In operation, liquid SO_3 is first metered into a vaporizer, then air-diluted. This maintains a constant controllable volume of gas flowing through the injection manifold (which provides adequate dispersion in the flue). The mixture is conveyed in heated lines to the injection point to prevent H_2SO_4 condensation and corrosion.

Acid vaporization—In this system, sulfuric acid is heated above its boiling point, vaporized, diluted with air and then injected into the flue ahead of the precipitator. Water vapor is always present in the acid vaporization system, so a heating system is necessary to keep gas temperature above the dew point. In addition, the manifold inside the flue must be insulated to prevent corrosion and premature condensation.

Gas distribution

As recently as 10 to 15 years ago, fully one-third of the particles treated in the precipitator were treated twice because of reentrainment caused by improper gas flow within the precipitator. Because of this, precipitators were usually sized larger than would otherwise be necessary.

However, increasingly stringent collection-efficiency requirements have tightened the criteria for what constitutes "good" gas distribution. The very high collection-efficiency levels currently required are realized with a gas-distribution pattern that permits maximum utilization of the gas-treatment zone.

Nothing will downgrade overall precipitator performance as thoroughly as maldistribution of flue gases. Careful attention to design of the flue leading to and from the precipitator (as shown in Fig. 7) can create a more uniform overall gas flow within the precipitator.

Dust reentrainment from the hoppers due to improper gas flow is a frequent cause of performance deficiency in high-efficiency precipitators. Variable-porosity distribution plates, fitted at the precipitator outlet, and proper baffling inhibit those pressure gradients that would normally promote hopper sweepage. The constricting device changes resistance across the gas stream and corrects what is considered to be a little-known and often-misunderstood flow phenomenon.

Catalytic conversion—In the catalytic conversion of SO_2 to SO_3, liquid SO_2 is vaporized in a steam-heated vaporizer. This vapor is then mixed with enough air to produce a mixture containing approximately 8% SO_2 by volume. This mixture is heated in an electric heater to about 840°F, and fed to a single-stage converter. About 70 to 75% of the SO_2 can be converted to SO_3 and injected into the flue gas.

Sulfur burning—In this system, molten sulfur is pumped from a storage tank to the sulfur burner. Liquid sulfur is atomized with high-velocity air and completely burned to SO_2 in the combustion chamber. The effluent SO_2—air mixture flows out of the sulfur burner at about 1,600°F and, after cooling to 650°F in an air cooler, is converted catalytically in a one-stage bed of vanadium oxide to SO_3. Conversion efficiency is about 72%. The dilute SO_3 gas, at 1,120°F, is then transported to the precipitator distribution manifold for gas-conditioning purposes.

Table II shows an economic comparison of the processes.

In addition to economics, several other factors favor the sulfur-burning system over the others. The inert sulfur is easily handled and stored. Furthermore, the only location of a corrosive or hazardous problem is upstream of the catalytic converter.

The author

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In this position, he analyzes customers' needs and provides technical backup. He has had 30 years of experience with precipitators and related equipment. Before joining Research Cottrell, he held several engineering positions in the field of air-quality control. He holds degrees in engineering and economics.

V-4.

ELECTROSTATIC PRECIPITATOR MAINTENANCE SURVEY

APCA TC-1 Particulate Committee

Electrostatic Precipitator Maintenance Survey

APCA TC-1 Particulate Committee
Principal Author: Robert L. Bump

In the latter part of 1974, the TC-1 Committee of the APCA undertook a survey of four (4) major user industries of electrostatic precipitators. The purpose of the survey was to establish the users' degree of satisfaction with this equipment from an operational and a maintenance viewpoint. Specific areas of maintenance requirements were investigated as well as the nature of difficulty experienced. The 174 responses received covered user experience with 243 precipitators of various manufacturers. This paper reports on the results of this survey and gives the statistics derived. The conclusions reached should be beneficial to the user and the manufacturer in the areas of product improvement and maintenance.

This is the first of this type of survey handled by the TC-1 Committee, and it will be followed by Fabric Filter and Scrubber information gathering questionnaires. Problem areas so defined will be enlarged upon in future seminars planned under APCA auspices.

The Federal Clean Air Act began an era of increased public awareness of the importance of protecting our environment. Individual states and municipalities have implemented and policed the laws which have been promulgated regarding permissible emission from various processes. In addition to the ability of a specific control device to limit emissions to the prescribed level, it is also obvious that it is important that the control be consistently effective. There would be little benefit from guaranteed performance during the efficiency tests and long periods of sub-standard operation due to equipment malfunction thereafter.

In order to assess the experience of the major user industries in recent years regarding actual operation and maintenance, the APCA TC-1 Committee embarked upon a survey in 1974. This survey was confined to electrostatic precipitators and four major industries were canvassed—electric utilities, cement, paper, and metallurgical. The objective was to obtain constructive input relative to actual experience in general and in certain specific areas. This information would provide the basis for the generation of statistics and recommendations from consulting engineers and manufacturers. In addition, it provides users with an insight into whether their experience is unique or shared by others in their own and other industries.

A quick reference to a typical electrostatic precipitator will show the major components, *i.e.*, collecting surfaces on which the material is precipitated; discharge electrodes which create the high voltage, uni-directional field; rapping system which dislodges the collected material; suspension insulators which support and insulate the high voltage system; and dust removal which consists of hoppers, drag scrapers or a hydraulic mode of evacuating the dust. A malfunction in any one of these areas usually results in outage of a portion of the precipitator.

The actual survey format used is shown in Figure 1. Effort was made to keep the form as simple, yet meaningful, as possible and, at the same time, to cover the areas which are commonly acknowledged to be troublesome. Approximately 400 forms were mailed and 174 responses were received (43.5%) which pertained to 243 precipitators of various manufacturers. Sixty-three electric utilities reported on 88 precipitators; 53 cement plants reported on 70 precipitators; 36 paper mills reported on 49 units; and 22 metallurgical processes reported on 36 precipitators. The equipment reported on has been in service from a minimum of 3 months to a maximum of 50 years. Average service life was in the 7 to 10 year range. It will be noted that percentages do not add up to 100% in most cases. This reflects the failure of respondents to address every question. The results are based on total response to a specific question as a percentage of total respondents from the industry.

Figure 1. Precipitator maintenance survey form.

Company:
Location:
Application: Temperature:
Years of Service:
*Equipment Manufacturer:
Over-All Experience with the Precipitator:

Operation:	Excellent	Good	Fair	Poor
Maintenance:	Excellent	Good	Fair	Poor

Areas of Maintenance Requirement

A. Discharge Electrode Failures

Frequency:	Frequent	Infrequent	Very Seldom
Type Failure:	Fatigue	Corrosion	Arcing
Magnitude of Problem:	Major	Minor	No Problem
Type of Electrode:	Weighted	Rigid	
	Material ________	Size ________	
	Shape: Round	Square	Barbed

B. Rappers or Vibrator Failures

Frequency:	Frequent	Infrequent	Very Seldom
Type Failure:			
Magnitude of Problem:	Major	Minor	No Problem
Type of Rapper:	Pneumatic Vibrator		Make ________
	Electric Vibrator		Make ________
	Electric Impulse		Make ________
	Mechanical Rappers		Make ________
Adequacy of Cleaning:	Good Fair	Poor	

C. Collecting Plate Failures

Frequency:	Frequent	Infrequent	Very Seldom	
Type of Failure:	Connection Points	Weld	Corrosion	
Magnitude of Problem:	Major	Minor	No Problem	
Type of Plate	Roll Formed	Welded	Material	Gauge

D. Dust Removal System Failures

Frequency:	Frequent	Infrequent	Very Seldom
Type of Failure:	Screw Conveyors	Dust Valves	Pluggage
Magnitude of Problem:	Major	Minor	No Problem
Type of Dust Removal:	Screw Conveyors	Pneumatic	Hydraulic

E. Insulator Failures

Frequency:	Frequent	Infrequent	Very Seldom
Type of Failure (Cause):			
Magnitude of Problem:	Major	Minor	No Problem
Type of Insulator:	Porcelain	Silica	Alumina

What do you consider to be your major precipitator maintenance problem both from the reliability and the expense point of view. A, B, C, D or E.
Other Precipitator Maintenance Problems:

*If you have equipment of more than one manufacturer, list the names here and designate them as A, B, C, etc. in filling out the data.

The first point of inquiry had to do with overall experience with the equipment from an operational and maintenance viewpoint. The results are shown in Tables I and II. The results on an individual industry basis were reasonably consistent one to the other. It did emerge, however, that the paper and cement industries consider maintenance to be a greater problem than the others.

Table I. Operation of precipitators.

Industry	Excellent	Good	Fair	Poor
Utilities	14.8%	45.5%	29.5%	10.2%
Cement	15.7	52.9	25.7	5.7
Paper	18.4	55.1	16.3	8.2
Metallurgical	16.7	63.9	5.6	5.6
Average %	16.0	52.3	22.3	7.8

Table II. Precipitator maintenance.

Industry	Excellent	Good	Fair	Poor
Utilities	13.6%	52.3%	13.6%	20.5%
Cement	5.8	50.0	37.1	5.7
Paper	8.2	46.9	36.7	6.1
Metallurgical	2.8	69.4	19.4	0
Average %	8.6	53.1	25.9	10.3

The survey then dealt with specific areas of potential difficulty. The first had to do with failure of discharge electrodes, with results presented in Table III. Of the three major types of failure normally experienced (fatigue, corrosion, or electrical arcing), 61.7% indicated that electrical erosion (arcing) was the principal cause of failure. Corrosion and fatigue failures ranked second and third.

Table III. Discharge electrode failure frequency.

Industry	Frequent	Infrequent	Very seldom
Utilities	29.5%	38.6%	28.4%
Cement	25.7	47.1	25.7
Paper	16.3	44.9	30.6
Metallurgical	5.6	58.3	33.3
Average %	22.2	45.3	28.8
		Magnitude of problem	
	Major	Minor	No problem
	22.6%	53.1%	21.0%

Failures in the precipitator rapping system were the next point of interest. These systems are normally electric or pneumatic vibrators or electromagnetic or mechanical impact type rappers. Referring to Table IV. As would be expected, the data indicated that the vibratory type of cleaning mechanism, whether pneumatic or electric, is a higher maintenance item than the impulse type.

Collecting surfaces were the next point of interest. These are normally fabricated or roll formed of 18–20 gauge material, 24–36 ft high, suspended at the top and guided at the bottom.

Table IV. Rapper/vibrator failure frequency.

Industry	Frequent	Infrequent	Very seldom
Utilities	9.1%	38.6%	47.7%
Cement	31.4	35.8	31.4
Paper	26.5	34.7	26.5
Metallurgical	30.6	30.6	11.1
Average %	22.2	35.8	33.3
		Magnitude of problem	
	Major	Minor	No problem
	10.3%	53.1%	28.4%
		Adequacy of cleaning	
	Good	Fair	Poor
	58.4%	32.1%	5.8%

Regarding problems of collecting surface origin, the poll indicated (Table V) the major cause of collecting surface failure cited was fatigue at the points of plate suspension. Corrosion was cited as the second major cause.

Removal of dust, once precipitated, has historically been one of the major causes of precipitator malfunction, as well as a contributory factor to other maintenance requirements such as discharge electrode failure. The survey indicated, referring to Table VI, by far the majority of the problems experienced were with dust hopper pluggage. Screw conveyors and dust valves were ranked second and third.

Suspension insulators, manufactured of glazed porcelain, fused silica, or alumina oxide are used to support and isolate the high voltage elements of a precipitator. These insulators are somewhat vulnerable to failure due to electrical arc over

Table V. Collecting plate failure frequency.

Industry	Frequent	Infrequent	Very seldom
Utilities	4.5%	7.9%	68.2%
Cement	7.1	14.3	64.3
Paper	16.3	32.7	42.9
Metallurgical	19.4	11.1	33.3
Average %	9.9	15.2	56.8
		Magnitude of problem	
	Major	Minor	No problem
	17.3%	32.1%	45.3%

Table VI. Dust removal system failure frequency.

Industry	Frequent	Infrequent	Very seldom
Utilities	36.4%	42.0%	20.%
Cement	27.1	40.0	27.1
Dry paper	25.0	50.0	12.5
Wet paper	2.4	9.8	63.4
Metallurgical	16.7	38.9	25.0
Average %	24.7	35.8	30.0
		Magnitude of problem	
	Major	Minor	No problem
	24.7%	49.0%	17.3%

Table VII. Insulator failure frequency.

Industry	Frequent	Infrequent	Very seldom
Utilities	8.0%	34.1%	48.9%
Cement	4.3	44.3	45.7
Paper	10.2	46.9	36.7
Metallurgical	16.7	50.0	22.2
Average %	8.6	42.0	41.6
	Magnitude of problem		
	Major	Minor	No problem
	9.5%	49.4%	37.9%

resulting from accumulation of dust or moisture on their surfaces. The scope of this potential problem is indicated in Table VII. It is apparent that this is not a significant source of operational difficulty.

The final phase of the inquiry related to the users opinion of which of the various areas of potential trouble was the major in his experience, both from a reliability and an expense point of view. The responses, again based on 174 returns dealing with 243 precipitators in four (4) major industries, are indicated in Table VIII.

Table VIII. Major maintenance problems.

