PD IEC TR 62681:2022

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# Electromagnetic performance of high voltage direct current (HVDC) overhead transmission lines

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# National foreword

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# TECHNICAL REPORT

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## Electromagnetic performance of high voltage direct current (HVDC) overhead transmission lines

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

# ELECTROMAGNETIC PERFORMANCE OF HIGH VOLTAGE DIRECT CURRENT (HVDC) OVERHEAD TRANSMISSION LINES

## FOREWORD

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IEC TR 62681 has been prepared by IEC technical committee 115: High Voltage Direct Current (HVDC) transmission for DC voltages above 100 kV. It is a Technical Report.

This second edition cancels and replaces the first edition, published in 2014. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) the limits of total electric field in some countries have been supplemented and improved;
b) the definition of 80 %/80 % criteria of radio interference has been clarified;
c) a table has been added for bipolar excitation which shows the parameters of the IREQ radio interference excitation function;
d) the clause of CEPRI research results of audible noise has been deleted;
e) the clause of main conclusion of audible noise has been deleted.

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The text of this Technical Report is based on the following documents:

| Draft | Report on voting |
|---|---|
| 115/289/DTR | 115/292/RVDTR |

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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- withdrawn,
- replaced by a revised edition, or
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# INTRODUCTION

Electric fields and magnetic fields are produced in the vicinity of a High Voltage Direct Current (HVDC) overhead transmission line. When the electric field at the conductor surface exceeds a critical value, known as the corona onset gradient, positive or negative free charges leave the conductor and interact with the surrounding air and ionization takes place in the layer of surrounding air, leading to the formation of corona discharges. The corona discharge will result in corona loss but also change the electro-magnetic properties around the HVDC overhead transmission lines.

The parameters used to describe the electromagnetic performance of an HVDC overhead transmission line mainly include the:

1) electric field,
2) ion current,
3) magnetic field,
4) radio interference,
5) audible noise.

To control these parameters in a reasonable and acceptable range, for years, a great deal of theoretical and experimental research was conducted in many countries, and relevant national standards or enterprise standards were developed. This document collects and records the status of study and progress of electric fields, ion current, magnetic fields, radio interference, and audible noise of HVDC overhead transmission lines. It is recognised that general technical discussion given in this document would be applicable for HVDC sub-stations as well; However, since layout of a station differs very differently, expressions given for HVDC overhead transmission line cannot be directly used as many assumptions would not hold good. Furthermore, an HVDC sub-station is not accessible to the general public, thus the numbers and limits given in this document are not applicable for HVDC sub-stations.

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# ELECTROMAGNETIC PERFORMANCE OF HIGH VOLTAGE DIRECT CURRENT (HVDC) OVERHEAD TRANSMISSION LINES

## 1 Scope

This document provides general guidance on the electromagnetic environment issues of HVDC overhead transmission lines. It concerns the major parameters adopted to describe the electromagnetic properties of an HVDC overhead transmission line, including electric fields, ion current, magnetic fields, radio interference, and audible noise generated as a consequence of such effects. If the evaluation method and/or criteria of electromagnetic properties are not yet regulated, engineers in different countries can refer to this document to:

– support/guide the electromagnetic design of HVDC overhead transmission lines,
– limit the influence on the environment within acceptable ranges, and
– optimize engineering costs.

## 2 Normative references

There are no normative references in this document.

## 3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

**3.1**
**corona**
set of partial discharges in a gas, immediately adjacent to an uninsulated or lightly insulated conductor which creates a highly divergent field remote from other conductors

[SOURCE: IEC 60050-212:2010, 212-11-44, modified – Note 1 has been deleted.]

**3.2**
**electric field**
constituent of an electromagnetic field which is characterized by the electric field strength $E$ together with the electric flux density $D$

Note 1 to entry: In the context of HVDC transmission lines, the electric field is affected not only by the geometry of the line and the potential of the conductor, but also by the space charge generated as a result of corona; consequently, electric field distribution may vary non-linearly with the line potential.

[SOURCE: IEC 60050-121:1998, 121-11-67, modified – The original note has been deleted and Note 1 to entry has been added.]

**3.3**
**space-charge-free electric field**
electric field due to a system of energized electrodes, excluding the effect of space charge present in the inter-electrode space

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**3.4**
**ion current**
flow of electric charge resulting from the motion of ions

**3.5**
**magnetic field**
constituent of an electromagnetic field which is characterized by the magnetic field strength $H$ together with the magnetic flux density $B$

[SOURCE: IEC 60050-121:1998, 121-11-69, modified – Note 1 has been deleted.]

**3.6**
**audible noise**
unwanted sound with frequency range from 20 Hz to 20 kHz

[SOURCE: IEC 61973:2012, 3.1.14]

## 4 Electric field and ion current

### 4.1 Description of the physical phenomena

Electric fields are produced in the vicinity of an HVDC transmission line, with the highest electric fields existing at the surface of the conductor. When the electric field at the conductor surface exceeds a critical value, the air in the vicinity of the conductor becomes ionized, forming a corona discharge. Ions of both polarities are formed, but ions of opposite polarity to the conductor potential are attracted back towards the conductor, while ions of the same polarity as the conductor are repelled away from the conductor. Space charges include air ions and charged aerosols. Under the action of an electric field, space charge will move directionally, and ion current will be formed. The physical phenomena of electric field and ion current are described in this Subclause 4.1.

The electric field and ion current in the vicinity of an HVDC transmission line are defined mainly by the operating voltage, line configuration, conductor radius and conductor surface. The voltage applied to line conductors produces an electric field distribution. Unlike High-Voltage Alternating Current (HVAC) transmission lines, the electric field produced by HVDC transmission lines does not vary with time and, consequently, does not produce any significant currents in humans or objects immersed in these fields.

The electric field is another aspect of the electrical property around an overhead HVDC transmission line. An electric field is present around any charged conductor, irrespective of whether corona discharge is taking place. However, the space charge created by corona discharge under DC conditions modifies the distribution of an electric field. The effect of space charge on electric fields is significant.

For the same HVDC transmission lines, the corona onset gradients of positive or negative polarities are different and the intensity and characteristics of corona discharges on positive or negative conductors are also different. Consequently, during the design of HVDC transmission lines, special consideration needs to be paid to the allowable values of the maximum ground-level electric field and ion current density [1][1].

[1] Numbers in square brackets refer to the bibliography.

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Corona on a conductor of either positive or negative polarity produces ions of either the positive or negative polarities in a thin layer of air surrounding each conductor [1]. However, ions with a polarity opposite to that of the conductor are drawn to it and are neutralized on contact. Thus, a positive conductor in corona acts as a source of positive ions and vice-versa. For a monopolar DC transmission line, ions having the same polarity as the conductor voltage fill the entire inter-electrode space between the conductors and ground. For a bipolar DC transmission line, the ions generated on the conductors of each polarity are subject to an electric field driven drift motion either towards the conductor of opposite polarity or towards the ground plane, as shown in Figure 1. The influence of wind or the formation of charged aerosols are not considered at this stage. Three general space charge regions are created in this case:

a) a positive monopolar region between the positive conductor and ground,

b) a negative monopolar region between the negative conductor and ground,

c) a bipolar region between the positive and negative conductors.

For practical bipolar HVDC lines, most of the ions are directed toward the opposite polarity conductor, but a significant fraction is also directed toward the ground. The ion drift velocity is such that it will take at least a few seconds for them to reach ground. Actually, the molecules travelling along ion paths are not always the same ions. In fact, collisions between ions and air molecules occur during the travel at a rate of billions per second and cause charge transfer and reactions between ions and neutral molecules, so the ions reaching the ground are quite different from those that were originally formed by corona near the conductor surface. The exact chemical identity of the ions, after a few seconds, will depend on the chemical composition and trace gases at the location.

