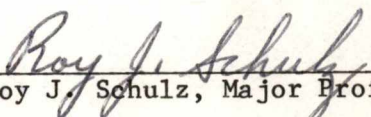
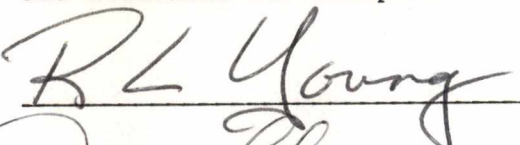
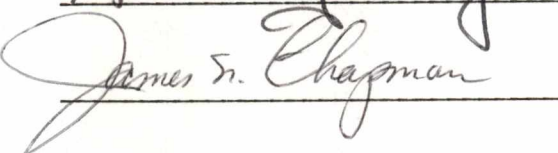


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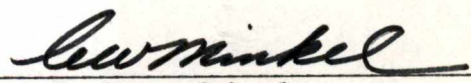
I am submitting herewith a thesis written by R. Keith Morehead, entitled "A Parametric Study of Electrostatic Precipitator Design Criteria for High Temperature Coal Fired MHD Power Generation Systems." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.


Roy J. Schulz, Major Professor

We have read this thesis
and recommend its acceptance:

Accepted for the Council:


The Graduate School

A PARAMETRIC STUDY OF ELECTROSTATIC PRECIPITATOR
DESIGN CRITERIA FOR HIGH TEMPERATURE COAL
FIRED MHD POWER GENERATION SYSTEMS

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

R. Keith Morehead

March 1985

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ABSTRACT

This work involves utilization of an established computer code to determine the potential of electrostatic precipitator designs to remove fine particles from the exhaust stream of an experimental high temperature coal fired MHD power generation system. Properties of the particulate and exhaust gas are discussed. Relationships of precipitator size to performance for different values of precipitator plate spacing, particle size distribution, and electrical operating conditions are determined. These are evaluated to determine the precipitator size required to meet New Source Performance Standards in each case.

The electrical operating conditions are predicted to have the most significant effect on performance. This is due to a low particulate layer resistivity and a phenomenon called ion quench related to the particle load and distribution. Precipitator size requirements ranging in SCA from 300 to 450 $\text{ft}^2/10^3$ acfm are predicted primarily as a result of possible variations concerning electrical conditions.

The results of this study are applicable not only to coal fired MHD topping cycle systems but also to other processes (coal burning or otherwise) in which the effluent contains high loading of particles with layer resistivity in the range of 10^9 to 10^{10} ohm-cm, particularly where a portion of these particles are submicron in size.

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I. INTRODUCTION

In an era of dwindling supply of available energy, accompanied by the degradation of earth's environment, more efficient use of our natural resources is essential. One method which shows promise for improving utilization of our coal resource is adaptation of the magnetohydrodynamic (MHD) generator to coal fired power production.

The advantages of successfully implementing an MHD process in combination with a coal fired electrical power plant are unquestionable [1]. The efficiency (i.e., overall thermodynamic efficiency) of the modern plant is, as in other power cycle devices, limited by the maximum temperature at which heat is input to the process. Over the years, transition to the use of pulverized coal and better combustor designs have raised obtainable furnace temperatures to the point that the maximum temperature is limited by the other properties of the equipment, in particular, the maximum temperatures that can be withstood by heat transfer surface materials.

An MHD generator can increase the cycle efficiency of coal fired steam facilities by taking the hot gases from coal burned at nearer optimum conditions, removing work in the form of electrical power and passing this effluent to the boiler at an energy state compatible with efficient steam production.

By injecting a seed material, usually a salt of potassium or cesium into the combustor, ionization is induced in the hot combustion

gases [2]. The resulting plasma is a conducting medium which, when passed through a magnetic field, generates electrical power directly.

The MHD topping process as it is called, however, produces some special problems for the downstream components designer. One of the major obstacles relates to the need to recover the seed material from the exhaust stream and the necessity of meeting environmental standards. The addition of the seed to the combustion of a very finely pulverized coal produces, at downstream stations, an effluent containing a high quantity of particulates, a significant portion of which are in a submicron size range and are difficult to remove from the stream.

The electrical properties of these particulates suggest electrostatic precipitation may be the method of choice for removing them. The principal advantage of an electrostatic precipitator, or ESP, is that very little pressure drop is usually incurred across the length of the equipment. While an ESP designed to perform comparably to a baghouse filter method of particulate removal applicable to the same process will usually require greater capital outlay, operating costs of a well designed precipitator will sometimes be low enough to make it economically attractive.

Currently, research is in progress at UTSI to determine whether an ESP is suitable to meet MHD system requirements. The studies are being conducted at the Coal Fired Flow Facility (CFFF), an experimental MHD facility located at The University of Tennessee Space

Institute (UTSI), Tullahoma, Tennessee. The work is being conducted by the Energy Conversion Research and Development Programs (ECP) organization at UTSI and with funding from the United States Department of Energy.

The objective of the computations described in the sections that follow has been to provide information to support and define the selection of a pilot model ESP for the CFFF and to point out several critical areas of adjustment that will be required in order to attain the peak operating conditions of the precipitator once installed. The study forms a basis for future work to determine first cost and operating cost for full scale power plants from which comparisons can be made with other particulate removal devices.

II. THE WIRE-PLATE PRECIPITATOR

Principles of Operation

Most ESP designs used in commercial power plants today are the wire-plate type, as shown in Figure 1, consisting of tall narrow ducts with a series of vertical wires in the center of the duct, evenly spaced downstream. The wires, which are supplied with pulsing negative direct current power, usually obtained from an unfiltered rectified alternating current, are called the emitting electrodes. Grounded sidewalls of the ducts form the collecting electrode plates. The plate surfaces are usually shielded in some manner, such as that shown in Figure 1, to reduce the likelihood that accumulated particles will be re-entrained into the effluent stream by the scrubbing effects of the stream.

An operating voltage, typically on the order of 20 to 50 kv, is applied between the wires and plates of an electrostatic precipitator. The electric field is very intense near the wire and initiates ionization by means of a corona discharge. This process is depicted in Figure 2. The result is that a large number of negative ions are created in the "quiescent zone" (in electrostatic terminology) between the corona region and the plates by means of electron attachment to electronegative molecules such as SO_2 , O_2 , and CO_2 . Note that the region of corona glow is exaggerated in Figure 2, and usually represents only about one percent of the interelectrode area.

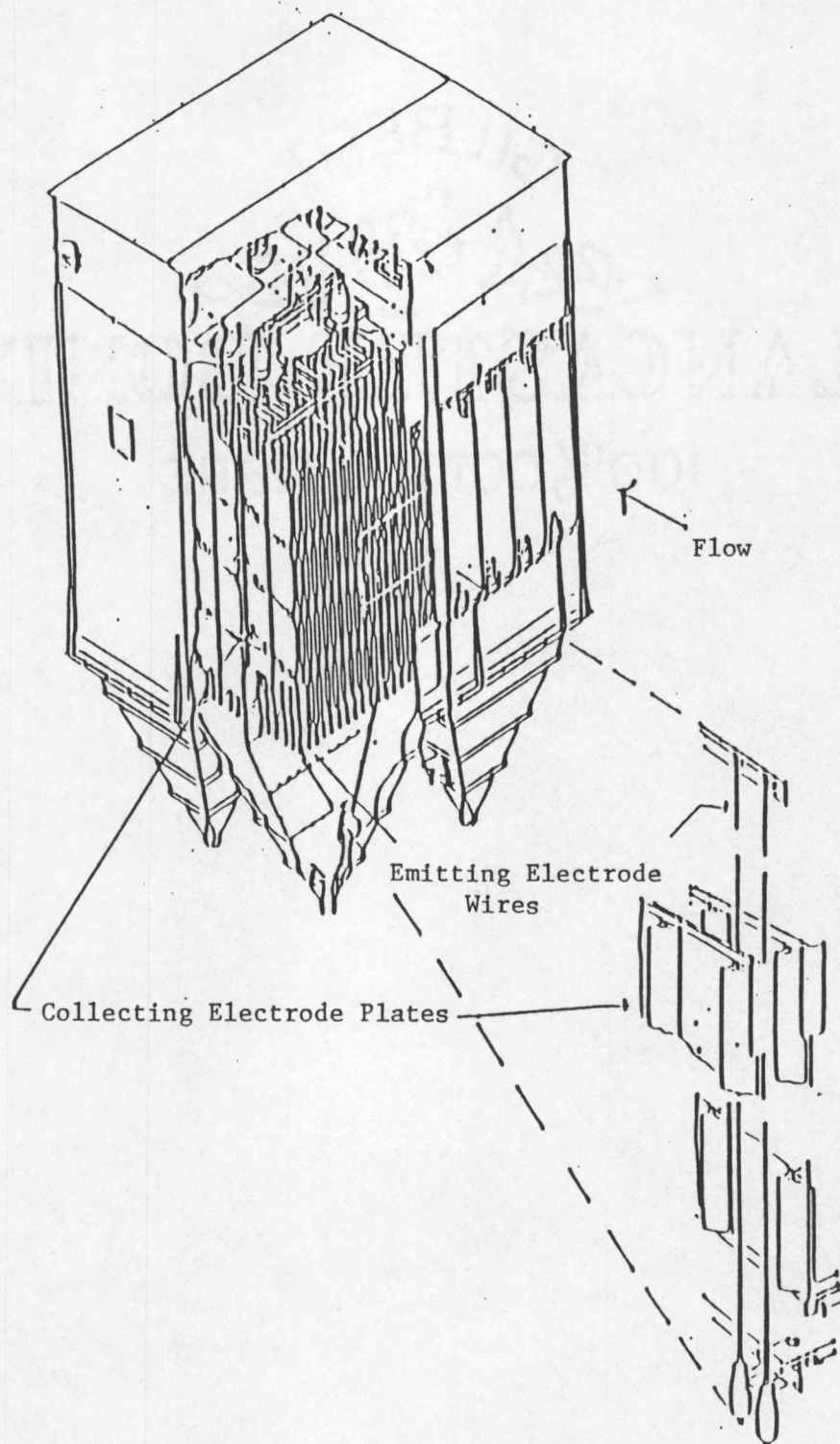


Figure 1. The Wire-Plate Electrostatic Precipitator.

