Charging and Transport of Aerosols near AC Transmission Lines: A Literature Review

Technical Report

Charging and Transport of Aerosols near AC Transmission Lines: A Literature Review

1008148

Interim Report, December 2003

Cosponsor
National Grid Transco Plc.
1-3 Strand, London WC2N 5EH
England

Project Manager
D. Renew

EPRI Project Manager
R. Kavet

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Exponent

ORDERING INFORMATION

Requests for copies of this report should be directed to EPRI Orders and Conferences, 1355 Willow Way, Suite 278, Concord, CA 94520, (800) 313-3774, press 2 or internally x5379, (925) 609-9169, (925) 609-1310 (fax).

CITATIONS

This report was prepared by

Exponent
420 Lexington Avenue Suite 408,
New York, NY 10170

21 Strathmore Road
Natick, MA 01760

Principal Investigator
W. Bailey
G.B. Johnson

T. Dan Bracken, Inc.
PO Box 82695
Portland, OR 97282

Principal Investigator
T. D. Bracken

This report describes research sponsored by EPRI and National Grid Transco Plc.

The report is a corporate document that should be cited in the literature in the following manner:

Charging and Transport of Aerosols near AC Transmission Lines: A Literature Review, EPRI, Palo Alto, CA, and National Grid Transco Plc., London, England: 2003. 1008148.

REPORT SUMMARY

It has been hypothesized that the charging of airborne pollutant particles by alternating current (AC) transmission lines results in enhanced deposition and retention of these particles in the respiratory tract. This report provides an overview of the effect of AC transmission line corona on ion formation and the transfer of charge to aerosols. A literature review identified gaps in the information required to model the charging of aerosols by AC transmission lines and their dispersal downwind, so that exposures predicted by hypothesis can be quantitatively evaluated.

Background

Concerns have recently been raised that alterations in the electrical environment by high-voltage AC transmission lines may potentially impact health by increasing exposure to inhaled pollutants. The hypothesis is that high-voltage lines produce corona around the conductors. The corona process generates small air ions, and a fraction of these small air ions attach to aerosols near the conductors or escape the region around the conductors. Those that are carried downwind also attach to aerosols. The aerosols have longer resident times in the atmosphere than ions. This allows the charged aerosols to be carried beyond the immediate vicinity of the transmission line by the wind. Researchers also postulated that increased charge on fine aerosol particles could increase their deposition in the lungs if inhaled. The hypothesis that describes the above chain of events represents a series of assumptions, each of which requires confirmation. Certain portions of this chain of events have been studied and discussed in the literature (such as AC line corona, ion-to-aerosol charging, and drift of space charge in the atmosphere). However, all of these have not been quantitatively linked together to produce a complete picture of the hypothesis leading from AC line corona to increased deposition of pollutant aerosols in the lungs. EPRI and National Grid Transco PLC cosponsored this literature review to provide as complete a picture as possible concerning the early stages of this chain of events occurring in the atmosphere.

Objective

To perform a literature review relevant to AC corona charging of aerosols and the potential for increased concentrations of charged aerosols downwind of AC transmission lines.

Approach

Investigators reviewed literature sources—including technical papers, journal articles, and reports—for their relevance to mechanisms of aerosol charging by AC transmission line corona and to migration of charged aerosols away from such sources.

Results

This review evaluated detailed information on the creation and fate of ions, and ion-to-aerosol charging and discharging due to AC corona. While information on the transport and expansion of space charge—and the resulting ground-level-charged aerosol level downwind of AC transmission lines—is limited, important characteristics of these processes were described by reference to more extensive measurements and modeling reported for DC transmission lines. This report provides an explanation for variability in the polarity of electric fields and space charge downwind of AC lines.

The results of studies of DC transmission lines can be considered as extreme limiting cases for the analysis of AC transmission lines. The literature suggests that it will be difficult to achieve sustained levels of space charge associated with electric fields greater than 10 kV/m because of opposite polarity space charge produced by corona on vegetation at ground level. The older studies of DC electric fields measured near lower voltage AC transmission lines point to the need to consider insulators and hardware as a possible source of corona-generated space charge. Peter Fews, et al., in *Atmospheric Research* made the assumption that space charge from transmission lines would not rise above the height of the conductors. Measurements of the vertical dispersion of space charge from DC sources indicate that Fews' assumption may not describe typical conditions and, in fact, leads to overestimation of space charge values at ground level. No information is available on how AC transmission-line corona affects the distribution of charge on aerosols of different sizes, which would affect the respiratory tract exposure of populations downwind of AC transmission lines.

EPRI Perspective

This review provides a better understanding of the physical processes involved in the formation of space charge downwind of AC transmission lines. The existing literature has focused largely on DC sources, and the review indicates how analyses of data on these sources can be used to estimate exposures near AC transmission lines. The insights from this review will provide a basis for modeling the creation and transfer of charge to aerosols near AC transmission lines. Such modeling, together with measurements of the distribution of charges on aerosols by size, are needed to quantitatively evaluate the exposures. In addition, the review has identified several assumptions about the dispersion of charged aerosols that may lead to overestimates of charge densities downwind. Information on dispersion of charged aerosols in this review underscores the need to directly measure the charge on aerosols instead of drawing inferences from indirect estimates based on measurements of DC electric fields at ground level.

Keywords

Aerosols
Corona
Ion
Space Charge
Health Effects

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1
INTRODUCTION

The earth has an electrical environment that consists of a vertical electric field, also known as its potential gradient, and space charge consisting of small air ions and larger charged aerosols. Concerns have recently been raised that alterations in the electrical environment by high voltage alternating current (AC) transmission lines may potentially have health impacts by increasing exposure to inhaled pollutants [1, 2, 3].

The hypothesis is that high voltage lines produce corona around the conductors. The corona process is a source of small air ions and a fraction of these small air ions escape the region around the conductors. They are then carried downwind where they attach to aerosols that have longer resident times in the atmosphere than ions. This allows the charged aerosols to be carried beyond the immediate vicinity of the transmission line by the wind. A fraction of the ambient aerosols could consist of pollutants such as automobile exhaust, smoke stack emissions, and biogenic materials. It is then also postulated that the change in charge on fine aerosol particles could increase their deposition in the lung if inhaled.

The hypothesis that describes the above chain of events represents a series of assumptions, each of which requires confirmation. Certain portions of this chain of events have been studied and discussed in the literature (such as AC line corona, ion-to-aerosol charging, and drift of space charge in the atmosphere). However, all of these have not been quantitatively linked together to produce a complete picture of the hypothesis leading from AC line corona to increased deposition of pollutant aerosols in the lung.

This report identifies existing papers and reports related to AC line corona, ion creation and drift, aerosol charging, space charge drift, and ground level electric fields. Information is provided on the relative levels of key parameters such as AC conductor gradients, charge densities, particle charging, vertical dispersion, downwind drift, and ground level electric fields. Information gaps in the reported literature leading from AC transmission lines to ground level electric fields and charge densities are identified.

2
AC CORONA AND SMALL IONS

Corona on a power line occurs when the conductor surface gradient (electric field) at the surface of the conductor exceeds the breakdown potential of air. The conductor surface gradient depends on the voltage on the conductor, the radius of curvature of the conductor, and the position of the conductor in relation to the ground and other line conductors and their voltage [4].

A conceptual view of the corona process for a negative electrode is presented in Figure 2-1. Corona is generally started by the electric field accelerating free electrons through the air. Some electrons absorb sufficient energy from the electric field to cause ionization when they collide with an air molecule; that is, the collision creates a new free electron and a positive ion. The electrons multiply producing what is called a Trichel pulse due to build up of slower moving positive ions. The fast moving electrons attach to neutral air and water molecules and become negative ions. The slower positive ions near the surface of the conductor reduce the local conductor surface field often below that needed for ionization. This chokes off the negative polarity Trichel pulse until the negative electric field sweeps the positive ions into the conductor allowing the process to begin again.

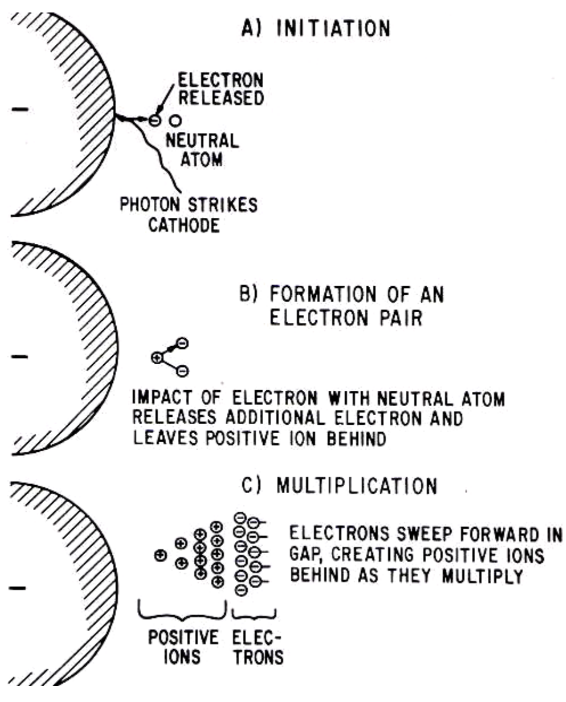

Figure 2-1
Start of Electron Avalanche from a Negative Electrode [5]

Trichel pulses are extremely fast. The pulse duration is in the 100-nanosecond range. Increasing the voltage increases the frequency of occurrence of Trichel pulses but decreases their amplitude. As the voltage is increased further, Trichel pulses give way to a pulse less glow. As the voltage is increased further, negative streamers appear.

A similar process occurs for positive polarity conductors. Corona begins with onset pulses. As the voltage is increased, onset pulses give way to a glow discharge called Hermstein's glow. Further increases in the voltage produce positive streamers.

Thus, with AC voltage, a conductor can exhibit both negative and positive corona. Figure 2-2 illustrates corona for the positive and negative half cycles of 60 hertz (Hz) voltage on a conductor.

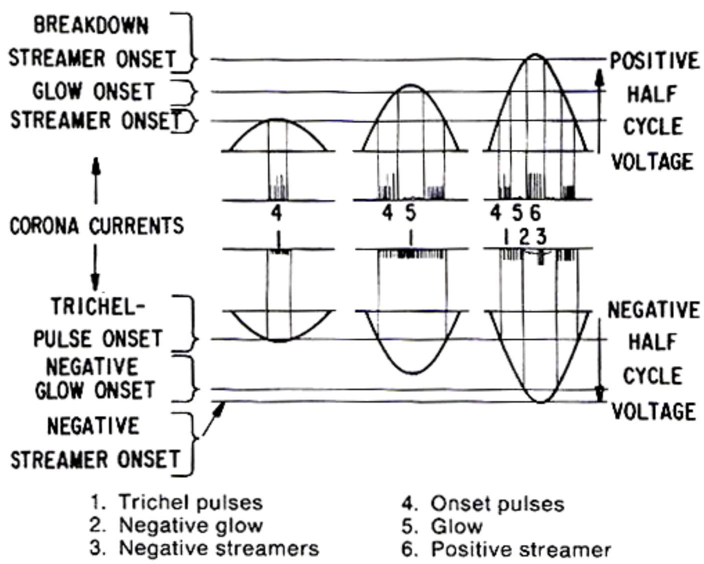

Figure 2-2
Possible Corona Modes with AC Voltage on a Conductor [5]

Onset of positive corona occurs at a slightly higher voltage than for negative corona in nitrogen, which comprises 80% of air. Therefore at low conductor surface gradients, negative corona will form in air before positive corona. At higher conductor surface gradients, beyond a critical corona onset voltage, positive corona streamers will be more extensive.

The electrical breakdown potential of air at sea level is approximately 30 kV/cm. The electric field necessary to produce corona at a conductor's surface for parallel lines can be expressed as:

$$E=30\bullet m\bullet\delta\bullet(1+0.301/\sqrt{\delta a})\ \text{kV/cm} \quad \textbf{Eq. 2-1}$$

where m is a surface roughness factor, a is the radius of the conductor in centimeters (cm), and δ is the relative air density [4]. The relative air density is given by

$$\delta = 3.92\ b/(273+T) \quad \textbf{Eq. 2-2}$$

where b is the barometric pressure in centimeters of mercury and T is the temperature in degrees Centigrade. The relative air density for standard temperature and pressure (76 cm of Hg and 25°C) is $\delta = 1$.

The electrons created during corona hydrate within a few microseconds to form negative small air ions. The positively charged air molecules also hydrate to form positive small air ions [6, 7, 8]. The velocity, v (m/S), of an ion in an electric field, E (V/m), is given by $v = \mu E$, where μ is the mobility of the ion in meters squared/volt-second ($m^2/V \bullet s$). Positive ion mobility is affected by both absolute humidity and age [9]. Negative ion mobility is affected by absolute humidity, but age has little impact due to the extremely fast hydration. Both polarities reach stable mobility within 1 to 2 seconds. The mobilities of negative small air ions are in the range of 1.7 to 2.0×10^{-4} $m^2/V \bullet s$ while the mobilities of positive small air ions are in the range of 1.0 to 1.4×10^{-4} $m^2/V \bullet s$.

