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1981 Annual Report: Electric and Magnetic Field Measurements

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Electronics and Electrical Engineering
Electrosystems Division
Washington, DC 20234

July 1982

Prepared for:

Department of Energy
Division of Electric Energy Systems
Washington, DC 20585

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1981 ANNUAL REPORT: ELECTRIC AND MAGNETIC FIELD MEASUREMENTS

R. H. McKnight, F. R. Kotter, M. Misakian, and J. N. Hagler

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

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Summary

The NBS program is concerned with developing methods for evaluating and calibrating instrumentation for use in measuring the electric field and various ion-related electrical quantities in the vicinity of high-voltage direct current (HVDC) transmission lines and in apparatus designed to simulate the transmission line environment.

The laboratory investigation of errors associated with above-ground operation of sensors for measuring vertical current density has been completed and a report prepared describing the results. Significant errors were observed for both unguarded and guarded sensors, ranging from 4 to 25% for the guarded plates and 10 to 35% for unguarded plates for a wide range of geometrical parameters. Preliminary results from a field day held in October 1981 are in agreement with the laboratory results.

A new low-speed air flow facility has been constructed. Using multiwire planar corona discharge ion sources, ion densities from $1.6 \times 10^5/cm^3$ to $1.4 \times 10^6/cm^3$ have been measured using an absolute filter technique. The space charge density is uniform to ±5% over most of the cross section of the test volume, but decreases in magnitude by about 20% in passing through the test volume. This loss appears to be due to ion-ion interactions.

Losses at the inlet of a parallel plate ion counter due to fringing fields have been determined using an ion counter with variable geometry. The inlet structure has been modeled using a two-dimensional finite element code and a program has been written to calculate the trajectories of ions moving in the counter inlet. The calculations predict a greater loss than actually observed but are in qualitative agreement with experimental results.

The above-ground operation of an ion counter has been investigated using a monopolar line and an experimental configuration in which the potential of the ion counter relative to the local space potential could be varied. The initial results show that the ion densities measured using the counter are relatively independent of counter potential where ions are strongly attracted to the counter. However, as the potential nears that of the average space potential near the counter, the indicated ion density drops significantly. These results represent only a limited set of measurements, but indicate problems associated with above-ground measurements of ion density.

The use of a high-efficiency particulate air (HEPA) or "absolute" filter in measuring net space charge density was investigated. The transmission of charge in an airstream through this type of filter has been determined to be less than 0.1% for a wide range of flow and ion density conditions. This result indicates that a HEPA filter may be useful in calibrating ion counters when ions of only one sign are present. In this case, the net space charge density and ion density are equivalent.

A retarding field scheme has been considered for use in measuring the mobility spectrum of the ions in the low-speed air-flow facility. The results of a limited number of measurements show that the method may be a useful one for this application but that a number of problems need further investigation, including the effects of space charge. Since the data reduction involves numerical derivatives, quality data is required and the use of signal averaging using a computer-controlled apparatus is indicated.

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Abstract

The NBS program is concerned with developing methods for evaluating and calibrating instrumentation for use in measuring the electric field and various ion-related electrical quantities in the vicinity of high voltage direct current (HVDC) transmission lines and in apparatus designed to simulate the transmission line environment.

The laboratory investigation of errors associated with above-ground operation of sensors for measuring vertical current density has been completed. Significant errors were observed for both unguarded and guarded sensors, ranging from 4 to 25% for the guarded plates and 10 to 35% for unguarded plates for a wide range of geometrical parameters. Preliminary results from a field day held in October 1981 are in agreement with the laboratory results.

A new low-speed air-flow facility has been constructed. Using multiwire planar corona discharge ion sources, ion densities from $1.6 \times 10^5/cm^3$ to $1.4 \times 10^6/cm^3$ have been measured using an absolute filter technique.

Losses at the inlet of a parallel plate ion counter due to fringing fields have been determined using an ion counter with variable geometry. Calculations based on a two-dimensional finite element code predict a greater loss than actually observed, but are in qualitative agreement with experimental results.

The above-ground operation of a parallel plate has been investigated using a monopolar line. The initial results obtained show that the ion densities measured using the counter are strongly dependent on ion counter potential. These results represent only a limited set of measurements, but indicate problems associated with above-ground measurements of ion density.

The transmission of charge in an air stream through a high efficiency particulate air (HEPA) filter has been determined to be less than 0.1% for a wide range of flow and ion density conditions. This result indicates that a HEPA filter may be useful in calibrating ion counters when the net space charge density and ion density are equivalent.

A retarding field scheme has been considered for use in measuring the mobility spectrum of the ions in the low-speed air flow facility. The results of a limited number of measurements show that the method may be a useful one for this application but that a number of problems need further investigation, including the effects of space charge.

I. INTRODUCTION

A determination of the electrical environment near high voltage transmission lines is important both to the line designer and to those utilities concerned with possible biological effects of the line. Adequate instrumentation and measurement procedures exist for characterizing ac lines [1][1], but the situation is in a much more rudimentary state for high voltage dc (HVDC) transmission lines.

The quantities primarily of interest are summarized symbolically in the equation $J = \rho KE$ where J (a/m^2) is the current density, ρ (C/m^3) the space charge density units, K (m^2/vs) a weighted ion mobility, and E (V/m) the electric field. This equation would appear significantly more complex if a suitable expression for K were written out explicitly. Other electrical quantities which also are of interest include the air conductivity and net space charge density. Related parameters are the mobility spectrum $\rho(K)$ and the ion species present near the ground. Measurements of $\rho(K)$ and identification of ion species are difficult tasks but may be necessary in the future. Concern with charge transport away from the line may require measurements of aerosol production and dispersal.

In previous reports we have discussed the adaptation of various instruments and measurement techniques developed by atmospheric electricity researchers to the HVDC measurement problem [2,3]. One important result of the NBS effort has been the development of facilities designed to provide, in the laboratory, a means of evaluating instruments under conditions similar to those found near a HVDC line. As discussed below, some laboratory results have also been directly compared with similar measurements made under a full-scale test line.

The parallel plate facility which was described in detail in earlier publications [4,5] has been used to complete an investigation of errors associated with vertical current density measurements. The permanent air flow system designed to produce a test volume containing space charge has been completed and evaluated.

In the following discussion of the FY81 effort, subtasks are described individually with each section self-contained including discussion.

Three reports published recently describe in detail some of the effort discussed below. These reports are:

(1) Measurement of Ion Current Density at Ground Level in the Vicinity of High Voltage DC Transmission Lines, R. H. McKnight, F. R. Kotter, and M. Misakian, NBSIR 81-2410, Dec. 1981.

[1] Numbers in brackets refer to the literature references listed at the end of this report.

(2) The Measurement of Net Space Charge Density Using Air Filtration Methods, R. H. McKnight, NBSIR 82-2486, April 1982.

(3) A Facility to Produce a Uniform Space Charge for Evaluating Ion Measuring Instruments, R. H. McKnight and F. R. Kotter, NBSIR 82-2517, June 1982.

2. PARALLEL PLATE APPARATUS

The development of a parallel plate apparatus for generation of dc fields with space charge [4] has been published in the Journal of Applied Physics [5]. This apparatus was used in the study of errors associated with measurements of vertical current density described below.

3. STUDY OF ERRORS ASSOCIATED WITH MEASUREMENTS OF VERTICAL CURRENT DENSITY

Conducting sensors, known as Wilson plates, are used to measure the vertical current to ground near HVDC transmssion lines. These sensors, which take the form of sensing elements surrounded by a guard band or ring, are usually operated several centimeters above ground to avoid problems with moisture, insects, and nearby foliage. This mode of operation introduces a source of error into the measurement since a grounded metal object located above the ground plane will cause a local enhancement of the electric field. In the FY80 annual report [2], our efforts to determine the enhancement factors for various sensors were described in detail. The approach to the problem will be briefly reiterated here. The enhancement of the electric field is geometrical (ignoring space charge effects) so that for a given sensor configuration, the enhancement factor may be determined by making ac measurements of displacement currents. It would be expected that these same enhancement factors would be observed for measurements made using dc fields plus ions produced by the parallel plate system.

During the present reporting period, experiments were completed which allow a comparison between ac and dc results. It was found that the dc measurements yielded enhancement factors which depended on the electric field and space charge density conditions existing in the parallel plate apparatus as well as on the electric field. However, for conditions like those expected under a HVDC transmission line [6], there was agreement between the ac and dc measurements. The results of the investigation are summarized in figure 1, which displays both ac results in the form of continuous curves and dc fields plus ions results which are shown as discrete data points. The data are plotted as a percentage error, for different sensor spacings above ground. The dc results are in terms of a parameter $\Delta E/E_g = |E_g - E_1|/E_g$ where E_g is the value of the field at the ground plane and E_1 is the value of the field 1 cm above the ground plane. The value of E_1 is calculated from the theoretical description

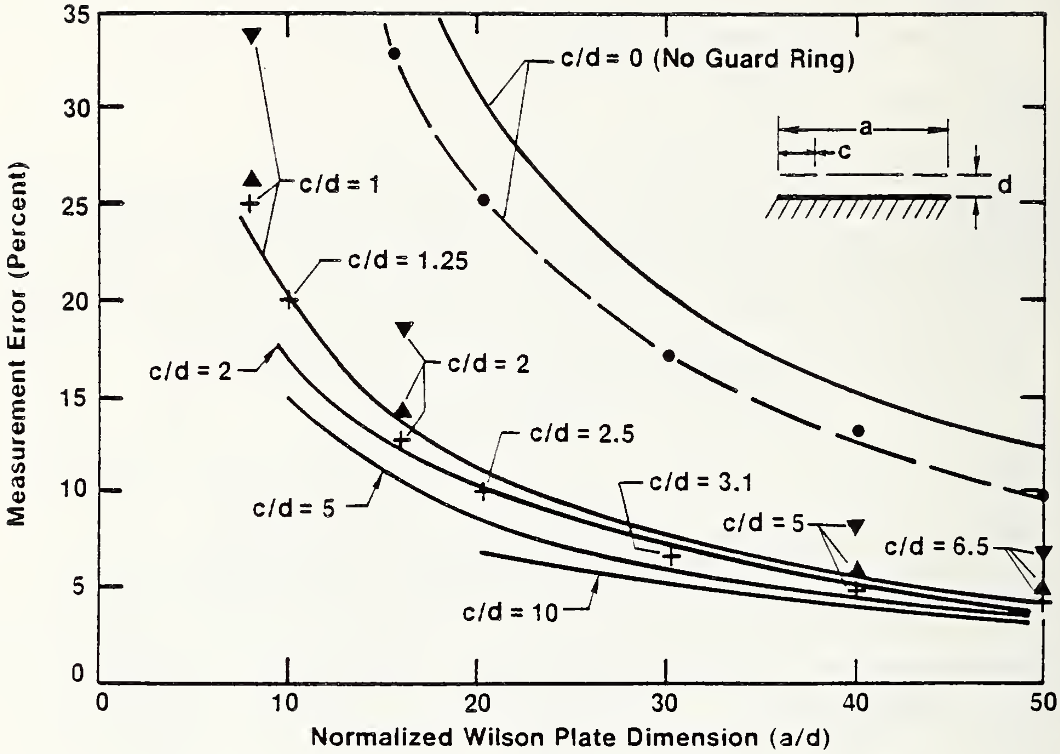


Figure 1. Errors in Wilson plate current density measurements as a function of guard ring width and elevation above the ground plane. The solid curves are results of measurements with alternating current. The $\Delta E/E_g$ parameter (see main text) values for the dc data plotted are as follows: + - 0.004; ▲ - 0.014; ▼ - 0.024, ● - 0.004.

of the parallel plate facility [4]. The parameter $\Delta E/E_g$ is an estimate of the normalized change in the electric field near the sensor due to space charge. It is clear from the figure that the percentage error is not independent of the dc operating conditions, but that there is good agreement between ac and dc data for small parameter values.

