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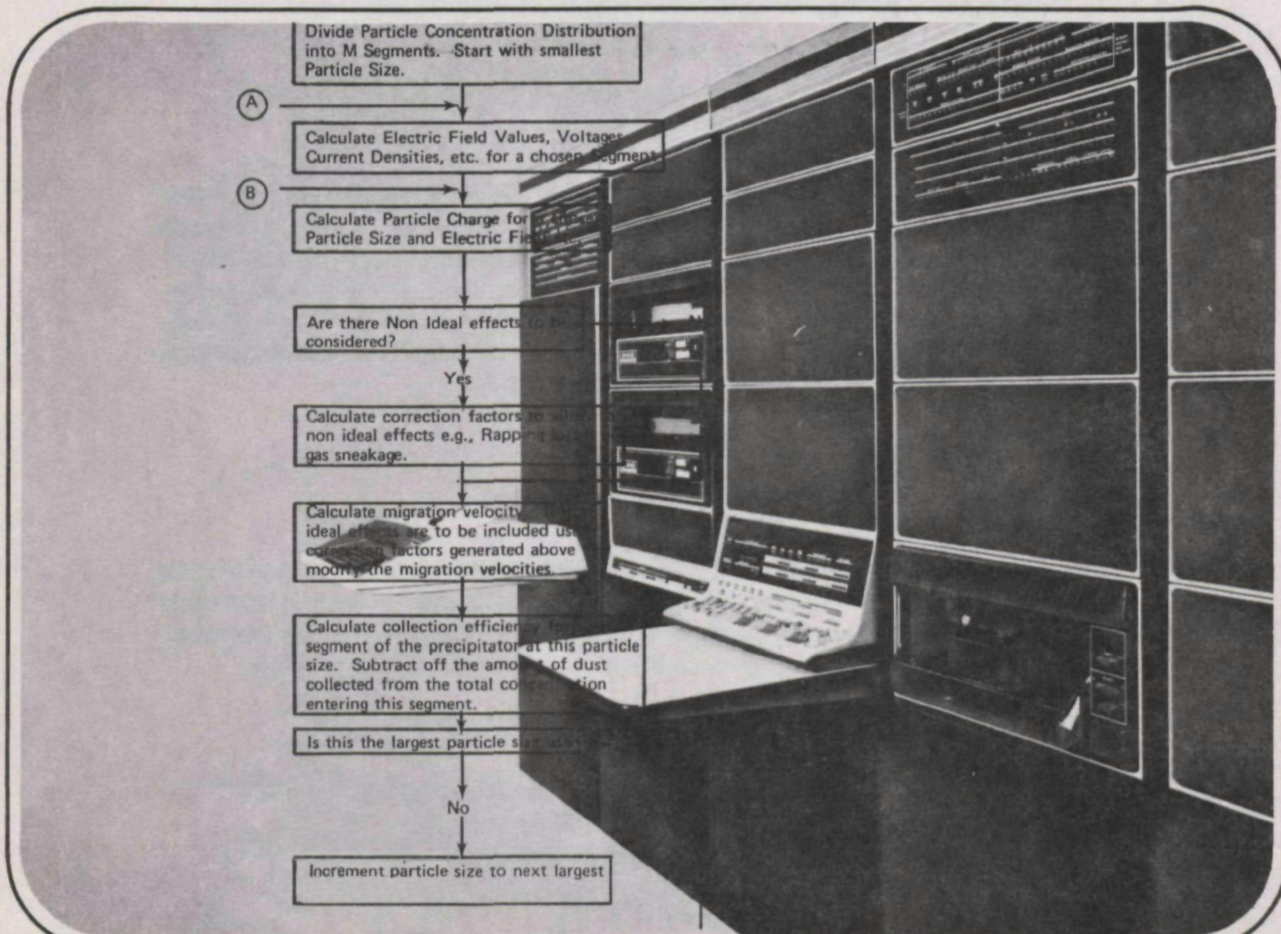
AN ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL



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PARTICULATE CONTROL HIGHLIGHTS: AN ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL

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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.