Electric field is another component of the electrical property around an overhead HVDC transmission line. Electric field is caused by electrical charges, both those residing on conductive surfaces (the transmission line conductors, the ground, and conducting objects) and the space charges. The effect of space charge on electric field is significant.

A nonlinear interaction takes place between electric field and space charge distributions in all three general space regions identified above in a), b), c). The nonlinearity arises because ions flow from each conductor to ground or to the conductor of opposite polarity along the flux lines of the electric field distribution: while at the same time, the electric field distribution is influenced by the ionic space charge distribution. In addition to the nonlinear interaction described above, the space charge field in the bipolar region is affected by other factors. Mixing of ions of both polarities in the bipolar region leads firstly to a reduction in the net space charge density and, secondly, to recombination and neutralization of ions of both polarities.

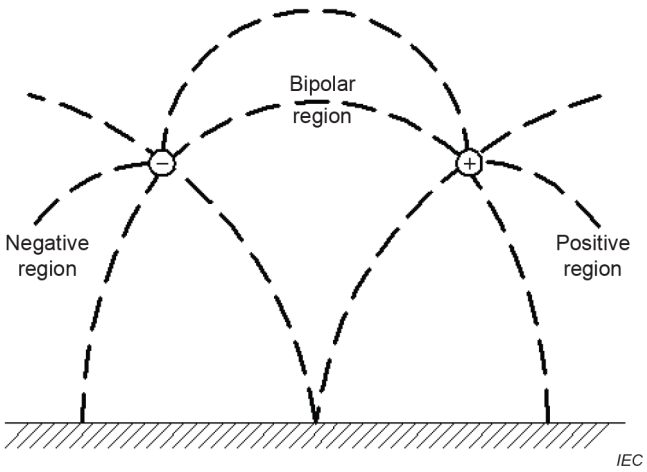


**Figure 1 – Monopolar and bipolar space charge regions of an HVDC transmission line [1]**

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The corona-generated space charge, being of the same polarity as the conductor, produces a screening effect on the conductor by lowering the electric field in the vicinity of the conductor surface and consequently reducing the intensity of corona discharges occurring on the conductor. In the monopolar regions, the space charge enhances the electric field at the ground surface. The extent of electric field reduction at the conductor surface and field enhancement at the ground surface depend on the conductor voltage as well as on the corona intensity at the conductor surface. In the case of the bipolar region, however, the mixture of ions of opposite polarity and ion recombination tend to reduce the screening effect on the conductor surface. This leads to a smaller reduction in the intensity of corona activity near the conductors than in the monopolar regions.

The electrical environment at ground level under a bipolar HVDC transmission line is, therefore defined mainly by three quantities:

1) electric field, $E$,
2) ion current density, $J$,
3) space charge density, $\rho$.

The electric field produced by HVDC overhead transmission lines is a vector defined by its components along three orthogonal axes. The space charge density is a scalar. The ion current density is also a vector, and it is affected by the electric field and space charge density.

Very small currents in some cases can flow through an object or person located under the line because of exposure to the electric field and ion space charge. From the point of view of environmental impact on persons and objects located under the line, the main consideration is the combined exposure to the electric fields and ion currents. The scientific literature indicates that exposure to the levels of DC electric field and ion current density existing under operating HVDC transmission lines poses no risk to public health, but may cause some induced current and annoyance effects to humans.

Design of HVDC transmission lines requires the ability to predict ground-level electric field and ion current distribution as functions of line design parameters such as the number and diameter of sub-conductors in the bundle, height above ground of conductors and pole spacing. Prediction methods are based on a combination of analytical techniques to calculate the space charge fields and accurate long-term measurements under experimental as well as operating HVDC transmission lines.

As described and illustrated in Figure 1, the ground-level electric field and ion current property under a bipolar HVDC transmission line can be thought primarily as a monopolar space charge field under each pole. The bipolar space charge field between the positive and negative conductors, however, has no significant impact on the ground-level electrical property. For the purpose of calculating the ground-level electric field and ion current distributions, therefore, analytical treatment of the monopolar space charge field between each of the positive and negative conductors and the ground plane is adequate.

Monopolar DC space charge fields are defined by the following equations:

$$\nabla \cdot E = \frac{\rho}{\varepsilon_0} \tag{1}$$

$$J = \mu \rho E \tag{2}$$

$$\nabla \cdot J = 0 \tag{3}$$

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where

$E$ and $J$ are the electric field and ion current density vectors at any point in space,

$\rho$ is the space charge density,

$\mu$ is the ionic mobility,

$\varepsilon_0$ is the permittivity of free space.

The first Equation (1) is Poisson's equation, the second Equation (2) defines the relationship between the current density and electric field vectors, and the third Equation (3) is the continuity equation for ions. Since electrons are existent in the zone very close to the conductors and attached to air molecules forming negative ions, they are not considered. The solution of these equations, along with appropriate boundary conditions, for the conductor-ground-plane geometry of the HVDC transmission line, determines the ground-level electric field and ion current distributions [1].

Corona activity on conductors and the resulting space charge field are influenced, in addition to the line voltage and geometry, by ambient weather conditions such as temperature, pressure, humidity, precipitation and wind velocity as well as by the presence of any aerosols and atmospheric pollution. It is difficult, if not impossible, to take all these factors into account in any analytical treatment of space charge fields. Information on the corona onset gradients of conductors, which is an essential input in the analytical determination of electric field and ion current density, is also difficult to obtain under practical operating conditions. For these reasons, analytical methods are employed in combination with accurate long-term measurements of ground-level electric field and ion current distributions under experimental as well as operating HVDC transmission lines, in order to develop prediction methods. Some of the information required in the analytical treatment, such as corona onset gradients of conductors, can be obtained only through experimental studies. Reliable experimental data are also essential in validating the accuracy of analytical or semi-analytical methods for predicting the ground-level electric field and ion current distributions under HVDC transmission lines.

NOTE 1 Industry consensus and standards have not been reached on appropriate analytical methods to capture all effects of weather in the calculation of enhanced fields due to space charge.

NOTE 2 As described in reference [4], the conditions most conducive to enhanced fields due to space charge (wet conductor conditions in fog, with zero wind) occur for a very small percentage of time over a given year.

NOTE 3 As further pointed out in reference [4], to attempt to address very rare conditions in the design of an HVDC transmission line is not fully justifiable, given the lack of clear standards, analytical methods, and consensus on the subject.

The atmosphere has a large quantity of aerosol particles. When such particles are present in the ion flow around a stressed HVDC conductor, the ions will be captured by the particle because of Brownian motion and the motion driven by electric force. A charging process dictated by ions diffusing to particles is called diffusion charging [2]. This mechanism does not involve any external electric fields and some experiments indicate that it has insignificant relations with electrical properties of particles. Electrical properties are characterized by electrical conductivity and permittivity. As the charge accumulates on the particle surface, the electric field around the particle gets stronger, leading to a reduction of diffusion charging rate. The other charging process controlled by electric field is named field charging [2]. Unlike diffusion charging, several experiments show that the charging process relies heavily on the electrical parameters. The physical mechanism behind this phenomenon is Maxwell-Wagner relaxation of the electric field around the particle in the presence of an external electric field [3].

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## 4.2 Calculation methods

### 4.2.1 General

Ground-level electric field and ion current distribution under HVDC transmission lines depend primarily on the conductor bundle and on the minimum height above ground of conductors. Pole spacing has a secondary influence on the electric field and ion current distributions, and is selected mainly on the basis of air gap clearances required to withstand the maximum values of overvoltage that can appear on the conductors.