During a field day held at Project UHV the first week in October 1981, an extensive series of measurements was made under an operating test line. The preliminary results of these measurements, which were made using Wilson plates actually employed in the field, are in good agreement with the laboratory results.

A detailed description of the investigation of errors associated with Wilson plate measurements has been prepared as a report [6] and has been submitted to DOE.

4. PRODUCTION OF SPACE CHARGE IN THE LABORATORY

A. Introduction

A new low-speed air-flow facility has been constructed for evaluating instruments which measure ion-related electrical quantities. This facility replaces an earlier system which was used in developing measurement techniques and ion sources. The earlier system and related research have been described in previous reports [2,3]. The new facility is illustrated schematically in figure 2. The aerodynamic design has been improved substantially. Provision has been made for incorporating high efficiency particulate air filters at the inlet. A variable-speed fan completes the system. For the work described below, the three-speed fan which was used earlier produced the air flow.

B. Approach

To evaluate the new facility, a number of investigations have been completed. Measurement locations are indicated in figure 2 (II, III, and IV). At each location, access holes permitted probes to be inserted at varying distances at different positions above the floor of the system.

A hot film anemometer was used to characterize the system air flow. The measurements indicate a substantial improvement over the earlier system. Turbulence levels are significantly lower, and the air speed in the test section is uniform except near the walls. No further efforts were made to improve the air flow, since the space charge produced in the system using an optimum source design was very uniform, as is shown later.

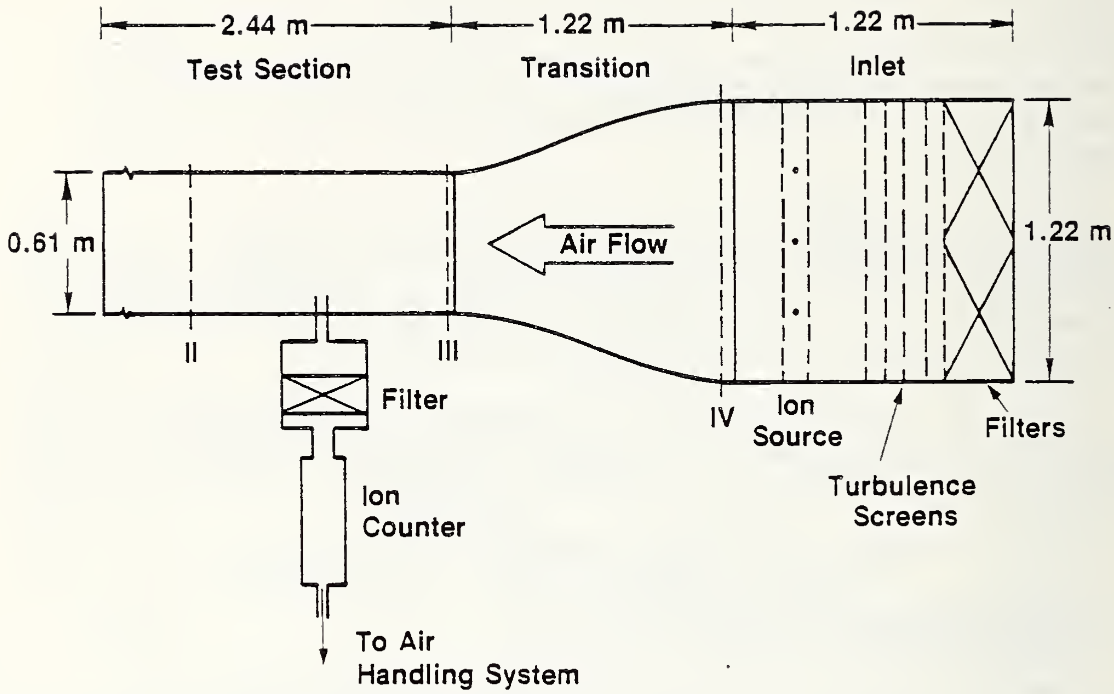


Figure 2. Top view of permanent low-speed air flow facility to produce space charge.

C. Results

The absolute filter system described in earlier reports [2,3] was used to measure the net space charge in the flow facility. The investigations reported here were made to determine, in the present system, the operational features of ion source configurations developed previously. These sources utilize a planar geometry in which a series of vertically oriented wires are placed midway between two wire-mesh ground planes. Provision has been made to allow variation of ground plane mesh size, number and diameter of corona wires, and wire-to-ground plane spacing. In all of the results discussed here, the wire was 64 µm stainless steel and the wire-to-ground-plane spacing was 10 cm. Parameters which were varied in the studies are listed below:

(a) Number of corona wires (1, 3, and 9),
(b) Screen mesh size (5 cm x 5 cm and window screen),
(c) Corona voltage (7, 10, 15, and 20 kV),
(d) Air speed at the source (0.5, 0.7, and 0.95 m/s).

Not all permutations were examined, although for each source configuration all three air speeds were used. For each source, the absolute filter system was used in a scanning mode to determine the net space charge density at locations II, III, and IV (fig. 2) for five different positions above the floor of the flow system. Representative results of these measurements are displayed on figures 3, 4, and 5. These figures show the net space charge density measured at midplane at the three locations of interest. Indicated on the drawings are the relative positions of the inlet and test section walls as well as the locations of the corona wires. All results shown were for a corona voltage of 10 kV, air speed at the source of 0.5 m/s, and no inlet filters.

In figures 3 and 4, the ground plane was the coarse 5 cm x 5 cm structure and there were one and three corona wires respectively. The source in figure 5 used nine corona wires and "window screen" ground planes. This particular configuration was determined earlier to be optimum in terms of the uniformity of space charge density produced in the test section.

A number of common features appear in all figures. There is a substantial decrease in net space charge density in going from location IV to location II (that is, farther downstream). Also, as the ions move downstream, the distribution becomes more uniform. The peaks due to the individual wires are observed at all locations for the one- and three-wire sources. The nine-wire source produces the most uniform net space charge density in the test section.

It is interesting to note the decrease in space charge density measured at IV as the number of corona wires is increased. This is probably due to the influence of the individual wires on their nearest

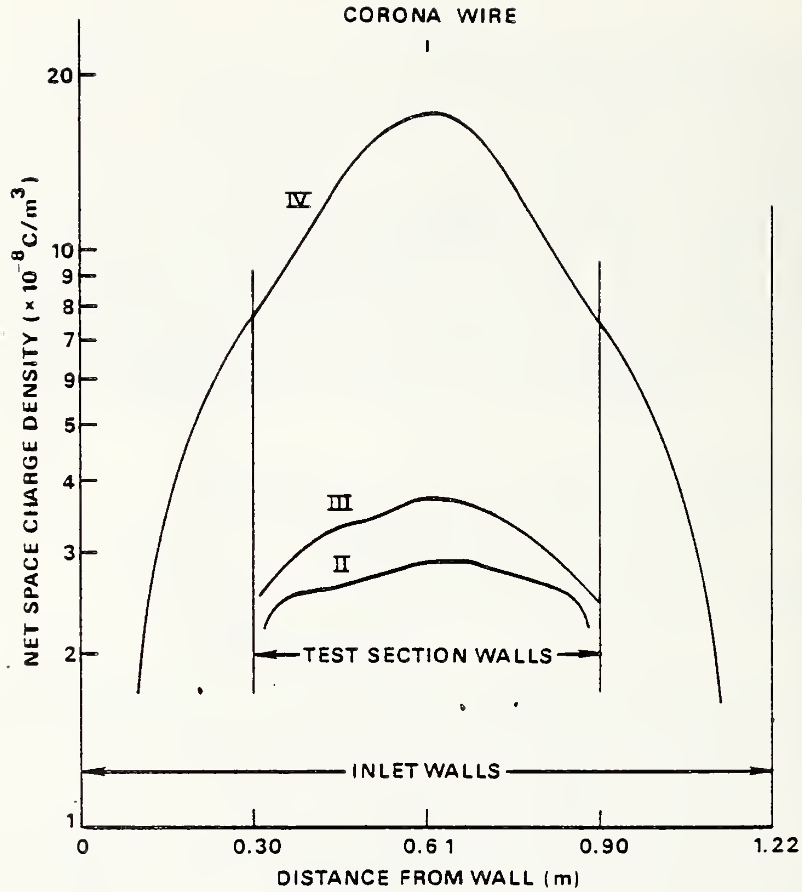


Figure 3. Net space charge measurements made at midplane at locations II, III, and IV. Relative positions of test section inlet walls are shown. Source configuration was 1 corona wire (position indicated) and coarse ground planes (see text).

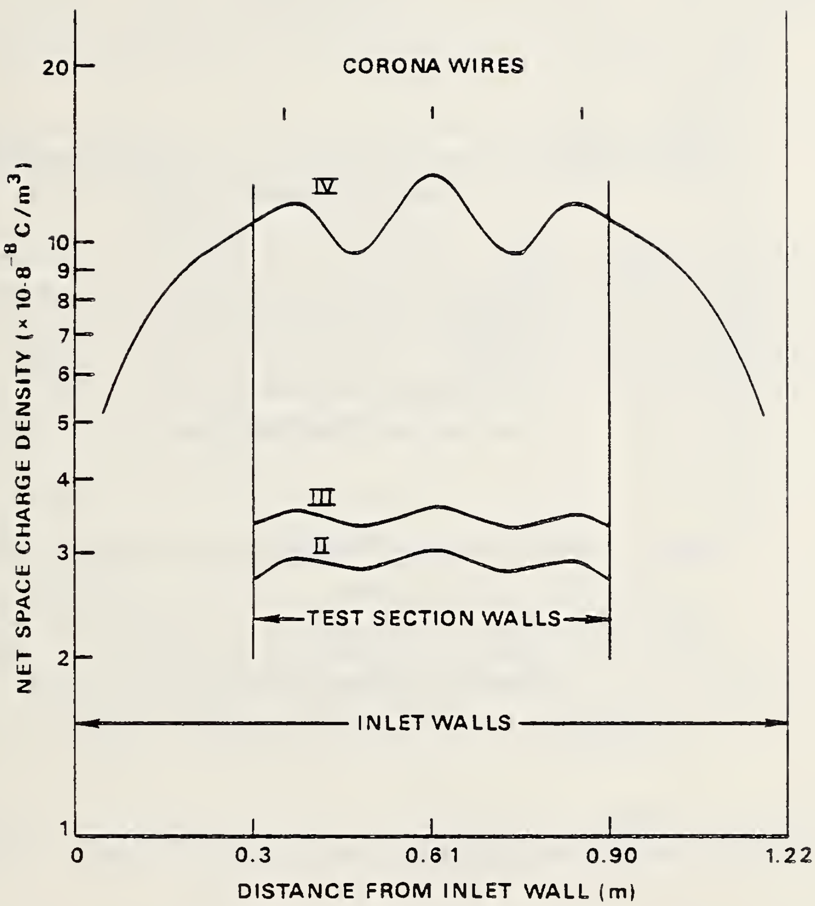


Figure 4. Net space charge measurements made at midplane at locations II, III, and IV. Source configuration was 3 corona wires (positions indicated) and coarse ground planes (see text).

