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Corona ions from powerlines and increased exposure to pollutant aerosols

A. P. FEWS*, D. L. HENSHAW, R. J. WILDING and P. A. KEITCH

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Abstract.

Purpose: To investigate corona ions emitted from high-voltage powerlines and assess their effects on exposure to environmental pollutant aerosols.

Materials and methods: The charge density of ions in air required to produce a given change in the observed DC field at ground level was calculated. A DC field mill meter was used to map the DC fields near 132, 275 and 400 kV powerlines.

Results: The Earth's natural DC field of around $\sim 100 \text{ V m}^{-1}$ was significantly modified near powerlines in 8 out of 14 cases. Typically, downwind of the powerlines the field direction was reversed giving values to -340 V m^{-1} . In one case, the effect extended more than 500 m from a 275 kV line.

Discussion: These results can be analysed in terms of the charge density present. This analysis suggests that typically 2000 excess negative charges per cm^3 are required to match the measured DC fields. Such space charge will result in unipolar aerosol charging in excess of the normal bipolar steady state charge distribution of pollutant aerosols. This may lead to increased lung deposition on inhalation.

1. Introduction

The authors are studying the ways in which the electric, E-field, component of the electromagnetic field from high-voltage ($> 100 \text{ kV}$) powerlines interacts with airborne pollutant aerosols, resulting in increased pollutant exposure to people living nearby. In particular, the authors have demonstrated, both theoretically and experimentally, that in a variety of weather conditions under high-voltage powerlines excess deposition of pollutant aerosols occurs on spheres representing the human head (Fews *et al.* 1999).

This paper discusses the role of corona ions emitted from high-voltage powerlines in providing a further possible mechanism in raising exposure to pollutant aerosols; in this case up to several hundred metres from the line. The basis of this mechanism is that corona ions, once produced, can attach to the pool of pollutant aerosols in air. The latter are then carried by the wind away from the powerline. The space charge resulting from these corona ions and

charged aerosols may be detected as a change in the Earth's natural DC electric field.

2. Theoretical considerations and methods

2.1. Powerline corona ions

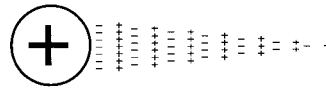
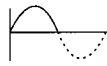
High-voltage transmission lines suffer corona losses of up to 1 mA per metre (Abdel-Salam and Abdel-Aziz 1994). This corresponds with up to 6.25×10^{15} charges per metre per second of line. Much of this charge may be assumed to be absorbed by the line and the pylon, but in absolute terms it must also be assumed that a substantial flux of ions can be continuously emitted into the atmosphere.

The mechanism by which corona ions are generated is well known. In air, corona initiation has been described by MacGorman and Rust (1998, p. 77). Here, the principle lies in the high electric field gradients produced around sharp points, which are sufficient to produce local ionization of the air. The growth of powerline corona is illustrated schematically in figure 1. Following primary ionization of the air, avalanching of charge takes place so that the total number of ions involved in corona loss can exceed the loss current. The polarity of the line influences the process of corona formation. In the positive half-cycle, electrons are accelerated into a higher field region feeding the avalanche. Conversely, in the negative half-cycle, electrons are repelled into a lower field region, which limits the avalanche process.

In the general case, whilst both positive and negative corona ions oscillate in the AC field, most of them recombine with the powerline. However, some of them escape (for example due to wind) and usually more of the negative ions escape than the positive ions because the negative ions tend to have a higher mobility and have oscillated further from the line. However, ions of both polarity quickly nucleate or attach to ultrafine aerosols. These aerosols are then dispersed by normal atmospheric processes, notably by the wind. On a slower time scale, the ultrafine particles will then go on to attach to larger aerosols.

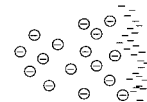
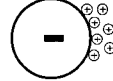
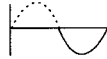
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(a) Positive half cycle



Electrons drawn to positive line undergo avalanche multiplication

(b) Negative half cycle



Electrons repelled from the powerline undergo avalanching, which is limited by the diminishing field away from the line

Figure 1. Schematic outline of the formation of corona ions.