	Discharge electrodes	Rapper/ vibrator	Collecting plates	Dust removal systems	Insulators
Utilities	35.2%	5.7%	13.6%	31.8%	1.1%
Cement	34.3	25.7	11.4	34.3	1.4
Paper	20.4	34.7	16.3	4.1	6.1
Metallurgical	25.0	33.3	22.2	19.4	25.0
Average %	30.5	21.4	14.8	25.1	5.8

Conclusions

There are several conclusions which may be drawn from the results of this survey:

1. Although there is obviously room for improvement on the part of precipitator manufacturers, the majority of the users are satisfied with the precipitator as a functioning piece of equipment. Only 7.8% gave a "Poor" rating.

2. Discharge electrodes are the principal source of malfunction and the area where design expertise should be directed. This point seems to be recognized by the manufacturers and there is evidence that design improvements and developments are in progress.

3. Careful attention to the design, operation, and maintenance of the dust removal system is extremely important. It is significant to note that the industry which reported the highest incidence of discharge electrode failure also reported the highest degree of hopper pluggage. Dust build-up into the high voltage system, in addition to inhibiting efficient performance, can cause serious damage and accelerated discharge electrode failure.

The TC-1 Committee of the APCA suggests that close cooperation between user and supplier, coupled with an exchange of information between the various user industries, will ultimately result in the mutual development of an electrostatic precipitator which fills the needs of all concerned

Finally, it should be pointed out that this survey is only the beginning of a comprehensive study of experience with high efficiency collectors of various types. Moreover, the scope of data presented herein is somewhat preliminary in that considerably more detail can be derived statistically from the information received. The TC-1 Committee will continue to work with this data base and will report additional findings, conclusions, and recommendations at a future time.

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V-5.

MAINTENANCE PROGRAM AND PROCEDURES TO OPTIMIZE ELECTROSTATIC PRECIPITATORS

by

J. Katz

Precipitator Technology, Inc.

Maintenance Program and Procedures to Optimize Electrostatic Precipitators

JACOB KATZ

Abstract—The electrostatic precipitator has proven to be a highly successful piece of equipment for the removal of suspended particulate matter in the gas streams discharged from cement kilns. Whether the high collection efficiency of the precipitator will be maintained on a continuous basis can often be related to proper maintenance procedures. This paper is primarily offered as a nontechnical coverage of some problems that may face the maintenance department of a cement plant after the installation of the precipitator. Whether these problems actually arise are subject to many variables, including the thought and care given to reliability features in the original design. Discussion is presented to facilitate a better understanding of how precipitator design and kiln operating parameters can affect maintenance procedures.

PRECIPITATOR APPLICATION FOR CEMENT KILNS

General

THE MAJOR application for electrostatic precipitators in the cement industry is to collect the particulate from the gases leaving the feed or back end of the cement producing kiln. Both wet and dry process rotary kilns have utilized precipitators successfully.

Early cement kiln precipitators, prior to the recent need to meet tight environmental standards, were primarily designed for 90 percent to 95 percent collection efficiencies. This level of collection simulated the philosophy of precipitator application for other industries as well. Unfortunately, this level of design efficiency usually left little performance margin, so that the failure of single components often led to unsatisfactory stack appearances. The maintenance department was, therefore, under continuous pressure to keep all components in service.

Several points of interest are listed.

1) Low efficiency precipitators can increase the maintenance burden.

2) Physical size of the precipitator (closely related to efficiency levels) is of less concern to maintenance personnel than the integrity of its component parts.

3) As precipitators increase in size to attain greater performance levels, the need for integrity of component parts increases at a much greater rate.

These points, while appearing to be in conflict, actually stress the vulnerability of the large new precipitators to maintenance difficulties, unless extreme care is taken in the design of the component parts.

Clinker Production

The production of Portland Cement utilizes an assortment of raw materials which are dried, calcined, and formed into a clinker inside a rotating kiln. While the actual raw mix may vary greatly, the main composition consists of calcium carbonate, silica, and alumina, or shale material.

The major difference between the wet and dry processes lies in the method of grinding the raw materials, and the state of the feed that enters the kiln. The wet process grinds the raw materials in a wet state, and the slurry feed consists of 33 percent to 44 percent by weight of water. In the dry process, the raw materials are dried before grinding, and the resultant product is fed into the back end of the kiln in a nearly dry state.

Process Variables Important to Precipitation

The chemical reactions and theories about what occurs inside the kiln is beyond the scope of this paper. We are concerned, however, with the composition of the waste gases and particulate matter that enter the precipitator. The following process variables are considered important to precipitator performance and will be discussed in greater detail with regard to how they affect maintenance problems:

1) concentration of particulate in kiln gases;
2) size distribution of waste dust;
3) moisture content of kiln gases;
4) gas temperature of kiln gases;
5) alkalic and chloride content of particulate matter in kiln gases.

THEORIES AND DESIGN OF PRECIPITATORS

General

There are countless differences in the design and hardware among the various vendors of electrostatic precipitators and this writer assumes that the reader is familiar with the physical components of a precipitator. Without the use of mathematical equations the precipitator will generally increase in collection performance under the following conditions.

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1) When the area of the collecting surface is increased in relation to the gas flow rate or quantity of waste gas passing through the collector per given unit of time, the coll n performance will improve.

2) ,nversely, for any given size precipitator, reduction of gas flow rate is beneficial.

3) An increase in the physical size of the individual particles passing through the precipitator is beneficial.

4) A decrease in the viscosity of the waste gases will generally increase the collection of particulate matter if all other factors are equal. Viscosity will decrease with a reduction of gas temperature.

5) A minor increase of the electric field in the precipitator can often materially improve collection performance. The voltage fields provide the driving force for movement of particles toward the collecting surfaces.

Effect of Precipitator Size for Cement Kiln Applications

Large precipitators are synonymous with high collection efficiency. The cross sectional area is generally large enough to obtain internal gas velocities as low as 3 ft/s for the 99 percent plus levels of performance. Several factors are noted for maintenance concern.

1) With very large precipitator designs, the inlet fields will collect a large percentage of dust, and difficulties in hopper evacuation may result. This is especially important with installations having high inlet loadings—over 5 grains actual cubic feet.

2) Dust buildup can readily occur in duct work and emr hambers directly ahead of the precipitator as the gas .city decreases rapidly to levels that exist within the collector.

3) With the large precipitator, maintenance personnel must identify and define repetitive problems and solve them quickly. As stated earlier, large numbers of component parts can provide a severe maintenance headache if troubles cause a snowballing effect.

Power Input to the Precipitator

The precipitator collects material from the gas stream by using electrical forces. The object is to increase the potential difference between electrode systems in order to maintain a high charging condition. A limiting factor is the electrical breakdown of the dielectric or gas space (called a sparkover) which then becomes a localized path of high current flow at one point in the electrode system.

For reference, the energization of a precipitator can be described briefly.

1) Transformation of a low voltage supply to suitable high voltage—alternating current. (See Fig. 1.)

2) Rectification of this high voltage ac into a pulsating dc.

3) Connection of this output of the rectifier is made to an internal precipitator electrode system that is insulated from ground. This part of the precipitator is at a negative higi ential and is now the source of energization.

4 .e high potential on the negative electrode (which could be a wire with a minimum diameter of 0.10 in)

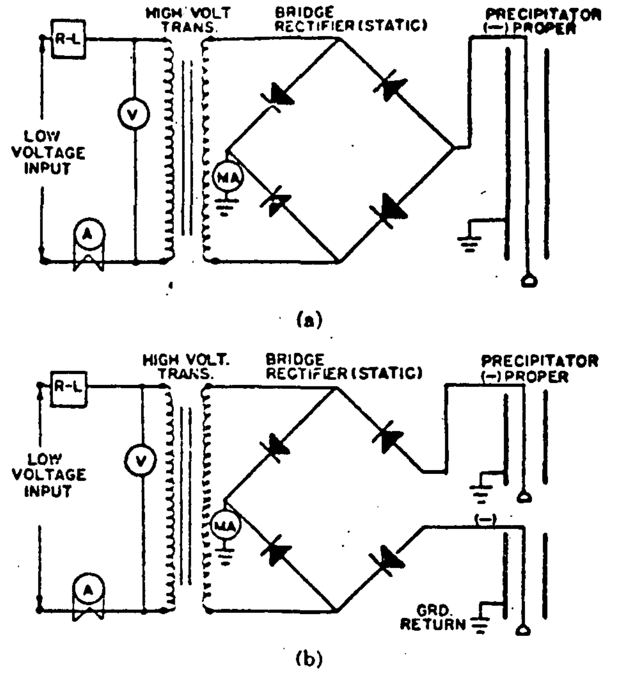

Fig. 1. Two possible rectifier circuits for electrostatic precipitators. (a) *Full-wave circuit schematic.* (b) *Double half-wave circuit schematic.*

causes a localized corona breakdown of the gas surrounding the electrode.

5) This corona sheath supplies the flow of electrons (either separately or more generally attached to gas molecules) through the gas space toward the passive electrode or collector plate which is at ground or positive potential. It is this electrical charging of particles by negative ion attachment that provides the transport mechanism for the particles to move through the gas stream to the collecting surfaces under the influence of the electric field. The distance between the 2 electrode systems can be 4 to 6 in.

6) The grounded electrode (collector plates), which also acts as the primary depositor of material collected, returns the total precipitator current to the rectifier so as to complete the electrical circuit. (See Fig. 1.)

The voltage transformers are especially designed for precipitator service with the ability to withstand winding stress when a severe sparkover occurs inside the collector. Ratings of transformers normally range from 15 to 120 kVA, with 45 000 to 55 000 secondary winding voltages and secondary output load currents to 2200 mA dc.

Modern rectifiers are of the silicon type and are usually mounted inside the transformer tank. Conversion kits are available to modify earlier installations containing rectifiers of the vacuum tube or mechanical type. One recent improvement in the control of power input has been the silicon-controlled rectifier (SCR) automatic voltage control circuit which mininizes the effect of electrical disturbances in the precipitator.

Important items of the control circuitry are the meters which monitor the variations in the electrical power input.

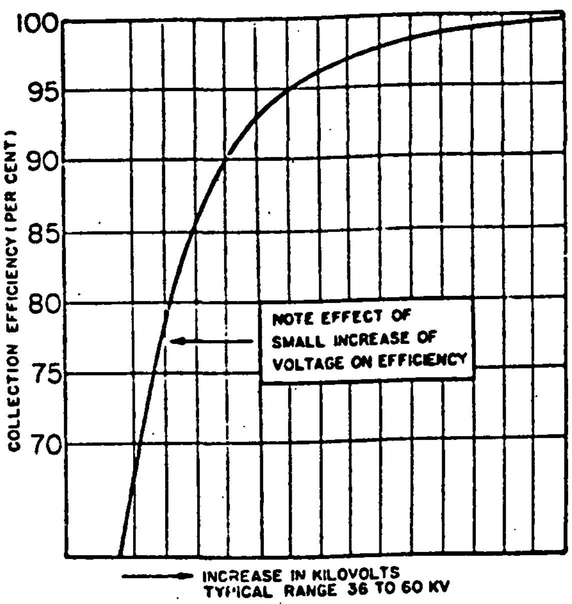

Fig. 2. Precipitator peak voltage. A typical electrostatic precipitator peak voltage versus collection efficiency curve—corona power versus efficiency curve would follow similar pattern.

The most commonly used meters are

1) voltage across the primary winding of the transformer in ac volts;
2) current in the primary winding of the transformer in ac amperes;
3) ground return current from the precipitator in dc amperes, which is usually designated as milliamperes in the smaller power supplies.

Two other meters sometimes found on control panels are

4) precipitator voltage through an appropriate voltage divider and noted as average dc kilovolts;
5) sparkmeter which integrates the electrical breakdowns in the precipitator as average sparks per minute.

The power supply must be matched correctly for the precipitator section or service expected, or several of the following difficulties can arise.

1) The impedance of the power supply, including a ballast resistance or reactor in the primary winding of the transformer, may not be sufficient to dampen the severity of the electrical breakdowns in the precipitator. This condition is especially likely to occur if the power supply rating is much larger than the operating power level.

2) If the physical size of the precipitator is too great for the size of the power supply, then the inherently lower precipitator voltages may cause decreased performance.

3) The gas and particulate conditions can drastically alter the voltage–current relationship and produce lower voltage fields than expected because of a limitation in the rating of the power supply.

High levels of voltage and useful corona power in the precipitator, all other conditions equal, will produce high collection efficiencies. Fig. 2 shows a typical performance curve of the effect on efficiency by changes in the peak voltage of a precipitator. This simple curve can only represent one situation because each precipitator will have its own characteristic curve based on many factors. The important point to remember is that small changes in voltage can produce substantial changes in power, hence, changes in the efficiency of the collector, especially at the lower levels of power input.

ELECTRICAL CHARACTERISTICS OF CEMENT KILN PRECIPITATORS

Design Characteristics

Every cement kiln precipitator will have specific electrical characteristics before the onset of gas and dust conditions. The design characteristics are primarily related to the following factors:

1) the distance between the high voltage electrode and collector surface;
2) high voltage electrode design (especially corona producing surface);
3) spacing of high voltage electrodes;
4) collector surface design;
5) power supply characteristics;
6) collector surface and electrode length related to power supply.

An important set of data which constitutes the electrical characteristics of a clean precipitator is obtained prior to the initial operation under gas and particulate conditions. This data, called air-load readings, represent precipitator sections energized without air movement and at ambient temperatures. It is best to energize the smallest possible electrical section. Sparkover should not be present at the maximum rated input of power.