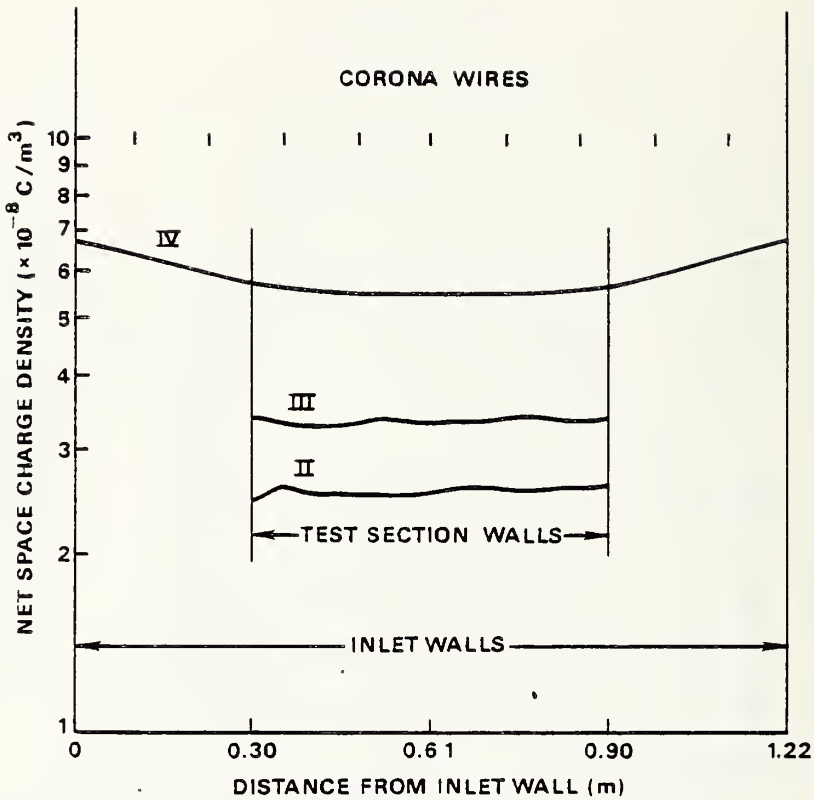


Figure 5. Net space charge measurements made at midplane at locations II, III, and IV. Source configuration was 9 corona wires (as indicated) and window screen ground planes.

neighbors. Calculations done for electrostatic precipitators indicate a lowering of the field around a corona wire as other wires are placed near it [7]. This will also affect the spatial distribution of the ions produced in the corona discharge. The increase near the walls seen for the nine-wire source reflects the influence of the walls and the source support structure on the outer corona wires.

The sources examined produced substantially different net space charge near the source, but in the test section only a 20% variation from source to source was seen.

Because the new air flow facility was constructed of insulating materials (plywood and hardboard) there was some concern over charging of walls during operation. To ascertain the effects of such charging, the transition section and inlet nearest the source were lined with aluminum foil. The only observable change was a slight increase in net space charge in the test section.

D. Discussion and Conclusions

The results of the measurements discussed here, which are similar to those made previously, may be summarized as follows:

(a) The net space charge measured in the system ranged from a maximum of 2.5×10^{-8} C/m^3 to 2.2×10^{-7} C/m^3. Assuming singly charged ions, this is a range of ion densities from 1.6×10^5/cm^3 to 1.4×10^6/cm^3.

(b) Changes in corona current as large as a factor of 10 result in only a 20% change in the measured net space charge.

(c) The net space charge density decreases by as much as a factor of three in going from location IV to location II (fig. 2).

(d) The optimum source configuration for producing a spatially uniform space charge is a multi-wire source with window screen ground planes.

The system is being used to investigate ion counters and net space charge measuring devices. A number of improvements and modifications are planned to optimize the system. A variable speed fan has been installed. Other changes include the construction of a retarding-field array to control the ion density, and development of a source to be located at the outlet of the transition section. This last task will allow much higher ion densities to be introduced into the test section.

5. INVESTIGATION OF SOURCES OF ERROR IN SPACE CHARGE DENSITY MEASUREMENTS USING ION COUNTERS

A. Introduction

The measurement of homopolar space charge density is most commonly done by using aspiration devices called ion counters. These instruments can be subject to large systematic errors due to improper design or operation. In earlier reports, we describe one such source of error which results from the effect of fringing fields at the inlet of the counter [2]. If the plates to which voltage is applied (the polarizing plates) are not recessed sufficiently behind the collector plates, the fringing fields to the wall of the ion counter enclosure can cause mobile ions to be precipitated to the wall. This loss, which depends on geometry, polarizing voltage, and the volumetric air flow through the system, can be significant as is seen in figure 6. Shown are current voltage curves for a counter which was constructed to allow the geometry of the plate structure to be changed. If there are no voltage dependent losses at the inlet due to fringing fields, then the current decreases as the polarizing potential increases. It is seen in figure 6 that there are losses even when the polarizing plates are recessed one plate spacing behind the collector plates.

B. Approach

An ab-initio analysis of the motion of ions near the ion counter inlet is not possible because of the complicated geometry. However, insight into the loss mechanisms can be gained by using a two-dimensional model and applying numerical analysis methods. A finite element code, resident on NBS computers, has been used to calculate the electric potential distributions and electric field at the inlet of the ion counter. The geometry assumed for the model calculation and the finite element triangulation resulting from the higher level code adaptation of the problem are shown in figure 7. In figure 8, the equipotential values are displayed. A solution was generated for one-half the geometry, since the reflection symmetry inherent in the problem was used to specify the appropriate boundary condition on the midplane. This saves computer space and computation time. An additional simplifying feature involves the assumption that the entrance to the counter is not open, but closed and grounded. The effect of this assumption will be determined in later calculations.

C. Results

The calculations were done for a polarizing potential of one unit and the equipotentials are drawn in units of 0.1 of the polarizing potential. For this example, in which the polarizing plates are recessed one plate spacing, there is little field leakage. In contrast,

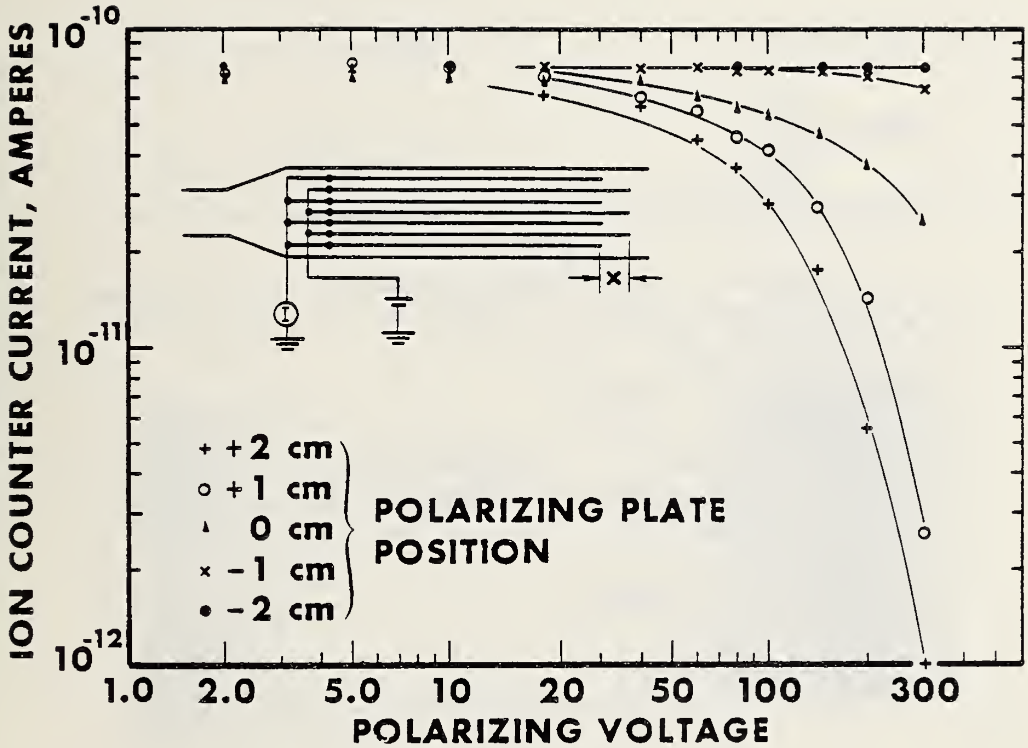
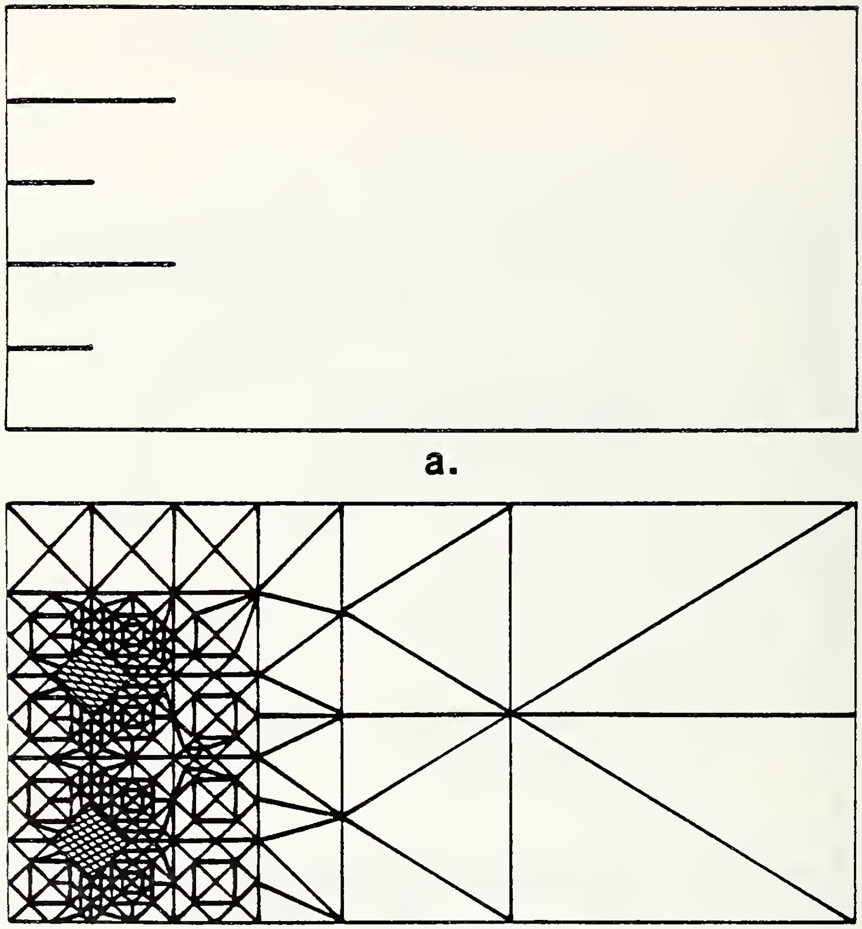


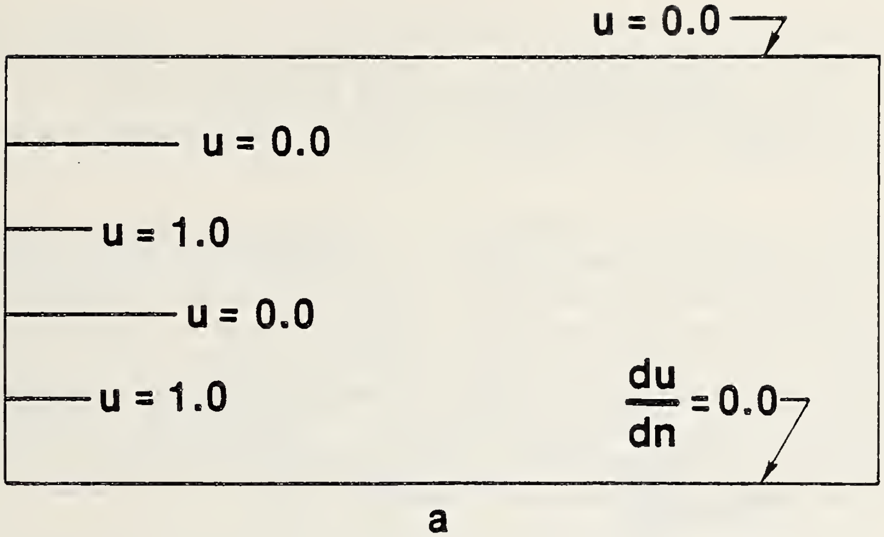
Figure 6. Ion counter output current as a function of polarizing voltage for different plate configurations. The displacement between the leading edges of the collection and polarizing plates is x. Positive values of x correspond to a situation where the polarizing plates protrude in front of the collector plates. For x = 0, the leading edges were flush. Because the ion density is independent of polarizing voltage over the range plotted, the ion counter current should be constant.



a.

b.