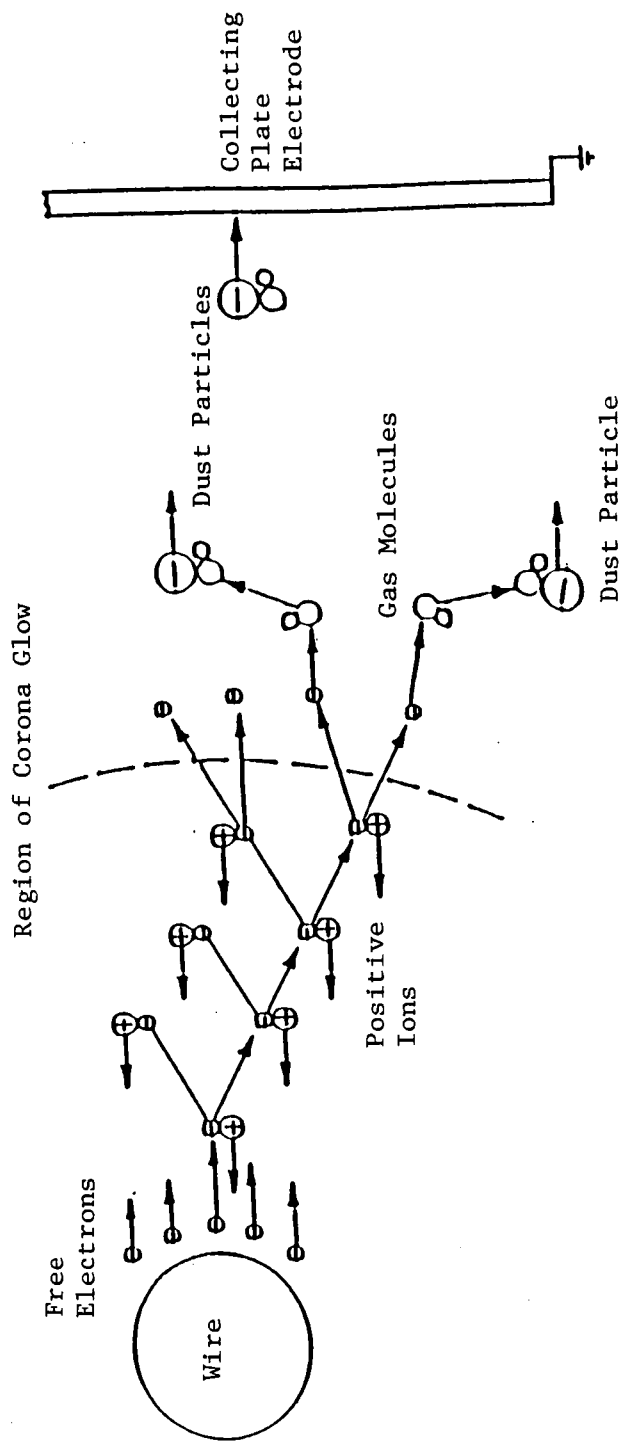


Figure 2. Ionization and Particle Charging in the Wire-Plate Precipitator.

The field drives the negative ions outward where many impinge on particulates in the gas stream. The particulates accumulate sufficient electric charge for the field to drive them to the collecting electrodes.

Electric forces cause the charged particles to form a layer on the collecting electrode plates. The plates are rapped or hammered cyclically, typically at one minute intervals, so that the outer portion of the particulate layer will detach from the plate and fall in a "slip-stick" manner down the plate into a hopper below for removal.

The component of charged particle velocity in the direction of the plates is of primary importance to the operation of the device. This component of velocity is called the electrical drift velocity, or migration velocity, and results from the electrical and viscous drag forces acting upon a suspended charged particle. The net result of these forces can be determined by integrating the equation of motion for the particle. The magnitude of this velocity component near the collection plate is shown in reference 3 to be

$$w_p = \frac{qE_p C}{6\pi a \mu} \quad (1)$$

where w_p = migration velocity near the collection electrode of a particle of radius "a" (m/sec),

q = charge on particle (coul),

E_p = electric field near the collection electrode (volt/m),

a = particle radius (m),

μ = gas viscosity (kg/m-sec),

C = Cunningham correction factor, or slip correction

$$\text{factor} = (1 + A'\lambda/a),$$

where $A' = 1.257 + 0.400 \exp(-1.10 a/\lambda)$, and

λ = mean free path of gas molecules (m).

The variation of theoretical migration velocity with particle size is shown in Figure 3 for a prescribed set of operating conditions. It has been established that migration velocity usually reaches a minimum for particles with diameters of .2 to .5 μm [4]. This can be explained by the complex interaction of field and diffusion charging process as described in reference 4.

Due to electric wind effects and transfer of momentum from the particles to the gas, laminar flow never occurs in industrial precipitators and as discussed by White [5], its existence is unlikely even in low velocity laboratory tests. The instantaneous gas velocities in the turbulent stream are then usually much greater than the average migration velocity. Migration velocity for particles smaller than about 0.6 μm in diameter is insignificant compared to the turbulent fluctuation velocities of the gas. The collection of these small particles then becomes dependent on transport by turbulent diffusion transverse to the mean flow direction. This diffusion thus projects them into the region of low velocity flow adjacent the plates where capture is assured.

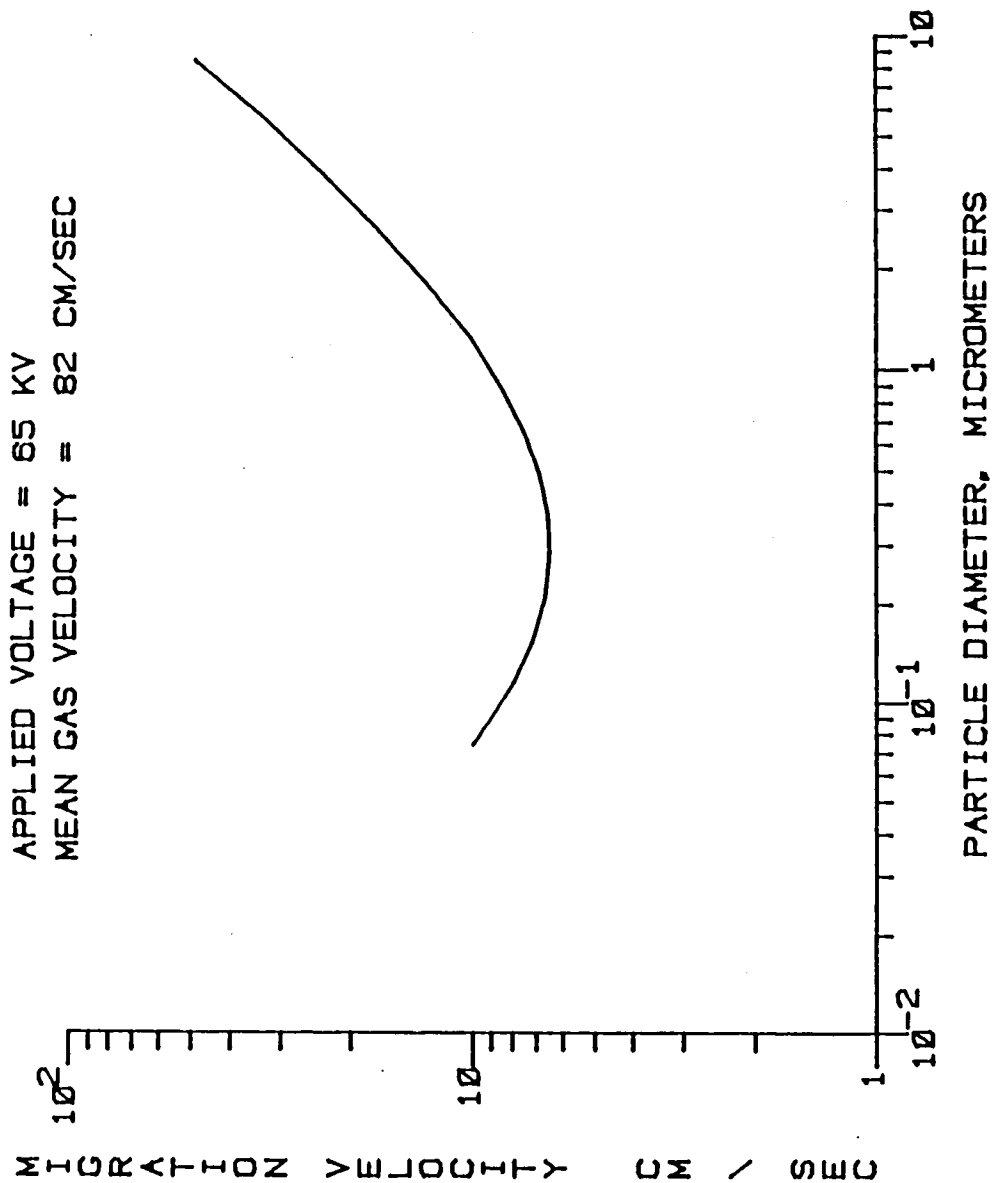


Figure 3. Variation in Theoretical Particle Migration Velocity with Particle Size.

An exponential relationship for collection in a precipitator was first observed by Deutsch and Anderson [5]. White explained this relationship using probability concepts and defining the effective thickness of the boundary "capture-layer" as

$$\delta = w_p \Delta t = \frac{w_p \Delta l}{v}$$

where Δl is a length increment of the precipitator and v is the mean flow velocity. A formulation of the equation for collection developed by White as described in reference 5 is

$$\eta_m = 1 - \exp(-A_p w_p / Q), \quad (2)$$

Where η_m = the collection fraction in a monodisperse aerosol,

A_p = collection area (M^2),

w_p = migration velocity near the collection electrode of the particles in the monodisperse aerosol (m/sec), and

Q = gas volume flow rate (m^3/sec).

The simplifying assumptions on which the derivation of equation (3) is based are:

- (1) The gas is flowing in a turbulent pattern at a constant, mean forward velocity.
- (2) Turbulence is small scale, fully developed, and completely random.
- (3) The particle migration velocity near the collecting surface is constant for all particles and is small compared to average gas velocity.

- (4) There is an absence of disturbing effect, such as particle re-entrainment, back corona, particle agglomeration, or uneven corona.

Faulkner and Dubard [3] make the following comments concerning the applicability of equation (2);

"In industrial precipitators, the above assumptions are never completely satisfied but they can be approached closely. With proper design, the ratio of the standard deviation of the gas velocity distribution to the average gas velocity can be made to be 0.25 or less so that an essentially uniform, mean forward-velocity would exist. Although turbulence is not generally a completely random process, a theoretical determination of the degree of correlation between successive states of flow and between adjacent regions of the flow pattern is a difficult problem and simple descriptive equations do not presently exist for typical precipitator geometries. At the present, for purposes of modeling, it appears practical and plausible to assume that the turbulence is highly random. For particles larger than 10 μm diameter, the turbulence does not dominate the motion of these particles due to their relatively high migration velocities. Under these conditions, equation (2) would be expected to underpredict collection efficiencies. The practical effect in modeling precipitator performance will be slight, however, since even equation (2) predicts collection efficiencies greater than 99.6% for 10 μm diameter particles at relatively low values of current density and collection area....."

Variables Affecting Performance

A general range of typical parameters of ESP designs from various sources [4,6,7] is shown in Table I. Specific collection area or SCA, which is collection plate area per unit flow volume, is the most commonly used means of specifying precipitator size. Caution must be used, however, when comparing precipitators on this criterion. For a given application, units of equal SCA and of similar type and quality

Table I
Typical ESP Parameters

Parameter Name	Dimension
Discharge Wire Diameter	0.10 - .015 inch
Wire-Wire Space	4-12 inches
Plate-Plate Space	8-12 inches
Specific Collection Area	100-750 ft ² /10 ³ acfm
Current Density	10-100 μ A/ft ²
Gas Velocity	2-8 ft/sec
Collection Efficiency	80-99.9%
Operating Voltage	20-55 kV average

may differ from each other only in plate height, length, and/or spacing but may not perform similarly. Interrelated effects of such variations in electric field, flow velocity, etc., may considerably affect collection in some cases and additional structural differences such as wire diameter and spacing, method and frequency of rapping, and degree of flow stream baffling might add to this difference.

The importance of the electric operating conditions is stated in Reference 3;

"The performance of a precipitator which has good mechanical and structural features will be determined primarily by the electrical operating conditions. Any limitations on applied voltage and current density will be reflected in the optimum collection efficiency which can be obtained."