During the positive half cycle of the voltage on the conductor, electrons are accelerated toward the conductor ionizing more air molecules in an ionization avalanche process while the positive ions are accelerated away from the conductor. As the conductor voltage becomes negative during the next half cycle the positive small air ions are pulled back into the conductor, any remaining negative small ions are pushed out from the conductor, and new negative ions are created when the voltage on the conductor becomes great enough. The cycle then repeats on the next half cycle, pulling negative ions back into the conductor, while pushing away positive ions. A representation of the ion current for positive and negative half cycles is presented in Figure 2-3.

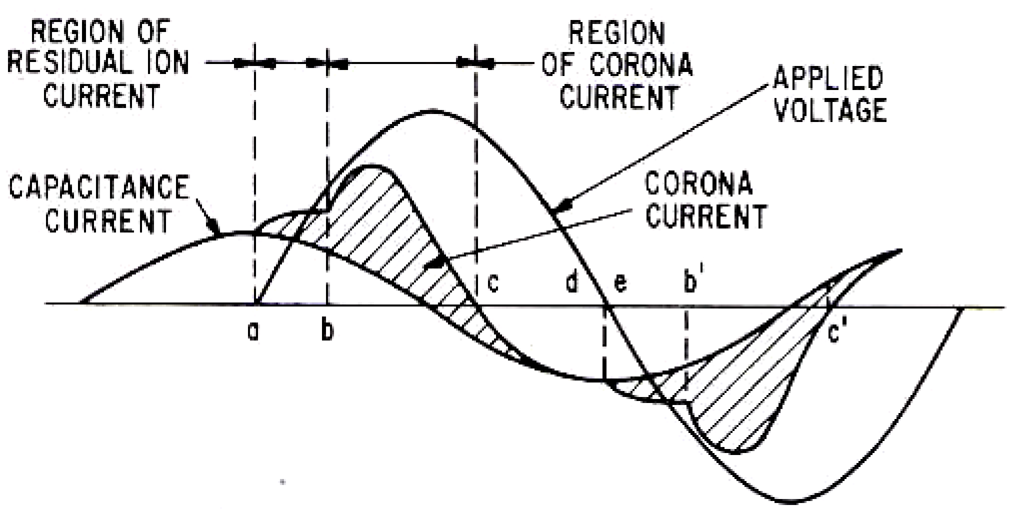

Figure 2-3
Corona Current Due to Ion Movement at Conductor [5]

Corona creates many ions near the conductor surface. However, the imbalance of ions (net ion charge) around the transmission-line conductors cannot be large in magnitude or extent since ground level AC electric fields are not noticeably affected by assumptions that AC transmission lines produce no ions and space charge [5].

The fraction of ions that escape the region of the conductors will primarily be dependent on their respective mobilities. Both polarity ions are moved by the wind. During the opposite polarity half-cycle on the conductor, the ions are pulled back into the conductor. The distance from a conductor where an ion can still be collected depends on its mobility, the electric field strength, wind, and the time with opposite polarity. The wind, electric field strength, and time are the same for ions of both polarities. Mobility is the only factor that differs for the two polarities. Lower mobility ions travel less distance during a half cycle than higher mobility ions. A greater fraction of the lower mobility ions do not make it back to the conductor for a given wind when compared to the higher mobility ions.

For conductor surface gradients in the range of 10 to 15 kV/cm or above, roughly equal numbers of positive and negative ions can be created in the region around the conductor due to debris, insects, and imperfections on the conductor surface. Corona loss for the line is the line voltage times the ion current with roughly equal corona current losses for positive and negative voltage half cycles. The fair weather corona loss can be represented by the loss from ion current flow plus losses going into processes resulting from ionization such as audible noise, radio noise, and ozone generation. The corona power loss in kilowatts (kW/m) can be written for a single conductor as

$$P\ (\text{kW/m}) = \pi D V e E \bullet (n^{+} \mu^{+} + n^{-} \mu^{-}) + \text{ionization processes} \qquad \textbf{Eq. 2-3}$$

where E is the local electric field in volts/meter (V/m), V is the line voltage to ground in kilovolts (kV), e is the charge on the electron in coulombs (C), n is the density of positive or negative ions (number/m^3), μ is the mobility of positive or negative ions in m^2/V-s, and D is the conductor diameter (m). For equal corona current to the conductor in each half cycle:

$$E \bullet n^{+} \mu^{+} = E \bullet n^{-} \mu^{-} \qquad \textbf{Eq. 2-4}$$

Thus $n^{-} = n^{+} \mu^{+}/\mu^{-}$ and the number of ions that escape the conductor is given by:

$$n_{esc} = n^{+} - n^{-} = n^{+} - n^{+} \mu^{+}/\mu^{-} = n^{+}\ (1 - \mu^{+}/\mu^{-}) \qquad \textbf{Eq. 2-5}$$

Therefore when both negative and positive corona is present we would expect an excess of positive ions to escape from the conductors.

On modern lower voltage transmission lines (<230 kV) conductor surface gradients are normally well below corona onset for both polarities. In this case, any perturbation of the field on the surface of the conductor, say caused by raindrops or condensation, could increase the gradient on the conductor above the onset for negative corona, but not positive corona. This would result in a surplus of negative charges surrounding the conductors. In this case, the charges that escape from the area around the conductor would be negative. This could explain the observation by Chalmers of negative fields under foggy misty conditions and lower voltage lines [31, 46].

AC transmission lines are designed to have a conductor surface gradient well below the corona onset threshold so they are essentially corona free in fair weather. However, small nicks in the conductor surface, debris on the conductors, insects deposited on the conductor, or rain drops deform or roughen the conductor surface allowing points on the conductor surface to exceed the onset level and corona occurs. [5, 10]

The surface roughness factor, m, in Equation 2.1 has typical fair weather values for stranded conductors of 0.80 to 0.85 [11]. For a 2.54 centimeter (cm) diameter conductor and a roughness factor of 0.8 this yields a critical corona onset gradient of approximately 30.4 kV/cm at the crest of the AC conductor voltage. Most AC transmission lines are designed to keep their peak conductor surface gradients below the 30 kV/cm (21 kV/cm rms) calculated above. Irregularities on the conductor surface due to raindrops in foul weather can lower the surface roughness factor (m) in Equation 2.2 into the range of 0.3 to 0.4.

The calculated AC conductor surface gradients of transmission lines of various voltages from throughout the United States and Europe are presented in Table 2-1. This provides a perspective on the range of conductor surface gradients that might be found for transmission lines of various voltage classes.

Whether the net ion flow away from the conductor is negative or positive depends on local conductor surface conditions and meteorological parameters. For a particular line, negative ions might predominate during periods with clean conductors while positive ions would predominate when corona was more active. However, the higher voltage lines in Table 2-1 would be more likely to generate net positive ion flow to the atmosphere, while the lower voltage lines would produce net negative ion flow.

Table 2-1
AC Transmission Line Conductor Surface Gradients by Voltage Class [12]

Voltage Class, kV	Conductor Diameter, cm	Conductors/ Phase	Surface Gradient for Each Phase, kV/cm rms		
215	1.9	2	13.21	14.20	13.21
230	2.8	1	14.80	15.48	14.80
345	4.4	1	14.59	15.42	14.59
362	4.1	1	16.10	16.99	16.10
500	4.1	2	15.99	17.01	15.99
500	3.0	3	16.47	18.08	16.47
525	4.6	2	14.92	15.95	14.92
750	3.5	4	17.33	18.59	17.33
765	3.0	4	20.14	21.63	20.14

The relative constancy of surface gradients for lines at 230 kV and above indicates that corona production levels for a single conductor do not necessarily increase with line voltage. However, the number of conductors in corona serving as sources of charge will increase as multiple-conductor bundles are introduced at the higher voltages.

The focus in the transmission-line literature to date has been on AC corona loss from the standpoint of power loss due to corona [5, 13, 14]. Fair weather corona losses on high-voltage transmission lines are many times less than foul weather corona losses. It is estimated that fair weather corona losses are 1/50 to 1/1000 of the foul weather losses and are similar or less than insulator losses [5]. Consequently, greater effort has been focused on determining the magnitude of foul weather corona loss because of its economic impact than on understanding the dynamics of ions in AC corona. There are no data available on ion densities and lifetimes in the immediate vicinity of AC transmission line conductors.

AC corona and ion-aerosol charging have been addressed but in the context of electrostatic precipitators that have high levels of ions and aerosols [15]. Although the ion-aerosol charging and discharging equations in this regime are informative they are different from the ion and aerosol densities near the conductors of overhead transmission lines.

Corona activity on high-voltage conductors is known to lead to the formation of ions. A review of the factors affecting ion formation and mobility explains why ions and charged aerosols with net positive charge should be expected under most conditions on higher voltage lines. However, a lower onset gradient for negative corona may support the production of negatively charged aerosols on lower voltage lines that are marginally in corona due to rain or condensation on the conductors. Consideration of typical AC transmission line designs for voltages above 215 kV indicates that conductor surface gradients on individual conductors remain the same as voltage is increased. However, the use of multiple conductor bundles to limit conductor surface gradients increases the volume where corona-generated ions are present and charging of aerosols can take place.

3

AEROSOL CHARGING AND DISCHARGING

Generation, movement, expansion, and decay of small air ions and aerosols have been investigated for various conditions. The simple case of unipolar ions charging and discharging monodisperse aerosols in an enclosed environment was discussed by Whitby et al. [16]. Whitby investigated the clearing time of aerosols from a room when exposed to various levels of small ions generated from a point source. He found that the mobility of aerosols generally decreased with increasing aerosol size from the smallest aerosol size that he used (0.05 microns) to 1 micron. For aerosol sizes greater than 1 micron, the aerosol mobility increased with aerosol size. Whitby found, that in closed rooms, intense point sources of small ions could produce median charge levels of 1 to 8 charges per aerosol for aerosol sizes less then 1 micron. Charge levels of 142 charges could be obtained on aerosols 3.6 microns or greater in size. Lower aerosol charge levels would be expected outdoors in an unconfined space.

Jones [17] described the creation and expansion of ion plumes from point sources. He reports observations of ion plumes and pulses 25 m downwind from an ion generator located 2.2 m above the ground. The results demonstrated how the charge and ground level field measured near a point source vary with time due to turbulence and changes in wind direction. There were relatively long periods when the plume did not pass near the ion sensor. These measurements indicated short-term temporal variability (~0.1 s) in the ion concentrations that was attributed to turbulence. These observations called into question the appropriateness of using a "Gaussian charge plume" or simple diffusion theory to describe the charged ion distributions for a point source outdoors. The observations also indicated that the electric field at ground level was much more stable than the ion concentration because the field measured at ground level is due to the entire vertical extent of the charge plume not just the local charge density.

Corona on an AC transmission line generates a bipolar small ion environment in the vicinity of each conductor as ions are created and pushed out and pulled in and collected by the alternating voltage on the conductor. The size of this region was estimated to be no more than 0.25 to 0.35 m from the conductor based on the corona onset field and small ion mobilities in the range of 1 to 2 x 10^{-4} $m^2/V{\cdot}s$ [18]. Most of the ions in this region are captured by the conductor on the opposite half-cycle or recombine with ions of the opposite polarity. However, a small fraction can be carried away from the conductor by wind and attachment to aerosols.

The attachment of small ions to aerosols occurs primarily by two mechanisms: diffusional charging and field charging. Diffusional charging is the dominant method of charging for small aerosol particles ($r<0.01$ µm) while field charging is the dominant charging method for larger aerosols ($r>0.1$ µm). Hoppel has investigated ion-to-aerosol attachment rates [19].

The ion-to-aerosol attachment process can be described in a simple bipolar environment by the spatial current density continuity equations:

$$\nabla \bullet j^+ = - \partial\rho^+/\partial t - \beta^+_o \rho^+ N_o - \beta^+_- \rho^+ N^- - \alpha n^+ n^- \qquad \textbf{Eq. 3-1}$$

for positive current density, and:

$$\nabla \bullet j^- = - \partial\rho^-/\partial t - \beta^-_o \rho^- N_o - \beta^-_+ \rho^- N^+ - \alpha n^- n^+ \qquad \textbf{Eq. 3-2}$$

for negative current density, where

α is the small ion recombination coefficient ,
β^+_o is the small positive ion to neutral aerosol attachment coefficient,
β^-_o is the small negative ion to neutral aerosol attachment coefficient,
β^+_- is the small positive ion to negative aerosol attachment coefficient,
β^-_+ is the small negative ion to positive aerosol attachment coefficient,
N_o is the neutral aerosol density,
N^+ is the positive aerosol density,
N^- is the negative aerosol density,
$n^+ = \rho^+/q$ is the positive small ion density, and
$n^- = \rho^-/q$ is the negative small ion density.

Similar continuity equations can be developed for the neutral and charged aerosols. Additional complexity can be introduced in the equations if the rates of attachment of ions to aerosols are known for various sizes of aerosols.

