

A SELF-CONSISTENT DEUTSCHIAN ESP MODEL

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16. ABSTRACT The report presents a new version of the EPA/Southern Research Institute electrostatic precipitator (ESP) model. The primary difference between this and the standard (Revision 3) versions is in the treatment of the particulate space charge. Both models apply the Deutsch equation to narrow particle size bands over short ESP lengths to determine collection efficiency. The standard version estimates space charge by a formula which predicts an effective mobility for ions and particles and a reduced ion density for particle charging. The estimated values are used to calculate the electric field at the plate and the particle charge, both required for the Deutsch equation. However, in the new version the particulate space charge is treated explicitly, allowing the interrelation of the particle charge and electric field calculations. The charge and field calculations are alternated until they become self-consistent within each length increment of the ESP. Self-consistency occurs when the charge used for the space charge in the field calculation is the same as that calculated using the results of the field calculation. The explicit treatment of the space charge directly relates the particle charge and electric field calculations, and therefore the collection efficiency calculation, to the dust load present in the gas stream. The report gives operating instructions for the new model.		
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## ABSTRACT

The electrostatic precipitator (ESP) model developed by Southern Research Institute (SRI) for EPA provides an acceptable simulation of the performance of cold-side utility fly ash ESPs with typical values of inlet mass loading. To increase the accuracy of model predictions in unusual situations, such as high inlet mass loading or abnormally low current, a revised version of the model has been developed. The revised model is unique in that it rigorously calculates the effects of particulate space charge on the interelectrode electric field and on subsequent particle charging.

This report provides operating instructions for the revised model, with examples of the input and output data. A discussion of the theory of the model is also included. Although the revised ESP model was developed on a main-frame computer, it can be run on an IBM PC-compatible microcomputer.

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## SECTION 1

### INTRODUCTION

A more general and more powerful mathematical model of electrostatic precipitation (ESP) has been developed by Southern Research Institute (SRI). The standard version of the ESP model developed by SRI for EPA, now in its third revision (1), provides an acceptable simulation of the performance of cold-side utility fly ash precipitators with typical values of inlet mass loading. To increase the responsiveness of the ESP model to situations having high inlet mass loading and/or abnormally low corona current, a revised version of the model has been prepared (2).

Both versions of the model apply the Deutsch equation to narrow particle size bands over short ESP length increments to determine particle collection efficiency. In the standard version, the effects of particulate space charge are estimated by a formula that predicts an effective mobility for combined ions and particles and a reduced ion density for particle charging. These estimated values are then used to separately calculate the electric field at the plate,  $E_{p1}$ , and the particle charge,  $Q$ , which are required for the Deutsch equation.

The revised version differs from the standard version in that the particulate space charge is treated explicitly, which allows the interrelation of the particle charge and electric field calculations. The charge and field calculations are alternated until they become self-consistent within each length increment throughout the entire ESP. Self-consistency occurs when the charge used for the space charge in the field calculation is the same as the charge calculated using the results of the field calculation. The explicit treatment of the space charge directly relates the particle charge and electric field calculations, and therefore the collection efficiency calculation, to the dust load present in the gas stream.

This report describes the revised model. The report covers the following topics:

- operating instructions for the revised model,
- a description of the input data, with an example,
- a description of the display on the computer screen during the operation of the revised model,
- a description of the output data, with an example,
- a discussion of the underlying theory of the revised model,
- a comparison of the logic in the revised and standard (revision 3, published by NTIS) models, and
- comparisons of the output data of the revised and standard models based on data from a utility ESP.



Appendix A is the input data chapter from the user manual for revision 3 of the ESP model. This appendix provides in-depth information about each item of the input data and describes all of the options available to the user of the ESP model.

Appendix B contains a revised model output data set. The data correspond to the input data set that is used for an example in this report.

Although the revised ESP model described in this report was developed on a main-frame computer, it can be run on an IBM PC-compatible microcomputer. Because the model performs a large number of mathematical calculations, it is recommended that the microcomputer be equipped with a math coprocessor to minimize the time required for running the model.

## SECTION 2

### CONCLUSIONS AND RECOMMENDATIONS

The revised ESP model represents an improvement over the standard model in that the calculations of particle charge and collecting electric field required for the Deutsch equation are not separate but are interrelated such that the charging and field calculations are made self-consistent in each length increment of the ESP. This is done by treating the particulate space charge explicitly and by alternating the calculations of particle charge and field until both become constant. The algorithms used in the revised model are conceptually rigorous, with the exception of the continued use of an average interelectrode electric field in the charging calculation. However, this field is not the voltage divided by wire-to-plate distance, as in the standard version of the model, but rather the spatial average of the field values obtained throughout the interelectrode space. Considering the random motion of fine particles through regions of different field strength and the computational problem of keeping track of particle charge accumulation, this may be the best way to perform the charge calculation. The revised algorithm contains no estimated effects such as the space charge adjustment or combined mobility of ions and particles that are found in the standard model. These features result in a model that is responsive to changes in dust load as well as electrical conditions. Since there are no estimates based on full-sized precipitators used in the calculation, the revised model can be used to calculate efficiencies for unusual cases such as pilot precipitators with very low currents.

Following the theoretical efficiency calculation, there are two non-rigorous corrections that are applied to model predictions. These are the calculation of rapping reentrainment and the correction of small-particle migration velocities. The rapping correction must be empirical in nature because no applicable theory exists. That a correction factor is necessary for a rigorously Deutschian model to match the small-particle migration velocities in full-size ESPs indicates a shortcoming in the Deutsch theory, possibly due to an oversimplification in the underlying assumptions of the theory. At this time, however, there are no competing theories of ESP particle collection that do not also require empirically derived constants.

The revised model has been tested against the SRI data base of conventional utility fly ash precipitators to verify that the same answers are obtained as from Revision 3. However, the revised ESP model has never been thoroughly tested for the high load conditions for which it was developed. To date, the only ESP that has operated long enough with LIMB for steady state testing and for which there exists reliable data is the Edgewater Unit 4 ESP. Neither the standard ESP model nor the revised model performance predictions were very close to the measured performance of the Edgewater ESP, for reasons discussed in Section 5 of this report. A better model test would be a smaller ESP, which would have lower efficiency than the Edgewater unit. This would ensure that there would be enough mass penetrating the ESP to minimize uncertainties in the impactor measurements. It would also reduce the effects of non-ideal conditions such as spontaneous reentrainment. Therefore, in order to develop a high level of confidence in the

revised model, it is recommended that a measurement program be performed using a smaller ESP.

## SECTION 3

### OPERATING INSTRUCTIONS

The revised ESP model, ESPREV.FOR, is written in Microsoft compatible FORTRAN and occupies 67,574 bytes of memory. The executable file, ESPREV.EXE, has been compiled for use with a math coprocessor. For use in systems lacking a math coprocessor, the program will need to be recompiled with the appropriate options. ESPREV.EXE occupies 264,298 bytes of memory. It is recommended that these files be copied onto a hard disk before use.

To run the model, type ESPREV and press enter. The program will prompt the user for the names of a file containing input data and a file into which to write the output data. Definitions of the input data are given in Table 1. Appendix A gives detailed descriptions of the input data. Descriptions of the video display generated by the model and the output data are given below. Due to the large amount of data generated by this model, the output data are written to a file. To obtain a hard copy of the data, it is necessary to print this file using a PRINT command. An option for shortening the amount of output data generated is provided.

#### INPUT DATA

The revised ESP model reads the same input data format as the standard version of the model. The instructions for creating a data set, excerpted from the standard model instruction manual, are given in Appendix A. New data sets may be created by writing the data into the prescribed data format using an editor or word processor (store in ASCII format), or by using the input data file creation program described in a separate topical report. The file creation program contains default values for some of the variables, prompts the user for the data, and writes the data into the correct format. The data set shown in Figure 1 is used as an example data set for this report. The data are for a hypothetical four-section ESP.

Although the input data format is the same as for the standard version of the model, there are changes in how some of that data are used and in what numbers are required. Table 1 briefly describes the data by line number. For each line, the data are listed sequentially by variable name. This list is included to facilitate understanding of Figure 1 and to indicate which data have been changed from the way they are used in the standard ESP model. Table 1 is not intended to fully explain the input data. For complete details of the meaning of each variable, refer to Appendix A. In Table 1, changes in the data are indicated by N/A (the variable does not apply to the revised model), NEW (this datum does not appear in previous versions of the model), or REV (this variable is used differently in the revised model). A blank in the space used for N/A, REV or NEW means that there is no change in the datum.

```

19 1 0 0 015.00    0    0    0 8.00 3.50
TEST PLANT 2:  4 SECTION ESP WITH 320 SCA, BITUMINOUS COAL SIZE DISTRIBUTION
 1 2 11511 2 0 1 1 1 3
10
  2.000  36.000  99.900 2400.00  100.00    1.200.000270    1.000.15E+070.20E+11
0.050.15 4.00.100.25 4.00.000.00 4.0
  0.010   0.070   0.100   0.140   0.220   0.340   0.500   0.700   1.000   1.400
  2.200   3.400   5.000   7.000  10.000  14.000  22.000  34.000 100.000
 16.300   3.400
410101010
2.7000E+04 4.3100E+04 4.9000E-01 2.7000E+04 7.5000E-02 4.5000E+00 1.8000E+01
3.0000E+00 3.3750E+05 5.0000E+00 3.0000E+02 1.0000E+00 2.3000E-05 9.0000E-01
2.7000E+04 4.2000E+04 7.3700E-01 2.7000E+04 7.5000E-02 4.5000E+00 1.8000E+01
3.0000E+00 3.3750E+05 5.0000E+00 3.0000E+02 1.0000E+00 2.3000E-05 9.0000E-01
2.7000E+04 3.9800E+04 7.4800E-01 2.7000E+04 7.5000E-02 4.5000E+00 1.8000E+01
3.0000E+00 3.3750E+05 5.0000E+00 3.0000E+02 1.0000E+00 2.3000E-05 9.0000E-01
2.7000E+04 3.8200E+04 9.8100E-01 2.7000E+04 7.5000E-02 4.5000E+00 1.8000E+01
3.0000E+00 3.3750E+05 5.0000E+00 3.0000E+02 1.0000E+00 2.3000E-05 9.0000E-01
99

```

Figure 1. Input data set ESPREV.DAT.

TABLE 1. REVISED ESP MODEL INPUT DATA

Line 1:

NENDPT	-	-	number of size band endpoints, 21 max, 99 to end program
NDATA	-	-	type of data set, 1 = full, 2 - 4 shortened
NRAP	-	N/A	type of rapping calculation (normal rapping only)
MODL	-	-	type of input data, 0 = normal, 1 = metric, other values N/A
NOPRNT	-	REV	shorter output if 0, expanded if 1
PATHL	-	-	optical path length for opacity, 0 = no opacity calculation
NCOMPS	-	N/A	index of refraction data are built in
NWAVES	-	N/A	"
NLAMDA	-	N/A	"
PCH2O	-	NEW	% H <sub>2</sub> O for calculation of gr/dscf and lb/10 <sup>6</sup> Btu. Format F5.2 in columns 31-35.
PCO2	-	NEW	% O <sub>2</sub> to go with % H <sub>2</sub> O. Format F5.2 in columns 36-40.
NOSNK	-	NEW	allows program to skip sneackage calculation in selected ESP sections for inclusion of prechargers, etc., where no sneackage is encountered. These data are given as 10 one place integers = 0 or 1 for a maximum of 10 sections. If NOSNK(I) = 0 or blank, sneackage is calculated for section I. If NOSNK(I) = 1, sneackage is not calculated for section I. E.g. 0100_____ : no sneackage occurs in the second section. Using <u>1</u> _____ has the same effect. Format 10I1 in columns 41-50. These data are blank in Figure 1.

Line 2: Title - no change

Line 3:

NEST	-	N/A	type of E field calculation (always rigorous)
NDIST	-	-	type of PSD data, cumulative mass or mmd
NVI	-	N/A	type of V-I data (measured data must be used)
NX	-	REV	maximum number of E-field grid points in X direction (wire-to-plate) is now 25
NY	-	-	number of grid points in Y (gas flow) direction
NITER	-	N/A	number of iterations to converge
NCALC	-	REV	calculations are for NCALC = 0 regardless of value given in input data. NCALC = 0 type of data must be used (i.e., Line 4, NN, must appear)
NRAPD	-	REV	if greater than 1, additional data will be read in but not used
NEFF	-	N/A	source of rapping dust = last section
NTEMP	-	N/A	cold-side only
NONID	-	REV	if greater than 1, additional data will be read in but not used

Line 4:

NN	-	-	number of increments in the integration of the particulate charging rate (typically 5)
----	---	---	--

TABLE 1. (continued)

Line 5:

DL	-	-	dust loading
PL	-	-	total ESP length
ETAO	-	N/A	estimated efficiency is not used in this model
DD	-	-	particle density
EPS	-	-	dielectric ratio
VRATIO	-	-	peak-to-average voltage ratio
US	-	-	ion mobility
FPATH	-	-	ionic path factor
EBD	-	N/A	electrical breakdown field strength
RHO	-	N/A	particulate resistivity

Line 6:

ASNUCK	-	REV	-	only the first set of non-ideal condition data (sneakage,
AZIGGY	-	REV		sigma g, and number of gas baffles) are used. If NONID is
AZNUMS	-	REV		greater than 1, additional data will be read but will not be
				used.

Lines 7 - 8:

ENDPT	-	-	particle size band endpoints (21 maximum)
-------	---	---	---

Line 9:

D50	-	-	particle size distribution mass median diameter
SIGMAP	-	-	particle size distribution standard deviation

Line 10:

NUMSEC	-	-	number of ESP sections
LSECT	-	-	number of length increments per section

Lines 11 - 12 (data for section 1):

AS	-	-	plate area
VOS	-	-	voltage
TCS	-	-	current
WLS	-	-	total wire length
ACS	-	-	corona wire radius
BS	-	-	wire-to-plate spacing
NWS	-	-	number of wires per lane
SYS	-	-	1/2 wire-to-wire spacing
VGS	-	-	gas volume flow rate
VGASS	-	-	gas velocity
TEMPS	-	-	gas temperature
PS	-	-	gas pressure
VISS	-	-	gas viscosity
LINCS	-	-	incremental length

TABLE 1. (continued)

Lines 13 - 14: data for section 2

Lines 15 - 16: data for section 3

Lines 17 - 18: data for section 4

Line 19:

Line 19 is the first line of the next data set. In this case, since only one data set is used, the only entry in line 19 is 99, the code to indicate that no more data sets are to be read.



## VIDEO DISPLAY

While the revised ESP model is running, certain information is requested from the user and other information is displayed on the computer screen to advise the user of the progress of the calculation. Figure 2 shows a portion of the screen display which was created during execution of the example data set. A line-by-line explanation of Figure 2 is given below.

Line 1. The program is started by entering the name of the executable version of the program (ESPREV).

Lines 2 - 3. The program does not have the name of a file from which to read input data. The file ESPREV.DAT has been specified.

Lines 4 - 5. The program does not have the name of a file into which to write the output data. The file ESPREV.OUT has been specified.

The program now has the information it needs to complete its calculations. No further action by the user is required until the simulation is over.

Line 6 - end. The rest of the data displayed on the screen are to reassure the user that the calculation is progressing and to indicate the current status of the calculation. The following data are displayed:

INCR - identifies the ESP length increment being calculated,

FIELD - shows how many times the electric field has been calculated in this increment,

Q - shows how many times the particulate charge has been calculated in this increment.

Last line. The final line will display the code lllll to indicate that the program has terminated normally. At this point, control will return to the keyboard.

## OUTPUT DATA

The ESP model output data are written into the file whose name was supplied at the beginning of the model run. To obtain a written copy, this file must then be printed. The following listing describes the output data. Items marked with an asterisk are not printed if the input variable NOPRNT is zero. The output data corresponding to the input data in Figure 1 are shown in Appendix B.

1. Input data. A tabulation of the input data is provided for reference.
2. Incremental data. For each length increment in the ESP, the following data are printed:
  - Charge suppression factor (if applicable). If the normal charging calculation would result in too much space charge for the convergence

C> ESPREV

Please enter an input data file name:

ESPREV.DAT

Please enter an output data file name:

ESPREV.OUT

ITERATION COUNTERS:	INCR =	1	FIELD =	1	Q =	1
ITERATION COUNTERS:	INCR =	1	FIELD =	3	Q =	2
ITERATION COUNTERS:	INCR =	1	FIELD =	5	Q =	3
ITERATION COUNTERS:	INCR =	1	FIELD =	7	Q =	4
ITERATION COUNTERS:	INCR =	1	FIELD =	9	Q =	5
ITERATION COUNTERS:	INCR =	1	FIELD =	11	Q =	6
ITERATION COUNTERS:	INCR =	2	FIELD =	1	Q =	1
ITERATION COUNTERS:	INCR =	2	FIELD =	2	Q =	2
ITERATION COUNTERS:	INCR =	3	FIELD =	1	Q =	1
ITERATION COUNTERS:	INCR =	3	FIELD =	2	Q =	2

.

.

.

ITERATION COUNTERS:	INCR =	37	FIELD =	1	Q =	1
ITERATION COUNTERS:	INCR =	37	FIELD =	2	Q =	2
ITERATION COUNTERS:	INCR =	38	FIELD =	1	Q =	1
ITERATION COUNTERS:	INCR =	38	FIELD =	2	Q =	2
ITERATION COUNTERS:	INCR =	39	FIELD =	1	Q =	1
ITERATION COUNTERS:	INCR =	39	FIELD =	2	Q =	2
ITERATION COUNTERS:	INCR =	40	FIELD =	1	Q =	1
ITERATION COUNTERS:	INCR =	40	FIELD =	2	Q =	2

Return code 11111

Figure 2. Video display during running of data set ESPREV.DAT.

of the electric field calculation, the program reduces the charge until convergence can occur. If charge suppression occurs, the factor by which the charge is reduced is printed with a message.

- Current density (J).\* The final values of the particulate, ionic, total (particulate + ionic), and input current densities on the plate are printed.
  - Electric field (E).\* The final values of the electric field at the plate and the average interelectrode electric field are printed.
  - Space charge (Rho).\* The particulate (which is uniform) and the average ionic space charge densities are printed.
  - Mass removal. The mass of particles per cubic meter of flue gas that was collected in this increment and up to this point in the ESP are printed.
  - Penetration. The percent of the original mass that has penetrated this increment of the ESP is printed.
3. Sectional data. At the end of each ESP electrical section, mass and percent penetration data corrected for the effects of gas sneackage are printed.
  4. Charge accumulation data.\* The charges accumulated on each particle size are tabulated for each ESP length increment. There will be places in the tabulation where the charge is reduced from the previous increment due to the averaging of charges when the sneackage gas is remixed.
  5. ESP Outlet Statistics. In this section, size-dependent values of efficiency, penetration, and migration velocity; and overall values of efficiency and penetration are printed. These values include the corrections for gas sneackage (calculated inside the incremental computation rather than afterward), non-uniform gas velocity ( $\sigma_g$ ), and small particle migration velocity error. (If NOPRNT = 1, the statistics are printed after each correction is made.) The data are then corrected for rapping emissions and reprinted.
  6. Summary. The final section summarizes the modeling results by printing the following information:
    - Data title,
    - SCA,
    - Sneackage fraction,
    - $\sigma_g$  (gas flow standard deviation),
    - Rapping puff size distribution,
    - Total efficiency and penetration without rapping,
    - Total efficiency and penetration with rapping,
    - Dust loadings in gr/dscf and lb/MBtu (if % H<sub>2</sub>O and O<sub>2</sub> were given),

- Plume opacity, total and part due to rapping (if PATHL is not 0),
- Stack diameter used in opacity calculation, and
- Extinction coefficient for calculating opacity for a different stack.

## SECTION 4

### THEORY

The underlying assumptions for the revised version of the model are listed below. A glossary of the variables used in this section is presented in Table 2.

1. The space charge due to charged particles is constant in a given length increment and is uniformly distributed in the gas stream. This allows the development of a rigorously Deutschian model, as these were the conditions for which the Deutsch equation was derived. The assumption of uniformity is particularly good for fine particles in a turbulent gas flow. The fine particles are especially important in ESP modeling as these are the most difficult particles for an ESP to collect.
2. The space charge due to ions is neither uniformly distributed nor constant because the ions follow the electric field lines, which are non-uniform in the interelectrode space.
3. The total space charge density is the sum of the particulate and ionic space charge densities ( $\rho = \rho_p + \rho_i$ ). In the revised model,  $\rho_p$  and  $\rho_i$  are treated separately and explicitly, in contrast to the estimated treatment of a combined ionic and particulate space charge found in the standard version of the model.
4. The current is ionic except in the laminar boundary layer at the collection plate. This is due to the assumption that the particles are stationary in a given length increment. This is a good approximation since the particulate mobility is several orders of magnitude less than the mobility of the ions. Since the particles are stationary, only the ionic current density appears in the current continuity equation ( $\nabla \cdot \vec{J}_i = 0$ ).
5. The ionic mobility,  $b_i$ , is used only in the calculation of the ionic current density on the plate ( $J_p = E_{p1} \rho_i b_i$ ). The mobility drops out of the equations in the remainder of the interelectrode space.
6. The particulate current density  $J_p$  is included when determining the total current density on the plate ( $\vec{J} = \vec{J}_i + \vec{J}_p$ ).  $J_p$  is computed from the calculated charges and Deutsch migration velocities of the different size particles ( $J_p = \sum_k N_k Q_k \omega_k$ ).

TABLE 2. GLOSSARY OF VARIABLES

$E$	Electric field in the interelectrode space (V/m)
$E_{pl}$	Electric field at the collection plate (V/m)
$E_{avg}$	Average electric field in the interelectrode space (V/m)
$Q$	Particle charge (C)
$\rho$	Total space charge density (C/m <sup>3</sup> )
$\rho_p$	Particulate component of $\rho$
$\rho_i$	Ionic component of $\rho$
$J$	Total current density on the collection plate (A/m <sup>2</sup> )
$J_p$	Particulate component of $J$
$J_i$	Ionic component of $J$
$N_k$	Number density of particles in the kth size band (number/m <sup>3</sup> )
$Q_k$	Charge on the particles in the kth size band (C)
$\omega_k$	Deutsch migration velocity of particles in the kth size band (m/s)
$I$	Measured plate current (amps)
$A$	Plate area (m <sup>2</sup> )
$V$	Electric potential (volts)
$\rho_f$	Free ion density used for charge calculation (C/m <sup>3</sup> )
$e$	Electron charge ( $1.6 \times 10^{-19}$ C)
$B$	Scale factor to increase or decrease charging rate
$b_i$	Ionic mobility (m <sup>2</sup> /V-s)
$\epsilon_0$	Permittivity of free space (C <sup>2</sup> /N-m <sup>2</sup> )

- The basic equations of the E field routine have been redefined, starting with Poisson's equation

and the current continuity equation

The equations are solved for  $V$  and  $\rho$  on a calculation grid, called the  $V/\rho$  grid, which stretches from wire to mid-wire to plate. The following notation is used on the  $V/\rho$  grid:



The equation for the potential at point 0 is

$$2(a_x^2 + a_y^2)V_0 = a_y^2(V_2 + V_4) + a_x^2(V_1 + V_3) + \frac{1}{\epsilon_0} a_x^2 a_y^2 \rho_0,$$

which is unchanged from previous versions of the model, except that  $\rho_0 = \rho_i + \rho_p$  explicitly. The space charge density equation is

$$\rho_0 = -K \pm \sqrt{K^2 + \epsilon_0 E_x \rho_2 / a_x + \epsilon_0 E_y \rho_3 / a_y},$$

where  $K = (\epsilon_0 E_x / a_x + \epsilon_0 E_y / a_y - \rho_p) / 2$ .