Figure 7. (a) Two dimensional geometry used in finite element calculations. (b) Computer-generated high level triangulation for geometry (a). Inside the crosshatched area, the triangulation was too dense to be displayed.



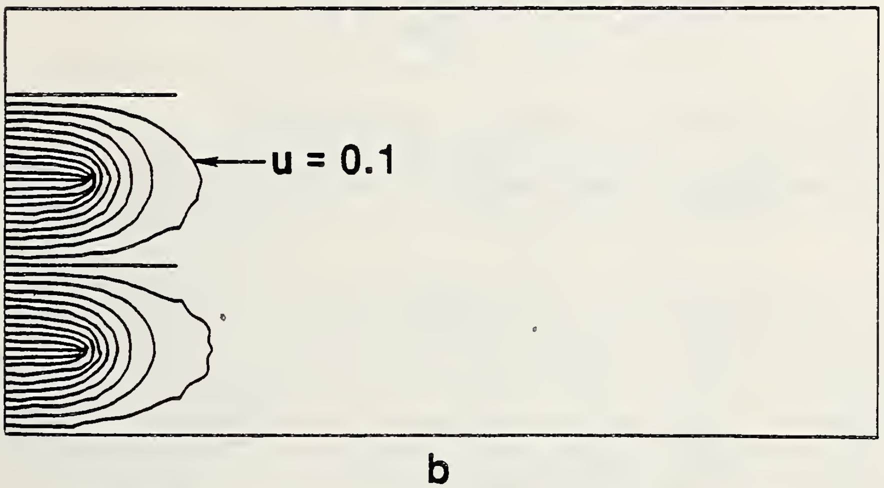


Figure 8. (a) Boundary conditions used in finite element calculation. (b) Computer generated equipotential curves, plotted in units of U = 0.1.

figure 9 displays the results of a calculation for a geometry where the polarizing plates protrude one plate spacing in front of the collector plates. Here the extent of the fringing fields is significant. Compare, for example, the location of the 0.1 equipotentials on figures 8 and 9.

While such plots are informative, they do not relate directly to the problem of losses at the inlet. In order to provide quantitative results, a program has been written to calculate the trajectories of ions carried into the ion counter by an air stream. The electric field as calculated using the finite element program and an appropriate air flow velocity field, are stored as arrays. In the program, an ion enters the counter at a particular point. The velocity at that (and any other) point is determined by adding vectorially the flow velocity vector and the electrical velocity vector:

$$\vec{v} = \vec{v}_{flow} + \vec{v}_E = \vec{v}_{flow} + k\vec{E}$$

where k is the ion mobility and E is the electric field at the point. Using this velocity, the ion is transported for a predetermined time and, at the new loction, the process is repeated. In this way a trajectory for the ion is estimated.

Sample trajectories for the geometry of figure 9 are shown in figure 10. The ion mobility was taken to be 1.4 $cm^2/V \cdot s$, the polarizing voltage 100 V and the air flow velocity was 42.4 cm/s into the counter. From such calculations it is possible to estimate the percentage of ions lost at the inlet for the model geometries shown. The calculated losses were larger than the measured losses. In the calculation, the air flow was assumed to be constant while in the ion counter, the flow converges to the active collection region. This increased flow rate would decrease the losses. In general, the calculations were in qualitative agreement with the experiment.

D. Discussion and Conclusions

It is somewhat more difficult to relate these calculations directly to experimental measurements. Primarily, this is the result of trying to model a complicated three-dimensional problem with a two-dimensional calculation. Also, in the actual ion counter the air flow is not uniform and there is some convergence of the air stream, since the air is restricted to flow only through the active volume of the counter. In figure 10, this would be the region inside the plate structure. This convergence implies there is a velocity component perpendicular to the counter axis. While we can measure the air flow speed using an anemometer, we do not have the capability of measuring velocity components.

The next step in this research will be to optimize the field calculations and to use a more realistic air flow field. Estimates will be made of the inward velocity component and the effect of

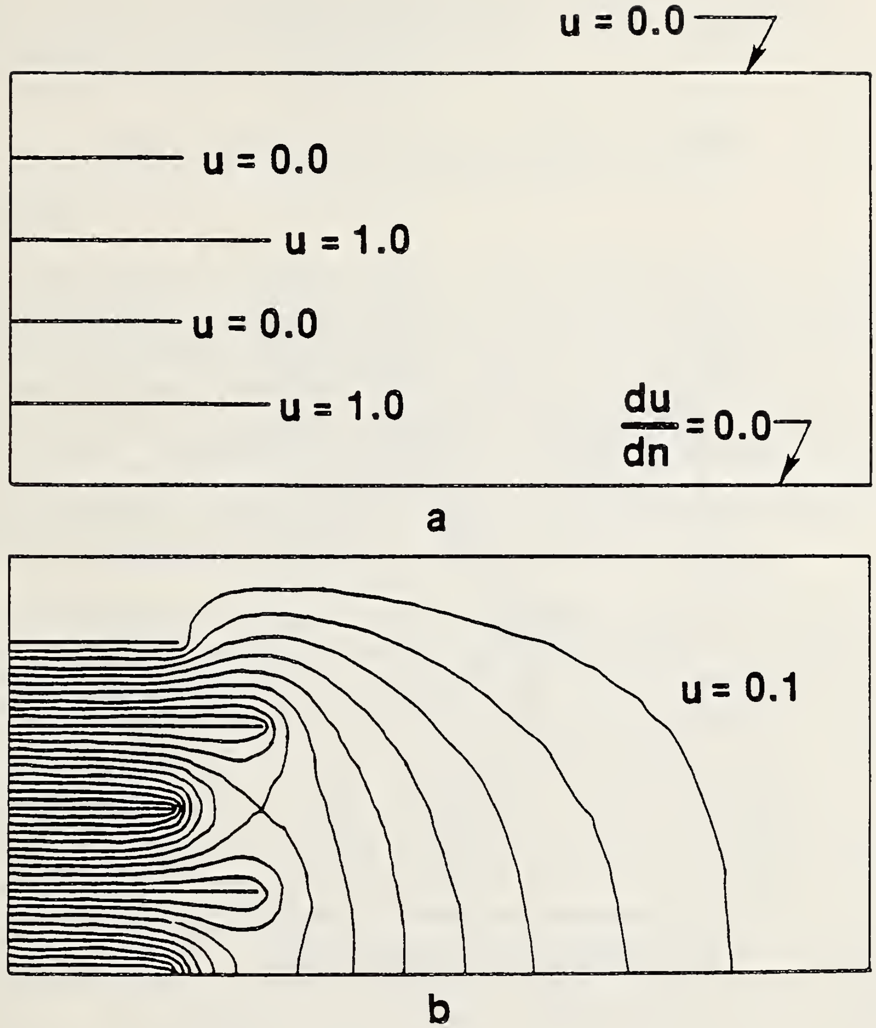


Figure 9. (a) Boundary conditions and geometry used for a model calculation in which the polarizing plates protrude in front of the collector plates.
(b) Computer generated equipotential curves, plotted in units of U = 0.1.

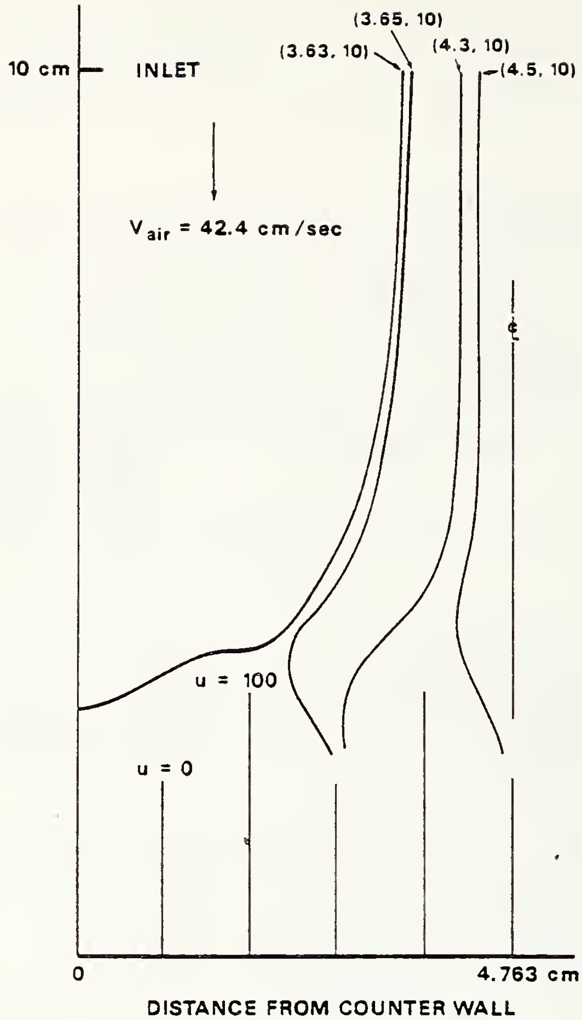


Figure 10. Trajectories of ions entering the ion counter at different initial locations (as shown). The geometry is that of figure 9.

changes in mobility and air speed on the trajectories will be investigated. By doing this, we would like to obtain a better correlation between theory and experiments.

6. ABOVE GROUND OPERATION OF ION COUNTERS

A. Introduction

Direct measurements of the space charge densities ρ^+, ρ^- near HVDC transmission lines are required to provide information necessary to characterize the electrical environment. A value of ρ can be inferred by using related measurements, since $J = \rho K E$ where J is current density, K is a suitably weighted average mobility and E is the electric field. One can solve for ρ if J and E are known from measurements and an estimate is made of K. However, a direct measurement is preferable and provides information which can be used to obtain K from the equation above.

A number of sources of error can cause uncertainty in ion counter measurements [8]. One important concern is the effect of operating an ion counter above the ground plane in the high electric field region found near a HVDC line. In particular, the question of what conditions must exist to allow an accurate measurement of ρ to be made must be answered. A critical parameter is the potential of the ion counter relative to the space potential around the counter. A cursory examination of the problem suggests that the space charge density determined may depend on whether ions are attracted to or are repelled from the counter. This in turn depends on the electrical potential of the counter. This question was addressed by Schwann [9] who concluded that for any electrical condition in which ions are attracted to the counter, an accurate measurement will be obtained. This is the case, for example, when the ion counter is operated above ground level, is at ground potential, and is detecting ions which are drawn to the counter. There are a limited number of experimental results available which address this problem, primarily of conductivity measurements aboard aircraft where self-charging is of concern [10, 11]. The results of these earlier experiments are not directly applicable to the present problem because of differences in geometry and measurement technique.