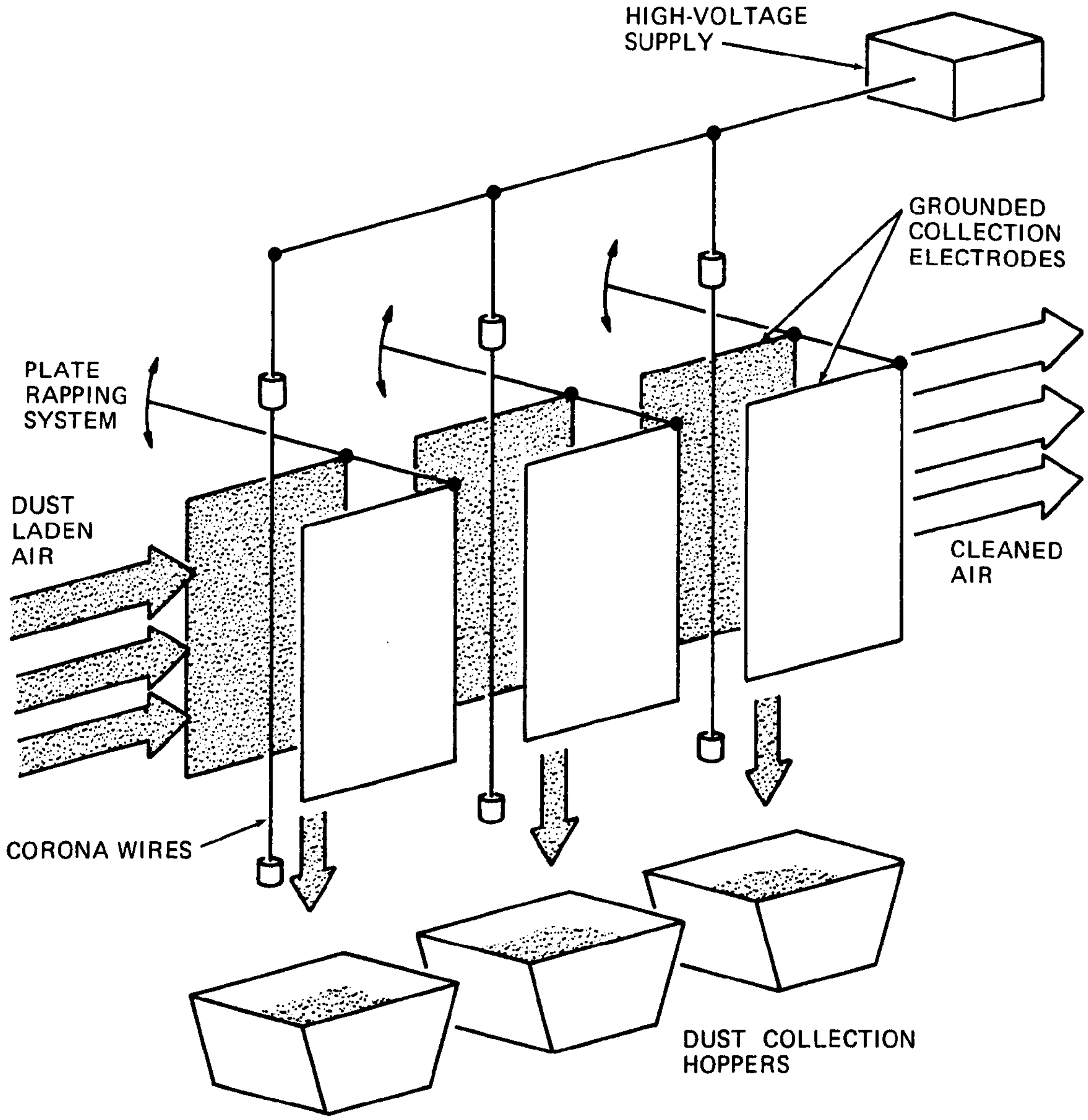

Figure 1. Schematic diagram of an electrostatic precipitator collecting dust.