Corona performance criteria, particularly for radio interference (RI) and audible noise (AN), are used to select the number and diameter of conductors in the bundle required on each pole. Conductor height and pole spacing have a secondary influence on the RI and AN performance.

Following the selection of the conductor bundle based on RI and AN design criteria, the minimum conductor height is selected on the basis of design criteria for ground-level electric field and ion current density. The conductor heights selected using these criteria are generally significantly higher than would be required from insulation and safety considerations.

Calculation of the desired ground-level electric field and ion current distribution for proposed HVDC transmission line configurations is, therefore, an essential step in selecting the minimum conductor height. Methods of calculation that are presently available for this purpose are described below.

Calculation methods for determining electric field and ion current distributions involve the solution of the boundary value problem described by the set of Equations (1) to (3) along with appropriate boundary conditions. The first rigorous analytical solution to the monopolar space charge modified field problem was obtained by Townsend [5] for the concentric cylindrical configuration. The main interest in this solution was to obtain the voltage-current characteristic for a thin wire at high voltage and in corona, placed concentrically inside a large metallic cylinder at ground potential.

Popkov [6] extended Townsend's solution to the geometry of a conductor above a ground plane and obtained a semi-empirical equation for determining the voltage-current characteristic. Popkov's solution is concerned mainly with the voltage-current characteristic and does not provide a solution for the ground-level electric field and ion current distribution.

Equations (1) to (3) define the monopolar corona problem for the general case of three dimensional electrode configurations. However, if the electrode geometry is characterized by symmetry in two dimensions, then the equations reduce to one dimensional form. For example, in the case of the concentric cylindrical geometry considered by Townsend, symmetry may be assumed to exist in the longitudinal and angular coordinates of the cylindrical coordinate system. The defining equations reduce, therefore, to one dimensional form in the radial coordinate, making it possible to obtain an analytical solution to the monopolar corona problem.

In the case of DC transmission lines, the geometry may be assumed to consist of a number of cylindrical conductors parallel to each other and also to the ground plane above which they are placed. This is essentially a two-dimensional geometry, since symmetry exists along the longitudinal direction of the conductors. The boundary value problem defined by Equations (1) to (3), therefore, reduces to a two-dimensional form in this case.

Since it is almost impossible to obtain analytical solutions to the two-dimensional space-charge-modified fields, such as those associated with DC transmission lines, it becomes necessary to use numerical techniques.

It should also be mentioned that the defining Equations (1) to (3) of monopolar corona do not take into account some of the practical considerations such as the influence of wind on the ion flow.

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### 4.2.2 Semi-analytic method

The first method for solving Equations (1) to (3) for multiconductor DC transmission line configurations was developed by Maruvada and Janischewskyj [7] [8]. The method, originally developed to calculate corona loss currents, involves the complete solution of the monopolar space charge modified fields and, consequently, the determination of the ground-level electric field and ion current density distributions. The method of analysis does not include the influence of wind.

The method of analysis is based on the following assumptions:

a) the space charge affects only the magnitude and not the direction of the electric field,

b) for voltages above corona onset, the magnitude of the electric field at the surface of the conductor in corona remains constant at the onset value.

The first assumption, often referred to as Deutsch's [9] assumption, implies that the geometric pattern of the electric field distribution is unaffected by the presence of the space charge and that the flux lines are unchanged while the equipotential lines are shifted. Since HVDC transmission lines are generally designed to operate at conductor surface gradients which are only slightly above corona onset values, corona on the conductors generates low-density space charge and the ions may be assumed to flow along the flux lines of the space-charge-free electric field. This assumption is much more valid for DC transmission lines than for electrostatic precipitators where corona intensity and space charge densities are very high.

The second assumption, which was also implied in Townsend's analysis, has been justified from theoretical as well as experimental points of view [8].

In mathematical terms, the first assumption implies that:

$$E = \xi E' \tag{4}$$

where

$E$ is the electric field vector in the presence of space charge,

$E'$ is the space-charge-free electric field vector,

$\xi$ is a scalar point function which depends on the charge density distribution. The value of $\xi$ at any point may be defined as the field modification factor.

This assumption has the distinct advantage of converting an essentially two dimensional problem into an equivalent one dimensional problem along the flux lines of the space-charge-free electric field. The boundary value problem defined by the partial differential Equations (1) to (3) are converted [8] to one described by the set of ordinary differential equations:

$$\frac{\mathrm{d}\Phi}{\mathrm{d}\varphi} = \xi \tag{5}$$

$$\frac{\mathrm{d}\xi}{\mathrm{d}\varphi} = -\frac{\rho}{\varepsilon_0 (E')^2} \tag{6}$$

$$\frac{\mathrm{d}\rho}{\mathrm{d}\varphi} = \frac{\rho^2}{\varepsilon_0 \xi (E')^2} \tag{7}$$

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where

$E'$ and $\varphi$ are the space-charge-free electric field intensity and potential respectively,

$\Phi$ is the potential in the presence of space charge,

$\rho$ is the charge density,

$\xi$ is the field modification factor, at any given point along the flux line.

The differential Equations (5) to (7) describe the variation of the dependent variables $\Phi$, $\xi$ and $\rho$ as functions of the independent variables $\varphi$ and $E'$ along a flux line of the space-charge-free electric field. For a given line configuration and applied voltage, the flux lines of the space-charge-free electric field can be traced and values of $E'$ and $\varphi$ along any flux line determined [8].

The boundary conditions required to solve Equations (5) to (7) are given in terms of the voltage applied to the conductor and the magnitude of the electric field at the surface of the conductor in corona. If the voltage applied to the conductor with respect to the ground plane is $U$, the space-charge-free electric field at the conductor surface corresponding to the voltage $U$ is $E'_s$, and the corona onset gradient of the conductor is $E_0$, then according to the second assumption, $\xi = \left(\frac{E_0}{E'_s}\right)$ at the conductor surface. The complete set of boundary conditions may then be written as

$$\Phi = U \text{ at } \varphi = U \tag{8}$$

$$\Phi = 0 \text{ at } \varphi = 0 \tag{9}$$

$$\xi = \left(\frac{E_0}{E'_s}\right) \text{ at } \varphi = U \tag{10}$$

If $E'_g$ is the space-charge-free electric field at the point where the flux line meets the ground plane and $\xi_g$ and $\rho_g$ are the computed values at this point of the field modification factor and charge density respectively, the electric field $E_g$ and ion current density $j_g$ at this point are obtained as,

$$E_g = \xi_g E'_g \tag{11}$$

$$j_g = \mu \xi_g \rho_g E'_g \tag{12}$$

Where $\mu$ is the ion mobility.

The method developed by Maruvada and Janischewskyj can be applied to determine the ground-level electric field and ion current distributions under monopolar or bipolar DC transmission lines with single or bundled conductors and with or without overhead ground wires [8].

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Application of the method developed by Maruvada and Janischewskyj requires knowledge of the geometric parameters of the line configuration, voltage applied to the line conductors and the corona onset gradients of the conductors. The calculation procedure requires the following steps:

1) for the given line configuration and conductor voltages, flux lines of the space-charge- free electric field, which originate on the conductors in corona and terminate on the ground plane, are traced;
2) for each flux line selected, the distribution of the electric field $E'$ is determined as a function of $\varphi$ along the flux line;
3) knowing the distribution of $E'$ as a function of $\varphi$ along the flux line, the boundary value problem defined by Equations (5) to (7) is solved, using the boundary conditions in Equations (8) to (10) to obtain $\Phi$, $\xi$ and $\rho$ as functions of $\varphi$ at all points along the flux line;
4) the magnitudes of the ground-level space charge modified electric field $E_g$ and ion current density $j_g$ at the point where the flux line terminates on the ground plane are then calculated using Equations (11) and (12);
5) by repeating steps 2 to 4 for a number of flux lines, the complete distributions of $E_g$ and $j_g$ along the ground plane are determined.

