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A PRELIMINARY STUDY OF THE EFFECTS OF TEMPERATURE AND COAL SOURCE ON EFFICIENCY OF ELECTROSTATIC PRECIPITATION OF FLY ASH FROM WESTERN COALS

by
Stanley John Selle

B. S. in Electrical Engineering, University of North Dakota 1968

A Thesis

Submitted to the Faculty

of the

University of North Dakota

in partial fulfillment of the requirements

for the Degree of

Master of Science

Grand Forks, North Dakota

February
1970

This thesis submitted by Stanley John Selle in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

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/s/ Prof. Palmer J. Reiten

/s/ Dr. Donald E. Severson

/s/ A. W. Johnson
Dean of the Graduate School

Permission

Title A Preliminary Study of the Effects of Temperature and Coal Source on Efficiency of Electrostatic Precipitation of Fly Ash from Western Coals

Department Mechanical Engineering

Degree Master of Science

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TABLE OF CONTENTS

Chapter

LIST OF TABLES

LIST OF ILLUSTRATIONS

ABSTRACT

The investigation was the first phase of a program to develop a pilot electrostatic precipitator test facility. The facility was to study the effects of various operating conditions on precipitator collection efficiency for fly ash from western coals.

A plate-type pilot electrostatic precipitator was built and modified to increase its applicability to the problems studied.

Results of tests, run to determine the effect of temperature on collection efficiency for fly ash from a single source, indicated the existence of an optimum operating temperature. Test results also showed that the coal and fly ash composition have an effect on precipitator collection efficiency and particle resistivity.

The need for more applicable particle resistivity measurements was determined. Recommendations were made with regard to improving the usefulness of the resistivity measurements and the pilot electrostatic precipitator test system.

INTRODUCTION

Electrostatic precipitation is taken to mean the removal of solid particles, from the gas in which they are suspended, by a process in which the motion necessary for precipitation is impressed upon the suspended particles by the interaction between an electric field, maintained within an electrode system, and a charge induced upon the surface of each particle (1).

The beginnings of electrostatic precipitation theory can be traced to the discovery of the inverse square law of electrostatics by Coulomb in the years from 1785 to 1789. The first United States patent on the process of electrostatic precipitation was taken out in 1886. The first successful commercial unit resulted from the work of Frederick G. Cottrell at the University of California. In 1906, he used the newly developed synchronous-mechanical rectifier and the high-voltage, alternating-current transformer to provide the high voltages required. In 1923 a power plant in Detroit, Michigan, installed the first full-scale electrostatic precipitator for the collection of fly ash from boiler flue gases (2).

The rapidly increasing concern about air pollution has prompted an increased interest in the use of electrostatic precipitators for particulate removal from the effluent gases of coal-fired power plants. The two types of air pollutants in the effluent of such plants are particulate matter and noxious gases. The initiation of new and stricter air pollution control laws in many cities and states has resulted in increased efforts by the power production industry, and others, to effectively combat the pollution problem. Power plants which previously had low-efficiency electrostatic precipitators, cyclones, or other gas-cleaning methods have found it necessary to either improve on old equipment and methods or install new ones. The installation of electrostatic precipitators is presently the most effective and economical way of meeting requirements for particulate control.

About two-thirds of the total capacity of the electrostatic precipitators in operation today is being used by the electric power industry for removal of fly ash. Few of these precipitators, however, are operating on plants burning the western coals, which are generally lower rank coals with a low sulfur content and ash characteristics much different from the eastern coals. The performance of units which have been installed on plants burning the western coals has been generally unsatisfactory, in that the collection efficiencies have been far less than predicted. No lignite-fired power plants in this country operate electrostatic precipitators, but as a result of the increasing emphasis on air pollution control, electrostatic precipitators can be expected to be required on all coal-fired power plants in the near future.

In view of the apparent need for more information concerning the operation of electrostatic precipitators on western coals, the Grand Forks Coal Research Laboratory of the United States Bureau of Mines initiated a program toward that end. A pilot electrostatic precipitator was constructed for use in conjunction with the 75 lb/hr pulverized-coal-fired furnace presently being used in ash-fouling studies (3).

The work described here is the first phase of the development of a pilot electrostatic precipitator test program for the study of precipitator operation on fly ash under various conditions. The pilot unit, as constructed and modified, is described, as well as the testing apparatus and procedure. Tests were run to determine the effects of temperature on precipitator collection efficiency for a single fly ash. Tests were also run, at a single temperature, on fly ashes from three different coals having widely different ash compositions. The results of these tests are presented, along with conclusions and recommendations for future work.

CHAPTER I

THEORY

The process of electrostatic precipitation consists of three basic operations. They are the electrical charging of the suspended particles, the collection of the charged particles in an electric field, and the removal of the collected material to an external receiver.

The application of a high, positive or negative D. C. voltage to a fine wire electrode results in a corona - the electrical breakdown of the gas near the electrode. Such a corona always generates an appreciable amount of ozone. Experiments have shown that a positive corona generates substantially lower amounts of ozone than a negative corona. As a result, electrostatic precipitators utilizing a positive corona have found use in air conditioning applications, where low ozone concentrations are required (4).

In large industrial applications, however, ozone production is of little significance. Large electrostatic precipitators usually use a negative corona, which is more stable and can be operated at a higher potential before arcing occurs. This higher operating potential results in increased collection efficiency, as will be discussed later. Electrostatic precipitation using a negative corona is the only method considered in this work.

The electrons produced by the negative corona move into the gas stream and charge those particles with which they collide. It is generally accepted that the charging collisions are brought about by two methods - bombardment charging and ion diffusion charging. In bombardment charging, the electrons move perpendicular to the gas stream under the influence of the applied electric field and attach themselves to the particles with which they collide; in ion diffusion charging, however, thermal motions of the electrons cause diffusion through the gas, and the charging of the particles is caused by collisions irrespective of the presence of an electric field. Although both methods operate simultaneously, it has been shown that ion diffusion charging is of importance only for particles with diameters less than about one-fourth micron (5).

The charged suspended particles move toward the grounded collector electrode under the influence of the electric field.

The collected particles are usually removed from the vertical collector electrode with a liquid wash or are shaken into a hopper by vibrating the electrode mechanically. A mechanical rapping method is the one used in electrostatic precipitators removing fly ash from flue gas and is the method that will be considered here.

Rapping must occur often enough to prevent a heavy buildup of collected particles on the collector electrode and the resulting corona breakdown or back corona, described later in this chapter. Another consideration in the rapping operation is the reentrainment of particles into the gas stream. For most effective rapping, it is desirable that enough buildup have occurred so that the particles are dislodged in the form of conglomerates. These conglomerates should be of sufficient size to tumble directly into the hopper under the influence of gravity. If rapping occurs too often, the collected material is dislodged as small particles which are easily reentrained and must be reprecipitated.

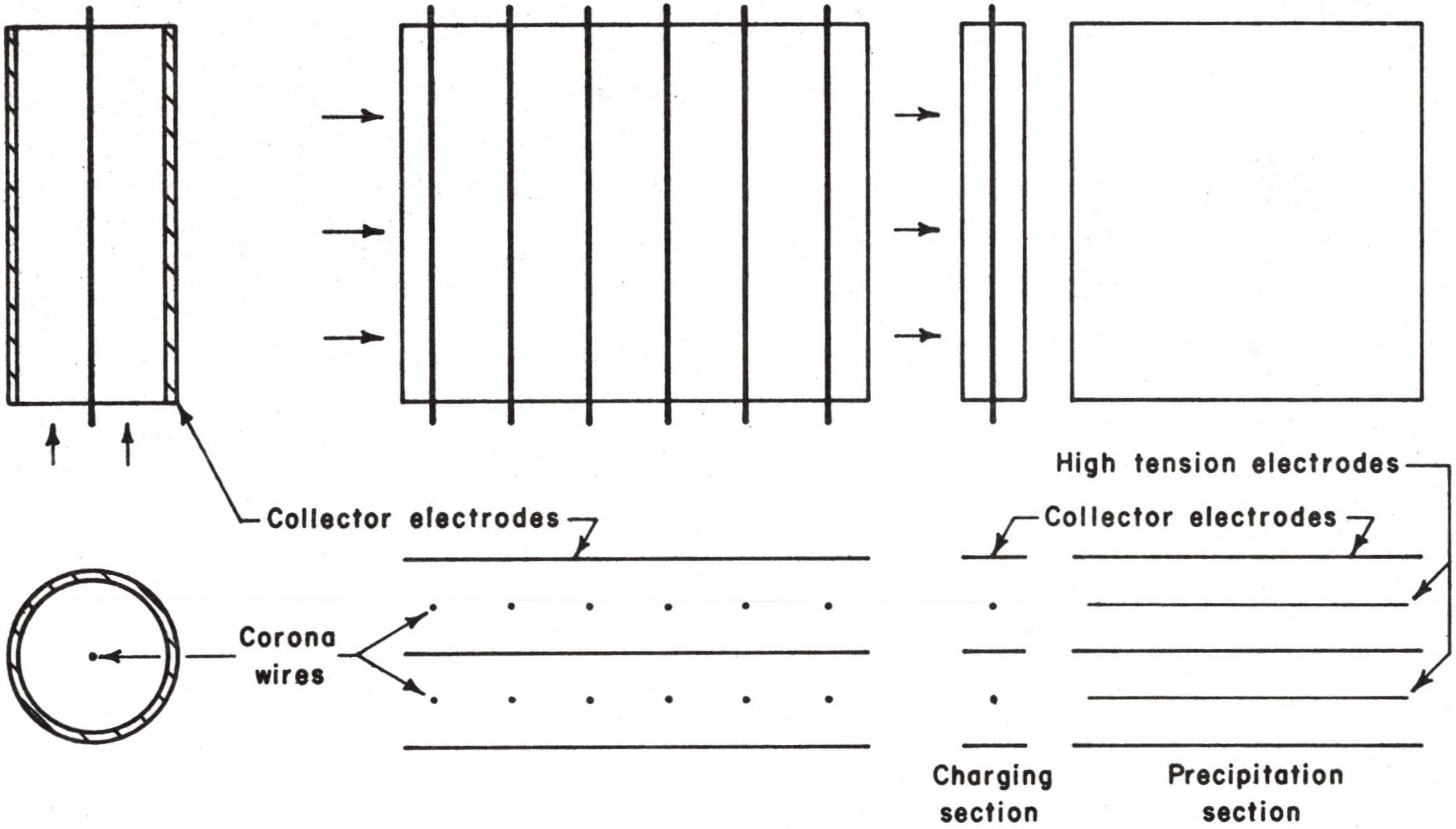
Related to the frequency of rapping is the rapping intensity. The intensity should be high enough to dislodge the collected material in conglomerate form, but low enough to inject the conglomerates only slightly into the gas stream. Most plants use low intensity, high frequency rapping - a frequency of one impact per minute being typical in many applications (6). It is clear from the above discussion that the rapping operation is quite important and can have a substantial effect on precipitator performance.

