Volume 15 No.1 2004

Documents of the NRPB

Particle Deposition in the Vicinity of Power Lines and Possible Effects on Health

Report of an independent Advisory Group on Non-ionising Radiation and its Ad Hoc Group on Corona Ions

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Working in partnership with the Health Protection Agency

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Report of an independent Advisory Group on Non-ionising Radiation and its Ad Hoc Group on Corona Ions

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This report from the Advisory Group on Non-ionising Radiation reflects understanding and evaluation of the current scientific evidence as presented and referenced in this document.

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INTRODUCTION

1 In recent years there has been an increasing awareness of the presence of electric and magnetic fields (EMFs) and radiations in the natural and working environments. These arise from a wide range of sources including: static fields from superconducting magnets, power frequency (extremely low frequency, ELF) electromagnetic fields from the electricity supply system, and radiofrequencies from radio and TV transmissions as well as mobile phones and radar.

2 The National Radiological Protection Board (NRPB) has a statutory responsibility for advising UK government departments on standards of protection for exposure to such radiations. To provide support for the development of NRPB advice on non-ionising radiations, the Director set up in 1990 an Advisory Group on Non-ionising Radiation (AGNIR) with terms of reference:

'to review work on the biological effects of non-ionising radiation relevant to human health and to advise on research priorities'

3 The Advisory Group was reconstituted in 1999 as an independent body and now reports directly to the Board of NRPB. The Advisory Group has, to date, issued a number of reports concerned with exposures to electromagnetic fields. It has considered their possible association with an increased risk of cancer (AGNIR, 1992, 1993, 1994a, 2001a,b, 2003). It has also reported on ELF electromagnetic fields and neurodegenerative disease (AGNIR, 2001c) and on health effects related to the use of VDUs (AGNIR, 1994b). The possibility of an increased risk of cancer associated with exposure to ELF electromagnetic fields has been closely considered and has been the subject of a number of national and international reviews (eg IARC, 2001). A recent report by the Advisory Group (AGNIR, 2001a) considered experimental and epidemiological studies relevant to an assessment of the possible risk of cancer arising from exposure to ELF electromagnetic fields. It concluded that:

'laboratory experiments have provided no good evidence that extremely low frequency electromagnetic fields are capable of producing cancer, nor do human epidemiological studies suggest that they cause cancer in general'

4 There was, however, some epidemiological evidence that prolonged exposure to high levels of ELF magnetic fields is associated with a small risk of leukaemia in children. Such levels of exposure are, however, seldom encountered by the general public in the UK. It was concluded that the evidence was currently not strong enough to justify a firm conclusion that such fields cause leukaemia in children. Unless, however, further research indicates that the finding is due to chance or some currently unrecognised artefact the possibility remains that intense and prolonged exposure to magnetic fields can increase the risk of leukaemia in children.

5 The report had considered a number of factors that can influence the extent of exposure of people to electromagnetic fields in both the natural and working environments. It had also considered developments in techniques for monitoring exposure. However, most of the studies it reviewed in relation to possible health effects were concerned with the direct effects of exposure of people to magnetic fields. There was

insufficient information about exposures to electric fields to come to a conclusion about any health effects. The Advisory Group noted, however, that a number of publications had addressed the issue of potential indirect effects arising from increased deposition of charged airborne particles in the respiratory system and on skin caused by the presence of large alternating current (AC) electric fields (Fews et al, 1999a,b; Swanson and Jeffers, 1999).

6 The physical principles for these effects are generally well understood, but their magnitudes are difficult to quantify in the complex and changing environments surrounding power transmission lines in the open air. However, the Advisory Group concluded that 'it has not been demonstrated that any such enhanced deposition will increase human exposure in a way that will result in adverse health effects to the general public'. It was felt though that this area merited further consideration and the Advisory Group was requested by the Board of NRPB to examine this further.