Air load readings for each section provide a maintenance tool for use after each outage, especially after internal work or cleaning has occurred. Comparison of readings on identical electrical sections can isolate areas of trouble over a long term period.

Gas Conditions and Electrical Power Input

The electrical characteristics of a cement kiln precipitator under normal process conditions can show a variety of meter readings. These readings, like the air load readings, should be recorded periodically to help ascertain malfunctions and process changes. Cement kiln precipitators will generally exhibit minimal sparkovers especially for wet process applications. Usually the dry process precipitator will have sparkovers in the inlet fields or sections, and in succeeding sections as well, if moisture contents below 12 to 15 percent by volume exist in the gas stream.

To aid maintenance personnel in evaluating changes in precipitator electrical readings, the following general gui‘‾ ies should help.

1) ...e higher the gas temperature entering the precipitator, the lower the voltage will appear compared to the electrical current reading.

2) When the moisture content of the kiln gases increases, for any given condition, the voltage will also tend to increase in value.

3) If reduced voltage exists because of sparkover, a rise in moisture may allow for an increase in the precipitator voltage level.

4) An increase in the concentration of particulate will tend to elevate voltages and reduce current flow.

5) A decrease in the particle size of particulate entering the precipitator will tend to raise voltage while suppressing current flow.

6) A higher gas velocity through the precipitator will tend to raise voltages and depress currents.

7) Air inleakage may cause sparkover in localized areas resulting in reduced voltages.

8) Under gas conditions, a number of precipitator fields in series energized by individual power supplies will show varying electrical readings. The voltage–current ratio will decrease in the direction of gas flow.

MAINTENANCE EFFECTS AND ELECTRICAL READINGS

... operation factors that have been discussed earlier did not take into consideration the maintenance variables that can complicate the analysis of the voltage–current observations. This section will combine some of these factors and show the cause and effect relationship for the purpose of maintenance aid.

Alignment of Electrodes

The net effect on the electrical readings by the characteristics of the gas and particulate will often be contingent upon the proper spacing or alignment between the electrodes. Meter readings may indicate one effect, while a close spacing or even a specific electrode design will cause a spark-sensitive precipitator. The comparison of similar electrical sections in a multiunit precipitator is useful to identify internal defects. There is no substitute for careful internal measurements and inspections.

The degree of misalignment allowable in a precipitator is dependent on a number of factors. It is, however, recommended that deviations of the high voltage electrodes be kept less than ½ in from the center of a 9-in gas passage.

One misaligned discharge electrode (possibly 1 in off center) can control the power input of an electrical section containing hundreds of parallel electrodes. This particular electrode could cause electrical breakdowns of the section at r... ced voltages. With proper automatic voltage control an... pedance, this condition might continue for many months. Without proper sparkover control, the high spark rate will produce metal erosion and consequently result in electrode damage and failure.

Discharge Electrode Buildup

While the negative electrode is the source of energization, it can also develop a coating of particulate. It is not unusual to observe a 1- to 3-in diameter buildup on certain wires, for example, and at various sections of the electrode. Large wire buildups may or may not be critical on the electrical characteristics dependent on the nature of the buildup. For example, a nonuniform buildup in the shape of beads over the total length of wire will not basically alter the meter readings or precipitator performance. If however, a uniform buildup of fine particulate coats the electrode so that it simulates a wire of larger diameter, then higher voltages may be required to initiate corona current. This condition can lead to a voltage sensitive precipitator in which sparkover occurs, because the voltage gradient is too great for the physical spacing.

Collector Electrode Buildup

Particulate buildup on the collector electrode or plate will substantially affect electrical readings. A thin resistive layer can cause a spark-sensitive precipitator. If not resistive, material buildups of 1- to 2-in thicknesses can occur without an electrical breakdown of the remaining space.

Since the grounded collector plate acts as a receptor for the precipitator current, a particulate layer made up of particles that resist a passage of electrons will cause a resistive sheath to form. This layer will tend to reduce current flow (consider this an increase of dielectric between the electrodes) and can raise the indicated voltage on the meter. The term used to describe the ability of the dust layer to pass current is called resistivity. Measurements are sometimes made to help determine the resistivity value of particulate usually expressed in ohm–centimeters. The use of this number as a sole criterion of resistivity can provide erroneous conclusions because many other factors also affect the sparkover characteristic of a precipitator section. It is well to know, however, that the occurrence of sparkover, which causes lower power inputs, can be overcome by methods of process modification or gas conditioning.

It is practically impossible to operate with collector electrodes in a completely clean condition. Normally ⅛ in to ¼ in buildups will be found on the collector surface. Unfortunately, the higher resistive material will tend to have better cohesive forces holding the particles together on the collector. The case where thick buildups occur can also produce changes in the voltage–current readings. Even though the voltage gradient may be similar for wider spaces, the increase in gas velocity through the narrowed passage will decrease the overall collector efficiency. The indicated voltage for the electrical section will be lowered by the narrowed passages.

SPARKOVER CHARACTERISTICS

The level of sparkover can affect the performance of the precipitator either by quantity or severity. Usually minimal sparkovers occur on the latter (discharge end) sections of the precipitator. The sparkover should be extinguished quickly and especially not extend into a power arc of several cycles. Whether or not this condition can occur is based on the electrical design of the section and power supply.

If a spark meter is not available, the movement of the primary circuit meter needles can be used to indicate the sparkover severity. Some basic concepts are as follows.

1) When a sparkover occurs on a modern power supply, controlled at the threshhold level, both the voltage and current meter needles can dip sharply.

2) The degree of needle movement will usually depend on the ratio of the operating current to the rated current of the power supply.

3) With some automatic voltage controls and older power supplies, a sparkover will be seen by a sharp drop on the voltmeter with an equally sharp rise on the ammeter needle.

4) With a well controlled power supply at approximately 100 sparks per minute, the decay of the voltmeter may be 15 V per fluctuation.

5) At the level of 100 sparks per minute, there should be a number of cycles where the meters come to rest before the fluctuations begin again.

6) Valid readings taken during the condition of 5) should record the high point of the voltmeter and low point of the ammeter.

7) It is possible that the internal sparkover could occur on a practically continuous basis so that no meter fluctuation is seen. This condition will show an abnormally low voltage and high current.

Summary of Sparkover Conditions

Because the presence of sparkover is a fundamental occurrence in precipitators, the following key points will be summarized.

1) Minimal sparkover is usually observed in wet process precipitators. Inlet fields are most susceptable.

2) Sparkover can be prevalent in dry process precipitators. This can occur in several fields in series and possibly in all fields.

3) Sparkover will normally occur randomly within a precipitator section unless there are defects at specific locations. This can involve misalignment of electrodes or cold air inleakage. The effect of the inleakage of cold air on electrical disturbances usually depends on the magnitude of air inflow which can be more severe when the induced draft fan follows the precipitator. The inlet field is most sensitive to sparkover when sufficient air inleakage occurs between the back end of the kiln and the precipitator to dilute the moisture benefit of the gas stream. Another key factor is a discontinuity of the collector surface due to construction damage or design. A severe mal-gas distribution entering the precipitator could also sensitize a local area. Heavy dust buildups on electrodes add to sensitivity for sparkover.

4) Heavy sparkover, especially if localized, will result in electrode damage if allowed to continue over a long period of time. Power supplies with manual control are mostly vulnerable to this condition. However, automatic control of voltage, if not working properly, can also produce electrode damage.

OTHER AREAS OF MAINTENANCE

Much time was devoted to the electrical monitoring and trouble detection by the observance of sparkover characteristics. Several trouble areas of precipitators are normally first found by drastic changes in the electrical meter readings.

Buildup of Dust in Hoppers

The buildup of flue dust in a hopper will eventually contact the high voltage electrode frame and produce a grounded condition for that particular field. With automatic voltage control, the voltage will decay to zero or to some low value while the current is maintained at current limit. With manual operation of the power supply, current will generally rise to cause trip-out of the power supply.

The hopper buildup problem is considered most important because of the possible damage to the electrode system, in addition to the loss of precipitation and manhours for correction. Key points are the following.

1) Make sure the dust evacuation or removal equipment is sufficient to keep ahead of the collected material. This problem can, and usually does occur in the inlet hoppers.

2) Keep hopper side walls, especially the apex of hoppers, above the dew point of the gases. Proper insulation and heat tracing are important. Eliminate openings in insulation which may cause air movement by convection.

3) Minimize air leakage into the hopper by way of the conveyor system.

4) Design factors such as slope of hopper walls, type of corners, internal baffles, and capacity can affect maintenance difficulties.

5) Exert caution in the use of hopper sidewall vibrators if substantial dust buildup occurs in the hopper. The design of the hopper apex should include sufficient means to unplug the hopper. Once the apex of the hopper is dust free, judicial use of a vibrator or hammer blows on strike pads can dislodge any upper buildups. The use of compressed air can also be helpful.

6) Methods to detect substantial hopper buildups and even de-energize the electrical field before the dust can reach the high voltage frame is highly recommended. While it is preferable to place more emphasis on the prevention of buildup, reliable detection methods are important.

Start-up and Shutdown Problems

Periods of start-up and shutdown of the process are critical for the precipitator. It is difficult to discuss all the aspects of this important area, but the following comments should help.

1) If hopper or support insulator heater elements are available, make sure these heat sources are in operation at least three hours before start-up.

2) Ascertain the combustible level in the gas exiting the kiln before electrical energization.

3) It is generally preferable to preheat the precipitator proper to as high a temperature as possible before energization of the power supplies. Gas temperatures of 180–200°F at the exit of the precipitator are recommended. If precipitator operation is required before this temperature range is reached, it is suggested that the outlet electrical fields be energized first at low power settings.

4) Place all rapper equipment in service prior to the start-up of kiln.

5) Make sure all hopper evacuation equipment is in operation before startup of the kiln.

6) Upon shutdown of process, it is suggested that the electrical sections of precipitator be de-energized before the gas temperature falls below 200–250°F at the exit of precipitator. Initiate orderly shutdowns of the precipitator from inlet to outlet fields. Keep rappers operating at maximum intensity. Gauge the time intervals for shutdown of the power supplies to minimize the discharge from stack. Each installation may require a different procedure, but the object is to effectively clean the electrode surfaces. The operation of the induced draft fan must be considered in the procedure. Keep all conveyors and hopper systems operable.

Maintenance of Support Insulators

All insulator surfaces exposed to gas conditions provide potential electrical paths to ground in the precipitator proper. Insulators are used in the top support structure for the high voltage discharge electrode frame. Another insulator application isolates the high voltage frame rapping mechanism from ground potential. Other insulators are sometimes used at the bottom of high voltage frame to provide stabilization. The insulator is usually a tub design or post for the top support structure. Enclosures are usually made up of individual compartments for the cement industry, but enclosure designs can vary. Some points of concern are the following.

1) Energization of the precipitator without the proper protection of insulator surface conditions can lead to electrical leakage and insulator failures. Preheating of some precipitators are required to minimize this condition.

2) Whenever precipitator fields are energized from a cold start, each power supply should be tested at low power input in the manual mode of control to determine whether insulator leakage exists. This can be detected by low voltage–high current readings, with a tendency to vary sharply. The *T–R* sets should be quickly de-energized. Frequent starts and stops by trained personnel can possibly dry out the leakage paths without permanent damage to the insulator surface. Otherwise, an additional waiting period before energization is indicated.

3) Insulation of the insulator compartments and heated air blown into compartments are effective aids to minimize insulator failures. Heater strips or elements can also be used in the compartments to keep insulator surfaces above the dew point.

4) The inner surface of a tub-design insulator is exposed to gas conditons. Cleaning of this surface during shutdowns is recommended.

5) Replacement of an insulator is a critical procedure. Extreme care must be taken to prevent misalignment of the high voltage frame, and this is especially important with a two-point suspension system. An ⅛-in deviation at the top support pivot can produce a spacing problem at the bottom of the precipitator.

Rapper Maintenance

Maintenance procedures for the care of rappers can be critical for cement kiln precipitators. The object of rapping is to dislodge the collected material from the electrode surfaces with minimal reentrainment of dust into the gas stream or physical damage to the components. The failure of the rapper can often lead to electrical disturbances because of excessive material buildup on electrode surfaces. The variety of rapper designs will generally include pneumatic, impact, electrical vibration, and electromagnetic impact. Other modes of rapping can also be supplied.

Reliability of the rapper system starts with proper design by the manufacturer, but plant maintenance can often correct repetitive trouble spots. Some critical areas include the following.

1) Compressed air used for pneumatic rappers should be moisture free. For some systems, insulation of the air line exposed to cold ambient temperatures is suggested.

2) A clean ambient environment for the rapper control cabinets is especially important for apparatus such as cam timers and armature relays.

3) Periodic check and adjustment of anvil gaps of the electric vibrators may be required.

4) Check for binding of rapper shafts that extend through the precipitator shell.

5) Breakage of bolts may be due to oversized bolt holes.

6) Failures of springs or coils in the electromagnetic type of rapper sometimes occur with extended periods of high intensity rapping.

7) Every component of a rapper system exposed to gas and dust conditions should be carefully checked during each outage for wear of rotating parts, alignment of shafts, and binding at packing glands.

A maintenance program will be enhanced by a knowledge of the ramifications of rapper performance. Some key points include the following.

1) The initial pattern of rapper frequency and intensity may require modification if there is a substantial change in the process. Internal inspections and observations of electrical disturbances can determine the extent of this modification.