The electric field produced by the operating applied voltage directly affects the rate and maximum value of charge accumulation on the particles, and in combination with the field strength, has a corresponding relation to migration velocity and collection efficiency (equations (1) and (2)).

The collected particulate layer has a very significant effect on electrical conditions. It is known that in the collection of ash materials forming highly resistive layers ($>10^{11}$ ohm-cm) such as ash from coals with low sodium and sulfur mineral content, a phenomenon called back corona occurs. At relatively low applied voltages a potential difference develops across the collected particle layer of sufficient magnitude to promote ionization in the interstitial spaces.

A supply of positive ions is created which flows toward a wire, neutralizing negatively charged particles and free ions in stream, degrading performance.

When voltage is applied in collectors where less resistive material accumulates, ionization can occur in the layer, but a smaller proportion of the voltage drop between plate and wires now occurs there. Accompanied by positive ion formation near the layer surface, the resulting potential difference across the interelectrode space may become large enough that sparks propagate from the layer toward the wire. The resulting short duration interruptions of the field are known as spark breakdowns or "sparkovers". In collection of layers of medium resistivity (10^{10} to 10^{11} ohm-cm) the peak performance applied voltage is often limited by the frequency of breakdown, the spark rate.

When layer resistivity is very low, another problem is sometimes encountered. The electric forces across the layer affect the cohesiveness of the particles to each other as well as the plate. Particles, especially those of smaller size and ones which do not agglomerate well, tend to become re-entrained in the flow stream.

In Figure 4, plots of particle layer resistivity versus temperature are shown. One set of data was obtained from laboratory studies of samples of particulate from two tests made at the CFFF. The other data shown represent a moderately resistive fly ash, described in Reference [4]. The resistivity of all samples is near

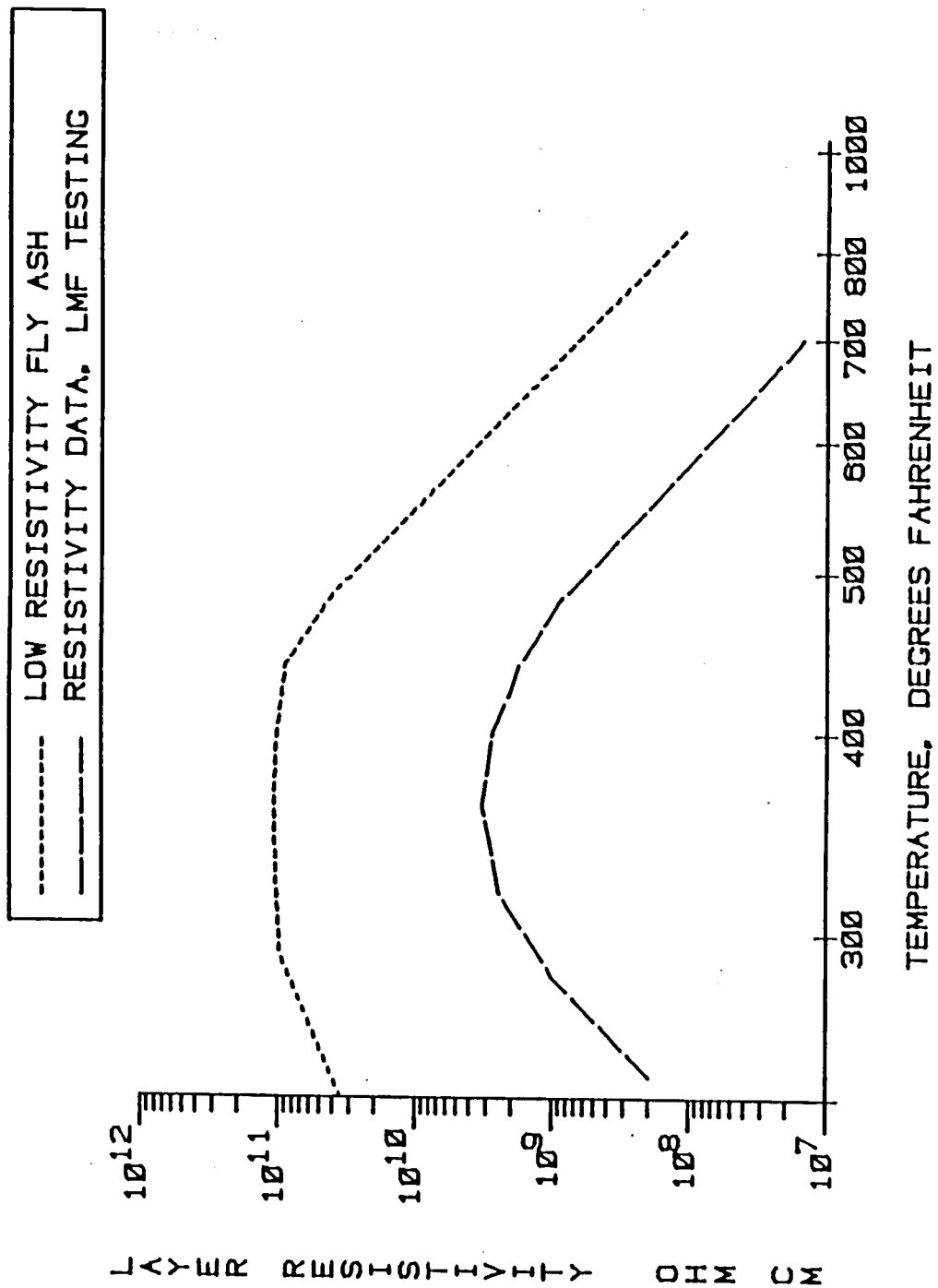


Figure 4. Effects of Temperature on Layer Resistivity.

peak at a temperature of 350°F, a temperature condition considered typical of commercial power plant ESP installations known as, a "coldside" condition, in which the precipitator is located downstream of the air preheater. For fly ash, the resistivity is bordering the level at which back corona can be expected, while for the CFFF samples it is in a region in which a high applied voltage can be used. This is the main reason for the expectation of good performance from an electrostatic precipitator for removing particles in a "coldside" MHD application.

For "hotside" installation conditions of approximately 700°F, the fly ash resistivity drops to a more desirable level, while the CFFF samples drop well below 10^8 ohm-cm. The uncertainties encountered in low resistivity applications include the possibility of re-entrainment and unknown factors concerning optimum electrical conditions required for particle collection. For this reason, no attempt has been made in the present study to evaluate "hotside" ESP performance for coal fired MHD applications.

Also affecting electrical operating conditions in an ESP are the particle load and size. Ions and charged particles produce electric fields which add to the electrostatic field in the interelectrode space. This is known as space charge. Since a significant portion of the current can be carried by the particulate with its low mobility, the space charge at the precipitator inlet can be large. Heavy concentrations of large particles or moderate concentrations of fine

particles entering the precipitator may result in a phenomenon called, alternatively, ion quench or corona suppression. The electric field in the region of the emitting electrode wire is suppressed by the particulate space charge to the degree that ionization rate and current density are significantly reduced. White [5] cites a case in which current density is decreased from clean gas currents on the order of milliamps to microamps by the infusion of only a few tenths of a grain per cubic foot of particles with diameter of 1 μm or less. As particulate is removed, a greater percentage of the current is carried by gas ions and the space charge effect is reduced. The effect of the reduction of dust concentration as particles are collected is to shift the voltage-current curves toward a higher current for a given voltage, as the gas progresses through the precipitator [4].

Considerable degradation of performance may occur if the ion quench effect is strong in a considerable portion of the precipitator's electrical length, i.e., if sufficient particles are not removed in initial length increments to reduce the space charge effect.

Particle size has multiple effects on space charge. As described in this section, migration velocity reaches a minimum for particles with diameters of .2 to .5 μm . However, the charge obtained per unit mass and the resulting space charge for a given mass load increases rapidly with decreasing particle diameter. The result of having numerous small particles in an exhaust stream is the attachment of a considerable portion of the available charge to highly immobile charge carriers.

Also of importance in the determination of electrical conditions is the distribution of the electric field. A field distributed such that a relatively large portion of the overall voltage drop occurs near the emitting wire results in a relatively higher rate of ionization and therefore higher current density. However, the accompanying decrease in field near the collecting plate causes a reduction in migration velocity for a given value of particle size and charge. This suggests that a more intense electric field near the wire is desirable near the entrance of the precipitator, where essentially uncharged particles dominate the stream, and a relatively stronger field near the plates is needed toward the exit, where the particles are nearly saturated with charge [6].

The electric field distribution is affected by dimensional characteristics of the precipitator, in particular, the wire to plate spacing, the wire diameter and the wire to wiring spacing. Use of relatively small wire diameters and duct widths result in a more intense field in the region of the wires than that seen with larger values for these parameters. Field strength near the wire is strongest for an optimum spacing between wires, however, this optimum value is dependent on plate spacing, wire diameter and exhaust gas properties. The degree of these effects is discussed in Reference 4.

Other factors limiting precipitator performance are combined under the term "nonideal effects". The gas flow nonideal effects include gas sneakage, which is bypassing of the electric field by the

flow stream, and nonuniform gas velocity distributions. Both of these effects can be diminished by proper baffle design in the equipment which leads to uniform velocity fields.

Re-entrainment, which can become extreme for reasons other than the low resistivity condition mentioned, occurs to some degree in all commercial precipitators and is increased in proportion to the levels of gas flow nonidealities. The intensity and frequency with which the plates are hammered are the primary variables which determine the magnitude of rapping re-entrainment. Unfortunately, the only applicable method for determining optimum values of these parameters and the amount of re-entrainment involved is usually by post installation experiment with the ESP. Re-entrainment is also the result of scouring of the outside of the collected layer by the flow stream, of electrical effects related to excessive sparking and of sweepage of the material from the hopper back into the flow stream.

Several important variables of the precipitation process, including those discussed, are shown in Tables II, along with values input to a computer model of electrostatic precipitation which will be discussed in the following section.

Table II
ESP Computer Code Input Variables

Parameter Type	Variable Name	Input Value(s)
Primary Constraints	gas temperature	350°F
	particle load	4.72 gr/ft ³
	flow volume	8500 cfm
	flow velocity	1 - 3.5 ft/sec
	required performance	99.6% efficiency (.4% penetration)
Particle Properties	particle size	study variable
	particle density	2662 kg/m ³
	layer resistivity	3.5 x 10 ⁹ ohm-cm
	layer breakdown strength	8.0 x 10 ⁵ volts/m
Miscellaneous Exhaust gas Properties	Pressure	1 atmosphere
	Viscosity	2.4 x 10 ⁻⁵ kg/m-sec
	Ionic mobility	2.7 x 10 ⁻⁴ m ² /v-sec
ESP Design Parameters	Wire to plate spacing	5 and 6 inches
	Wire to wire spacing	6 - 12 inches
	Electrical section (fields) in direction of flow	4
	Section Length	6 ft.
	Plate (collection) area per section	480 - 1240 ft ²

III. THE ESP COMPUTER MODEL

The primary tools for completing this study have been "The Environmental Protection Agency Electrostatic Precipitator Computer Model" and its associated texts, "A Mathematical Model of Electrostatic Precipitation, (Revision 3) Volume I, Modeling and Programming" and "...Volume II, Users Manual" prepared by Southern Research Institute (SRI) of Birmingham for the Environmental Protection Agency. The current version of the program, a complete listing of which is found in Appendix C of Volume I, contains 3600 lines of Fortran code consisting of a main program and 27 subroutines. A description of the math model including equations solved and assumptions made, is contained in Section 6 of Volume I, and programming of the model described in the following section. These details will not be discussed in the present study.