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

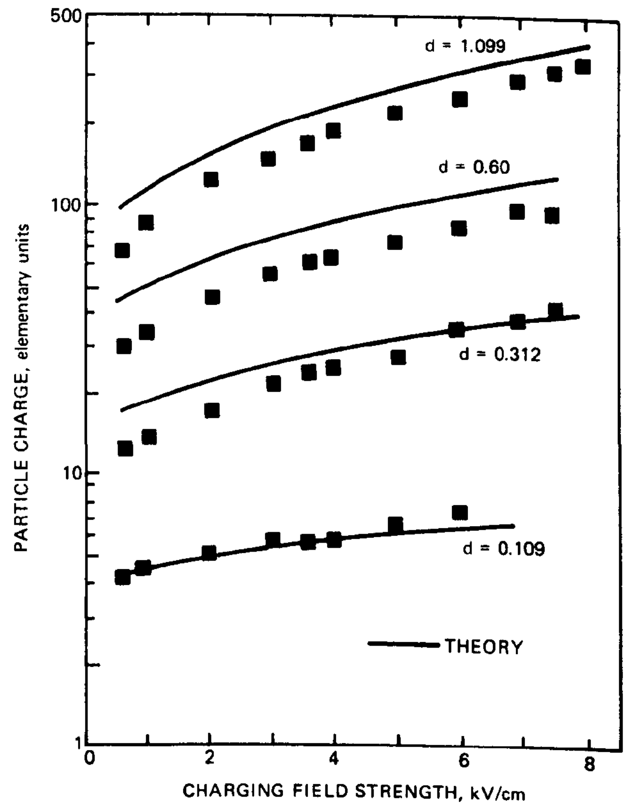

Figure 2. Particle charge vs. electric field strength for laboratory aerosols of four different diameters. $N_0t = 1 \times 10^{13}$ sec/m^3.

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

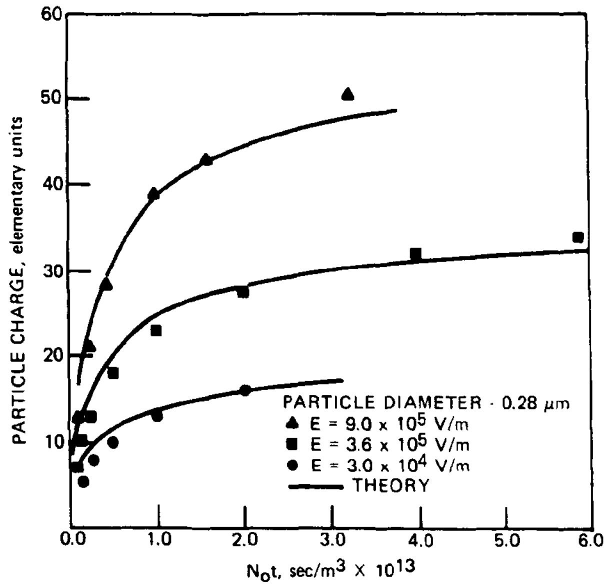

Figure 4. Particle charge vs. N_0t for three values of electric field.