2) The dust buildups on electrode systems will not clean uniformly with normal rapper designs. There is rapping attenuation and harmonics that occur in any given electrode structure. The concern is that the random buildup areas do not adversely effect the electrical power input to the precipitator. It is better to add several rappers than to operate existing rappers above a feasible maintenance limit.

3) Gas, dust, and fume characteristics are critical to the effective removal of collected materials on the electrodes. High alkalie levels at certain gas temperatures can aggravate buildup problems. In this case, it may be desirable to modify the cause of the buildup rather than enlarge the rapper system.

4) The type of rapping blow can be critical. If an electric vibrator is ineffective in a certain installation, the impact blow may be found beneficial.

Failures of Electrodes

Whether failures of discharge electrodes or damage to collector surfaces occur in cement kiln precipitators depends on both design features and the process characteristics. The following comments may be beneficial.

1) Isolated failures of discharge electrodes can readily occur during the first months of operation. Fabrication or construction defects may surface during this early period. Continuous electrode failures are abnormal, and an attempt should be made to determine the cause of the failures.

2) Patterns and locations of failures should be noted. The type of failure break will indicate whether it is caused by metal fatigue or electrical erosion.

3) Repeated failures of discharge electrodes opposite obstructions on collector surfaces are indicative of electrical erosion. The presence of severe sparkover will usually coincide with this condition.

4) Corrosion of electrode surfaces will generally occur at the bottom or outer walls of the precipitator. Air inleakage may cause some localized corrosion damage.

5) If mechanical breaks are noted in the electrodes closest to the rapper mechanism, then the reduction of rapper impact is mandatory.

6) If electrode damage is noted at the bottom corners opposite a precipitator section, then the oscillation of the high voltage discharge frame may be suspect.

7) The most critical location of wire electrode failures may occur opposite the top and bottom terminations of the collector surfaces under certain design conditions.

8) The buildup of hopper dust that extends into the bottom structure of a precipitator section can produce localized electrode damage.

9) Severe temperature gradients can cause some bowing and distortion of collector surfaces.

10) The use of electrical readings and characteristics over a period of time may be important to ascertain reasons for electrode failures. Sparkover may not be tolerated on some installations depending on the degree of electric control or mechanical design.

SUMMARY

This paper is primarily offered as a nontechnical coverage of some problems that may face the maintenance department of a cement plant after installation of an electrostatic precipitator on kiln gases. Whether these problems actually arise are subject to many variables including the thought and care given to reliability features in the original design.

The following references can help plant personnel gain greater insight into the theory and application of precipitators. Remember, however, that the success or failure of any given installation will often rest on process effects, frequent comprehensive internal inspections, and correction of repetitive maintenance problems. This care can sometimes result in acceptable performance from a marginal collector.

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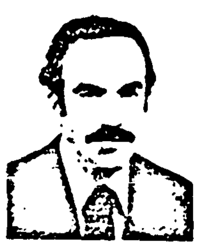

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From 1950 to 1956 he was Test and Service Engineer with Research-Cottrell, Inc., where he worked primarily on electrostatic precipitator applications. From 1956 to 1963 he was with the Duquesne Works of the United States Steel Corporation. From 1964 to 1968 he was an Adjunct Instructor of air pollution studies at the Graduate School of Public Health, University of Pittsburgh, Pittsburgh, Pa. Since 1964 he has worked as a consultant, based in Munhall, Pa., in the air pollution field. He is presently with Precipitator Technology, Inc., Munhall, Pa. His experience includes work on the evaluation and upgrading of electrostatic precipitators for the cement, utility, and iron and steel industries with specialized work in source sampling of particulate emissions from a variety of industrial processes.

Mr. Katz is a member of the Pennsylvania and National Society of Professional Engineers, the Association of Iron and Steel Engineers, the American Society of Mechanical Engineers, Power Test Code 21/27, subcommittee PTC 21/27, and committee PTC 28. He is also a member of the Air Pollution Control Association, and chairman of their committee TC-1 and subcommittee TC-1.

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OPERATIONAL MONITORING AND MAINTENANCE OF INDUSTRIAL ELECTROSTATIC PRECIPITATORS FOR OPTIMUM PERFORMANCE

by

R. L. Cunningham, P.E.

Eastman Kodak Co.

OPERATIONAL MONITORING AND MAINTENANCE OF INDUSTRIAL ELECTROSTATIC PRECIPITATORS FOR OPTIMUM PERFORMANCE

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ABSTRACT

This paper is directed primarily to operating and maintenance personnel. Designers or precipitator manufacturers also may be interested in this information. We wish to outline our experiences and our methods in order to assist others in maintaining optimum precipitator performance.

A first portion presents Kodak's expectation of operations in monitoring units and details the tools and methods we have employed. The use of voltage and current meters, opacity monitors, graphs, visual checks, and training is detailed with a view to problems and their solution.

The second portion of this paper details maintenance and its scheduling. Also, it examines several corrective actions which have been taken.

Introduction

Kodak Park is Eastman Kodak Company's largest industrial complex. Located in Rochester, New York, this photographic and chemical production facility is like a small, self-contained city. The complex provides most utility services -- steam, electric, refrigeration, compressed gases, waste disposal, waste water treatment, and telephone. More than 30,000 employees work here, in more than 200 buildings spread over 1,900 acres.

As in small cities, concerns are always present that our need for highly reliable and economical utilities -- critical in today's complex manufacturing processes -- be properly balanced by our respect for the environment, which has been of extreme importance at Kodak since the company's earliest days. This requires, among other things, that continual, reliable and optimum performance is achieved on our electrostatic precipitators (E.S.P.'s). Literature is available with general discussions recommending that units be maintained and watched closely, but there is not much detail on how this should be done. Scant help is offered on the use of monitoring procedures and equipment. There is a need for guides to continual operation and maintenance and this need has been voiced outside Kodak.

We wish to share our experiences with you in this presentation, hoping you may profit from our experiences and that we may learn from yours.

Our facilities are shown in these tables:

BOILER

Type	Steam Load (1000#/hr)
.Two Multiple Retort Underfeed Stokers	340 (Combined Load)
.Two Multiple Retort Underfeed Stokers	400 (Conbined Load)
.One Oil Fired with Forney-Verloop Burners	450
.One Oil and Coal Fired Cyclone	400
.One Oil and Coal Fired Cyclone	400
.One Oil and Coal Fired Cyclone	550
.One Oil and Coal Fired Cyclone	400
.One Refuse/Oil Tangentially Fired	150

E.S.P.

Manufacturer	Design Efficiency	Design Gas Volume (1000 ACFM)	Design Gas Temp.
Research-Cottrell	95%	181	450°F
Research-Cottrell	95%	181	450°F
Research-Cottrell	90%	162	354°F
Research-Cottrell	95%	152	330°F
Research-Cottrell	95%	152	330°F
Research-Cottrell	98.3%	204	325°F
Universal Oil Products	96.5%	161	350°F
Wheelabrator-Frye	99%	101.5	625°F

Our work includes operation, maintenance, and design modifications of these facilities. The boilers are located in three different buildings approximately 1 1/2 miles apart. The E.S.P.'s are all outdoors.

All of our units have one inlet and one outlet section. Two units will (by June 1st) have two fields and controls per section. The remaining units have only one field per section. The power sets are rated 45 kV (ave.) and from 250 to 750 mA.

Program Set-up

Continual good performance of E.S.P.'s requires more than merely checking the unit once every year via an emissions test. The units require continual monitoring since redundant parallel or series passages were not considered economical during the years these units were installed.

When we started this extra scrutiny of our E.S.P.'s we found these areas of concern:

1). A need for continual good preventive maintenance schedules.

2). A need for good communication of problems, coordination of work, and documentation of operation and maintenance.

3). A need to impress operators and maintenance personnel with their important role in maintaining clean flue gases via proper E.S.P. and boiler operation.

4). A need for training personnel in the theory, maintenance, and operation of E.S.P.'s.

5). A need to provide guides to determine whether an E.S.P. is malfunctioning or is operating at optimum efficiency.

6). A need to overcome such difficulties as having to shut down two boilers in order to maintain an E.S.P.

Management support must be present to insure commitment of effort and money. This support we have and continue to receive.

A successful "precipitator team" was formed consisting of engineers from Kodak's design group and environmental group, from the utilities development engineering group (one mechanical and one electrical), and from the utilities operating department (chairman of team). In addition, two group leaders from electrical maintenance and two representatives from the responsible operating departments were on the team. This concept worked for us because of the "do it" attitude of its members.

The team analyzed problems and solutions, made recommendations, developed awareness of the need, and monitored progress of efforts to insure continual optimal performance. Operating and maintenance procedures were written by members of the team.

Operations

The two functions that operations can perform to minimize emissions are (1) insure good combustion control and (2) monitor boilers and E.S.P.'s for signs of improper operation so that corrective action can be taken. We found that monitoring an E.S.P. was difficult because we were not sure what constituted poor performance under given conditions. If a kilovolt meter on one field said 30 kV or 50 kV, operations were unable to say "this is good or bad". To assist the Operating Department several things were done:

1). A redesigned log sheet was put in service and filled in once each trick by operations as they made checks of each unit's control room. We now record the primary volts and amps, secondary volts and amps, spark rate, opacity of the flue gas in the breeching, boiler load, flue gas temperature, and type of fuel. The electricians and an engineer in the operating department review the logs and opacity charts. Besides observing meter readings and charts, operators inspect ash handling systems to insure proper operation and to prevent high hopper-ash problems.

2). An operating procedure was written to help guide operators in monitoring and operating units.

- Graphs of flue gas opacity versus boiler load and the voltage-current characteristics of each field were made. The opacity graph (Figure 1) is a regression based on readings of boiler load versus opacity. A line parallel to the regression line, but two standard deviations above it, is drawn. Any opacity above this second line now is reported on a defective equipment report to be checked and responded to. For example, if the boiler is operating at 400,000 lbs/hr. and the opacity is 10%, a report is required (see Figure 1). This report acts as a prompter, saying "Something may be wrong, please check". The electrician or operating department engineer then tries to determine the probable cause of abnormality.

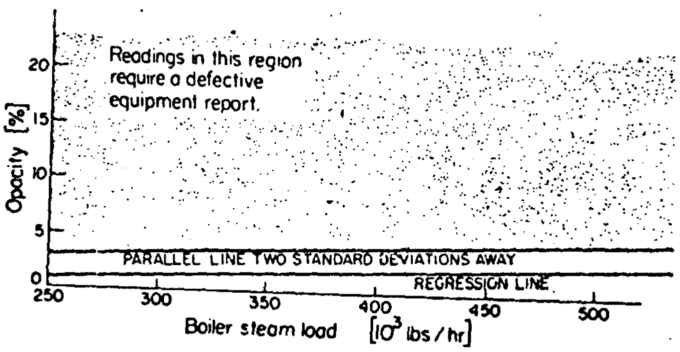


Figure 1

- The voltage-current (V-I) characteristic (Figure 2) is drawn by first obtaining voltage versus current after any maintenance shutdown (unit is clean and air is at ambient temperature) for each field; then the calculation to compensate for expected flue gas temperature during operation is made (For theory refer to text by H.J. White in bibliography, Chapter four[9].) Normal operation (with dust load) should yield V-I characteristics to the right of the temperature-compensated curve. This is caused by space charge suppression as discussed in the theory. (Caution: units with very low resistivity dust may not have their V-I operating curve suppressed to right of the temperature-compensated, theoretical curve.) Any combination of voltage and current reading to the left of this curve is reported on a defective equipment report.

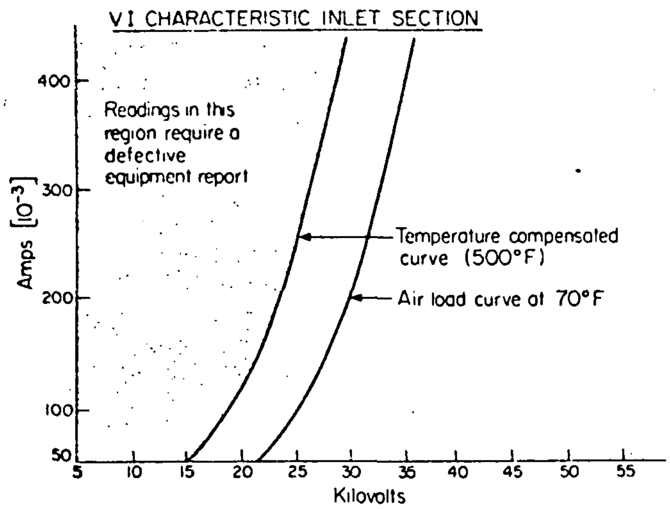


Figure 2

.The transformer-rectifier ratings are posted so that the operators can report current or voltage readings that are zero or over the ratings.

.Notification of problems is usually done with a written note on a standard form reporting defective equipment. This report is seen by operating department supervision and a utilities electrician. A reply is written down when the situation is corrected and kept on file for the given unit to document E.S.P. problems and corrective action taken.

.Kilovolts (kV) and milliamperes (mA) are currently being charted for each high-voltage bus. We have been experimenting to see if using these graphs like a Quality Control Chart is feasible. When the process level (kV or mA) changes significantly or a trend occurs, this question should be asked, "Why?". The answer may be an E.S.P. malfunction or just a significant change in boiler load or fuel characteristics (say percent ash). An example of such a graph is shown in Figure No. 3.