7 To provide input to the work of the Advisory Group, an Ad Hoc Group was set up with terms of reference:

> **'to provide the Advisory Group on Non-ionising Radiation with advice on the possible effects of corona ions or electric fields on intakes of radioactive particles or other airborne pollutants and to advise on the need for further work'**

8 Airborne particles having the greatest effects on health include radon decay products, chemical pollutants, spores, bacteria and viruses. If inhaled, some become deposited in the airways of the respiratory system. Others can be deposited on the skin. Since charged particles are more likely than uncharged particles to be deposited when close to the walls of the airways or the skin, an increase in the proportion that are charged could lead to an increase in adverse health effects. Such an increase could arise from the generation of corona ions by power lines. These positive or negative ions arise when voltages of a few thousand volts or greater cause electrical breakdown of the air by corona discharges. A further increase in the deposition of charged particles could also arise due to an increase in the probability of impact with surfaces in the presence of electric fields. Hence, the two issues considered by the Ad Hoc Group were:

(a) to what extent do pollutants become charged in the vicinity of power lines and how significant is the resulting increase in their deposition in the respiratory system or on the skin,

(b) how significant is the increase in deposition of naturally charged particles on the skin or in the respiratory system as a result of the strong electric fields present below power lines.

9 The review by the Ad Hoc Group was subsequently considered by the Advisory Group in the context of possible consequences of changes in exposure to pollutants for human health. This report, therefore, incorporates both the review by the Ad Hoc Group and the assessment of potential health impact by the Advisory Group.

10 Airborne particles may range in size from about 0.001 μm to more than 10 μm and their concentrations vary widely both with time and with place. They can be formed by dispersion as a result of the resuspension of deposited particles or the breaking up of larger objects and by condensation, a term used to include the condensation of gases to produce liquid or solid particles as well as the formation of solids as the result of chemical reactions between gases. Particles may also be formed by the agglomeration of smaller particles already present in the environment.

11 The rate of deposition of particles striking a surface depends on their movement through the air and the various mechanisms and factors that influence this are described in paragraphs 24–28 and 117–141. They include gravitational sedimentation, inertial impaction and diffusion (Brownian motion), as well as the effects of air flow and turbulence and the charge, if any, on the particle. Their relative importance depends upon the mass and nature of the particles but they can all affect the motion of particles in the ambient air, as well as their deposition in the respiratory tract and on the skin.

12 The first publications to draw attention to the possibility of an increase in health effects as a result of the influence of electric fields from power lines on the deposition of charged particles did so in the context of exposure to radon and its decay products (Henshaw et al, 1996a). However, further papers have considered the effect of charge on the deposition of a range of other pollutants including chemicals, bacteria and viruses (Fews et al, 1999a,b). Exposure to pollutants is discussed in paragraphs 29–37 with particular reference to radon and its decay products and chemical pollutants. Paragraphs 38–51 summarise present understanding of the toxicity of airborne pollutants.

13 The increase in the proportion of particles that are charged as a result of corona discharge is considered in paragraphs 52–87. The name corona, the Latin word for crown, was used by mariners to describe the pale light often accompanied by hissing that occurred from ships' masts during electrical storms. These effects are the result of the ionisation of the air by the strong divergent electric fields present at the surface of sharp metallic points, small diameter wires, etc, when they are raised to a high voltage. The ions that are formed in this way can be positive or negative. The section reviews the sources and behaviour of corona ions in the atmosphere. It also considers how particles can become charged by trapping ions so leading to an increase in the proportion of charged particles. In general, particles smaller than 0.1 μm in diameter usually carry no charge, whereas larger particles usually carry at least one positive or negative electronic charge.

14 Airborne pollutants enter the body by inhalation and may then be deposited in the respiratory system. The extent to which inhaled particles deposit in the various regions of the respiratory system depends upon physical factors such as their size, shape and density, as well as charge. Paragraphs 88–116 consider these various factors and the models that have been developed to predict deposition in the various regions. The principal model that is used for describing the behaviour of inhaled radioactive particles is the Human Respiratory Tract Model (HRTM) developed by the International Commission on Radiological Protection (ICRP, 1994). This is considered to give a good representation of the behaviour of inhaled particles in the size range from 0.001 to 100 μm. Although the HRTM was not developed to address specifically the effect of electrostatic charge it is possible to use it to make some predictions about how charge may affect deposition in the respiratory system.