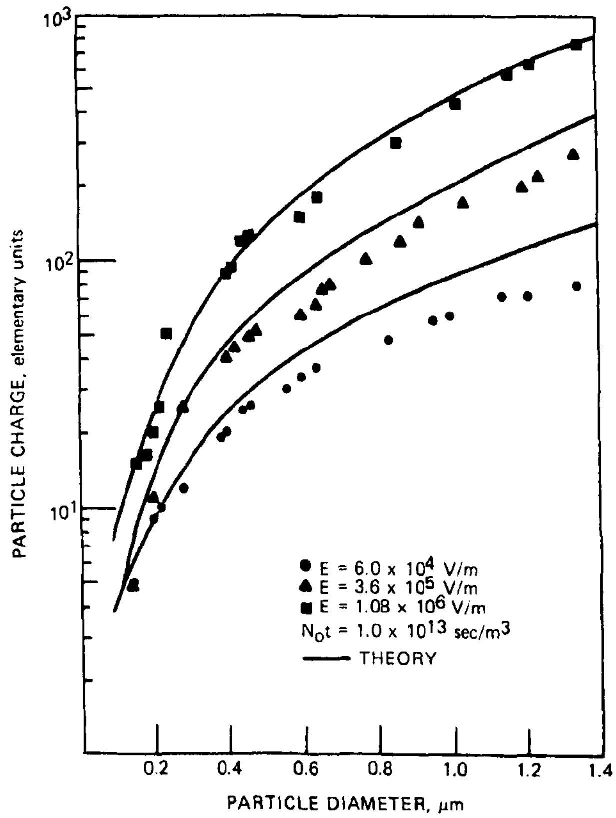

Figure 3. Particle charge vs. diameter for three values of electric field.

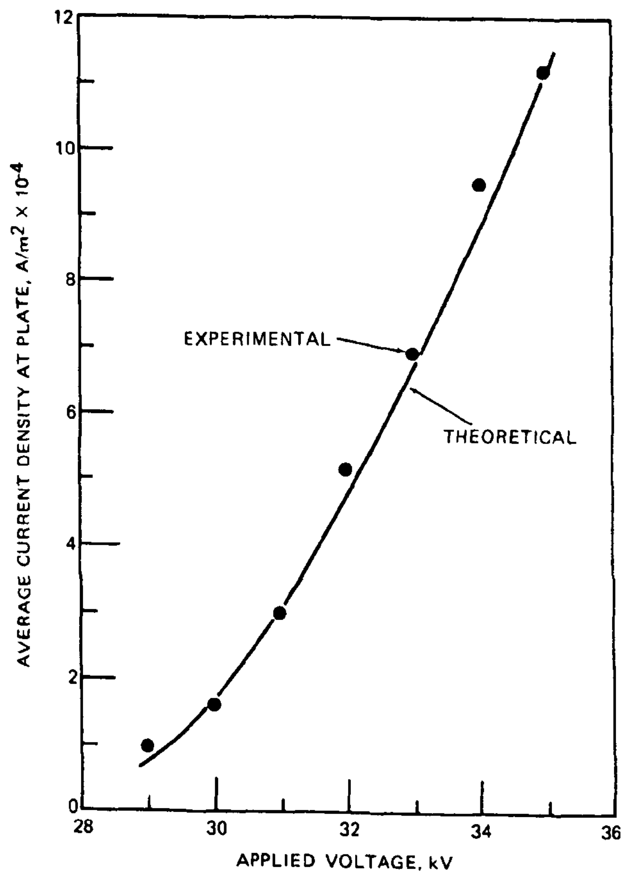

Figure 5. Average current density at the collection plate vs. the corona voltage.