Revision 1 of the program, with which work in the present study was begun in the spring of 1983, as stated by SRI [8], had the capability of performing the following operations:

- (1) predict collection efficiency as a function of particle diameter, electrical operating conditions, and gas properties;
- (2) calculate clean-plate, clean-air voltage-current characteristics for wire-plate geometries;
- (3) determine particle charging by unipolar ions as a function of particle diameter, electrical conditions, and residence time;
- (4) estimate the effects of particles on the electrical conditions under the assumption that effects due to particulate layer can be ignored;

- (5) account for electrical sectionalization;
- (6) predict particle capture at the collection electrode based on the assumption of completely-random turbulent flow, uniform gas velocity, and particle migration velocities which are small compared to the gas velocity;
- (7) employ empirical correction factors which adjust the particle migration velocities obtained without rapping losses in order to account for unmodeled effects;
- (8) account for the non-ideal effects of nonuniform gas velocity distribution, gas bypassage of electrified regions, and particle re-entrainment from causes other than rapping by using empirical correction factors to scale down the ideally calculated particle migration velocities; and
- (9) account for rapping re-entrainment by using empirical relationships for the quantity and size distribution of the re-entrained mass.

In the intervening periods from the original acquisition of Revision 1 and initiation and completion of this study, SRI made many improvements on the model culminating in a subsequent version, Revision 3, received in (August) 1984. Revision 3 has many additional features, [3,9] however, two are of primary interest:

- (1) a modification of numerical techniques for calculating particle charges and electrical fields which has resulted in about a 90% reduction in program run time.
- (2) an addition of a subroutine based on empirical data obtained from precipitators collecting fly ash which provides a state-of-the-art correlation between particle layer resistivity and electrical operating points.

Of the numerous program options available, two modes of program operation were found to be most applicable to this study. These are sequence 1 operation and sequence 2 operation in this study and are described as follows.

Sequence 1 Operation

- a. Particle size statistics are read in. These can be in the form of either the characteristic parameters of a log normal distribution, or the mass percents of particles with diameters smaller than specified diameters. In the latter case, the program fits the data to a log normal distribution.
- b. The precipitator is divided into length increments.
- c. Electrical operating conditions are estimated or optimum conditions are generated from the empirical routine and the results entered as known operating points. These can be entered either as average operating points or specified values for each electrical section.
- d. Space charge is calculated. Using an estimated ideal collection efficiency and known applied voltage and current density, the amount of material being removed per increment and the particulate space charge in each length increment are determined. This allows the calculation of a reduced ion mobility which results from particles being much less mobile carriers of charge than free ions or electrons.

- e. Electric field distribution is determined from values of applied voltage and wire to plate spacing. The charging field and the electric field at the plate are calculated. Nonuniformity of the electric field is estimated by dividing the length increments into many subincrements and making iterative calculations over each.
- f. Charge on each particle size at the end of each subincrement is calculated.
- g. Migration velocity is calculated. Using equation (1) migration velocity is calculated for each particle size at the end of each length increment.
- h. Particle removal rate is determined. Using equation (3) the number of particles removed from each size band is calculated.
- i. A new estimate of overall ideal mass collection efficiency is determined.
- j. Space charge is recalculated and the intervening steps are repeated. Using newly obtained estimated collection efficiency, iterations are repeated until convergence on ideal collection efficiency is obtained.
- k. Adjustments for non-ideal effects are made based on estimations of the effects on nonuniform gas flow distribution, sneakage (portion of the flow bypassing the electric field) and rapping re-entrainment.

Sequence 2 Operation

In the second program sequence an analytical technique determines electrical conditions.

1. A clean plate current density is computed for a specified value of applied voltage and the electric field is prescribed by this routine. The applied voltage is the average value for the length of the precipitator.
2. From the field conditions the particle charge is determined in the same manner as before but prior to the space charge calculation. Thus, the order in which the calculations are performed is altered (i.e., to c,e,f,d) with some special differences:
 - 2.1 Average operating voltage must be specified and may be somewhat arbitrary while the empirical routine of sequence 1 operation predicts optimum conditions.
 - 2.2 For sequence 2 operation of results are not biased by properties applicable only to fly ash collectors.
 - 2.3 In addition to wire to plate spacing, sequence 2 operation considers specific wire diameters, wire spacings, and plate sizes, whereas the empirical mode of sequence 1 operation essentially gives data for a precipitator with average values of these parameters.
3. Of special significance for this study is the space charge determination which is performed in sequence 2 as outlined

in Appendix A of Reference 1. It has the feature that if the calculated charge accumulated by the particles individually (Step f), in a given subincrement of length is in excess of the total available, the program indicates that an insufficient ionization situation exists in the specified length increment; this reflects the physical phenomenon called ion quench.

4. An estimate of "dirty gas" average operating current is obtained for the precipitator. In this mode of program operation, however, it has no bearing on the ensuing efficiency calculations.
5. The migration velocity determination, using equation (1) is based on the assumption that charging rates have been met, i.e., ionization deficiencies are negligible. Particularly important is that even if the space charge routine indicates ion quench exists a considerable number of length increments into the percipitator calculation still proceeds on this assumption.

From this point calculation continues much as in sequence 1 operation, the only difference being that there is no iteration over efficiency needed. This is because the space charge calculation does not require estimated efficiency as an initial condition.

IV. PROCEDURE

The object of the study was to evaluate the capability of a variety of standard wire-plate precipitator designs to meet the particulate removal requirements at the CFFF. The approach was to calculate values of collection efficiency - percent of total particle mass removed from the stream - for relevant ranges of flow conditions, particle properties, and precipitator design criteria using the "EPA Electrostatic Precipitator Computer Model" to perform the determinations. The particulate removal requirement was based on EPA New Source Performance Standards.

The main thrust of parametric variation was narrowed to manipulation of four variables; particle size distribution, electrical operating conditions, wire to plate spacing, and overall precipitator size. The decision to focus the study on the effects of changes in the four parameters was based on consultation with SRI personnel, recommendations found in reference 5, 6 and 9, constraints provided by CFFF conditions, and preliminary evaluations using the model.

Difference in Wire to Plate Spacing

Wire to plate spacings of 5 inches (10 inch duct) and 6 inches (12 inch duct) were chosen from ranges for typical commercial power plant applications given in Reference 6.

Variation of Particle Size Distribution

Two particle size ranges were used and these were chosen among extremes from CFFF samples showing reasonably good fit to log normal curves. Plots representing the curves to which these were fit are shown in on log scale in Figure 5. More recent test results indicate that the distribution obtained from test LMF1C-3, with 1.1 mass median diameter and 2.8 geometric standard deviation, is more representative of typical CFFF effluent stream conditions.

Range of Electrical Operating Conditions

Electrical operating conditions used in this study were determined by two methods. These were selected after the discovery that efficiency values obtained using sequence 2 operation would very likely be invalid. This belief resulted from running the model in sequence 2 operation and noting that ion quench was indicated for practically designed precipitators collecting CFFF ash. In fact, these early runs indicated that the condition would exist in a considerable portion of the precipitator except when specific collection area approached $900 \text{ ft}^2/10^3 \text{ acfm}$, on the order of three times that of collectors used in typical power plant installations.

The basic procedure for both methods was to estimate one set of operating electrical conditions which reflected negligible quench reduction in operating current and another in which the quench effect

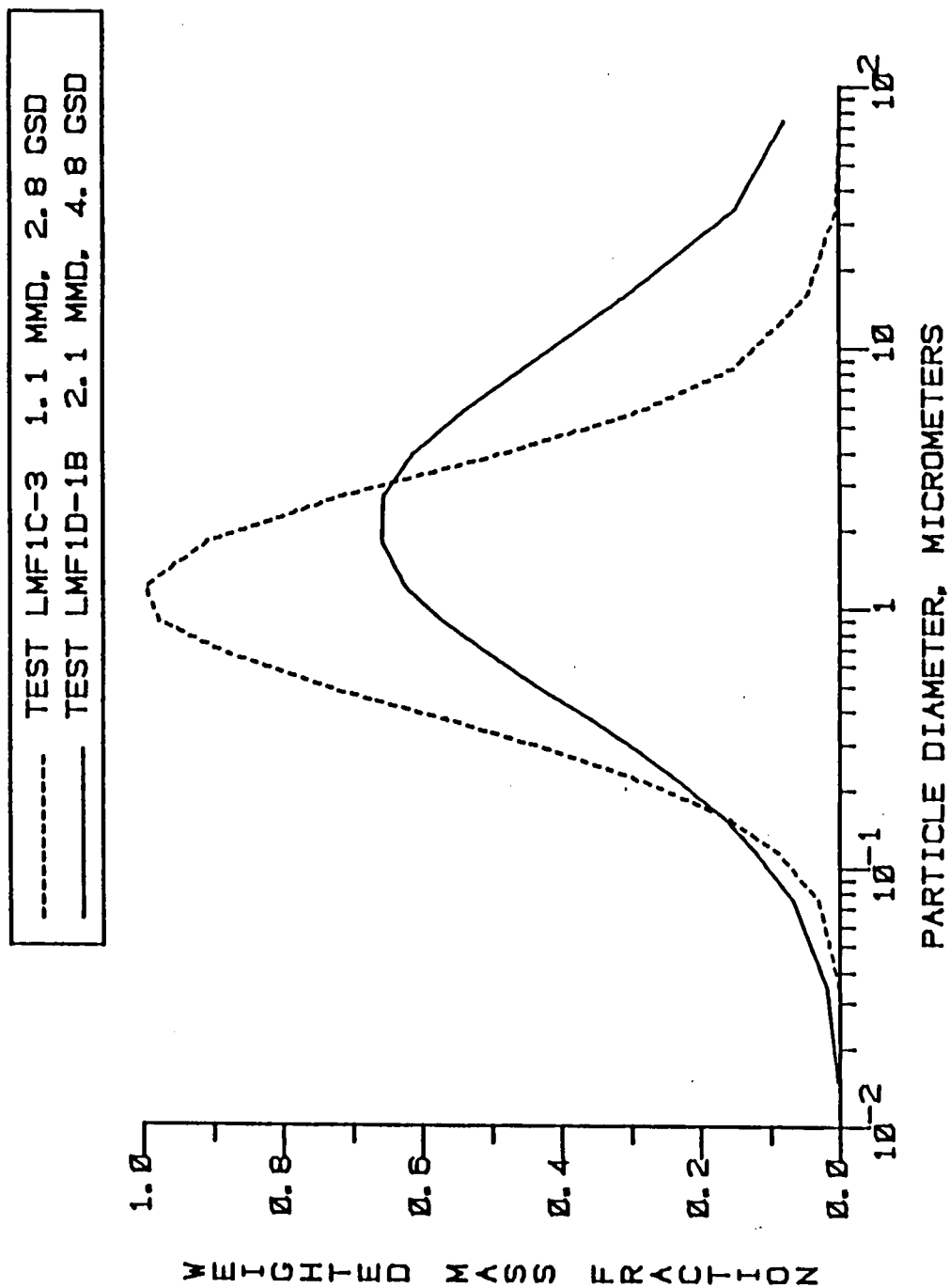


Figure 5. Particle Distribution Extremes.

was dominant. The two sets of operating conditions were then utilized in sequence 1 program operation to determine best and worst cases of reduction in performance due to quench. The method for estimating the conditions labeled method 1 determination and method 2 determination in this study, are described below.