The equation for  $\rho$  is similar to that of the standard version of the model with the following exceptions:

1. In the revised version, the particulate and ionic space charge densities are treated explicitly and summed to find the total space charge ( $\rho = \rho_p + \rho_i$ ).
2. Mobility does not appear in the revised equations. The only mobility which could occur in a stationary cloud of charged particles is the ionic mobility, and it cancels algebraically in the interelectrode space.
3. In the standard version of the model,  $K$  does not contain the  $-\rho_p$  term that arises from the explicit treatment of the space charge. The sign before the square root is taken as negative for negatively charged particles. The close similarity in the equations allows the use of the existing  $E$  field subroutine structure with only minor changes in the FORTRAN code.

Following the solution of the  $V/\rho$  grid and the subsequent calculation of  $E_{avg}$  and  $E_{p1}$ , the particulate charge is calculated. Charging is calculated by the rigorous charging procedure used in the standard version of the model. To obtain correct charging in an iterative charging procedure, the charges on the particles are reduced to the values from the previous length increment in each iteration before recharging using the most recent values of  $E_{avg}$  and free ion density ( $\rho_f$ ). The value of the free ion density is obtained from

$$\rho_f = -B\rho_i/e,$$

in which  $\rho_i$  is the average ionic space charge on the  $V/\rho$  grid,  $e$  is the elemental charge and  $B$  is a factor  $\leq 1$  that may be used to reduce the charge in a given  $E$  field/particulate charge ( $E/Q$ ) iteration to avoid nonconvergence of the  $V/\rho$  calculation. Steps have been taken to ensure that the amount of charge reduction in a given  $E/Q$  iteration is less than in the previous iteration. This results in slow and steady growth of the particulate charge until full charge is reached without causing nonconvergence of the  $V/\rho$  calculation. Full charge is defined as that charge that would be achieved if all of the available free ions were used for charging.

Once the particles are charged, the program returns to the  $E$  field calculation, where the most recent charge values are used in the space charge calculation. The calculations of ionic and particulate space charge density,

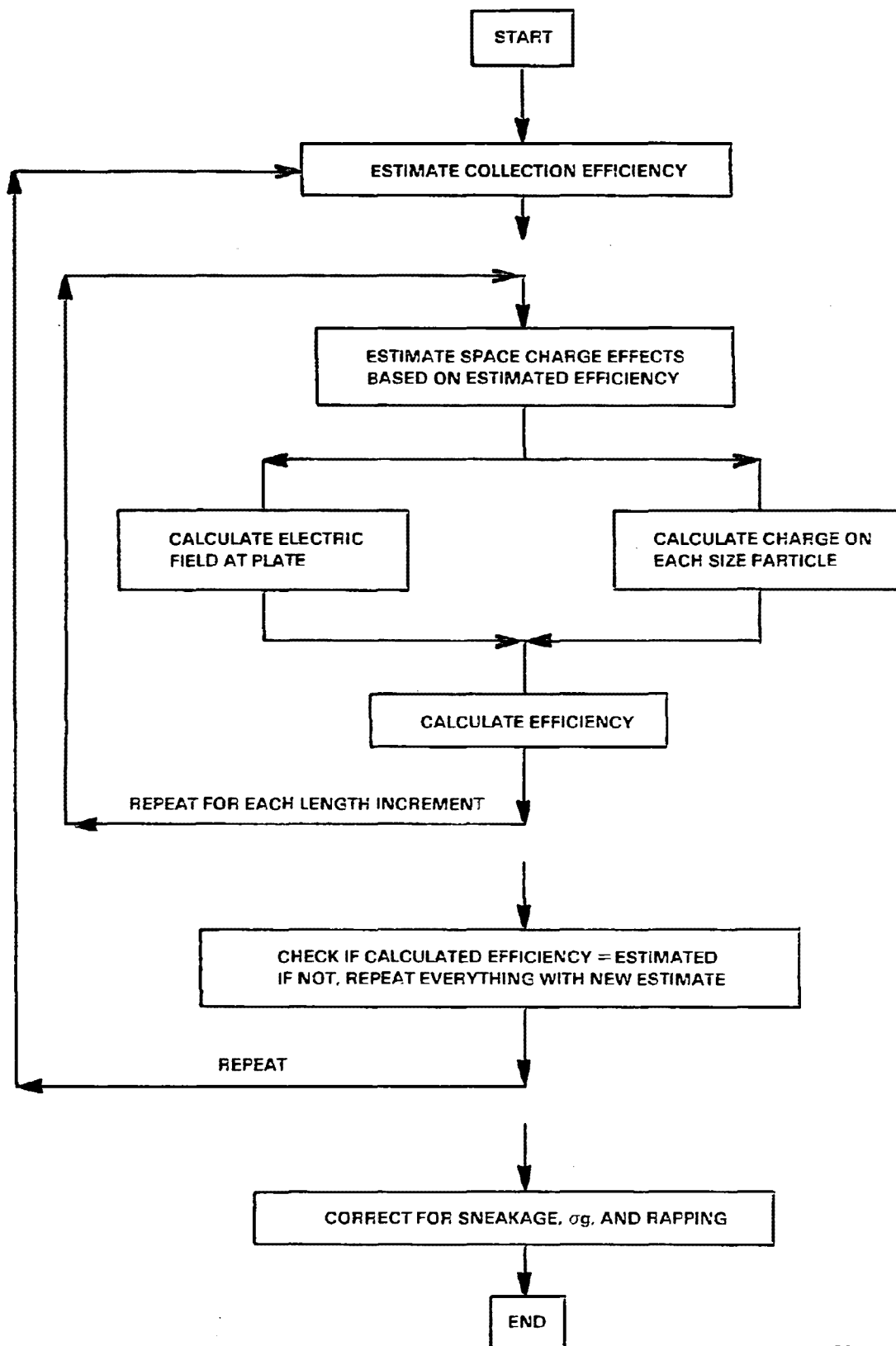


average field and collecting field (E field at the plate), plate current density, and particle charge are all iterated to self-consistency within each computational length increment. After the charge calculation in each iteration, if full charge has been reached (i.e.,  $B = 1.0$ ), the average E field is tested for convergence. If the value of E averaged across the calculation grid is within 5% of its previous value, the E/Q calculation is assumed to have converged. In modeling some ESPs, it may prove impossible to build up full particulate charge without causing  $V/\rho$  nonconvergence. In this case, the particulate charge is made as large as possible and the E/Q calculation is assumed to have converged with reduced charging. This usually occurs only in the first few increments of the ESP. Following the termination of the E/Q calculation, the collection efficiency is calculated for each particle size using the Deutsch equation. The number of particles in each size band remaining in the gas stream is determined, and the efficiency calculation proceeds to the next length increment in the ESP.

A comparison of the logic used in the standard and revised versions of the ESP model may be obtained from Figures 3 and 4. Both versions of the model use iteration to achieve self-consistency in the calculation. In the standard model, an estimated value of the overall collection efficiency must be furnished as part of the input data. This value is used to estimate the space charge effects, as shown in Figure 3. The particle charge and collecting electric field are then calculated independently of each other in each incremental length. The test of convergence is made when the overall collection efficiency is compared to the estimated value. If the two do not agree, the calculated value is taken as the new estimate and the entire process is repeated until the efficiency values do agree or the maximum number of iterations is reached.

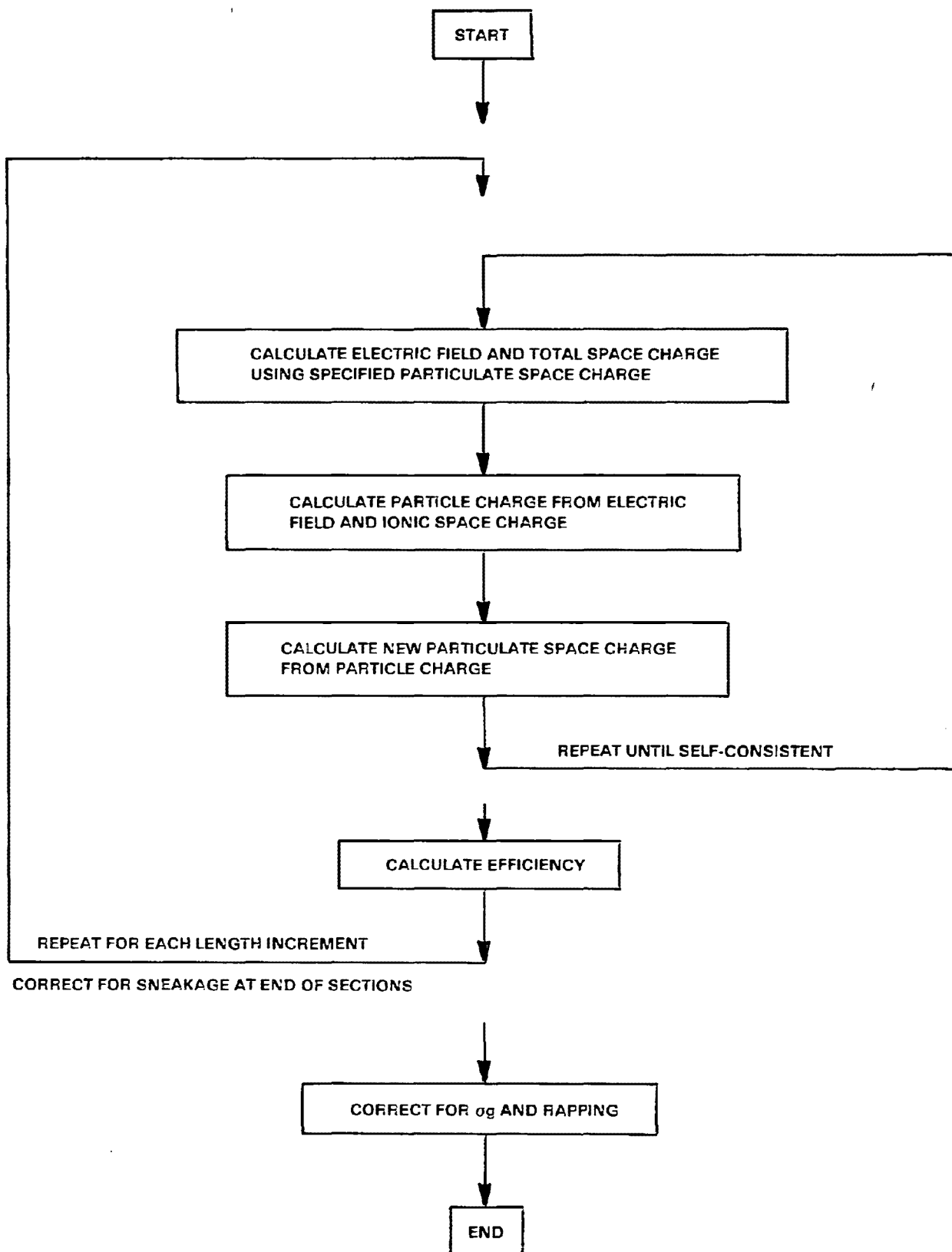
By comparison, in the revised model, each increment is made fully self-consistent before the calculation proceeds to the next length increment (Figure 4). Since the space charge effects are developed within each increment, the need for an estimated efficiency is eliminated. Further, since the E field and particulate charge calculations are interrelated, the fields and charges in each increment are consistent with each other. This feature is unique to the revised ESP model and represents a significant improvement in the state of precipitator modeling.

The algorithm in the revised ESP model includes corrections for the non-ideal effects of gas sneakage, non-uniform gas flow, and rapping reentrainment. Gas sneakage occurs when a portion of the particle-laden gas passes through the ESP in a non-electrified path, such as along the roof or dust hopper. These particles are not subjected to charging and collection. The effects of gas sneakage have been incorporated into the revised model in the following way. At the beginning of each section, a specified fraction of the particles in each size band is set aside while the remaining particles are subjected to the precipitation process. At the end of each section, the set-aside particles are remixed with the other particles. To account for the reduction in charging due to sneakage, the particle charge is averaged downward at the end of each section.



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Figure 3. Logic diagram for the standard version of the ESP model (Revision 3).



5598-87

Figure 4. Logic diagram for the revised version of the ESP model.

The effect of a non-uniform gas velocity in an ESP is to reduce the collection efficiency. In the standard version of the ESP model, this is done by applying a correction factor to the exponent of the Deutsch equation for each size band. The correction factor is obtained from an equation which describes a family of curves that were generated by calculating the efficiency of a pilot ESP for a range of gas velocities and then summing the efficiencies according to the distribution of the gas velocities measured in the ESP. For correctness, such a study should be made for each ESP being studied. However, this is not practical and the correction factor based on the pilot study has been used with good results for a wide range of ESPs. Since no better method for performing this correction is available, the correction is made in the same way in the revised ESP model.

To correct the efficiency calculation for the effects of rapping reentrainment, the rapping routine from the standard ESP model has been adapted to the revised model. This routine was based on a study of utility fly-ash precipitators. The algorithm adds mass to the ESP outlet emissions, in an amount proportional to the mass collected in the final ESP section. This additional mass is distributed among the particle size bands according to a 6- $\mu\text{m}$ -mm log-normal distribution.

## SECTION 5

### COMPARISON OF RESULTS

The revised version of the ESP model has been compared to the standard version on the basis of computed changes along the length of the precipitator in values of the following parameters:

- accumulated particle charge,
- average and collecting electric field,
- total, ionic and particulate space charge density,
- ionic and particulate current density at the plate, and
- total particulate mass penetration.

The results of the comparison for a pulverized-coal-fired power plant precipitator are shown in Figures 5 through 11. The ESP chosen for this comparison features a 25-cm (10-in.) plate spacing, good electrical power input, and a moderate dust loading of  $3.7 \text{ g/m}^3$  (1.6 gr/acf). The ash has a moderate resistivity ( $2 \times 10^{10} \text{ ohm-cm}$ ) and a particle size distribution that is typical for fly ashes from eastern bituminous coal. Figure 12 shows a percent penetration comparison based on measured data for the Edgewater Unit 4 LIMB test.

Figure 5 shows the rate of charge accumulation for three particle sizes. Although the predicted charging rate is reduced for the revised model, comparison with experimental data shows that the fit to the data is equally good with either model. The reduction in the charge can be attributed to the reduced average electric field used in the charging calculation (shown in Figure 6). The reason for the field reduction in the revised model is that the average field is calculated by averaging the electric field over the  $V/\rho$  grid in each length increment. Figure 6 shows that the average electric field is dependent on the particulate space charge and decreases as particles are collected. In the standard version, the value of the average field is obtained by dividing the applied voltage in each field by the wire-to-plate distance. The steps in the field curve for the standard version are due to changes in the applied voltage between fields.

Figure 6 also shows the enhancement of the collecting electric field (the field at the plate) due to charged particles. This effect is observable because the revised version of the model calculates the effects of space charge on the electric field explicitly. The standard version, which does not directly relate the field calculation to particle charge, does not show this phenomenon. This is an important effect because the Deutsch migration velocity is directly proportional to the field at the plate.

Figure 7 compares the total space charge density at the plate (directly opposite the wire) for the standard and revised versions of the model. In the standard model, no specific requirements are made on the space charge density regarding the number of charged particles in the gas stream. The calculation is made as if only ions were present, except that an effective mobility for combined motions of ions and particles is used instead of the ionic mobility. In the

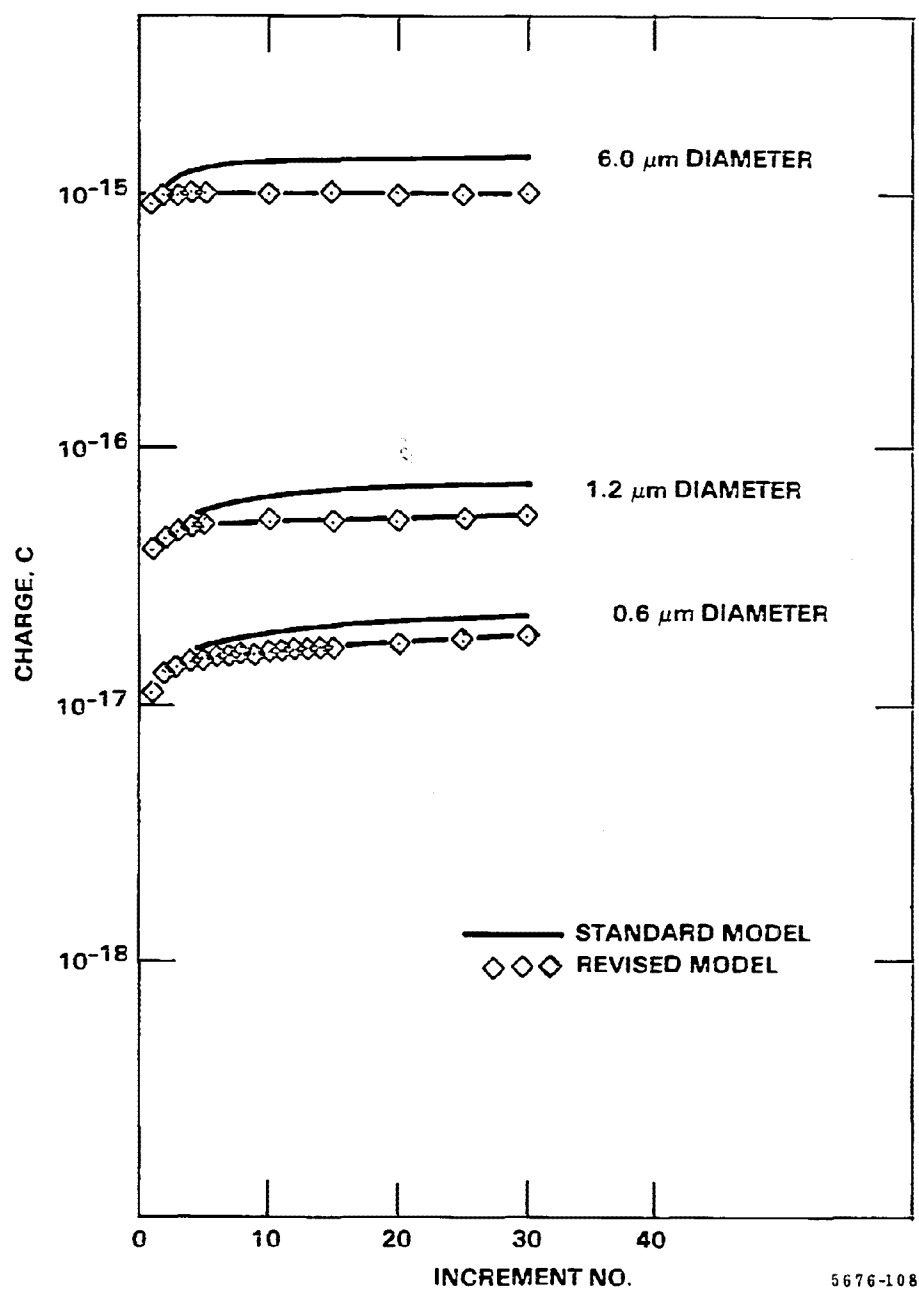
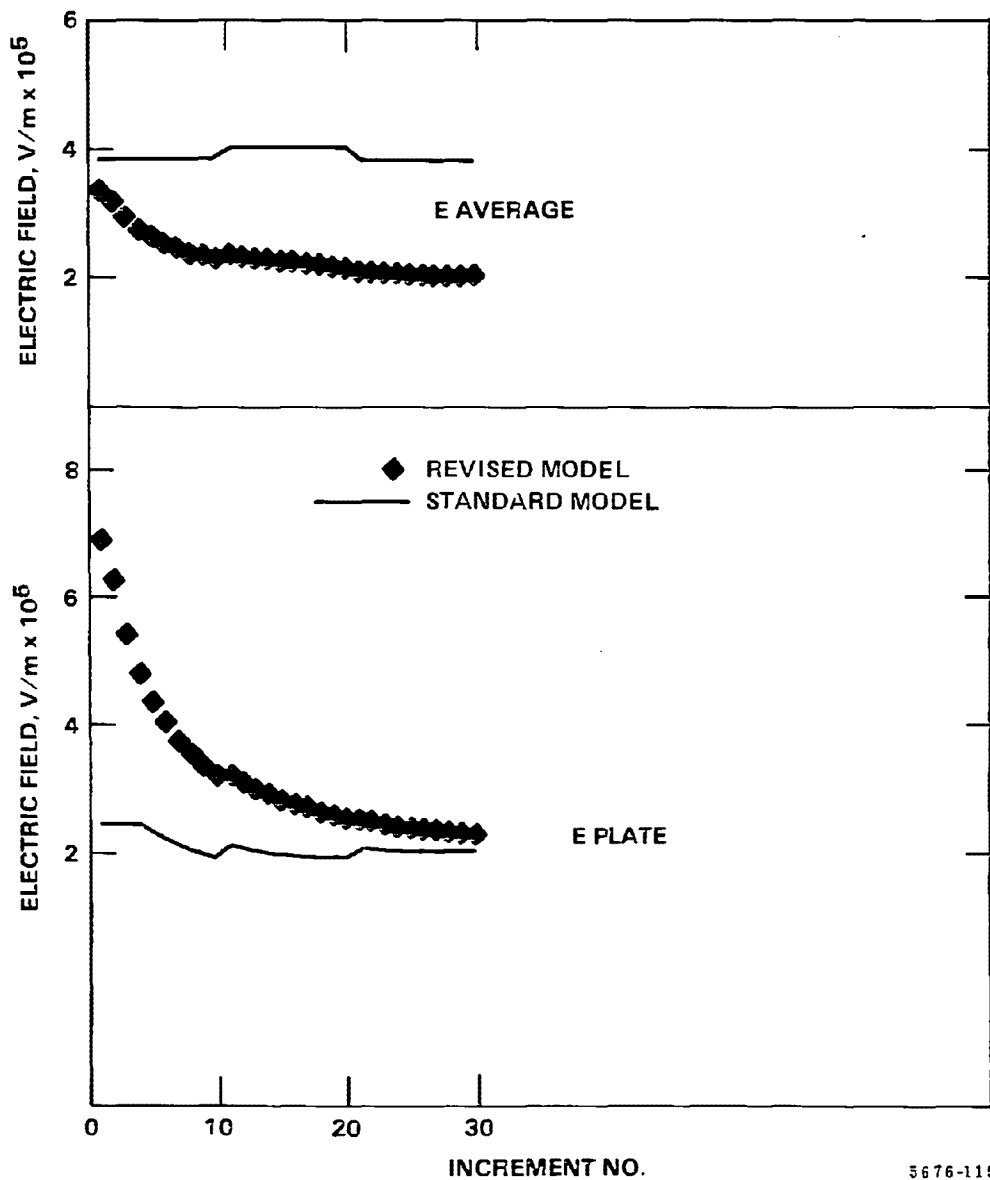


Figure 5. Particulate charge calculated by the standard and revised versions of the ESP model.