B. Experimental Approach

At NBS we have completed a preliminary series of experiments the results of which suggest that there are serious problems associated with making off-ground space charge density measurements. A short monopolar line was erected in the laboratory as shown in figure 11. An ion counter and electrometer which were isolated from electrical ground were located as indicated. The electrical potential of the measuring system (called the system bias in following discussions)

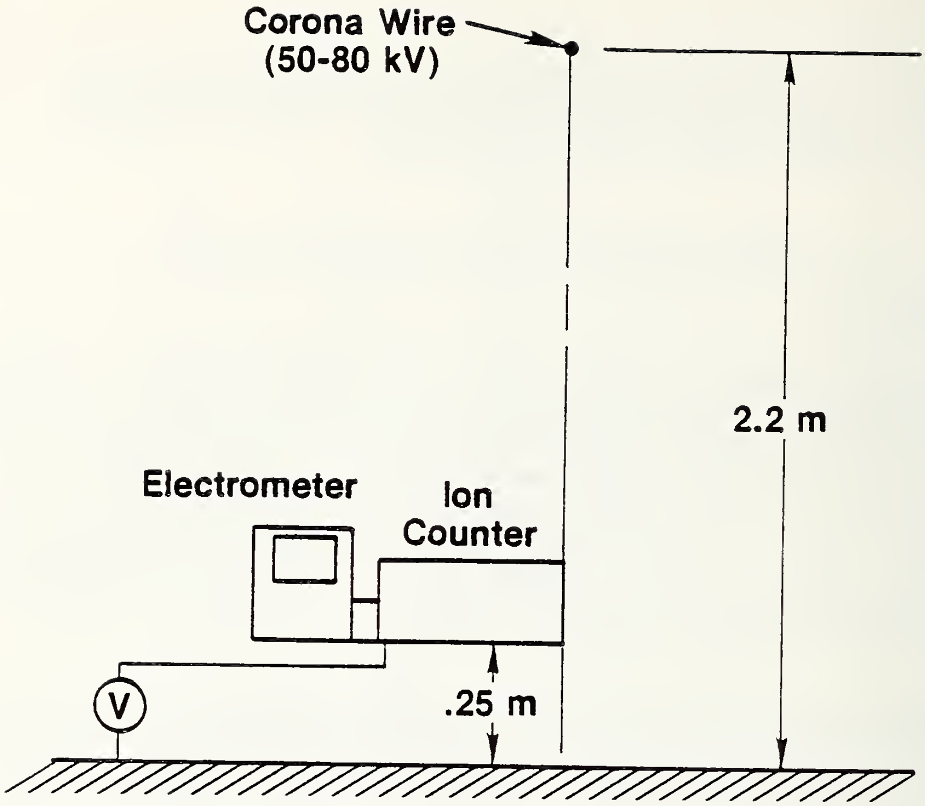


Figure 11. End view of experimental arrangement for studies of off-ground ion counter operation. Corona wire diameter was 254 μm. The electrometer and ion counter were isolated from ground. The wire length was approximately 6 m.

could be varied up to 30 kV. Measurements were made for both positive and negative line voltages of 50 and 80 kV. Two different ion counters were used, but only the results obtained with a counter in which the air flow could be varied are reported. Similar results were obtained for both counters.

The lab in which the experiment was conducted contained various other pieces of equipment. As a result, it would not be expected that the electrical conditions under the line would be uniform along the line. All measurements reported were taken with fixed geometry. The room temperature was 25 °C and relative humidity 40%. Total uncertainty in flow and current measurements is estimated to be less than 10% except for the 3.3×10^{-3} m^3/s flow condition, which is slightly outside the flowmeter calibration range. Since these were preliminary measurements, no attempt was made to improve measurement accuracy. The ion counter polarizing voltage was 218 V which assured that all small ions entering the counter would be collected for all flow conditions.

C. Results

For a given line operating condition and ion counter flow rate, the counter bias was varied over the range ±15 kV, a range which included the space potential near the ion counter. The results of one series of measurements is shown in figure 12, which is a plot of space charge density as a function of bias voltage for different counter flow rates. What is shown is a strong dependence on bias voltage and lack of consistency among different flow rate measurements.

The cause of the discrepancies among these measurements was found to be field penetration into the opening of the ion counter. This field penetration resulted in a conduction current to the collector plates for conditions with no air flow and no polarizing voltage on the counter. This current is shown in figure 13 as a function of bias voltage. The current goes to zero at a voltage of 11 kV, which is near the space potential measured using a radioactive source and an electrostatic voltmeter [12]. This conductive current was considered as a systematic error and was subtracted from the current obtained under normal operating conditions.

In figure 14, the corrected results are shown for three different flow rates. The agreement between the two high flow rates is excellent, while the difference between these two and the third may be due to an error in flow measurement mentioned earlier.

D. Discussion and Conclusions

The results show that for bias conditions where ions are strongly attracted to the counter (bias voltage 0 - +15 kV), the calculated ρ is approximately constant. However, as the bias voltage approaches the average space potential, the calculated ρ drops dramatically. This result strongly suggests that the actual value of ρ is unknown.

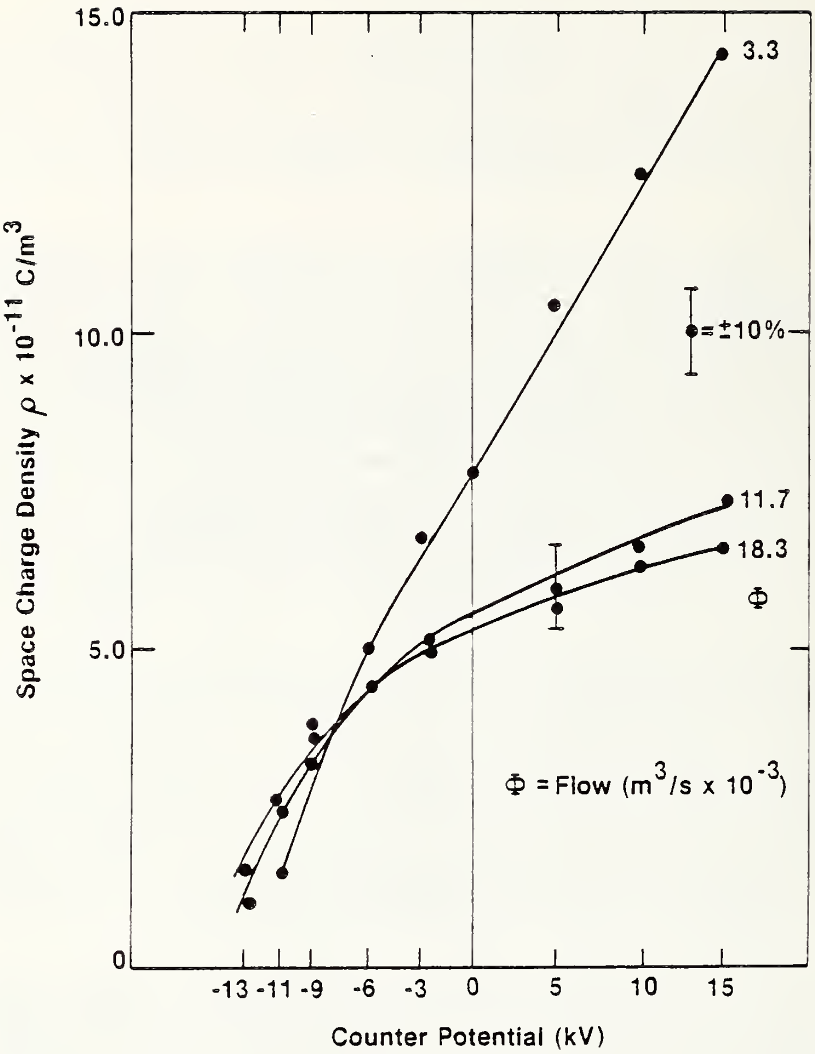


Figure 12. Space charge density determined for different flow rates as a function of ion counter potential. Corona wire was operated at -80 kV. No corrections were applied to data (see text).

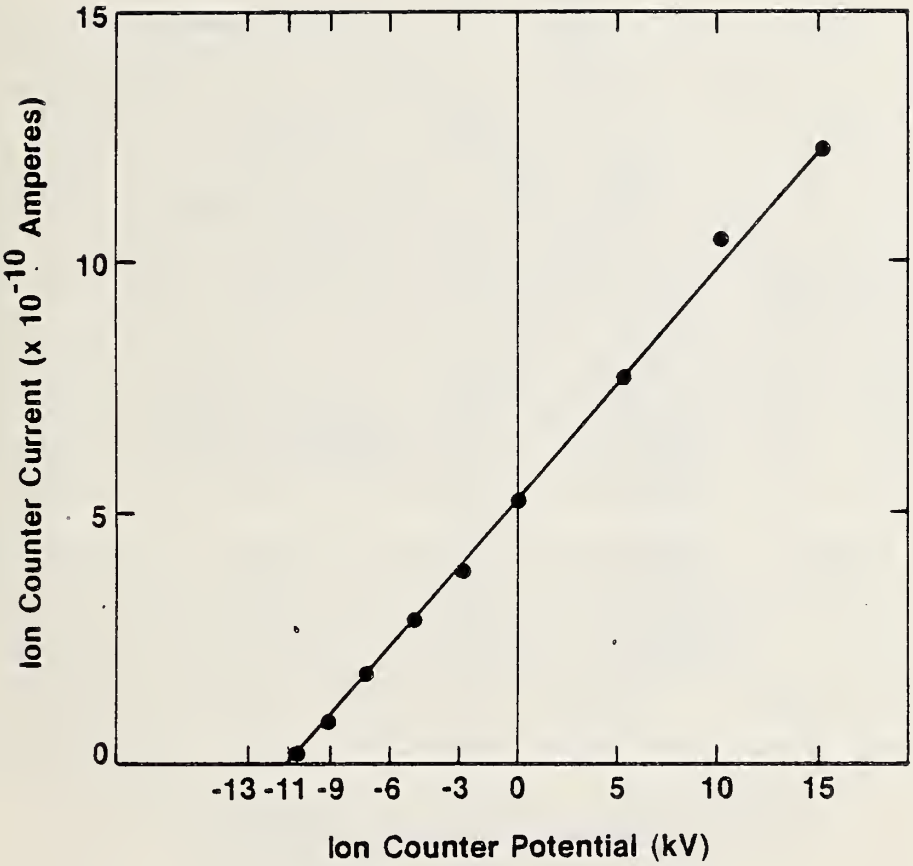


Figure 13. Conduction current to ion counter as function of ion counter potential. Polarizing plates were grounded and air flow through counter was zero. Corona wire was at -80 kV.

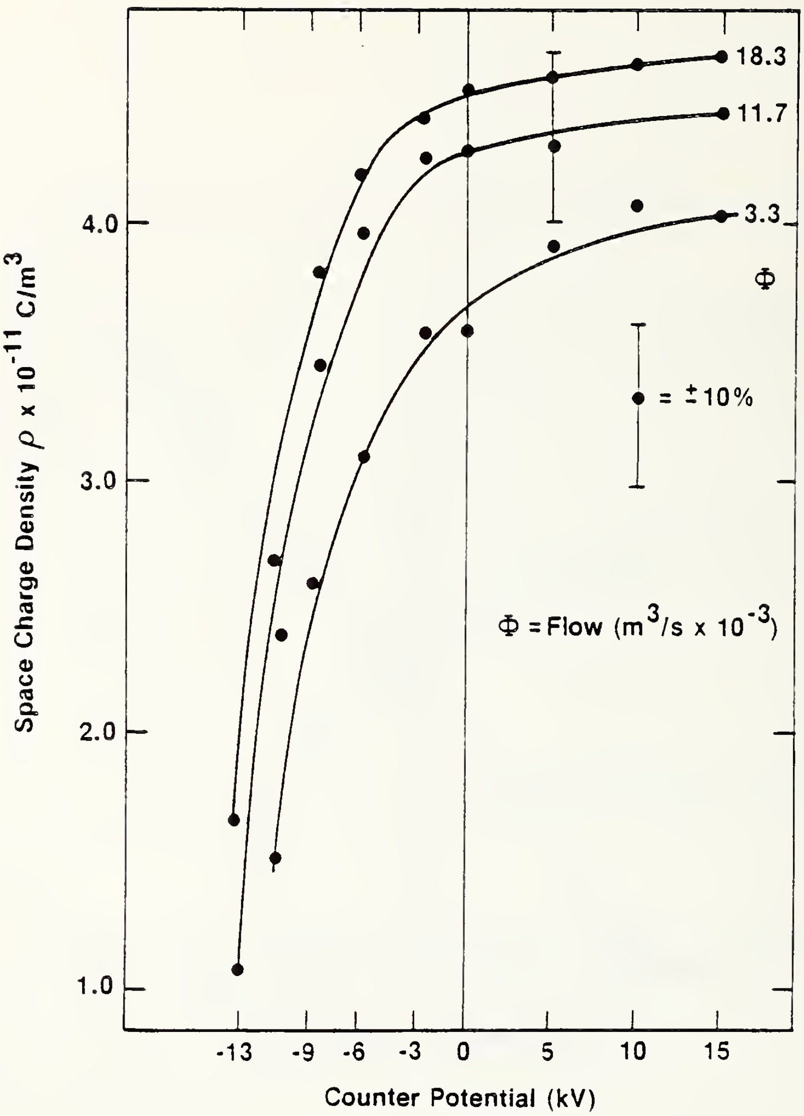


Figure 14. Space charge density determined for different flow rates and ion counter potential. These results are those of Figure 12 corrected for leakage current (see text and fig. 13).