Since small ion charge densities dominate over charged aerosol densities in the region near transmission line conductors in corona, charging of aerosols by small ions may be simplified. Following the approach of Hoppel [20], the movement of an aerosol through the region of small ions is computed. Due to the large size (1 to 0.01 μm) and low mobility (10^{-6} to 10^{-8} $m^2/V{\bullet}s$) of aerosols, wind derived motion will play a greater roll in the aerosols motion than the electric field of the transmission line. Most of the charging and discharging of the aerosols by small air ions takes place in the region near the conductors for an AC transmission line. This yields the level of charged aerosols immediately downwind of the line. Thus, the level of charged aerosols leaving the region of the conductors serves as the source term for charged aerosols moving downwind of the line.

The charged aerosols are carried by the wind away from the transmission line. As the charged aerosols move downwind they disperse vertically due to atmospheric turbulence and to a much lesser extent due to the electrical repulsion of the predominant charge. An early attempt to consider the impact of vertical dispersion of charged aerosols was made by the Minnesota Environmental Quality Board (MEQB) in an analysis of space charge from a ±400 kV DC line [21].

One method to model the transport of charged aerosols downwind is by a Gaussian plume model that is used for atmospheric dispersion of aerosols [22]. The form of the dispersion equation for a linear source is:

$$X(x, z) = \{2q/\sqrt{2\pi}\sigma_z(x)w\}\bullet\{e^{-(z-h)^2/(2\sigma_z^2(x))} + e^{-(z+h)^2/(2\sigma_z^2(x))}\} \qquad \textbf{Eq. 3-3}$$

where X is the aerosol concentration in particles/m^3
x and z are the distances from the line source and ground, respectively,
h is the height of the source,
q is the source strength in particles/sec/m
w is the wind speed in m/s, and
$\sigma_z(x)$ is an empirical parameter based on turbulence of atmosphere.

The model does not consider reduction of the charged aerosols due to atmospheric conduction or enhanced vertical dispersion due to mutual repulsion of the charged aerosols but could give an upper bound to the charged aerosol level. This model is discussed further in the next section using transmission line corona loss current as a source to estimate charged particle distributions downwind of a transmission line.

Hoppel has calculated the ion-aerosol attachment rates (charging and discharging) for the aerosol size distribution and small ion mobilities expected in an outdoor environment [19, 23]. Generation of small air ions was assumed to arise from natural atmospheric and ground-level processes such as cosmic rays and radon decay. Small ion densities were assumed to be a few hundred ions/cm^3 and aerosol densities to be a few tens of thousands of particulates/cm^3.

Hoppel also considered ion-aerosol dynamics in the more highly charged environment of a monopolar 400 kV high voltage DC line [20]. The corona loss current for the monopolar line was 2.3 micro amps/meter. For this line, Hoppel estimated that 3 to 5% of the total corona loss current of the DC line would be transferred to aerosols in clean rural air while 8 to 12% of the total corona loss current would be transferred to aerosols in moderately polluted air. Downwind of the monopolar DC line Hoppel calculated ground level electric fields in the range of 1 to 5 kV/m for clean rural air and 3 kV/m to 14 kV/m for moderately polluted air. The charged aerosols expanded vertically as they move downwind of the line.

However, the downwind ground-level fields may be limited to levels below the predicted values. Fields at ground level above 10 kV/m are unlikely because this level is much higher than the field necessary to produce point discharge corona from ground cover [24]. Point discharges from ground cover have been reported at fields of 1.5 to 2.0 kV/m [25]. Shlanta and Moore isolated a 4 m^2 of sod covered with grass on a slightly raised portion of a meadow and found a corona current of 10^{-8} ampere/m^2 during a thunderstorm when the ground level field was approximately 10 kV/m [26]. This current corresponds to a small ion release of over 6 x 10^6 ions/cm^2/s. Thus, corona on ground cover produces ions that cancel the field due to overhead charged aerosols.

Hoppel calculated the final charge state for a distribution of aerosol sizes as part of the ion-aerosol attachment analysis. His analysis provides a worst-case scenario for an AC transmission line since opposite polarity ions that would discharge the aerosols were not included. Also, the rate of ion depletion was not taken into account. For the DC line case, the concentrations of ions close to the conductor were sufficiently large that losses of ions by various means could be neglected. However, this assumption may not hold for the AC line case where the available ions are lower in number and more limited in their physical distribution.

Hoppel extended his consideration of ion-aerosol dynamics to the case of a bipolar high voltage DC line where sources of both polarities of small air ions were present and separated by 12.2 m [27]. For this case, the ground-level field 400 m downwind was calculated to be approximately 2.4 kV/m for clean rural air and 8.7 kV/m for moderately polluted air.

The bipolar analyses, although informative, are not directly applicable to an AC high voltage line because the polarity of the DC conductors were constant in time and separated by 12.2 m. There is less opportunity for recombination at the conductors than at AC conductors where the two sources are at the same location and change polarity each half cycle. Failure to include ion depletion and aerosol discharging also limits the application of the bipolar DC case for AC conductors since the ion density levels from AC lines are expected to be less in number and exist over a much smaller region. Also aerosol discharging through attachment of an oppositely charged small air ion will be much more likely in the region near an AC line. To understand the processes governing aerosol charging downwind of AC transmission lines, it is helpful to consider these processes downwind of DC transmission lines because of the ready availability of measurements and some modeling. Measurements of the charged aerosol density downwind of a monopolar DC test line at +500 kV were made at 70 m, 150 m, and 300 m for several wind speeds up to 10 m/s [28]. The small ion density under the DC line was 140,000 to 160,000 ions/cm^2 for wind speeds from 0 m/s to 10 m/s.

At 70 m downwind of the line the small ion density had decreased significantly and was only a few 100 ions/cm^3 for calm winds (0 m/s). The small ion density at 70 m quickly increased to over 10,000 ions/cm^3 for wind speeds above 0.5 m/s and continued to increase linearly with wind speed to 10 m/s. For a wind speed of 10 m/s, the small ion density at 70 m was approximately 45,000 ions/cm^2.

The small ion density at 150 m showed an initial increase with wind speed from zero up to 2 m/s and then decreased with increasing wind speed. The small ion density peaked at approximately 9,000 ions/cm^3 for a wind speed of 2 m/s. At 10 m/s the small ion density at 150 m was approximately 5000 ions/cm^3.

The small ion density at 300 m increased from a few hundred ions/cm^3 to approximately 5000 ions/cm^3 for winds of 1.5 m/s and then decreased with increasing wind speeds to less than 1000 ions/cm^3. The decrease in charge density with higher wind speeds may indicate greater levels of turbulent diffusion in the atmosphere and increased vertical mixing of the charge density.

The charge density of aerosols was also measured at 70 m, 150 m, and 300 m. The charge density showed an increase from calm wind conditions (0 m/s wind) up to wind speeds of 1 m/s and then remained relatively flat or decreased slightly with increasing wind speed. The charged aerosol density peaked at approximately 11,000 charges/cm^3 at 70 m for 2 m/s wind speed. At 150 m the charged aerosol density peaked at approximately 4,500 charges/cm^3 for 1 m/s winds. At 300 m the charged aerosol density peaked at approximately 3,000 charges/cm^3 for 1 m/s winds. For 10 m/s winds, the charge densities were approximately 10,000 charges/cm^3, 3,500 charges/cm^3, and 1,500 charges/cm^3 at 70 m, 150 m, and 300 m, respectively.

The measured charge density at 150 m for a wind speed of 2 m/s was 4,500 charges/cm^3 compared to the predicted level of approximately 10,000 charges/cm^3. The measured level at 150 m for a wind speed of 10 m/s was 3,500 charges/cm^3 compared to a predicted value of 3,000 charges/cm^3. Although the experimental conditions summarized above differ from the monopolar model developed by Hoppel, the agreement between them is probably within the uncertainties and variability of both the measurement and modeling processes. The model overestimated space charge for a 2 m/s wind speed but predicted a charge density slightly lower than was measured at 10 m/s. This may imply the aerosol size distribution assumed by Hoppel was too large or that the small air ion density and its extent from the conductor was not accurately represented.

The charging of aerosols also depends on their size. Larger aerosols can achieve an increased level of charge before electrostatic repulsion will prevent any further charging. Harrison provided a calculation of the mean charge on an aerosol of a particular size based on the densities of positive and negative small ions [29].

$$\langle j \rangle = \{4\pi\varepsilon_o akT/e^2\}\{\ln [n^+\mu^+/n^-\mu^-]\} \qquad \textbf{Eq. 3-4}$$

where j is the number of charges on the aerosol,
a is the radius of aerosol in microns
n^+ is the positive small ion density in ions/cm^3,
n^- is the negative small ion density in ions/cm^3,
μ^+ is the positive ion mobility in cm^2/V s,
μ^- is the negative ion mobility in cm^2/V s,
ε_o is the permittivity of free space,
e is the elemental charge,
k is the Boltzman constant, and
T is the temperature in Kelvin.

For a small air ion imbalance of 500 positive ions/cm^3 and 5,500 negative ions/cm^3 and a 0.2 μm radius aerosol at room temperature, the average charge state of the aerosol will be seven (negative).

Direct measurements of the charge distribution on aerosols by size have been made by Johnson downwind of a DC line [30]. In ambient conditions of roughly equal numbers of negative and positive small air ions (600 to 800 ions/cm^3), the average number of charges on an aerosol was zero. However, the number of charges on individual aerosols varied from several negative to several positive charges. A typical size-charge distribution for aerosols in the 0.3 to 0.6 μm range is shown in Figure 3-1.

Measurements of the charge-size distribution were also taken downwind of a monopolar –500 kV DC line. The aerosol charge distribution in Figure 3-2 shows a shift favoring the negative charge state of the aerosols. Several percent of the charged aerosols still have a positive charge even though they are downwind of a negative monopolar DC line.

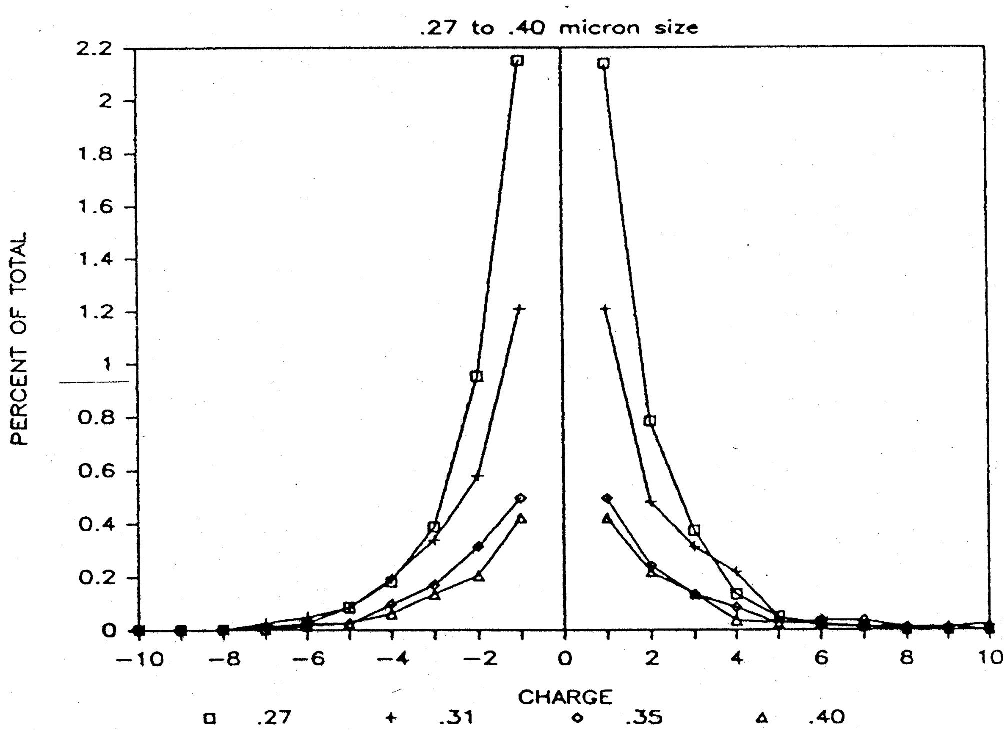

Figure 3-1
Charge Distribution for Ambient Aerosols by Size in μm as a Percent of Total Aerosols [30]