As a result of the initial charge separation, clouds of unipolar aerosols or *space charge* might be expected to be found some distance from powerlines. This could result in the setting up of DC fields in the air comparable with or greater than the typical DC field of the Earth of $\sim 100 \text{ V m}^{-1}$. This process does indeed occur and the effect of powerline corona ions on DC fields in the atmosphere is well documented. Chalmers (1952, 1967) found negative potential gradients downwind of 132 kV cables during mist and fog. The effects were observed up to 5 km from the cables. At various locations DC fields varied from $+210 \text{ V m}^{-1}$ through zero to -1000 V m^{-1} . Chalmers suggested that the results were consistent with the production of mainly negative ions which were carried downwind of the powerline.

Mühleisen (1953) made similar observations as far as 7 km from a 220 kV line. In conditions other than mist and fog, there appeared to be a preponderance of positive charges. At distances up to 500 m from the powerline the author observed DC fields from $+300$ to $+2000 \text{ V m}^{-1}$. However, the author

commented that the magnitude of the effects were due to cables whose diameters were too small to be suitable for the voltage carried.

Corona loss from DC transmission lines has been extensively investigated (Bracken *et al.* 1978, HVDC Transmission Line Reference Book 1993), but DC power transmission is rare and this paper only considers corona ions emitted from conventional AC transmission lines.

2.2. Modification of the Earth's DC field by space charge ions

The Earth's natural DC field can be considered to be created by a layer of positive space charge in the sky and a corresponding layer of negative charge across the surface of the Earth. The field, E (V m^{-1}), can be related to a density of space charge by applying Gauss's Law:

$$\sigma = \epsilon_0 E \quad (1)$$

where σ (C m^{-2}) is the charge density at a surface

and ϵ_0 is the permittivity of free space of $8.85 \times 10^{-12} \text{ C}^2 \text{ N}^{-1} \text{ m}^{-2}$. Thus, to support a typical Earth's field of 100 V m^{-1} , application of equation 1 yields an area charge density of 5.5×10^9 charges m^{-2} .

This natural field is modified in the presence of additional space charge, as observed by Chalmers and Mühleisen cited above, and the amount of this space charge required to produce the effect can be calculated. The present authors consider a sheet of space charge in the xy plane, of area charge density σ and height above ground h along the z -axis. The powerline is situated at the x -axis (running along $y=0$) and the charge sheet is semi-infinite, being created at the powerline and existing only in the downwind direction ($y>0$). Since the Earth is a conductor, the field lines will be normal to the surface of the Earth, and the field can be calculated at ground level (E) by summing the contributions to the vertical component of the field (δE_z). This contribution, δE_z , due to an element of area $\delta x \delta y$ of the sheet, is given by:

$$\delta E_z = \frac{\sigma h \delta x \delta y}{4\pi\epsilon_0(h^2 + x^2 + y^2)^{3/2}} \quad (2)$$

This approach is similar to that of Jones and Jennings (1977) who considered charge plumes blowing downwind from chimney stacks. Since the Earth is a conductor, the space charge can be considered to be always accompanied by a mirror charge of opposite sign at an equal distance below the Earth's surface. Application of equation 2 at a distance l from the powerline along the y -axis, followed by integration over x , yields the observed E-field, E , at ground level:

$$E = E_{DC} + \int_{y=0}^{\infty} \frac{\sigma h \cdot \exp(-y/Y_0)}{\pi\epsilon_0[(y-l)^2 + h^2]} dy \quad (3)$$

The exponential factor has been added to represent the fall off of charge density with scale distance Y_0 by neutralization and dispersal, and E_{DC} is the background DC field of the Earth.

Figure 2 shows the simulated E-field profile from numerical integration of equation 3 upwind and downwind of the powerline using $h=20 \text{ m}$, $\sigma = -3.2 \times 10^{-9} \text{ C m}^{-2}$ (equivalent to 2×10^6 negative charges per cm^2), $Y_0 = 200 \text{ m}$ and $E_{DC} = 100 \text{ V m}^{-1}$. The values used result in a simulated E-field profile, which is generally representative of the measured profiles indicating that substantial charge densities must be present to explain the observations. Note that this is the imbalance of the negative over the positive charge density, and that the total (bipolar) charge density (positive and negative) will be higher unless positive charges are absent.