Earlier authors [9-11] infer that the flat region is one where there is a reliable measurement. This conclusion is not substantiated by the present measurements, since the counter at space potential should represent a minimum perturbation to the system. It would be expected that for this condition an accurate measurement of ρ would result.

One possible explanation for this observation is that for the large electric fields at the counter (approximately 30 kV/m) electrical forces dominate and when ions are not attracted directly to the counter inlet, the aerodynamic forces are too small to cause ion flow into the counter. Inlet air speeds are 0.5 - 1.5 m/s just inside the inlet, while at 30 kV/m an ion with a mobility of $1 \times 10^{-4} m^2/V \cdot s$ will have a speed due to electrical forces of 3 m/s. Clearly the net flow near the inlet is complicated and will depend on the orientation of the counter opening relative to the local field direction as well as the flow rate into the counter. In the aircraft measurements cited previously [10,11], fields as high as 50 kV/m near the conductivity device inlet were observed, but these were for situations where ions were attracted to the aircraft. When the aircraft was not charged, there was no electric field near the inlet of the Gerdien tube. These experimental conditions are not analogous to the present situation.

As a result of these preliminary measurements, an unavoidable conclusion is that accurate off-ground measurements of space charge densities cannot be made until there is a more complete understanding of the effect of ion counter bias on the measurement. In particular, it may be undesirable to operate an ion counter at space potential rather than in a grounded condition. A number of relevant experiments have been considered and will be part of any future work in this area.

7. MEASUREMENT OF NET SPACE CHARGE DENSITY USING AIR FILTRATION METHODS

A. Introduction

The use of air filtration techniques to measure net space charge is more than 80 years old [13]. Various filter materials have been used, but the most efficient filters are known as high efficiency particulate air (HEPA) filters. These filters, which have very high efficiencies for removing small particles from an air stream, have also been shown to be very efficient at removing charge from an air stream [14-16]. A series of measurements has been completed at NBS which indicate a HEPA filter transmits less than 0.1% of the incident charge for a wide range of charge densities and flow rates.

B. Approach

In the filtration method, an air stream containing ions is drawn through a filter. As indicated above, HEPA filters remove more than 99.9 % of the ions from the air stream. The resultant current I to ground from the electrically isolated filter can be measured. By knowing the volumetric flow rate ϕ the net space charge density ρ

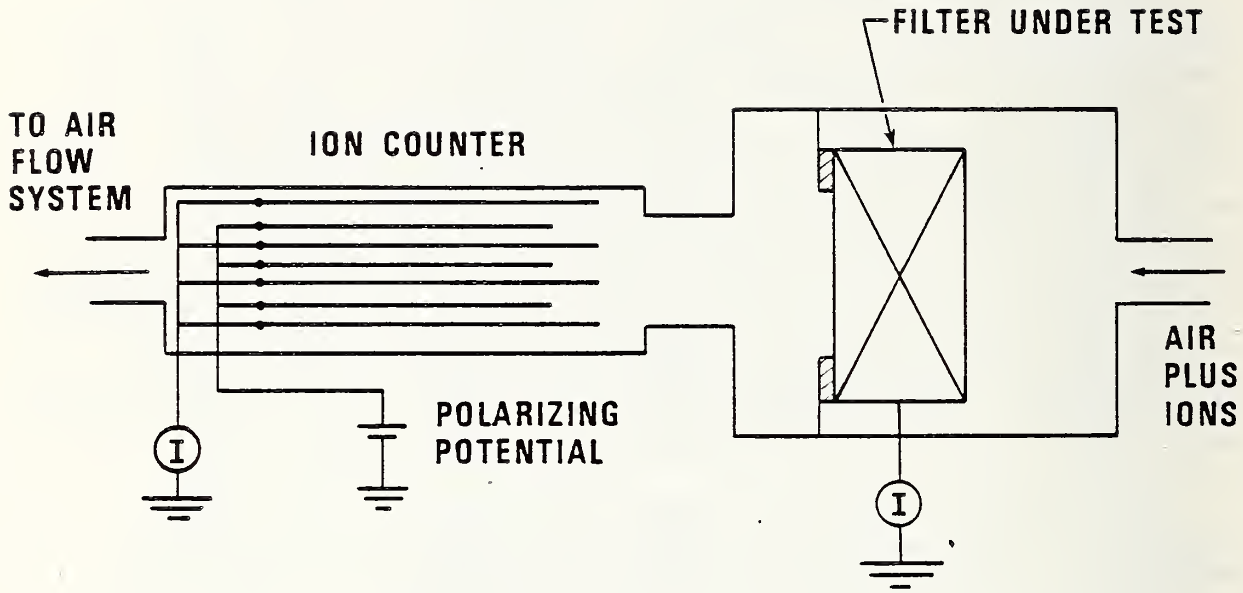


Figure 15. Experimental configuration for measurements in which the ion counter is used to measure transmitted charge density.

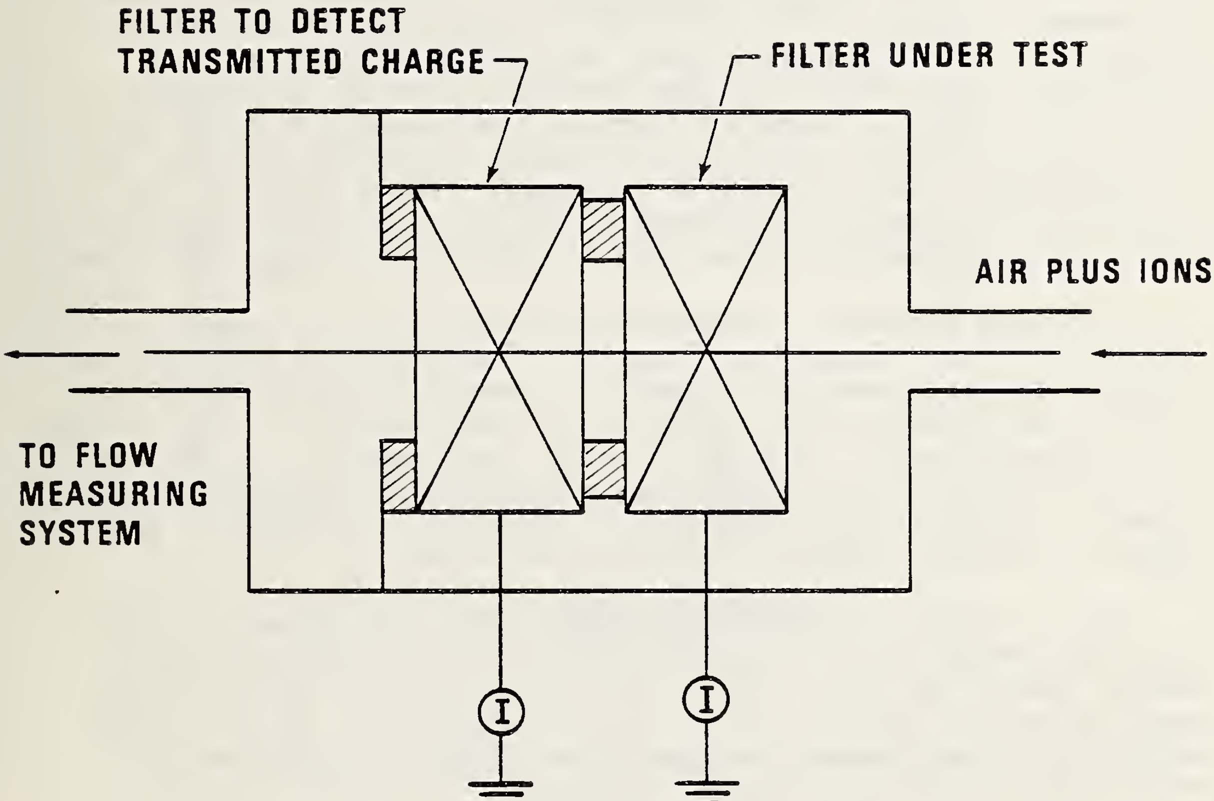


Figure 16. Experimental configuration for measurements in which a filter is used to measure transmitted charge density.

can be calculated from $\rho = I/\phi$. The measurements described below were designed to measure the fraction of charge transmitted through the filter as a function of various experimental variables.

These studies were made using the low speed air flow facility described in section 4. The two experimental configurations used in the measurements are shown in figures 15 and 16. In each case, the filter under test was followed by a device to detect the transmitted space charge. This second device was either a second filter or an ion counter. The use of two different measurement techniques allowed a check for any possible systematic errors. The measurement process was somewhat circular. The first set of measurements involved the ion counter as a detector and these measurements showed that substantially less than 1% of the incident charge was transmitted by the HEPA filter. The HEPA filter was then used as a detecting filter to measure the transmission of other (non-HEPA) filters. One of these other filters was found to transmit less than 10% of the incident charge for the conditions of interest. This filter was then used as a detecting filter and the HEPA transmission remeasured.

Ions were extracted from the test volume of the low speed air flow facility as indicated in figure 2. The volumetric flow rate was measured using a commercial flowmeter. Measurements were made for positive and negative ions together, for conditions where ions of only one sign were present. A related set of measurements involved the use of an alpha particle source located near the inlet to the filter assembly. In this mode of operation large numbers of positive and negative ions were present in nearly equal numbers.

The ion counter was operated with a polarizing potential which was large enough to ensure collection of all ions with mobilities greater than 0.005×10^{-4} $m^2/V{\cdot}s$ for all flow conditions. No means were available to measure the mobility spectrum $\rho(K)$, but I-V curves made with the ion counter indicated more that 90% of the ions had mobilities greater than 0.5×10^{-4} $m^2/V{\cdot}s$.

C. Results

The results of measurements on the HEPA filter are summarized in figure 17. It is clear that for all data presented the transmission is substantially less than 0.1%. The cause of the differences between the transmissions measured using the ion counter and filter as a detector is unknown, but may be due to mobility dependent response of the filters and the ion counter.