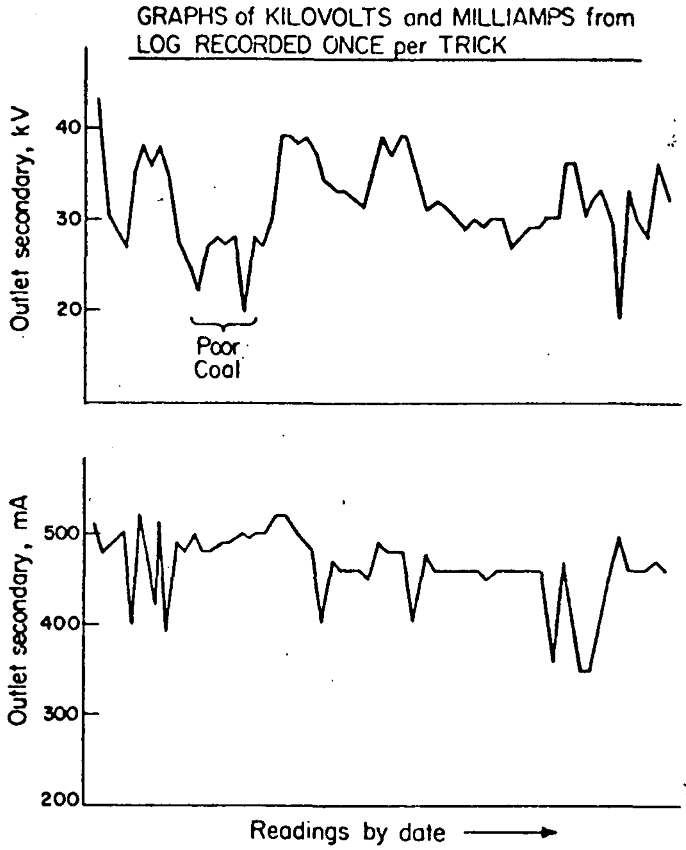


Figure 3

.In addition, operators check for abnormal noises, insure the ash handling system is functioning correctly, note high sparking conditions, check lights that indicate rapper operation, and check that air flow (at intakes) to support bushing compartments is adequate.

.All the above items are operating procedures reviewed with each shift by the operating department supervision. They included procedures to insure that warm ($>$ 225°F) dry air has been supplied to support bushing compartments for more than 30 minutes before energizing the E.S.P. during start-up.

3). Additional monitoring of the rappers, vibrators, and air supply to high voltage support bushings is done once per week via a physical inspection on the roof. A log check-off is made by the electrical operations group. This check consists of insuring that each rapper operates (in correct sequence), insuring that air pressure to bushing compartments is greater than in E.S.P., and insuring that positive nitrogen pressures are present in the high-voltage bus duct (pipe and guard) to insure dry environment on two of our units.

Maintenance

1). Maintenance electricians also examine the logs and graphs used by the operating department to check for possible problems.

2). The electricians are responsible for responding to most of the defective equipment reports indicating possible problems. Routine maintenance items such as broken wires or control circuit problems are easily handled without seeking engineering assistance.

3). Weekly checks (besides roof inspections) consist of general checks of control room and warm air system to support bushing compartments.

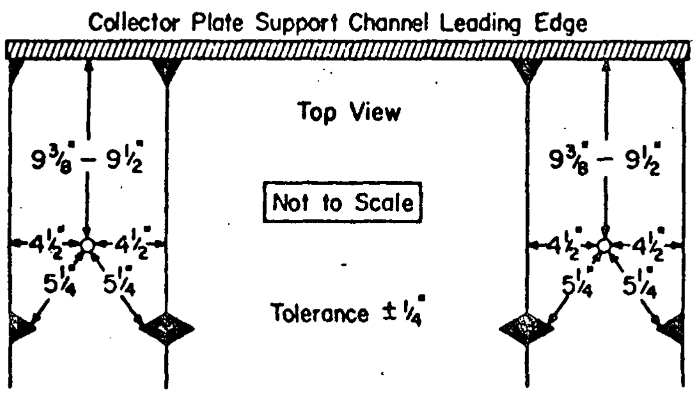
4). An annual maintenance check-list has been developed for each unit. The effort required for these checks is at least 400 labor hours per unit. An abbreviated listing is:

.Before securing the unit, check rapper operation, warm air system, and air load test (right after boiler shutdown).

.Secure and ground the E.S.P.

.Before cleaning the unit, check for grounds, failures of voltage divider stack or diodes, ash build-ups on wires or plates, pluggage of diffusion plate, and indications of arcing on (or cracks in) insulators. We use a motorized 2500 volt megger for the above electrical checks. The high voltage frame and the high voltage bus are meggered together and separately.

.After washing, make a more thorough internal inspection. Check for alignment (see Figure 4), evidence of corrosion, condition of rappers and rapper rods, structural integrity (such as condition of hanging bolts), existence of bowed or torn plates, evidence of arcing, and foreign material.



O - High voltage electrode

Figure 4

.Check and clean all insulators, replace if cracked.

.Check bus duct, warm air supply system, and all compartments for dust, moisture, tracking, or holes.

.Check transformer-rectifier for oil leaks, oil level, oil dielectric strength, oil appearance; check the surge-arrestor air gap, metering and control networks for tracking to ground, cleanliness of ground switch connections, need to replace door seals, etc.

.Check vibrators and rappers--inspect rapper boot seals and support rods, check vibrator for water, corrosion, or grounds.

.Check warm air supply fans and motors.

.Check control system -- wiring, terminals, devices, meter calibration; recondition distributor switch and timer; check diode and SCR foreward and reverse bias resistance with megger; check cabinet vent fan and motor.

.Recheck interior for foreign material, close access doors and account for <u>all</u> personnel.

.Megger frame and bus (together and separately) with 2500 V. power megger.

.Lock all doors and retrieve all interlock keys.

.Energize unit and take static air load test. Note voltage at which corona starts. Use these data to make V-I characteristic curve for each field. Double check waveforms with scope (current, voltage, and SCR firing).

.Adjust controls for optimum: voltage limit and current limit at maximum equipment ratings, spark limit at less than 100 per minute, sensivity pot to respond to sparking and not to 60 Hz line signals.

.Repair roof, if necessary, after all work is done. This is necessary to insure insulation integrity if the unit does not have pent-house or double roof.

5). Opacity monitors are checked once each month (on site) by instrument maintenance personnel. This insures blowers are operating, alignment of unit is okay, lenses are clean, etc. We have had filters made to allow calibration bench checks of units. A standard report form is being set up to record all maintenance and calibration work done on opacity monitors.

Design Changes and Problem Areas

.To assist in controlling sparking we have modified our units with Research-Cottrell's newest SCR proportional rate controller.

.We are investigating replacing some old saturable core controls with new SCR controls.

.Some of the bolts supporting the collecting plate frame have worn badly where they pass through the channel iron to which the plates are held. We have replaced these 5/8 inch bolts with 1 inch bolts.

.To prevent cracked support bushing insulators (crocks), we are modifying our warm air supply system for the support bushing compartments. In some cases this has required two fans and motors in parallel for one unit to insure a reliable air supply.

.We make sure that there is proper temperature in the insulator compartments to prevent condensation ($>$ 225°F and $<$ 500°F, for ceramic insulators). We do not energize E.S.P. while flue gas is cold and insure adequate air flow into compartment to provide positive pressure with respect to E.S.P.

.To prevent wire failures, we are using shrouds in new designs which prevent arcing at top and bottom of wire where plate stiffeners reduce clearance between plate and wire. Good gas flow is required. This may require modeling or field changes to redistribute air. Bad wires and wires where space to plate is below tolerable level are removed. These steps are essential if efficiencies of 99% (plus) are to be obtained.

.It is important that plates be inspected during delivery and erection. Flue gas temperatures greater than design specifications for the plates must not be allowed. If one bowed plate occurs, it might be possible to cut out the bad section. Another approach for correcting bowed plates is allowing the plates to hang free for several days and to straighten themselves out.

.Problems to avoid with ash systems and alarms (besides poor system) are inadequate hopper capacity to withstand short maintenance shutdowns for ash system, and nuisance ash-level alarms. We are presently making arrangements to try nuclear level detectors to eliminate nuisance alarms. High ash levels at the least short out a field and may, worse yet, completely ruin the alignment.

.Loss of insulation on E.S.P. or hoppers must be avoided. On one unit wind ripped off the insulation on the corner of an outlet section. Holes developed in the metal casing within four to five months.

.Annual maintenance has prompted:

-Placing hoists on E.S.P. roofs to get materials up and down.

-Installing public address systems to call down for assistance, and avoid repeated, long, up and down trips.

-Purchasing cement coring bits to core out solidified ash in rapper sleeves.

.Rappers and vibrators must be kept in good operating condition to optimize collection efficiency. Some rappers can actually fall apart at high rapping intensity. One style of horizontal rappers wore its circular sleeves into elipses. Cam timer contacts fail infrequently and require periodic checking. Internal hammer rapping systems seem good except for one feature: shutdown of unit is required for maintenance of hammers. Besides reintrainment, high intensity rapping may cause structural damage.

.Plate failures must be prevented to avoid long and costly shutdowns. One of our units had separation of interconnected plates and some bowing of plates that caused a baseball-size hole to be burned in one plate. Some units had shearing of plates at the top next to the stiffener. This required support rods to be installed. The vendor has a new method of fixing this problems with tapered, end-support plates. We are scheduling this repair now.

.Transformer-rectifier failures are costly and cause down time even if a spare set is available. We recommend not buying units with voltage divider resistors encased in the same oil as the transformer-rectifier. If the resistor fails, it can contaminate the transformer oil. We had one transformer failure on a unit probably caused by excessive sparking operation for many years. The controls (tube type circuit with saturable reactor in transformer primary) could not control the rapid sparking condition. This is another reason for buying the latest SCR controls. We buy transformer-rectifiers immersed in oil and not Askeral wherever possible. Oil can be reconditioned while in service and sampling and testing of oil is easier. In addition, environmental regulations on PCB's are becoming very restrictive.

.One unit had a center column failure (fortunately not complete). The column was reinforced to prevent failures. This shows the need for review of structural design with the vendor when purchasing new units.

.Roofing problems result primarily from water leaking into insulation and into the unit. Some roofs have become very thin, especially the metal around rapper sleeves. We have welded ten-inch, square, stainless-steel plates onto the roof area around these rapper sleeves. Tar paper roofing obtains many holes from heavy traffic that occurs on any overhaul of the E.S.P.

.Controls and meters sometimes fail. An oscilloscope is used to check the firing circuit. Printed circuit boards should be replaced if faulty. Develop a periodic maintenance check on these controls as with control circuits for other equipment.

.On one unit our pipe and guard protection for high voltage bus rusted away. The primary cause was being in the path of the exhaust head water vapor. We have supplied nitrogen to the bus duct, insulated the duct, and insulated the support bushing enclosure to maintain high voltage bus system integrity.

.We have had to lift rectifier apparatus out of the transformer oil two or three inches with a crane to replace low voltage bushings which have cracked. Special care to protect insulating fluid from contamination was required. Be careful in tightening the bolts on these insulators!

Training sessions for operators, maintenance personnel and engineers are required to:

1). Develop an awareness of the need for operational monitoring, maintenance, and documentation to insure optimum cleaning of flue gases.

2). Develop a better understanding of the basics of precipitator operation.

3). Develop an appreciation of the extent of environmental regulations. Many people do not realize the detailed requirements to be met in testing, in record retention, in making reports, etc. that are presently or will be in effect.

In summary, there is a very definite need for:

.Management support

.Logs to monitor E.S.P.'s

.Opacity meters to monitor E.S.P.'s

.Operating procedures

.Interpretation of logs

.Continual training for maintenance personnel and engineers

.One engineer (or group) responsible for proper E.S.P. functioning.

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V-7.

PARTICULATE CONTROL HIGHLIGHTS: AN ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

by

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ABSTRACT

Electrostatic precipitators are widely used for controlling emissions of fly ash and other dusts from industrial sources. Research on the process of electrostatic precipitation has resulted in a computerized mathematical model that can be used for estimating collection efficiency for precipitators of different designs operating under various conditions. Mathematical expressions based on theory are used for calculating electric fields and dust particle charging rates. Empirical corrections are made for non-ideal effects such as a non-uniform gas velocity distribution. The model is expected to aid in improving precipitator design and in selecting optimum operating conditions.

THE COVER:
The EPA has sponsored research to develop a computer model to predict electrostatic precipitator performance. The model is available to industry and the public upon request. A reference to the computer model is given at the end of this report.

CONTENTS

FIGURES

AN ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

The availability of high speed digital computers makes it possible for the engineer to examine complex industrial processes by constructing mathematical models of them which can be used, for example, to show the effect that a variation in a process parameter such as temperature or pressure will have on the rate or direction of the process. An example of the use of this technique is the modeling of the process of electrostatic precipitation which is used for removing dust and ash from industrial exhaust gases.

Particulate air pollution is produced by many industrial processes, such as metallurgical smelters, iron and steel furnaces, incinerators, electric power generating plants, and cement kilns. Electrostatic precipitators, sometimes called precipitators, are used in all of these industries to control air pollution.

Well designed electrostatic precipitators typically remove better than 98% of the dust in the exhaust gas they treat. The collected dust can be re-introduced into the manufacturing process, sold to other industries for raw material, or disposed of, for example, in a landfill.