The electrostatic precipitator may be a tubular or plate-type, single- or two-stage device, as shown in figure 1. In the single-stage device, the charging and collecting operations occur in the same stage, while in the two-stage device they occur separately. A plate-type, single-stage electrostatic precipitator is the type used in power plant installations.

In most large installations, the precipitator is further divided into sections, each with its own power supply, discharge electrodes, and collecting plates. Experience has shown that collection efficiency always improves with increased sectionalization. Improvement results from the decreased effect of sparkover or other disruptions in any one section on the overall collection efficiency. The unit can also be operated at higher voltages, and the particles reentrained as a result of rapping one section can be reprecipitated in a later section, if the sections are rapped sequentially (7) (8).

The equation for electrostatic precipitator collection efficiency - the percentage of particles removed from the gas stream - takes on an exponential form. The Deutsch equation was determined empirically by

Note: Arrows indicate direction of flow



A. Single stage tube type

B. Single stage plate type

C. Two stage plate type

Fig. 1.--Basic electrostatic precipitator configurations.

Evald Anderson in 1919 and theoretically derived by W. Deutsch in 1922 (9). Further work on the Deutsch equation has been done by several authors (10) (11).

One form of the Deutsch equation is

$$n = 1 - e^{-\frac{\omega A}{Q}}$$

where n = precipitator efficiency, percent,

ω = drift velocity, feet per second,

A = precipitator collector electrode area, square feet,

and Q = gas flow, cubic feet per second.

It is assumed that the dust is uniformly distributed in the gas stream at both the beginning and end of the process, and that the drift velocity is effectively a constant (12). From this equation, it can be seen that the efficiency can be improved by increasing the specific collecting area, A/Q, or increasing the drift velocity, ω.

The specific collecting area is a basic design criterion used by the designers of industrial electrostatic precipitators. The value chosen determines the physical size of the unit. A typical range of values for specific collecting area in units on coal burning power plants is from 150 to 250 square feet of collector plate area per thousand cubic feet of flue gas per minute, depending on the difficulty with which the fly ash is precipitated and the collection efficiency desired (13).

The drift velocity is the electrically induced migration velocity of the particle toward the collecting electrode and can be expressed as (14)

$$\omega = \frac{E_o E_p a}{2\pi\mu}$$

where E_o = charging field strength, statvolts per centimeter,

E_p = collecting field strength, statvolts per centimeter,

a = particle radius, centimeters,

and μ = gas viscosity, poise.

In a single-stage precipitator E_o is assumed equal to E_p, so that

$$\omega = \frac{aE^2}{2\pi\mu}$$

where E is the field strength. It can be seen that high field strengths, high voltages, are important to efficient operation, and that larger particles can be removed with greater efficiency. Since the Deutsch equation assumes a uniform particle size, it can be seen that a knowledge of the size distribution of the particles to be precipitated is a necessity for effective precipitator design.

The Deutsch equation serves to illustrate some of the factors affecting electrostatic precipitator efficiency, however, it does not take into consideration everything that occurs in the process (15) (16) (1 Experiment has shown that other factors have an effect on the drift velocity (18). Among them are reentrainment, gas velocity, particle resistivity and temperature.

It is important to minimize reentrainment because of the significant effect it can have on efficiency. Proper design can minimize reentrainment, since it occurs in an electrostatic precipitator as a result of improper rapping, as previously described, or erosion due to poor gas flow. The most important erosion effects are direct scouring of the collected dust on the collector electrode, carry-through of dust falling from the collector electrodes during rapping, and sweepage of dust from the collection hoppers (19). Reentrainment losses can be overcome by lowered gas velocity, improved rapping methods, improved flow characteristics, and, generally, improvements in design.

Gas velocity is a basic factor in precipitator design because it determines the dimensions of the unit, since the precipitator must be long enough to allow an adequate treatment time for the particles in the gas to be completely charged and collected. Since velocity is a function of gas volume flow rate, the precipitator is usually designed to give required results at maximum loading. Any decrease in load will then serve to improve performance. The optimum value of velocity for fly ash precipitators appears to be about 4-7 ft/sec (20).

Particle resistivity is the most important physical property to consider in electrostatic precipitation. It has been found that only those particles having resistivities between 10^4 and 10^{10} ohm-centimeters can be effectively removed in commonly designed electrostatic precipitators. Low precipitator efficiency can result from operation on particles with resistivities above or below this range.

The particles with resistivities below 10^4 ohm-centimeters rapidly lose their charge on reaching the collector electrode. Simultaneously, the particles are recharged due to the ionic current created by the corona discharge, and as a result, the negative charge is effectively neutralized. The dust particles then assume the same charge as the collector electrode and are repelled back into the gas stream (21).

Operation on particles with resistivities above 10^{10} ohm-centimeters is characterized by excessive sparking at lower voltages and lower operating efficiency. This phenomenon can be explained by noting that the effective precipitating field is that which exists between the charging electrode and the surface of the collecting electrode. As the high resistivity particles are collected and build up on the collecting electrode, a high voltage must exist across the collected material to allow the charges to go to ground. This high voltage drop results in a decrease in the effective precipitating voltage between the charging electrode and the surface of the collected particles, the collecting surface. As the buildup increases, the dust layer may break down electrically and initiate a glow, or back corona, on the surface of the collected dust. The back corona tends to neutralize the main action of the precipitator, lowering efficiency because of reentrainment losses and sparkover at lower voltages (22) (23) (24).

Particle resistivity has been shown to be a function of temperature, with the maximum value for fly ash usually found between 280° F and 290° F (25). The conductivity of a particle depends on both surface and volume factors. In surface conduction the electrical charges are carried in the surface moisture and chemical films adsorbed on the particle. In volume conduction, they travel through the interior of the particle, and conductivity depends on the composition and temperature of the particles. At lower temperatures, surface conduction dominates and keeps resistivities low, until a temperature is reached at which the surface moisture and chemical films are removed from the surface. Volume conduction then dominates, and resistivity decreases as temperature increases.

The dominance of surface conduction at low temperatures indicates the importance of conditioning agents such as moisture and sulfur trioxide. Experiments have shown that the lower the sulfur content of a coal, the higher the resistivity of its fly ash (26). The problems encountered with electrostatic precipitators operating on fly ash from plants burning the low-sulfur western coals, therefore, can probably be largely traced to their low sulfur content - less than one percent in most cases.

The relationship between surface conduction, temperature and conditioning agents also indicates why it is best, from the designer's point of view, to make resistivity measurements either on site or in the presence of conditioning agents equivalent to those to be encountered in practice (27) (28).

CHAPTER II

APPARATUS

The pilot electrostatic precipitator used in this study was a plate-type, single-stage unit with two sections in series, as shown in figures 2 and 3. The unit was designed by Precipitair Pollution Control, Incorporated, and constructed at the Grand Forks Coal Research Laboratory. The unit was designed for use in conjunction with the 75 lb/hr pulverized-coal-fired furnace, already in operation for ash-fouling studies, figure 4.

The unit was designed to handle 100 to 250 cubic feet per minute of flue gas at temperatures from 100 to 600 degrees Fahrenheit. Collection efficiencies were to range from 90 to 99.6 percent for coals containing .5 to 1.5 per cent sulfur. Each of the two sections of the unit was provided with its own variable high voltage supply, with a negative half-wave output of up to 40,000 volts at 20 milliamps. The electrical diagram for the power supply is shown in figure 5.

The pilot precipitator construction was of hot rolled steel, with the collecting plates of the same material. The discharge electrodes were made of 1/8 inch X .020 inch thick number 316 stainless steel.

There were two sections in series, each section consisting of 3 ducts. The ducts were 6 inches wide, 2 feet high and 2 feet long and were formed by 4 collecting plates, 2 feet high by 2 feet long. The discharge electrodes were held rigid by a steel frame and each duct contained four electrodes. Each section had twelve discharge electrodes served by a single high voltage supply.

The collector electrodes were cleaned by rapping the frame containing the plates. The rapping operation was performed by striking the rapping anvils, shown in figure 2, with an air hammer.

A preliminary series of tests were run to develop the testing apparatus, test procedures and operating procedures for the unit. Improvements were made in the testing apparatus and test procedures as needed.

Early tests on the unit indicated that the most effective operating voltage, just below sparkover, could not be achieved during some operations. An additional input transformer was installed, which allowed voltages up to 42,000 volts at the precipitator discharge electrodes.