Method 1 Determination

Electrical conditions for a best case of negligible quench effect were calculated using the empirical electrical condition generating routine supplied with "ESP Computer Model..." Revision 3 [3,9]. Using a recommended design condition of four electrically isolated sections or fields in the direction of flow and a layer resistivity of 3.5×10^9 ohm-cm, current and voltage operating points were determined for each section. The current-voltage plots are shown in Figure 6, and the "adjusted" operating points generated by this method are tabulated in Table III.

To develop worst case electrical conditions resulting from ion quench, a distortion of the voltage-current relationship was estimated based on recommendations by SRI personnel. The distortion in the first section, where the greatest number of particles and as a result the greatest quench effect would be seen, was estimated by shifting the curve to the right a distance equivalent to the voltage difference between sections 1 and 3. The final section was assumed to see no quench effect and intervening sections were plotted proportionally between the two as shown in Figure 7. Quench (worst case) adjusted

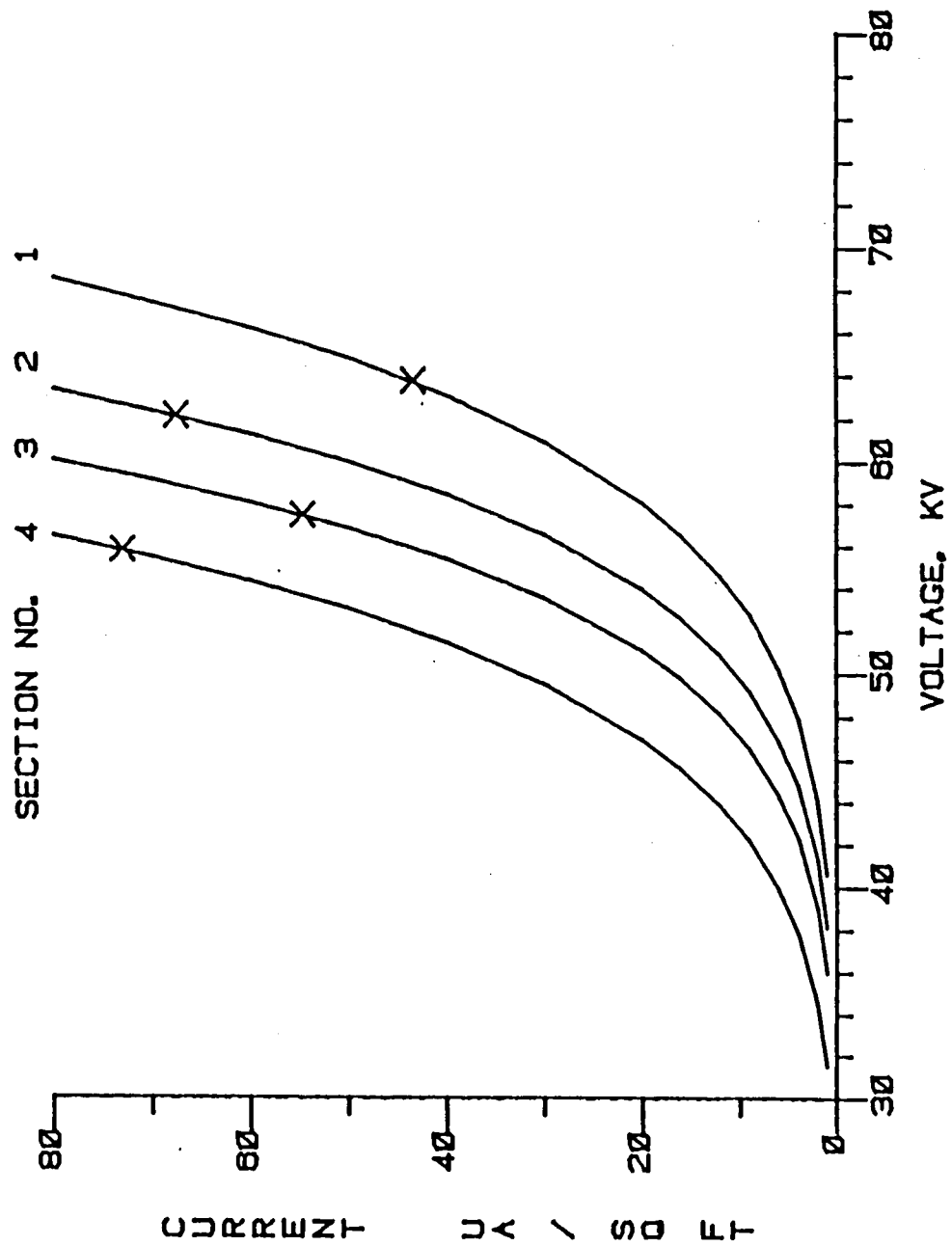


Figure 6. Unadjusted Operating Conditions, 6 Inch Precipitator.

Table III
Empirically Calculated Operating Points

Section	Applied Voltage (kV)	Unadjusted Current Density ($\mu\text{A}/\text{ft}^2$)	Quench Reduced Current Density ($\mu\text{A}/\text{ft}^2$)
1	63.74	43.51	16.84
2	62.16	67.73	34.81
3	57.47	54.71	36.74
4	55.82	73.05	73.05

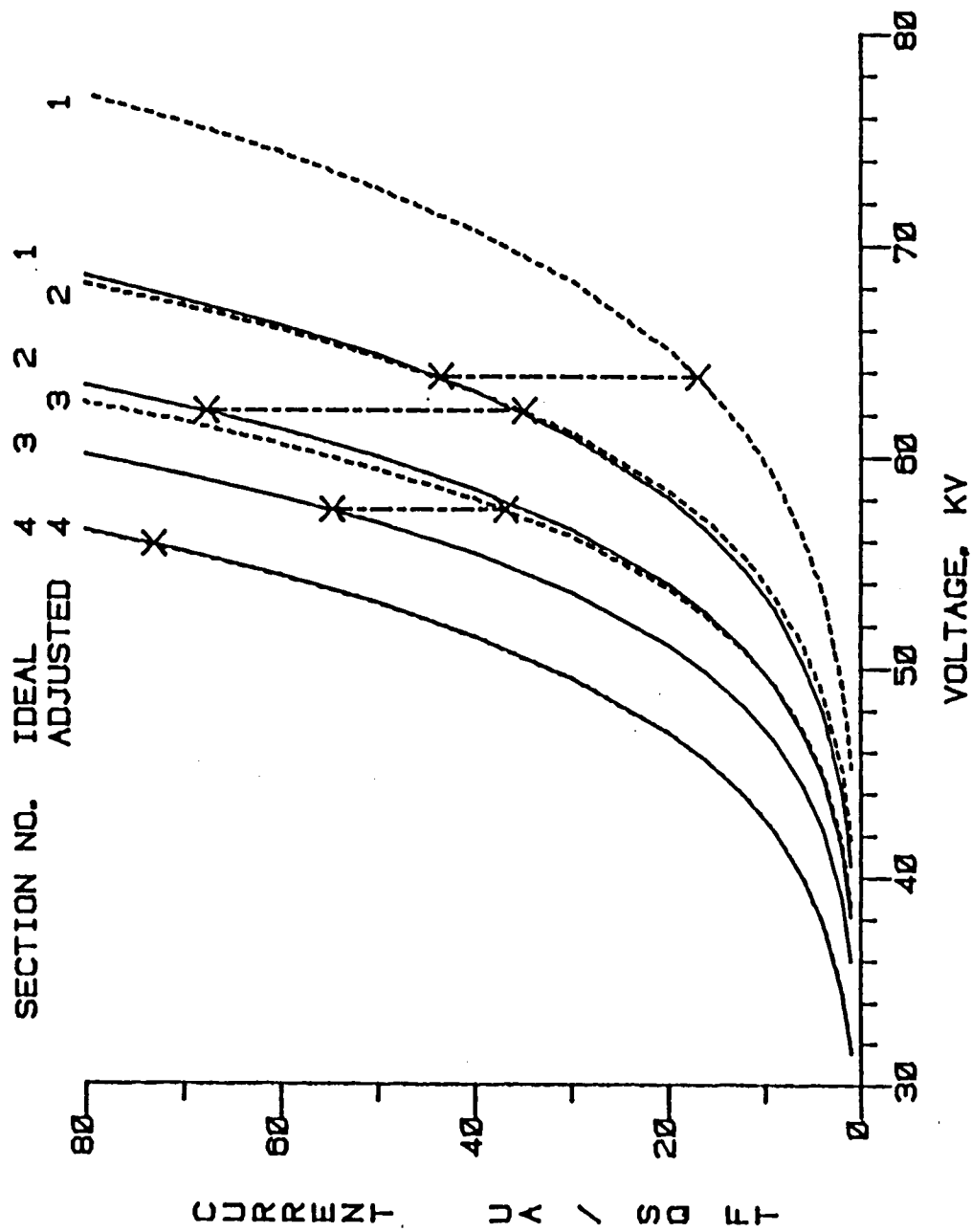


Figure 7. Adjusted Operating Condition Determination, Empirical Method.

operating current conditions were then found (continuing with Figure 7) by projecting the previously determined optimum voltages to the newly generated relationships. The operating points for these conditions are also tabulated in Table III.

The version of the computer model FORTRAN subroutine modified by the author to generate, in addition to the original curves and operating points, the adjusted curves and operating points is included in Appendix A.

The primary disadvantage of this approach relates to its reliance on data obtained from studies of cold-side fly ash collection. Note also in Table III that the operating current determined in Section 2 for the no quench condition is higher than in section 3, a seemingly unlikely physical situation. This result is not obtained when resistivities more typical of fly ash are input to this routine.

Secondly, the method 1 routine presents data for an essentially geometrically average precipitator, with plate spacing being the only parameter dimensional input, while several other parameters are known to have a considerable effect on optimum electrical conditions [5].

Method 2 Determination

In the second method for estimating a range of possible electrical operating conditions, the ideal electrical conditions were determined as before and an alternate approach was used for estimating the quench adjusted values. To estimate the quench reduced operating conditions, sequence 2 operation was performed only for the purpose of

obtaining a reduced operating current and the efficiency determination ignored. As described previously the selection of the average applied voltage value in this sequence is arbitrary and the value chosen was the 63.74 kv input identical to that found optimum for the first section by the empirical method. The voltage value and the determined average current were then directly inserted as electrical inputs for sequence 1 operation. Advantages of this method over method 1 are that precipitator geometry played an integral part of the determination. Emitting electrode diameter and spacing and, most importantly, precipitator size are taken into account.

The variation of average electrical conditions vs. SCA generated by this method are listed in Table IV along with the method 1 values. As precipitator size is increased, a proportionally smaller fraction of the precipitator sees the quench effect and average current density rises. As can be seen in Table IV, method 2 models this effect while method 1 does not.

Doubts concerning the reliability of the reduced operating current values obtained from sequence 2 operation and the arbitrary selection of optimum operating voltage are the primary detractors to the method 2 approach. Use of average electrical conditions rather than specific operating conditions for each section may also be a factor.