2.3. Aerosol charging

Corona ions of either positive or negative charge created from electrical discharges quickly attach to or nucleate ultrafine aerosols by condensing on them a mono-molecular layer of water vapour or trace pollutant gases in air (e.g. Borra *et al.* 1995). Such aerosols are 1–4 nm in size. In the present context the term *ion* therefore means an ultrafine aerosol. A proportion of such ions emitted from powerlines may remain in the form of charged ultrafine aerosols, while others will attach to and charge up existing pollutant aerosols in air. At the same time, those aerosols that are already charged to the natural Boltzmann type equilibrium may pick up additional charges. It should be noted that aerosol particles exposed to unipolar ions, as appears predominant in the present case, have a considerably higher saturation charge than the steady state equilibrium from background bipolar small air ions (Hinds 1982, p. 302).

The aerosol attachment coefficient β of small ions to aerosols of diameter d is given by:

$$\beta(d) = \frac{1}{4} \pi v_0 d^2 \quad (4)$$

where $v_0 = 172 \text{ m s}^{-1}$, the mean thermal velocity of the small ions (Porstendorfer 1994). The aerosol size spectrum will be simplified by considering that aerosols have a mean size outdoors of 200 nm. It follows that the rate at which small ions are attached to aerosols is

$$\frac{dN_i}{dt} = \frac{1}{4} \pi v_0 d^2 N_i N_a \quad (5)$$

where N_i is the number concentration of ions and N_a the 200 nm aerosol number concentration. Since only 200 nm aerosols are being considered, multiple charges are neglected because less than 20% of these aerosols will be multiply charged. In these conditions the characteristic time scale, t_a , for aerosol charging is given by:

$$t_a = \frac{4}{\pi v_0 d^2 N_i} \quad (6)$$

and for the removal of the free small ions:

$$t_i = \frac{4}{\pi v_0 d^2 N_a} \quad (7)$$

For normal conditions away from the powerlines, typical values are $N_a \sim 10^4 \text{ cm}^{-3}$ and $N_i \sim 500\text{--}1000 \text{ cm}^{-3}$, giving $t_a \sim 3 \text{ min}$ and $t_i \sim 20 \text{ s}$. Therefore, any non-equilibrium charge imposed by the corona ions will take 3–30 min to be neutralized by the normal air ions.

This simple treatment corresponds with diffusion

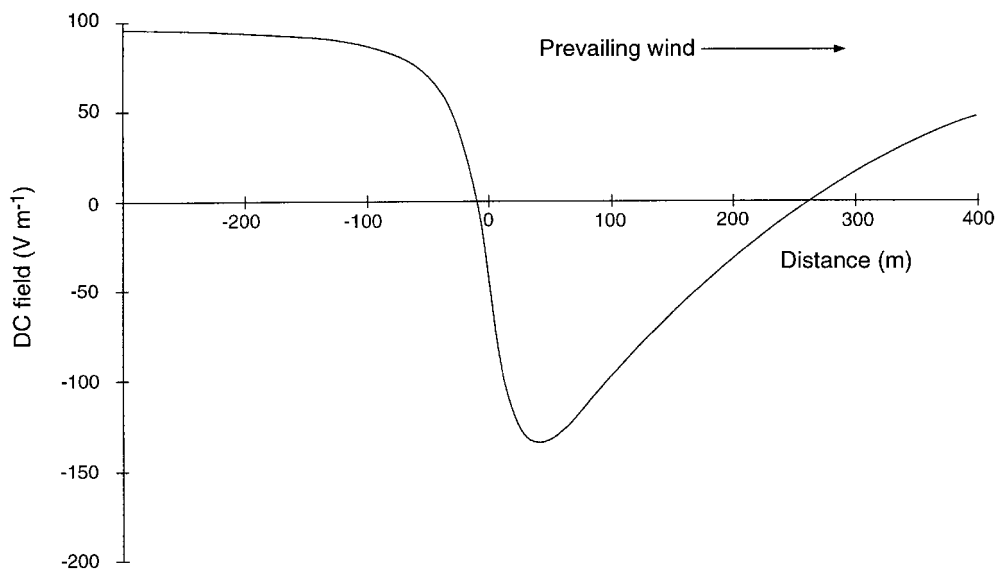


Figure 2. Predicted profile of DC field at ground level near powerlines. The powerline is situated at the origin.

aerosol charging. In practice, field charging will also occur, which for the particle diameter considered here will increase the charging rate by a factor of two to three (Hinds 1982, p. 302). This will be considered in detail in a future publication.