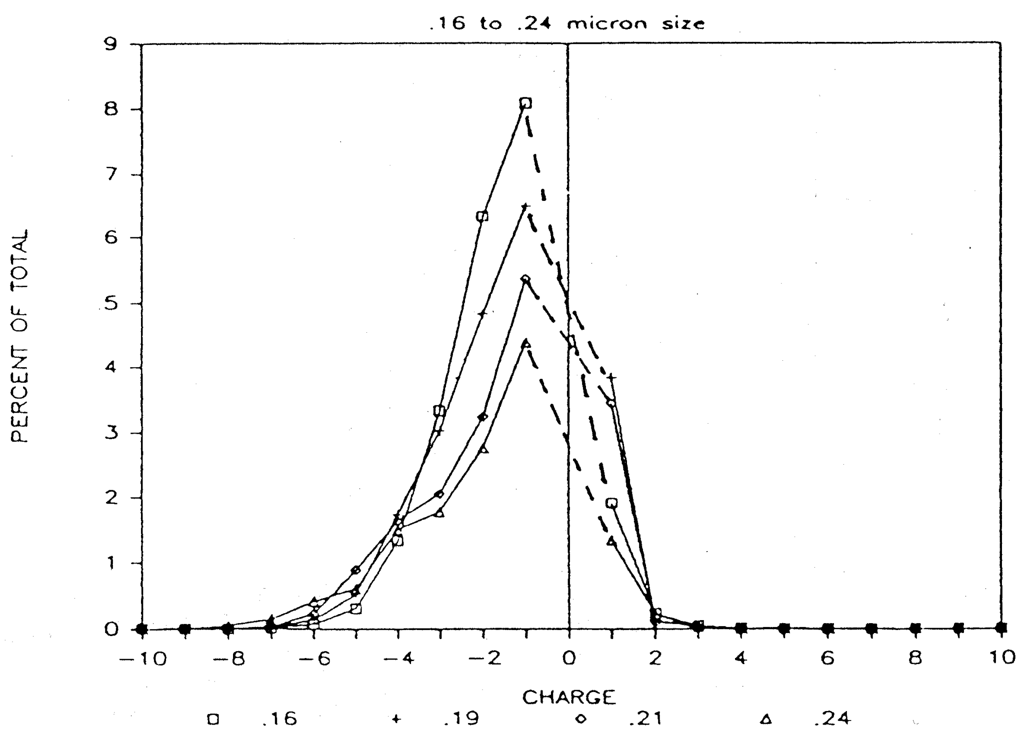

Figure 3-2
Charge Distribution for Aerosols 70 m Downwind of the Negative Pole of a DC Line by Size in μm as a Percent of Total Aerosols [30]

To date most direct measurements of aerosol charging and aerosol charge densities from transmission lines have been made using DC transmission lines. Direct measurements of charged aerosols within 100 meters of monopolar DC transmission lines in heavy corona have shown that charged aerosol levels are generally 10,000 charges/cm^3 or less, have only single digit charge states, and even when the charge distribution is shifted by the DC line, some of the aerosols still retain opposite charge [30].

For the DC lines, ions of one polarity exist over an extended area from the conductor to ground. This makes charging of aerosols passing by the line more likely than for an AC line. With more aerosols charged near a DC line, their effects downwind will be more evident than those from AC lines. Therefore the predictions and, especially, the observations of space charge near DC transmission lines in active corona provide upper bound estimates for space charge related processes downwind of AC transmission lines.

Corona on transmission line conductors creates a zone around the conductors in which both positive and negative ions are formed. The processes involved in the transfer of charge from these ions to aerosols involve charging by the electric field and by diffusion. Little research has focused on these processes for AC transmission lines and so much of our knowledge is based on measurements and modeling of these processes for DC transmission lines. In fact, the results of studies of DC transmission lines can be considered as extreme limiting cases for the analysis of AC transmission lines. Of particular importance is that current loss from the conductor, and therefore the downwind charge on aerosols is related to the ambient levels of aerosols; higher aerosol concentrations are associated with higher downwind levels of space charge. Based upon other measurements, it is predicted that it will be difficult to achieve sustained levels of space charge associated with electric fields greater than 10 kV/m because of corona production of opposite polarity space charge at ground level vegetation at higher field levels.

4
CHARGED AEROSOL DRIFT

The drift and expansion of space charge as it moves downwind from its source is an important element in determining the ground-level electric field and charge density. There is a body of literature on atmospheric space charge density, its drift and vertical extent in relation to ionization sources, and associated ground level electric field [31-41, 17, 42, 20, 28, 27, 30, 3].

Vonnegut and his colleagues designed several measurement methods for use on planes and used them to survey the vertical extent of the potential gradient due to space charge densities and the resulting ground-level electric fields [44, 34, 35, 36]. Figure 4-1 is a vertical profile of the atmospheric potential gradient at altitudes from 300 m to 2,500 m made by Vonnegut over Jacksboro, Texas under ambient conditions [32].

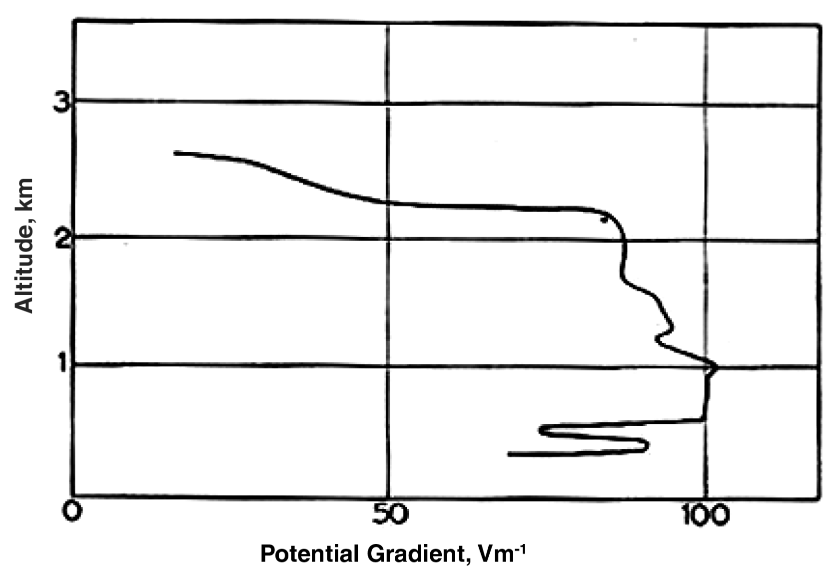

Figure 4-1
Variation of Potential Gradient with Altitude in Region Unaffected by Artificial Space Charge Measured near Jacksboro, TX [32]

In Figure 4-1, the fair weather field increased with altitude, indicating a layer of negatively charged air. Vonnegut assumed that atmospheric clouds were developing from a surface layer one km thick (note inflection point in vertical profile of potential gradient at approximately 1 km). Vonnegut integrated the potential curve from ground to 1 km and computed an average net space charge density in the column of air below 1 km of 1.5 charges/cm^3.

Vonnegut used a fine wire (0.04 cm) suspended approximately nine meters above the ground on small insulating fiberglass poles for a length of 14 km. The wire could be energized up to 50 kV and provide currents of up to 10 mA. The usual operating current loss was 3 to 4 mA for the 14 km length of wire. Higher levels of current loss were obtained when the wire voltage was negative as opposed to positive. No appreciable current flow could be obtained until the wire voltage exceeded approximately 5 kV [38]. He noted that the artificial introduction of space charge from the thin wire was quite similar to the natural introduction of charge into the atmosphere by a point discharge where the current varied linearly with potential and wind speed [45].

Comparing the current loss from the wire with the flux of space charge a few hundred meters down wind, Vonnegut found that the ground based potential gradient was approximately 2,000 V/m. Using Poisson's equation to calculate the flow of charge from the line for a 5 m/s wind yielded a current of only 1 mA. This was in contrast to approximately 4 mA of loss current measured to the wire. Vonnegut's conclusion was that the difference between measured wire current and the calculated source current based on the ground potential gradient measurements was due to the charge on small air ions flowing directly from the line to ground near the line [33, 38].

Vonnegut performed several studies in which he artificially introduced space charge into the atmosphere by corona generated by a small wire charged at a high DC potential [32, 33, 38, 40]. He was able to detect changes in the ground-level electric field of approximately -500 V/m at a distance of 9 km down wind of the 14 km long thin wire. He also made measurements of the space charge density and potential gradient at heights above ground of 300 m and more from an airplane. Space charge concentrations of 20 to 400 charges/cm^3 per cubic centimeter were measured at heights of 300 m above ground (Figures 4-2 and 4-3) [38].

Figure 4-3 shows that elevated levels of space charge (300 charges/cm^3) were observed within 1 to 2 km downwind of the line at an altitude of 300 m. The charge density decreased with distance from the line. The 100-charge/cm^3 contours were approximately 8 km downwind and the 25-charges/cm^3 contour was approximately 14 km downwind. The decrease in the charge density with distance followed the decrease seen in the potential gradient contours of Figure 4-2. The potential gradient and charge density measurements used to construct the contour maps shown in Figures 4-2 and 4-3 are presented in Figure 4-4.

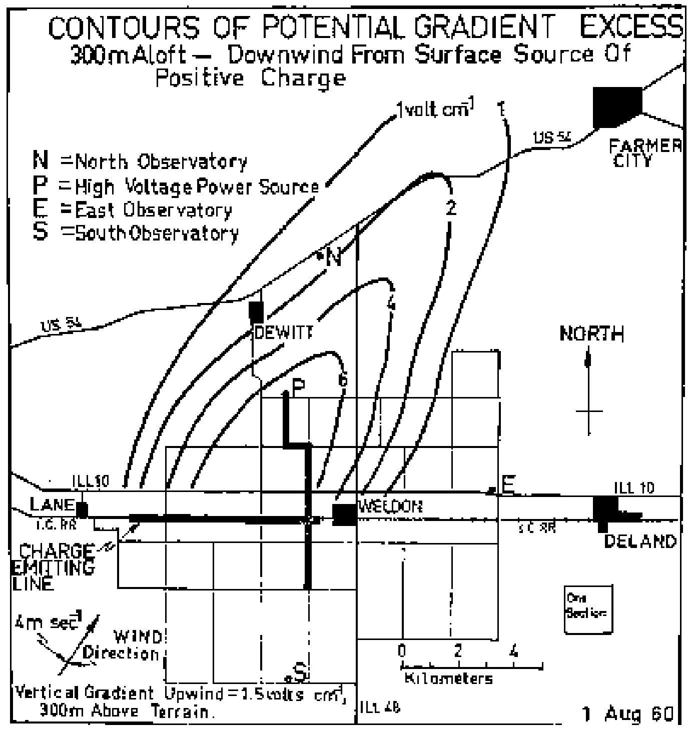

Figure 4-2
Contour Lines of Atmospheric Potential Gradient at an Altitude of 300 m Downwind of a Thin DC Wire Operating at a Positive DC Voltage [38]

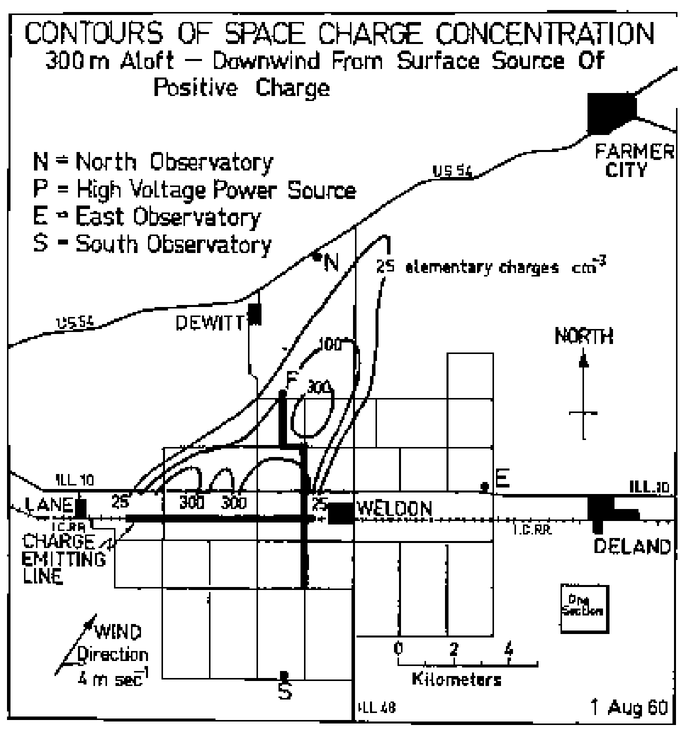

Figure 4-3
The Contours of Space Charge Density Downwind of a 14 km Long Thin Wire Energized at Positive Polarity. Measurements made at a Height above Ground of 300 m [38]