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Figure 6. Calculated electric fields for the standard and revised versions of the ESP model.

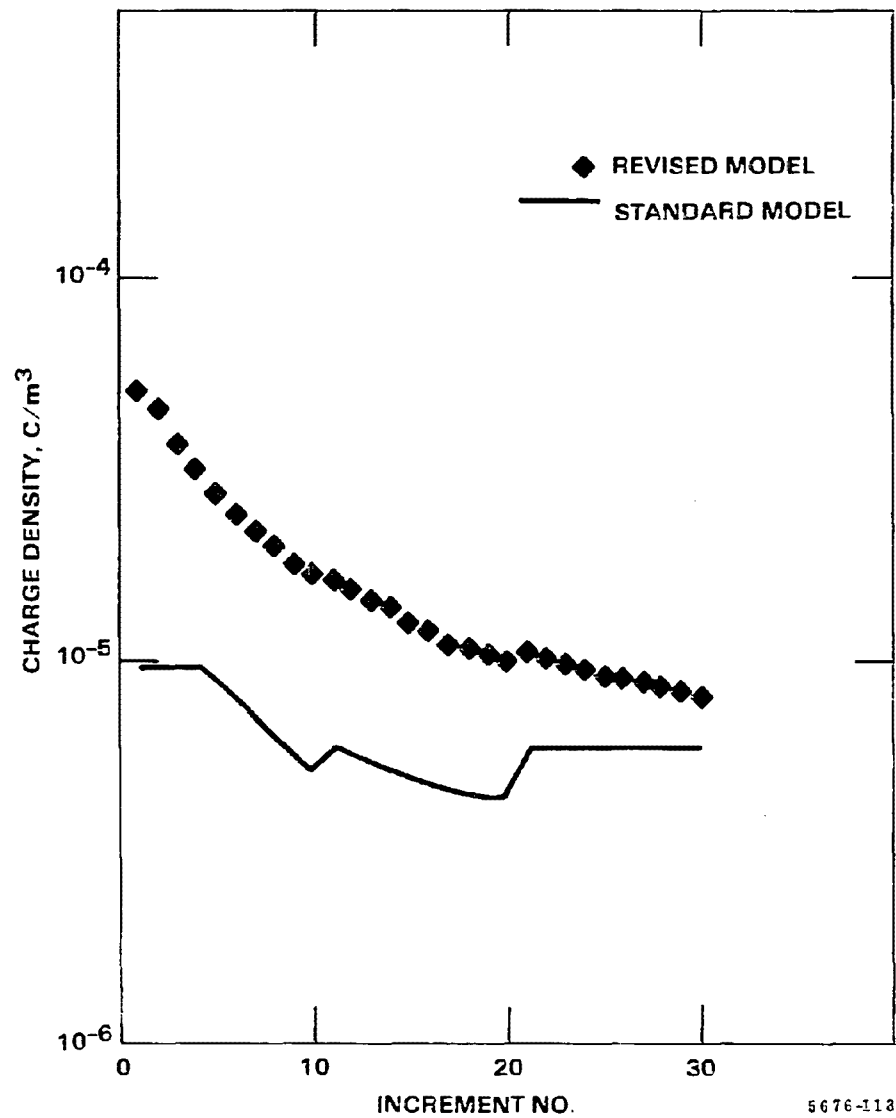


Figure 7. Total space charge density calculated by the standard and revised versions of the ESP model. The calculation is at the plate directly opposite the wire.



revised model, where the particulate and ionic space charge are treated explicitly, the total space charge density at every point in the interelectrode space is constrained to be equal to or greater than the minimum charge density provided by a uniformly-distributed, stationary cloud of charged particles. As shown in Figure 7 the space charge density starts at a high value due to the rapid charging of entrained particles and then decreases as particle collection takes place.

In Figure 8, the total space charge density for the revised model shown in Figure 7 has been broken down into its ionic and particulate components. Comparison of the figures shows that in the first half of the ESP, the particulate space charge density is the major component of the total space charge density. Only in the last few increments of this example does the ionic space charge exceed the particulate space charge. These data are not available in the combined-ions-and-particles treatment used in the standard version of the model, but may be easily obtained from the revised model which keeps track of ions and charged particles separately.

In contrast to the dominance of the particulate space charge density, the current density on the plate is overwhelmingly ionic in nature. Figure 9 shows this for both the standard and revised versions of the model. Note that the particulate and ionic current densities are plotted on the same scale, demonstrating the difference in magnitude between the two components. The minimum difference is a factor of 10, with the average difference exceeding 2 orders of magnitude.

Figure 10 shows the incremental mass penetration calculated for the standard and revised versions of the model. The greater collecting electric field in the revised model produces a greater efficiency (lower penetration) even though the ultimate particle charge is less than in the standard version. These curves represent the ideal efficiency only and do not contain any non-ideal effects.

Figure 11 shows the effects of 5% gas sneakage. The remixing of the gas which had bypassed the electrified portion of the ESP causes a sudden increase in the number of particles present at the end of each ESP section. This is clearly shown in Figure 11 by the vertical lines at increments 10, 20, 30, and 40.

Figure 12 shows the results of modeling the data taken at Edgewater Unit 4 during the May 1989 humidified LIMB tests. The data for this modeling were taken on May 24 (5 fields on line) and May 26 (3 fields on line). The data were modeled for a single gas condition, 5 percent sneakage with  $\sigma_g = 0.15$ , which is typical of a modern ESP in good repair. The data show the following:

- no convergence difficulties were encountered when modeling the high space charge using the revised model,
- the revised model predicts less penetration than the standard version of the model, and
- neither model's predictions are very close to the measured penetrations.

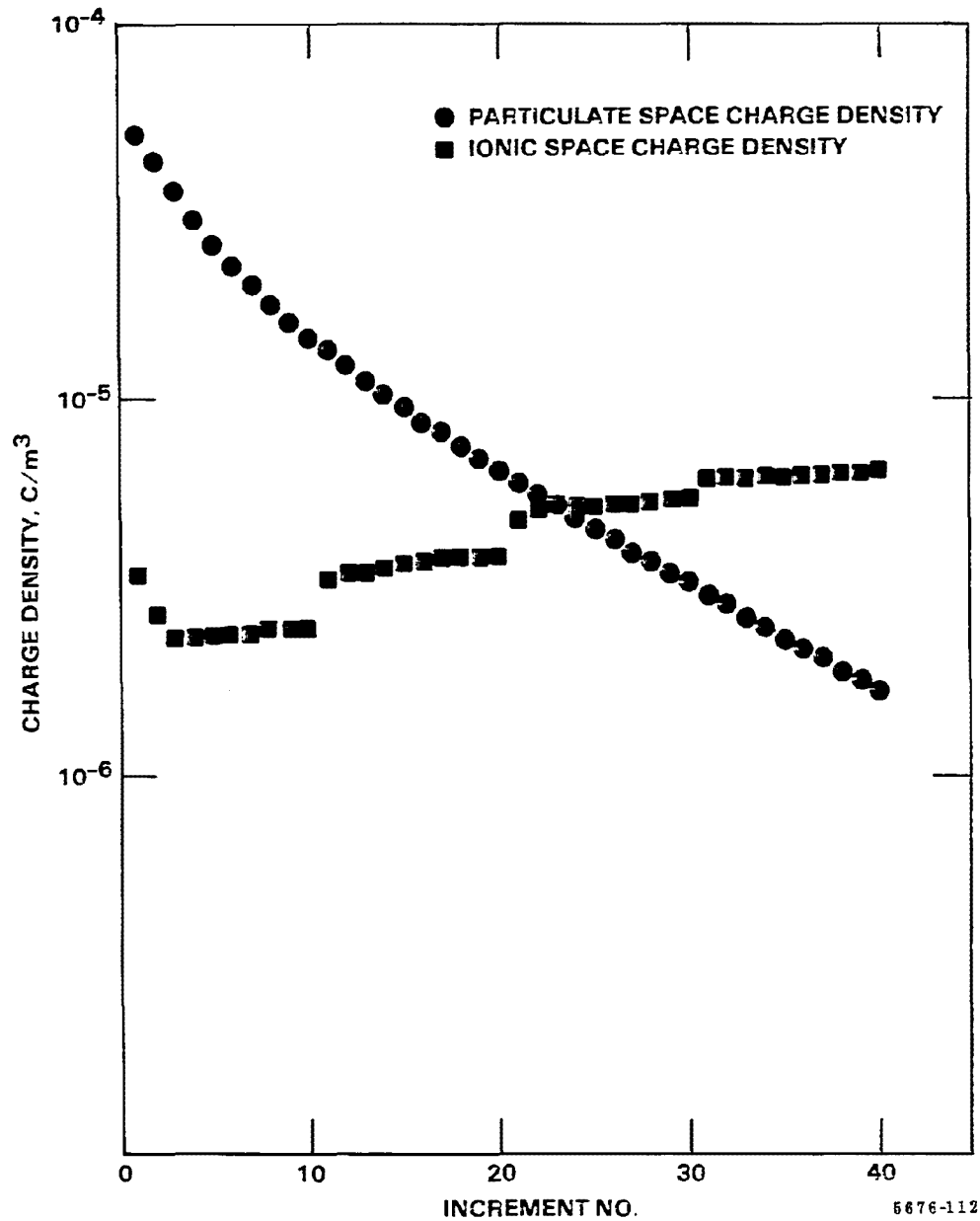


Figure 8. Particulate and ionic components of the space charge calculated by the revised version of the ESP model. The calculation point is at the plate directly opposite the wire.

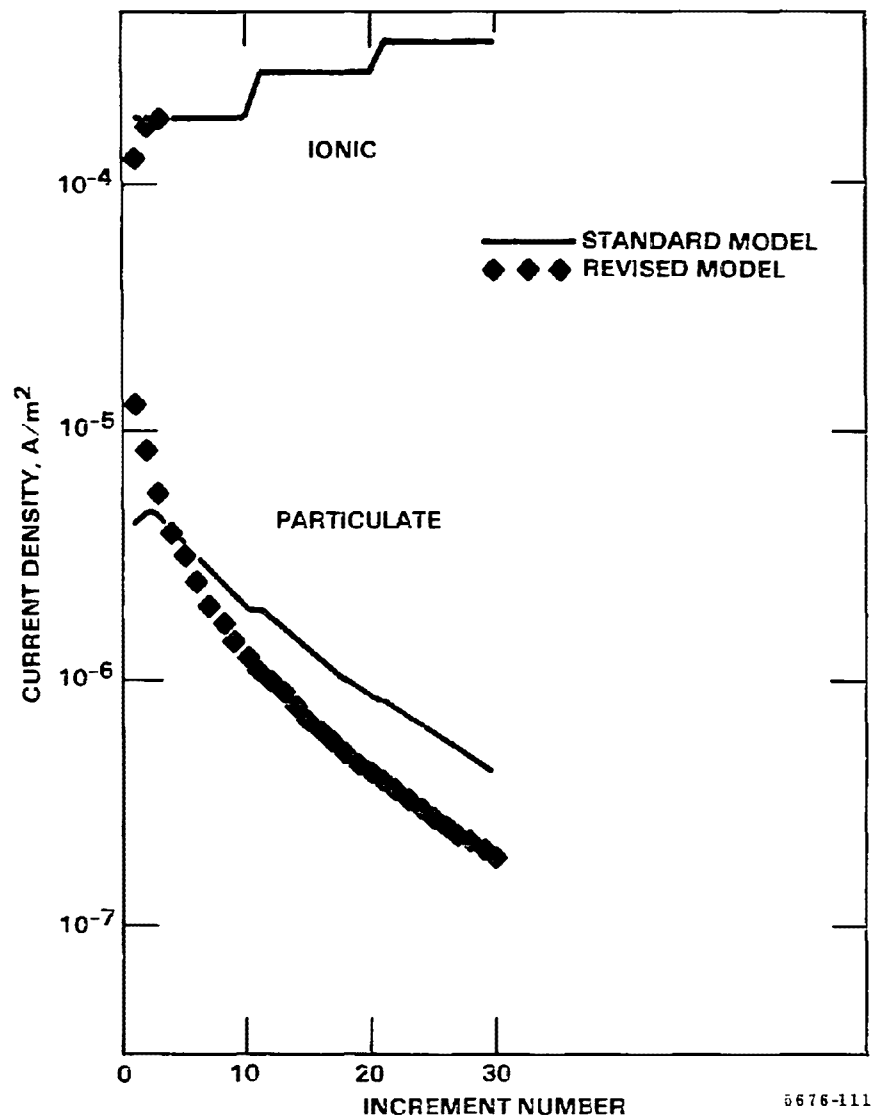


Figure 9. Ionic and particulate current densities predicted by the standard and revised versions of the ESP model.

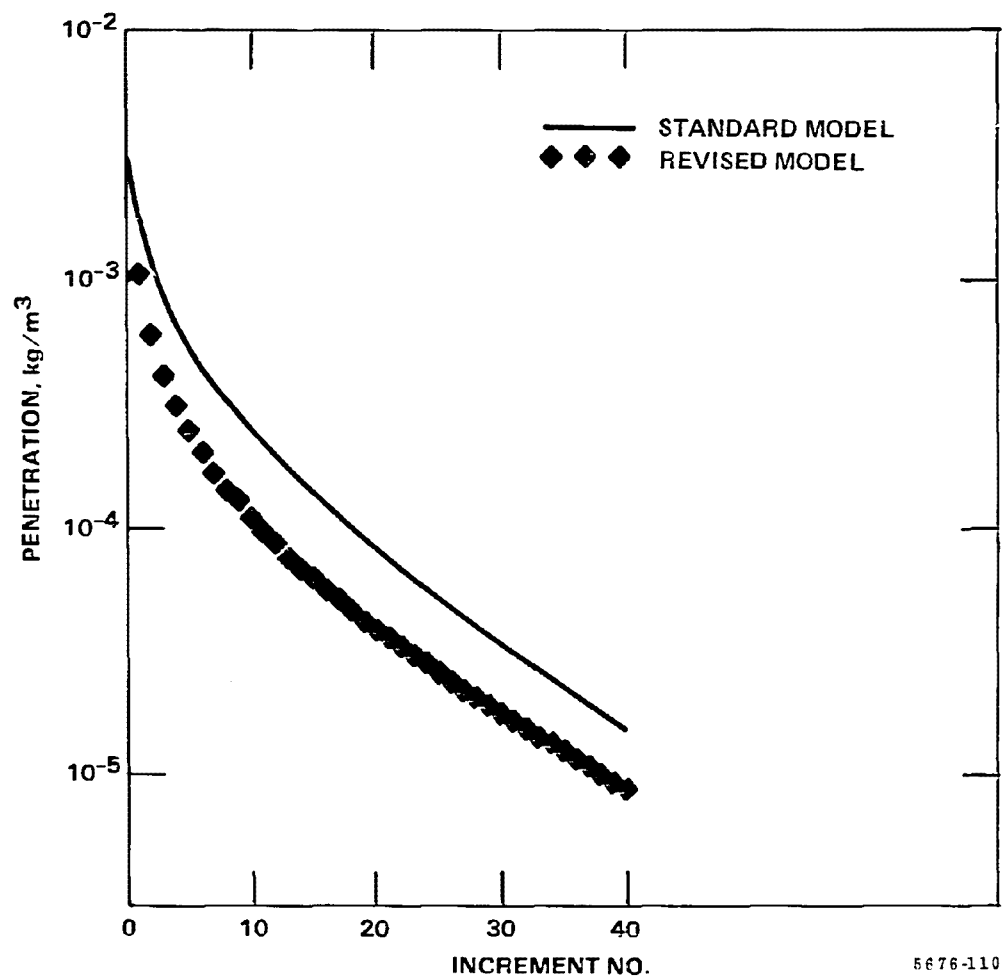


Figure 10. Mass penetration calculated by the standard and revised versions of the ESP model.

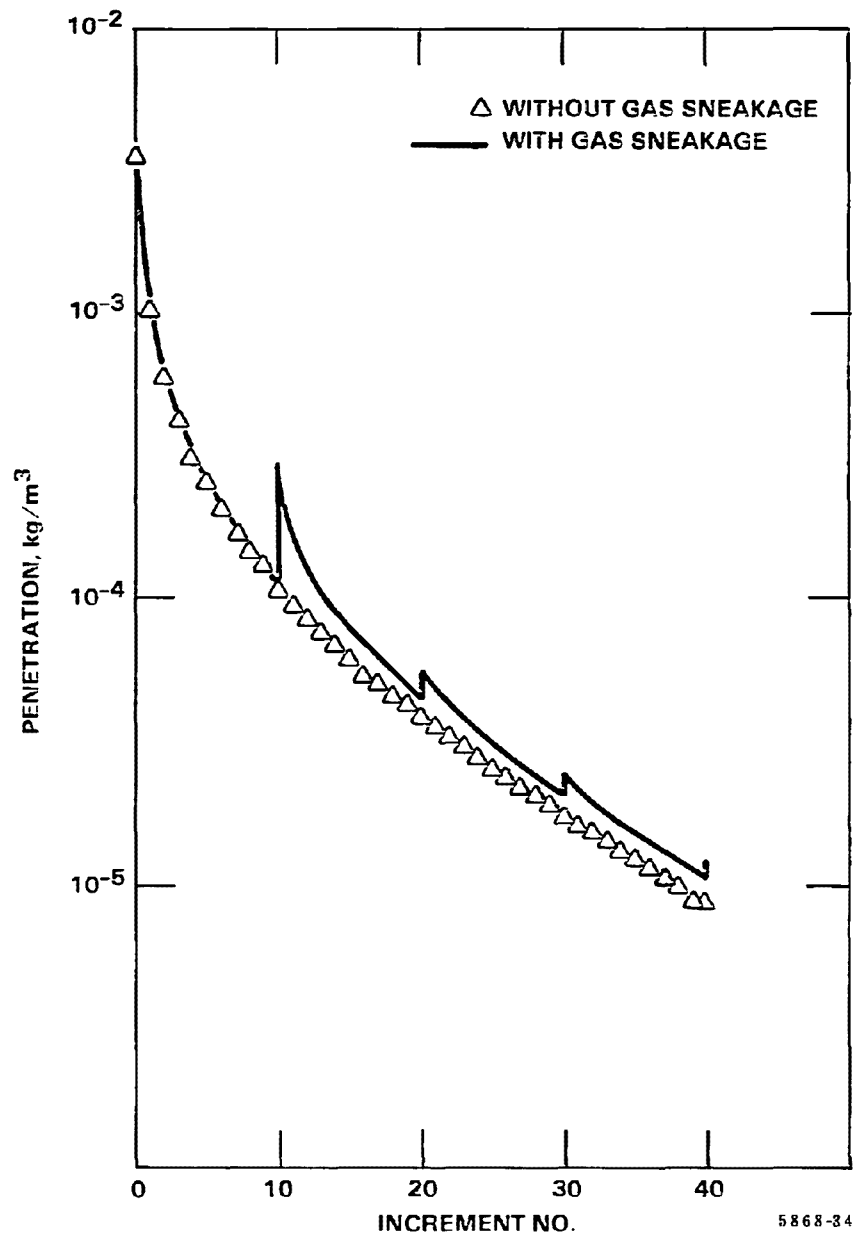


Figure 11. Mass penetration calculated by the revised version of the ESP model with 5 percent gas sneakage.

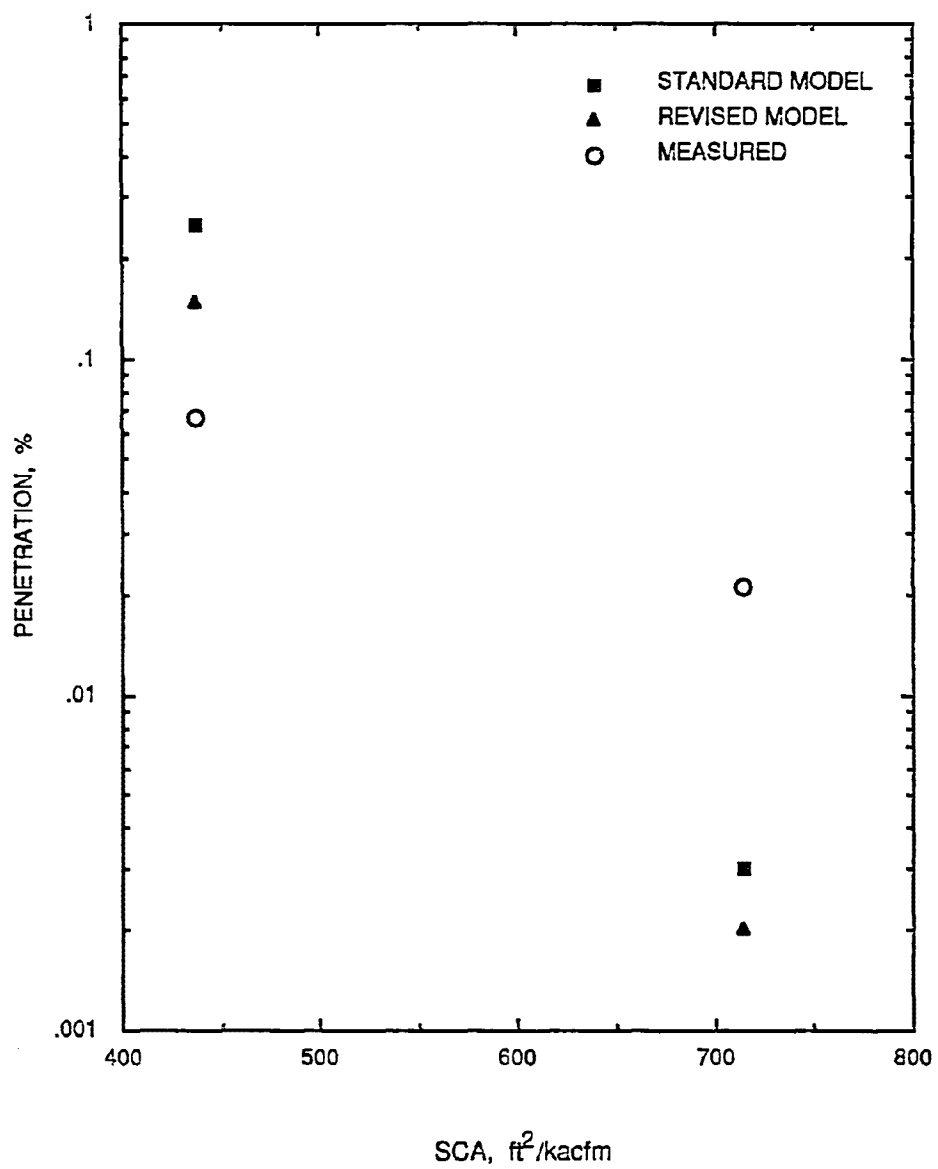


Figure 12. Measured and calculated percent penetration for the Edgewater Unit 4 ESP.