2.4. DC field mill meter measurements

DC field measurements were made using a Chubb JCI 140C field mill meter. At the head of the meter the electric charge is measured on a series of rotating vanes, which by Gauss's Law may be used to derive the E-field at that point. The meter was mounted on a tripod at a height of 1 m above the ground. In order to use the meter for measuring E-fields in the atmosphere, the meter and tripod assembly were calibrated together by measuring the known field between a pair of large area parallel plates across which a known voltage was applied. This calculation was checked by a simulation of the meter on its tripod in a uniform E-field using a numerical solution of Laplace's equations.

2.5. Measurements near powerlines

Measurements of atmospheric DC fields were made several hundred metres either side of 132 and 275 kV powerlines, and up to 75 m from a 400 kV powerline in rural areas within a radius of 30 km around Bristol, UK. The measurements were carried out in a line transverse to the powerline over distances that were limited by land accessibility. The measurements were made on open flat ground, clear of trees, metal objects or other obstructions, except where

specifically noted. In each case the weather conditions were noted; in particular the speed and direction of the wind. In all, 12 separate powerline sites were examined which satisfied these conditions. Two sites were revisited several months later, making 14 sets of measurements in all.

3. Results

Table 1 summarizes the results of the measurements for eight cases where significant changes in DC fields were observed. This was defined as a change of at least 100 mV^{-1} compared with the Earth's field, where this was not associated with shielding of the line. In these cases this field change was observed in the downwind direction and not in the upwind direction. This distance in the downwind direction is included in table 1. The minimum E-field and the maximum change in field, ΔE , are given. In most cases it was evident that the measurements were not taken far enough away from the line for equilibrium with the Earth's natural DC field to be reached. This is revealed in the distance over which changes in E-fields were observed, which generally corresponds with the whole distance over which the measurements were taken. Thus, for example, the measurements at Brake Farm showed effects over a distance of 60 m, but this was the limit of measurement due to accessibility to the farmer's land. A common feature was the asymmetry of the field strength either side of the line. In cases where a cross-wind was present, the field direction became negative downwind of the line.

For the remaining six cases, only two showed no

Table 1. Measurements of atmospheric DC electric fields near high-voltage powerlines where significant changes were observed.

Location/OSGB map reference	Date	Powerline voltage (kV)	$E_{\min}$ (V m^{-1})	ΔE (V m^{-1})	Distance (m)	Weather summary
South-west Bath 710588	30/10/98	132	- 60	101	> 120	No wind
Rangeworthy 709855	11/12/98	132	- 67	147	> 185	Slight wind
Totteroak 737848	09/12/98	132	- 342	558	> 520	Misty with light to moderate wind
Westend site 1 454689	30/10/98	132	- 48	150	40	Moderate wind, recent heavy rain
North Widcombe 576582	15/07/99	132	- 100	180	> 210	Dry, moderate wind
Townsend 572564	16/06/99	132	- 110	150	> 180	Hot and sunny, light breeze
Oldbury 628936	18/11/98	275	- 88	255	> 580	No wind, clear sky
Brake Farm 672830	16/10/98	400	- 82	123	> 60	Wind gusting, overcast

$E_{\min}$ is the minimum recorded E field. ΔE is the difference between $E_{\min}$ and the Earth's DC field, and 'distance' is the distance over which the measured field changes by more than 100 V m^{-1} compared with the Earth's field.

effect other than the expected shielding of the Earth's DC field. The remaining four cases showed changes that fell below the criterion of a 100 V m^{-1} change in DC field.