D. Discussion and Conclusions

The HEPA filter has been shown to be highly efficient at removing charge from an air stream. This implies that for conditions where space charge is predominately made up of ions of one polarity, a direct comparison can be made between the net space charge density determined by a filter and the polar space charge density measured by an ion counter. By using a source of space charge such as that

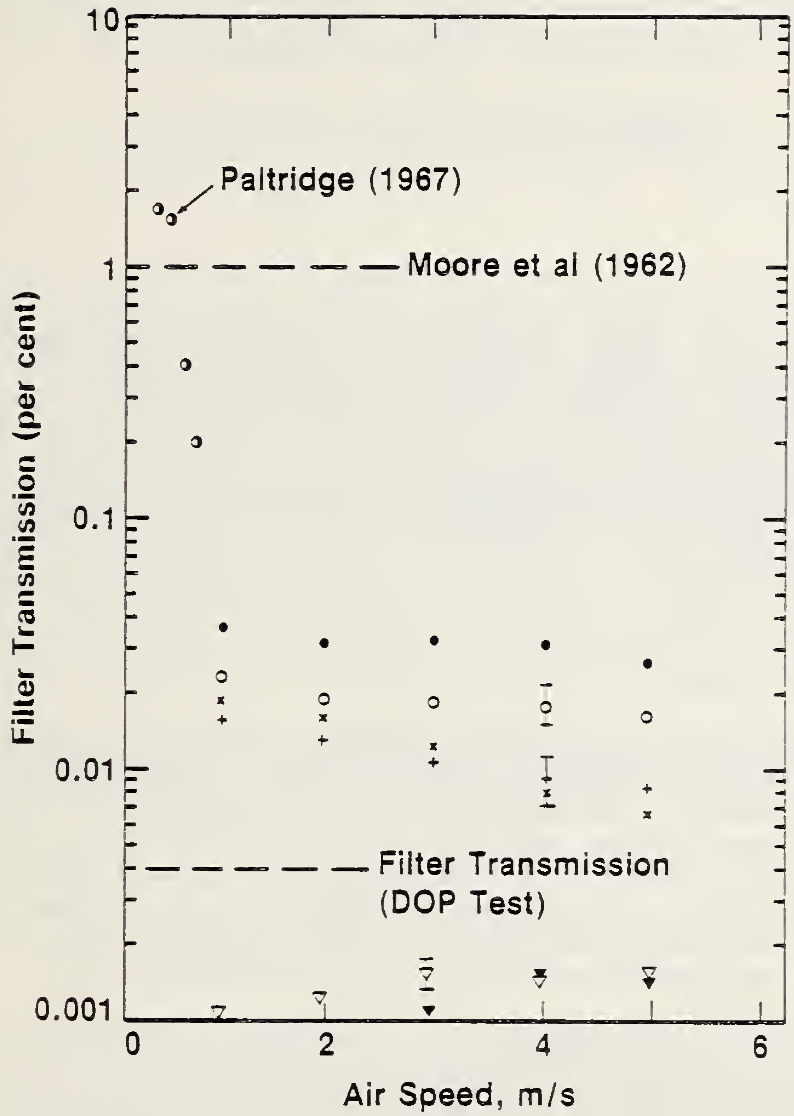


Figure 17. Summary of HEPA filter transmission measurements. Shown for comparison are the results of Moore et al. Paltridge and the factory measured transmission (DOP test). Filter-filter measurements--• - positive ions, o - negative ions. Filter-ion counter measurements--+ - positive ions, x - negative ions. Filter-ion counter measurements (alpha source)--▼ - positive ions, ▽ - negative ions.

produced by the low speed air flow facility, the HEPA filter can be used to calibrate ion counters. This can be done by directly comparing measurements of net space charge density made using the two instruments when ions of only one sign are present. Other sources of error, such as ion losses in ducting, would also have to be determined.

8. MEASUREMENTS OF MOBILITY SPECTRUM USING RETARDING FIELD METHOD

A. Introduction

The ions making up a given space charge ρ have a distribution of mobility values $\rho(K)$. These mobilities reflect the different ion species present in the space charge and are determined by the "age" of the ions, the gas mixture of which the ions are a part, etc. Techniques for measuring $\rho(K)$ for small ions using classical air flow methods are described in the literature [17,18] and extensively analyzed in the monograph by Tammet [8]. Similar measurements of the mobility of charged aerosols are used to infer a size distribution. Mobility measurements are of interest in that they provide information about a collection of ions. There is, however, no way of extracting direct information about the identification of ionic species from mobility data and so the most useful studies of ions involve mobility measurements combined with mass spectrometric identification of ions.

Knowledge of $\rho(K)$ is useful and necessary if there is to be a complete understanding of devices used to measure space charge densities. For example, the response of an ion counter to a space charge sample depends on the mobility spectrum of the space charge. This may also be the case for certain filtration methods used to measure net space charge. As a result, consideration has been given to different approaches to measuring the mobility spectrum of ions produced in the low speed air flow facility discussed earlier.

Classical methods developed by atmospheric electricity scientists involve the use of cylindrical Gerdien tubes with either a continuous or divided geometry [18]. In each case, an I-V curve is generated for the device under constant flow conditions. Numerical derivatives are required to obtain $\rho(K)$ from the I-V curve; two for the continuous Gerdien tube and one for the divided Gerdien tube. This in itself presents difficulties but a more fundamental problem is caused by the presence of the space charge inside the instrument. The self-field due to the space charge sufficiently modifies the applied field so that the simple electrostatic analysis ignoring space charge is inappropriate. As a result of this, an alternative approach was taken which was particularly appropriate for the air flow system, but which is also susceptible to space charge effects. Only differential measuring techniques appear to be relatively immune to space charge effects.

B. Approach

A retarding field technique similar to that used in measurements of electron energies was adopted. The approach is illustrated in figure 18(a). The ions are carried downstream in the flow facility at constant speed by the air stream. They pass through a grounded screen and enter a uniform field region. By applying an adjustable voltage (V) to the center screen, the fraction of the ions to be prevented from passing through the retarding field region can be varied.

In the region between the plates, the net speed will be $v - kE$, where v is the air speed, k the ion mobility and E the electric field. Only ions with $kE<v$ will pass through the screen. The limiting mobility is

$$k_0 = V/E.$$

This is a simplified discussion which ignores such effects as field penetration through the screens, turbulence, diffusion space charge influence, etc. These ions which do pass through the filter are detected downstream with a HEPA filter assembly (fig. 2).

This technique can be analyzed mathematically as shown below. Assume a distribution of space charge density $\rho(K)$ where

$$\int_0^\infty \rho(k)dk = \rho_0,$$

where ρ_0 is the total space charge density. If the ions are passed through some region which has a filter characterisitic $G(k)$, then only some fraction ρ_1 of ρ_0 will be transmitted,

$$\rho_1(k_0) = \frac{1}{\rho_0} \int_0^\infty G(k,k_0)\rho(k)dk.$$

In the following discussion, ρ_0 is assumed to be equal to 1.

If we have a retarding field analyzer, the idealized form of $G(k,k_0)$ is shown in figure 18(b). With this form of G, all ions with $k<k_0$ will pass through the filter where $k_0 = v/E$, v = air speed and E is the opposing electric field. The electric field is calculated from $E = V/d$, where V is the potential of the retarding screen and d is the screen-to-screen spacing.

For this form of G, ρ_1 can be calculated as

$$\rho_1 = \int_0^\infty G(k,k_0)\rho(k)dk = \int_0^{k_0} \rho(k)dk.$$

Then, taking the derivative of ρ gives $d\rho_1/dk_0 = \rho\ (ko)$. A change of variable is required to relate the raw data to the relationships above, since what is required is a derivative with respect to V, the retarding voltage. Using the following relationship,

$$k_0 = v/E = v/(V/d) = vd/V$$

we can write $dk_0 = -(vd)/V^2 \, dV$

and finally obtain

$$d\rho/dK_0 = (-V^2/vd) \, d\rho/dV \, .$$

C. Results

Examples of data obtained using this technique are shown in figure 19. Although the curves appear smooth, there is uncertainty in each point and the curves are not very reproducible. Using these data and calculating a numerical derivative, values for $\rho(k)$ can be determined. The results of two different measurements for negative ions taken on different days are shown in figure 20. The variations introduced by the numerical derivatives are obvious, as is a large high mobility tail which appears to be an artifact of the measurement technique, possibly due to space charge effects.

In figure 21 are shown mobility spectra for positive and negative ions taken on different days, but with the same flow and electrical conditions (except for polarity).

Some attempts were made to use various smoothing techniques to improve the spectra obtained. Although some "peaks" disappeared, the overall results were not satisfying. Better raw data are required if the technique is to prove satisfactory.

D. Discussion and Conclusion

During this preliminary work, it became clear that computer-aided data acquisition would be necessary. This would allow a series of scans through the retarding voltage which would result in significant averaging. This procedure would certainly improve the raw data and smooth the numerical derivative. A more serious problem appears to be one alluded to earlier in the discussion of the use of Gerdien tubes - namely, the perturbation of the applied field by the space charge. A recent paper considers this phenomena in a discussion of electron energy measurements using retarding field methods [19].

It appears likely that reliable measurements of $\rho(k)$ for ion densities $10^5/cm^3$ or greater may have to be done using differential instruments, where the space charge inside the device is limited. Such devices are described in the literature [20]. An air blast

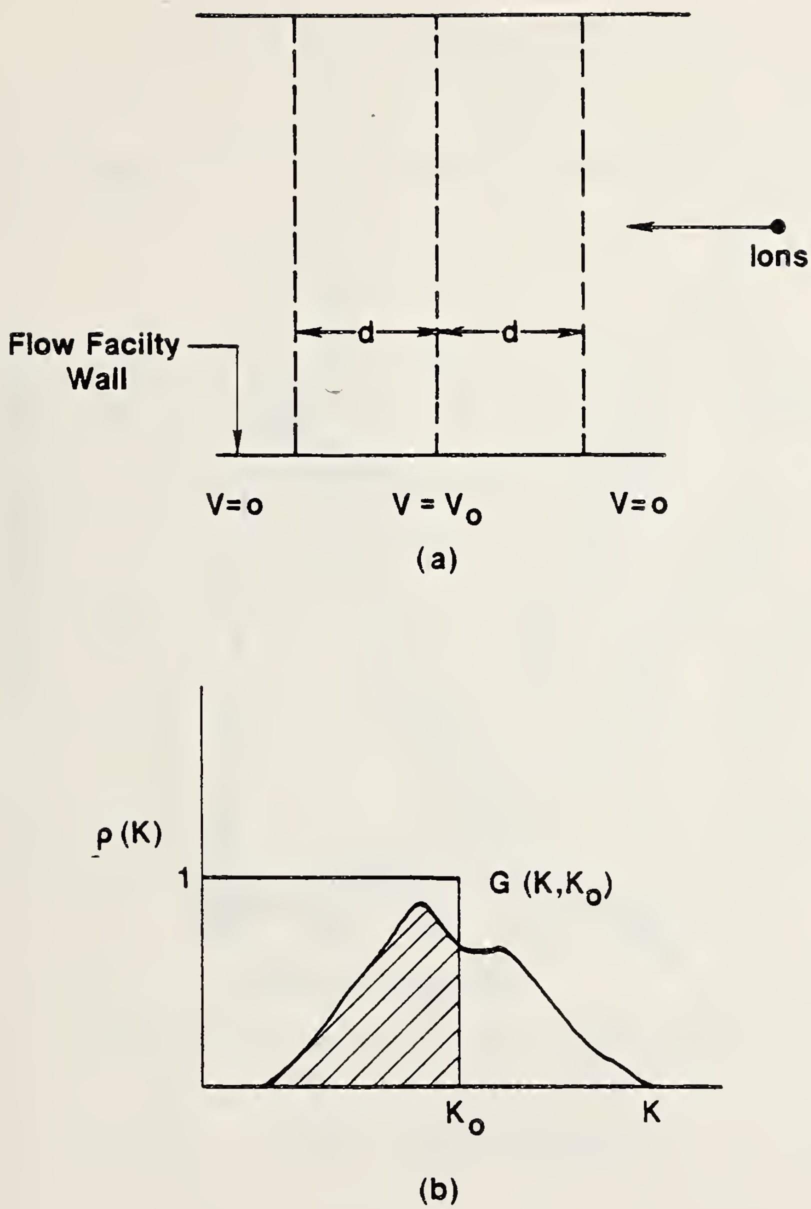


Figure 18. (a) Schematic of retarding field analyzer. The actual assembly was located near III in fig. 2. Screen material was aluminum window screen. (b) Representation of transmission function $G(k,k_o)$ for retarding field analyzer. Shaded portion of $\rho(k)$ would be transmitted.