Figure 12 shows that for 3 fields, the ESP performed better than predicted by either model. However, for 5 fields the measured performance was only slightly better than for 3 fields. Both models indicate that the 5-field performance should have been about an order of magnitude better than it was. This may be the result of abnormally high reentrainment of the humidified ash. The cause of the better-than-predicted penetration with 3 fields is not known. Some factors which may have contributed to the high efficiency are listed below.

- The ESP had been switched from 5 fields (first field = field 2) to 3 fields (first field = field 4) at the end of the previous day's testing. There may not have been enough time for a 3-field configuration to come to equilibrium, resulting in lighter than normal reentrainment from the third field.
- The V-I data for the first field show an unusually low current density, averaging  $0.13 \text{ nA/cm}^2$ , compared to  $4.7 \text{ nA/cm}^2$  for the 5-field configuration. Space charge corona suppression may have contributed to this. However, no similar reduction was observed in the 5-field configuration.

The net result is that this was not a good test for model validation. A similar measurement program on a smaller ESP with less efficiency (so that more mass could be collected in the impactors), that has been running long enough to equilibrate, and that does not show abnormal V-I characteristics or high reentrainment, would provide a better test.

## SECTION 6

### EVALUATION

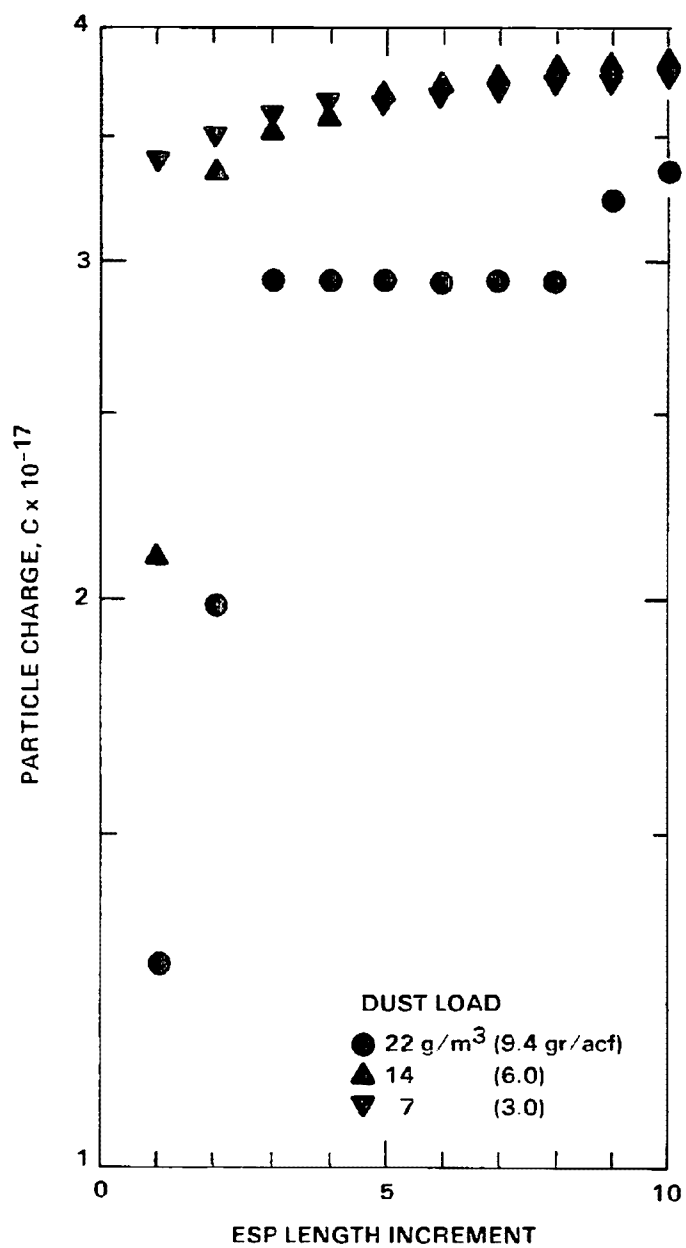
The primary reason for the development of the revised ESP model was to provide a precipitator performance model that is responsive to changes in dust loading. This goal has been met. The preceding data comparisons show that the revised model clearly demonstrates the effects of its explicit space charge calculation. The sensitivity of the revised model to changes in dust load is shown in Figure 13, where the calculated particle charge for a  $1.2\ \mu\text{m}$  diameter particle is plotted as a function of distance down the precipitator. The plant which provided the model input data has an abnormally high inlet dust load of  $22\ \text{g/m}^3$  (9.4 gr/acf). In Figure 13, the dust load has been arbitrarily reduced for comparison. The lowest dust load, a value typical of many ESPs, shows high initial charging followed by a slow increase due to diffusion charging. The middle value shows a decreased charging rate for the first two length increments, followed by slow charge increase at about the same level as the curve for low dust load. For the highest dust load (the actual dust load for this ESP) the charging rate is greatly reduced in the first three length increments. In the next five increments, the charging is totally suppressed until the space charge is reduced by particle collection, after which charging resumes. Similar total suppression of charging due to high mass loading has been measured on a pilot ESP at SRI (3). Note that these are not real data, as the dust load cannot be changed without changing the electrical operating conditions of the ESP. However, these hypothetical data illustrate the point that the revised ESP model reacts to changes in dust load. The standard ESP model gave the same charge for all dust loads, yielding a curve which closely resembles the curve for the lowest dust load in Figure 13.

Another example of the sensitivity of the revised ESP model to changes in dust loading is shown in Figure 14, where ESP penetrations calculated by the standard and revised ESP models are compared. It is expected that as the space charge decreases, the collecting electric field, and consequently the collection efficiency, will also decrease. This effect is shown in the figure for both models. However, changing the dust loading produces much greater variation using the revised model, where space charge is used explicitly in the electric field calculation. Note that although the percent penetration will be lower with higher inlet mass loading, it is usually not enough to overcome the extra mass, resulting in higher mass emissions. As in the previous example, these data were generated by varying the dust load and nothing else in the data sets. The curves might have different shapes if measured operating data for varied dust loads were used.

The second reason for revising the ESP model was to eliminate the three deficiencies that have been identified in the standard model:

1. The space charge effects are not explicitly calculated but are estimated based on an effective mobility which accounts for fast moving ions and slow moving particles. The effective mobility is not a composite of mobilities but is given by an equation that applies only to small particles near the collection plate.





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Figure 13. Particle charging rates predicted by the revised ESP model for three input dust loads.

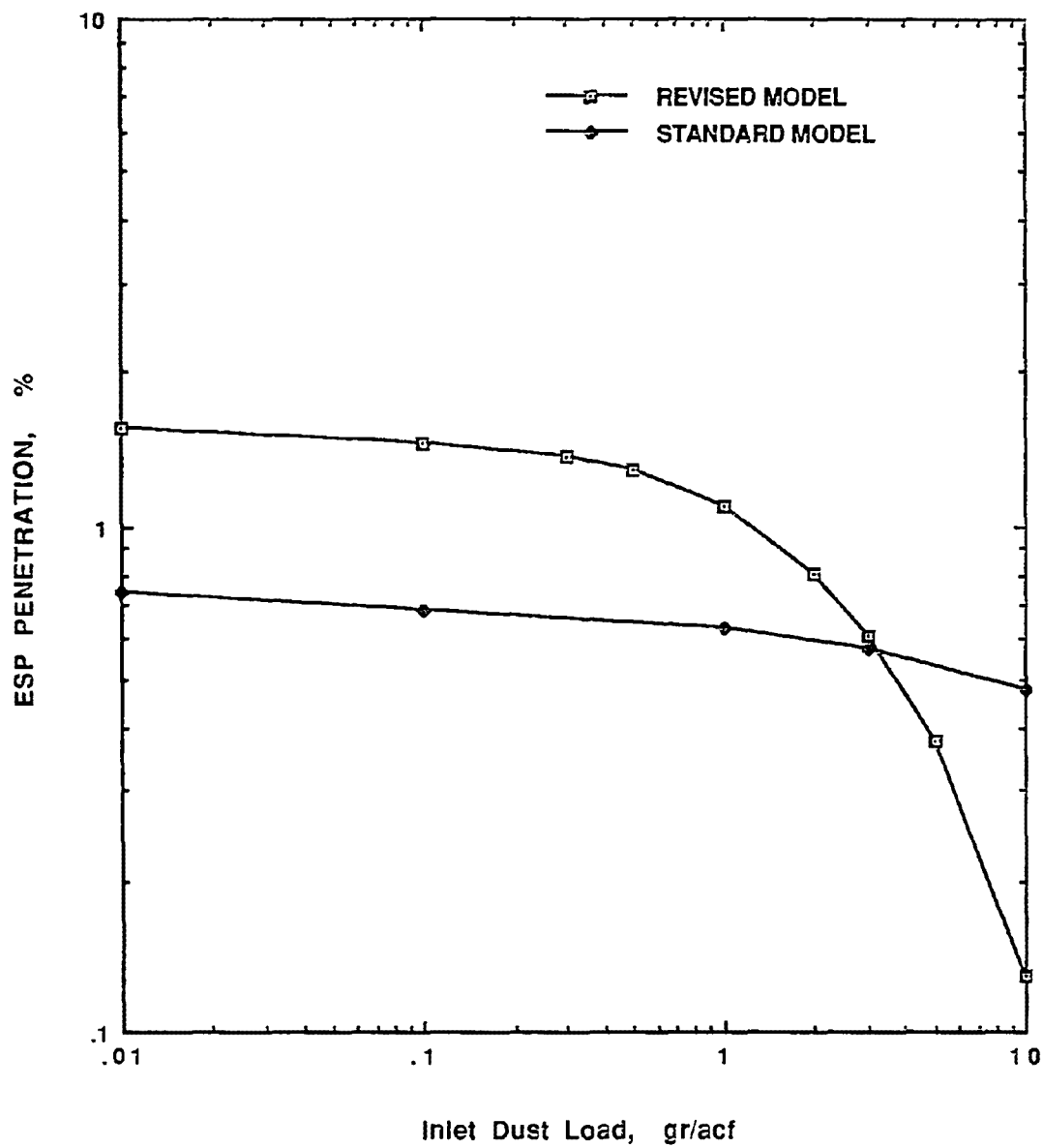


Figure 14. ESP percent penetration as a function of inlet dust load.

2. The electric field and particle charge calculations are not mathematically connected.
3. An empirical correction factor must be applied to the average migration velocities of small particles to make their calculated efficiencies match measured data.

The first two deficiencies were eliminated by the structure of the revised model. It was hoped that making the revised model rigorously Deutschian would remove the need for an empirical correction factor for small-particle migration velocities (the third deficiency). That this was not the case can be seen in Figure 15, which shows the ratios of measured migration velocity to migration velocity calculated by the revised model without the correction factor, for 10 cold-side utility ESPs. These plants were chosen from the SRI ESP data base (4). The measured migration velocities were determined from the fractional penetration data using the Deutsch equation. The calculated data were generated using the values for gas leakage and non-uniform gas velocity standard deviation that have proven to be most typical of the power plants in the data base (0.05 and 0.15 respectively), and include the effects of rapping reentrainment. The curve in Figure 15 represents a second-order least-squares fit to the data. This curve is very similar to the curve produced by the same data using the standard ESP model. By including an empirical correction factor similar to the one in the standard model, the performance projections can be corrected, as shown in Figure 16.

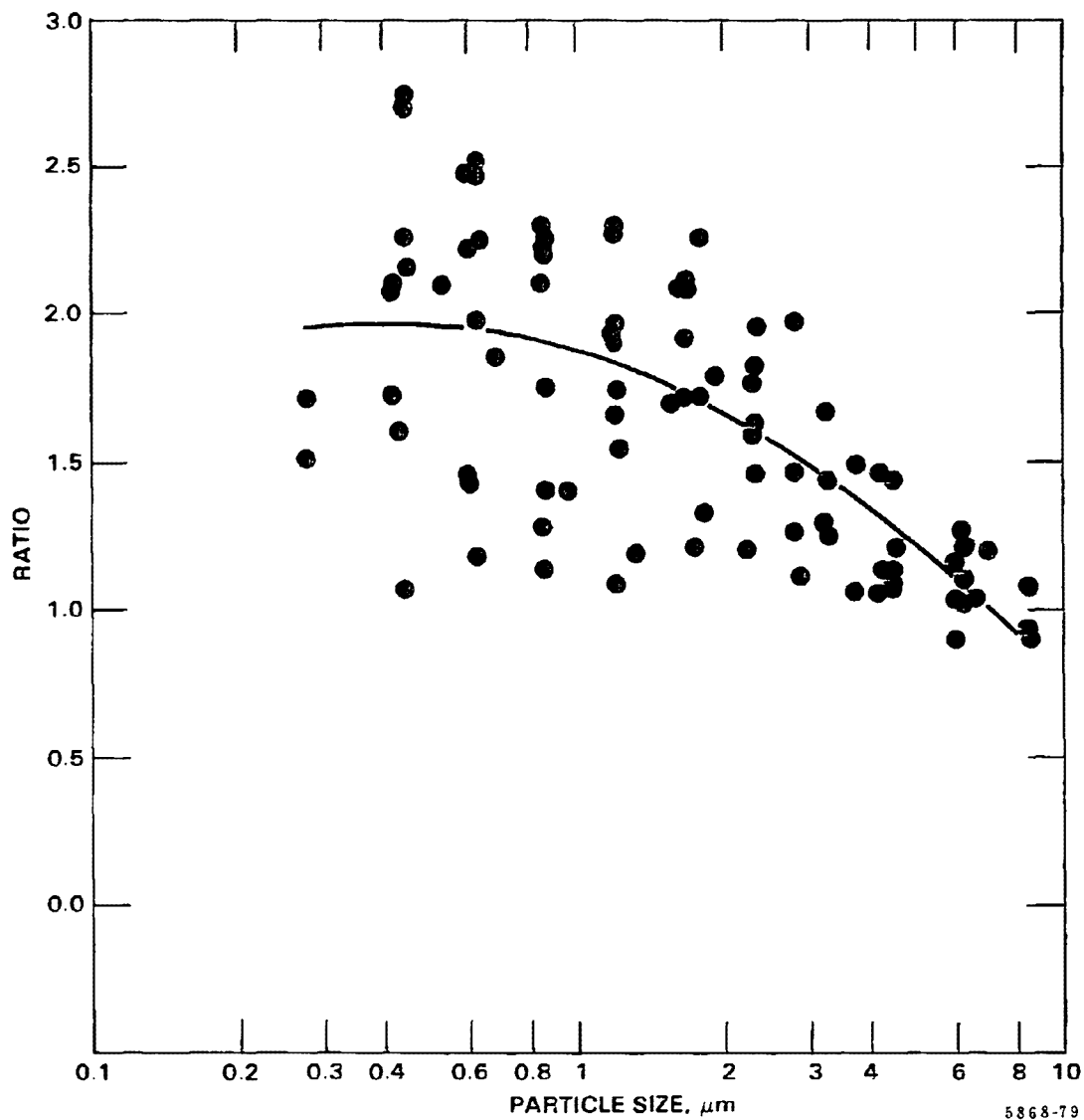


Figure 15. Ratio of measured migration velocity to computed migration velocity for 10 plants (revised model without the ramp function). The curve is a second-order least-squares fit to the data.

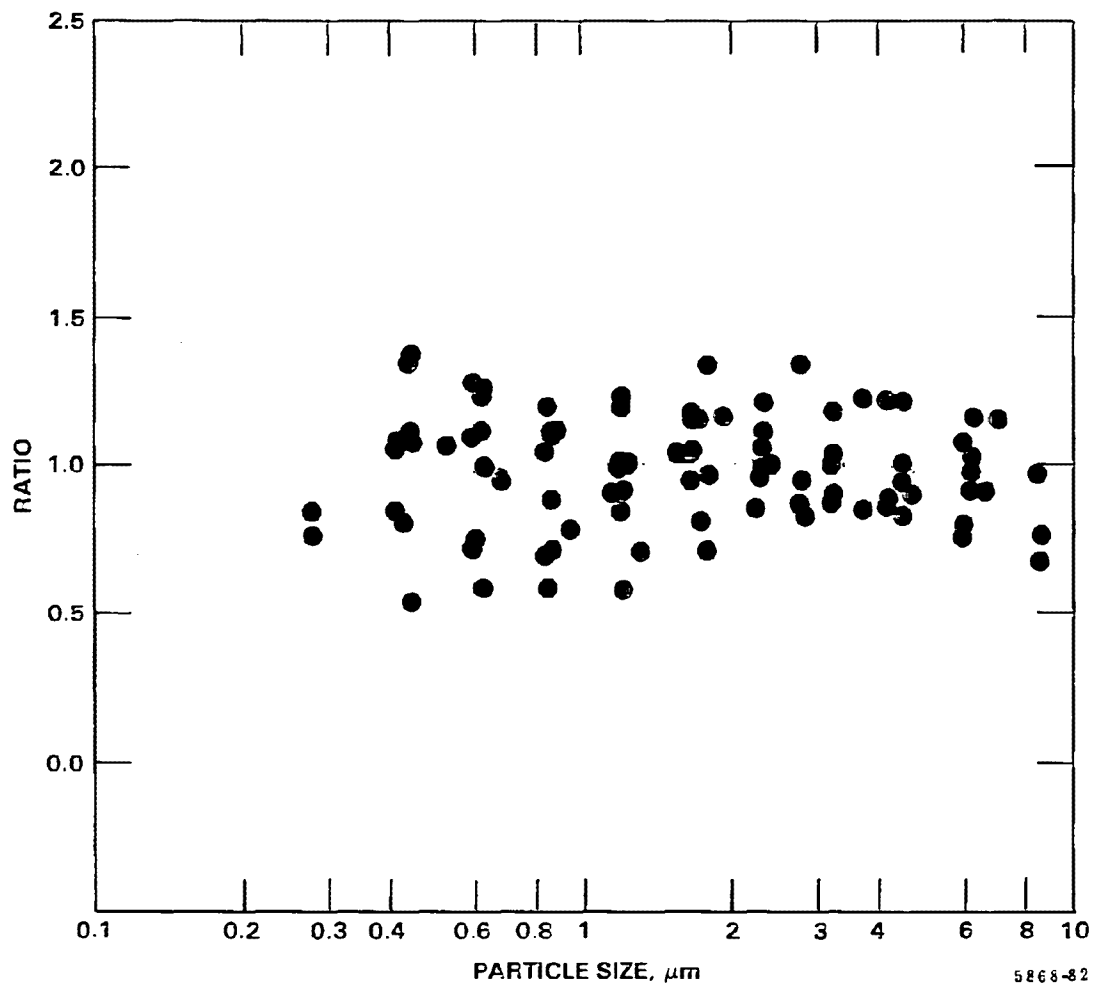


Figure 16. Ratio of measured migration velocity to computed migration velocity for 10 plants (revised model with revised ramp).

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3. Faulkner, M. G., DuBard, J. L., and Sparks L. E. The Effect of High Mass Loading on Fly Ash Precipitators. In: Proceedings: Sixth Symposium on the Transfer and Utilization of Particulate Control Technology, Volume 2. EPA-600/9-86-031b (NTIS PB87-147-625). U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1986.
4. DuBard, J. L., and Dahlin, R. S. Precipitator Performance Estimation Procedure. EPRI CS-5040. Electric Power Research Institute, Palo Alto, California, 1987.

## Appendix A

### DESCRIPTION OF INPUT DATA<sup>a</sup>

#### GENERAL DESCRIPTION

The format of the original computer program which performs the calculations in the model for electrostatic precipitation has been re-structured to make the inputting of data less cumbersome. The number of cards which is necessary to input data has been reduced significantly by allowing different operating conditions to be analyzed from one basic set of input data. Due to the fact that several options are available in using the model, the number of cards and type of information in the input data may vary from one set of data to the next. Thus, it is necessary for the user to be familiar with the logic associated with the input data in order to ensure that the desired operations will be performed.

The input variables may be read into the program entirely in metric units or in mixed British and metric units depending on the value of the variable MODL described below. Non-metric data are internally converted to metric units prior to performing the calculations. The input variables and format specifications are discussed in detail in the following section. Where both British and metric units are given, the British units are to be used when mixed units are selected and the metric when all-metric input is selected. Figure A-1 contains a flow chart which shows the logic involved in entering the data.

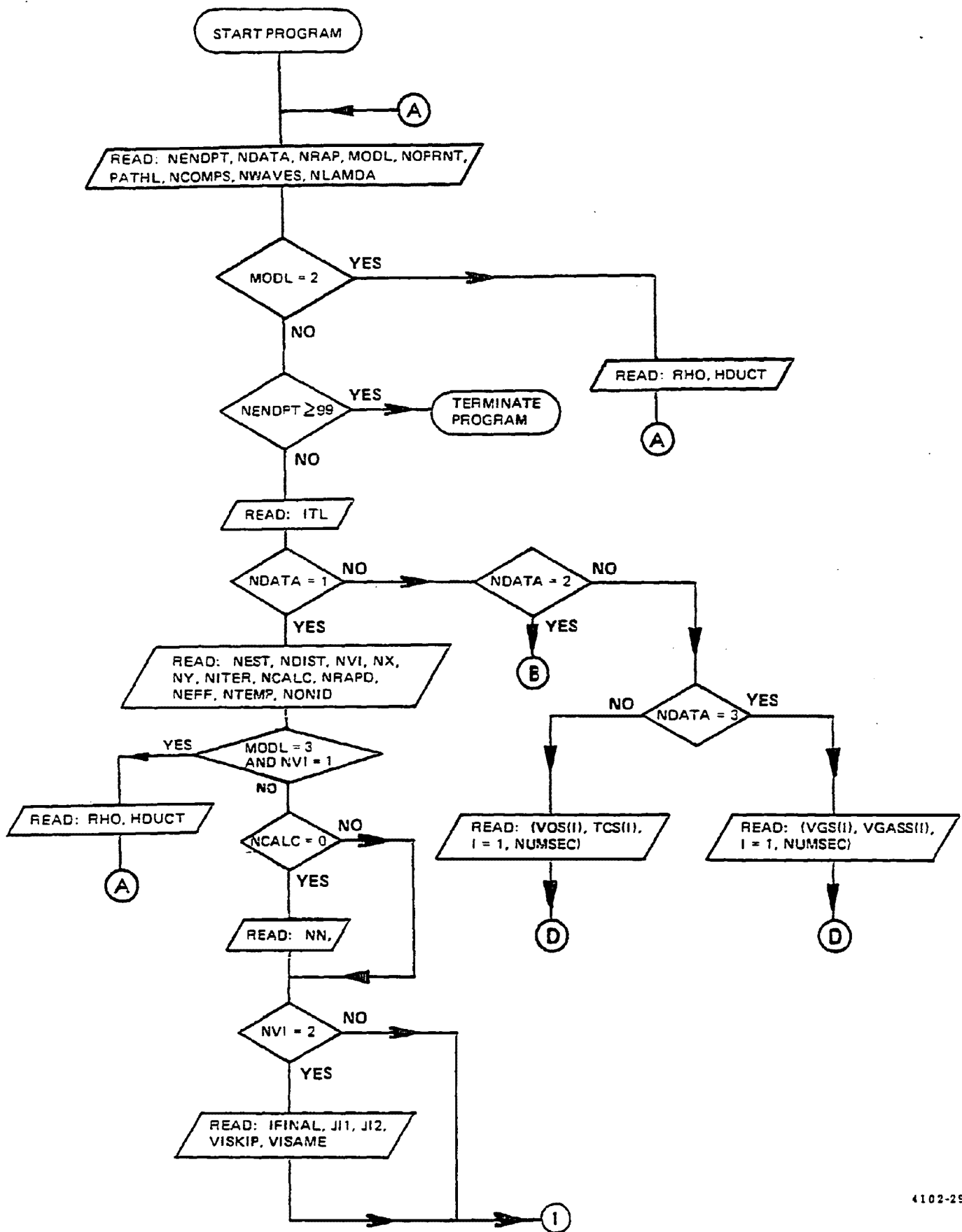
#### CONSTRUCTION OF THE BASIC DATA SET

The following is a sequential listing of the variables in the first group of data which is read in, along with the descriptions of the variables and the format specifications.