To illustrate the results in table 1, figure 3 shows the DC field measurements with distance either side of a 132 kV powerline at Totteroak. The powerline runs north-west to south-east. Downwind of the

powerline the field was negative for over $\sim 250 \text{ m}$ and remained below the nominal Earth's field up to the limit of measurements 500 m downwind. The negative E-field peaked at around -350 V m^{-1} . Figure 4 shows the DC field measurements with distance either side of a 275 kV powerline near Oldbury Power Station. The powerline runs north-west to south-east and the measurements commenced

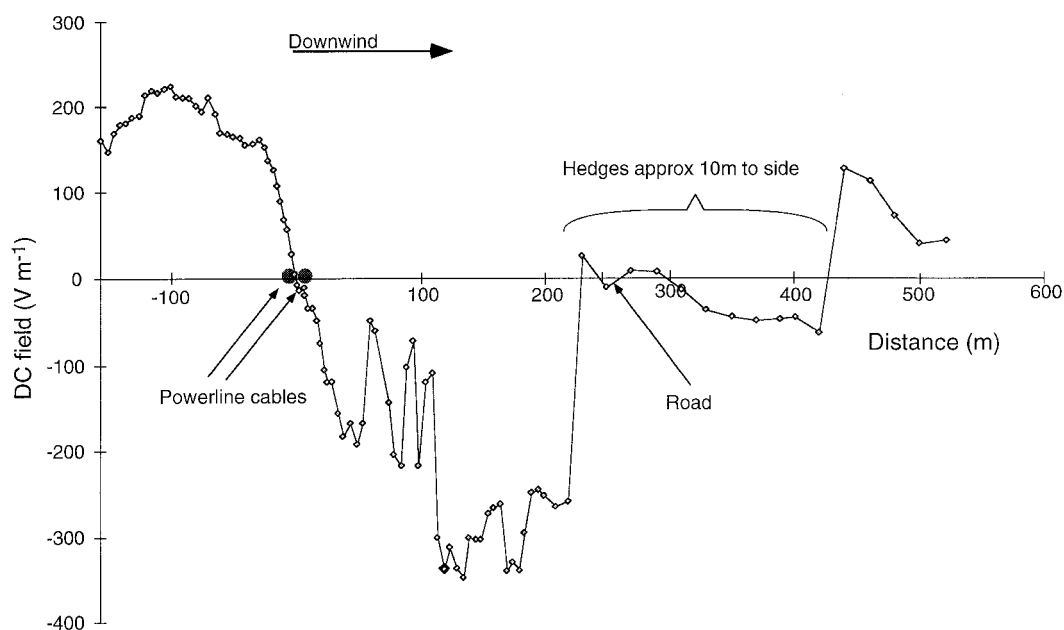


Figure 3. DC field measurements near 132 kV powerline at Totteroak.

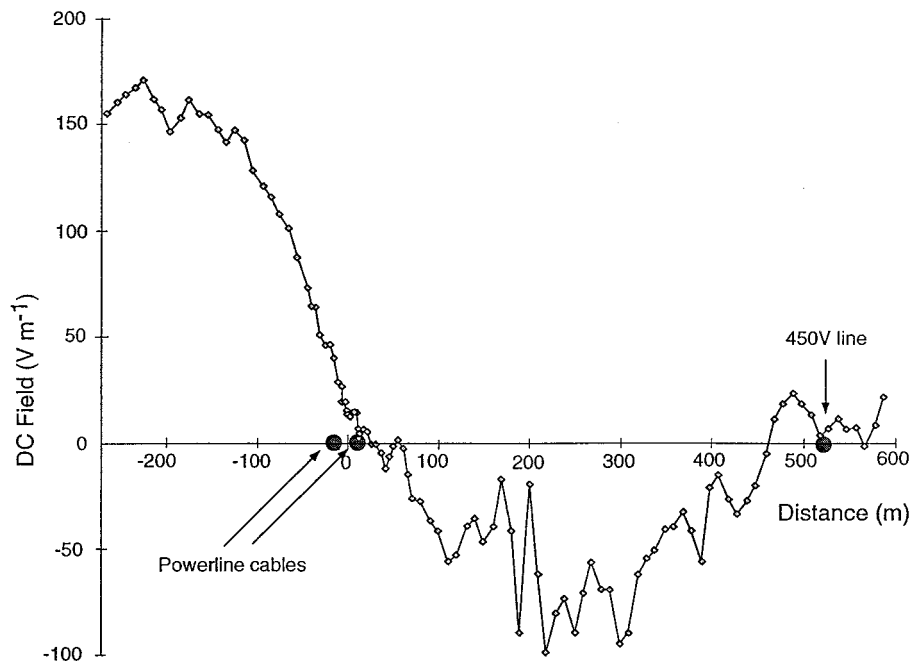


Figure 4. DC field measurements near 275 kV powerline at Oldbury.