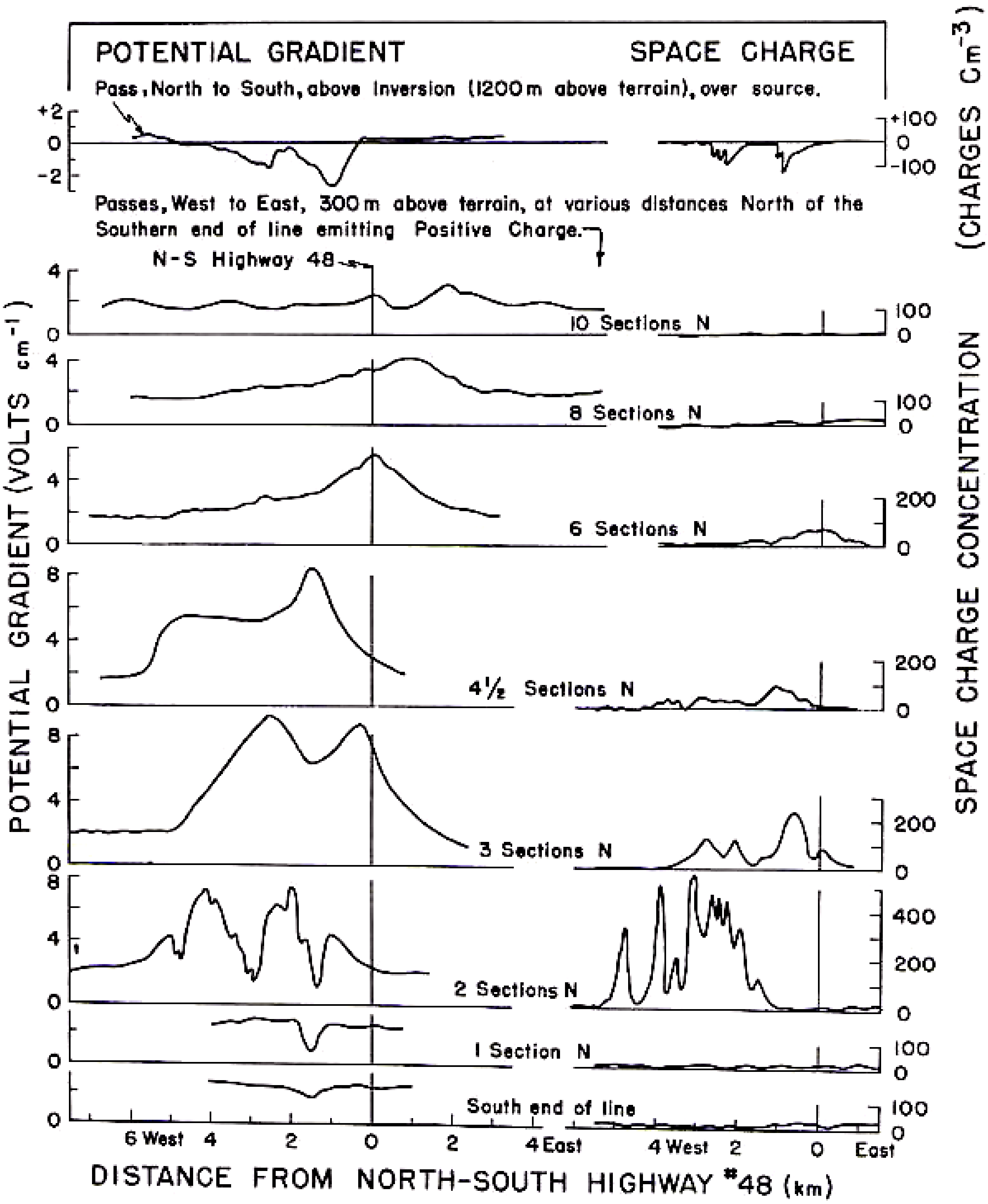

Figure 4-4
Measurements of the Potential Gradient and Space Charge Density at 300 m Altitude for Various Distance Downwind of the DC Line [38]

Figures 4-2, 4-3, and 4-4 indicate that the space charge from a line dispersed vertically to heights well in excess of the height of the line releasing the charge. The line producing the charge was at a height of 9 m. Charge densities of over 300 charges/cm^3 were measured at heights of 300 m above ground downwind of the line.

Low-level flights at 75 and 150 m altitudes over the line indicated that significant amounts of the space charge (500 charges/cm^3) were at heights equal or above 75 m a few hundred meters downwind of the line. This is in contrast to the assumption made by Fews that the space charge released by a line remains at or below the height of the line tower (20 m or less) [3].

The ground level electric field depends on the total amount of charge contained in the column of air above the measurement. Estimates of the ground-level space charge density based solely on ground level field measurements and an assumed vertical extent of a column of space charge can be misleading. Simultaneous ground level electric field measurements along with direct measurements of the space charge density provide a better picture of the space charge at and above ground level. Vonnegut noted this problem in discussing his measurements of potential gradient and space charge.

> *"It must be recognized that, even when the observer is in the midst of a region of high space charge density, the gradient will be zero if net equal amounts of the same charge are above and below. Similarly, it should be recognized that, because of the action-at-a-distance resulting from electric charge, an observer may experience strong electric gradients even though he is in a region where the air carries no space charge whatsoever." [38]*

During the course of his measurements, Vonnegut noted fair weather space charge densities in the range of +300 charges/cm^3 to -600 charges/cm^3. Fair weather ground-level fields ranged from slightly negative to approximately 300 V/m. Fields under clouds but without rain ranged from -3000 V/m to +2000 V/m. During rain, fields of over 5000 V/m were measured.

During his series of measurements of space charge and ground-level electric field, Vonnegut and his colleagues made several attempts to measure a perturbation in the atmospheric ground-level electric field near AC high voltage power lines in Illinois, Tennessee, and elsewhere. Although he had the demonstrated technical methods and instrument sensitivity to detect changes in the atmospheric field and charge density from AC transmission lines, he was not able to measure any perturbation of the atmospheric field or charge density by these AC lines [37].

Measurements of the vertical space charge density in the region from ground level to 150 m above ground downwind of the DC Pacific Intertie were made during fair weather and snow conditions at the Bonneville Power Administration (BPA) DC Test Site near Grizzly Mountain in central Oregon [30]. Measurements were made using a space charge cage carried aloft by helium-filled weather balloons. Measurements of the electrical environment at ground level were available from instrumentation installed by the BPA at the test site. Data on the above ground space charge density were collected during three days in December. The DC line was operating bipolar at ±500 kV. The conductor height was 12 to 15 m above ground.

Vertical profiles of the charge density were obtained at locations 150 m and 300 m downwind of the line during fair weather and dry-snow conditions. The wind speed perpendicular to the line was 0.9 m/s (2 mph). The peak of the small ion density under the DC line was approximately 135,000 charges/cm³. By 23 m downwind from the line, the small ion density had decreased to 8000 charges/cm³.

The vertical profiles of the charge density from ground level to a height of 150 m above ground downwind of the line at locations 150 m and 300 m downwind are plotted in Figure 4-5. At the 150 m location downwind, the space charge increased from approximately 300 charges/cm³ at ground level to approximately 1,100 charges/cm³ at 60 m above ground and then decreased to about 600 charges/cm³ by 150 m above ground. Moving further downwind to 300 m from the line, it is clear that the charge plume was expanding vertically: the charge density at ground level decreased to 200 charges/cm³ and the peak charge concentration of 1,000 charges/cm³ now occurred at approximately 100 m above ground. The charge density decreased for heights above 100 m falling to approximately 700 charges/cm³ at 150 m above ground.

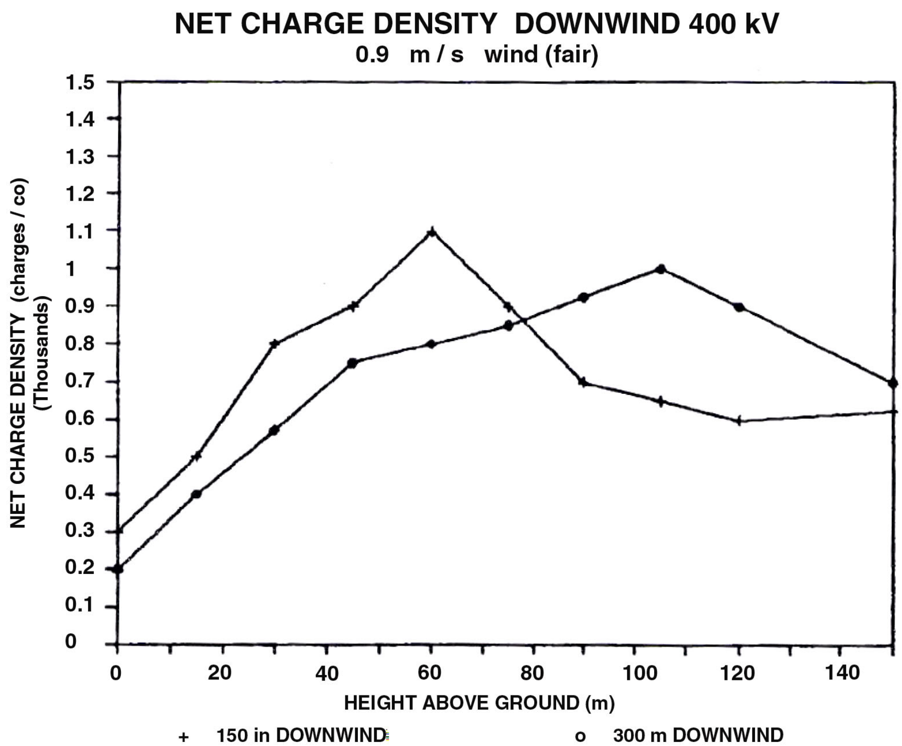

Figure 4-5
Vertical Profile of the Charge Density in Low Wind Conditions at Two Locations 150 m and 300 m Downwind of the DC Pacific Intertie in Fair Weather Conditions. Small Air Ion Density under the Line was Approximately 100,000 charges/cm³

Measurements of the vertical profile of the charge density were also obtained during dry snow conditions with a wind speed of 9 m/s. The vertical profile of the charge density during snow is plotted in Figure 4-6. The peak small ion density directly under the line was 90,000 charges/cm³ while the small ion density at 23 m downwind was 67,000 charges/cm³. Due to the fixed location of ground based small ion measurement, the actual peak of the small ion density under the line was likely shifted by the wind and was more than 90,000 charges/cm³.

During snow conditions when the number of small ions being produced by the DC line was greater and wind speeds were also greater, the charge densities being carried downwind were also greater, peaking at the 150 m downwind measurement location at 14,000 charges/cm^3 at height of 80 m and then decreasing with further increases in height. The charge densities decrease with distance downwind. At the 300 m location the peak charge density of 8,000 charges/cm^3 occurs for a height of 45 m and then decreases for further increases in height. Figure 4-6 indicates that even for relative high winds and very low mobility particles (snow), there is significant vertical expansion of the space charge. Figure 4-6 illustrates that the charge plume is still diffusing and expanding vertically even in strong wind conditions. This would appear to be in contradiction to the assumption that downwind space charge does not rise much above the height of the source [2].

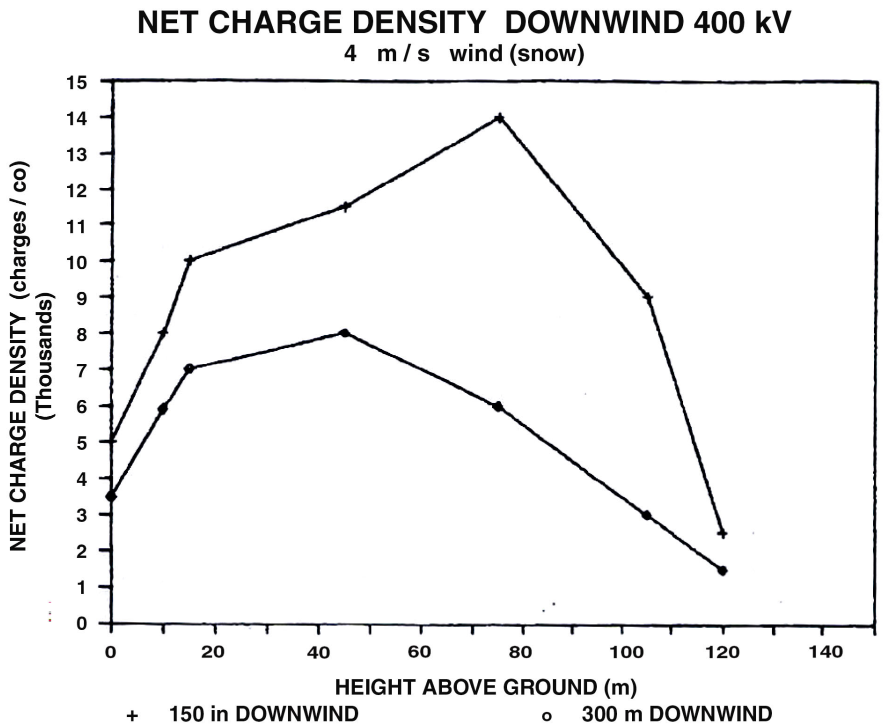

Figure 4-6
Vertical Profile of the Charge Density in High Wind Conditions at Two Locations 150 m and 300 m Downwind of the DC Pacific Intertie in Dry Snow Conditions. Small Air Ion Density Under the Line was Approximately 100,000 charges/cm^3

Measurements of the vertical profiles of space charge density indicate that sources of space charge near ground can affect downwind space charge concentrations several hundred meters into the air and several hundred meters downwind [44, 34, 35, 36, 28, 30]. Reported measurements have focused on long line sources of space charge. Variations in wind speed and direction over short periods do not have as great an impact on line sources as they would for point sources of charge. This makes long line sources of charge easier to study with more stable effects. However, some investigators of atmospheric space charge believed that insulators or some other point source at the tower location of high voltage lines was the source of the space charge that was measured downwind of power lines [31, 46].