One of the largest sources of industrial air pollution that must be controlled is the fly ash produced in coal fired electrical power plants. Electrostatic precipitators are widely used in the power industry and in 1976 they were used to remove an estimated 40 million tons of fly ash from coal fired boiler stack gases in the United States.

The widespread use of precipitators provided the impetus for research by the Environmental Protection Agency into the operating mechanisms of these control devices to obtain information that can be used in the design of more efficient equipment. As part of this effort, a mathematical model of the electrostatic precipitation process has been developed.

Figure 1 shows a schematic drawing of an electrostatic precipitator. The precipitator shown is typical of those which are used to collect fly ash. The dust laden flue gas enters the precipitator from the left and flows between negatively charged wire electrodes and nearby grounded plate electrodes. The wire electrode is charged to a high potential (20-40 kV) by an unfiltered dc power supply outside the precipitator housing. The applied voltage is high enough to produce a visible corona discharge in the gas immediately surrounding the wire electrodes. Electrons set free in the discharge collide with gas molecules producing gas ions that in turn collide with dust particles and give them negative charges. In the strong electric field between the wire and plate electrodes the electrically charged dust particles migrate to the plates where they are deposited, giving up their charge. Eventually a thick layer of dust builds up on the plates. With vertically mounted wire and plate electrodes the accumulated dust layer can be conveniently removed from the plate by periodically rapping it by means of an automatic hammer. The dislodged dust layer falls into hoppers in the bottom of the precipitator housing, from which it is removed for disposal. The plates continue to collect dust until they are rapped again.

Most industrial precipitators are quite large because large volumes of particulate laden flue gases must be treated. A large electric utility power boiler burning coal may require several precipitators, each of which will typically contain over 500 collection plates 10 meters high and 3 meters wide. Each precipitator will treat a million cubic meters of flue gas per hour, recover several tons of fly ash during that time, and cost perhaps $5 million. On such a scale, the need for accurate design predictions of the and geometry of precipitator components is apparent. Also, as precipitators are applied to various industrial processes, the scaling rules discovered by precipitator manufacturers for one application may not work in another.

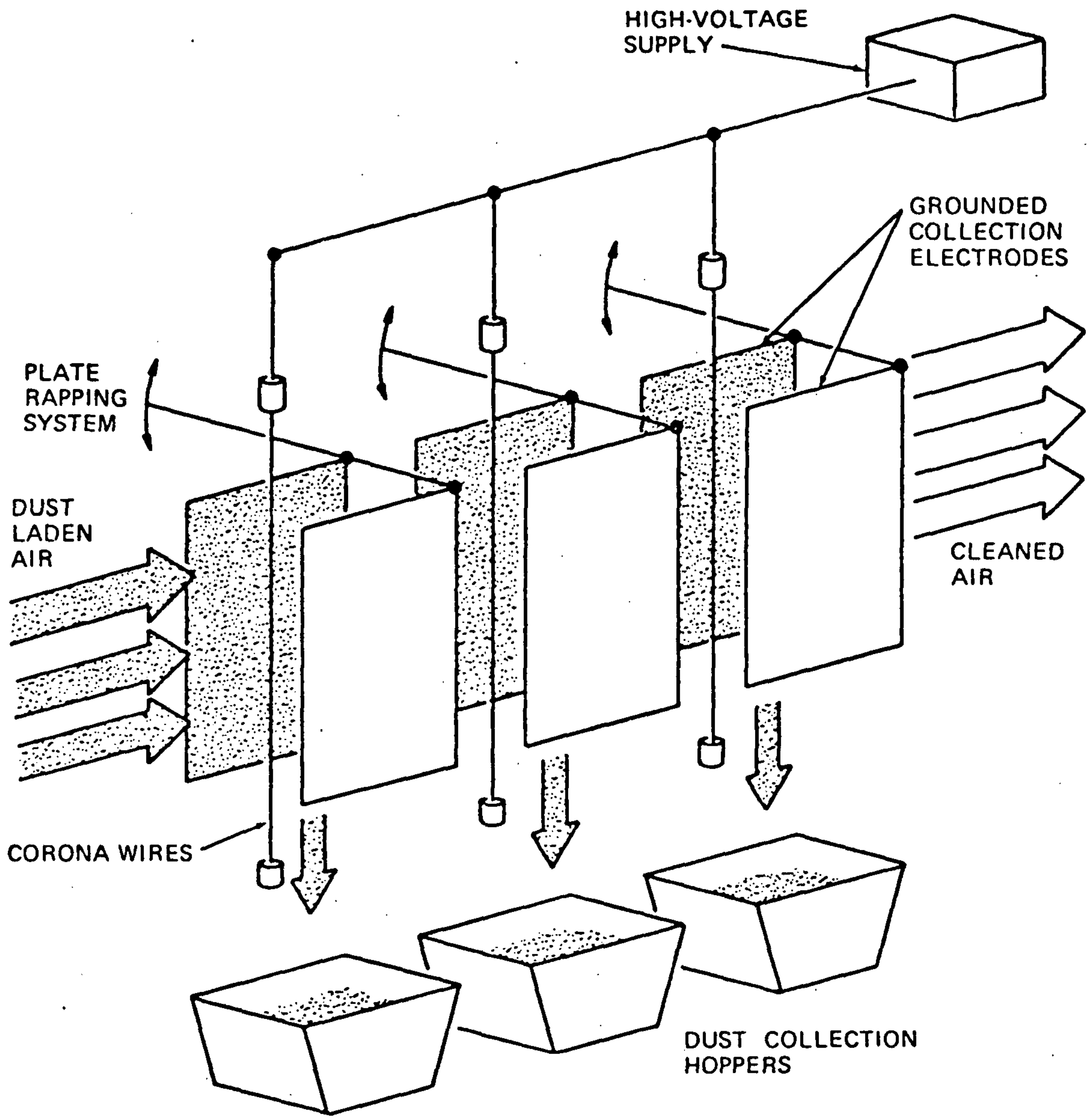

Figure 1. Schematic diagram of an electrostatic precipitator collecting dust.

MODELING A PRECIPITATOR

Most of the models that one sees are physical entities - a miniature representation of some aircraft or ship, for example. The quality of the model is in direct proportion with the accuracy which the original design is minutely reproduced. Another kind of model is the abstract construct. Thus, a theory, for example, is a model because it seeks to represent how something in nature works or acts. Instead of wood or metal, a theory is a model made up of facts, each fact pieced together with another fact until some representation of nature has been made. The quality of this model is judged by how well it predicts what nature will do in the situations that it was designed to model.

Therefore any object or phenomenon can be modeled. What is important is that the model can be either a concrete or an abstract structure. A mathematical model of some process is then no more than a representation of the process by mathematical formulae tied together with some overriding procedure or logic. This report deals with a mathematical model of electrostatic precipitation; the model is simply some fundamental theories of physical processes tied together by the logic of a computer program.

The idea of modeling the electrostatic precipitation process has great appeal if only because of economic considerations. On a more fundamental level, the modeling of any complex process is useful because it promotes an understanding which is otherwise only available from a costly "cut and try" approach.

Modeling the electrostatic precipitation process is complicated because a variety of physical phenomena must be accounted for in order to predict precipitator performance. The process is also sensitive to a number of parameters which must be accurately measured or estimated. The efficiency of particle collection for a given particle size is a function of ash or dust properties (chemical composition, resistivity, density, particle size distribution), precipitator operating parameters (applied voltage, temperature, gas composition, gas flow rate) and precipitator geometry (collecting plate area, internal dimensions).

Historically, the first aspect of precipitator performance to be studied was the effect of various precipitator operating parameters on collection efficiency. The first successful electrostatic precipitators for controlling industrial dust emissions were developed by F. G. Cottrell in 1910. Shortly afterwards, one of Cottrell's associates, Evald Anderson, recognized that the efficiency of dust collection was exponentially related to such parameters as gas velocity and collecting plate area. In 1922 the German investigator W. Deutsch put this relationship into a more comprehensive form that incorporated concepts from electrical theory. The equation developed by Deutsch predicts precipitator collection efficiency at a particular particle size for turbulent flow conditions and depends upon three parameters: the area of the grounded collection electrode, the volume flow rate of the gas passing through the precipitator, and the migration velocity of the dust particle to the collection electrode. The last of these, the migration velocity, is the net velocity of the dust particle to the collection electrode resulting from the opposition of two forces, the force of electrostatic attraction and the viscous drag of the gas, which retards movement of the particle. The migration velocity depends on the charge on the particle, the electric field near the collection electrode, the gas viscosity, the particle diameter, and an empirical correction factor called the Cunningham or slip correction factor.

The Deutsch equation is idealized in that it assumes thorough mixing of the gas due to turbulent flow, a uniform concentration of uniformly sized (monodisperse) dust particles, and a constant migration velocity for these particles. Any comprehensive modeling effort must make allowance for these restrictions. In the computer modeling scheme which has been developed, the precipitator was divided into short sections and the Deutsch equation applied to each section, over several particle size ranges.

Two other fundamental aspects of precipitator operation which must be described before any model is built are particle charging and electric field estimation, both of which are needed to find the migration velocity.

Finding the charge acquired by a dust particle in the presence of free gas ions and an electric field is a complex calculation. Briefly, there are two ways in which a dust particle can acquire charge in a precipitator. If the particle is larger than one or two microns in diameter then the applied electric field is responsible for most of the charge on the particle. This type of charging, called field charging, depends on an induced electric field to be set up on the dust particle. Then ions moving in the electric field set up on the particle are attracted to it, impact, and give it charge. The particles continue to acquire charge until the resident charge on the particle is large enough to repel the incoming ions. The particle has then reached a saturation charge and can gain further charge only by random collisions with energetic ions. This second process, the diffusion of ionic charge to dust particles, is the predominant charging mechanism for particles smaller than about one micron in diameter. For particles near one micron in size both charging mechanisms operate and the particle gains charge by field charging and diffusion charging.

Theories which describe particle charging typically do well in estimating particle charge for either diffusion charging or field charging conditions, but in the particle size range where both types of charging occur, a simple sum of the charging due to each mechanism is incorrect. A more sophisticated theory is needed. Fortunately, recent work sponsored by the Environmental Protection Agency has produced a more comprehensive theory of particle charging. This theory agrees with experiment to within 25%. For particle sizes and charging times in the range of interest for precipitator operation, the agreement with experiment is within 15%.

Figures 2 through 4 show comparisons of theory and experiment for a variety of experimental charging conditions. Figure 2 shows particle charge as a function of charging field strength for four particle sizes. Here the product of the charging ion concentration, N_0, and the time that the particle is charged, t, is equal to 1.0×10^{13} sec/m^3. This N_0t product is in the correct range for precipitator operation but is lower than a more usual value of 4×10^{13} sec/m^3. Figure 3 shows particle charge as a function of particle diameter for three charging field strengths. The value of 3.6×10^5 volts/meter is probably most representative of precipitator operation. As in Figure 2 the N_0t product is 1.0×10^{13} sec/m^3. Figure 4 shows particle charge as a function of the N_0t product for several charging field strengths; these data are for a particle diameter of 0.28 μm.

One last fundamental aspect of precipitator operation must be described before a model of electrostatic precipitation is possible. This is the

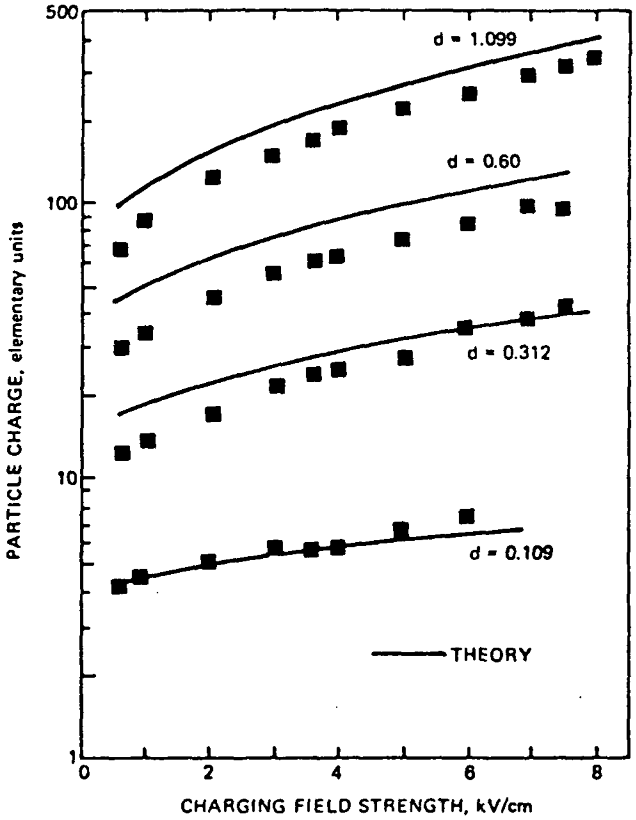

Figure 2. Particle charge vs. electric field strength for laboratory aerosols of four different diameters. $N_0t = 1 \times 10^{13}$ sec/m^3.

calculation of the electric field inside the precipitator as a function of position. A correct value of the electric field is needed to calculate both migration velocity and particle charge.