### 4.2.3 Finite element method

Gela and Janischewskyj [10] developed the first finite element method (FEM) for solving the monopolar space charge modified field problem without recourse to Deutsch's assumption. One of the main objectives of this study was to evaluate the errors which might result by the use of Deutsch's assumption in the Maruvada and Janischewskyj method.

The Gela and Janischewskyj method was developed specifically for the case of a monopolar DC line with a single conductor above ground [11] [12]. However, the method has the potential of further development for cases of lines with bundled conductors, overhead ground wires, etc.

For the FEM analysis, the defining Equations (1) to (3) of monopolar DC corona are expressed in terms of potential as,

$$-\nabla\cdot\nabla\Phi = \frac{\rho}{\varepsilon_0} \tag{13}$$

$$-\nabla\cdot\left(\rho\nabla\Phi\right) = 0 \tag{14}$$

$$\nabla\Phi = -\mathbf{E} \tag{15}$$

The set of Equations (13) to (15) is solved iteratively for $\Phi$, by updating and recalculating the spatial distribution of $\rho$ at the beginning of each iteration. The FEM [13] with linear triangular elements is employed to solve the partial differential Equations (13) and (15) for $\Phi$ at each iteration step. The iterative procedure is initiated with the first estimate obtained using the Maruvada and Janischewskyj method. Convergence of the iterative process is considered to have taken place when no further improvements are observed in $\rho$ and both Equations (13) and (14) produce the same value of $\Phi$.

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Since Equations (13) and (14) are of second order, only two boundary conditions are needed to obtain a solution. These are provided by the values of $\Phi$ on the conductor surface and on the ground plane. The boundary condition that the magnitude of the electric field at the surface of the conductor in corona remains constant at the onset value, is not necessarily enforced during the solution of Equations (13) and (14). The extent to which this boundary condition is violated at any particular iteration provides information for updating and correcting the distribution of $\rho$ for the next iteration, until convergence is achieved.

The final results of the iterative solution are values of $\rho$ and $\Phi$ at the nodes of the finite element grid. Values of $E$, $\rho$ and $j$ at any points of interest, such as along the surface of the conductor or the ground plane, are derived subsequently.

Computational results obtained by the application of Gela and Janischewskyj method to the case of a monopolar DC line configuration with a single conductor lead to the following observations [12]:

a) distributions of electric field intensity at ground are not sensitive to Deutsch's assumption;

b) Deutsch's assumption can give rise to significant errors in the current density profiles at ground, particularly for certain line configurations operating at voltages well above corona onset;

c) however, for practical DC transmission line configurations and normal operating voltages, the use of Deutsch's assumption provides results of acceptable accuracy.

#### 4.2.4 BPA method

A simplified method of analysis was developed at the Bonneville Power Administration (BPA) [14] for determining the ground-level electric field and current density under monopolar and bipolar DC transmission lines. In addition to the two assumptions mentioned in 4.2.2 and 4.2.3, other simplifying assumptions were made to develop the computer program ANYPOLE which was made available in the public domain. The other simplifying assumptions made in developing this program are:

– the conductor bundle is replaced by an equivalent single conductor with the same capacitance as the conductor bundle;

– the ion current is assumed to be uniformly distributed around a single conductor or an equivalent single conductor replacing the bundle.

Gaussian flux tube concept is used to obtain numerical solutions to the electric field and ion current distributions along the ground plane.

#### 4.2.5 Empirical methods of EPRI

Empirical methods are generally derived from extensive experimental data obtained preferably on operating HVDC transmission lines, but also on full-scale test lines. In order to derive valid and accurate methods, the experimental data are obtained for lines of different voltages and configurations with a wide range of values for parameters such as conductor bundle, conductor height and pole spacing in the case of bipolar lines. The validity is usually restricted to the range of values of line parameters for which the experimental data, used to derive the empirical method, was obtained. Extrapolation of the empirical method outside the range of these parameters can give rise to significant errors.

Unfortunately, empirical methods based on good experimental data are presently not readily available for determining the ground-level electric field and ion current distributions under monopolar or bipolar DC lines.

A semi-empirical method, called the "degree of corona saturation" method, was proposed ([15], [16]) for calculating ground-level electric fields and ion currents under bipolar DC lines. This technique is incorporated in the workstation, an EPRI proprietary program. The basic principle of the method is given by the equation.

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$$Q = Q_e + S\,(Q_S - Q_e) \tag{16}$$

where

$Q_e$ is the electrostatic value of any parameter (electric field, ion current density or space charge density),

$Q_S$ is the saturated value of the parameter

$S$ is the degree of saturation.

The electrostatic value $Q_e$ of the parameter can be calculated using the well-established electrostatic field theory. It should be noted that the electrostatic values of current density and charge density are zero.

Equations were derived for the saturated values of $Q_S$ of the electric field, ion current density and charge density, based on laboratory tests on reduced-scale models with thin wires of monopolar and bipolar DC line configurations [17]. The degree of corona saturation factor $S$ was derived from full-scale tests carried out on a number of bipolar DC line configurations.

It should be noted that the degree of corona saturation method is not a purely empirical method as described at the top of this Subclause 4.2.5. It involves some theoretical modelling and an assumption that results of scale model tests on thin wires can be extrapolated to the case of full-scale lines with practical conductor bundles. Questions were also raised on the difficulty in justifying some of the assumptions involved in the theoretical modelling from the point of view of basic corona physics.

### 4.2.6 Recent progress

Following the work of Gela and Janischewskyj, other FEM solutions were obtained for the space charge modified fields of both monopolar and bipolar DC transmission lines [18], [19]. In some of these studies, the solution was obtained assuming that the charge distribution on the conductor surface, rather than the electric field, was known and used as a boundary condition. Because of this assumption, these methods can be used to interpret experimental results but not for predicting the ground-level electric fields and ion current distributions for different transmission line designs with specified voltages applied to the conductors.

In other FEM based solutions [20] [21] [22] [23], the electric field boundary condition was used and, consequently, they can be used to predict the electric field and ion current distributions under practical DC transmission line configurations.

Using ion transit-time formalism, useful approximate calculations have been made [24] for space charge densities in a broad range of systems containing air ions.

In addition to those calculation methods mentioned in 4.2.2 to 4.2.5, the finite difference method [25], charge simulation method [20], multigrid method [26] and finite element method and finite volume method [27] are also used to predict the ground-level electric field under HVDC transmission lines.

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## 4.3 Experimental data

### 4.3.1 General

In order to check the validity and accuracy of the calculation methods for ground-level electric field and ion current density distributions under HVDC transmission lines, it is necessary to compare the results of calculation with experimental data obtained on corona test lines and, preferably, on operating lines. The experimental data used in any comparison need to be measured using appropriate instrumentation and need to meet requirements of reliability and accuracy. It is also preferable to obtain long-term statistical data under different weather conditions. In addition to the electrical parameters required to characterize the electric field and space charge environment, the measurements need to include parameters defining the ambient weather conditions such as temperature, pressure, humidity, wind speed and direction and precipitation.

There may be uncertainties of measured values on electromagnetic fields from different laboratories and companies due to the use of different measuring techniques and instruments. This can lead to a difficulty in the measurement result interpretation and comparison. In this document, only the measurement results in different references are given, and the data are not evaluated.