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

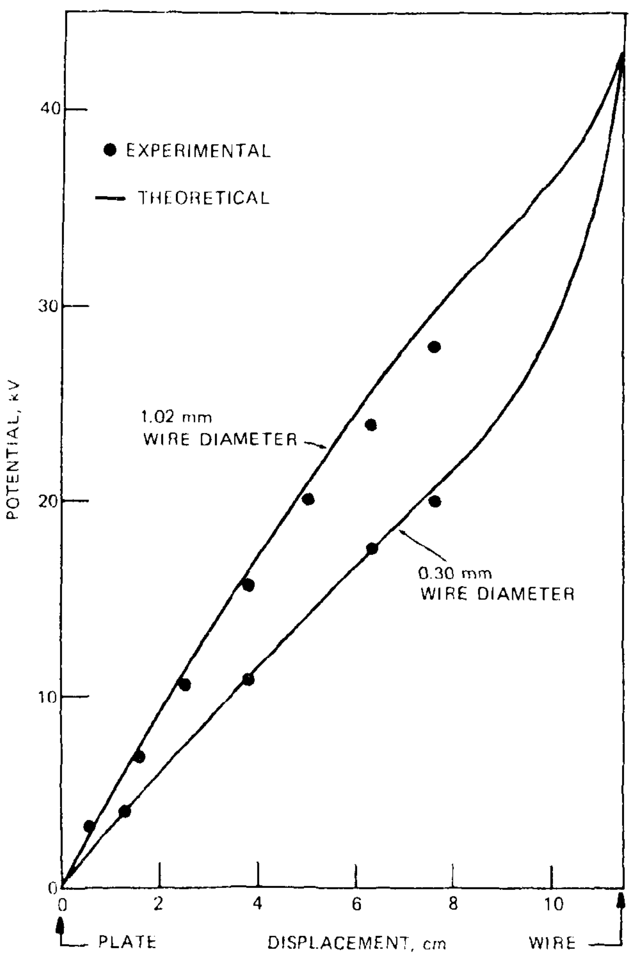

Figure 6. Electric potential vs. position between the corona wire and collection plate.

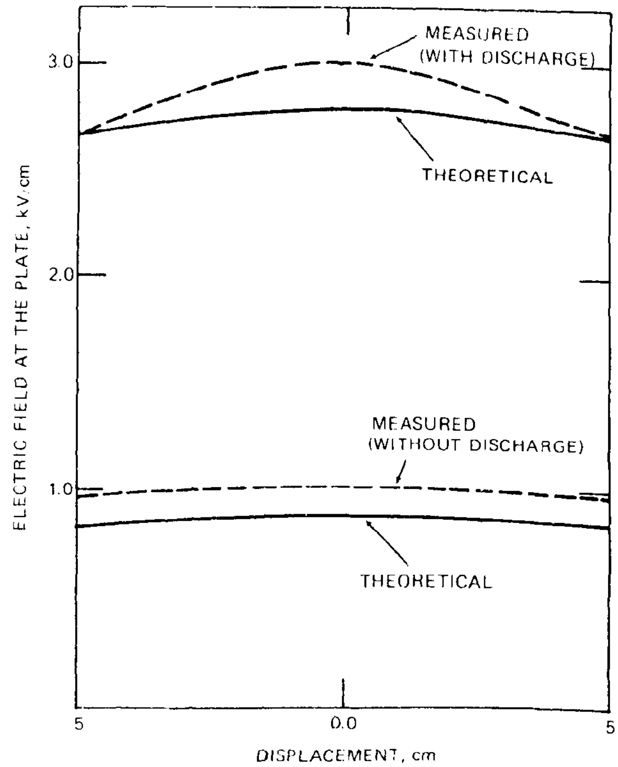

Figure 7. Electric field of the collection plate vs. position. Corona wires are directly across from positions −10, 0, 10,

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.