Table IV
Estimated Average Operating Points, 12 Inch Duct

Determination Method	Type	Precipitator Size, SCA (ft ² /10 ³ acfm)	Average Applied Voltage (kV)	Average Current Density (μ/ft ²)
1 (Empirical)	Unadjusted	225-600	59.8	59.7
1 (Empirical)	Quench reduced	225-600	59.8	40.5
2 (Analytical)	Quench reduced	225	63.7	3.1
2 (Analytical)	Quench reduced	300	63.7	6.1
2 (Analytical)	Quench reduced	375	63.7	11.2
2 (Analytical)	Quench reduced	450	63.7	17.2
2 (Analytical)	Quench reduced	525	63.7	24.4
2 (Analytical)	Quench reduced	600	63.7	30.0

Variation in Precipitator Size

The precipitator size parameters predominantly used in the study, ranging in SCA from 225 to 600 ft²/10³ acfm in increments of 75, were chosen somewhat arbitrarily to overlap the range of values normally seen in coal fired applications. Note that SCA was not an input variable to the model and the described size variations were achieved by varying the input plate area and hence the cross sectional area for a fixed exhaust gas volume and precipitator length.

Selection of Base Test Case

A "base test case" was developed consisting of negligible quench operating condition, a plate spacing of 12 inches shown to be preferable in studies by Foote [7], and the particle size distribution from test LMF1C-3 seen in Figure 4, page 29. The latter was originally chosen with the expectation that this would represent a worst performance case since the mass median diameter was only slightly more than half that found in some former tests. More recent studies at the CFFF have actually shown this distribution to be representative.

Efficiency calculations were performed for the "base test case" and values of percent of particle penetration through the precipitator, which is defined as 100 minus collection efficiency, were determined for each increment of specific collection area. Comparisons were then made of this case with others calculated using different combinations of values for the three independent parameters.

V. RESULTS

Data from the performance calculation of the base test case are shown in Figures 8 through 11 as a dashed line compared to a solid line representing an efficiency requirement of 99.6% based on EPA New Source Performance Standards.

In Figure 8 the performance is compared for precipitators with different plate spacings. A unit with the basic 12 inch duct (6 inch wire to plate) is seen to meet requirements at an SCA of 310 while the narrower spacing requires at about 330. This is estimated to be primarily the result of the 20% increase in velocity (or decrease in particle residence time) in the latter case for the fixed length, fixed flow volume decrease in plate spacing. The current densities generated from empirical correlation here are identical for both spacings and the effect of plate spacing on the electric field is not considered a major factor in these plots.

Figure 9 shows the performance for the two relevant particle size distributions with an SCA decrease of only about $10 \text{ ft}^2/10^3 \text{ cfm}$ for the larger mass median diameter distribution. The reason for the insensitivity of the SCA to these two mass median diameter values is seen from Figure 5 where the portion of particles contained in the difficult-to-collect size range below .6 micron is essentially the same for both distributions.

This emphasizes a very important concept for designers of downstream components for which electrostatic precipitation is applicable.

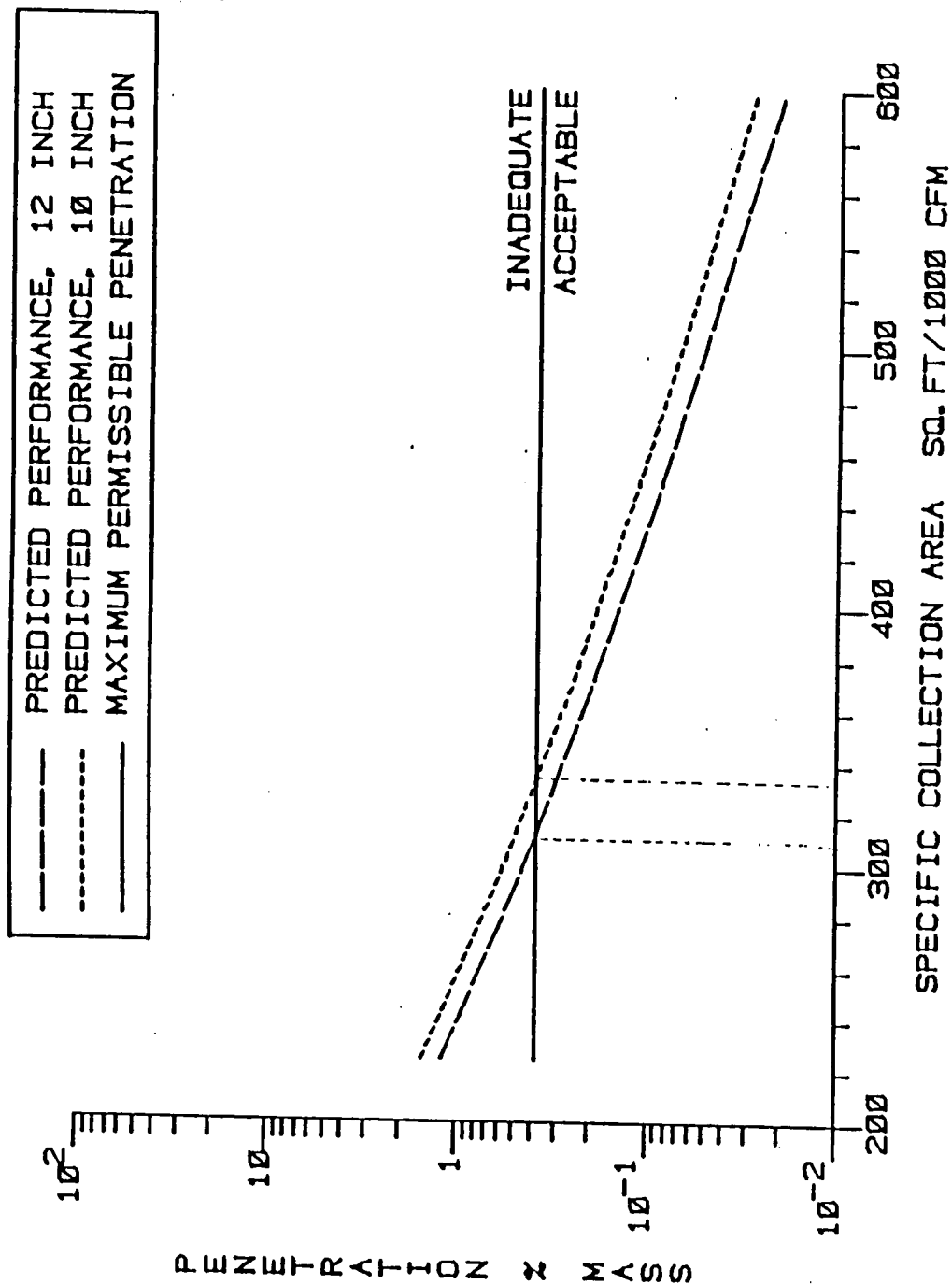


Figure 8. Effects of Plate Spacing on Precipitator Performance.

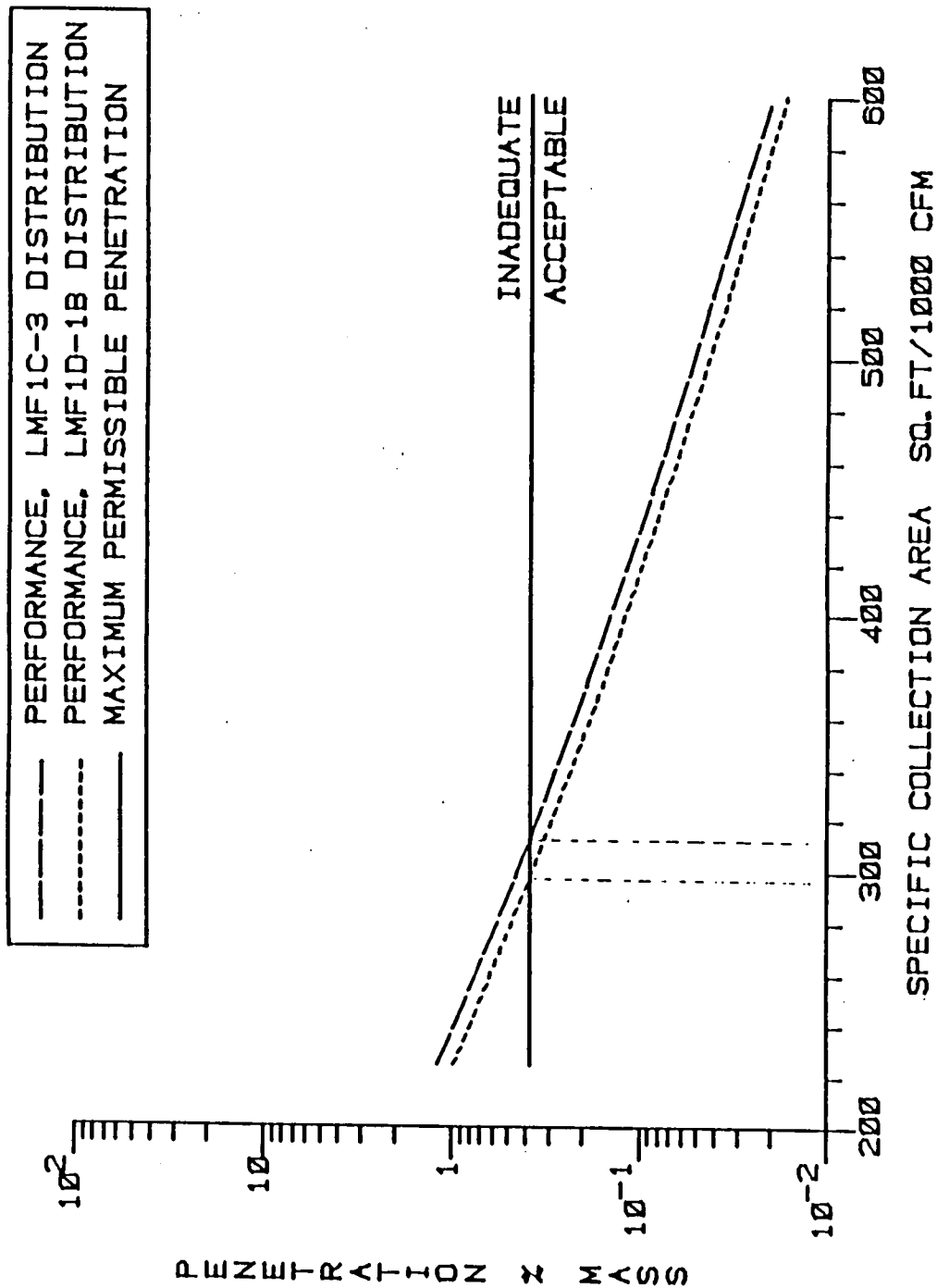


Figure 9. Effects of Particle Size on Precipitator Performance.