### 4.3.2 Instrumentation and measurement methods

For both monopolar and bipolar DC lines, the electrical environment at ground level is characterized by the electric field intensity, ion current density and space charge density. In the case of bipolar DC lines, although ions of both polarities are created and mix in the bipolar region between the conductors, an essentially monopolar space charge of either positive or negative polarity exists at the ground level. In the presence of wind, the positive and negative ion profiles will shift and positive ions may drift toward the ground surface on the negative pole side of the DC line and vice-versa, depending on the direction of wind. The instrumentation and measurement methods for characterizing the electrical environment in the vicinity of DC lines are described in IEEE Std 1227 [28].

Different techniques have been used to measure the electric fields of HVDC over-head transmission lines, and basically two types of instruments are used to measure the electric field strength at ground level:

a) field mills;

b) vibrating plate electric field meters.

Both instruments measure the electric field strength by measuring modulated capacitively induced currents sensed by metal electrodes.

Field mills are commonly used to measure the electric field strength at ground level. A field mill instrument [29] consists essentially of a fixed sensing electrode above which a rotating shutter electrode is placed. As the sensing electrode is alternately exposed to and shielded from the electric field, a current is induced between the sensing electrode and ground that is proportional to the electric field strength. Measurement of the induced current, or voltage across known impedance that is located between the sensing electrode and ground, determines the electric field strength.

A vibrating plate instrument [30] consists of a sensing electrode placed below an aperture in a metallic plate and vibrated using a mechanical driver. The vibrations modulate charges induced in the sensor plate and the resulting current is proportional to the electric field strength. Measurement of the induced current, therefore, provides an indication of the electric field strength.

Ion current density at ground level is determined by measuring the current collected by a flat plate, known as a Wilson plate [31], located flush with the ground plane. The current density $J$, averaged over the area $A$ of the plate, is given by:

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$$J = \frac{I}{A} \tag{17}$$

Where $I$ is the current collected by the plate.

Monopolar charge density is measured using aspirator-type ion counters [32]. The air ions are drawn through a parallel plate collector system using a motor driven blower. Alternate plates are connected together and a polarizing potential is applied between the two sets of plates. Collection of the ions on plates of opposite polarity gives rise to a current, which is measured using an electrometer. The charge density $\rho$ measured by the ion counter is given as

$$\rho = \frac{I}{M_0} \tag{18}$$

where

$I$ is the measured ion current

$M_0$ is the volumetric air flow rate.

Guidelines for the measurement of ground-level electric field strength, ion current density and space charge density under HVDC transmission lines are provided in the IEEE Std 1227 [28]. For accurate unperturbed measurement of these quantities the field meters, Wilson plates and ion counters are generally installed below ground so that the measuring interfaces of the instruments are flush with the ground plane. Significant errors may be caused in the measured quantities if these instruments protrude above the ground plane [28] unless values are corrected based upon measured form or correction factors for the altered geometry. The influence of a DC electric field on measurement of monopolar space charge densities with an ion counter can be made negligible when the measurements are performed in the ground plane, and oriented vertically or horizontally above the ground plane with an attractive potential applied to the ion counter housing. This assumes that the collecting electrode(s) in the ion counter is adequately shielded from the external electric field. The impact of rain and snow on the measurement instrumentation can also be considered during installation and use. Errors can result during rain or snow unless the instrumentation has been installed so that it can successfully operate during these conditions.

Because of large variations caused by weather conditions, long-term measurements are necessary to obtain statistical distributions as well as lateral profiles of the principal parameters. This is achieved by making simultaneous long-term measurements at several points in a plane perpendicular to the transmission line at mid-span [33], [34]. The measurement locations generally include points directly below the positive and negative conductors and at lateral distances of 15 m, 30 m and 60 m from the conductors on both sides of the line. More measuring points may be selected, depending on the availability of instruments, to obtain better lateral distributions.

If possible, the measurements need to be carried out at several locations along a line to take into account climatic differences that can occur at different locations on long HVDC lines. Climatic data at a number of points along the line can also be collected separately to establish the prevalence of conditions that could lead to increased field and ion current levels.

Calibration of the instruments is an essential part of the measurement program. A special parallel-plate apparatus [35], capable of generating known electric fields, ion current densities and space charge densities is required to calibrate all the instruments. Periodic calibration of the instruments, identification of possible sources of error and taking appropriate precautions [28] are necessary to ensure the validity and accuracy of the data acquired.

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In addition to electric field strength, ion current density and monopolar space charge density, instruments have also been developed [28] for the measurement of electrical conductivity of air with a device known as Gerdien tube and the net space charge density using either a Faraday cage or a filter device. Conductivity measurements are rarely carried out under DC lines, but net space charge measurements are sometimes made at large distances from DC lines, mainly to detect the presence of charged aerosols.

### 4.3.3 Experimental results for electric field and ion current

Only a limited amount of experimental data are available in peer-reviewed publications on the corona performance of DC transmission lines, especially on operating lines and particularly on the ground-level electric field and ion current distributions. This may be attributed to a large extent to the technical difficulties and costs involved in making accurate and simultaneous long-term measurements at a number of points along a line perpendicular to the transmission line. Periodic calibration of the instruments is necessary to ensure acceptable accuracy of the long-term measurements.

Experimental data in peer-reviewed publications includes those obtained on outdoor test lines as well as operating HVDC transmission lines. However, test line data obtained at voltages well above the transmission voltages presently used and line dimensions (pole spacing and conductor height) outside the range used for practical line design [36] [37] are not included in this document. With this exclusion, the data available for possible comparison with any methods of calculation reduce to those obtained on four operating DC transmission lines [34] [38] [39] [40] [41] [42] and two test lines [43] [44]. Except for the BPA line [34], all other lines are located at approximately the sea level.

Details of line design parameters, adopted instrumentation and measurement program are described in the following. Statistical summaries of the experimental data obtained at each of the four test sites are also included.

For a bipolar horizontal line, the largest fields occur just outside each conductor. At all locations, the range of values of electric field depending on the variability of space charge. To describe the variable nature of electric field, the median and practical maximum are often given. The median level ($L_{50}$) is that exceeded 50 % of the time during the measurement period. Characterization of the practical maximum is also done in terms of an exceedance level, such as the $L_5$ exceedance level, i.e. the level exceeded only 5 % of the time.

The more and detailed experimental results for the electric field and ion current are shown in Annex A.

### 4.3.4 Discussion

The experimental data presented in 4.3.3, obtained on four operating DC transmission lines and three test lines, are probably the best data available in published literature. However, the database is not large enough to get significant conclusions regarding the influence of line parameters on ground-level electric field and ion current distributions.

The BPA ±500 kV DC line data are probably the best long-term data obtained in different weather conditions. The FURNAS ±600 kV DC line data was obtained during four one-month periods distributed over one year. The use of vibrating-plate field meters inverted and placed above a ground plane casts some doubt on the accuracy of electric field measurements in the presence of space charge in this study [28].

The test duration in the case of Manitoba Hydro ±450 kV DC line study is too short (four days). The short test duration and the use of single set of instruments for lateral profile measurements make it difficult to obtain an accurate statistical description of the data. Finally, the IREQ ±450 kV DC line data, although it is good from the aspect of test duration (one year) and instrumentation, were obtained on a test line rather than an operating line.

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The BPA study has shown a significant asymmetry between the measured values of electric field and ion current density under the positive and negative poles of the line, with the levels under the negative pole being 2 to 3 times higher than those under the positive pole. This trend is also observed in the case of FURNAS line data, with the electric field and ion current levels under the negative pole being more than two times higher than those under the positive pole. No significant asymmetry has been observed, however, in the results obtained in the case of IREQ test line. Data at HVTRC have indicated asymmetry of field and ions for the polarities but vary by season. During the mid to late summer, the results under the positive pole were higher than those under the negative pole but opposite during the winter/very dry periods.