15 Paragraphs 117–141 consider the deposition of charged particles on exposed skin that occurs even if no electric fields are present. This deposition can, however, be increased by the approximately vertical AC electric field present under a power line. The field causes charged particles to oscillate up and down so that those just above a surface may strike the surface and stick to it. The probability of this happening is strongly affected by the nature of the air flow in this region.

16 The extent of any effect of corona ions on health will depend upon the extent of any increase in exposure to pollutants, the extent to which these pollutants are causes of disease, and the numbers and types of individuals who are exposed. Paragraphs 142–150 provide a perspective on the potential for corona ions to influence the health of an exposed population.

17 Paragraphs 151–164 summarise the general conclusions of the report and paragraph 165 makes recommendations for further work. A glossary explains technical terms that are used.

AIRBORNE PARTICLES

18 Most of the particles present in air are too small to be seen individually, although, if there are enough, they form a visible cloud of dust, smoke or water droplets. The technical term for such a cloud is an 'aerosol' but this term has been avoided in this report since it is more commonly used to describe the spray of droplets from a pressurised can.

19 The particle 'size' is readily defined by its diameter if it is spherical as is the case for small liquid droplets. However, most solid particles have irregular shapes so their sizes are defined by an 'equivalent diameter', often their 'equivalent volume diameter', which is the diameter of a sphere with the same volume as the particle.

20 The nature of the particles in the air varies enormously and includes water droplets, fragments of rock and soil, bacteria, viruses, pollen grains, spores, smoke, exhaust fumes, and other pollutants.

21 Airborne particles range in size from about 0.001 μm to more than 10 μm and have size distributions as represented in Figure 1. The processes that create airborne particles – and the mechanisms that cause particles to grow, agglomerate, and deposit from the air – are all size-dependent (see below), so particles of some sizes are more common than others. Typically they form three *modes*, as shown (the origins of each mode are outlined below). However, the size distributions and relative importance of the modes will depend on the particular situation, and vary both with location and with time in any one location. There can also be additional modes, due to local sources of particles. The number and mass distributions are very different, reflecting the fact that, for example, a single 1 μm particle has the same mass as one million 0.01 μm particles. So while most of the particles are smaller than 0.1 μm, their total mass is mainly due to those larger than 0.1 μm. The distribution by surface area shows intermediate behaviour; this could be of significance to the behaviour of pollutants that condense on to the surfaces of existing particles in the atmosphere. Airborne particles are mostly formed by dispersion or condensation.

Dispersion

22 Dispersion is the resuspension of deposited particles or the breaking up of larger objects. Examples include dust raised by mechanical disturbance (ploughing, driving on a dirt road, machining), and sea spray formed by breaking waves. Dispersion tends to produce particles larger than about 1 μm in size, because it is difficult to break up smaller particles than this. These processes mainly give rise to the coarse mode shown in Figure 1.