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

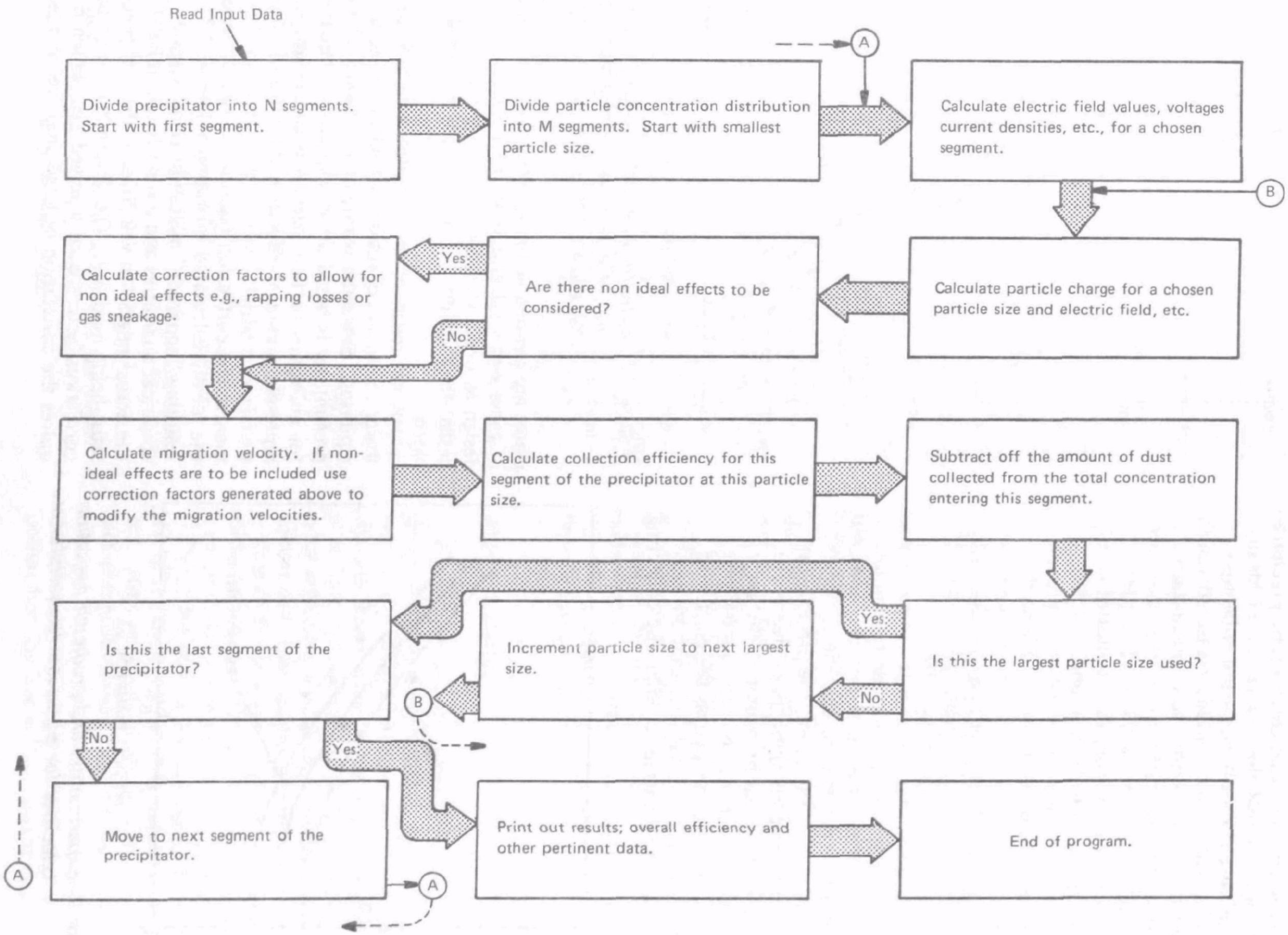

Figure 8. Simplified flow chart of the computer program to calculate precipitator performance.

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.

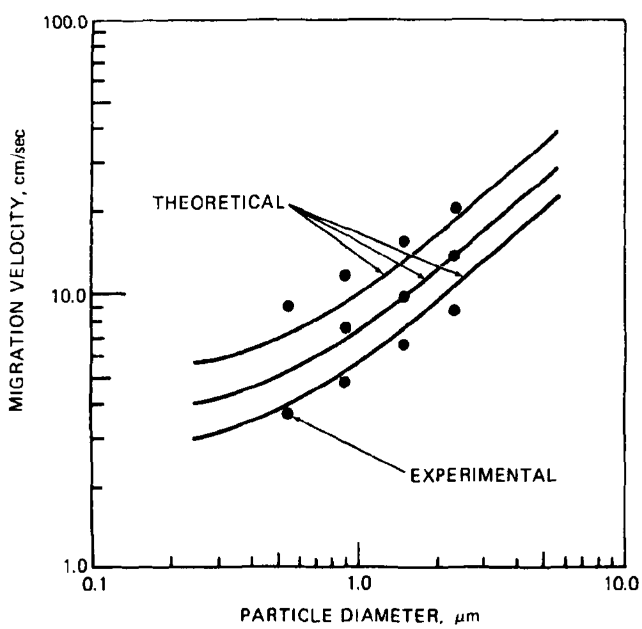

Figure 9. Experimental and predicted migration velocities for a laboratory precipitator.