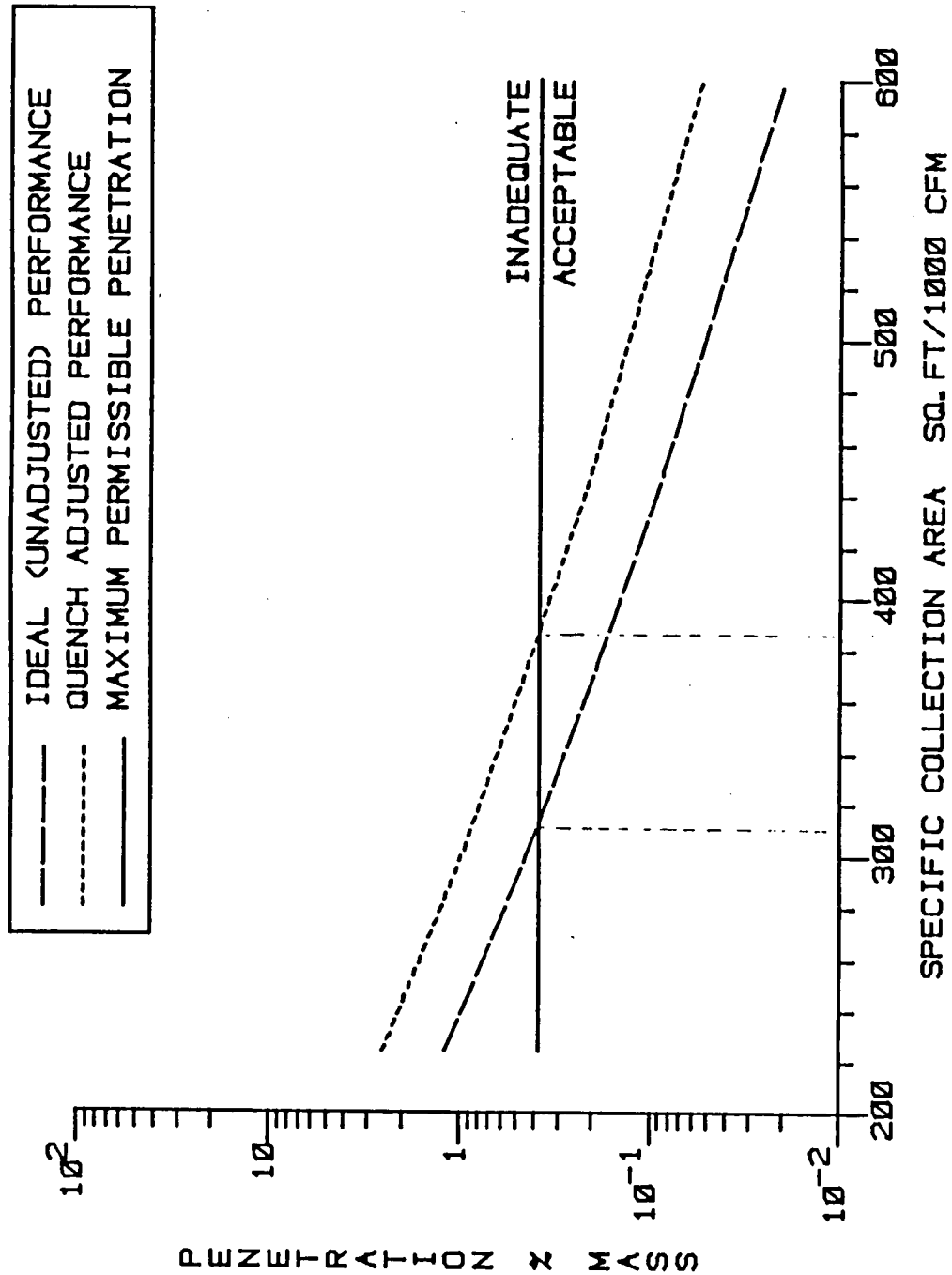


Figure 10. Effects of Ion Quench, Empirical Method.

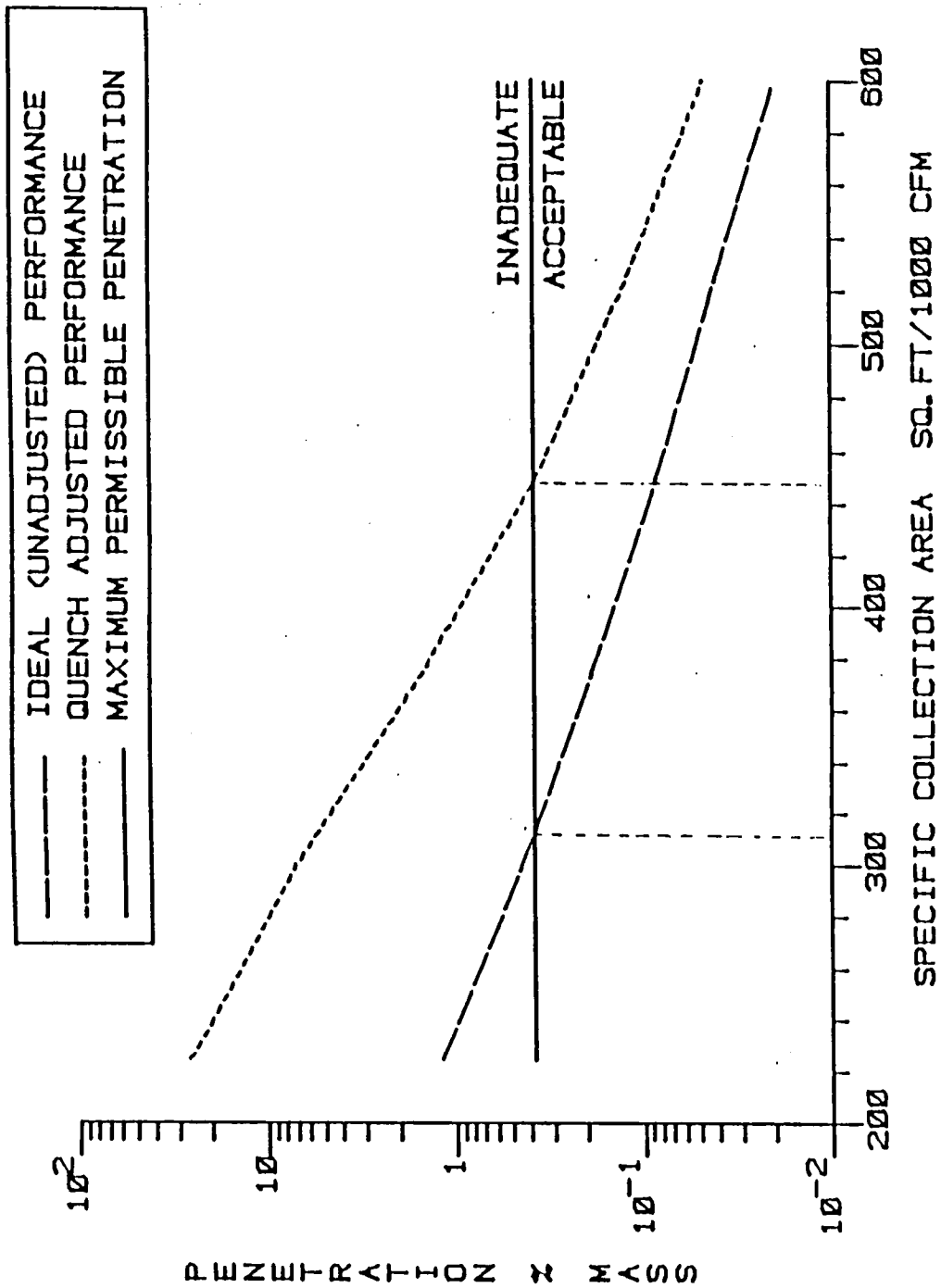


Figure 11. Effects of Ion Quench, Analytical Method.

The concept is that the mass of particles in the submicron diameter ranges has the most degrading effect on performance and this cannot be accounted for merely by the smallness of the log mean or median diameter. Therefore the particle size distribution as well as mean diameter will need to be taken into account for proper equipment selection.

Figures 10 and 11 show estimated best case and worst case size requirements resulting from ion quench using electrical conditions generated from methods 1 and 2 respectively. As previously stated, case negligible quench conditions were developed identically in both methods and are exhibited by the "base test" case dashed line. Efficiency calculations using the empirical method 1 determination electrical operating conditions resulted with the worst case requiring about a 25% larger precipitator than the unadjusted case. The results of analytical method 2 determination, shown in Figure 11, indicated a possible requirement of $450 \text{ ft}^2/10^3 \text{ cfm}$ or nearly 50% higher than the negligible effect case.

An input data set for the "base test case" is included in Appendix B and a set used to generate the method 2 determination quench reduced average current density is included in Appendix C. Both sets, which have been included for the benefit of model users, are for an SCA of $300 \text{ ft}^2/10^3$.

Additional work was required with the model in order to find practical ways to reduce the quench effect using the sequence 2

program operation. Indications were that use of relatively small wire diameters and proper selection of wiring spacing, particularly in the entering section of the precipitator, may considerably reduce quench. Quantification of these results has not been attempted since the charge determinations by this method do not include space charge effects.

Attempts to duplicate empirically generated electrical operating conditions with the analytical routine, though unsuccessful, demonstrated some important points. The empirical routine selects operating current based on an average field strength of applied voltage divided by the wire to plate spacing. For example, for a given layer resistivity in which optimum operating points were shown for 12 inch duct to be 60 kv and $30 \mu\text{a}/\text{ft}^2$, would give the same current value for a 10 inch duct and 50 kv applied voltage. Attempts to duplicate this with the analytical routine indicated that such a relationship existed only if wire spacing and diameter were also proportionally downsized and, in fact, differences in clean plate current density on the order of 50% were observed when only voltage and plate spacing were reduced.

VI. CONCLUSIONS

The study has pointed out several items of concern regarding application of an electrostatic precipitator for particulate collection at the CFFF.

1. Ion quench, or corona suppression, will exist in the device at normal operating conditions. This is the result of high particulate mass load, almost 5 grains/acf, of particles of which approximately 1.3 grains/acf are below $.6 \mu\text{m}$ in diameter.
2. The degree to which ion quench degrades performance will depend on the strength of the electric field near the emitting wire electrodes, particularly in the early stages of collection, the front of the precipitator. This study predicts ion quench may increase precipitator size requirements by as much as 50%.
3. The electric field near the wire is limited primarily by the maximum applied voltage at which the device can operate and secondarily on dimensional considerations such as wire diameter, wire to plate spacing and wire to wire spacing.
4. The maximum usable applied voltage is limited by the resistivity of the collected particulate layer. The resistivity value determined by laboratory experiments on CFFF samples, $3.5 \times 10^9 \text{ ohm-cm}$, suggests the probability that a very high applied voltage, on the order of 65 kv, may be used in removal of particles from CFFF exhaust.

5. The effect of using a wider plate spacing for a precipitator of given SCA is to increase performance, primarily by increasing particle residence time in the precipitator. A decrease in required precipitator size of approximately 7% was predicted for a 12 inch duct precipitator as opposed to a 10 inch duct. This gain will be offset somewhat by reduced field strength in the region of the wire for the wider spacing.
6. Expected variations in particle size distributions during CFFF operations are predicted to have almost negligible impact on performance.

Present plans for precipitator installation at the CFFF incorporate an ability to test a wide range of precipitator sizes by varying flow volume over a fixed collection area. The results of this study indicate the need to have the additional capability of testing over a wide range of applied voltages and also to be able to monitor closely the relation of voltage to current in each section of the precipitator.

Experiments with the ESP at the CFFF, which will attempt to correlate changes in wire diameter and wire spacing to ESP electrical conditions, will also be very useful for finding optimum ESP performance for general applications in standard coal-fired power producing plants.

The purpose of this study has been to define the limits of design criteria for an electrostatic precipitator for the CFFF and to provide insights into the effectiveness of a precipitator applied to a full scale MHD power generation plant. A very good method for expanding the state-of-the-art in the ESP field will be to continue to use the "ESP Computer Model" in the research being conducted by the Energy Conversion Programs at UTSI. This work should provide a considerable amount of information helpful both to magnetohydrodynamic power generation research but also to the study of the general electrostatic precipitator process.