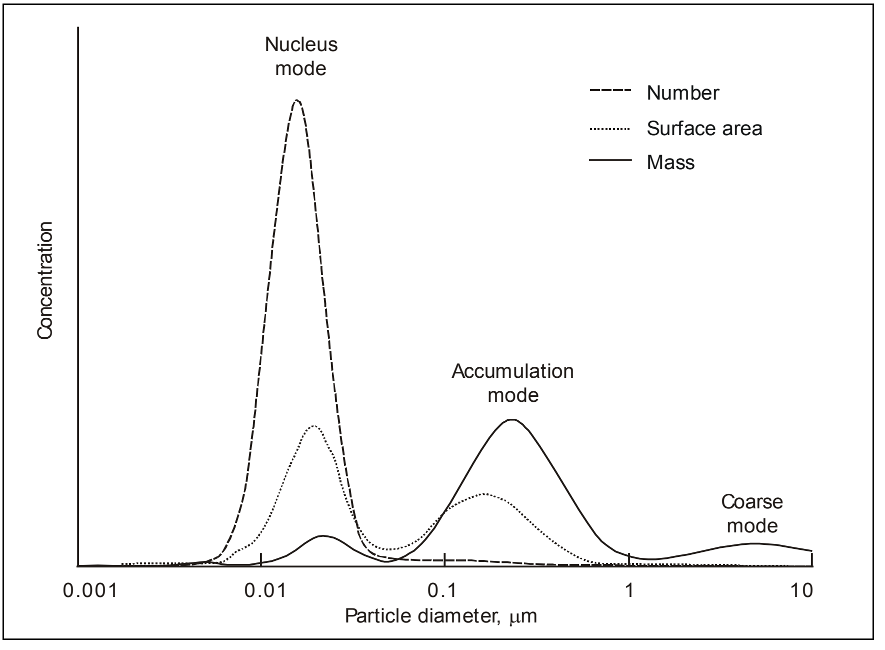


FIGURE 1 *Size distributions of airborne particles by number, surface area, and mass (the diagram is illustrative; real distributions depend strongly on location and vary with time – see text)*

Condensation

23 Small (0.001–0.01 µm) liquid or solid particles may form as vapours condense, or as a result of chemical reactions between gases that form solids. These small particles, shown in Figure 1 by the nucleus mode, act as condensation nuclei for the formation of larger particles. However, further growth may also be the result of other processes, including agglomeration or coagulation, when particles collide and stick together. The final particles in these growth stages give rise to the accumulation mode in Figure 1.

Particle dynamics

24 The three main mechanisms that govern the dynamics of uncharged airborne particles in the ambient air, in the respiratory tract if they are inhaled, and in many air sampling instruments are gravitational sedimentation, inertial impaction, and diffusion (Brownian motion) (see Figure 2).

Gravitational sedimentation

25 Particles are denser than air and so fall ('sediment') under the action of gravity. The particle at first accelerates towards the ground, but as its speed rises, the retarding force (viscous drag) caused by the viscosity of the air steadily increases until eventually the two forces balance. The particle then falls at a constant speed known as the settling (or terminal) velocity and this increases with particle diameter and density. Figure 3 shows settling velocities for spherical particles of unit density (1 g cm^{-3}) in mm s^{-1}. For 10 µm particles, the settling velocity is a few mm s^{-1} and so particles larger than this do not usually stay airborne for very long. However, for 0.1 µm particles, the settling velocity is only 0.001 mm s^{-1}. So these take 20 minutes to fall just 1 mm and particles of this size and smaller are quite stable in air. The settling velocity is used to define the 'aerodynamic equivalent diameter' of a particle, which is the diameter of a unit density sphere with the same settling velocity.