The equations which describe the behavior of the electric field in a precipitator are well known. The difficulty is their solution. Their solution is obtained by numerically solving the appropriate partial differential equations subject to the wire-plate geometrical configuration of the electrostatic precipitator. A computer program was written to perform the calculations and yield a voltage-current relationship for a given wire-plate geometry. The distribution of voltage, electric field, and charge density are also calculated by the computer program for each corona wire voltage and the associated current to the collection electrode. The agreement between theory and experiment is within 15%.

Figures 5 through 7 show how the predictions of this computer program agree with measurements made of the current density, electric field, and potential values at various places in a wire-plate electrode system. Figure 5 shows the average current density at the collecting electrode (plate) as a function of the voltage applied to the wire. In this experiment a 1.3 mm wire was used. Here the agreement between theory and experiment is excellent. Excellent agreement is also seen in Figure 6, which presents a comparison of predicted and measured potential as a function of the distance between the corona wires and the grounded collection plate. Results for two wire diameters, 1.016 mm and 0.3048 mm, are shown. Figure 7 shows the electric field at the collection plate as a function of displacement. Corona wires are located directly across from the points -10, 0, and 10 cm at the plate. Positions -5 and 5 correspond to positions at the plate, midway between corona wires. Again, the agreement with theory is good, and within 8%.

Now a computer model of the electrostatic precipitation process can be constructed. The

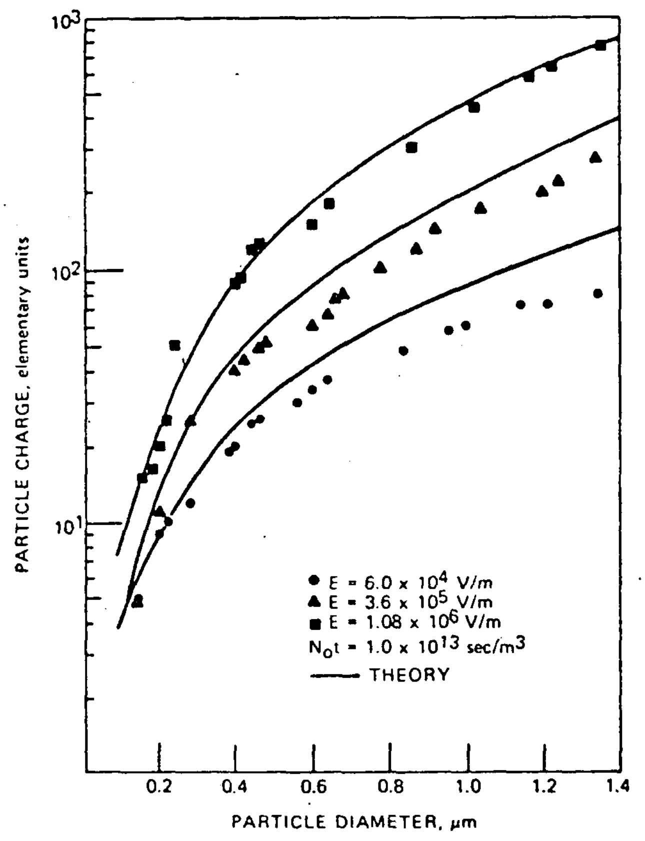

Figure 3. Particle charge vs. diameter for three values of electric field.

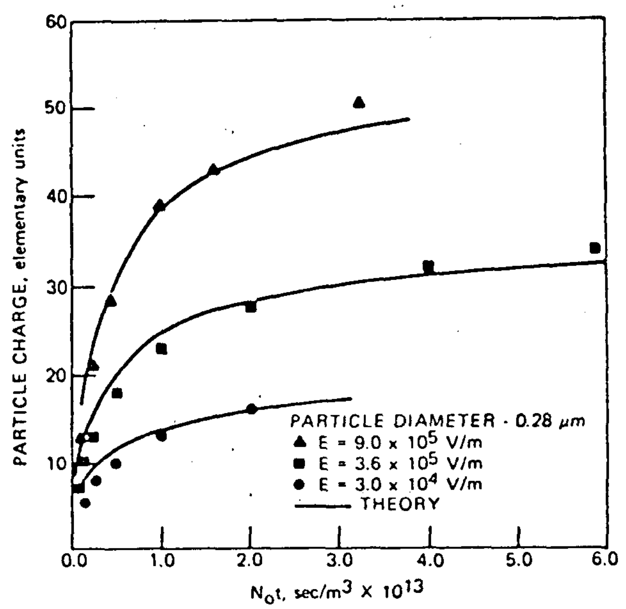

Figure 4. Particle charge vs. N_0t for three values of electric field.

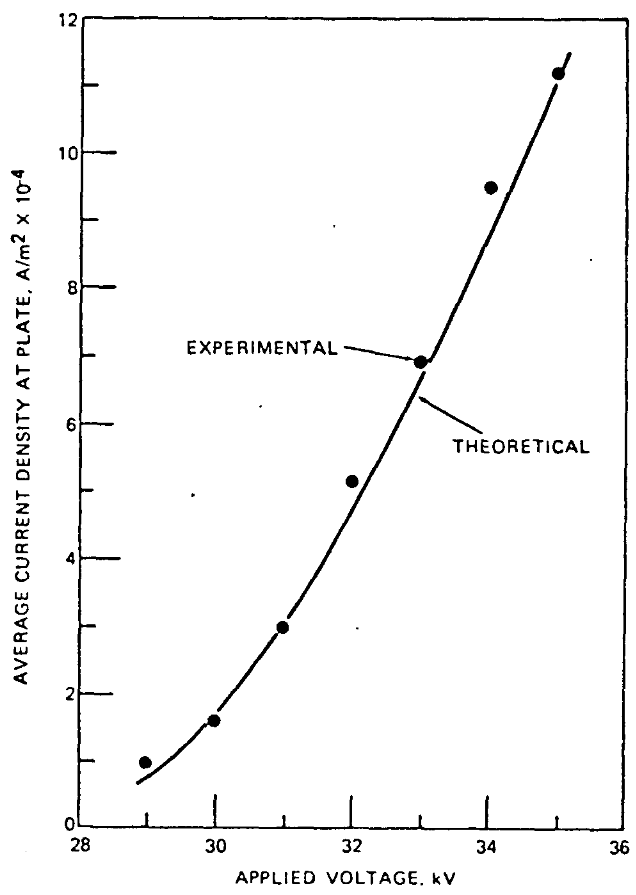

Figure 5. Average current density at the collection plate vs. the corona voltage.

computer model is simply a codified procedure which uses a mathematical description of each of the fundamental aspects of precipitator operation discussed above to predict the behavior of an actual precipitator. As discussed above, the method used is to break the precipitator into many small sections. As the simplified flow diagram, Figure 8 shows, the particle-size distribution entering the precipitator is broken down into a number of narrow size bands with a median particle size calculated for each band. Calculations are made separately for each size band as the dust moves through the segmented precipitator. In each segment of the precipitator, the electric field, particle charge, migration velocity, and collection efficiency are calculated for the median particle size and the percent collected is subtracted from the concentration entering that segment. This procedure is repeated for the next and each succeeding segment until the entire precipitator has been traversed. In this way each size band passes through the simulated precipitator and an overall collection efficiency is found for the various median sizes. The precipitator has then been modeled. That is, its collection efficiency has been predicted over the range of particle sizes which experiment has shown that it must collect.

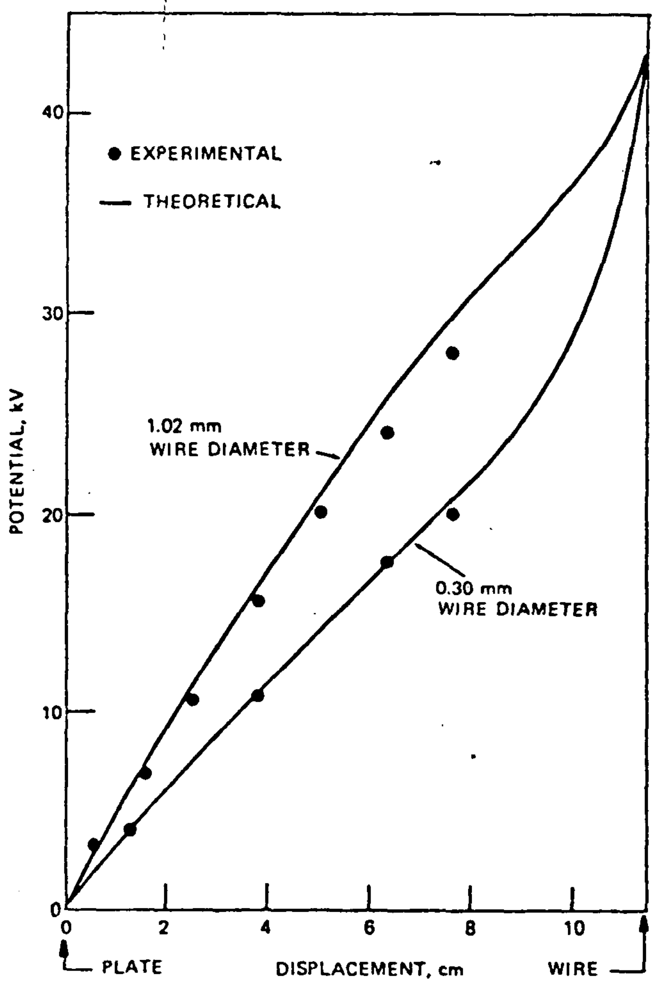

Figure 6. Electric potential vs. position between the corona wire and collection plate.

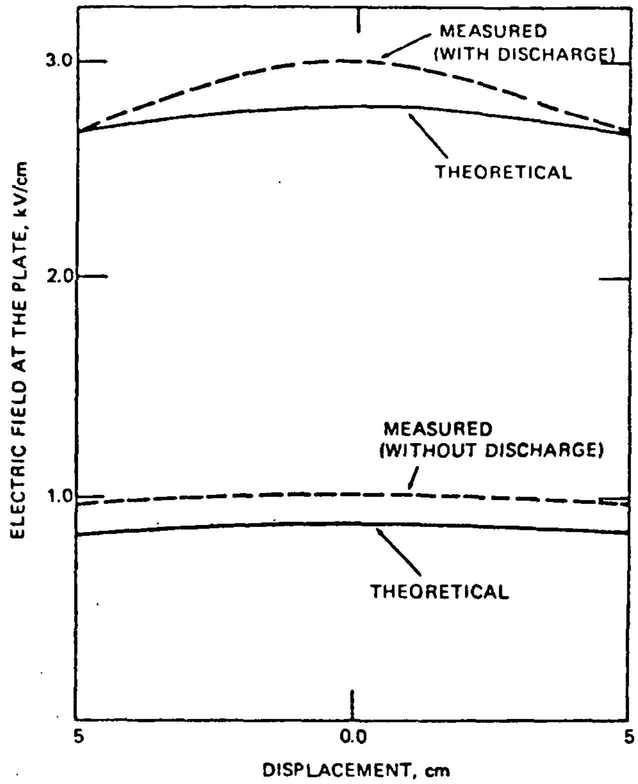

Figure 7. Electric field of the collection plate vs. position. Corona wires are directly across from positions −10, 0, 10,

VALIDATING THE PRECIPITATOR MODEL

In order to validate a modeling procedure, the predictions of the model must be compared with the behavior of actual systems. This precipitator

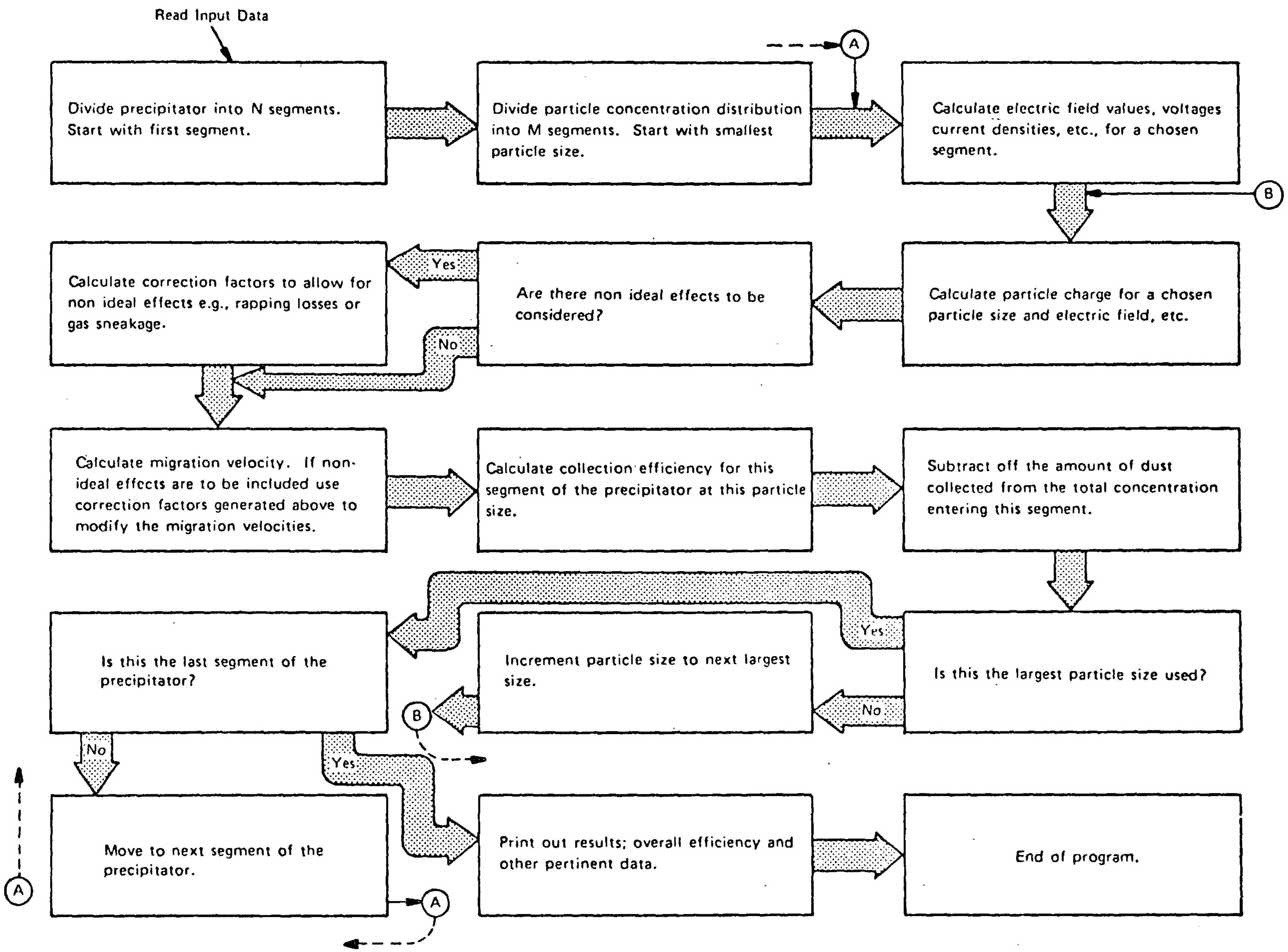

Figure 8. Simplified flow chart of the computer program to calculate precipitator performance.