250 m south-west of the powerline. The sign of the E-field was negative over a distance of 450 m south-west of the line. On the other side of the powerline the field rose steadily to around 160 V m^{-1} .

The results in figures 3 and 4 may be compared with the model calculation of figure 2. The scaling distance of $r_0 = 200 \text{ m}$ is purely illustrative, and the purpose of figure 2 is to show that the features seen in figures 3 and 4 are expected from the model. The features are that: (a) the upwind field is flat and close to the Earth's DC field; and (b) the downwind field decays to the Earth's field over this scaling distance. In practice the scaling distance will vary with particular conditions, depending, for example, on how far they travel and how quickly they are neutralized.

4. Discussion

4.1. Analysis of the experimental observations

The immediate feature from figures 3 and 4 and table 1 is that changes in DC fields are commonly observed near high-voltage powerlines and that significant effects can occur over several hundred metres. In one case, Oldbury, this corresponds to 580 m from the powerline. Although these effects are easily observed they do not occur all of the time. Thus, apart from the results in table 1, four sets of measurements showed clear effects but were below the criterion of 100 kV m^{-2} changes in the DC field. Two of these were re-measurements at Rangeworthy and Oldbury in June 1999 in quite different weather

conditions compared with the original measurements in October and December 1998. Thus, the authors believe that the local weather conditions are important in determining the effect.

In the case where positive effects were seen, some differences in the power cables should be noted. The conductors on the 132 kV line are single cables and on the 275 kV line there are generally pairs of conductors (about 20 cm apart). One reason for this is to reduce the corona loss on the 275 kV lines by reducing the effective electric field at the cable surface. The conditions for corona are more likely on older lines that are pitted, and/or lines that have accumulated dirt so that sharp edges are present. In the present work it has not been possible to assess the condition of individual lines.

The effects shown in table 1 cannot be attributed to shielding of the Earth's field by the powerline because this occurs only very close to the line. Indeed, on some of the DC profiles, a local dip in the DC field was seen $\pm 20 \text{ m}$ from the line; the distance over which shielding of the Earth's field is expected.

A limit on the number of corona charges can be made from the change to the observed DC field. From table 1 it can be seen that near a powerline the change in field ΔE was in the range $100\text{--}500 \text{ V m}^{-1}$. The mean of these values was 200 V m^{-1} . The model results in figure 2 were prepared using an aerial charge density of -2×10^{10} charges per m^2 , which produced a value of ΔE within $\pm 50 \text{ m}$ of the powerline, corresponding to the mean

of the measured data. This areal charge density corresponds to a volume charge density of -2000 charges per cm^3 when spread over an arbitrary thickness of 10 m . This thickness will be somewhat less than the powerline height because the charges will initially be emitted from the powerline and then are likely to drift towards the Earth due to the attraction from the mirror charge sheet (as evidenced by the reversal of the natural DC field). Note that the 2000 charges per cm^3 represent the charge imbalance of negative charges that must be present. If positive charges are also present then 2000 excess negative charges per cm^3 must still occur and this therefore represents the minimum charge density in this scenario. For a typical aerosol concentration of 10^4 cm^{-3} , this corresponds to 20% unipolar charging (or the aerosols carrying extra charge). In the equilibrium case, $\sim 36\%$ of the aerosol particles are uncharged, and the unipolar charging will change this equilibrium substantially.

In practice, two mechanisms of aerosol charging can be considered. First, there is charging by ions and electrons within the region of corona discharge itself where large excess numbers of positive and negative charge will exist. This can result in rapid aerosol charging on a timescale of less than 1 s because this process requires ion densities in excess of 10^5 to 10^6 ions cm^{-3} , which will only occur close to the powerline cables. Secondly, there is charging by the lower charge densities of unipolar (negative) charge streaming from the lines that have been observed with the DC field measurements.