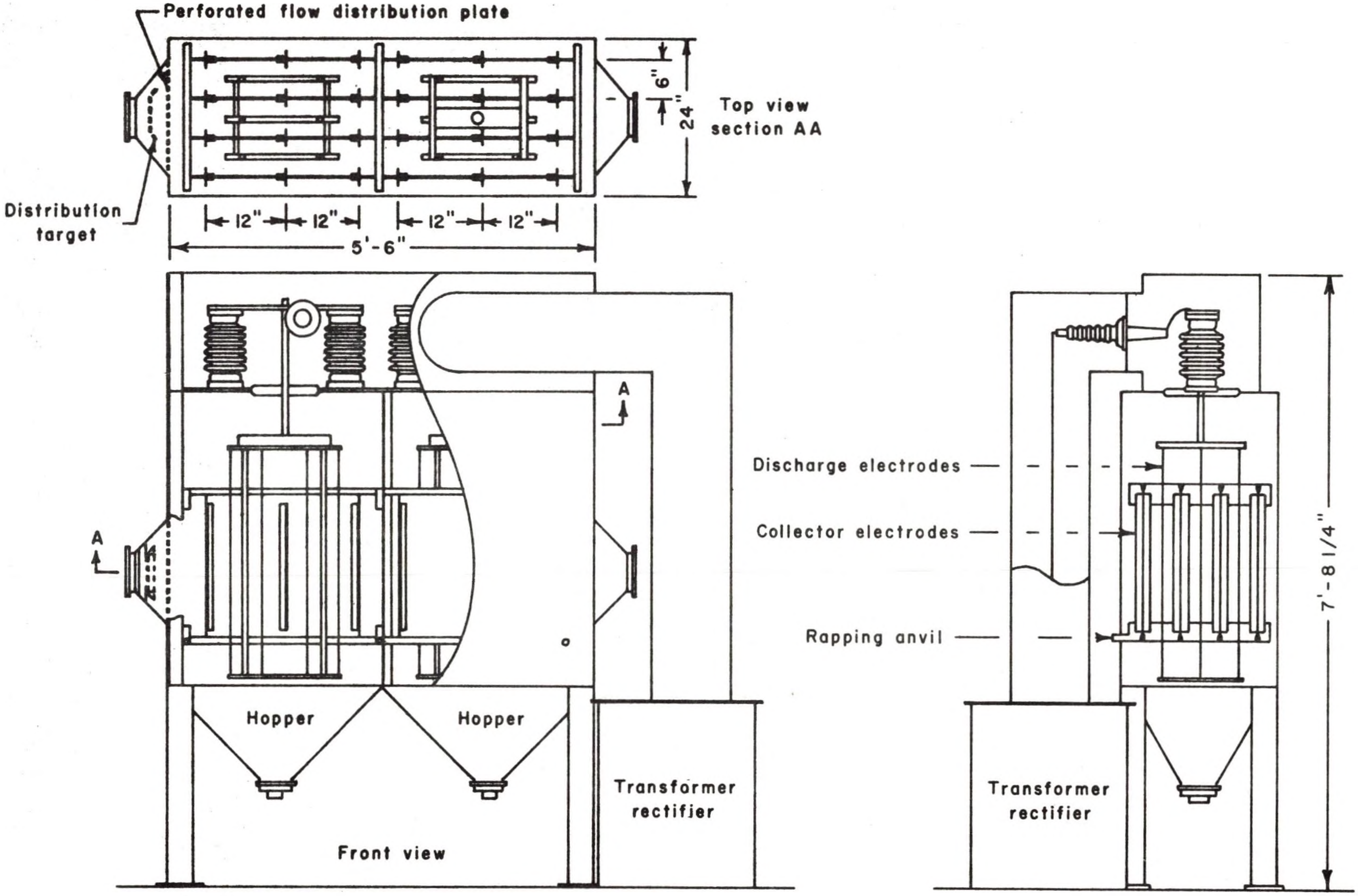


Fig. 2.--Pilot electrostatic precipitator.

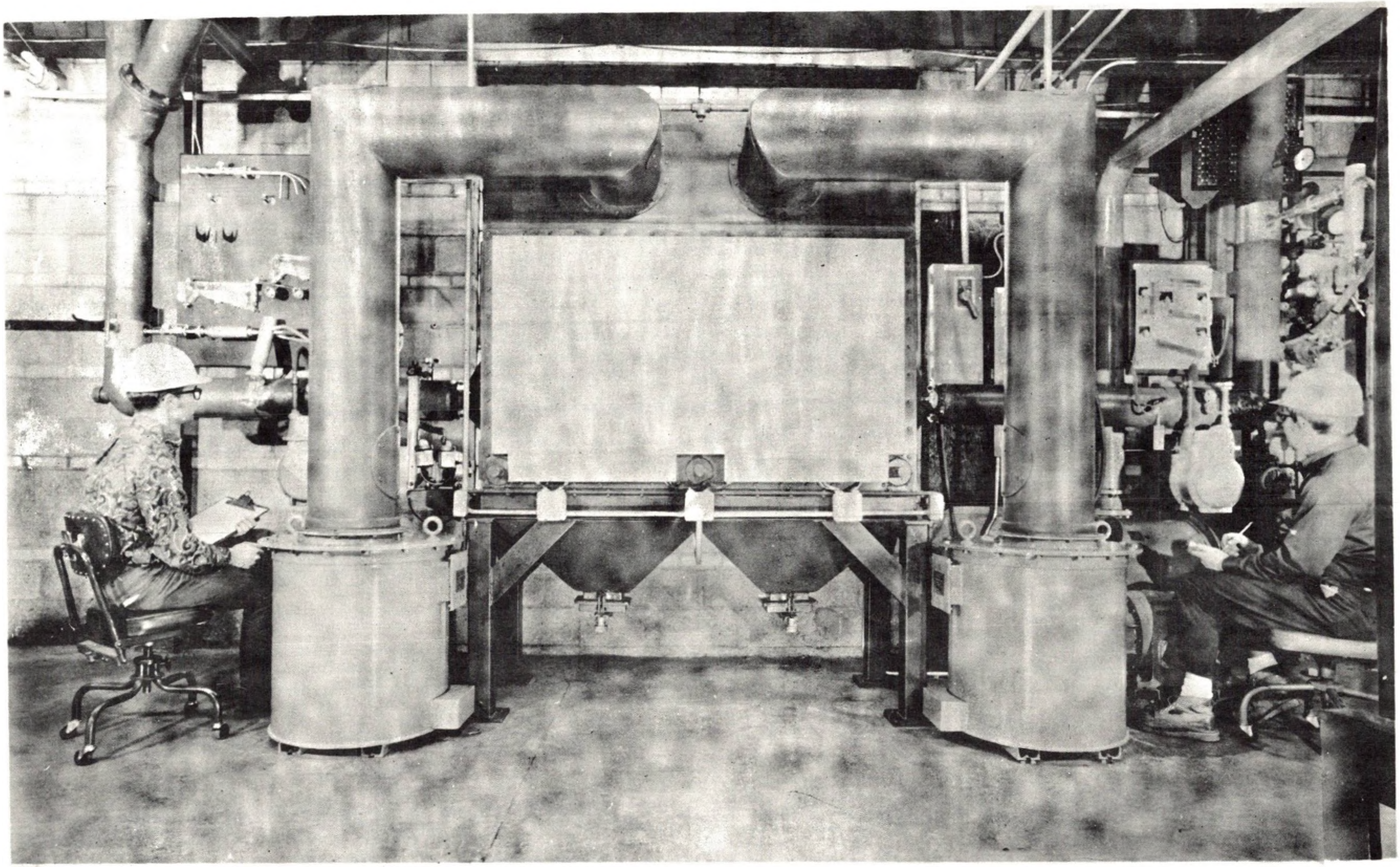


Fig. 3.--Pilot electrostatic precipitator with test in progress.

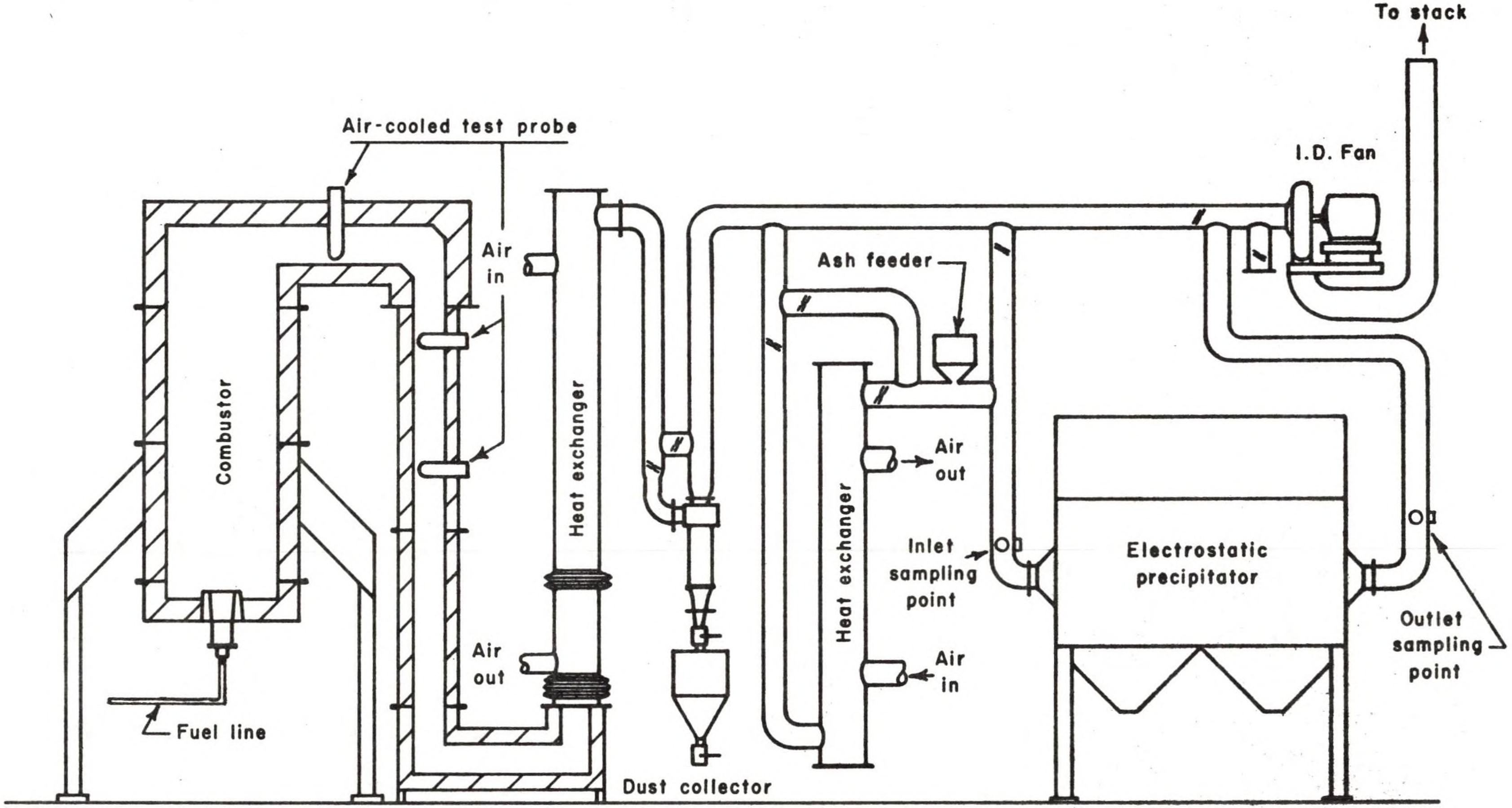


Fig. 4.--75 lb/hr furnace and pilot electrostatic precipitator test system.