Chalmers noted three situations that strongly implicated something on or near the transmission line towers as the source of the ions:

> *"It may be remarked that it has seemed that, in fine weather the effects, which are then small, come more readily from the 66 000 lines then [sic] from the 132 000 line." (p. 158)*
>
> *"But downwind the potential gradient was found to depend upon the distance from a line along the wind direction and passing through the pylon; when close to this line on the downwind track, the potential gradient had a minimum value of about – 150 Vm-1, but when the distance, along the track parallel to the cables, was 100 m from this line, the potential gradient was similar to that upwind." (p. 158)*
>
> *"During foggy weather, when passing close to the pylons supporting the cables, there is often audible hissing due to breakdown at the insulators, and this has been noticed on some of the occasions when the negative fields have been largest." (p. 157) [31]*

Chalmers concludes that:

> *"While it appeared likely that the source of the negative charges would be at the insulators, rather than along the wires, this has not been previously investigated…" (p. 613) [46]*
>
> *"Since we know that the insulation breakdown does occur at the insulators, it seems reasonable to suggest that this is where the ions originate, but the present observations are not able to confirm this." (p. 158) [31]*
>
> *"Measurements of negative electric fields must be regarded with suspicion until it is established that these fields do not originate from charges produced at pylons." (p.159) [31]*
>
> *"Further investigation of the effect could only be made by using many continuous recording field measuring instruments situated at various points in relation to the pylons…" (p.159) [31]*

Chalmers raised the possibility that at least in this case measurements of elevated fields downwind from an AC power line did not necessarily indicate that corona on the line was the source of the space charge. The source of the ionization could have been a point source on or near the transmission line tower, such as scintillation on the insulator surfaces, a cracked or damaged insulator, or a bolt or piece of loose hardware protruding too far. Damage at a localized point on a conductor could also have been an intense fair weather corona source that released more ions than general fair weather corona along the entire line.

The possibility of point sources merits consideration in collecting and analyzing electric field data near transmission lines. Although most lines are designed to be corona free during fair weather there is usually some corona activity caused by protrusions on the conductors. Modern lower voltage lines, such as 69- and 132 kV lines, have lower conductor surface gradients and so are less likely to be in corona (Table 2-1). Therefore the fields near these lines may more likely be due to point sources.

One method of determining whether the downwind space charge being observed is from general corona on transmission line conductors or from a localized point source would be to use multiple simultaneous recording devices positioned at several locations parallel to the line and adjacent to a pylon of possible interest. This would help to define the contribution of such sources to corona-generated space charge apart from that produced by line sources.

In order to obtain an indication of the differences in particle concentrations one might see downwind from a line source of particulates versus a point source of particulates, the United State Environmental Protection Agency (EPA) atmospheric dispersion model for particulate dispersion was used [22]. This model uses a Gaussian plume model for dispersion of particulates downwind similar in concept to that described in Section 3, Equation 3-3.

Air dispersion modeling for charged particles was conducted using the EPA preferred model, Industrial Source Complex-Short Term dispersion model (ISCST3). ISCST3 is a steady-state Gaussian plume model that is used to assess particulate concentrations from a wide variety of sources associated with an industrial complex. It is the most widely used model that has been applied and tested in numerous applications.

ISCST3 was used to generate modeling results for ground level concentrations of particulates. This model can account for line and volume sources, plume rise as a function of downwind distance, separation of point sources, and terrain and atmospheric conditions within limits. For this modeling effort, the latest version of the ISCST3 model, Version 02035, was used.

Dispersion modeling was performed for both a point source and a line source. The measurement locations were placed on flat terrain. The line source was represented by an elevated area source with a very large ratio of length to width. To effectively model the dispersion of the charged particle emissions, an AREAPOLY algorithm was used to limit the number of modeling runs yet enhance the accuracy of modeling results.

The modeling runs estimated the downwind ground level concentrations under two wind speeds 2.2 m/s and 4.5 m/s (5 mph and 10 mph) and two atmospheric stability conditions (stable atmosphere and turbulent atmosphere with convective mixing). The stable condition was represented by a stability category of four and a mixing height of 1,000 m. For the turbulent condition, the stability category used was one with a mixing height of 2,000 m. Levels of particulate generation were assumed based on estimated fair weather corona loss levels for a 500 kV line and equivalent insulator losses at one tower [5]. Particulate generation levels were based on direct conversion of escaped corona-loss charges to particulates based on one particle per second equaling one elemental charge per second. Conversion of the power loss did not deduct power lost to corona effects such as radio noise, audible noise, visible light, or ozone creation. Due to the nature of the model, ion recombination, aerosol discharging, or charge repulsion were not included. The computed particulate levels are unrealistically high because of the simple assumptions used to convert loss current to particulate generation. The purpose of this modeling was to look at fundamental differences between downwind dispersion of particulates from a point source versus a line source. The results are presented graphically in Figures 4-7 and 4-8 for a line source and for a point source, respectively. Results are presented for four locations downwind (500 m, 1,000 m, 2,000 m, and 5,000 m), two wind speeds (2.2 m/s and 4.5 m/s) and for two atmospheric conditions (stable and turbulent atmospheres).

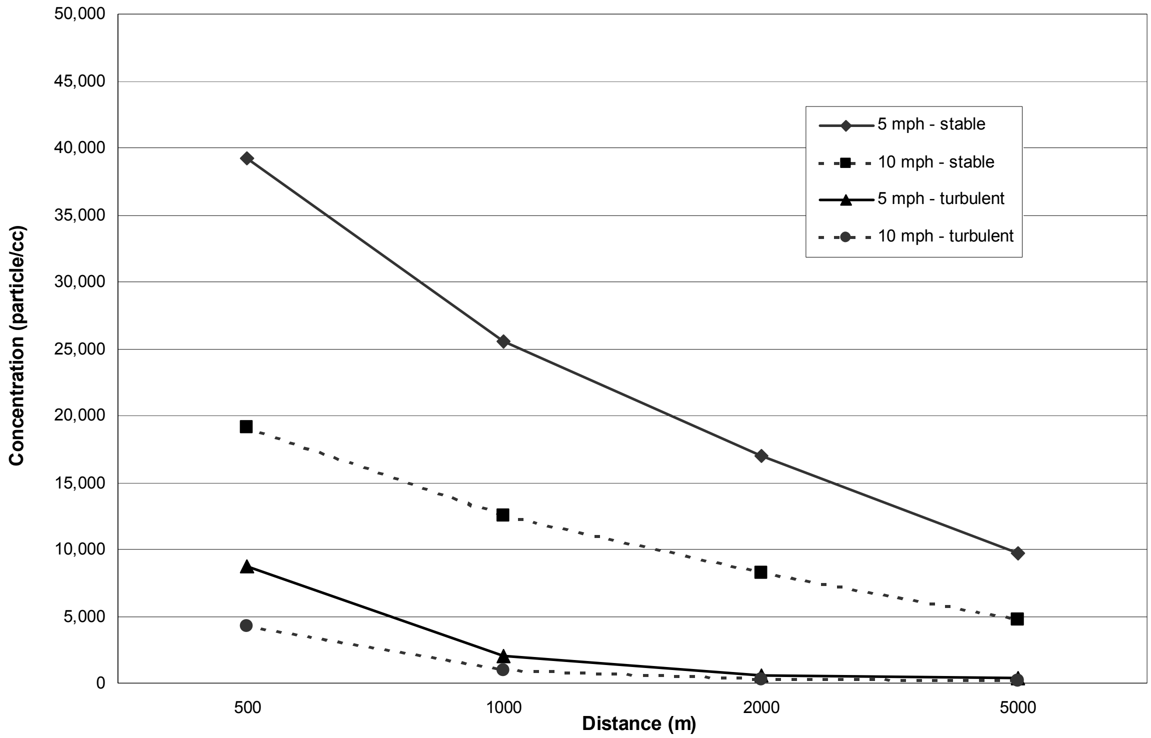

Figure 4-7
Calculated Dispersion of Particulates Downwind from a Line Source

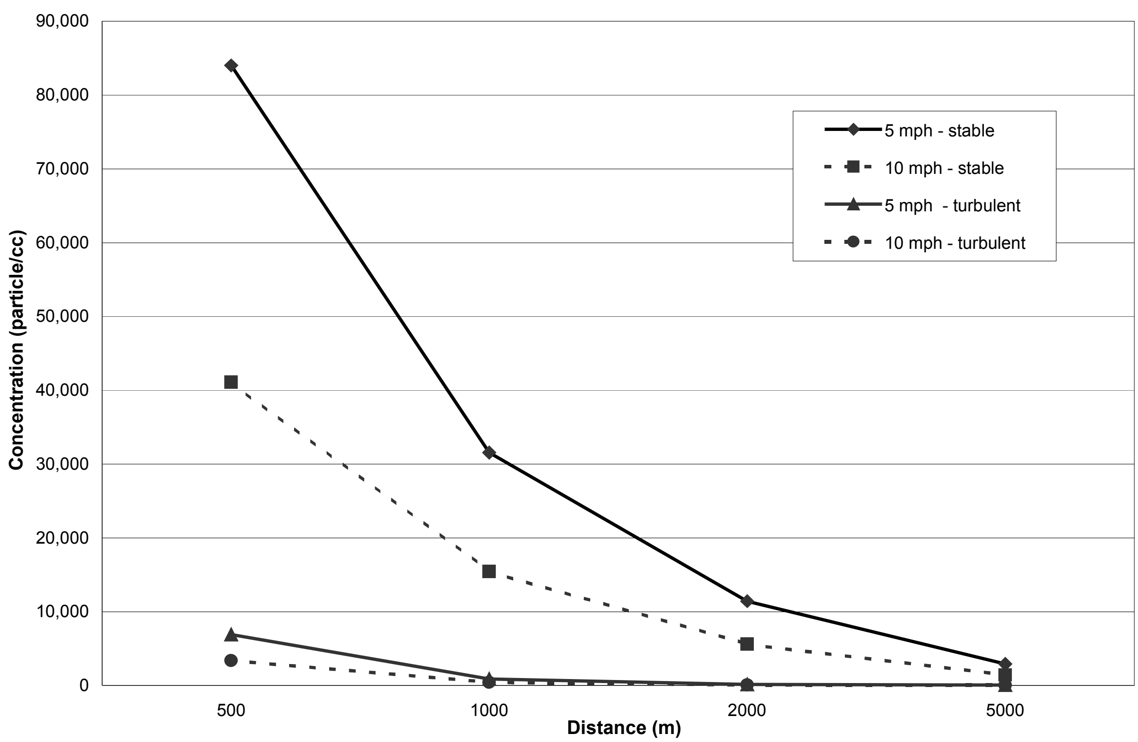

Figure 4-8
Calculated Dispersion of Particulates Downwind from a Point Source

Qualitatively, a point source in stable atmospheric conditions has higher particle densities closer to the source than an equivalent line source does, but the densities drop off much faster with distance than for a line source. Under turbulent conditions it will be difficult to tell a point source from a line source, but a point source will tend to have lower densities than an equivalent line source. Comparison of the likely particle densities that one might encounter from a line source or point source, indicate the need for multiple measurements, preferably simultaneous, at several location downwind (and upwind) of the probable source. This confirms the suggestions by Chalmers as to the need for multiple and simultaneous field and charge density measurements [31].

An extensive literature on the dispersion of space charge overhead in relation to ground level DC electric fields was reviewed. Studies of space charge and electric fields downwind of DC test lines and DC transmission lines indicate that space charge can be transported to heights of 75 to 300 m above ground. Even snowflakes, with less mobility, can transport charge many meters above a line source. These data indicate that the assumption of Fews et al. that space charge from transmission lines would not rise above the height of the conductors may not describe typical conditions, and leads them to overestimate higher space charge values at ground level [3]. The older studies of DC electric fields measured near lower voltage AC transmission lines point to the need to consider insulators and hardware as a possible source of corona-generated space charge. To evaluate how the dispersion of particles from such point sources might differ from line sources, the dispersion of particles was modeled under stable and turbulent atmospheric conditions. Particle concentrations close to the point source were estimated to be higher than for a line source. However, the concentrations from the point source diminish more rapidly with distance so that line sources are more dominant at greater distances.

5
GROUND LEVEL ELECTRIC FIELD AND CHARGED AEROSOL DENSITY

The electric field of the Earth in fair weather is normally in the range of a few 100 V/m, but can vary dramatically with weather conditions reversing direction or, on rare occasions, reaching values of 40,000 V/m [24, 47, 48]. Such variation in the Earth's electric field with time and location make it difficult to measure the impact of transmission lines on downwind ground level electric fields unless multiple locations upwind and downwind of a transmission line are measured simultaneously.

Measurements have shown that the creation and release of corona-generated ions on a high voltage DC conductor can charge aerosols. These charged aerosols are then carried downwind producing modifications in the atmospheric space charge densities and electric fields [30, 38, 28, 49].