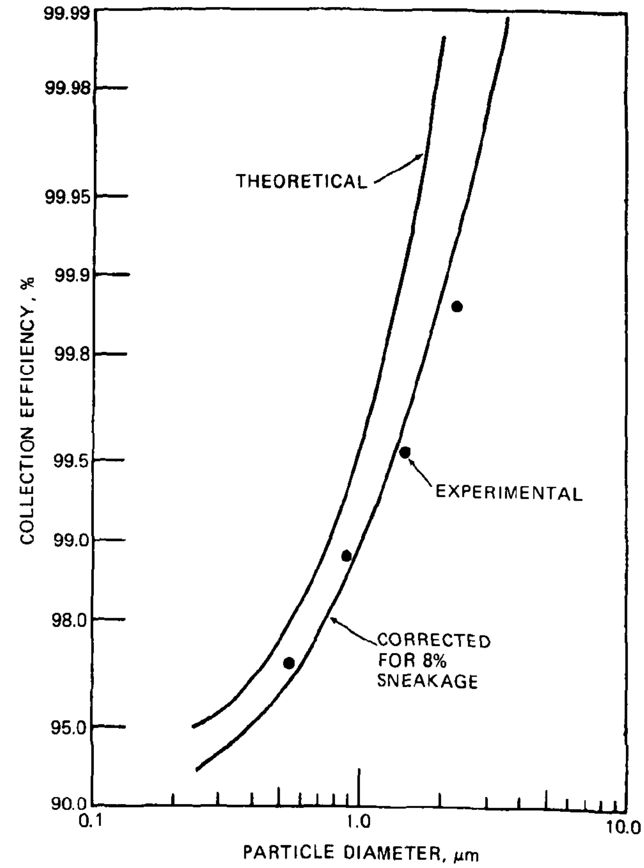

Figure 10. Experimental and predicted collection efficiency vs. particle diameter for a laboratory scale precipitator.

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.

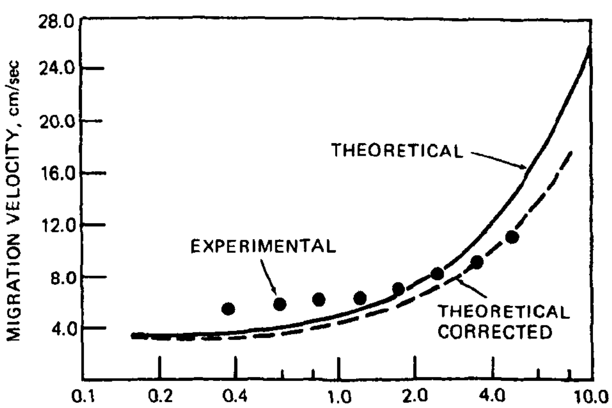

Figure 11. Experimental and predicted migration velocity vs. particle diameter for a full scale precipitator.

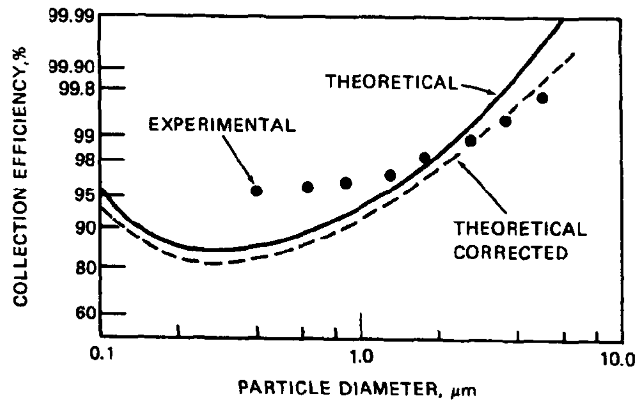

Figure 12. Experimental and predicted migration velocities vs. particle diameter for a full scale precipitator.

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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Mathematical Models	Dust	Collection Efficiency		11G
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