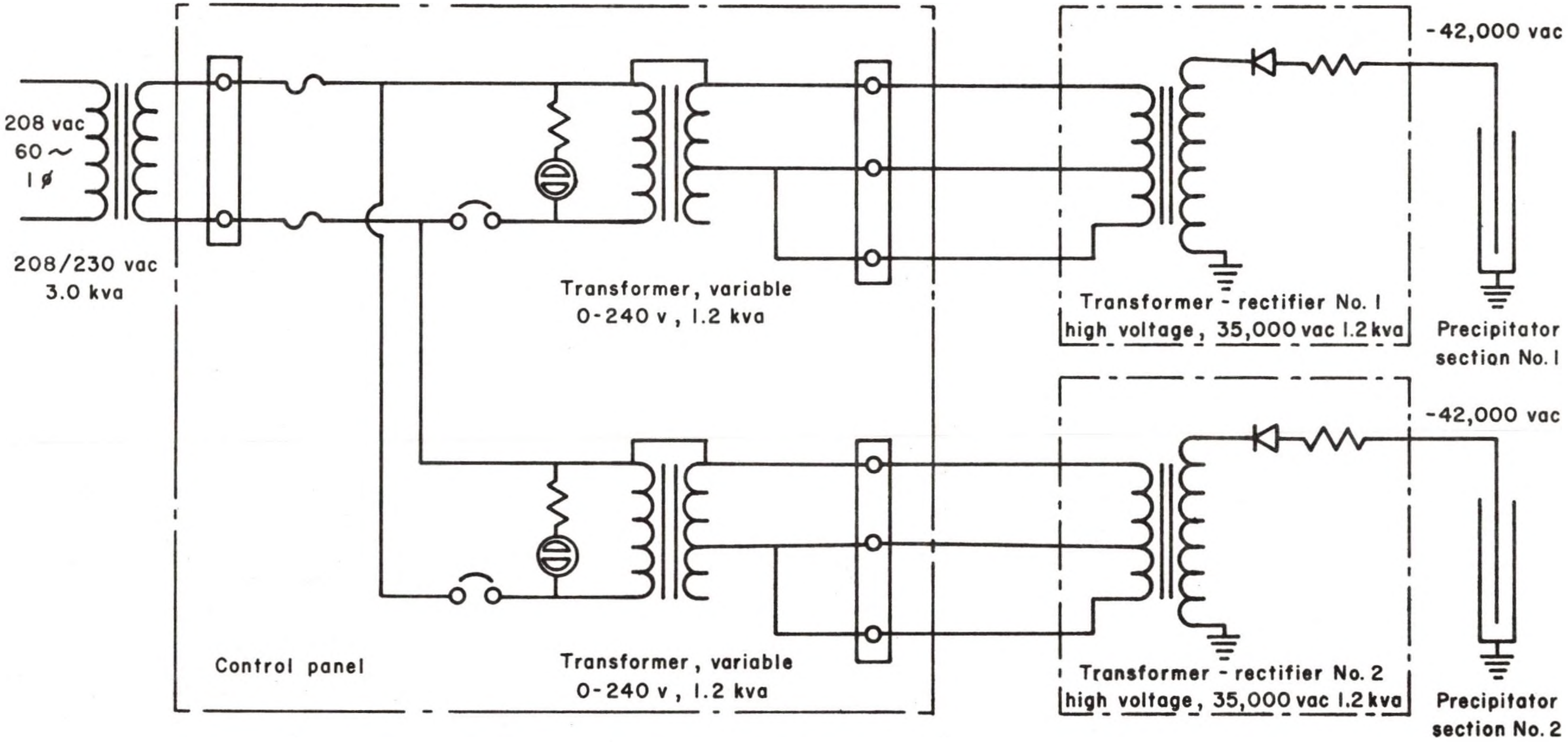


Fig. 5.--Electrical diagram for electrostatic precipitator.

During these early tests, it was found that air leakage into the precipitator was quite substantial with the unit operating at its customary vacuum of 6 inches of water. The leakage was diminished by improving seals and replacing bolts with welds, wherever possible.

Problems were encountered, during the early tests, with a large temperature drop across the precipitator. At lower inlet gas temperatures, condensation would sometimes occur in the second section. A maximum drop of about 135° F was observed for inlet temperatures over 500° F. The installation of insulation and external heaters on the body of the unit reduced the temperature drop to a more acceptable 80° F at the high inlet temperatures. Virtually uniform temperatures could be maintained throughout the precipitator for inlet temperatures up to 350° F.

Further tests indicated that the unit was operating at over 99 per cent efficiency under all conditions. Since the constant high collection efficiency made it impossible to determine realistically the actual effect of various operating conditions, attempts were made to bring the precipitator efficiency down into a more usable range. To that end, only one of the sections was operated at a time.

The specific collecting area of the unit as designed was 240 ft^2/1000 cfm at a gas flow of 200 cfm. This was quite a high value when compared with the usual range of from 150 to 250 ft^2/1000 cfm for commercial units, especially, since the velocity was a very low 1.1 ft/sec compared with the 4-7 ft/sec used in large units. The use of only one section at a time cut the specific collecting area in half, but reduced the collection efficiency only slightly.

The specific collecting area was further decreased and the velocity increased by removing the outer sets of plates and electrodes. Using baffles, the total flow was restricted to the central one-third of the precipitator. This reduced the specific collecting area to 80 ft^2/1000 cfm and increased the velocity to 3.33 ft/sec. This resulted in somewhat decreased efficiencies, between 96 and 98 per cent, but was still not satisfactory. Tests were then made with only one of the sections in operation at a time, cutting the specific collecting area still further, to 40 ft^2/1000 cfm. It was determined that operation of the second section only resulted in a range of efficiencies of 88 to 95 per cent. This proved to be a satisfactory range from the standpoint of investigating the effect of varying conditions on precipitator collection efficiency.

The dust loading achieved in the initial tests made in conjunction with the ash-fouling studies on the 75 lb/hr furnace averaged from .30 to .60 grains/ft^3, a very low dust loading when compared with the

2.0 to 5.0 grains/ft^3 encountered in industry. The low dust loading was the result of the large quantity of fly ash lost by deposition within the furnace and the flue system. Loading the coal with 30 pounds of fly ash per 100 pounds of coal before burning, increased the dust loading to over 1.0 grain/ft^3. This method proved to be unsatisfactory because of the large quantities of fly ash that had to be added and the increased problems with deposition.

In an attempt to obtain a higher and more easily controlled dust loading, an adjustable mechanical feeder was installed to inject fly ash directly into the flue gas. The feeder used springs attached to rotating arms to force the fly ash through an orifice and into the gas stream. The feeder allowed the required dust loading to be achieved. However, completely satisfactory operation, in terms of constant dust loading, was not achieved.

To simplify operations, natural gas was burned in the furnace, instead of coal. The fly ash was then fed into the hot flue gas just ahead of the precipitator inlet.

CHAPTER III

TEST PROCEDURE

Prior to the beginning of a pilot electrostatic precipitator test, the gas flow rate through the precipitator was adjusted to the desired level. The adjustment was made by allowing the unwanted flue gas to bypass the electrostatic precipitator and go directly to the I.D. fan, as shown in figure 4. The gas flow rate was monitored at the precipitator inlet by means of a stationary flow indicator.

The desired precipitator inlet gas temperature was obtained by controlling the amount of flue gas flowing through the heat exchanger ahead of the precipitator, see figure 4. The temperature across the precipitator was maintained as constant as possible with the external heaters on the precipitator body.

After the required gas flow rate and inlet gas temperature had been reached and stablized, the fly ash feeder was started. Electrical power was supplied to the precipitator, with the optimum operating voltage, just below sparkover, maintained throughout the test. The precipitator was rapped before each test to keep the initial precipitator conditions as reproducible as possible.

The test basically consisted of the determination of the flue gas flow rate, isokinetic sampling of the flue gas, and removal of the suspended fly ash from a measured quantity of gas by means of a filter (29). The measured dust loads at the inlet and outlet of the precipitator were then used to calculate collection efficiency. The quantities measured and calculations used are given in the appendix.

The inlet and outlet flue gas flow rates were determined using type s pitot tubes, one of which is shown in figure 6. The pitot readings were taken at eight points, four in each of two perpendicular traverses of the flue duct. The test points were such that the duct was divided into two equal areas and four points were sampled in each area (30).

The dust sampling equipment consisted of a sampling probe, filter and holder, condenser, flow meter and vacuum pump. The apparatus is shown in figure 6. Figure 3 shows a sampling test in progress. A flow diagram for this equipment is given in figure 7.