Electric field intensity and ion current density levels under BPA ±500 kV DC line were compared with calculations made using the BPA analytical method. It was found that the calculations agreed with the $L_{10}$ levels of the measured probability distribution in fair weather conditions. It was also found that agreement between the calculated and measured levels was quite good for negative pole, but very poor for positive pole [186]. Similarly, a limited comparison was made between the measured lateral profile under the positive pole of the Manitoba Hydro DC line and calculations made using the Maruvada and Janischewskyj method [12]. It was found that calculations agreed well with measurements if a conductor surface irregularity factor of 0,4 was assumed.

Some new phenomena have been discovered in the test study in China and are shown as follows.

a) Effect of conductor pollution on the total electric field

   The previous pollution study is mainly about the effect on insulation level, and in the electromagnetic weather study, more attention is focused on rain, snow, and general pollution as by dust, smoke and insects. A test in the winter of 2007 [181] shows that the total electric field is larger when the conductor is dry and has been subject to pollution for a long period. After cleaning, the total electric field decreases greatly. The total electric field of clean conductor is almost half of that of a polluted conductor. So, it is necessary to study a quantitative description for pollution level and quantitative analysis for the effect of pollution on the total electric field.

b) Increase of the total electric field at ground with low humidity

   During the test in winter, it is discovered that the total electric field is obviously increased when the humidity is very low, but the current is almost the same [181]. There is no report about this phenomenon in domestic or international articles, and the mechanism needs to be studied in the future.

   Based on a review of published literature, it is concluded that the available experimental data on the electric field and ion current property under DC transmission lines is inadequate at present for purposes of rigorous comparison with existing methods of calculation or deriving any empirical methods of calculation.

## 4.4 Implication for human and nature

### 4.4.1 General

Static electric fields and space charge (i.e., air ions and charges on aerosols) are produced by DC transmission lines, but they are also generated by natural sources. This Subclause 4.4 summarizes scientific research on these electrical parameters in relation to humans and animals in nature. It also summarizes the conclusions of reviews prepared by scientific organizations and discusses applicable standards and guidelines.

### 4.4.2 Static electric field

Although static electric fields are present at varying levels in nature, relatively little biological research has been performed because the physical interaction of a static electric field with a human or animal body is confined to charges on the surface of the organism. No currents or electric fields are induced inside the body. At sufficiently high levels, a static electric field can be sensed by the movement of body hair [45] [46] [182].

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A psychophysical study of the ability of human subjects under carefully controlled conditions to detect a static electric field reported a range of perception thresholds, but the average critical detection value was 40,1 kV/m; when air ions were present in high concentrations, the threshold was lower [47]. Testing conducted outdoors indicated that most people would not detect static electric fields at a level under 25 kV/m [48] [163]. It should be noted that the enhanced electric field under an HVDC line is not expected to be over 50 kV/m.

Other studies of human subjects exposed to static electric fields over a range of field strengths between 1 kV/m and 90 kV/m of varying duration, including daily exposures for up to 6 months, report no consistent behavioural or physiological responses (e.g. [49] [50] [51] [52]).

A variety of studies have also examined behavioural and biological responses of animals to static electric fields. Except for a few isolated reports of behavioural responses to high-strength static electric fields, these studies report no effects [183]. It should be noted that, if the field could be detected by animals, this sensory stimulus could be expected to affect a range of spontaneous and trained behaviours.

Some of the most important studies in this group are those that looked for evidence of toxicity at longer durations of exposure. Fam found no adverse effects of long-term exposures of rats and their offspring to 340 kV/m static electric fields [53]. Kellogg and Yost reported no difference in the longevity of mice exposed to 2 kV/m static electric fields or ambient field conditions [54]. A laboratory at The Rockefeller University reported that exposure of rats to static electric fields of 3 kV/m and 12 kV/m for 2 h, 18 h, and 66 h had no effect on behaviour or brain neurotransmitter activity [55] [56] [57].

Under most circumstances, the static electric fields from a 500-kV DC transmission line would not be strong enough to be perceived, particularly outside the right-of-way (ROW). The absence of a mechanism by which static electric fields could produce an exposure to cells inside the body combined with the absence of human and animal evidence for adverse effects are important considerations in the assessment of potential effects. If a person (or large object) were to be very well insulated from the ground in a static electric field substantially greater than 25 kV/m, however, transient spark discharges to grounded objects could lead to annoying shocks, like a carpet shock in one's home.

### 4.4.3 Research on space charge

#### 4.4.3.1 General

Since their discovery [58], air ions and charged aerosols have been studied for effects on humans and animals, as well as microorganisms, plants and insects. Within each of these species, there are few studies of substantial depth and quality and with findings that have been verified by other independent investigators. Most studies fail to control crucial aspects of the experimental situation that can significantly influence the outcome of the experiment.

For the purposes of this document, the focus will be limited to studies of humans and animals. Since exposures to air ions in nature and laboratories necessarily involve exposure to some charged aerosols, all studies reflect exposures to both forms of space charge to a greater or lesser extent.

As with static electric fields, the interaction of space charge with an organism is limited to the surface of the body with the exception that air ions and aerosols may attach to the interior of the respiratory tract during respiration. Given the potential for internal exposures from airborne ions and aerosols by respiration and the prevalence of media and scientific attention to potential behavioural and psychological effects of air ions, research on these two topics is the focus of the following discussion.

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#### 4.4.3.2 Air ions

The effects of artificially generated air ions on humans have been studied for both experimental and clinical therapeutic purposes. A wide range of concentrations has been tested on humans, but there is no good evidence that effects attributed to air ion exposure are more likely at higher ion concentrations.

Some experimental sources of air ions also produce excessive levels of ozone, an irritant gas, but few investigators have checked for or measured this potential source of inaccuracy. Measurements and calculations of ozone levels near DC transmission lines show that the amounts generated are small and disperse to levels that are barely measurable and, thus, have no health safety environment (HSE) consequence. Ion concentrations are generally lower than $1{,}0 \times 10^5$ ions/cm$^3$ at DC transmission lines in fair weather and lower than $2{,}0 \times 10^4$ ions/cm$^3$ at the edge of the right-of-way (ROW). Some examples of typical air ion concentrations (ions/cm$^3$) found at other locations are: (HSE can be defined)

- Fair weather open space $7{,}0 \times 10$ to $2{,}0 \times 10^3$ ions/cm$^3$
- In large towns up to $8{,}0 \times 10^4$ ions/cm$^3$
- 0,30 m (12 in) above burning match $2{,}0 \times 10^5$ to $3{,}0 \times 10^5$ ions/cm$^3$
- 60,96 m (200 ft) from small waterfall $1{,}5 \times 10^3$ to $2{,}0 \times 10^3$ ions/cm$^3$
- 1,52 m (5 ft) downwind of vehicle exhaust about $5{,}0 \times 10^4$ ions/cm$^3$

While some studies have suggested that positive ions may adversely affect pulmonary function [59] [60] [61] [62], other more systematic and quantitative experiments, as well as a double-blind clinical study, have not substantiated this suggestion [63] [64] [65] [66] [67] [184].

In some early studies, the investigators reported respiratory irritation. Respiratory dryness or irritation symptoms were reported in one of these early studies by about 20 % of subjects exposed to $5{,}0 \times 10^3$ ions/cm$^3$ to $1{,}0 \times 10^4$ ions/cm$^3$ [68]. The study, however, was blind (not double-blind) and was conducted during the winter, when upper respiratory symptoms are common, as pointed out by the study's author.