Changes in the ground level electric field or space charge downwind of operating AC lines have also been reported. Studies that have measured static electric fields and corona-generated space charge from AC transmission lines are listed in Table 5-1. Most of the studies measured only ground-level electric fields. However, a few also measured ground-level ion densities. None of the studies reported measurements of charged aerosols. Historically, measurements were made on low voltage lines, presumably with smaller diameter conductors than would be used on present lines of the same voltage class. Over the last several years, measurements have been reported near lines from 132 kV up to 400 kV.

The duration of measurements reported varies greatly from anecdotal to long-term. Corona is a highly variable phenomenon dependent on meteorological and conductor-surface conditions. Therefore characterization of effects related to corona, such as audible noise and electromagnetic interference, are generally given in statistical terms. Not surprising then, space charge effects also showed great variability over periods from seconds to seasons. Ideally, this variability should be quantified by long-term measurements. Unfortunately, there was only one study that performed such long-term measurements and it employed only a limited number of measurement locations [43].

Even without extensive long-term monitoring, some patterns did emerge from the measurements listed in Table 5-1. First, the measurements confirmed the variability that is associated with corona-generated space charge and its attendant electric field changes. During some measurement period there were large changes in electric field at ground level downwind of AC transmission lines, with changes in polarity even possible. Elevated fields may appear during one measurement period but not during another for the same location. [31, 3, 51, 54]. However, over long periods the mean and median levels of electric fields and ion densities at ground level were comparable to ambient (upwind) levels [43].

Table 5-1
Summary of Static Electric Field and Space Charge Measurements Near AC Transmission Lines

Reference	Location	Line Type	Number of Sites	Measurement Distances, m	Number/Duration of Measurements	Electric-Field Change, V/m	Electric-Field or (Space-Charge Polarity)†	Comments
Carroll & Lusignan, 1927* [50]	California, USA	220 kV	1	4.6 m & 9.1 m (under conductor)	nr	nr	Negative	Visible and audible corona; Polarity of space charge unchanged by operation at 240 kV or 260 kV
Chalmers, 1952 [31]	Durham, UK	66 and 133 kV	22	up to several km	More than 66, duration unknown	>100 V/m to > 800 V/m	Negative and positive	Negative charge during mist and rain; positive during fair weather
Mühleisen, 1953** [54]		220 kV					Positive and negative	Negative electric fields in mist and fog; positive electric field in other conditions
Bent & Hutchinson, 1966 [51]	Durham, UK							Powerline effect assumed:
		nr	nr	nr	11	Negative	Negative	Mist and fog
				nr	4	Positive	Positive	Clear sky and high visibility
		275 kV		17000	8	Negative	Negative	Humid summer nights (dew?)
Groom and Chalmers, 1967 [46]		132 kV	1	40 m	One day	150 V/m	Negative	Fog; tests indicate that the corona source was the pylon not the conductors
Hendrickson, 1983 [42]	Minnesota, USA	345 kV	1	100, 200 m	1 24-hour period	<300 V/m	Positive	Change of electric field related to wind speed

* as described in Harris & Albertson (1984)
** as described in Fews et al. (1999)
† Positive field is into the earth.
nr = not reported
nm = not measured

Table 5-1
Summary of Static Electric Field and Space Charge Measurements Near AC Transmission Lines (Continued)

Reference	Location	Line Type	Number of Sites	Measurement Distances, m	Number/Duration of Measurements	Electric-Field Change, V/m	Electric-Field or (Space-Charge Polarity)†	Comments
Harris & Albertson, 1984 [50]	Minnesota, USA	345 kV	1	<100 m	6 days, total of 17 hr	nm	(Positive)	Increase in +ions and decrease in -ions
Fews et al., 1999 [1]	Bristol, UK	132 kV	6	profiles up to 520 m	At several m intervals, duration not known	100 to 500 V/m, mean 200 V/m	Mostly negative	Elevated fields in 8 of 14 cases; calculated space charge
		275 kV	1	profiles up to 580 m	At several m intervals, duration not known	255V/m maximum	Negative	
		400 kV	1	profiles up to 75 m	At several m intervals, duration not known	123 V/m maximum	Negative	
Fews et al., 2002 [3]	Bristol, UK	132 kV	6	50, 100 m	11 periods of 12- to 18-minute duration	-118 to +613 V/m change in means	Mostly positive	Elevated fields in 21 of 22 cases; calculated space charge
		275 kV	1	50 m	1 period of 13 minutes	-19 V/m change in means	Negative	
		400 kV	2	50 m	5 periods of 10- to 14-minute duration	-296 to +53 change in means	Positive and negative	
		400 kV	1	18 to 800 m	18 periods of 25- to 117-minute duration	-58 to +756 V/m change in means	Mostly positive	
Bracken et al., 2003 [43]	New Hampshire, USA	230 kV	1	19 to 80 m	5436 hrs (1-minute averages) over 2.5 yrs	100 to 1500 V/m (99^{th} percentile of changes)	Positive	Field elevation for ~9% of total time; for ~20% of downwind time; Measured ion densities
		345 kV	1	24, 55 m	6384 hrs over 2.5 yrs	100 to 200 V/m	Positive	Field elevation for ~1% of total time; for ~2% of downwind time; Measured ion densities

* as described in Harris & Albertson (1984)
** as described in Fews et al. (1999)
† Positive field is into the earth.
nr = not reported
nm = not measured

Second, changes in the electric field from ambient levels were both positive and negative. A positive field refers to the field with an excess of positive charges overhead; that is, a positive electric field is into the earth. For lower voltage lines in Table 5-1, the downwind field changes tended to be negative, while for higher voltage lines the field changes tend to be associated with positive space charge. Long-term measurements near 230- and 345 kV lines showed predominantly positive polarity effects in terms of both electric fields and ion densities [43].

The observation of conditions with both negative and positive space charge from lines (or a point source on the line) was consistent with our understanding of corona. Negative corona has a lower onset voltage gradient and under certain conditions may predominate. At higher voltage gradients, positive ions are more likely than negative ions to escape from the area of the conductor and may lead to a predominance of positive space charge.

Third, changes in electric fields from upwind values were observed at distances up to several hundred meters and further from AC transmission lines [31, 3]. The levels were highly variable at these distances and generally less than a few hundreds of volts/meter. The elevated levels of static electric fields from AC transmission lines were much less than those from DC transmission lines at these same distances [49].

Fourth, another possible source of space charge downwind of power lines was identified as localized corona on hardware or insulators or electrical breakdown across gaps on the structures. Newer well-engineered lines would not have these sources. However, they may have produced the elevated electric fields observed by early investigators [31, 46]. It is also possible that very early low-voltage lines were in corona along the conductor because of undersized conductors.

Several researchers have used ground-level potential gradient measurements to calculate the space charge density [1, 3]. This is an acceptable method if the distribution of the space charge density with height is known and properly taken into account. Assuming uniform horizontal charge distributions, the ground level potential gradient (electric field) is a measure of the total charge contained within the column of air above the ground measurement point. The ground level field can be calculated from Gauss's Law as:

$$E_{gnd} = \int_{o}^{h} \rho(z)dz/\varepsilon_o \qquad \textbf{Eq. 5-1}$$

Where ρ is the space charge density in Coulombs/m^3

ε_o is the permittivity of free space in farad/meter

h is the height (m) of the column of air containing the space charge.

As can be seen from Equation 5-1 knowing the variation of $\rho(z)$ with height is critical in calculating the electric field at the surface of the ground. Vonnegut warns of misleading assumptions in relating measurements of the potential gradient and local charge density.

> *"…it should be recognized that, because of the action-at-a-distance resulting from electric charge, an observer may experience strong electric gradients even though he is in a region where the air carries no space charge whatsoever." [38]*

If only ground level electric fields are measured and then space charge density is calculated from the ground level electric field, the calculated space charge density depends on the height of the column assumed to contain the space charge. The literature has shown that the space charge density can vary widely with altitude and thus affect the ground level electric field [37]. However, even if the space charge density at ground level is known, its significance with respect to its potential effect on deposition within the respiratory tract cannot be appreciated unless the distribution of charge on aerosols of various sizes is also known.

Changes in the ground level electric field or space charge downwind of operating AC lines have also been reported. Besides the measurements by Few et al. (2002), other studies that have measured static electric fields and corona-generated space charge from AC transmission lines provide additional insight into these phenomena [3]. The measurements by Bracken et al. (2003) confirm the variability that is associated with corona-generated space charge and its attendant electric field changes [43]. This and other studies report that during a measurement period there can be large changes in electric field at ground level downwind of AC transmission lines at distances up to several hundred meters and further from AC transmission lines. The levels are highly variable at these distances and generally less than a few hundreds of volts/meter. Maximum values measured during short periods do not estimate the lower long-term average values that are of interest in assessing human exposure. The older literature points to corona on hardware or insulators or electrical breakdown across gaps on the structures as another source of corona-generated space charge. Newer well-engineered lines will not have these sources. If only ground level electric fields are measured and then space charge density is calculated from the ground level electric field, the calculated space charge density depends on the height of the column assumed to contain the space charge. The literature has shown that the space charge density can vary widely with altitude and thus affect the ground level electric field. The extent of the vertical dispersion of space charge downwind of corona sources is found to be much greater than has been assumed by Fews et al. [3], which means that his estimated concentrations of space charge at ground level are overestimated.

Gaps in our knowledge and critical areas of investigation identified by this literature review are:

- Although detailed modeling has been done of the ion creation process and the ion-aerosol attachment rates of DC transmission lines, a similar effort is needed to understand the charging of aerosols near AC transmission lines in quantitative terms.
- Knowledge of total charge density at ground level is insufficient characterize the distribution of charge on aerosols of different sizes and resulting effect of charge on their mobility. This information is important to address the final assumption in the Fews et al. hypothesis, viz. that the charge on aerosols will increase the deposition of aerosols in the respiratory tract [3].

6 SUMMARY

Fews and Henshaw [1, 2] have raised the question whether health impacts of airborne aerosols due to charging of aerosols by AC power lines is a potential source of adverse health effects. This hypothesis is based on the following assumptions:

- corona on AC transmission lines generate air ions
- the charge on air ions is transferred to aerosols and the latter become highly charged
- highly charged aerosols exhibit minimal dispersal as they move downwind of the line
- the electric field and mobility of charged aerosols increase the concentration of charged aerosols at ground level
- increased charge on aerosols produced by AC transmission lines is sufficient to meaningfully increase the deposition and retention of the aerosol in the lungs.

Although some aspects of these hypotheses have a physical basis, other aspects of the hypothesis are highly speculative, and the conclusion that power lines could substantially affect human exposure to airborne particles or lead to adverse health effects is unwarranted [52]. This view is shared in a more recent assessment by the National Radiological Protection Board of Great Britain [53]. Nevertheless, only a comprehensive quantitative analysis of the overall hypothesis and its implications for exposure will provide a strong basis for evaluating the merit of the hypothesis.

This review summarizes data in the literature to provide a better understanding of the physical processes pertaining to the first four assumptions that form the basis for the Fews et al. hypothesis. These processes involve the nature of corona on AC transmission lines and the formation of air ions, the charging of aerosols by the electric field and diffusion, the dispersion of ions and charged aerosols away from transmission lines, and the use of measurements of DC electric fields downwind of AC lines to estimated exposures to charged aerosols.

AC Corona and Small Ions

Corona activity on high-voltage AC and DC conductors is known to lead to the formation of ions. A review of the factors affecting ion formation and mobility explains why positive ions and charged aerosols should be expected under most conditions on higher voltage lines. However, a lower onset gradient for negative corona may support the production of negatively charged aerosols on lower voltage lines that are marginally in corona due to rain or condensation on the conductors. Consideration of typical AC transmission line designs for voltages above 215 kV indicates that conductor surface gradients on individual conductors remain the same as voltage is increased. However, the use of multiple conductor bundles to limit conductor surface gradients increases the volume where corona-generated ions are present and charging of aerosols can take place.

Aerosol Charging and Discharging

Corona on transmission line conductors creates a zone around the conductors in which both positive and negative ions are formed. The processes involved in the transfer of charge from these ions to aerosols involve charging by the electric field and by diffusion. Little research has focused on these processes for AC transmission lines and so much of our knowledge is based on measurements and modeling of these processes for DC transmission lines. In fact, the results of studies of DC transmission lines can be considered as extreme limiting cases for the analysis of AC transmission lines. Of particular importance is that current loss from the conductor, and therefore the downwind charge on aerosols is related to the ambient levels of aerosols; higher aerosol concentrations are associated with higher downwind levels of space charge. Based upon other measurements, it is predicted that it will be difficult to achieve sustained levels of space charge associated with electric fields greater than 10 kV/m because of corona production of opposite polarity space charge at ground level vegetation at higher field levels.