The sampling points for the dust sampling probe were the same as those for the pitot tube. Equal time was spent at each of the test points. The total test time had to be sufficient to allow the collection of a large

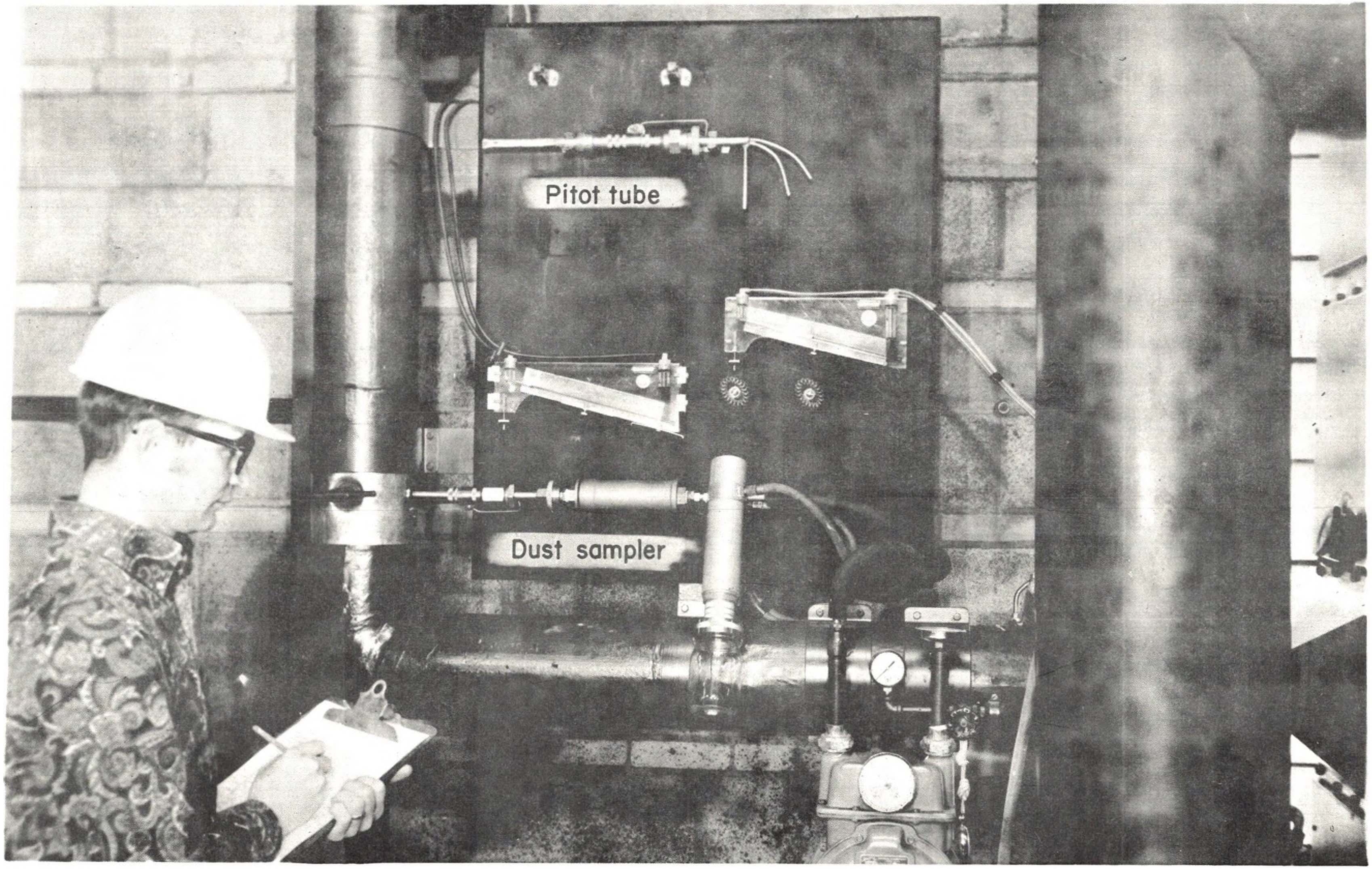


Fig. 6.--Test equipment.

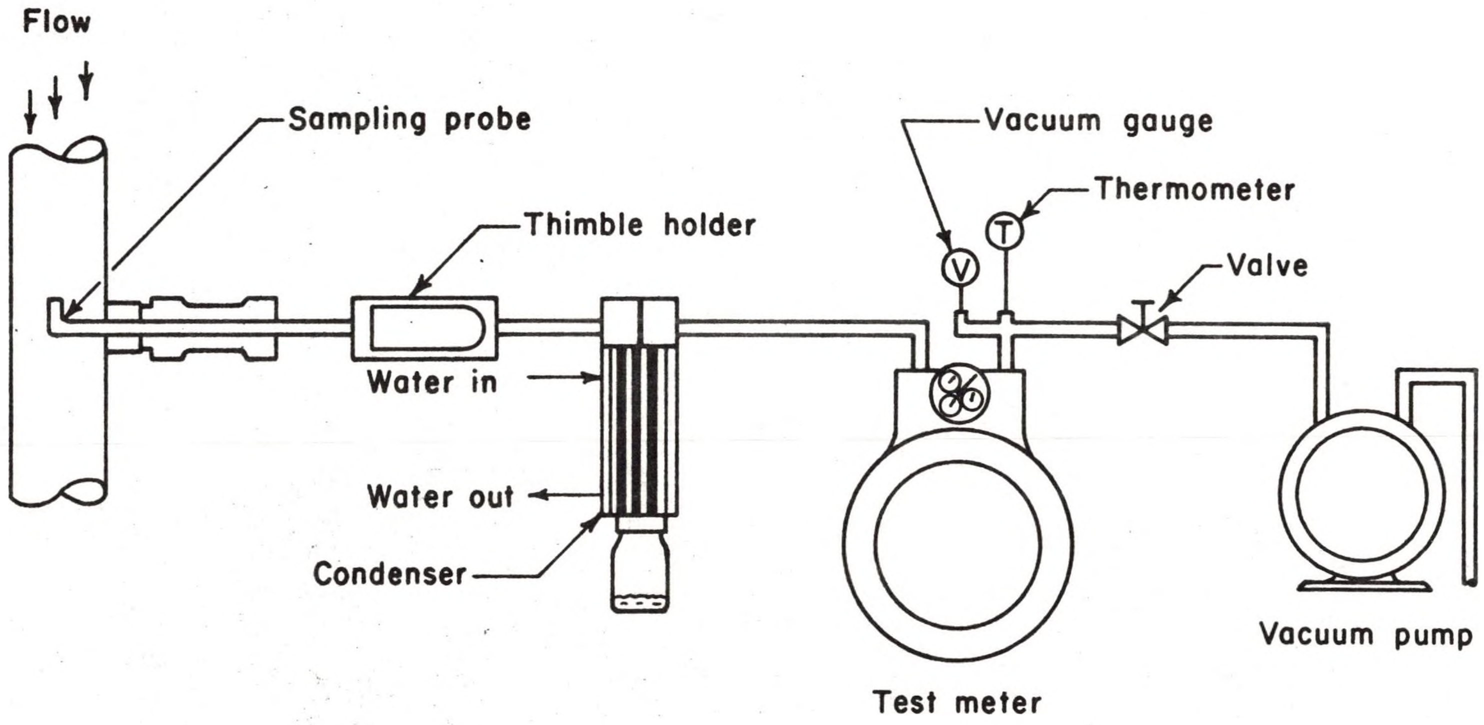


Fig. 7.--Flow diagram for dust sampling equipment.

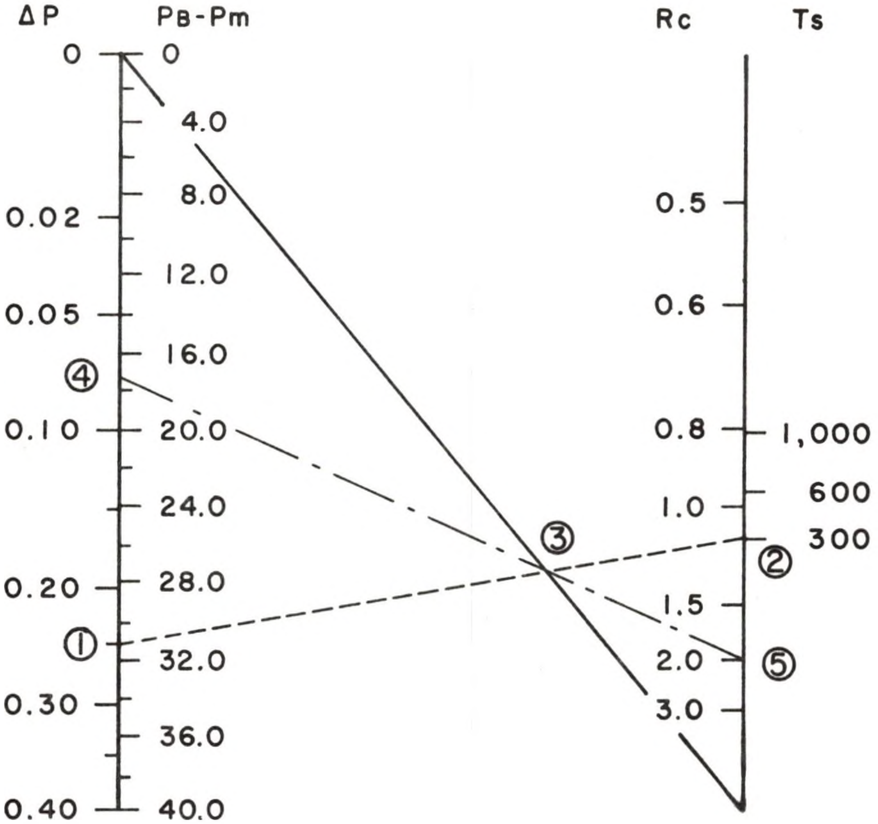
enough sample at the precipitator outlet to prevent problems with weighing statistics. It was found that the outlet sample should weigh at least 0.1 gram, and that a total test time of 48 minutes was sufficient. A single filter was used for the entire test.

By knowing the velocity head at each point, as determined by the pitot tube, along with the duct and meter conditions, the gas sampling rate required for isokinetic sampling could be determined at each sampling point using a nomograph especially developed for this apparatus by Dr. Donald E. Severson, professor of Chemical Engineering, University of North Dakota. The nomograph, along with an explanation of its use, is shown in figure 8.

The isokinetic extraction of the gas sample was important to insure accurate dust loading data. If the velocity of the extracted sample exceeds that of the flue gas, particles that would not have passed through the area occupied by the sampling nozzle will be drawn into the nozzle. If the sampling velocity is lower than that of the flue gas, particles that should have been collected will be diverted around the nozzle (31). In this work, an attempt was made to keep the sampling velocities within 10 per cent of the isokinetic values to minimize the resulting errors (32).

The fly ash was removed from the gas sample by an alundum filter, which was dried and weighed before and after sampling. The gas sample then passed through a water cooled condenser to condense the moisture in the gas before it reached the test meter.

The quantity of gas sampled, as measured by the test meter, was corrected to flue conditions. The dust loading was obtained by dividing the weight of fly ash collected in the filter by the sampled volume. The dust loading when multiplied by the measured flue gas flow rate, could be expressed in terms of a total dust rate. The total dust rates, in pounds per hour, into and out of the precipitator were used to determine efficiency.