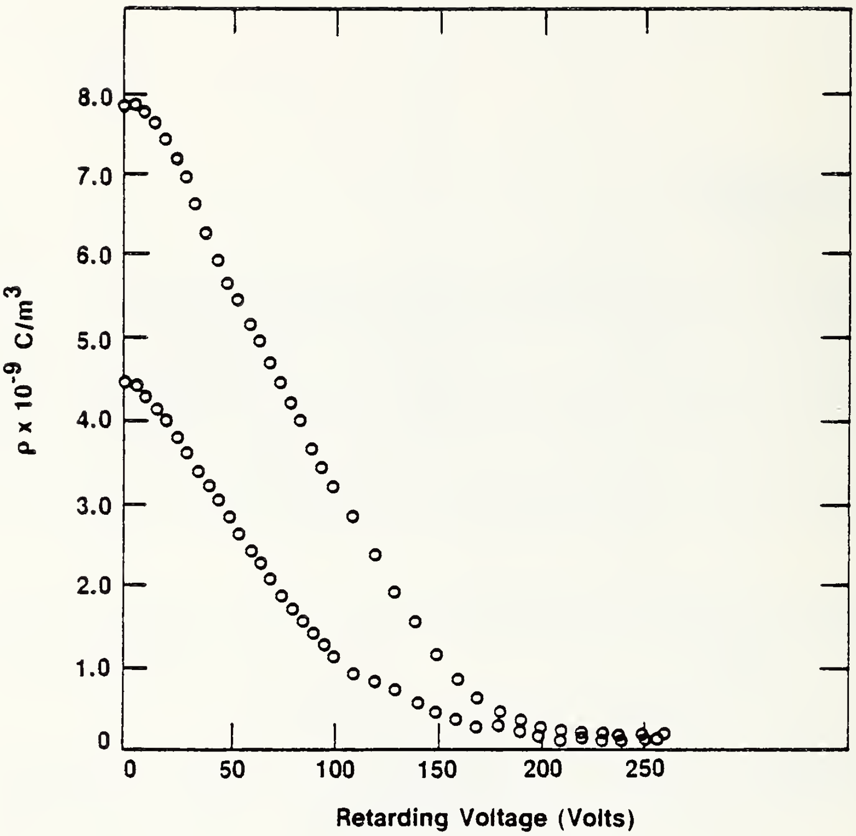


Figure 19. Space charge density detected downstream from analyzer (fig. 18). Shown are results for both positive and negative ions.

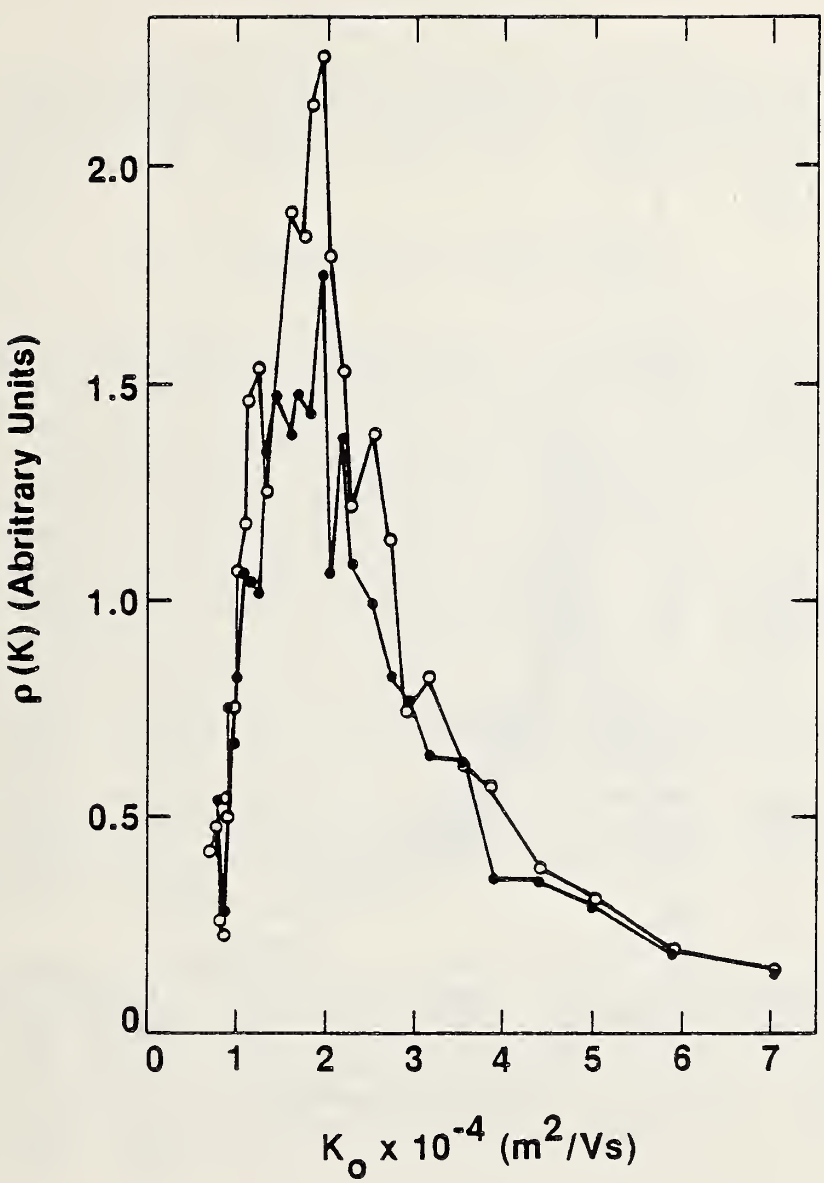


Figure 20. Mobility distribution ρ(k) for negative ions taken on two different days. Results shown are obtained from raw data as described in the text. No smoothing techniques were employed.

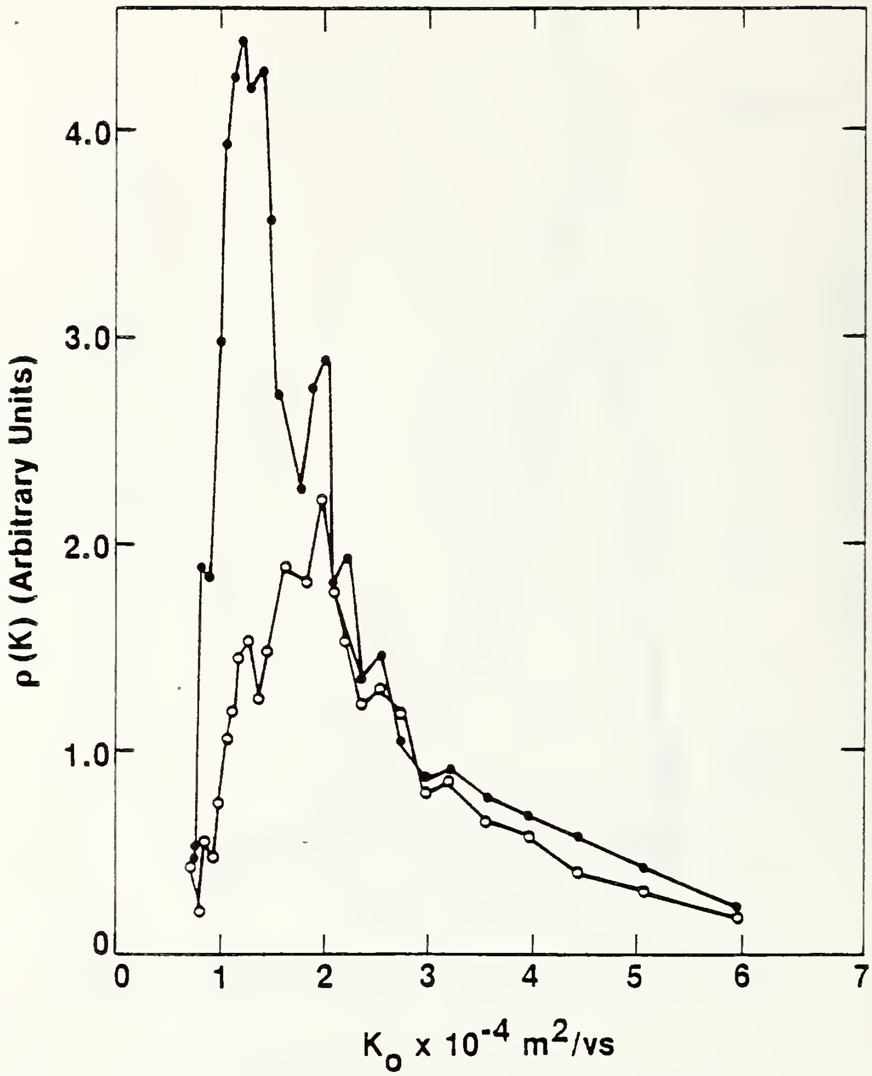


Figure 21. A comparison of mobility distribution for positive and negative ions taken on different days, but for similar flow and electrical conditions. Data are unsmoothed.

system has been adopted for use at Project UHV and used to measure mobility spectra for different sources [21]. This measurement problem, in the present context, remains unsolved and will require considerable future effort.

9. DISCUSSIONS AND CONCLUSIONS

The individual efforts described in this report show continuing progress toward the goals of the project. Completion of the investigation of errors associated with above-ground operation of sensors for measuring vertical current density has provided guidelines for substantially improving the accuracy of these measurements. Considerable effort has been expended in studying errors associated with measurements of net space charge and ion density. Part of this effort has been the construction and evaluation of a facility to produce a test volume containing space charge. The use of this facility in investigating air filtration methods for the measurement of net space charge density has led to a potentially useful scheme for calibrating ion counters. If the space charge is made up of ions of predominately one polarity, then ion density and net space charge density are equivalent. In this case, a measurement of net space charge density can be made using a filtration method and can be directly compared with that made using an ion counter. The uncertainties in this procedure are associated with the filtration method and are known or can be estimated.

Two sources of error directly associated with the operation of ion counters have also been investigated. The study concerned with losses at the counter outlet due to fringing fields has been completed. The second and more severe problem is associated with operation of an ion counter above the ground plane. The work discussed in this report has shown clearly that these off-ground measurements are affected by the ion counter potential.

In the future, further investigations of the electrical environment around a HVDC transmission line will require mobility measurements and an identification of ionic species present near the ground. Knowledge of the mobility spectrum of ions is also required in the laboratory when evaluating ion counter performance. A preliminary evaluation of a retarding field method for measuring the mobility spectrum of ions in the low speed air flow facility has been described. This method is specialized and is not of general usefulness. An increase in emphasis on ion identification and mobility measurements is considered essential to an increased understanding of the complex electrical environment near a HVDC transmission line and should form an important part of any laboratory effort in this area.

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10. SUPPLEMENTARY NOTES

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11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

The NBS program is concerned with developing methods for evaluating and calibrating instrumentation for use in measuring the electric field and various ion-related electrical quantities in the vicinity of high voltage direct current (HVDC) transmission lines and in apparatus designed to simulate the transmission line environment.

The laboratory investigation of errors associated with above-ground operation of sensors for measuring vertical current density has been completed. Significant errors were observed for both unguarded and guarded sensors, ranging from 4 to 25% for the guarded plates and 10 to 35% for unguarded plates for a wide range of geometrical parameters. Preliminary results from a field day held in October 1981 are in agreement with the laboratory results.

A new low-speed air-flow facility has been constructed. Using multiwire planar corona discharge ion sources, ion densities from $1.6 \times 10^5/cm^3$ to $1.4 \times 10^6/cm^3$ have been measured using an absolute filter technique.

Losses at the inlet of a parallel plate ion counter due to fringing fields have been determined using an ion counter with variable geometry. Calculations based on a two-dimensional finite element code predict a greater loss than actually observed, but are in qualitative agreement with experimental results.

The above-ground operation of a parallel plate has been investigated using a monopolar line. The initial results obtained show that the ion densities measured using the counter are strongly dependent on ion counter potential. These results represent only a limited set of measurements, but indicate problems associated with above-ground measurements of ion density.

The transmission of charge in an air stream through a high efficiency particulate air (HEPA) filter has been determined to be less than 0.1% for a wide range of flow and ion density conditions. This result indicates that a HEPA filter may be useful in calibrating ion counters when the net space charge density and ion density are equivalent.

A retarding field scheme has been considered for use in measuring the mobility spectrum of the ions in the low-speed air flow facility. The results of a limited number of measurements show that the method may be a useful one for this application but that a number of problems need further investigation, including the effects of space charge.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

current density measurements; high efficiency particulate air filter; high voltage dc transmission lines; ion counter; ion density; net space charge density.

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