- (1) NENDPT is the number of discrete points on the cumulative percent versus particle diameter curve. NENDPT is specified by the user and must have a value of at least 1 but not greater than 21. After the collection efficiency has been calculated for one data set, the program will begin reading data for another efficiency calculation starting with this data group. If NENDPT has a value of 99, the program terminates. Thus this data group will be

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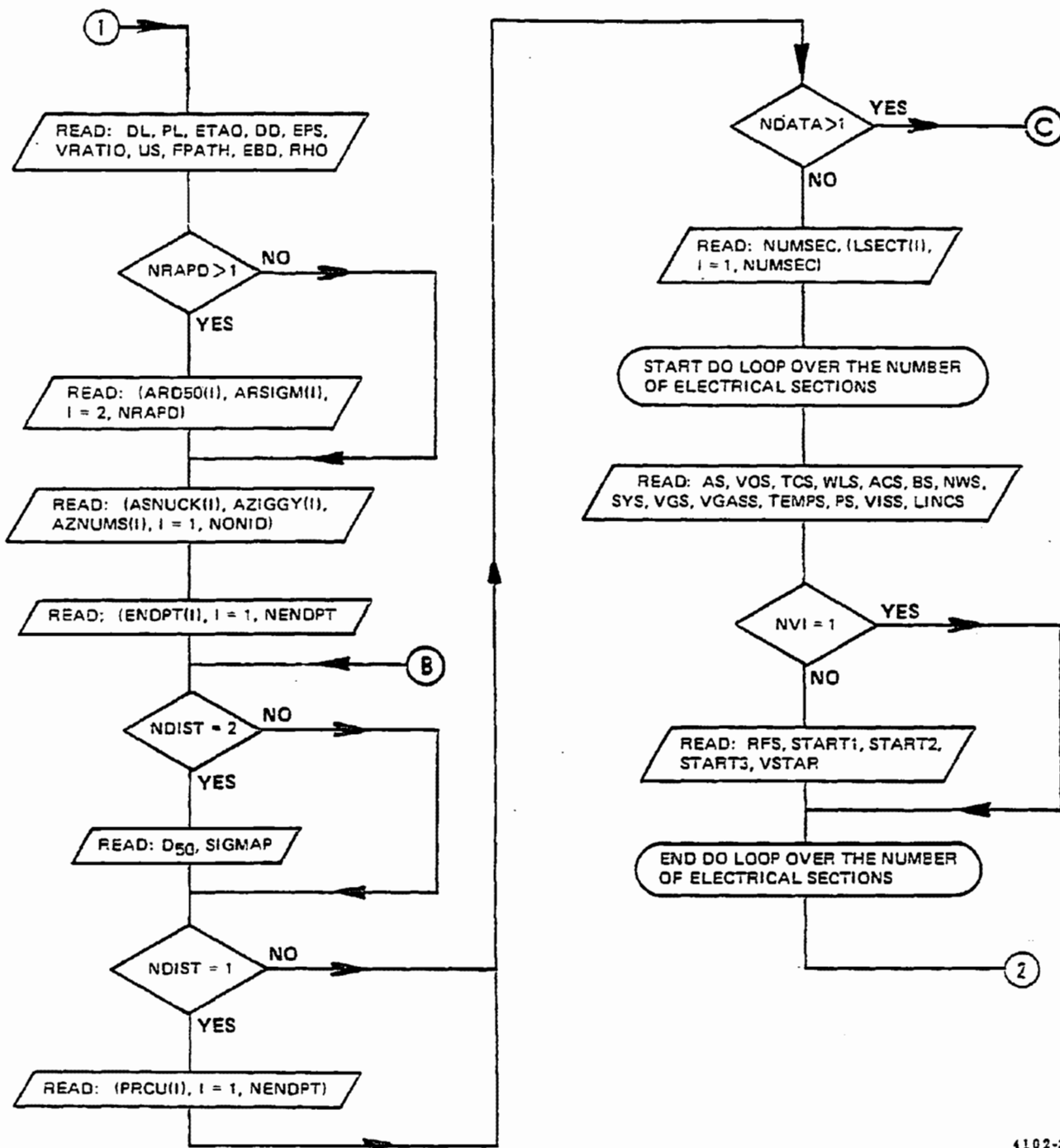
<sup>a</sup>This appendix was taken from the EPA/SRI ESP model report.<sup>1</sup> References to Volume 1 in this appendix refer to Volume 1 of the ESP model report.



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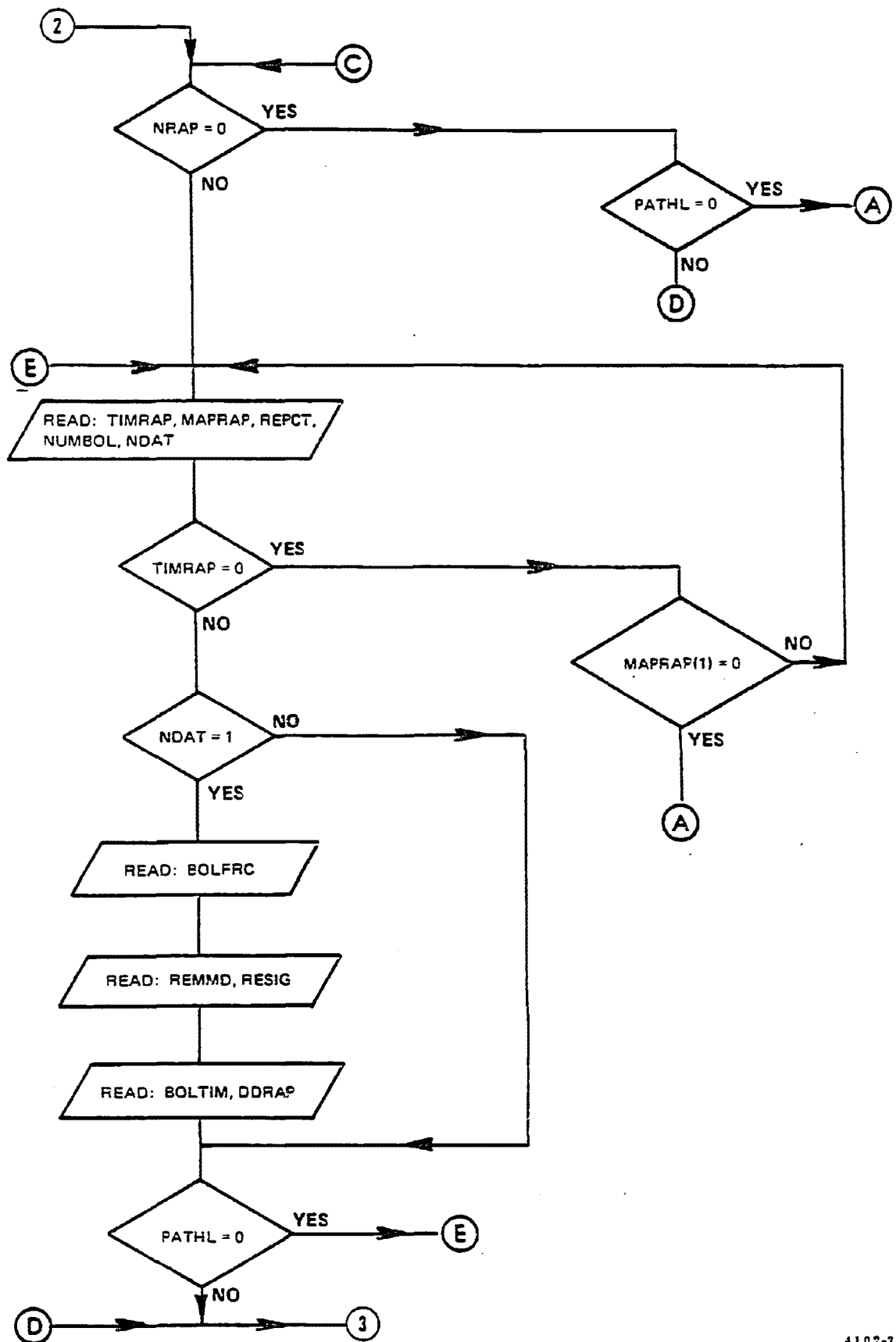
Figure A-1. Flow chart for the input data logic (Sheet 1 of 4).





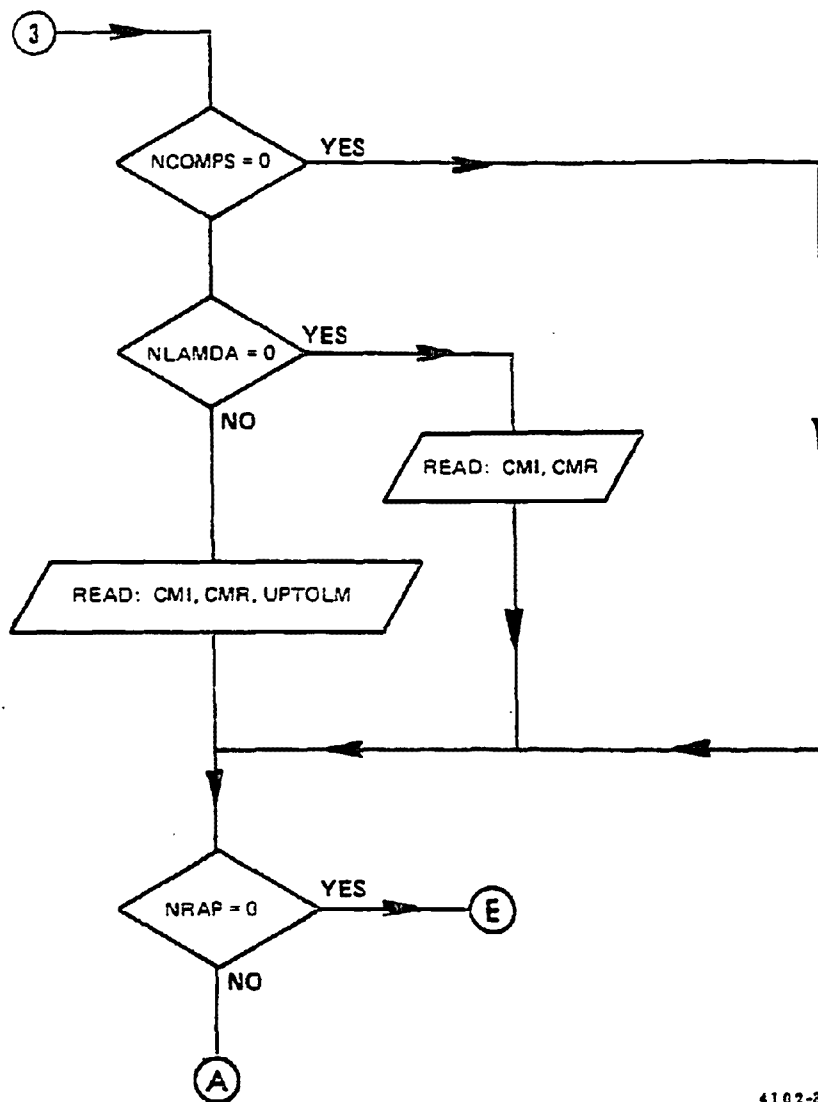
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Figure A-1. Flow chart for the input data logic (Sheet 2 of 4).



4102-31

Figure A-1. Flow chart for the input data logic (Sheet 3 of 4).



4102-82

Figure A-1. Flow chart for the input data logic (Sheet 4 of 4).

the first group of each data set and will also be the final card in the input data. If 21<NENDPT<99, the program will terminate abnormally during execution. NENDPT is read in with an I2 format and must be right justified in columns 1-2.

(2) NDATA

is an indicator which tells the program to look for a certain type of data set. NDATA can have four possible values which will cause the program to look for the following data set types:

- 1 - A complete data set must be entered. NDATA must have this value on the first data set.
- 2 - Only cards 1 and 2 and data concerning size distribution information must be entered. All other data remain as defined in the previous data set. NDATA can have this value only after a basic data set has been run. This value of NDATA allows one to examine the effects of particle size distribution on precipitator performance with all other variables held fixed.
- 3 - Only cards 1 and 2 and information concerning the gas volume flow and gas velocity must be entered. All other data remain as defined in the previous data set. NDATA can have this value only after a basic data set has been run. This value of NDATA allows one to examine the effects of specific collection area (SCA) on precipitator performance with all other variables held fixed.
- 4 - Only cards 1 and 2 and information concerning the applied voltage and current must be entered. All other data remain as defined in the previous data set. NDATA can have this value only after a basic data set has been run. This value of NDATA allows one to examine the effects of the electrical conditions on precipitator performance with all other variables held fixed.

NDATA is read in with an I2 format and must be right justified in columns 3-4. If NDATA  $\neq$  1,2,3, or 4, an error message will be given by the computer at the point in the program where NDATA is used in a "computed go to statement". Depending on the particular computer, the program may or may not terminate at this point. If the program continues to execute, it may terminate abnormally at a later point in the program due to incorrect usage of the

input data. If the program terminates normally, the calculations may or may not be correct, depending on the input data and the action taken by the computer.

- (3) NRAP is an indicator which determines the type of rapping reentrainment correction which will be performed. If NRAP = 0, the correction is performed by the same empirical process used in the previous versions of this model. If NRAP = 1, 2, or 3, a different process is used in which additional data are read into the program. From these data, the particle statistics of the reentrained dust are determined. The program then repeats the efficiency calculation for the input dust plus the reentrained dust, which is introduced into the gas flow at that point in the ESP at which it was rapped loose. The additional data required for dynamic rapping will be described later in this section. The values 1, 2, or 3 determine the amount of ESP outlet information which is printed with 1 giving extensive details on individual particle statistics and 3 giving summaries only. These effects are described fully in the next section of this report. NRAP is read in with an I2 format and must be right justified in columns 5-6.
- (4) MODL is an indicator which specifies the type of data to be read into the program and may have values from 0 to 3. If MODL = 0, mixed British and metric data are to be used. For MODL = 1, all data must be in metric units. If MODL = 2, an internal data set is used and the only other data required from the user is the resistivity of the input particles and the wire to plate spacing. This data set is described later in this appendix. For MODL = 3, the program terminates after printing the voltage-current curves for the ESP. The options and data sets required when MODL = 3 are described in the section on unknown operating conditions. MODL is read in with an I2 format and must be right justified in columns 7-8.
- (5) NOPRNT is an indicator which may have the values of 0 or 1. If NOPRNT = 0, the printed output includes data on particle charging and, if opacity is calculated, the differential extinction coefficient for each particle size band. If NOPRNT = 1, particle charging data is not printed and only total opacity figures are printed. NOPRNT is read in with an I2 format and must be right justified in columns 9-10.

- (6) PATHL is the path length over which the opacity calculation will be made and is in units of ft or m. PATHL is read in with an F5.2 format in columns 11-15. If PATHL = 0.0, no opacity calculation is performed.
- (7) NCOMPS is the number of indices of refraction for which the opacity is to be calculated. NCOMPS may have values from 0 to 10. If NCOMPS = 0 the two default values of the index of refraction are used. These are  $1.50 + 0.0i$  and  $1.50 - 0.10i$ . If NCOMPS = 1 to 10, the calculation is performed for the values which are read into the program. NCOMPS is read in with an I2 format and must be right justified in columns 19-20.
- (8) NWAVES is the number of wavelengths at which opacity will be calculated and may have values of 0 or 1. If NWAVES = 0, the calculation is performed at 10 different points in the spectrum. If NWAVES = 1, the calculation will be performed at a wavelength of 0.55  $\mu\text{m}$  only. NWAVES is read in with an I2 format and must be right justified in columns 24-25.
- (9) NLAMDA is the number of indices of refraction which must be read in to perform the opacity calculation using an index of refraction that varies with wavelength. NLAMDA may have values from 0 to 10. If NLAMDA = 0, the index of refraction is assumed to be independent of wavelength and no extra data must be read in. If NLAMDA > 0, then NLAMDA indices of refraction and their associated wavelengths are read into the program. If NLAMDA > 0, NCOMPS must have a value of 1 or 2. If NCOMPS = 0, the value of NLAMDA is ignored. If NCOMPS > 2, and NLAMDA > 0, NCOMPS is set equal to 2. NLAMDA is read with an I2 format and must be right justified in columns 29-30.

The overall format for this group is [5I2, F5.2, 3(3X,I2)]. The data contained in this group is on the first card and this card must be the first card in each new data set. However, only the first two parameters, NENDPT and NDATA, are required. The remaining seven parameters are optional. If only the first two parameters are given, the operation of the program is the same as for Revisions I and II except that execution is much faster. Consequently, data sets for the previous version of this model are still usable and will result in the same printed output as before. The use of the optional parameters will result in the inclusion

of the extra processes described in the preceding parameter definitions. The last four parameters (PATHL, NCOMPS, NWAVES, and NLAMDA) define the opacity calculation and are interrelated as shown in Table A-1.

Data group 2 is for specifying information which will identify the data set which is under consideration. All or part of columns 1-80 on data card 2 can be used in identifying the data set. The overall format for this card is (40A2). This data group must be the second card in each new data set.

At this point, the third and successive data groups depend on the choice of the value of NDATA. The basic data set must be read into the program before shortened data sets can be used. For NDATA=1, the program reads in the data groups in the basic data set in the sequence discussed below.

The following is a sequential listing of the variables in data group 3, along with the descriptions of the variables and the format specifications.

- (1) NEST is an indicator which can have the values of 1 and 2. If NEST = 1, the program will perform extensive, detailed calculations in order to determine precipitator performance. If NEST = 2, estimation procedures are used to determine precipitator performance. Both of these options have been discussed in detail. Use of the estimation procedure will result in considerable savings in computer time and can be used to establish trends or to establish ranges over which to apply the more rigorous calculations. NEST is read in with an I2 format and must be right justified in columns 1-2.
- (2) NDIST is an indicator which can have the values of 1 and 2. If NDIST = 1, the user must supply the inlet particle size distribution corresponding to the size bands specified by the variable ENDPT. If NDIST = 2, the program will construct a log-normal particle size distribution for these size bands based on the parameters D50 and SIGMAP. The technique used to construct the log-normal size distribution is described in Volume 1. NDIST is read in with an I2 format and must be right justified in columns 3-4.
- (3) NVI is an indicator which can have the value 1 or 2. If NVI = 1, the user must supply known or measured values of the operating applied voltage and current.

TABLE A-1. OPACITY RELATED INPUT DATA

PATHL	VALUE OF PARAMETER		CALCULATIONS PERFORMED	
	<u>NCOMPS</u>	<u>NWAVES</u>	<u>NLAMDA</u>	
0.	--	--	--	No opacity calculation performed
>0	0	0	--	Opacity calculated at 10 wavelengths using default values of index of refraction
>0	0	1	--	Opacity calculated at 1 wavelength using default values of index of refraction
>0	1,2	0	0	Opacity calculated at 10 wavelengths using NCOMPS user supplied values of index of refraction
>0	1 to 10	1	0	Opacity calculated at 1 wavelength using NCOMPS user supplied values of index of refraction
>0	1,2	0	1 to 10	Opacity calculated at 10 wavelengths using NLAMDA user supplied values of frequency dependent index of refraction



If  $NVI = 2$ , the program will construct a voltage-current curve (or curves) for a specified wire-plate geometry up to a voltage which is specified by the user. Refer to the section on unknown operating conditions (p. A-34) to determine when this option should be used.  $NVI$  is read in with an I2 format and must be right justified in columns 5-6.

(4)  $NX$  is the number of grid points in the x-direction (perpendicular to the gas flow) which is used in the numerical techniques that determine the electrical conditions.  $NX$  cannot exceed a value of 15. If  $NVI = 1$ , sufficient accuracy can normally be obtained with  $NX > 11$ . If  $NVI = 2$ ,  $NX$  should be set equal to 15.  $NX$  is read in with an I2 format and must be right justified in columns 7-8.

(5)  $NY$  is the number of grid points in the y-direction (parallel to the gas flow) which is used in the numerical techniques that determine the electrical conditions. If  $NVI = 1$ , sufficient accuracy can normally be obtained with  $NY > 9$ . If  $NVI = 2$ ,  $NY$  should be set equal to 15.  $NY$  is read in with an I2 format and must be right justified in columns 9-10.

(6)  $NITER$  is an indicator which serves two different purposes. If  $NVI = 1$ , the value of  $NITER$  determines the maximum number of iterations the program will make on a loop which converges on overall mass collection efficiency. If the overall mass collection efficiency converges within 0.05% before  $NITER$  iterations, the calculation of collection efficiencies is completed at this point.  $NITER$  serves the purpose of cutting the calculation off in a reasonable amount of time when convergence requires more iterations and computer time than is warranted. For normal inlet mass loadings and particle size distributions a value of  $NITER = 2$  is sufficient. For high inlet mass loadings or very fine particle size distributions a value of  $NITER = 3$  or 4 may be necessary to provide sufficient accuracy. If  $NVI = 2$ , the value of  $NITER$  determines the number of iterations which will be performed over each incremental length of the precipitator in order to obtain self-consistent solutions for the electrical conditions. In its present stage of development, the calculation procedure yields the same results for all values of  $NITER$ . Thus, in this case, set  $NITER = 1$ . The

calculation procedure is discussed in Appendix A of Volume 1. NITER is read in with an I2 format and must be right justified in columns 11-12.