Explanation of the Use of the Nomograph:

Step 1: Locate value of ΔP on extreme left-hand edge of nomograph. ΔP is the pressure differential measured by the pitot probe in inches of water. ΔP = .25 inches[a].

Step 2: Locate value of T_s on extreme right-hand edge of nomograph. T_s is the temperature in the duct at the sampling point. T_s = 300° F.

Step 3: Draw a line connecting points 1 and 2 and intersecting the central line of the nomograph at point 3.

Step 4: Locate value of P_B-P_m on the inner scale of the left-hand side of the nomograph. P_B is the barometric pressure and P_m is the meter vacuum, as measured by the vacuum gauge on the test meter. $P_B - P_m$ = 17.5 inches of mercury.

Step 5: Draw a line from point 4, through point 3, and intersecting the inner scale on the right-hand side of the nomograph at point 5. The value at this point is the correct meter rate in cubic feet per minute for the operating conditions given. R_c = 2.0 cfm.

[a] Numerical values are for example purposes.

Fig. 8.--Nomograph used to determine isokinetic sampling rate.

CHAPTER IV

TEST RESULTS AND DISCUSSION

The results of the tests run on the pilot electrostatic precipitator, along with the operating conditions for each test, are shown in table 1. The table indicates that the gas temperature, inlet gas flow rate, specific collecting area, and gas velocity could be quite satisfactorily reproduced.

The voltage at the discharge electrodes was maintained at the most effective level, just below sparkover, during all the tests. This operating voltage, however, decreased as the buildup of collected fly ash on the collector electrode plates increased. The value given in table 1, for discharge electrode voltage, is the average of the voltages required throughout the course of a test. These changes in the most effective operating voltage during the course of a test, and the differences in this voltage from test to test under the same operating conditions, illustrate the need for greater control over the conditions of the precipitator interior. Especially important is the surface of the collector plates. In rapping the collector electrodes before each test, an attempt was made to obtain reproducible precipitator interior conditions, at least at the beginning of the tests.

The problems encountered in maintaining a constant fly ash feed rate over the course of the tests are illustrated by the results of the dust loading measurements. The dust loading varies over a range of .65 to 1.70 grains/ft^3. The test results, however, indicate no apparent discrepancies which can be traced to this seemingly large range of dust loads.

The precipitator efficiency was determined by comparing the dust loads, in pounds per hour, at the inlet and outlet of the precipitator.

Figure 9 is a plot of the data obtained from tests with Colstrip fly ash at various operating temperatures. Colstrip is a subbituminous coal mined in Montana. The fly ash used in these tests was collected at the J. E. Corette station of the Montana Power Company, Billings, Montana.

The test results indicate good reproducibility of data from tests run the same day, but oftentimes poor reproducibility from tests run on different days. For example, in table 1, tests PF8-1 and PF8-2 were run on the same day, as were PF14-1 and PF14-2, with good agreement.[1] However, agreement between the two sets of data, run on different days, is poor.

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[1] The run numbers are interpreted as follows:
PF indicates precipitator tests with feeder operating.
--8- indicates day of run, i.e. PF8-1 and PF8-2 were run on the same day.
---1 indicates the order of the tests run on a single day.

TABLE I

TEST RESULTS FROM THE PILOT ELECTROSTATIC PRECIPITATOR

Run Number	Average Gas Temperature,[a] °F	Inlet Gas Flow Rate[b] CFM	Specific Collecting Area[c] Ft^2/1000 CFM	Gas Velocity[d] FPS	Voltage at Discharge Electrodes[e] KV	Dust-Loading[f] grains/ft^3 In	Dust-Loading[f] grains/ft^3 Out	Dust-Loading[f] lb/hr In	Dust-Loading[f] lb/hr Out	Precipitator Efficiency, Per Cent
Tests With Colstrip Fly Ash Collected at J. E. Corette Power Plant										
PF10-1	250	196.7	40.7	3.28	36	1.22	.072	2.07	.137	93.4
PF10-2	250	196.7	40.7	3.28	35	1.70	.095	2.88	.181	93.7
PF15-1	253	202.8	39.4	3.39	38	.97	.054	1.69	.106	93.7
PF15-2	251	202.8	39.4	3.39	38	1.16	.072	2.03	.142	93.0
PF 6-3	275	191.9	41.7	3.20	37	1.67	.086	2.76	.157	94.3
PF10-3	273	200.3	39.9	3.35	34	1.03	.073	1.78	.140	92.1
PF10-4	275	200.3	39.9	3.35	33	1.67	.132	2.88	.254	91.2
PF15-3	275	209.9	38.1	3.51	36	1.18	.102	2.13	.201	90.6
PF15-4	276	209.8	38.1	3.50	35	1.46	.132	2.63	.261	90.1
PF 3-1	299	203.1	39.4	3.39	36	.90	.034	1.57	.065	95.9
PF 3-3	300	203.3	39.4	3.40	37	.98	.032	1.72	.061	96.5
PF13-1	294	194.7	41.1	3.25	41	1.15	.045	1.93	.083	95.7
PF13-2	295	194.8	41.1	3.25	40	1.61	.064	2.70	.119	95.6

TABLE 1 --continued

Run Number	Average Gas Temperature,[a] °F	Inlet Gas Flow Rate[b] CFM	Specific Collecting Area[c] Ft^2/1000 CFM	Gas Velocity[d] FPS	Voltage at Discharge Electrodes[e] KV	Dust-Loading[f]				Precipitator Efficiency, Per Cent
						grains/ft^3		lb/hr		
						In	Out	In	Out	
PF 4-1	346	210.0	38.1	3.51	35	.65	.038	1.17	.073	93.8
PF 4-2	350	210.0	38.1	3.51	34	.87	.056	1.57	.107	93.2
PF 4-3	350	210.0	38.1	3.51	35	.74	.053	1.34	.100	92.5
PF 5-1	385	198.6	40.3	3.32	33	1.24	.080	2.12	.144	93.2
PF 5-2	395	200.4	39.9	3.35	32	1.41	.096	2.42	.173	92.9
PF 5-3	397	200.2	40.0	3.34	32	1.45	.116	2.50	.210	91.6
PF 5-4	397	200.3	39.9	3.35	32	1.30	.099	2.24	.180	92.0
PF 8-1	437	207.2	38.6	3.46	31	1.19	.124	2.12	.219	89.7
PF 8-2	443	207.9	38.5	3.47	29	1.37	.159	2.45	.281	88.5
PF14-1	426	206.3	38.8	3.45	33	1.45	.085	2.58	.152	94.1
PF14-2	448	208.0	38.5	3.47	32	1.51	.103	2.71	.184	93.2
			Tests With Beulah Fly Ash Collected From 75 lb/hr Furnace							
PF11-1	291	198.2	40.4	3.31	37	.92	.071	1.58	.131	91.7
PF11-2	293	197.9	40.4	3.30	38	1.01	.067	1.72	.125	92.0
PF11-3	295	198.1	40.4	3.31	38	1.00	.077	1.70	.144	91.5
			Tests With Velva Fly Ash Collected From 75 lb/hr Furnace							
PF12-1	295	197.7	40.5	3.30	39	1.36	.072	2.32	.134	94.2
PF12-2	296	197.6	40.5	3.30	38	1.45	.089	2.47	.167	93.3
PF12-3	297	197.7	40.5	3.30	38	1.29	.089	2.20	.167	92.4

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[a] Average of gas temperatures measured at inlet and outlet of precipitator.

[b] As measured at duct conditions using a pitot tube.

[c] Only one duct and last section in use.

[d] Based on inlet gas flow.

[e] Only last electrode bank active. This value is the average of the voltages required during a test.

[f] Determined at duct conditions of temperature and pressure.

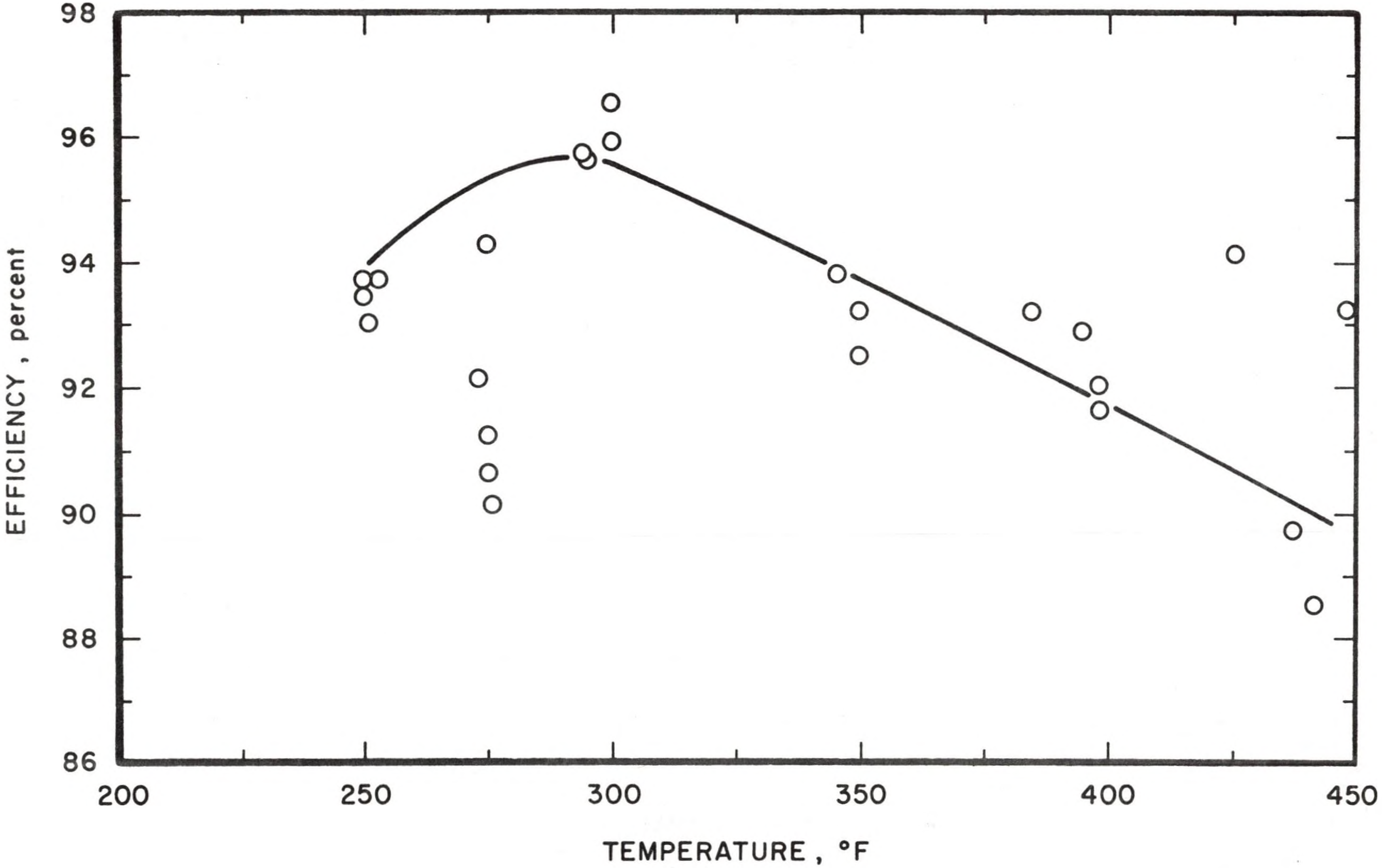

Fig. 9.--Efficiency vs temperature for Colstrip fly ash as determined by pilot electrostatic precipitator tests.