Charged Aerosol Drift

An extensive literature on the dispersion of space charge overhead in relation to ground level DC electric fields was reviewed. Studies of space charge and electric fields downwind of DC test lines and DC transmission lines indicate that space charge can be transported to heights of 75 to 300 m above ground. Even snowflakes, with less mobility, can transport charge many meters above a line source. These data indicate that the assumption of Fews et al. [3] that space charge from transmission lines would not rise above the height of the conductors may not describe typical conditions, and leads them to overestimate higher space charge values at ground level. The older studies of DC electric fields measured near lower voltage AC transmission lines point to the need to consider insulators and hardware as a possible source of corona-generated space charge. To evaluate how the dispersion of particles from such point sources might differ from line sources, the dispersion of particles was modeled under stable and turbulent atmospheric conditions. Particle concentrations close to the point source were estimated to be higher than for a line source. However, the concentrations from the point source diminish more rapidly with distance so that line sources are more dominant at greater distances [3].

Ground Level Electric Field and Charged Aerosol Density

Changes in the ground level electric field or space charge downwind of operating AC lines have also been reported. Besides the measurements by Few et al. (2002), other studies that have measured static electric fields and corona-generated space charge from AC transmission lines provide additional insight into these phenomena [3]. The measurements by Bracken et al. (2003) confirm the variability that is associated with corona-generated space charge and its attendant electric field changes [43]. This and other studies report that during a measurement period there can be large changes in electric field at ground level downwind of AC transmission lines at distances up to several hundred meters and further from AC transmission lines. The levels are highly variable at these distances and generally less than a few hundreds of volts/meter. Maximum values measured during short periods do not estimate the lower long-term average values that are of interest in assessing human exposure. The older literature points to corona on hardware or insulators or electrical breakdown across gaps on the structures as another source of corona-generated space charge. Newer well-engineered lines will not have these sources. If only ground level electric fields are measured and then space charge density is calculated from the ground level electric field, the calculated space charge density depends on the height of the column assumed to contain the space charge. The literature has shown that the space charge density can vary widely with altitude and thus affect the ground level electric field. The extent of the vertical dispersion of space charge downwind of corona sources is found to be much greater than has been assumed by Fews et al. [3], which means that his estimated concentrations of space charge at ground level are overestimated.

Gaps in our knowledge and critical areas of investigation identified by this literature review are:

- Although detailed modeling has been done of the ion creation process and the ion-aerosol attachment rates of DC transmission lines, a similar effort is needed to understand the charging of aerosols near AC transmission lines in quantitative terms.
- Knowledge of total charge density at ground level is insufficient characterize the distribution of charge on aerosols of different sizes and resulting effect of charge on their mobility. This information is important to address the final assumption in the Fews et al. hypothesis, viz. that the charge on aerosols will increase the deposition of aerosols in the respiratory tract [3].

7 REFERENCES

1. Fews, AP; Henshaw, DL; Wilding, RJ; Keitch, PA. 1999. Corona ions from power lines and increased exposure to pollutant aerosols. Int. J. Radiat. Biol. 75:1523-1531.

2. Henshaw, DL. 2002. Does our electricity distribution system pose a serious risk to public health. Medical Hypotheses. 59:39-51.

3. Fews, AP; Walding, RJ; Keitch, PA; Holden, NK; Henshaw, DL. 2002. Modification of atmospheric DC fields by space charge from high-voltage power lines. Atm. Res. 63:271-289.

4. Cobine, JD. 1958. Gaseous Conductors. New York: Dover Publications.

5. *Transmission line reference book-345 kV and above, 2nd edition,* EPRI, 3412 Hillview Avenue, Palo Alto, CA: 1982.

6. Shahin, MM. 1969. Nature of charge carriers in negative coronas. J. Chem. Phys. 64:106-110.

7. Mohnen, VA. 1977. Formation, nature, and mobility of ions of atmospheric importance. Electrical Processes in Atmospheres, Proceedings of the Fifth International Conference on Atmospheric Electricity, 2-7 September 1974. H. Dolezalek and R. Reiter (eds.). Deitrich Steinkopff Verlag, Darmstadt, 1977, 1-17.

8. Perkins, MD and Eisele, FL. 1984. First spectrometric measurements of atmospheric ions at ground level. J. Geophys. Res. 89:9649-9657.

9. Fujioka, N; Tsunoda, Y; Sugimura, A; Kenji, A. 1983. Influence of humidity on variation of ion mobility with lifetime in atmospheric air. IEEE Trans. Pwr. App. Sys., Vol. PAS-102:911-916.

10. Newell, HH and Wharburton, FW. 1956. Variations in radio and TV interference from transmission lines. AIEE Trans. Pwr. App. Sys. PAS-75:420-426.

11. Peterson, WS. 1933. AIEE Trans., Volume 52.

12. IEEE. 1973. IEEE Committee Report, CIGRE/IEEE survey on extra high voltage transmission line radio noise. IEEE Trans Pwr. App. Syst. PAS-92:1019-1028.

13. Anderson, JG; Baretcky, M; MacCarthy, DD. 1966. Corona loss characteristics of EHV transmission lines based on project EHV research. IEEE Tran. Pwr. App. Sys. PAS-85:1196-1212.

14. Abdel-Salam, M; Abdel Aziz, EZ. 1994. A charge simulation based method for calculating corona loss on AC power transmission lines. J. Phys. D. 27:2570-2579.

15. Ehrlich, RM and Melcher, JR. 1987. AC corona charging of particles. IEEE Trans. Ind. App. IA-23:103-107.

16. Whitby, KT; Liu, BYH; Peterson, CM. 1965. Charging and decay of monodispersed aerosols in the presence of unipolar ion sources. J. Colloid Sc. 20:585-601.

17. Jones, CD. 1977. Ion concentration variations at short distances downwind of continuous and quasi-instantaneous point sources. Pestic. Sci. 8:84-95.

18. Giao, TN; Jordan, JB. 1968. Modes of corona discharges in air. IEEE Trans. Pwr. App. Sys. PAS-87:1207-1215.

19. Hoppel, WA. 1985. Ion-aerosol attachment coefficients, ion depletion, and the charge distribution on aerosols. J. Geophys. Res. 90:5917-5923.

20. *Study of drifting, charged aerosols from HVDC lines*. EPRI EL1327, EPRI, Palo Alto, CA: 1980.

21. Minnesota Environmental Quality Board; Bailey, WH. 1982. A health and safety evaluation of the ±400 kV DC powerline, Report to the Minnesota Environmental Quality Board. December 1982.

22. Environmental Protection Agency (EPA); Turner, DB. 1970. Workbook of atmospheric dispersion estimates, office of air quality, Publication AP-26. EPA, Research Triangle Park, North Carolina, 27711.

23. Hoppel, WA and Frick, GM. 1986. Ion-aerosol attachment coefficients and the steady-state charge distribution on aerosols in a bipolar ion environment. Aerosol Sci. Tech. 5:1-21.

24. Chalmers, JA. 1967. Atmospheric Electricity, 2nd edition. Oxford: Pergamon Press.

25. Golde, RH. 1997. Physics of Lightning, Vol. 1. London: Academic Press, 99-117.

26. Shlanta, A and Moore, CB. 1972. Ozone and point discharge measurements under thunderclouds. J. Geophys. Res. 77:4500-4510.

27. *Field-effect research at the high voltage transmission research center, Section 4-Development of a numerical model of the electrical environment near and downwind of the bipolar HVDC transmission line,* EPRI, Palo Alto, CA: 1991. 4-1 to 4-59.

28. Carter, PJ and Johnson, GB. 1988. Space charge measurements downwind from a monopolar 500 kV HVDC test line. IEEE Tran Pwr. Del. 3:2056-2063.

29. Harrison, RG. 1996. Ionisers and electrical aerosol removal, Proceedings of Xth Ann Conf. of the Aerosol Society, Swansea, April 1996, 38-43.

30. EPRI and Johnson, GB. *HVDC Transmission Line Reference Book*, EPRI, Palo Alto, CA: 1993. TR-102764.

31. Chalmers, JA. 1952. Negative electric fields in mist and fog. J. Atm. Terr. Phys. 2:155-159.

32. Vonnegut, B and Moore, CB. 1959. Preliminary attempts to influence convective electrification in cumulus clouds by the introduction of space charge into the lower atmosphere. Recent Advances in Atmospheric Electricity. 17-331.

33. Vonnegut, B; Maynard, K; Sykes, WG; Moore, CB. 1961a. Technique for introducing low-density space charge into the atmosphere. J. Geophys. Res. 66:823-830.

34. Vonnegut, B; Moore, CB; Harris, CK. 1961b. Agrimeter for measurement of atmospheric electrical potential gradient. J. Met. 18:812-815.

35. Vonnegut, B; Moore, CB, Mallahan, FJ. 1961c. Adjustable potential-gradient-measuring apparatus for airplane use. J Geophys. Res. 66:2393-2397.

36. Vonnegut, B and Moore, CB. 1961d. Apparatus using radioactive probes for measuring the vertical component of atmospheric potential gradient from an airplane. Am. Metr. Soc. 42:773-777.

37. Moore,CB; Vonnegut,B; Semonin,RG; Bullock,JW; Bradley,W. 1962. Fair-weather atmospheric electric potential gradient and space charge over central Illinois, Summer 1960. J. Geophys. Res. 67:1061-1071.

38. Vonnegut, B; Moore, CB; Stout, GE; Staggs, DW; Bullock, JW; Bradley, WE. 1962a. Artificial modification of atmospheric space charge. J. Geophys. Res. 67:1073-1083.

39. Vonnegut, B; Moore, CB; Semonin, RG; Bullock, JW; Staggs, DW; Bradley, WE. 1962b. Effect of atmospheric space charge on initial electrification of cumulus clouds. J. Geophys. Res. 67:3909-3922.

40. Vonnegut, B; Smallman, CR; Harris, CK; Sykes, WG. 1967. Technique for the introduction into the atmosphere of high concentrations of electrically charged aerosol particles. J. Atm. Terr. Phys. 29:781-792.

41. Muir, MS. 1972. Electric space charge in the atmosphere. J. Atm. Terr. Phys. 34:941-946.

42. Hendrickson, R. 1983. Measurement of space charge from an AC high-voltage transmission line. Letter to editor-Transmission/Distribution Health & Safety Report, August 1983.

43. Bracken, TD; Senior, RS; Bailey, WH. 2003. DC electric fields from corona-generated space charge near AC transmission lines. *Submitted.*

44. Moore, CB; Vonnegut, B; Mallahan, FJ. 1961. Airborne filters for the measurement of atmospheric space charge. J Geophys. Res. 66:3219-3226.

45. Milner, JW and Chalmers, JA. 1961. Point discharge from natural and artificial points, Quart. J. Royal Meteorol Soc. 87:592-596.

46. Groom, KN and Chalmers, JA. 1967. Negative charges from high-tension power cables in fog. J. Atmos. Terr. Physics. 29:613-615.

47. Vonnegut, B and Rchnitzer, BW. 1974. Instrument for measuring maximum thunderstorm electric field intensity. Rev. Sci. Inst. 45:941-946.

48. Higashiyama, Y; Muto, S; Hori, K. 1979. Characteristics of discharge current from a needle electrode and its application to detection of a thundercloud approach. Electrical Engineering in Japan. 99:941-946.

49. Chartier, VL; Stearns, RD; Burns, AL. 1989. Electrical Environment of the uprated Pacific NW/SW HVDC Intertie. IEEE Trans. On Power Delivery, 4:1305-1317, April 1989.

50. Harris, R and Albertson, V. 1984. Ion emission from EHV transmission lines, In: Trends in Electric Utility Research CW Bullard and PJ Womeldorff (eds.). New York: Pergamon Press.

51. Bent, RB and Hutchinson, WCA. 1966. Electric space charge measurement on the electrode effect within height of 21 m mast. J. Atm. Terr. Phys. 28:53-73.

52. Swanson, J and Jeffers DE. 2000. Comment on the papers: increased exposure to pollutant aerosols under high voltage power lines; and Corona ions from powerlines and increased exposure to pollutant aerosols. Int. J. Radiat. Biol. 76:1685-1691.

53. National Radiological Protection Board (NRPB). 2001. Documents of the NRPB. Volume 12. ELF electromagnetic fields and the risk of cancer. Chilton, Didcot, Oxon OX11 0RQ.

54. Mühleisen, R. (1953. Die luftelektrischen elemente im großstadtbereich. Z. Geophysik, 29:142-160. *Cited in Fews et al., 1999.*

55. Carroll, JS and Lusignan, JT. 1927. The space charge that surrounds a conductor in corona. Trans. Amer. Inst. Elect. Eng. 1350-1357.

Program:
EMF Health Assessment

About EPRI

EPRI creates science and technology solutions for the global energy and energy services industry. U.S. electric utilities established the Electric Power Research Institute in 1973 as a nonprofit research consortium for the benefit of utility members, their customers, and society. Now known simply as EPRI, the company provides a wide range of innovative products and services to more than 1000 energy-related organizations in 40 countries. EPRI's multidisciplinary team of scientists and engineers draws on a worldwide network of technical and business expertise to help solve today's toughest energy and environmental problems.

EPRI. Electrify the World

Printed on recycled paper in the United States of America

1008148

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com