(7) NCALC

is an indicator which can have the values of 0 and 1. If NCALC = 0, particle charge is determined by using equation (12) in Volume 1. Due to the number of times particle charge must be calculated and the use of numerical techniques in order to solve the charging equation, the particle charging calculations for NCALC = 0 take a considerable amount of computer time. If NCALC = 1, particle charge is estimated empirically by using the sum of the charges predicted from classical field and thermal charging theories [see equation (15) in Volume 1]. In this case, particle charge can be determined very rapidly from analytical expressions. Thus, in those cases where a significantly shorter run time is more important than the best accuracy possible, NCALC should be set equal to 1. If NEST = 2, particle charge will be performed as if NCALC = 1 regardless of the value of NCALC. NCALC is read in with an I2 format and must be right justified in columns 13-14.

(8) NRAPD

is an indicator which specifies the number of rapping puff particle size distributions which will be utilized by the program in predicting the effect of rapping reentrainment on overall mass collection efficiency. NRAPD must have a value of at least 1 and can not exceed a value of 10. If NRAPD = 1, the program will determine the rapping puff particle size distribution based on the average of data obtained from several field tests on full-scale precipitators. These tests yield an average rapping puff particle size distribution with a mass median diameter (MMD) of 6.0  $\mu\text{m}$  and a geometric standard deviation ( $\sigma_p$ ) of 2.5. The technique which is used to predict rapping losses is discussed in Volume 1. If NRAPD is greater than 1, the user must supply a MMD and  $\sigma_p$  of a log-normal distribution corresponding to each value of NRAPD greater than 1. The program will determine the rapping puff particle size distribution based on the specified combinations on MMD and  $\sigma_p$ . The case for NRAPD = 1 will always be performed. Each rapping puff particle size distribution is used in conjunction with the same basic ideal calculation and its effect is determined with very little expenditure of computer time. NRAPD is read in with an I2 format and must be right justified in columns 15-16.

- (9) NEFF is an indicator which can have the values of 1 and 2. If NEFF = 1, the total mass reentrained at the outlet due to rapping is determined from the mass collected in the last field under adjusted no-rap conditions. If NEFF = 2, the total mass reentrained at the outlet due to rapping is determined from the mass which would be collected in the last field under unadjusted ideal conditions. NEFF should normally be taken to be 1 since this case is physically meaningful. A value of NEFF = 2 will result in rapping losses which are significantly greater than for NEFF = 1. Thus, a value of NEFF = 2 should only be used when a precipitator design which is conservative with respect to rapping losses is desired. NEFF is read in with an I2 format and must be right justified in columns 17-18.
- (10) NTEMP is an indicator which can have the values of 1 and 2. The mass reentrained due to rapping will differ for cold-side and hot-side precipitators. If NTEMP = 1, the mass reentrained due to rapping is estimated based on an equation for cold-side precipitators. If NTEMP = 2, the mass reentrained due to rapping is estimated based on equation for hot-side precipitators. NTEMP is read in with an I2 format and must be right justified in columns 19-20.
- (11) NONID is an indicator which specifies the number of combinations of normalized gas velocity standard deviation ( $\sigma_g$ ) and gas bypassage fraction and/or particle reentrainment fraction without rapping (S) which are to be used to simulate the possible nonideal conditions. The procedures used to account for these nonideal effects are described in Volume 1. NONID must have a value of at least 1 and can not exceed a value of 15. Each set of nonideal conditions is used in conjunction with the same basic ideal calculation and its effect is determined with very little expenditure of computer time. NONID is read in with an I2 format and must be right justified in columns 21-22.

The overall format for this data group is (11I2) and all the data are contained on the third data card.

The next data group which is read in depends on the values of NCALC and NVI. If NCALC = 0, the rigorous charging theory is used. In this case, the following is a sequential listing of the

variables in the next data group which is read in, along with the descriptions of the variables and the format specifications.

- (1) NN is the number of increments in the Runge-Kutta integration of equation (12) in Volume 1. A value of  $NN = 5$  will provide sufficient accuracy for normal use. Greater values found in data sets created for previous versions of the model may be used but will result in an increase in computer time for no appreciable increase in accuracy.  $NN$  is read in with an I2 format and must be right justified in columns 1-2.
- (2) NUMINC was previously the number of increments in the Simpson's Rule integration over  $\theta$  in equation (12) in Volume 1. Since this integration is now done by the Gaussian Quadrature method, this variable is no longer used. Data sets containing this variable may still be used, however, as the space allowed to NUMINC, columns 3-4, is not used for any other purpose.

The overall format for this data group is (I2) and all the data are contained on a single card. If NCALC = 1, the above data group is not read into the program.

If  $NVI = 2$ , the model must calculate a voltage-current curve. In this case, the following is a sequential listing of the variables in the next data group which is read in, along with the descriptions of the variables and the format specifications.

- (1) IFINAL is an indicator which causes the calculation of successive points on the voltage-current curve to cease after IFINAL points. This indicator allows the user to have the voltage-current calculation terminated at a point before the specified operating voltage is reached whenever it is taking an excessive number of points to reach the specified operating voltage. IFINAL is read in with an I2 format and must be right justified in columns 1-2.
- (2) J11 is an indicator which allows the initial increment size on current density in the calculation of the voltage-current curve to be changed after J11-1 points are determined on the curve. Since the voltage-current calculation finds the applied voltage corresponding to a specified value of current density, this indicator allows the user to cover a large range of current densities without using an excessive number of points. J11 is read in with an I2 format and must be right justified in columns 3-4.

- (3) JI2 is an indicator which allows the second increment size on current density in the calculation of the voltage-current curve to be changed after JI2-1 points are determined on the curve. JI2 serves the same function as JI1 and JI2 must have a value greater than JI1 for proper usage. JI2 is read in with an I2 format and must be right justified in columns 5-6.
- (4) VISKIP is an indicator which may have the values of 0 and 1. If VISKIP = 0, a voltage-current curve will be calculated up to a specified operating voltage for each successive length increment of the precipitator. If VISKIP = 1, only the operating current density which corresponds to a specified operating voltage will be calculated based on an estimation procedure discussed in Volume 1. In most cases, the user will want to set VISKIP = 1 since this will result in a prediction of the operating current density in each increment of length of the precipitator without using the large amounts of computer time required by the calculation of a voltage-current curve. Only extremely detailed analysis would warrant setting VISKIP = 0. VISKIP is read in with an I2 format and must be right justified in columns 7-8.
- (5) VISAME is an indicator which may have the values of 1 and 2. The proper use of VISAME can result in significant savings in computer time whenever the applied voltage is the same in each electrical section. If the applied voltage is the same in each electrical section, set VISAME = 1 and only one "clean" voltage-current curve will be calculated. If VISAME = 1, as many data sets as desired can be read into the program and all calculations will be based on the one "clean" voltage-current calculation. The use of VISAME = 1 is especially beneficial in studying hypothetical cases due to the large savings in computer time. If the applied voltage differs from one electrical section to the next, the user must set VISAME = 2. Whenever the operating voltage and current are unknown and the user must specify the use of the voltage-current calculations (NVI = 2), the quickest run time will occur when VISKIP = 1 and VISAME = 1. The longest run time will occur when VISKIP = 0 and VISAME = 2. VISAME is read in with an I2 format and must be right justified in columns 9-10.

The overall format for this data group is (5I2) and all data are contained on single card. If NVI = 1, the above data group is not read into the program.

The following is a sequential listing of the next data group which is read in, along with the descriptions of the variables and the format specifications.

- (1) DL is the inlet particulate mass loading in units of grains/ft<sup>3</sup> or kg/m<sup>3</sup>. DL is read in with a F8.0 format and must be left justified in columns 1-8.
- (2) PL is the total electrical length of the precipitator in units of ft or m. PL is read in with a F8.0 format and must be left justified in columns 9-16.
- (3) ETAO is the overall mass collection efficiency in units of percent and it has two different interpretations depending upon the value of NVI. If NVI = 1, ETAO represents the measured or estimated overall mass collection efficiency and is used as a test for convergence in an iteration loop on overall mass collection efficiency. If NVI = 2, ETAO simply represents the desired design efficiency and is not used in the calculations. ETAO is read in with a F8.0 format and must be left justified in columns 17-24.
- (4) DD is the density of the particles in units of kg/m<sup>3</sup>. DD is read in with a F8.0 format and must be left justified in columns 25-32.
- (5) EPS is the dielectric constant of the particles for use in the particle charging calculations and is dimensionless. Values of EPS must be equal to or greater than 1. In most industrial applications, the flue gas is sufficiently humidified that the particle surface becomes conductive and a value of EPS = 100 can be used to simulate a conductor. EPS is read in with a F8.0 format and must be left justified in columns 33-40.
- (6) VRATIO is the ratio of the peak voltage to the average voltage and is dimensionless. In the calculation of particle charge, it is assumed that the particles will charge to an extent determined by the peak voltage rather than the average voltage. For industrial applications, VRATIO has a value around 1.2. VRATIO is read in with a F8.0 format and must be left justified in columns 41-48.

(7) US

is the ionic mobility at standard temperature (273 K) and standard pressure (1 atm) and is in units of  $\text{m}^2/(\text{V-sec})$ . This mobility is referred to as the "reduced mobility". Values to use for reduced ionic mobilities for flue gas compositions are not well-established at the present time. The reduced ionic mobility for air is in the range  $1.2-2.1 \times 10^{-4} \text{m}^2/(\text{V-sec})$ . Reduced ionic mobilities for flue gas compositions have been reported that are considerably larger than those reported for air. These values cover the range of  $2.2-5.4 \times 10^{-4} \text{m}^2/(\text{V-sec})$ . Some reported values of reduced ionic mobility for various gas compositions are given in Table A-2. Since the ionic mobility has a strong influence on the electrical conditions through the current and electric field distributions, this is an important parameter in determining precipitator performance. A value of  $2.7 \times 10^{-4} \text{m}^2/(\text{V-sec})$  should provide a representative value to use for flue gases emanating from coal-fired boiler applications. US is read in with a F8.0 format and must be left justified in columns 49-56.

(8) FPATH

is a parameter which is used in the field charging equation and is dimensionless. FPATH represents the number of ionic mean free paths over which the momentum of the ions will persist and allow the ions to reach the surface of the particle even though the saturation charge has been reached. The effect of this parameter is to increase the saturation charge. FPATH normally should have a value in the range 0-2. It is recommended that FPATH be assigned a value of 1. FPATH is read in with a F8.0 format and must be left justified in columns 57-64.

(9) EBD

is the electrical breakdown strength of the gas or the particulate layer in the region near the plate and is in units of V/m. The value of this parameter is a strong function of the resistivity of the collected particulate layer and the condition of the collection plates. At present, mathematical techniques which are based on physical principles do not exist for predicting the value of EBD under differing conditions. Thus, experimental data and prior experience must be used to choose appropriate values of EBD. In practical applications, EBD falls in the range of 2-15 kV/cm. A value of 2 kV/cm should provide a conservative estimate of EBD whereas a value of 15 kV/cm would

TABLE A-2

## REDUCED EFFECTIVE NEGATIVE ION MOBILITIES FOR VARIOUS GAS COMPOSITIONS

Gas Composition (Volume Percent)					Reduced Effective Ion Mobility (cm <sup>2</sup> /V-sec)
<u>N<sub>2</sub></u>	<u>CO<sub>2</sub></u>	<u>O<sub>2</sub></u>	<u>SO<sub>2</sub></u>	<u>H<sub>2</sub>O</u>	
				100.0	0.67 ± 0.17 <sup>a</sup>
		100.0			2.46 ± 0.06 <sup>b</sup>
	100.0				1.08 ± 0.03 <sup>b</sup>
			100.0		0.35 <sup>c</sup>
			(Laboratory Air)		1.03 <sup>d</sup>
			(Laboratory Air)		1.26 - 1.96 <sup>e</sup>
79.4	14.7	4.6	0.2	0.6	5.39 <sup>f</sup>
73.5	13.6	4.2	0.2	8.4	2.93 <sup>f</sup>
65.9	12.2	3.8	0.2	17.8	2.23 <sup>f</sup>
71.0	11.2	3.7	0.0	14.0	2.35 <sup>f</sup>
75.7	11.6	3.2	0.0	9.4	3.02 <sup>f</sup>
75.1	11.5	3.2	0.1	9.9	2.74 <sup>f</sup>
78.5	10.9	3.6	0.0	7.0	3.36 <sup>f</sup>
78.3	19.8	3.6	0.1	7.0	2.67 <sup>f</sup>
77.9	10.8	3.6	0.3	7.0	2.70 <sup>f</sup>
77.6	10.7	3.7	0.7	7.0	2.43 <sup>f</sup>

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- b. E. W. McDaniel and H. R. Crane, Rev. Sci. Instru. **28**, 684 (1959).
- c. E. W. McDaniel and M. R. C. McDowell, Phys. Rev. **114**, 1028 (1959).
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- e. J. Bricard, M. Cabane, G. Modelaine, and D. Vigla, Aerosols and Atmospheric Chemistry. Edited by G. M. Hidy, New York, New York, 27 (1972).
- f. H. W. Spencer, III, "Experimental Determination of the Effective Ion Mobility of Simulated Flue Gas." In Proceedings of 1975 IEEE-IAS Conference, September 28, 1975, Atlanta, Georgia.



in most cases provide the most optimistic value. The value of EBD is used whenever NVI = 2 and a voltage-current curve is generated. If the field at the plate exceeds the value of EBD at any point on the curve, a message to this effect is printed out with the voltage-current calculation terminating at the corresponding applied voltage and current density. These values of voltage and current are then used in the projection of precipitator performance. EBD is read in with a F8.0 format and must be right justified in columns 65-72.

(10) RHO

is the resistivity of the collected particulate layer and is in units of ohm-cm. The resistivity to be used must be determined experimentally by either in situ or laboratory methods. RHO is used in the model only if the operating conditions are unknown. For this use refer to the section on unknown operating conditions (p. A-34). RHO is read in with an 8.2 format and must be right justified in columns 73-80.

When the operating voltages and current are specified, the value of RHO has no effect on the operating conditions. To estimate the effects of a change in RHO, the procedures listed under unknown operating conditions must be used.

The above data group has an overall format of (9F8.0, E8.2) and is contained on a single data card. This data set must be read in with each basic data set, i.e. when NDATA = 1.

The next data group which is read in depends on the value of NRAPD. If NRAPD is greater than 1, the following is a sequential listing of the variables in the next data group, along with the descriptions of the variables and the format specifications.

- (1) ARD50(I) is an array containing the mass median diameters in  $\mu\text{m}$  for log-normal particle size distributions of the different rapping puff distributions which will be utilized in the model. The values of this variable are read in with a F4.0 format and must be left justified in columns 1-4, 9-12, 17-20, 25-28, 33-36, 41-44, 49-52, 57-60, 65-68, and 73-76.
  
- (2) ARSIGM(I) is an array containing the geometric standard deviations for log-normal particle size distributions of the different rapping puff distributions which will be utilized in the model.

Values of ARD50(I) and ARSIGM(I) with the same index are used together to construct a log-normal particle size distribution. The values of this variable are read in with a F4.0 format and must be left justified in columns 5-8, 13-16, 21-24, 29-32, 37-40, 45-48, 53-56, 61-64, 69-72, and 77-80. ARSIGM(I) can not have a value less than 1.

The above variables must be read in for I=2 up to I=NRAPD where NRAPD can not exceed a value of 10. The overall format for this data group is [10(2F4.0)] and is contained on a single data card. If NRAPD=1, this data group is not read in. In this case, only one rapping puff particle size distribution will be considered where ARD50(1) = 6.0 in  $\mu\text{m}$  and ARSIGM(1) = 2.5. This case is built into the program and relates to experimental data discussed in Volume 1.

The following is a sequential listing of the variables in the next data group which is read in, along with the descriptions of the variables and the format specifications.

- (1) ASNUCK(I) is an array containing different fractions of gas flow which bypass the electrified region in each baffled stage of the precipitator and/or different fractions of the mass collected in each stage of the precipitator which are reentrained due to factors other than rapping. The values of this variable are read in with a F4.0 format and must be left justified in columns 1-4, 13-16, 25-28, 37-40, 49-52, and 61-64 of the first two data cards in the group and in columns 1-4, 13-16, and 25-28 of the third data card in the group. ASNUCK(I) must lie in the range 0.0 to 1.0.
- (2) AZIGGY(I) is an array containing different normalized standard deviations for the inlet velocity distribution of the gas flow. The values of this variable are read in with a F4.0 format and must be left justified in columns 5-8, 17-20, 29-32, 41-44, 53-56, and 65-68 of the first two data cards in the group and in columns 5-8, 17-20, and 29-32 of the third data card in the group. AZIGGY(I) must be equal to or greater than 0.0.
- (3) AZNUMS(I) is an array containing the number of baffled stages in the precipitator. The values of this variable are read in with a F4.0 format and must be left justified in columns 9-12, 21-24, 33-36, 45-48, 57-60, and 69-72 of the first two data cards in the group and in columns 9-12, 21-24, and 33-36 of the third data card in the group. The values of AZNUMS(I) must be whole numbers.

The values of ASNUCK(I), AZIGGY(I), and AZNUMS(I) with the same index are used together to simulate one set of nonideal parameters and to produce one set of no-rap efficiencies. The values of I are determined by NONID which must have a value of at least 1 and can not exceed a value of 15. Thus, at least one set of these parameters must be read in. It is recommended that the user take the first set of these variables to be ASNUCK(1) = 0.00, AZIGGY(1) = 0.00, and AZNUMS(1) = actual number of stages so that efficiencies under ideal conditions will be obtained. In practical situations, a well-operating precipitator will have values of ASNUCK and AZIGGY of approximately 0.1 and 0.25, respectively.

The overall format for this data group is [6(3F4.0)] and the data group is contained on 3 or less cards. For NONID < 6, 6 < NONID < 12, and 12 < NONID < 15, the number of data cards necessary are 1, 2, and 3, respectively. This data group must be read in with each basic data set.

The next data group which is read in consists of a single array. The description of this array and its format specification are given below.

- (1) ENDPT(I) is an array containing values of particle diameters corresponding to points on a curve of inlet mass cumulative percent versus particle diameter. The number of diameters read in must equal the value of NENDPT which can not exceed a value of 21. The diameters must be entered in order from smallest to largest in units of  $\mu\text{m}$ . The smallest diameter can not be less than 0.01  $\mu\text{m}$  and the largest diameter can not exceed 1,000  $\mu\text{m}$ . These diameters are used to construct particle size intervals and a particle size histogram. The midpoints between successive particle diameters constitute NENDPT-1 average particle diameters which are used in the program to characterize the different particle size bands. In constructing the particle diameters to be used in the calculations, it is recommended that greater resolution be built into the fine particle size range of 0.1-3.0  $\mu\text{m}$  since the lower efficiencies are obtained in this size range. The values of ENDPT(I) are read in with a F8.0 format and must be left justified.

The overall format for this data group is (10F8.0) and the data group is contained on 3 or less data cards. For NENDPT < 10, 10 < NENDPT < 20, and NENDPT = 21, the number of data cards necessary are 1, 2, and 3, respectively. This data group must be read in with each basic data set.

The next data group which is read in depends on the value of NDIST. If NDIST = 2, the following is a sequential listing of the variables in the next data group, along with the descriptions of the variables and the format specifications.

- (1) D50 is the mass median diameter of a log-normal inlet particle size distribution and is in units of  $\mu\text{m}$ . The value of D50 must lie between 0.01 and 1,000  $\mu\text{m}$ . The value of D50 is read in with a F8.0 format and must be left justified in columns 1-8.
- (2) SIGMAP is the geometric standard deviation of a log-normal inlet particle size distribution and is dimensionless. The value of SIGMAP must be equal to or greater than 1. The value of SIGMAP is read in with a F8.0 format and must be left justified in columns 9-16.

The program uses the values of D50 and SIGMAP to construct a log-normal particle size distribution over the range and size bands determined by the values of ENDPT(I). Any mass which is not in the size range determined by ENDPT(I) will be put into the size band with the largest midpoint. This must be done to ensure that the sum over all size bands of the percentage of total mass in each size band will equal 100%.

The above data group has an overall format of (2F8.0) and is contained on a single data card. This data set is not read in if NDIST = 1.

If NDIST = 1, the next data group which is read in consists of a single array. The description of this array and its format specification are given below.

- (1) PRCU(I) is an array containing values of cumulative percents corresponding to points on a curve of inlet mass cumulative percent versus particle diameter. The number of cumulative percents read in must equal the value of NENDPT which can not exceed 21. The cumulative percents must match the particle diameters specified in the array ENDPT(I). The cumulative percents are entered in units of %. The first value of PRCU(I) must be 0% and the last value must be 100%. The program determines the percentage by mass in each particle size band from the values contained in ENDPT(I) and PRCU(I). The user must supply values of PRCU(I) based on measured or known particle size information for the particular application under consideration. The values of PRCU(I) are read in with a F8.0 format and must be left justified.

The overall format for this data group is (10F8.0) and the data group is contained on 3 or less data cards. For  $NENDPT \leq 10$ ,  $10 < NENDPT \leq 20$ , and  $NENDPT = 21$ , the number of data cards necessary are 1, 2, and 3, respectively. This data group is not read in if  $NDIST = 2$ .

The following is a sequential listing of the variables in the next data group which is read in, along with the descriptions of the variables and the format specifications.

- (1) NUMSEC is the number of electrical sections in the direction of gas flow. The maximum number of electrical sections which can be accounted for in the program listed in Volume 1 is 10. The value of this variable is read in with an I2 format and must be right justified in columns 1-2.
- (2) LSECT(I) is an array containing values of the number of incremental lengths to be taken in each electrical section in the direction of gas flow. These values are determined by the user with increasing values of I corresponding to electrical sections moving from the inlet to the outlet of the precipitator. The total number of incremental lengths in all sections must not exceed 99. It is not necessary to have the same number in each section. The values of this variable are read in with an I2 format and must be right justified.

The overall format for this data group is (I2, 10I2) and the data group is contained on a single data card. This data group must be read in with each basic data set.

The following is a sequential listing of the variables in the next data group which is read in, along with the descriptions of the variables and the format specifications.

- (1) AS(NSECT) is the total collection plate area for a given electrical section and is in units of  $\text{ft}^2$  or  $\text{m}^2$ . The values of this variable are read in with an E11.4 format and must be right justified in columns 1-11.
- (2) VOS(NSECT) is the applied voltage in a given electrical section and is in units of volts. If  $NVI = 1$ , the value of  $VOS(NSECT)$  corresponds to a measured or known value. If  $NVI = 2$ ,  $VOS(NSECT)$  corresponds to an applied voltage up to which a voltage-current curve will be calculated. Then, this applied voltage along with the corresponding current will

be used in the calculation of precipitator performance. The values of this variable are read in with an E11.4 format and must be right justified in columns 12-22.