Such discrepancies probably arise from varying conditions within the precipitator from day to day, as partly evidenced by differences in the operating voltages. The problem could possibly be overcome by the statistical analysis of a greater number of data points than were collected here. However, a large number of tests would probably be required, resulting in a long and expensive process with doubtful results. It would seem, therefore, that a wiser course would be the improvement of control over such varying precipitator conditions, and the further study of the causes of the variations and their effects on operation.

Resistivity has been shown to vary with temperature, and precipitator efficiency to vary with resistivity (33). It seems reasonable to assume, therefore, that there is a temperature, or at least a range of temperatures, at which electrostatic precipitator collection efficiency would be maximum. Recent successful attempts to improve efficiency by lowering operating temperatures from 335° F to 260° F at the J. E. Corette plant tend to support such an assumption. In view of these considerations, the author has chosen to draw the interim curve shown in figure 9, until further studies can provide a more precise result. Thus, a maximum collection efficiency is indicated in the vicinity of 300° F.

In table 2 are shown the results of a second series of tests run to study the effect, on precipitator efficiency, of operation on fly ash from three different coal sources.

TABLE 2

RESULTS OF PILOT PRECIPITATOR TESTS RUN ON FLY ASH FROM DIFFERENT COAL SOURCES[a]

Coal Source	Pilot Electrostatic Precipitator Collection Efficiency, Per Cent
Colstrip	95.9[b]
Beulah	92.0
Velva	93.3

[a] All tests were run at a nominal temperature of 295° F.

[b] Average measured efficiency.

The results of coal analyses run on representative samples of the three coals are given in table 3. The Beulah and Velva coals are Lignite mined in western North Dakota. It can be seen that all three coals have a low sulfur content - less than 1 per cent.

The results of ash analyses run on the fly ash samples used in these tests are given in table 4. The Colstrip sample is the same one used in the tests to determine temperature effects. The Beulah and Velva fly ash samples were collected from the cyclone dust collector on the 75 lb/hr furnace during earlier test runs. These results indicate that there are substantial differences in the ash compositions of the three fly ashes.

Figure 10 illustrates the results of particle resistivity measuremen made at the Morgantown Research Center of the Bureau of Mines. The value were obtained in a dry nitrogen atmosphere (34) (35). The two uppermost curves resulted from two tests run on the Colstrip fly ash sample used for the electrostatic precipitator tests described here. These curves indicate good reproducibility of the data obtained from the resistivity measurements on a single sample. The other Colstrip sample tested was collected at the Grand Forks Laboratory in a previous series of tests, as was the Beulah sample.

Table 5 contains the results of ash analyses of the two different Colstrip fly ash samples. The differences in ash composition likely resu from changes in the coal composition from the mine.

The differences in ash composition and in ash resistivity indicate that particle resistivity is indeed a function of ash composition and can change during the course of operation of a power plant. These changes in ash resistivity, resulting from changes in coal composition at the mine, if large, could have a substantial effect on the operation of an electrostatic precipitator. If so, the possible changes in coal composit at the mine could be important information to the designer of an electrostatic precipitator for such a plant - especially in the case of the coal whose fly ash is difficult to precipitate.

It should be pointed out that the values of particle resistivity obtained in the laboratory equipment at the Morgantown Research Center show highly prohibitive resistivities at the lower temperatures - much above the accepted maximum value of between 10^{10} to 10^{11} ohm-cm for effective electrostatic precipitation (36). The resistivities in actual operations appear to be lower than indicated here, since the fly ash has been effectively precipitated - not only in the pilot unit, but in the large commercial unit in operation at the J. E. Corette station where the Colstrip fly ash sample used in these tests was collected.

TABLE 3

RESULTS OF COAL ANALYSES[a]

Proximate Analysis	Percent of Coal, As Fired		
	Colstrip	Beulah	Velva
Moisture	19.39	29.19	30.13
Volatile matter	30.92	29.45	28.66
Fixed Carbon	41.34	33.60	36.01
Ash	8.35	7.76	5.20
Total	100.00	100.00	100.00
Ultimate Analysis			
Hydrogen	5.84	6.17	6.18
Carbon	54.59	44.91	45.93
Nitrogen	0.89	0.67	0.76
Oxygen	29.42	39.74	41.71
Sulfur	0.91	0.75	0.22
Ash	8.35	7.76	5.20
Total	100.00	100.00	100.00

[a] As performed by the Pittsburgh Coal Research Center of the Bureau of Mines.

TABLE 4

RESULTS OF ASH ANALYSES[a]

Component	Percent of Ash		
	Colstrip[b]	Beulah[c]	Velva[c]
Loss on ignition at 800° C	0.2	1.0	2.1
Silica, SiO_2	42.9	11.6	13.9
Aluminum oxide, Al_2O_3	25.2	11.3	8.5
Ferric oxide, Fe_2O_3	5.7	5.8	5.6
Titanium oxide, TiO_2	0.8	0.5	0.2
Phosphorous pentoxide, P_2O_5	0.4	0.8	0.4
Calcium oxide, CaO	20.8	22.3	43.4
Magnesium oxide, MgO	4.5	7.7	9.7
Sodium oxide, Na_2O	0.2	10.0	6.6
Potassium oxide, K_2O	0.2	0.6	0.2
Sulfur trioxide, SO_3	1.1	22.8	8.7
Total	102.0	94.4	99.3

[a] As performed at the Grand Forks Coal Research Laboratory.

[b] As collected at the J. E. Corette Power Plant, Montana Power Company, Billings, Montana.

[c] As collected from the Cyclone dust collector on the 75 lb/hr furnace.

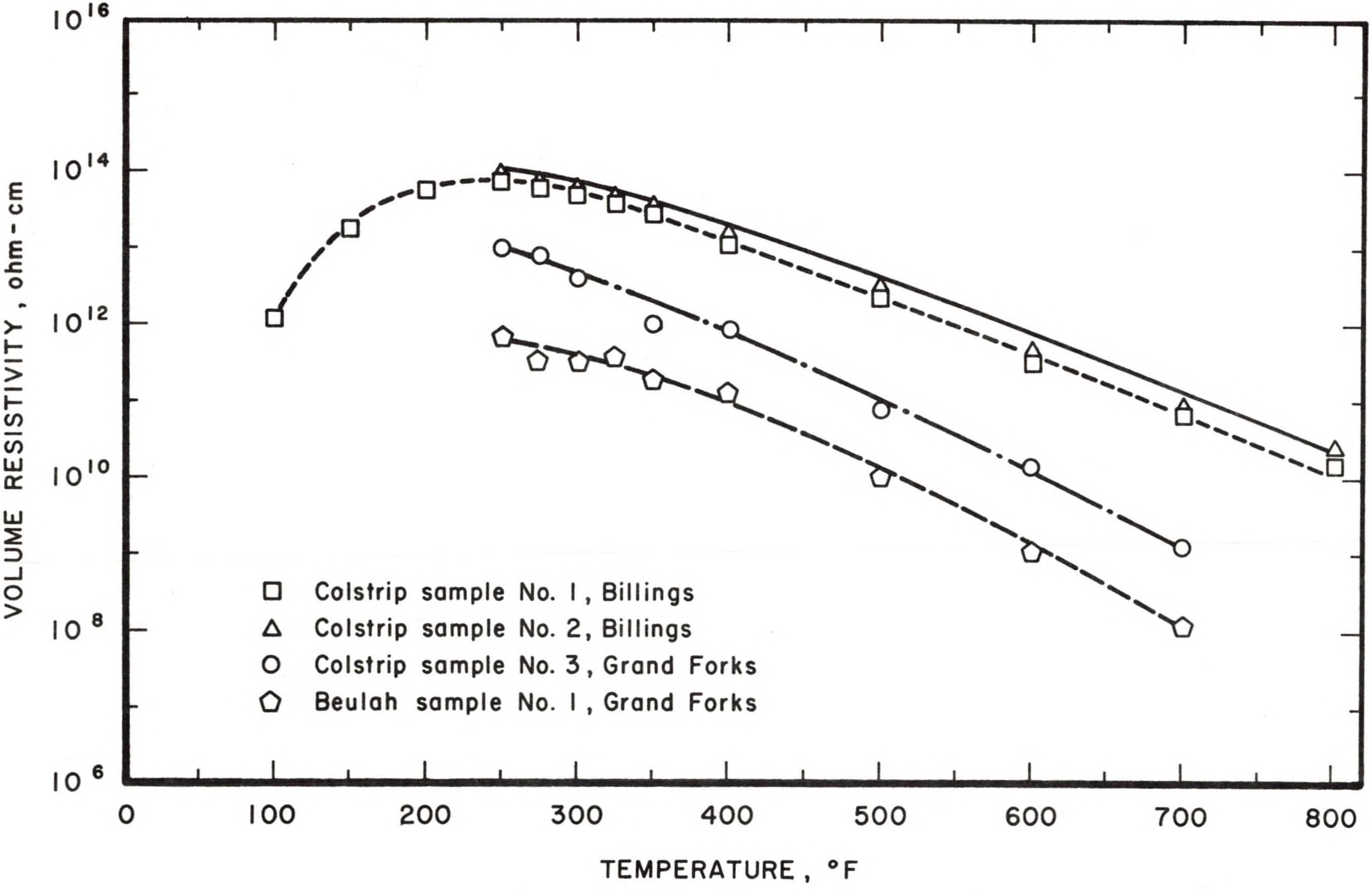

Fig. 10.--Particle resistivity as a function of temperature.