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APPENDIXES

APPENDIX A

MODIFIED ELECTRICAL CONDITION GENERATING SUBROUTINE

```

DIMENSION AJ(4),BJ(4),AE(4),BE(4),CUR(14),CURR(14),VOLT(4,14)
DIMENSION CE(4),DE(4),AMP13(4),AMP14(4)
DIMENSION AAMP(4),AAMPP(4),VOS(14)
DATA CURR/1.,2.,4.,6.,9.,12.,16.,20.,30.,40.,50.,60.,70.,80./
DATA AJ/ 6.455, 6.839, 5.497, 5.718/
DATA BJ/-0.5013,-0.5214,-0.3905,-0.4005/
DATA AE/-3.5394,-3.4209,-3.1735,-2.3438/
DATA BE/ 0.3841, 0.6546, 0.5755, 7.5195/
OPEN(UNIT=6,NAME='VI2.DAT',TYPE='NEW')
C RESISTIVITY = 3.50E+09 OHM-CM
RHO= 3.5 E+09
TYPE*, 'ENTER WIRE TO PLATE SPACING IN INCHES'
ACCEPT*, HDUCT
TYPE*, 'ENTER MAXIMUM POWER SUPPLY, IN K.V.'
ACCEPT*, VMAX
TYPE*, VMAX
VMAX=VMAX
RHOLOG=ALOG10(RHO)
HAFDUC=HDUCT*2.54
VNMAX=0.0
NNN=0
4 CONTINUE
FLDMAX=ALOG10(VMAX/HAFDUC)
DO 21 K=1,4
DO 14 N=1,14
CUR(N)=CURR(N)*1.0764
AMP=ALOG10(CUR(N))
IF(N.EQ.13)AMP13(K)=AMP
IF(N.EQ.14)AMP14(K)=AMP
EFIELD=(AMP-AE(K))/BE(K)
EFIELD=10.0**EFIELD
VOLT(K,N)=EFIELD*HAFDUC
14 CONTINUE
AAMP(K)=AJ(K)+BJ(K)*RHOLOG
C IF(K.EQ.1.AND.AAMP(K).GT.1.4299)AAMP(K)=1.4299
C IF(AAMP(K).GT.1.7309)AAMP(K)=1.7309
C IF(AAMP(K)+RHOLOG.GT.13.1761)AAMP(K)=13.1761-RHOLOG
FIELD=(AAMP(K)-AE(K))/BE(K)
IF(FIELD.LE.FLDMAX)GO TO 2
AAMP(K)=AE(K)+FLDMAX*BE(K)
VOS(K)=VMAX
VNMAX=VMAX
GO TO 3
2 CONTINUE
FIELD=10.0**FIELD
VOS(K)=FIELD*HAFDUC
IF(VNMAX.LT.VOS(K)) VNMAX=VOS(K)
3 CONTINUE
AAMP(K)=10.0**AAMP(K)
AAMPP(K)=AAMP(K)/1.0764
21 CONTINUE

```

```

      IF(NNN.EQ.1)GO TO 7
C     WRITE VI CURVE
      WRITE(6,5800)
5800  FORMAT(1H1)
      WRITE(6,5850)
5850  FORMAT(40X,'*****')
      WRITE(6,5851)
5851  FORMAT(40X,'*',35X,'*')
      WRITE(6,5852)
5852  FORMAT(40X,'*',9X,'E.P.A. ESP MODEL',10X,'*')
      WRITE(6,5851)
      WRITE(6,5853)
5853  FORMAT(40X,'*',4X,'I.E.R.L.-R.T.P. AND SO.R.I.',4X,'*')
      WRITE(6,5851)
      WRITE(6,5854)
5854  FORMAT(40X,'*',12X,'REVISION III',11X,'*')
      WRITE(6,5851)
      WRITE(6,5850)
      WRITE(6,125)RHO,HDUCT
125  FORMAT(///' EPRI/SRI 1982 CORRELATION OF COLD SIDE ESP OPERATING '
&,'POINTS'///' EPRI CONTRACT RP629-5 DR. R. F. ALTMAN,PROJECT '
&,'MANAGER'///' UTSI VERSION OF SUBROUTINE INTERN W/SO.R.I. LINES '
&,'#59-61 OMITTED'///' INPUT DATA: RESISTIVITY',11X,'=',1PE11.2
&,' OHM-CM'///' WIRE-TO-PLATE SPACING =',0PF7.2,'IN')
7     CONTINUE
      IF(NNN.EQ.1)GO TO 9
      WRITE(6,8) VMAX
8     FORMAT(//2X,'MAXIMUM ALLOWABLE APPLIED KV.=' ,F6.2//)
      GO TO 10
9     CONTINUE
      WRITE(6,11) VMAX
11    FORMAT(/////2X,' FIELD QUENCH ADJUSTED DATA'//
& ,2X,'MAXIMUM PREDICTED APPLIED KV.=' ,F6.2///// )
10    CONTINUE
      DO 23 K=1,4
      WRITE(6,115)K
115   FORMAT(///' V-I CURVE DATA FOR SECTION',12)
      WRITE(6,116)(VOLT(K,N),N=1,14)
116   FORMAT(///' KILOVOLTS: ',14F6.2)
      WRITE(6,118)(CURR(N),N=1,14)
118   FORMAT(///' UA/FT2: ',14F6.1)
      WRITE(6,119)K
119   FORMAT(///' THE OPERATING POINT FOR SECTION',12,' IS:')
      WRITE(6,120)VOS(K),AAMPP(K)
120   FORMAT(///' KILOVOLTS:',F8.2,/' UA/FT2:
& ,F8.2)
23    CONTINUE
      VMAX=VNMAX
      IF(NNN.EQ.1)GO TO 5
C
C USING PREVIOUSLY DETERMINED CURRENT AND VOTAGE VALUES, NEW VALUES FOR
C AE(J) AND BE(J) ARE FOUND FOR FIRST THREE SECTIONS
C
      CE(1)=VOLT(1,14)+VOLT(1,14)-VOLT(3,14)
      PROP=(CE(1)-VOLT(4,14))/(VOLT(1,14)-VOLT(4,14))
      CE(2)=VOLT(4,14)+(PROP*(VOLT(2,14)-VOLT(4,14)))
      CE(3)=VOLT(4,14)+(PROP*(VOLT(3,14)-VOLT(4,14)))
      DE(1)=VOLT(1,13)+VOLT(1,13)-VOLT(3,13)
      PROP=(DE(1)-VOLT(4,13))/(VOLT(1,13)-VOLT(4,13))
      DE(2)=VOLT(4,13)+(PROP*(VOLT(2,13)-VOLT(4,13)))
      DE(3)=VOLT(4,13)+(PROP*(VOLT(3,13)-VOLT(4,13)))
      DO 6 J=1,3
      CE(J)=ALOG10(CE(J)/HAFDUC)
      DE(J)=ALOG10(DE(J)/HAFDUC)
      BE(J)=(AMP14(J)-AMP13(J))/(CE(J)-DE(J))
      AE(J)=AMP14(J)-(CE(J)*BE(J))
6     CONTINUE
5     CONTINUE
      NNN=NNN+1
      IF(NNN.EQ.1)GO TO 4
      STOP
      END

```

APPENDIX B

INPUT DATA SET NEGLIGIBLE QUENCH EFFECT EFFICIENCY CALCULATION

2101000002	ESP BASE TEST CASE	IMPACTOR DATA F/LMFID-1B	6"WIRE TO PLATE			
01020111090300001020102						
0510						
4.72	24.0	99.70	2662.0	100.0	1.2	0.00027 1.0
0.0 0.0	4.0 0.1	0.254.0				800000.3.50E+09
.01	.02	.05	.1	.13	.18	.24
.75	1.0	1.46	2.15	3.16	4.64	6.81
100.						.32
2.06	4.8					10.0
0406060606						
+6.370	E+02+6.373	E+01+2.770	E+04+5.300	E+02+1.250	E+01+6.000	E+00+1.000 E+01
+3.600	E+00+8.500	E+03+2.668	E+00+3.500	E+02+1.000	E+00+2.400	E-05+1.000 E+00
+6.370	E+02+6.216	E+01+4.310	E+04+5.300	E+02+1.250	E+01+6.000	E+00+1.000 E+01
+3.600	E+00+8.500	E+03+2.668	E+00+3.500	E+02+1.000	E+00+2.400	E-05+1.000 E+00
+6.370	E+02+5.747	E+01+3.485	E+04+5.300	E+02+1.250	E+01+6.000	E+00+1.000 E+01
+3.600	E+00+8.500	E+03+2.668	E+00+3.500	E+02+1.000	E+00+2.400	E-05+1.000 E+00
+6.370	E+02+5.582	E+01+4.650	E+04+5.300	E+02+1.250	E+01+6.000	E+00+1.000 E+01
+3.600	E+00+8.500	E+03+2.668	E+00+3.500	E+02+1.000	E+00+2.400	E-05+1.000 E+00
99						

APPENDIX C

INPUT DATA SET AVERAGE CURRENT DETERMINATION

```

2101000001
ESP IMPACTOR DATA F/LMF1D-1B 6"WIRE TO PLATE WITH V/I CURVE (E5.DAT)
0102021515010001020102
0510
3002030101
4.72 24.0 99.70 2662.0 100.0 1.2 0.00027 1.0 800000.3.50E+09
0.0 0.0 4.0 0.1 0.254.0
.01 .02 .05 .1 .13 .18 .24 .32 .42 .56
.75 1.0 1.46 2.15 3.16 4.64 6.81 10.0 21.5 46.4
100.
2.06 4.8
0410101010
+6.370 E+02+6.373 E+04 +5.300 E+02+1.250 E-01+6.000 E+00+1.000 E+01
+3.600 E+00+8.500 E+03+2.668 E+00+3.500 E+02+1.000 E+00+2.400 E-05+6.000 E-01
+9.000 E-01+7.860 E-04+1.000 E-06+1.000 E-06+6.370 E+04
+6.370 E+02+6.373 E+04 +5.300 E+02+1.250 E-01+6.000 E+00+1.000 E+01
+3.600 E+00+8.500 E+03+2.668 E+00+3.500 E+02+1.000 E+00+2.400 E-05+6.000 E-01
+9.000 E-01+7.860 E-04+1.000 E-06+1.000 E-06+6.370 E+04
+6.370 E+02+6.373 E+04 +5.300 E+02+1.250 E-01+6.000 E+00+1.000 E+01
+3.600 E+00+8.500 E+03+2.668 E+00+3.500 E+02+1.000 E+00+2.400 E-05+6.000 E-01
+9.000 E-01+7.860 E-04+1.000 E-06+1.000 E-06+6.370 E+04
+6.370 E+02+6.373 E+04 +5.300 E+02+1.250 E-01+6.000 E+00+1.000 E+01
+3.600 E+00+8.500 E+03+2.668 E+00+3.500 E+02+1.000 E+00+2.400 E-05+6.000 E-01
+9.000 E-01+7.860 E-04+1.000 E-06+1.000 E-06+6.370 E+04
99

```

VITA

R. Keith Morehead was born in Mayfield, Kentucky, in 1947 and graduated from Mayfield High School in 1965. He received a Bachelor of Science degree in Mechanical Engineering in 1970 from the University of Kentucky. After graduating he worked in various industrial and government settings with the plurality of his experience being in the design and installation of air pollution control systems. He applied for and was granted a graduate research assistantship at The University of Tennessee Space Institute, Tullahoma, Tennessee, in 1983.