- (3) TCS(NSECT) is the total current in a given electrical section and is in units of amperes. If NVI = 1, the value of TCS(NSECT) corresponds to a measured or known value. If NVI = 2, TCS(NSECT) has no meaning in terms of input data since it will be calculated in the program. In this case, the appropriate columns on the data card can be left blank or any arbitrary number can be entered. The values of this variable are read in with an E11.4 format and must be right justified in columns 23-33.
- (4) WLS(NSECT) is the total effective wire length in a given electrical section and is in units of ft or m. The values of this variable are read in with an E11.4 format and must be right justified in columns 34-44.
- (5) ACS(NSECT) is the corona wire radius in a given electrical section and is in units of in. or mm. The values of this variable are read in with an E11.4 format and must be right justified in columns 45-55.
- (6) BS(NSECT) is the wire-to-plate spacing in a given electrical section and is in units of in. or m. The values of this variable are read in with an E11.4 format and must be right justified in columns 56-66.
- (7) NWS(NSECT) is the number of discharge electrodes per given electrical section per gas passage and is dimensionless. The values of this variable normally should not exceed 20. If the values do exceed 20, use 20 in the program. These values are used to determine the number of terms in a series summation which determines the electrostatic electric field distribution and 20 terms are more than sufficient to reach convergence. The values of this variable are read in with an E11.4 format and must be right justified in columns 67-77.
- (8) SYS(NSECT) is one-half of the wire-to-wire spacing in a given electrical section and is in units of in. or m. The values of this variable are read in with an E11.4 format and must be right justified in columns 1-11.

- (9) VGS(NSECT) is the total gas volume flow rate in a given electrical section and is in units of actual  $\text{ft}^3/\text{min}$  or  $\text{m}^3/\text{sec}$ . The values of this variable are read in with an E11.4 format and must be right justified in columns 12-22.
- (10) VGASS(NSECT) is the gas velocity in a given electrical section and is in units of  $\text{ft}/\text{sec}$  or  $\text{m}/\text{sec}$ . The values of this variable are read in with an E11.4 format and must be right justified in columns 23-33. The gas velocity must be consistent with the gas volume flow rate and the precipitator geometry in each electrical section. These are related by
- $$\text{VGASS}(I) = [\text{LINCS}(I) * \text{LSECT}(I) * \text{VGS}(I)] / [\text{AS}(I) * \text{BS}(I) * \text{Constant}],$$
- where the constant = 1 for metric units and 5 for British units.
- (11) TEMPS(NSECT) is the gas temperature in a given electrical section and is in units of  $^{\circ}\text{F}$  or  $^{\circ}\text{C}$ . The values of this variable are read in with an E11.4 format and must be right justified in columns 34-44.
- (12) PS(NSECT) is the gas pressure in a given electrical section and is in units of atmospheres. The values of this variable are read in with an E11.4 format and must be right justified in columns 45-55.
- (13) VISS(NSECT) is the gas viscosity in a given electrical section and is in units of  $\text{kg}/(\text{m} \cdot \text{sec})$ . Table A-3 gives values of viscosity for different temperatures and water contents for a gas composition whose components are those of air. This table provides values of viscosity which cover most cases found in practice although some extrapolation is necessary for those cases involving hot precipitators where temperatures are greater than  $300^{\circ}\text{C}$ . The values of this variable are read in with an E11.4 format and must be right justified in columns 56-66.
- (14) LINCS(NSECT) is the incremental length size which will be taken in a given electrical section and is in units of  $\text{ft}$  or  $\text{m}$ . If  $\text{NVI} = 1$ , LINCS(NSECT) should be given a value of approximately 1  $\text{ft}$  although larger values can be used with some loss in accuracy in order to save computer run time. If  $\text{NVI} = 2$ , LINCS(NSECT) must be given a value equal as near as possible to the wire-to-wire spacing in order for the numerical procedure to be valid. In any case, the product of LSECT(NSECT) and

TABLE A-3. VALUES OF VISCOSITY FOR AIR AT VARIOUS TEMPERATURES AND WATER CONTENTS <sup>a</sup>

°C	Percent H <sub>2</sub> O										
	0	1	2	3	4	5	6	7	8	9	10
10	1.767	1.758	1.748	1.739	1.730	1.721	1.712	1.702	1.693	1.684	1.675
20	1.810	1.801	1.792	1.783	1.774	1.765	1.755	1.746	1.737	1.728	1.719
30	1.854	1.844	1.835	1.826	1.817	1.808	1.799	1.790	1.780	1.771	1.762
40	1.900	1.887	1.878	1.869	1.860	1.850	1.841	1.832	1.823	1.814	1.805
50	1.938	1.929	1.920	1.911	1.902	1.892	1.883	1.874	1.865	1.856	1.847
60	1.979	1.970	1.961	1.952	1.943	1.934	1.925	1.916	1.907	1.898	1.888
70	2.020	2.011	2.002	1.993	1.984	1.975	1.966	1.957	1.948	1.939	1.930
80	2.059	2.050	2.042	2.033	2.024	2.015	2.006	1.997	1.988	1.979	1.970
90	2.099	2.090	2.081	2.072	2.063	2.054	2.046	2.037	2.028	2.019	2.010
100	2.137	2.129	2.120	2.111	2.102	2.093	2.085	2.076	2.067	2.058	2.049
110	2.175	2.167	2.158	2.149	2.140	2.132	2.123	2.114	2.105	2.097	2.088
120	2.213	2.204	2.195	2.189	2.178	2.169	2.161	2.152	2.143	2.135	2.126
130	2.250	2.241	2.232	2.224	2.215	2.207	2.198	2.189	2.181	2.172	2.164
140	2.286	2.277	2.269	2.260	2.252	2.243	2.235	2.226	2.218	2.209	2.201
150	2.321	2.313	2.304	2.296	2.288	2.279	2.271	2.262	2.254	2.245	2.237
160	2.356	2.348	2.339	2.331	2.323	2.315	2.306	2.298	2.289	2.281	2.273
170	2.390	2.382	2.374	2.366	2.358	2.349	2.341	2.333	2.325	2.316	2.308
180	2.424	2.416	2.408	2.400	2.392	2.383	2.375	2.367	2.359	2.351	2.343
190	2.457	2.449	2.441	2.433	2.425	2.417	2.409	2.401	2.393	2.385	2.377
200	2.489	2.482	2.474	2.466	2.458	2.450	2.442	2.434	2.426	2.418	2.410
210	2.521	2.513	2.506	2.498	2.490	2.482	2.475	2.467	2.459	2.451	2.443
220	2.552	2.545	2.537	2.530	2.522	2.514	2.507	2.499	2.491	2.483	2.476
230	2.583	2.575	2.568	2.560	2.553	2.545	2.538	2.530	2.523	2.515	2.507
240	2.613	2.606	2.598	2.591	2.583	2.576	2.569	2.561	2.554	2.546	2.539
250	2.642	2.635	2.628	2.621	2.613	2.606	2.599	2.592	2.584	2.577	2.570
260	2.671	2.664	2.657	2.650	2.643	2.636	2.628	2.621	2.614	2.607	2.600
270	2.699	2.692	2.685	2.678	2.671	2.664	2.657	2.650	2.643	2.636	2.629
280	2.727	2.720	2.713	2.706	2.700	2.693	2.686	2.679	2.672	2.665	2.658
290	2.754	2.747	2.740	2.734	2.727	2.720	2.714	2.707	2.700	2.694	2.687
300	2.780	2.773	2.767	2.761	2.754	2.748	2.741	2.734	2.728	2.721	2.715

X 10<sup>-5</sup> kg/(m-sec)<sup>a</sup> Calculations according to:

C.R. Wilke. A Viscosity Equation for Gas Mixtures. J. Chem. Phys., 18(4):517-519 (April, 1950).



LINCS(NSECT) must equal the total length of the given electrical section. The values of this variable are read in with an E11.4 format and must be right justified in columns 67-77.

The overall format for this data group is [7(E11.4)] and the data group is contained on two data cards. This data group must be read in with each basic data set.

The next data group which is read in depends on the value of NVI. If NVI = 2, the following is a sequential listing of the variables in the next data group which is read in, along with the descriptions of the variables and the format specifications.

- (1) RFS(NSECT) is the roughness factor for the wires in a given electrical section and is dimensionless. In precipitation practice, if the wires are scratched or dirty but not completely coated with air, then the values of RFS(NSECT) lie in the range 0.5-1.0. A value of 1.0 corresponds to wires which are in perfect condition. The effect of decreasing the roughness factor is one of increasing the current that can be achieved at a given voltage level. If the wires are completely covered with dirt, then the effect may be one of increased wire diameter with a roughness superimposed. This situation would lead to compensating effects. The values of this variable are read in with an E11.4 format and must be right justified in columns 1-11.
- (2) START1(NSECT) is the chosen initial current density at which the calculation of a voltage-current curve starts in a given electrical section and is in units of  $A/m^2$ . In generating the voltage-current curve, the current density increments in steps of START1(NSECT) until a change is specified. The values of this variable are read in with an E11.4 format and must be right justified in columns 12-22.
- (3) START2(NSECT) is a chosen increment in current density which is used in place of START1(NSECT) when the JI1-th point on the voltage-current curve is reached and is in units of  $A/m^2$ . The values of this variable are read in with an E11.4 format and must be right justified in columns 23-33.
- (4) START3(NSECT) is a chosen increment in current density which is used in place of START2(NSECT) when the JI2-th point on the voltage-current curve is reached and is in units of  $A/m^2$ . The values of this variable

are read in with an E11.4 format and must be right justified in columns 34-44.

- (5) VSTAR(NSECT) is an estimate of the applied voltage corresponding to the first point on the voltage-current curve as defined by START1(NSECT) and is in units of volts. If VSTAR(NSECT) is close to the actual applied voltage, the calculation will be performed faster. However, whatever the choice of VSTAR(NSECT), it will not affect the accuracy of the calculation. The values of this variable are read in with an E11.4 format and must be right justified in columns 45-55.

The overall format for this data group is [7(E11.4)] and the data group is contained on a single data card. If NVI = 1, this data group is not read in.

The data input starting with AS(NSECT) above must be repeated for each electrical section of the precipitator, proceeding from the inlet to the outlet of the precipitator. Thus, the data group containing AS(NSECT) and possibly the data group containing RFS(NSECT) must be read in NUMSEC different times.

At this point, the basic data set has been entered into the program and precipitator performance will be projected based on this data. The last card in the data section must have a 99 in columns 1-2. This causes the program to terminate normally.

#### CONSTRUCTION OF SHORTENED DATA SETS

Once the basic data set is processed, then all the parameters which are needed by the program to calculate precipitator performance are stored in memory. By using values of NDATA equal to 2, 3, or 4, shortened data sets can be entered after the basic data set in order to analyze the effects of particle size distribution, specific collection area, and electrical conditions on precipitator performance. In the shortened data sets, the values of a small number of variables which are stored in memory are changed to new values in order to produce a new set of data.

In each shortened data set, the first two data groups and data cards which are read in are the same as those discussed for the basic data set. The value of NDATA on the first data card determines the variables in memory that will be changed. The effects of particle size distribution on precipitator performance can be analyzed by setting NDATA = 2. In this case, the third data group which is read in depends upon the value of NDIST which is stored in memory. If NDIST = 2, an inlet mass median diameter (D50) and geometric standard deviation (SIGMAP) must be read in

according to the same specifications discussed for the basic data set. If NDIST = 1, cumulative percents [PRCU(I)] corresponding to the particle sizes [ENDPT(I)] stored in memory must be read in according to the same specifications discussed for the basic data set. After the third data group is read in, the shortened data set is complete. By repeating this type of shortened data with different choices of D50 and SIGMAP or PRCU(I), the effects of particle size distribution can be analyzed with the use of only a few data cards.

The effects of specific collection area (SCA) on precipitator performance can be analyzed by setting NDATA = 3. In this case, the following is a sequential listing of the variables which are inputted in the third data group, along with the descriptions of the variables and the format specifications.

- (1) VGS(I) is the total gas volume flow rate in a given electrical section and is in units of actual  $\text{ft}^3/\text{min}$ . The values of this variable are read in with an E11.4 format and must be right justified in columns 1-11, 23-33, and 45-55.
- (2) VGASS(I) is the gas velocity in a given electrical section and is in units of ft/sec. The values of this variable are read in with an E11.4 format and must be right justified in columns 12-22, 34-44, and 56-66.

There must be a value of VGS(I) and VGASS(I) entered for each electrical section. The overall format for this data group is [3(2E11.4)] and the data group is contained on 4 or less cards depending on the value of NUMSEC which is stored in memory. For NUMSEC  $\leq 3$ ,  $3 < \text{NUMSEC} \leq 6$ ,  $6 < \text{NUMSEC} \leq 9$ , and NUMSEC = 10, the number of data cards necessary are 1, 2, 3, and 4, respectively.

After this data group is read in, the shortened data set is complete. By repeating this type of shortened data set with different choices of VGS(I) and VGASS(I), the effects of specific collection area can be analyzed with the use of only a few data cards.

The effects of applied voltage and current on precipitator performance can be analyzed by setting NDATA = 4. In this case, the following is a sequential listing of the variables which are inputted in the third data group, along with the descriptions of the variables and the format specifications.

- (1) VOS(I) is the applied voltage in a given electrical section and is in units of volts. If the value of NVI stored in memory is 1, the value of VOS(I)

corresponds to a measured or known value. If the value of NVI stored in memory is 2, VOS(I) corresponds to an applied voltage up to which a voltage-current curve will be calculated. Then, this applied voltage along with the corresponding current will be used in the calculation of precipitator performance. The values of this variable are read in with an E11.4 format and must be right justified in columns 1-11, 23-33, and 45-55.

- (2) TCS(I) is the total current in a given electrical section and is in units of amperes. If the value of NVI stored in memory is 1, TCS(I) corresponds to a measured or known value. If the value of NVI stored in memory is 2, TCS(I) has no meaning in terms of input data since it will be calculated in the program. In this case, the appropriate columns on the data cards can be left blank or any arbitrary number can be entered. The values of this variable are read in with an E11.4 format and must be right justified in columns 12-22, 34-44, and 56-66.

There must be a value of VOS(I) and TCS(I) entered for each electrical section. The overall format for this data group is [3(2E11.4)] and the data group is contained on 4 or less cards depending on the value of NUMSEC which is stored in memory. For  $\text{NUMSEC} < 3$ ,  $3 < \text{NUMSEC} < 6$ ,  $6 < \text{NUMSEC} < 9$ , and  $\text{NUMSEC} = 10$ , the number of data cards necessary are 1, 2, 3, and 4, respectively.

After this data group is read in, the shortened data set is complete. By repeating this type of shortened data set with different choices of VOS(I) and TCS(I), the effects of voltage and current can be analyzed with the use of only a few data cards.

#### DYNAMIC RAPPING DATA SET

If  $\text{NRAP} \neq 0$  on the first data card, then additional data will need to be read into the program for the dynamic rapping process. This data, which is defined below, follows the basic data set. The maximum number of incremental lengths is limited to 45 when dynamic rapping is used.

- (1) TIMRAP is the time at which a rap occurs. This variable is read in with an F10.5 format in columns 1-10. TIMRAP is specified in minutes.
- (2) MAPRAP(I) is an indicator which specifies which increments of the precipitator are included in the rap. (These increments are the same calculation increments

defined by the variable LSECT in the basic data set.) Since the maximum number of increments is 45, MAPRAP is read in with a 45I1 format. If TIMRAP > 0 and MAPRAP(I) > 0, then the Ith increment of the precipitator is defined as having been rapped. The program sets the dust thickness on the collection plate at increment I equal to 0 and stores a portion of the collected dust for reintroduction into the gas flow at that point. If TIMRAP > 0 and MAPRAP(I) = 0, then the Ith increment was not rapped. If TIMRAP = 0 and MAPRAP(1) ≠ 0, the program will treat the next card as the beginning of an all new rapping scheme. In this case, the next card read in will be the first TIMRAP card of the new scheme. If TIMRAP = 0 and MAPRAP(1) = 0, the rapping calculation is terminated and the program resumes normal operation. The next card that will be read in this case is card 1 of the basic data set. MAPRAP is located in columns 11-55.

- (3) REPCT is the fraction of the dust collected in one electrical section that is reentrained during the time required for the gas to flow past one computational length increment, LINCS. This is defined by

$$\text{REPCT} = \frac{F}{\text{NLANES}} * \frac{\text{Duration of gas flow past one increment}}{\text{Total duration of each rapping puff}},$$

where F is the total fraction of the collected dust that will be reentrained during a rap and NLANES is the number of parallel lanes in the section which are rapped at different times.

- (4) NUMBOL is the number of data points in the reentrainment profile. NUMBOL is read in with an I2 format and must be right justified in columns 61-65.

- (5) NDAT is an indicator which can assume the values of 0 or 1. If NDAT = 1, the subsequent cards will define the rapping profile. If NDAT = 0, the existing rapping profile will be used in this rap. NDAT is read in with an I5 format and must be right justified in columns 66-70.

The overall format for this card is (F10.5, 45I1, F5.3, 2I5). This card is used to define each rap of the precipitator. If two or more sections of the precipitator are rapped at the same time, a single card can contain all of the necessary information. However, any rap which occurs at a different time will require another TIMRAP card.

If NDAT = 1 on the TIMRAP card, the following cards must be inserted following that card to define the rapping profile:

- (1) BOLFRC(I,J) are the data points used to construct the normalized histogram of fractions of dust reentrained in a given time interval. There must be NUMBOL values of BOLFRC on the card. BOLFRC is read into the program with an F6.3 format.

The overall format of this card is (13F6.3). The program expects the number of BOLFRC cards to equal the number of precipitator sections (NUMSEC) so that a different reentrainment histogram may be read in for each section. After NUMSEC cards are read, the following data is expected:

- (1) REMMD(I,J) are the mass median diameters for a log-normal size distribution associated with each step of the histogram defined by BOLFRC(I,J). There must be NUMBOL values of REMMD on the card. REMMD is read with an F6.3 format and must be in units of  $\mu\text{m}$ .
- (2) RESIG(J) is the geometric standard deviation of the log-normal size distributions defined by REMMD. The value of RESIG must be equal to or greater than 1. RESIG is read in an F6.3 format immediately following the last value of REMMD(I,J).

The overall format of this card is (13F6.3). The program expects to read NUMSEC REMMD cards to match the NUMSEC BOLFRC cards. After these cards are used, the following card is read in:

- (1) BOLTIM(I) are the durations in seconds of each of the steps of the rapping histogram. The sum of the values of BOLTIM(I) is the total duration of the rapping emissions and must obey the following relation:

$$\sum \text{Boltim}(I) = \text{NLANS} * \text{Total duration of each rapping puff}$$

The total duration of the rapping emissions must not exceed the time between raps as the model cannot correct for overlapping rapping puffs. There must be NUMBOL values of BOLTIM on the card in an F6.3 format.

- (2) DDRAP is the particle density of the reentrained dust. DD rap is in units of  $\text{kg/m}^3$  and is read in with an F6.3 format.

The overall format of this card is (13F6.3). Only 1 BOLTIM card will be read in as the durations of the steps in the histogram are assumed to be the same for all sections of the precipitator. The rapping profile must be read in after the first TIMRAP card. Thereafter, it may be read in if it is changed. After the BOLTIM card is read in, the next card expected by the program is a new TIMRAP card.

#### OPACITY DATA SET

In the calculation of precipitator outlet opacity, additional data is required if NCOMPS is greater than 0. If  $\text{NCOMPS} > 0$  and  $\text{NLAMDA} = 0$ , user supplied values of the real and imaginary parts of the index of refraction must be read into the program:

- (1) CMR(I) is the real part of the user supplied index of refraction. This quantity is read in with an F5.3 format.
- (2) CMI(I) is the imaginary part of the user supplied index of refraction. CMI(I) is read with an F5.3 format.

The NCOMPS values of CMR(I) and CMI(I) are read in as data pairs with an overall format of [6(2F5.3)].

If  $\text{NCOMPS} > 0$  and  $\text{NLAMDA} > 0$ , then the index of refraction changes with wavelength. In this case the following data are read in:

- (1) CMR(J) is the real part of the user supplied index of refraction for wavelengths ranging from the value of UPTOLM(J-1) (assumed to be  $0.43 \mu\text{m}$  if  $J = 1$ ) to the value of UPTOLM(J). CMR is read in with an F5.3 format.
- (2) CMI(J) is the imaginary part of the user supplied index of refraction for wavelengths ranging from the value of UPTOLM(J-1) to the value of UPTOLM(J). CMI is read in with an F5.3 format.
- (3) UPTOLM(J) is the upper limit of the wavelength band for which CMR(J) and CMI(J) are the correct indices of refraction. UPTOLM is in units of  $\mu\text{m}$  and is read in with an F5.3 format. The final value of UPTOLM(J) must be equal to or greater than 0.70.

The NLAMDA values of CMR(J), CMI(J), and UPTOLM(J) are read in the form of data groups, each complete for a given value of J. The overall format for this data is [4(3F5.2)].

#### UNKNOWN OPERATING CONDITIONS

The model may be used to calculate voltage-current curves and collection efficiencies for precipitators with unknown operating voltages and currents. Table A-4 summarizes the options available to the user and makes recommendations on the applicability of each. If collection efficiency data for a utility fly ash precipitator is desired, the following data set should be used.

The first data card has the same format as the first card in the basic data set. MODL must be set to 2 in column 8. Since the remainder of the data in this data group is redefined in subroutine INTERN, the rest of the card may be left blank if desired.

Data group 2 contains the following 2 data.

- (1) RHO is the resistivity of the collected particulate layer expressed in ohm-cm. RHO is entered with an E8.2 format and must be right justified in columns 1-8.
- (2) HDUCT is the wire-to-plate spacing in units of inches. HDUCT is read with an F5.2 format in columns 11-15.

If the ESP being studied is similar to a utility fly ash precipitator, the above procedure may be used. However, if the ESP is much different from a utility fly ash precipitator, a different procedure should be used. This procedure is enabled when NVI is set to 2 in data group 3. The description of the data required for this case is contained in the construction of the basic data set section of this Appendix (p. A-1).

If only voltage-current curves are desired, the required data set again depends on whether the ESP is similar to a utility fly ash precipitator. If the ESP is similar, then the first 3 data groups are the same as for the basic data set described earlier in this Appendix. To get the voltage-current calculation, the following values must appear:

- (1) Card 1: MODL = 3 in column 8 (the rest of the card may be blank), and
- (2) Card 3: NVI = 1 in column 6 (the rest of the card may be blank).



TABLE A-4. USER OPTIONS WHEN THE OPERATING VOLTAGE AND CURRENT ARE NOT KNOWN

Desired Calculation	Variables				Procedure Recommended	Comments
	MODL	NVI	VISKIP	VISAME		
Collection efficiency of a utility fly ash precipitator.	2	1	n/a	n/a	Yes	Uses internal data set based on 17 field tests of cold-side utility fly ash precipitators to generate efficiencies for a range of SCA values. Fast.
	0 or 1	2	1	1 or 2	No	Calculates approximate V-I curves; then calculates efficiency for a derived operating point. Slow. VISAME=2 (different voltages in each section) is slower than VISAME=1 (same voltage).
Collection efficiency for an ESP that is much different from a utility fly ash ESP.	2	1	n/a	n/a	No	Precipitator test data used in internal data set are not similar to this application. Accuracy may be low. Fast.
	0 or 1	2	1	1	Yes	Calculates approximate voltage-current curves; then calculates efficiency for a derived operating point. Uses the same operating point in each ESP section. Slow.
	0 or 1	2	1	2	No	Same as above except calculates a new operating point for each ESP section. Slower.
	0 or 1	2	0	2	No	Same as above except calculates electric fields and potentials in each ESP length increment. Very slow.