TABLE 5

ASH ANALYSES OF TWO COLSTRIP SAMPLES[a]

Component	Percent of Ash	
	Billings Sample	Local Sample
Loss on ignition at 800° C	0.2	0.6
Silica, SiO_2	42.9	43.1
Aluminum oxide, Al_2O_3	25.2	24.0
Ferric oxide, Fe_2O_3	5.7	9.3
Titanium oxide, TiO_2	0.8	1.0
Phosphorous pentoxide, P_2O_5	0.4	0.4
Calcium oxide, CaO	20.8	13.2
Magnesium oxide, MgO	4.5	5.5
Sodium oxide, Na_2O	0.2	1.1
Potassium oxide, K_2O	0.2	0.4
Sulfur Trioxide, SO_3	1.1	3.4
Total	102.0	102.0

[a] As performed at the Grand Forks Coal Research Laboratory.

The reason for this discrepancy can probably be traced to the measurement of the particle resistivity in a dry nitrogen atmosphere, rather than in the flue gas atmosphere in which the particles are precipitated. As a result, this method of resistivity measurement cannot show the effects of moisture, sulfur trioxide and other conditioning agen in the flue gases. These conditioning agents have been shown to affect surface conduction, which is the dominant mode of charge conduction at th lower temperatures.

It is certainly reasonable to expect that the particle resistivities as measured under actual precipitator operating conditions, would be lowe at the low temperatures than is indicated by these laboratory measurement There might also be some effect on the temperature at which the maximum resistivity occurs. Although these resistivity measurements correctly indicate the general shape of the resistivity curves and are quite correc for high temperature resistivity measurements, where volume conduction dominates, they probably do not indicate realistic values for the low temperatures being considered here.

Table 6 presents the results of size analyses conducted at the Morgantown Research Center. The Colstrip sample was the one used in the precipitator tests. The Beulah sample was a composite of several samples obtained at the inlet of the precipitator with the dust loading apparatus figures 6 and 7, while operating in conjunction with the 75 lb/hr furnace The third sample was collected from the hopper of the pilot electrostatic precipitator following a representative test. A comparison of the result for the two Beulah samples indicates that the electrostatic precipitator removes even the smaller-sized particles well.

The results of the size analyses indicate that the Colstrip fly ash sample from the J. E. Corette plant contained larger particles than those samples collected from the 75 lb/hr furnace at the Grand Forks Laboratory This would partially explain the higher collection efficiency obtained for the Colstrip ash in table 2. The lower efficiency indicated for the Beulah fly ash compared with that for the Velva fly ash, however, can probably be completely attributed to differences in ash composition and particle resistivity.

TABLE 6

RESULTS OF SIZE ANALYSES[a]

Particle Size (Microns)	Cumulative Weight Percent Oversize		
	Colstrip[b]	Beulah[c]	Beulah Precipitator Catch[d]
20.4	23.15	2.97	1.21
19.1	27.64	3.42	1.77
18.4	42.51	4.50	2.39
14.7	58.64	7.58	4.49
7.0	78.10	39.38	32.39
3.2	91.37	67.68	64.67
2.0	96.66	93.17	93.90
0.0	100.00	100.00	100.00

[a] As analyzed on Bahco Classifier at the Morgantown Research Center of the Bureau of Mines.

[b] As collected at the J. E. Corette Power Plant, Montana Power Company, Billings, Montana.

[c] As filtered from flue gas sample at precipitator inlet.

[d] As collected from hopper of electrostatic precipitator.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The pilot electrostatic precipitator, as originally designed and constructed, operated at such high efficiencies, over 99 per cent under all conditions, that it was not possible to use it to compare the effects of various operating conditions on collection efficiency. The high efficiencies were the result of the unit being designed with a very high specific collecting area and a very low gas velocity, as compared with those encountered in large commercial units. Tests on the unit as originally designed did indicate, however, that fly ash from the low-sulfur western coals can be effectively precipitated in such a unit.

Modification of the original unit, decreasing the specific collecting area to one-sixth of the original and increasing gas velocity threefold, reduced the collection efficiency of the unit to between 88 and 95 per cent. This made it possible to study the effects of various factors on precipitator collection efficiency. Data was obtained from tests on the effects of temperature and fly ash source on efficiency.

Reproducibility of the test data for any given day was good, but lack of control over precipitator conditions resulted in some variations from day to day. This lack of reproducibility limits the reliability of the results, but they indicate that for Colstrip fly ash there is an optimum operating temperature near 300° F. Results of the tests run on fly ash from three different western coals, with different coal and ash compositions, reaffirm that the resistivity and, as a result, the operating efficiency of a precipitator are affected by the fly ash source.

There is limited correlation between the laboratory measurements of particle resistivity made in a dry nitrogen atmosphere and the increased precipitator efficiency found at 300° F, in the case of the Colstrip fly ash. However, these laboratory resistivity measurements also failed to predict the increased collection efficiency obtained at the J. E. Corette power station by lowering the operating temperature from 335° to 260° F. Hence, the need for more realistic resistivity measurements - preferably under operating conditions - is indicated.

The results indicate that more experimental work would be required before one could determine the validity of using results obtained from tests on a small pilot electrostatic precipitator to predict performance trends in full-scale units. Time limitations did not allow the investigation of a number of additional factors expected to affect precipitator operation.

Because of the need for more information on the factors affecting th precipitation of fly ash from the western coals, the test work, of which this was the first phase, should be continued and expanded.

It is recommended that a tubular pilot electrostatic precipitator be constructed and tested to determine if it would be a better test unit tha the plate-type precipitator used in these tests. There are indications that representative values of specific collecting area and gas velocity could be more readily realized with such a unit, and that conditions coul be more easily controlled.

Further study of particle resistivity measurements is recommended, the goal being to correlate the resistivity measurements and the pilot precipitator tests in order to make more reliable use of both in predicti electrostatic precipitator operating trends. Consideration should be given to the possibility of integrating a resistivity measuring device into the test apparatus, or, at least, finding a source of more applicabl resistivity measurements.

The studies should be expanded to include the effects of sulfur and other constituents of the coal and ash, rapping procedures, conditioning agents, particle size, and other factors possibly affecting precipitator operation.

Improvements should be made in the equipment used to feed the fly as into the flue gas in order to increase the reliability and controllabilit of the dust loading operation. It may also prove desirable in future tests to burn coal in the 75 lb/hr furnace and add additional fly ash to the gas stream to achieve the desired dust loading, rather than burning natural gas in the furnace as was done here.

It would appear that a pilot electrostatic precipitator test program a desirable and productive undertaking. Every effort should be made to expand the test program to allow adequate and accurate reproduction of actual conditions, in order to provide data that is accurate and useful t the designers of electrostatic precipitators for plants utilizing the western coals.

APPENDIX

The quantities as measured in the precipitator tests and used in the subsequent calculations were:

A = Area of flue in square feet.

d = Diameter of sampling nozzle in inches.

P_b = Barometric pressure in inches of mercury.

P_m = Average suction at test meter in inches of mercury.

P_s = Average absolute pressure in the flue in inches of mercury = P_b - flue vacuum.

t = Length of test in minutes.

T_m = Average meter temperature in degrees Rankine.

T_s = Average temperature of the flue gas in degrees Rankine.

V_m = Volume of gas sample, as measured by test meter, in cubic feet.

V_w = Volume of water condensed in cubic centimeters.

W_t = Weight of dust sample in grams.

$(\Delta P)^{1/2}$ = Average square root of the velocity heads, in inches of water, measured at each of the sampling points by the pitot tube.

The following calculations were used to determine; 1. volume flow rate, 2. deviation from isokinetic sampling, and 3. dust loading (37).

1. Volume flow rate:

Average flue gas velocity in feet per second,

$$V_s = 2.48 \times (\Delta P)^{1/2} \times (T_s)^{1/2} \times \frac{29.92}{P_s}^{1/2}.$$

Gas volume flow rate, in cubic feet per minute,

$$V_F = V_s \times A \times 60.$$

2. Deviation from isokinetic sampling:

Volume of condensate converted to vapor volume, in cubic feet, at meter conditions,

$$V_v = .00267 \times \frac{V_w \times T_m}{P_b - P_m} .$$

Meter correction factor for condensed water,

$$M_c = \frac{V_m}{V_m + V_v} .$$

Corrected meter rate, in cubic feet per minute,

$$R_c = 0.33 \times \frac{T_m}{T_s} \times V_s \times d^2 \times \frac{P_s}{P_b - P_m} \times M_c .$$

Actual average meter rate, in cubic feet per minute,

$$R_m = \frac{V_m}{t} .$$

Average deviation from isokinetic conditions, in per cent.

$$R = \frac{R_m - R_c}{R_c} \times 100.$$

3. Dust-loading:

Total gas volume sampled, in cubic feet per minute, converted to flue conditions,

$$V_t = (V_m + V_v) \times \frac{P_b - P_m}{P_s} \times \frac{T_s}{T_m} .$$

Dust loading, in grains per cubic foot,

$$\text{grains/cu ft} = 15.43 \times \frac{W_t}{V_t} .$$

Dust loading, in pounds per hour,

$$\text{lb/hr} = \text{grains/cu ft} \times V_F \times \frac{60}{7000} .$$

The above calculations were done for both the inlet and outlet test positions.

The efficiency of the electrostatic precipitator, in per cent, was determined by comparing the dust loading, in pounds per hour, at the inlet and outlet of the unit.

$$\text{Efficiency} = \frac{(\text{lb/hr})\text{in} - (\text{lb/hr})\text{out}}{(\text{lb/hr})\text{in}} \times 100.$$

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