In a series of double-blind clinical studies [61], positive ions were more effective in producing irritation symptoms than negative ions at the lower exposure levels, but not at higher exposure levels ($10^5$ ions/cm$^3$). Symptoms were minor and included headache, nasal obstruction, husky voice and sore throat, itching nose, or dizziness in 16 subjects exposed to $3{,}2 \times 10^4$ positive ions/cm$^3$. Similar symptoms were experienced in 4 of 13 subjects exposed similarly to negative ions. Studies also have shown, however, that exposure to air ions did not result in respiratory irritation symptoms at exposure levels of $1{,}0 \times 10^4$ ions/cm$^3$ [65], $1{,}25 \times 10^5$ ions/cm$^3$ [64], and $5{,}0 \times 10^5$ ions/cm$^3$ [66].

Subjects with asthma, hay fever, or chronic obstructive pulmonary diseases seemed not to be at excess risk of irritation symptoms [61] [63].

Although some studies have suggested beneficial effects of short-term exposure to negative air ions for the treatment of allergies or asthma [59] [60] [64], other more rigorous studies have demonstrated that neither negative nor positive ions have a substantial effect on symptoms of asthma or hay fever, an effect on response to allergens or irritants at the transmission lines, or an effect on histamine sensitivity in the asthmatic [63] [65] [67] [69] [70].

Evidence of an effect of air ions on either short- or long-term lower respiratory diseases is lacking. Air ions or their reaction products, however, are reported to affect sputum production or viscosity in short-term lower respiratory diseases [62] [66]. More recent studies of rats exposed to $3{,}5 \times 10^5$ ions/cm$^3$ suggest that exposure activated goblet cells without producing damage to the trachea [71].

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As with the human studies, exposures of rats or mice to air ions are not reported to cause clear or consistent effects. These include studies of respiration rates at ion levels greater than $3{,}0 \times 10^5$ ions/cm$^3$ [72] [73]. Life-long exposures of mice (about 2 years) reportedly reduced the longevity of mice exposed to negative ions ($2{,}0 \times 10^3$ ions/cm$^3$ or $2{,}0 \times 10^5$ ions/cm$^3$) compared to mice in the grounded control or groups exposed to positive ions [54]. The data were internally inconsistent and there was no apparent dose-response relationship. The authors acknowledge in an earlier report of data from the study that a vitamin deficiency in the mice and "the prevalence of proteus infections markedly complicates the interpretation of the cause of death for affected experimental animals" [74].

Studies in which mice were exposed to influenza virus, pneumonia, or C. immitis fungus and air ions showed no consistent relationship between exposure level or ion polarity and outcome at levels of $1{,}0 \times 10^4$ to $5{,}0 \times 10^5$ ions/cm$^3$ [75] [76] [77] [78] [79]. In these latter studies, differences between exposed and unexposed animals were not greater at higher exposure levels nor was there consistency as to effects of ions of either polarity. In the longest series of experiments from Krueger's laboratory, there was no explanation for the failures to replicate effects despite the similarity of exposures and other conditions [76] [77] [78] [79].

Studies of air ions have been conducted more frequently on psychological and behavioural parameters than on physiological parameters. One reason was the nationwide publicity given to anecdotal claims in several American national magazines in the 1960s that artificially generated negative air ions would improve mood and feelings of wellbeing while positive ions would increase subjective complaints. To this date, such notions have generated much popular interest but little scientific support. The relevant research is summarized below.

A variety of studies have examined the effects of positive and negative ions on indicators of human behavioural states, which could be considered to be indicative in some way of mood. The better studies were carried out in a controlled fashion. Of these controlled studies, some report no effect of positive or negative ions on mood (McGurk et al. at $8{,}0 \times 10^4$ ions/cm$^3$ [80], Chiles et al. At $2{,}6 \times 10^4$ ions/cm$^3$ [81], Finnegan et al. at 1 841 ions/cm$^3$ [82], Hedge and Collins at $2{,}0 \times 10^4$ ions/cm$^3$) [83], while others reported an effect as discussed below.

Hawkins et al. reports that a 3-week exposure to negative ions at $2{,}7 \times 10^4$ ions/cm$^3$ improves the ratings of health relating comfort, but the responses were not consistent across shifts or work areas [84]. The differences in subject ratings between exposed and unexposed time periods were smaller than those produced by temperature and humidity alone.

Charry and Hawkinshire report exposure for 1,5 h between $2{,}0 \times 10^4$ ions/cm$^3$ and $3{,}0 \times 10^4$ ions/cm$^3$ lowered indices of sociability and increased tension [85].

Siegel reported that exposure to both positive and negative ions at $1{,}0 \times 10^5$ ions/cm$^3$ had no effects on five of seven mood indicators, but indicators of vigour and friendliness were enhanced with exposure to air ions of either polarity [86].

Several studies have looked for therapeutic effects of air ion exposure on the mood of patients with depression related to seasonal affective disorder. A reduction in depressive symptoms was recorded for patients exposed to $2{,}7 \times 10^6$ ions/cm$^3$ but not those exposed to $1{,}0 \times 10^4$ ions/cm$^3$ [87], a finding also reported in later studies [88] [89]. Perez et al. reports that negative air ionization is associated with lower depression scores particularly at the highest exposure level [185]. No adverse symptoms were attributed to exposure to air ions in any of these three studies. The mechanism for how air ions could have contributed to these results, however, is not clear. Simple sensory stimulation could be involved since the presentation of auditory stimuli, bright light, or high levels of air ions all were reported to reduce ratings of depression, mood disturbance, and anger within 13 min to 30 min [90].

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An additional consideration is suggested by the Terman and Terman study in which the responses of subjects in all treatment groups (including air ions) were correlated significantly with pre-treatment expectations of potential benefit. These results raise the issue of placebo responses [88].

Several groups of investigators have hypothesized that behavioural, psychological, and respiratory responses of humans and animals to air ions are related to effects on the metabolism of the neurotransmitter, serotonin. A clinical physician in Israel suggested that increases in positive ion concentrations associated with hot dry weather conditions or higher levels generated artificially at $1{,}0 \times 10^5$ ions/cm$^3$ increased levels of serotonin and its metabolite in the blood and urine of patients. Negative ions were reported to reduce the levels of serotonin and its metabolite [91] [92] [93]. These studies are of limited value because of the poor experimental control over their conduct, including exposures and analysis [94] [95].

Krueger's laboratory conducted similar studies in mice and reported changes in the levels of serotonin in the blood of mice (see [96] for summary and review), but others have been unable to replicate this effect [74] [96]. The Krueger laboratory also reported changes in the concentration of serotonin in the brains of mice and rats exposed to levels between $4{,}5 \times 10^4$ ions/cm$^3$ and $5{,}0 \times 10^5$ ions/cm$^3$ for as little as 12 h or for as long as 20 days, but no effect on serotonin or its metabolite in the brains of rats exposed to $5{,}0 \times 10^5$ ions/cm$^3$ for 2 h, 18 h, or 66 h [57].

The quality of research studies on air ions is low because of the difficulty associated with characterization of exposures, the control of relevant physical factors, and other design and analysis issues. The data does not indicate an established response among humans or animals at air ion levels less than $1{,}0 \times 10^4$ ions/cm$^3$. At levels between $1{,}0 \times 10^4$ ions/cm$^3$ and $1{,}0 \times 10^5$ ions/cm$^3$, a wide variety of biological and behavioural responses have been investigated, but the studies in aggregate provide no reliable basis to conclude that such exposures influence biological responses. For responses that are reported, there are other studies that report contradictory findings. The expectation that larger or more reliable effects might be observed at still higher exposure levels, i.e. greater than $1{,}0 \times 10^5$ ions/cm$^3$, was not supported, but too few studies at levels above $1{,}0 \times 10^6$ ions/cm$^3$ have been performed to characterize responses to extremely high levels.