(continued)

TABLE A-4. (CONTINUED)

<u>Desired Calculation</u>	<u>Variables</u>				<u>Procedure Recommended</u>	<u>Comments</u>
	<u>MODL</u>	<u>NVI</u>	<u>VISKIP</u>	<u>VISAME</u>		
Voltage-current curves only for a utility fly ash precipitator.	3	1	n/a	n/a	Yes	Uses internal data set to generate voltage-current curves. No efficiency calculated. Fast.
	3	2	1	1 or 2	No	Calculates voltage-current curve for first section only using approximate procedures. No efficiency calculated. Slow.
Voltage-current curves only for an ESP that is much different from a utility fly ash ESP.	3	1	n/a	n/a	No	Uses internal data set to generate voltage-current curves. Precipitator test data used in internal data set are not similar to this application. Accuracy may be low. Fast.
	3	2	1	1 or 2	Yes	Calculates voltage-current curve for first section only using approximate procedures. No efficiency calculated. Slower.

Card 4 will contain the following data:

- (1) RHO is the resistivity of the collected particulate layer expressed in ohm-cm. RHO is entered with an E8.2 format and must be right justified in columns 1-8.
- (2) HDUCT is the wire-to-plate spacing in units of inches. HDUCT is read with an F5.2 format in columns 11-15.

Voltage-current curves and operating points for a six section ESP will be printed. If the ESP is not similar to a utility fly ash precipitator, a complete data set appropriate for an efficiency calculation with NVI set to 2 is required. If MODL = 3 on card 1, the calculation will terminate after the calculation and printing of the voltage-current curve data for the first electrical section.

#### REFERENCE

1. Faulkner, M. G., and DuBard, J. L. A Mathematical Model of Electrostatic Precipitation (Revision 3). EPA-600/7-84-069a,b,c. (Volume I, Modeling and Programming: NTIS PB84-212-679; Volume II, User's Manual: NTIS PB84-212-687; FORTRAN Source Code Tape: NTIS PB84-232-990). U. S. Environmental Protection Agency, Research Triangle Park, North Carolina. 1984.

## Appendix B

OUTPUT DATA FILE ESPREV.OUT CORRESPONDING TO THE  
INPUT DATA FILE SHOWN IN FIGURE 1

```
*****
*
*          EPA ESP MODEL          *
*
*          AEERL AND SRI          *
*
*  REVISED ESP MODEL -  DECEMBER 1990  *
*
*****
```

INPUT DATA FOR DATA SET NUMBER 1

TITLE: TEST PLANT 2: 4 SECTION ESP WITH 320 SCA, BITUMINOUS COAL SIZE  
DISTRIBUTION

### CALCULATION PARAMETERS

```
*****
TYPE OF DATA SET (1 - 4)          NDATA      1
MODEL TYPE (0 - 3)                 MODL       0
REDUCED PRINTING (0 - 3)           NOPRNT     0
RIGOROUS OR ESTIMATED FIELD CALCULATION (1 OR 2)  NEST      1
RIGOROUS OR ESTIMATED CHARGE CALCULATION (0 OR 1) NCALC     0
VI CURVES KNOWN OR CALCULATED (1 OR 2)  NVI      1

DIMENSION OF X GRID (15 MAX)       NX         15
DIMENSION OF Y GRID (15 MAX)       NY         11
MAX NUMBER OF ITERATIONS TO CONVERGENCE  NITER     2
NUMBER OF INTEGRATION INCREMENTS IN CHARGE CALC  NN        10
ESTIMATED EFFICIENCY (%)           ETAO      99.90
```

### PHYSICAL PARAMETERS

```
*****
INLET MASS LOADING                 DL          2.000 GR/ACF
PARTICLE DENSITY                   DD          2400. KG/M3
DIELECTRIC RATIO                   EPS          100.0
ION MOBILITY                       US          .270E-03 M2/V/S
RESISTIVITY                        RHO          .200E+11 OHM-CM
```

TOTAL ESP LENGTH	PL	36.00 FT
COLD SIDE OR HOT SIDE (1 OR 2)	NTEMP	1
PEAK-TO-AVERAGE VOLTAGE RATIO	VRATIO	1.20
ELECTRICAL BREAKDOWN STRENGTH	EBD	.150E+07 V/M
PERCENT WATER	PCH2O	8.00 %
PERCENT O2	PCO2	3.50 %

#### PARTICLE SIZE DATA

\*\*\*\*\*

NUMBER OF SIZE BAND END POINTS	NENDPT	19
TYPE OF SIZE DATA (1=MEASURED, 2=CALC)	NDIST	2

SIZE DISTRIBUTION MMD	D50	16.30 UM
STANDARD DEVIATION	SIGMAP	3.40

SIZE BAND END POINTS	ENDPT	.010 UM
		.070
		.100
		.140
		.220
		.340
		.500
		.700
		1.000
		1.400
		2.200
		3.400
		5.000
		7.000
		10.000
		14.000
		22.000
		34.000
		100.000

#### SECTIONAL DATA

\*\*\*\*\*

NUMBER OF ESP SECTIONS	NUMSEC	4		
NO. INCREMENTS PER SECTION	LSECT	10	INCREMENTAL LENGTH	LINGS
		10		.90 FT
		10		.90
		10		.90
		10		.90

#### SECTION NO. 1

\*\*\*\*\*

VOLTAGE	VOS	.431E+05 V
CURRENT	TCS	.490E+00 A
PLATE AREA	AS	.270E+05 FT2

TOTAL WIRE LENGTH	WLS	27000.00 FT
CORONA WIRE RADIUS	ACS	.0750 IN.
NUMBER OF WIRES	NWS	18
WIRE-TO-PLATE SPACING	BS	4.50 IN.
WIRE-TO-WIRE SPACING	SYS*2	6.00 IN.
GAS VOLUME FLOW RATE	VGS	.338E+06 ACFM
GAS VELOCITY	VGASS	5.00 FT/S
GAS TEMPERATURE	TEMPS	300.00 DEG F
GAS PRESSURE	PS	1.000 ATM
GAS VISCOSITY	VISS	.230E-04 KG/M/S

#### SECTION NO. 2

\*\*\*\*\*

VOLTAGE	VOS	.420E+05 V
CURRENT	TCS	.737E+00 A
PLATE AREA	AS	.270E+05 FT2

TOTAL WIRE LENGTH	WLS	27000.00 FT
CORONA WIRE RADIUS	ACS	.0750 IN.
NUMBER OF WIRES	NWS	18
WIRE-TO-PLATE SPACING	BS	4.50 IN.
WIRE-TO-WIRE SPACING	SYS*2	6.00 IN.

GAS VOLUME FLOW RATE	VGS	.338E+06 ACFM
GAS VELOCITY	VGASS	5.00 FT/S
GAS TEMPERATURE	TEMPS	300.00 DEG F
GAS PRESSURE	PS	1.000 ATM
GAS VISCOSITY	VISS	.230E-04 KG/M/S

#### SECTION NO. 3

\*\*\*\*\*

VOLTAGE	VOS	.398E+05 V
CURRENT	TCS	.748E+00 A
PLATE AREA	AS	.270E+05 FT2

TOTAL WIRE LENGTH	WLS	27000.00 FT
CORONA WIRE RADIUS	ACS	.0750 IN.
NUMBER OF WIRES	NWS	18
WIRE-TO-PLATE SPACING	BS	4.50 IN.
WIRE-TO-WIRE SPACING	SYS*2	6.00 IN.

GAS VOLUME FLOW RATE	VGS	.338E+06 ACFM
GAS VELOCITY	VGASS	5.00 FT/S
GAS TEMPERATURE	TEMPS	300.00 DEG F
GAS PRESSURE	PS	1.000 ATM
GAS VISCOSITY	VISS	.230E-04 KG/M/S

#### SECTION NO. 4

\*\*\*\*\*

VOLTAGE	VOS	.382E+05 V
CURRENT	TCS	.981E+00 A
PLATE AREA	AS	.270E+05 FT2

TOTAL WIRE LENGTH	WLS	27000.00 FT
CORONA WIRE RADIUS	ACS	.0750 IN.
NUMBER OF WIRES	NWS	18
WIRE-TO-PLATE SPACING	BS	4.50 IN.
WIRE-TO-WIRE SPACING	SYS*2	6.00 IN.
GAS VOLUME FLOW RATE	VGS	.338E+06 ACFM
GAS VELOCITY	VGASS	5.00 FT/S
GAS TEMPERATURE	TEMPS	300.00 DEG F
GAS PRESSURE	PS	1.000 ATM
GAS VISCOSITY	VISS	.230E-04 KG/M/S

#### NON-IDEAL PARAMETERS

\*\*\*\*\*

NUMBER OF NON-IDEAL DATA SETS                      NONID    3

SNEAKAGE FRACTION	.05	GAS VEL. SIGMA	.15	NO. BAFFLED STAGES	4.00
	.10		.25		4.00
	.00		.00		4.00

#### RAPPING PARAMETERS

\*\*\*\*\*

TYPE OF RAPPING CALCULATION (0,5=OLD ESTIMATION, 1-3=DYNAMIC)    0

NUMBER OF RAPPING DATA SETS	NRAPD	1
SOURCE OF RAPPING DUST	NEFF	1
FIRST RAPPING DUST MMD	ARD50	6.0 UM
FIRST RAPPING DUST SIGMA	ARSIGM	2.5

#### OPACITY PARAMETERS

\*\*\*\*\*

OPACITY PATH LENGTH	PATHL	15.00 FT
NO. INDICES OF REFRACTION (0-10)	NCOMPS	0
NO. WAVELENGTHS FOR OPACITY CALC (0=10,1=1)	NWAVES	0
NO. INDICES OF REFRACTION FOR VARIABLE INDEX (0-10)	NLAMDA	0

\*\*\*\*\*

INPUT MASS LOADING = 4.580E-03 KG/ACM

\*\*\* ESP INCREMENT NO.    1 \*\*\*

MASS REMOVED (KG/M3) = 2.247E-03	CUM. MASS REMOVAL = 2.247E-03
UNCORRECTED % PEN       =    48.3463	

\*\*\* ESP INCREMENT NO.    2 \*\*\*

MASS REMOVED (KG/M3) = 7.354E-04	CUM. MASS REMOVAL = 2.983E-03
UNCORRECTED % PEN       =    31.4444	

\*\*\* ESP INCREMENT NO.    3 \*\*\*

MASS REMOVED (KG/M3) = 3.814E-04	CUM. MASS REMOVAL = 3.364E-03
UNCORRECTED % PEN       =    22.6795	

*** ESP INCREMENT NO. 4 ***	
MASS REMOVED (KG/M3) = 2.357E-04	CUM. MASS REMOVAL = 3.600E-03
UNCORRECTED % PEN = 17.2632	
*** ESP INCREMENT NO. 5 ***	
MASS REMOVED (KG/M3) = 1.589E-04	CUM. MASS REMOVAL = 3.759E-03
UNCORRECTED % PEN = 13.6118	
*** ESP INCREMENT NO. 6 ***	
MASS REMOVED (KG/M3) = 1.135E-04	CUM. MASS REMOVAL = 3.872E-03
UNCORRECTED % PEN = 11.0036	
*** ESP INCREMENT NO. 7 ***	
MASS REMOVED (KG/M3) = 8.446E-05	CUM. MASS REMOVAL = 3.957E-03
UNCORRECTED % PEN = 9.0625	
*** ESP INCREMENT NO. 8 ***	
MASS REMOVED (KG/M3) = 6.478E-05	CUM. MASS REMOVAL = 4.021E-03
UNCORRECTED % PEN = 7.5736	
*** ESP INCREMENT NO. 9 ***	
MASS REMOVED (KG/M3) = 5.095E-05	CUM. MASS REMOVAL = 4.072E-03
UNCORRECTED % PEN = 6.4025	
*** ESP INCREMENT NO. 10 ***	
MASS REMOVED (KG/M3) = 4.081E-05	CUM. MASS REMOVAL = 4.113E-03
UNCORRECTED % PEN = 5.4645	
*** CORRECTION FOR .05 SNEAKAGE ***	
SNEAKAGE MASS (KG/M3) = 2.289E-04	CUM. MASS REMOVAL = 4.113E-03
MASS PENETRATION = 4.668E-04	INLET MASS LOADING = 4.580E-03
CORRECTED % PENETRATION = 10.1913	
*** ESP INCREMENT NO. 11 ***	
MASS REMOVED (KG/M3) = 1.419E-04	CUM. MASS REMOVAL = 4.255E-03
UNCORRECTED % PEN = 6.6182	
*** ESP INCREMENT NO. 12 ***	
MASS REMOVED (KG/M3) = 6.138E-05	CUM. MASS REMOVAL = 4.316E-03
UNCORRECTED % PEN = 5.2710	
*** ESP INCREMENT NO. 13 ***	
MASS REMOVED (KG/M3) = 4.068E-05	CUM. MASS REMOVAL = 4.357E-03
UNCORRECTED % PEN = 4.3782	
*** ESP INCREMENT NO. 14 ***	
MASS REMOVED (KG/M3) = 3.046E-05	CUM. MASS REMOVAL = 4.388E-03
UNCORRECTED % PEN = 3.7098	
*** ESP INCREMENT NO. 15 ***	
MASS REMOVED (KG/M3) = 2.395E-05	CUM. MASS REMOVAL = 4.412E-03
UNCORRECTED % PEN = 3.1842	



*** ESP INCREMENT NO. 16 ***	
MASS REMOVED (KG/M3) = 1.940E-05	CUM. MASS REMOVAL = 4.431E-03
UNCORRECTED % PEN = 2.7585	
*** ESP INCREMENT NO. 17 ***	
MASS REMOVED (KG/M3) = 1.601E-05	CUM. MASS REMOVAL = 4.447E-03
UNCORRECTED % PEN = 2.4071	
*** ESP INCREMENT NO. 18 ***	
MASS REMOVED (KG/M3) = 1.342E-05	CUM. MASS REMOVAL = 4.460E-03
UNCORRECTED % PEN = 2.1127	
*** ESP INCREMENT NO. 19 ***	
MASS REMOVED (KG/M3) = 1.138E-05	CUM. MASS REMOVAL = 4.472E-03
UNCORRECTED % PEN = 1.8629	
*** ESP INCREMENT NO. 20 ***	
MASS REMOVED (KG/M3) = 9.730E-06	CUM. MASS REMOVAL = 4.482E-03
UNCORRECTED % PEN = 1.6494	
*** CORRECTION FOR .05 SNEAKAGE ***	
SNEAKAGE MASS (KG/M3) = 2.333E-05	CUM. MASS REMOVAL = 4.482E-03
MASS PENETRATION = 9.849E-05	INLET MASS LOADING = 4.580E-03
CORRECTED % PENETRATION = 2.1505	
*** ESP INCREMENT NO. 21 ***	
MASS REMOVED (KG/M3) = 1.444E-05	CUM. MASS REMOVAL = 4.496E-03
UNCORRECTED % PEN = 1.7296	
*** ESP INCREMENT NO. 22 ***	
MASS REMOVED (KG/M3) = 9.737E-06	CUM. MASS REMOVAL = 4.506E-03
UNCORRECTED % PEN = 1.5168	
*** ESP INCREMENT NO. 23 ***	
MASS REMOVED (KG/M3) = 7.852E-06	CUM. MASS REMOVAL = 4.514E-03
UNCORRECTED % PEN = 1.3451	
*** ESP INCREMENT NO. 24 ***	
MASS REMOVED (KG/M3) = 6.650E-06	CUM. MASS REMOVAL = 4.520E-03
UNCORRECTED % PEN = 1.1998	
*** ESP INCREMENT NO. 25 ***	
MASS REMOVED (KG/M3) = 5.722E-06	CUM. MASS REMOVAL = 4.526E-03
UNCORRECTED % PEN = 1.0747	
*** ESP INCREMENT NO. 26 ***	
MASS REMOVED (KG/M3) = 4.985E-06	CUM. MASS REMOVAL = 4.531E-03
UNCORRECTED % PEN = .9657	
*** ESP INCREMENT NO. 27 ***	
MASS REMOVED (KG/M3) = 4.367E-06	CUM. MASS REMOVAL = 4.535E-03
UNCORRECTED % PEN = .8703	

*** ESP INCREMENT NO. 28 ***	
MASS REMOVED (KG/M3) = 3.855E-06	CUM. MASS REMOVAL = 4.539E-03
UNCORRECTED % PEN = .7860	
*** ESP INCREMENT NO. 29 ***	
MASS REMOVED (KG/M3) = 3.414E-06	CUM. MASS REMOVAL = 4.543E-03
UNCORRECTED % PEN = .7114	
*** ESP INCREMENT NO. 30 ***	
MASS REMOVED (KG/M3) = 3.036E-06	CUM. MASS REMOVAL = 4.546E-03
UNCORRECTED % PEN = .6450	
*** CORRECTION FOR .05 SNEAKAGE ***	
SNEAKAGE MASS (KG/M3) = 4.923E-06	CUM. MASS REMOVAL = 4.546E-03
MASS PENETRATION = 3.444E-05	INLET MASS LOADING = 4.580E-03
CORRECTED % PENETRATION = .7519	
*** ESP INCREMENT NO. 31 ***	
MASS REMOVED (KG/M3) = 3.364E-06	CUM. MASS REMOVAL = 4.549E-03
UNCORRECTED % PEN = .6411	
*** ESP INCREMENT NO. 32 ***	
MASS REMOVED (KG/M3) = 2.845E-06	CUM. MASS REMOVAL = 4.552E-03
UNCORRECTED % PEN = .5789	
*** ESP INCREMENT NO. 33 ***	
MASS REMOVED (KG/M3) = 2.505E-06	CUM. MASS REMOVAL = 4.554E-03
UNCORRECTED % PEN = .5242	
*** ESP INCREMENT NO. 34 ***	
MASS REMOVED (KG/M3) = 2.227E-06	CUM. MASS REMOVAL = 4.557E-03
UNCORRECTED % PEN = .4756	
*** ESP INCREMENT NO. 35 ***	
MASS REMOVED (KG/M3) = 1.989E-06	CUM. MASS REMOVAL = 4.558E-03
UNCORRECTED % PEN = .4321	
*** ESP INCREMENT NO. 36 ***	
MASS REMOVED (KG/M3) = 1.779E-06	CUM. MASS REMOVAL = 4.560E-03
UNCORRECTED % PEN = .3933	
*** ESP INCREMENT NO. 37 ***	
MASS REMOVED (KG/M3) = 1.602E-06	CUM. MASS REMOVAL = 4.562E-03
UNCORRECTED % PEN = .3583	
*** ESP INCREMENT NO. 38 ***	
MASS REMOVED (KG/M3) = 1.443E-06	CUM. MASS REMOVAL = 4.563E-03
UNCORRECTED % PEN = .3268	
*** ESP INCREMENT NO. 39 ***	
MASS REMOVED (KG/M3) = 1.302E-06	CUM. MASS REMOVAL = 4.565E-03
UNCORRECTED % PEN = .2983	

\*\*\* ESP INCREMENT NO. 40 \*\*\*

MASS REMOVED (KG/M3) = 1.175E-06 CUM. MASS REMOVAL = 4.566E-03  
 UNCORRECTED % PEN = .2727

\*\*\* CORRECTION FOR .05 SNEAKAGE \*\*\*

SNEAKAGE MASS (KG/M3) = 1.721E-06 CUM. MASS REMOVAL = 4.566E-03  
 MASS PENETRATION = 1.420E-05 INLET MASS LOADING = 4.580E-03  
 CORRECTED % PENETRATION = .3101

\*\*\*\*\*

# ESP OUTLET STATISTICS

\*\*\* OUTLET DATA CORRECTED FOR SNEAKAGE, SIGMA G,  
 AND SMALL PARTICLE MIGRATION VELOCITY ERROR \*\*\*

DIAMETER UM	EFFICIENCY	PENETRATION	EFFECTIVE MIG VEL
.0400	.999731	.000269	.130644
.0850	.994865	.005135	.083786
.1200	.989648	.010352	.072645
.1800	.982905	.017095	.064671
.2800	.978976	.021024	.061383
.4200	.980865	.019135	.062879
.6000	.985836	.014164	.067661
.8500	.991178	.008822	.075186
1.2000	.995030	.004970	.084307
1.8000	.997619	.002381	.096000
2.8000	.998845	.001155	.107499
4.2000	.999076	.000924	.111038
6.0000	.999116	.000884	.111749
8.5000	.999785	.000215	.134203
12.0000	.999931	.000069	.152239
18.0000	.999963	.000037	.162186
28.0000	.999967	.000033	.163892
67.0000	.999967	.000033	.163965

CORRECTED TOTAL EFFICIENCY = 99.950  
 PENETRATION = .050

\*\*\* CORRECTION FOR RAPPING REENTRAINMENT \*\*\*

DIAMETER UM	EFFICIENCY	PENETRATION	EFFECTIVE MIG VEL
.0400	.999684	.000316	.128116
.0850	.994769	.005231	.083492
.1200	.989492	.010508	.072406
.1800	.982640	.017360	.064427
.2800	.978561	.021439	.061073
.4200	.980290	.019710	.062409
.6000	.985121	.014879	.066878
.8500	.990345	.009655	.073752
1.2000	.994119	.005881	.081630

1.8000	.996684	.003316	.090736
2.8000	.997969	.002031	.098531
4.2000	.998320	.001680	.101547
6.0000	.998499	.001501	.103331
8.5000	.999308	.000692	.115643
12.0000	.999584	.000415	.123750
18.0000	.999739	.000261	.131129
28.0000	.999842	.000158	.139113
67.0000	.999932	.000068	.152462

TOTAL EFFICIENCY WITH RAPPING = 99.917  
 PENETRATION = .083

\*\*\*\*\*

TEST PLANT 2: 4 SECTION ESP WITH 320 SCA, BITUMINOUS COAL SIZE DISTRIBUTION

ESP SCA = 319. FT<sup>2</sup>/KACFM  
 SNEAKAGE = .05  
 SIGMA G = .15  
 RAPPING MMD = 6 UM WITH SIGMA = 2.5

TOTAL EFFICIENCY WITHOUT RAPPING = 99.950  
 PENETRATION = .050

TOTAL EFFICIENCY WITH RAPPING = 99.917  
 PENETRATION = .083

DUST LOADINGS: INLET = 3.12856 GR/DSCF  
 OUTLET = .00258 GR/DSCF  
 = .00435 LB/MBTU

VISIBLE EMISSIONS: OPACITY = 1.60 %  
 (NO-RAP) = 1.33 %  
 (RAPPING PUFF) = .27 %

STACK DIAMETER = 4.58 M  
 EXTINCTION COEFF. = .0035 1/M

\*\*\*\*\*