model has been compared with measured migration velocities and collection efficiencies for laboratory scale and full scale electrostatic precipitators. Figure 9 shows the comparison of ideally calculated migration velocities and collection efficiencies with experimentally measured values obtained from a laboratory scale precipitator. The values obtained in Figure 9 were taken for three different current densities. The good agreement with laboratory data indicates that the model is fundamentally sound. Other measurements made with the laboratory scale precipitator indicate that perhaps 8% of the particulate laden air does not pass through the charging regions. If this sneakage is taken into account, even better agreement with theory is achieved, as is shown in Figure 10.

When the precipitator model is compared with field data and an attempt is made to simulate the behavior of full scale precipitators, non-ideal effects must be included or else the agreement is generally poor. Therefore, the precipitator model is not complete until these effects are allowed for. In a real precipitator, the gas velocity across a duct may be very nonuniform, the flue gas stream can bypass the electrified regions (sneakage) and particles that are once collected can be reentrained when the collecting plates are cleaned (rapping reentrainment). All of these non-ideal effects are to some extent design related. However, even with careful design they usually are reduced but not eliminated.

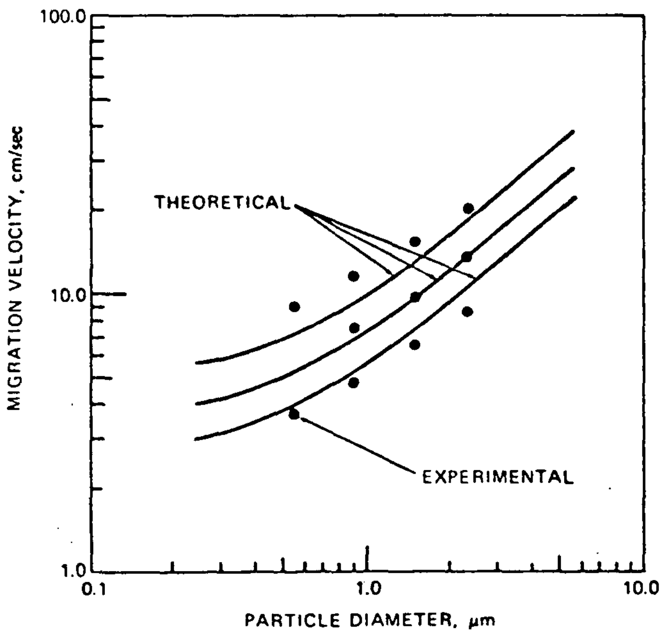

Figure 9. Experimental and predicted migration velocities for a laboratory precipitator.

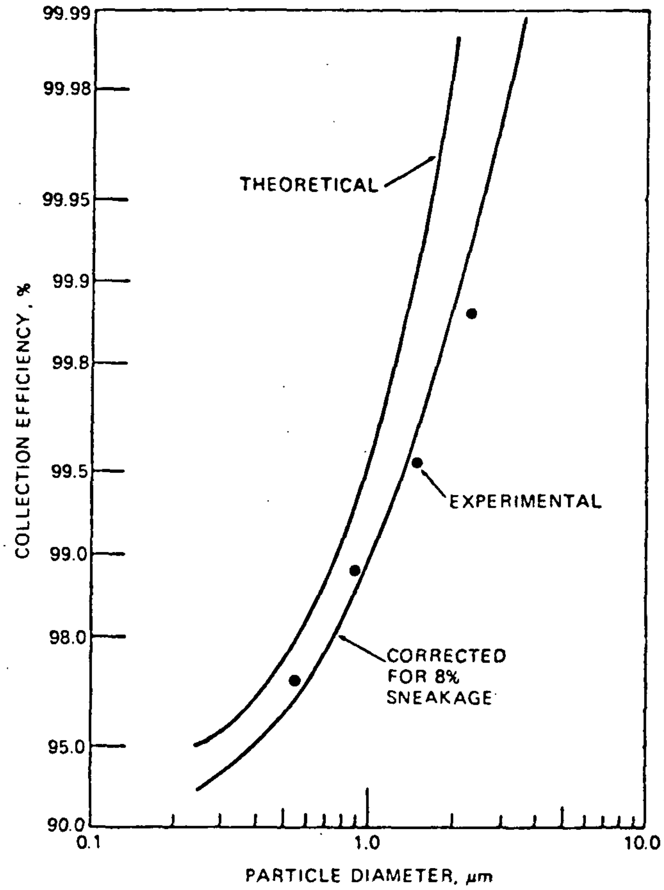

Figure 10. Experimental and predicted collection efficiency vs. particle diameter for a laboratory scale precipitator.

The net result of the non-ideal effects is to lower the ideal collection efficiency of the precipitator. Since the mathematical model of the precipitator is based on an exponential equation for individual particle sizes, it is convenient to represent non-ideal effects in the form of correction factors which apply to the exponential argument. The correction factors are used to modify the ideally calculated migration velocities. The resulting "apparent" migration velocities are empirical quantities and are no longer related to the actual migration velocities in the real precipitator being modeled. The determination of the correction factors is an involved task which requires the correlation of large amounts of field information, taken at existing electrostatic precipitators. These results have also shown that the current density, applied voltage, and particle size distribution are the most important variables in the calculation of overall mass collection efficiency for a given collection electrode area-precipitator gas flow ratio. The theoretical calculation of ideal overall collection efficiency of a typical boiler effluent in an electrostatic precipitator generally predicts a higher value than is observed. Corrections to the idealized or theoretical collection efficiency to estimate the effects of non-uniform gas flow, reentrainment of dust due to rapping, and gas sneakage all reduce the overall values of calculated efficiency to the range of values obtained from field measurements. The calculations suggest that the theoretical model may be used as a basis for quantifying performance under field conditions when sufficient data on the major non-idealities are available. Considerable effort has been expended to learn about modeling non-ideal effects and their inclusion in the precipitator model. To date the results are promising; however, much study and evaluation remains to be done.

Figures 11 and 12 show experimentally measured and model predicted values of migration velocity and collection efficiency as a function of particle diameter for a full scale precipitator. This precipitator collected fly ash from a coal fired power boiler and operated at an average temperature of 150°C. These figures illustrate the kind of agreement which is currently realized. Two curves are shown on each graph.

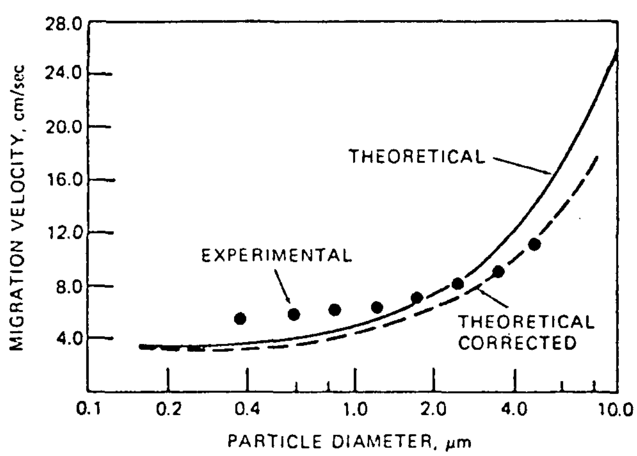

Figure 11. Experimental and predicted migration velocity vs. particle diameter for a full scale precipitator.

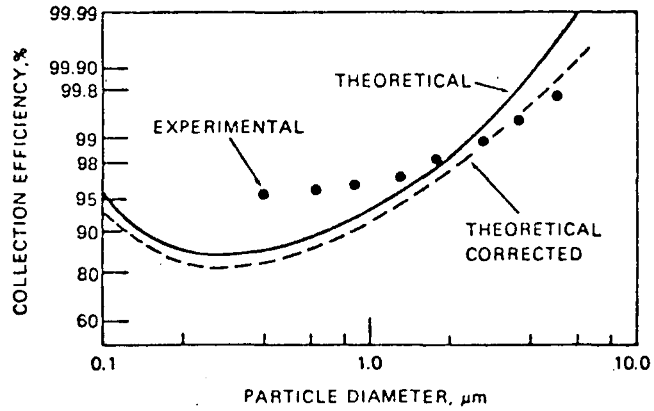

Figure 12. Experimental and predicted migration velocities vs. particle diameter for a full scale precipitator.

The upper curve is an "ideal" calculation. The lower curve takes into account a correction for a non-ideal gas velocity distribution. Other non-ideal effects were not taken into account; however, a continuing effort to model these effects is underway.

The theory has been compared with a broad range of laboratory and field data. The results of these comparisons indicate that the mathematical model provides a basis for indicating performance trends caused by changes in precipitator geometry, electrical conditions, and particle-size distribution.

APPLICATIONS

Precipitator size depends on the quantity of gas flow, the gas composition, the collection efficiency, the electrical properties of the dust, and the size distribution of the dust. Present practice is to base the size on that of an existing precipitator collecting dust from a similar source, on pilot plant tests, or from empirical relationships.

One of the unknown factors in design is the allowable current density. Selection of the design current density involves a prediction of the resistivity of the dust to be collected. If the resistivity is low then high current densities are possible. High resistivity dusts are difficult to collect and precipitators must be operated at reduced current densities. These dusts are often encountered in flue gas streams from power boilers burning low sulfur content coals. The art of precipitator design is based to a great extend on being able to recognize the relevant factors influencing resistivity and allowable current density.

In the electric power industry many types of empirical relationships have been developed to permit the selection of design parameters from coal composition. But none of these relationships are founded in a consistent theory of precipitator operation. Even these relationships are not appropriate for some of the high efficiency precipitators currently being installed. What is needed, and what the Environmental Protection Agency is attempting to provide with the mathematical model of electrostatic precipitation is a theoretical base for prediction of electrostatic precipitator design parameters. Cost considerations alone suggest that a useful mathematical model of electrostatic precipitation would benefit both the manufacturer and the user of these devices. The actual dollar savings are dependent on precipitator size, operating temperature, gas volumetric flow rate, collection plate area and difficulty of erection. But all of these factors, with the exclusion of the physical construction, can be estimated with the help of the precipitator model. Furthermore, savings would be introduced at the design stage.

Another useful application of the modeling effort is in troubleshooting problems in existing precipitators. The remedy to a problem can be tried out on the computer before money and time are commited. Once the fix is determined, costs can be realistically estimated because all of the needed modifications have been determined in advance.

With this mathematical model of electrostatic precipitation, the Environmental Protection Agency hopes that precipitator design can move in the direction of a science rather than an art. It is recognized that the model is not perfect, especially in a comprehensive estimation of nonideal effects. However, a continuing effort of research and development is underway to improve the model and insure its applicability to a wide range of gas cleaning situations.*

** A more detailed description of the computer model is contained in "A Mathematical Model of of Electrostatic Precipitators", by J. P. Gooch, J. R. McDonald, and S. Oglesby, Jr. 1975. NTIS-PB 246188. This report can be ordered from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.*

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15. SUPPLEMENTARY NOTES IERL-RTP project officer is Dennis C. Drehmel, Mail Drop 61, 919/541-2925.

16. ABSTRACT The report describes a computerized mathematical model that can be used to estimate the collection efficiency of electrostatic precipitators (ESPs) of different designs, operating under various conditions. (ESPs are widely used to control emissions of fly ash and other dusts from industrial sources.) Mathematical expressions based on theory are used to calculate electric fields and dust particle charging rates. Empirical corrections are made for non-ideal effects such as a non-uniform gas velocity distribution. The model is expected to aid in improving ESP design and in selecting optimum ESP operating conditions.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Air Pollution	Estimating	Air Pollution Control	13B	14B
Electrostatic Precipitators	Fly Ash	Stationary Sources		21B
	Dust	Collection Efficiency		11G
Mathematical Models		Particulates	12A	
Collection Efficiency				

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