#### 4.4.3.3 Charged aerosols

In the 1930s and the 1940s, investigators in Germany experimented with electrified water droplets and other aerosols used in the treatment of a variety of respiratory conditions. These exposures produced a very large number of charges per particle. While there were anecdotal reports of relief of symptoms, apparently no double-blind studies were performed to confirm any beneficial effects [97]. Such exposures to highly charged aerosols would be expected to increase their deposition in the respiratory tract as predicted by Wilson [98].

Fraser reported that a large number of charges (> 1 000) per particle were necessary to produce a 2-fold increase in the deposition of particles in the respiratory tract of rabbits [99]. Melandri et al. reported that 30 to 110 charges/particle were required to increase the deposition of small particles (0,3 µm to 1,1 µm) in human subjects by 13 % to 30 % [100].

Researchers at a physics research laboratory at Bristol University have hypothesized that corona on AC transmission lines causes electrical charges to attach to particles so as to enhance their retention in the respiratory tract and can affect health by increasing exposure to ambient pollutants [101] [102].

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There has been no empirical demonstration that the levels of charge on aerosols under this hypothesis, however, would be sufficient to enhance deposition of aerosols. This hypothesis has been criticized on the grounds of physical modelling [103] [104]. Jeffers reported that modelling and analyses of power lines and air ionizers indicate that particles are unlikely to become sufficiently charged to increase deposition within the respiratory tract [104]. This topic was investigated by an independent group of scientists for the NRPB, who concluded that charged ions (corona ions) were not likely to contribute to significant health effects [48].

This hypothesis could also be applied to DC transmission lines. Johnson has made direct measurements of the charge on aerosols by size downwind from a monopolar DC transmission line [16] [106] [107]. In ambient conditions of roughly equal numbers of negative and positive small air ions (600 ions/cm$^3$ to 800 ions/cm$^3$), the net average number of charged aerosols was zero. The number of charges on individual aerosols, however, varied from several negative to several positive charges for these conditions. When the DC transmission line was in heavy corona, the charged aerosol levels were generally 10 000 charges/cm$^3$ or less at ground level near the line (within 30 m or 100 ft) and had only single digit charge states. Even when the charge distribution was shifted by the ions produced by the DC transmission line, some of the aerosols still retained charge opposite to the polarity of the DC transmission line.

#### 4.4.3.4 Studies of DC transmission lines

Studies also have been performed on the health and behaviour of humans and animals living near or under DC transmission lines. An effect of ion current is the charging of objects. The voltage that the object acquires depends on the magnitude of the ion current and on the impedance between object and ground. If a person touches the object, the person may discharge it through a spark. However, such sparks occur infrequently because most objects do not accumulate enough charge.

Haupt and Nolfi reported on a home survey of 438 respondents in 128 households in an exposed and a control suburb along the Pacific Intertie, a transmission line then operated at ±400 kV [108]. No differences in short-term symptoms or overall health were found between the two groups. Exposures were estimated by distance alone; the investigators assumed for the purposes of the analysis that residents living within about 0,22 km (0,14 miles) of the line were exposed and those living 1,04 km to 1,36 km (0,63 miles to 0,85 miles) distant were not exposed. Although the data were well-collected and the analyses conducted carefully and perceptively, the report is not technically robust and, therefore, has limited value. Other limitations have been discussed in a letter to the editor [109].

An epidemiology study of the performance and reproduction of over 500 herds of dairy cows near a ±400kV DC transmission line in Minnesota was performed for the Minnesota Environmental Quality Board (MEQB) [110]. Data on approximately 24 000 milking cows, including average daily milk production, percent of animals that experienced high and very high drops in milk production, and annual average herd milk production in first and third lactations, were compared across six categories of distance ranging from 0 miles to 1/4 mile or 0,4 km (stratum 1) out to 6 miles to 10 miles or 9,6 km to 16 km (stratum 6) and time periods before and after energization of the line in 1979. Similarly, data on reproduction, including inter-calving intervals, abortions, infertility-related culling, and mortality, were analyzed. No differences were reported in any of these variables before or after energization or as a function of distance from the transmission line. The strengths of this study include the very large number of cows studied and the very sensitive, if non-specific, indicators of adverse effects.

Investigators at Oregon State University compared the health and productivity of 200 cow-calf pairs randomly assigned to pens directly under or 615 m away from the Pacific Intertie ±500 kV DC transmission line. No differences between the animals in the exposed and control pens were noted with regard to breeding activity, conception rate, calving, calving interval, body mass of calves at birth, body mass at weaning, or mortality over a 3-year period. The average exposure of the animals in pens under the line was about 5 kV/m and 13,000 ions/cm$^3$ [111].

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As part of this study, the investigators also monitored the activities of the exposed and control cattle at 13 min intervals during a 24 h period each month [112]. The distribution of cattle along feed troughs in the exposed and control pens was similar and unrelated to measures of the static electric field and there were no major differences in the time spent in various behaviours. Although small differences in the distribution of cattle within the pens were noted, the investigators reported that the differences were not correlated with fluctuations in the static electric field or noise levels.

In China, in combined AC and DC electric fields under AC and DC test line sections in the same corridor, a large number of tests have been carried out to investigate the sensitivity of human subjects. The tests have investigated the effects of both insulated human bodies touching earthed metal objects, and earthed human bodies touching insulated metal objects [187].

### 4.4.4 Scientific review

#### 4.4.4.1 General

Over the last 30 years, health agencies have convened groups of scientists to review biological research on exposures to static electric fields and air ions. These groups assembled by the MEQB, the International Agency for Research on Cancer (IARC), the Health Protection Agency of Great Britain (HPA), and the World Health Organization (WHO) have included dozens of scientists with diverse skills that reflect the different research approaches required to answer questions about health. These scientists evaluated the strengths and weaknesses of individual studies in the literature and then evaluated all of the research together to determine what effects of exposures, if any, might be expected at different levels of exposure, i.e., a comprehensive weight-of-evidence review. These weight-of-evidence reviews and their conclusions are summarized below.

#### 4.4.4.2 Minnesota environmental quality board

In 1981, the MEQB convened a expert panel of seven scientists to evaluate the health and safety aspects of a recently constructed ±400 kV transmission line in Minnesota to determine if permits for the line protected public health and safety and what, if any, additional standards were necessary to protect public health [113]. Their review continued over several years and the majority report concluded that air ions are not well established as a cause for biological effects, and even if these effects were to be substantiated, they posed no hazard to human or animal health. The science advisors later evaluated additional research and monitoring data and again concluded that there was little likelihood that either chronic or acute exposure to small air ions and static electric fields at levels measured either on or downwind of the ROW of the DC transmission line would cause adverse health effects [114].

#### 4.4.4.3 International Agency for Research on Cancer (IARC)

The primary mission of the IARC is to coordinate and conduct research on the causes of human cancer, the mechanisms of carcinogenesis, and to develop scientific strategies for cancer prevention and control. The best-known activity of the IARC is the preparation of reviews of technical physical factors (i.e. IARC Monographs) to assess the possibility that they can increase the risk of human cancer. IARC's Monographs have included assessments of chemicals, complex mixtures, occupational exposures, physical and biological agents, and lifestyle factors. National health agencies use this information as scientific support for their actions to prevent exposure to potential carcinogens.

Interdisciplinary working groups of expert scientists are convened by the IARC to review the published studies and evaluate the weight of evidence that an agent can increase the risk of cancer. Their reviews are performed according to scientific principles, procedures, and criteria. Since 1971, more than 900 agents have been evaluated.

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