The total charge density, as discussed above, must occur in the air between the region near the powerline height and the ground. However, it is likely that the small ion density will have nearly returned to the background level before the ions can reach the ground, for the reason that these small ions will already have combined with the large airborne particles (the $\sim 200\text{ nm}$ aerosol). To ascertain this experimentally, ground level measurement of both small and large ions will be separately required because when the corona loss is very high, neither the small nor the large ions may have time to reach equilibrium before they disperse or contact the ground. It is possible that corona discharge may occur more in still and damp conditions, giving higher space charges than in the present measurements, which were in more normal conditions and generally with a wind blowing.

4.2. Mechanisms of increased dose from inhaled pollutant aerosols

Cohen *et al.* (1998) have demonstrated the increased lung deposition of charged compared with

uncharged aerosols. The authors measured the deposition of 20 nm and 125 nm charged and uncharged aerosols in casts of the human tracheo-bronchial tree made of conducting material to mimic the situation *in vivo*. They found a five- to six-fold increase in lung deposition when the particles were charged compared with uncharged.

The question of whether increased lung deposition of inhaled aerosols occurs near powerlines that have been charged by corona ions therefore arises. This needs to be addressed in future work, taking into account that the above estimate of aerosol charging of 20% is probably a lower limit.

It may also be noted that Brockhaus *et al.* (1988) found higher lead and cadmium levels in the blood, teeth and urine of children near industrial sites. There was a particular effect around lead and zinc smelters. The observations provide direct evidence of the accumulation of industrial pollutants in children. In related work, Henshaw *et al.* (1995) found higher levels of ^{210}Pb -supported ^{210}Po in the teeth of children living near major motorways in the UK, indicating the uptake of vehicle exhaust pollution by children. Both these observations must be presumed to occur during the normal proportion of time which children spend outdoors (averaging around 10%). If such particles infiltrate indoors, then a comparable increase in lung deposition could occur indoors to that expected outdoors. Such infiltration, albeit of normally charged particles, is commonly observed (Porstendorfer 1994). It should be noted, however, that such infiltrated particles may have a shorter lifetime indoors due to deposition on walls and other surfaces and so the particle concentration may be lower. In any case, the relation between outdoor and indoor aerosol concentrations is well established, and presumably this same relation applies to both charged and neutral particles, in which case a comparable increase in lung deposition can occur indoors to that expected outdoors.

Jennings and Jones (1976) and Jones and Jennings (1977) found high electric fields at ground level due to industrial chimney stack fumes. It follows from the work of Brockhaus *et al.* that increased uptake of pollutants by children from these fumes might be expected. However, these measurements alone do not assess whether the charge on pollutant aerosols *per se* are a factor in uptake.

4.3. Possible health implications

Motor vehicle exhausts are a dominant source of urban pollution in industrialised countries and their adverse health effects on respiratory and cardiovascular disease are also well recognized (Seaton *et al.*

1995). Any increase in lung deposition of these pollutants as a result of aerosol charging by powerline corona ions would therefore have implications for known health effects of urban pollution.

The incidence of child leukaemia is also associated with traffic density and its associated pollution (Savitz and Feingold 1989, Lindquist *et al.* 1991, Robinson 1991, Nordlinder and Järnholm 1997, Forastiere *et al.* 1998). Childhood leukaemia is associated with EMF exposures, but in the absence of a convincing causative mechanism the association has remained controversial. However, it is the studies carried out under high-voltage powerlines (transmission lines) that have been the most consistent in showing a leukaemia link (Ahlbom *et al.* 1993, Feychting and Ahlbom 1993, Olsen *et al.* 1993, Verkasalo *et al.* 1993, NRPB 1994, NIEHS 1998). It is largely on the basis of the transmission line studies that the NIEHS Report to the US Congress has recommended that the power industry continue its current practice of siting powerlines to reduce exposures (NIEHS 1999). This includes the policy (in the USA) of avoiding erecting powerlines over houses.

In summary, the results presented in this paper raise the possibility that corona ions from powerlines result in increased lung deposition of inhaled pollutants by people living nearby. Of particular note is the fact that this could be effective several hundred metres from powerlines and that all the types of high-voltage lines studied (132 kV and above) are commonly affected.

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