FIGURE 2 *Main mechanisms of particle deposition*

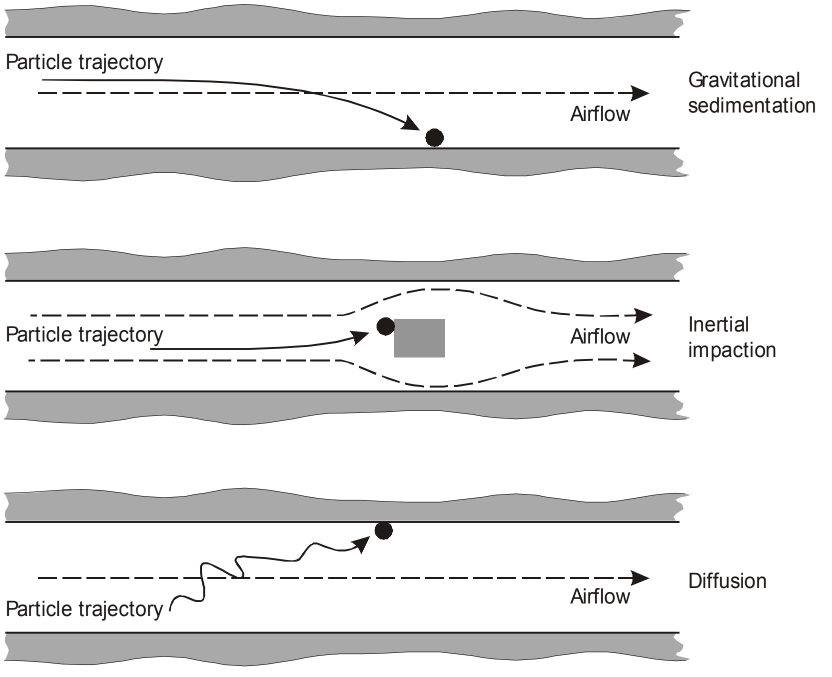
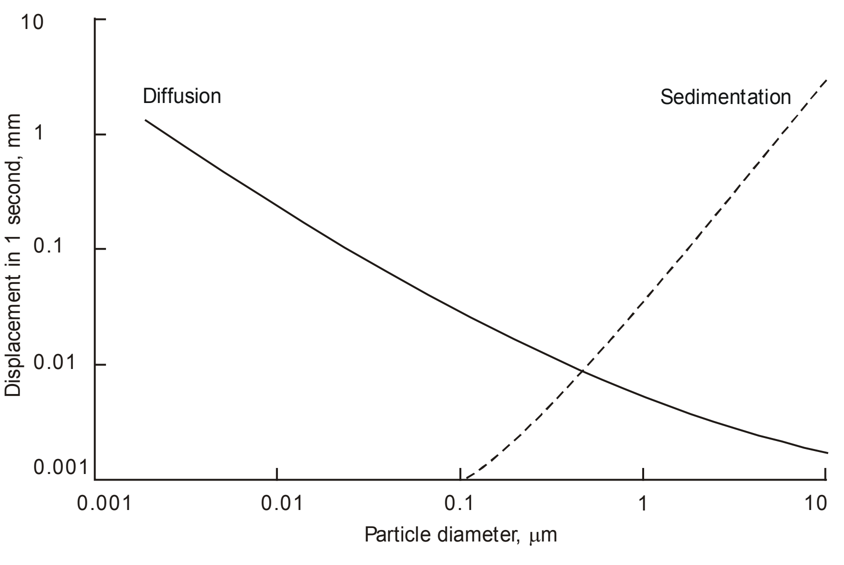


FIGURE 3 *Relative importance of gravitational sedimentation and diffusion as a function of particle size (for unit density spheres, data taken from Raabe, 1994)*



For gravitational sedimentation the displacement is the vertical distance the particle falls in 1 second. For diffusion the displacement is the typical (root mean square) distance the particle travels as a result of Brownian motion in 1 second.

Inertial impaction

26 When the air moves in a fixed direction, viscous drag causes the particles to move with it. However, when air flows around an obstruction, the path of each particle departs somewhat from that of the airstream because its inertia (momentum) causes it to follow its original direction rather than the direction of flow and possibly collide with the obstacle. The probability of this occurring increases with the size and density of the particle and hence depends on the aerodynamic equivalent diameter of the particle as well as on the airstream velocity. Sedimentation and impaction are therefore both known as 'aerodynamic' processes.

Diffusion

27 The constant bombardment by air molecules to which particles are subjected causes them to undergo random movement known as Brownian motion. The average distance that a particle moves relative to the airstream ('displacement') in a given time increases with decreasing particle size, but does not depend on its density. Diffusion increases with increasing temperature, because of the resulting increase in molecular velocity, and so is described as a thermodynamic process. Figure 3 shows how the displacement in 1 second depends on particle diameter. Diffusion is important compared with sedimentation for particles of size below about 1 μm but its effects are negligible for large particles.

28 It will be seen later (see the table, page 20) that a high proportion of airborne particles of size greater than 0.1 μm carry a positive or negative charge, ne, where e is the electronic charge and n is a small integer. The motion of these particles is also affected by electric forces if electric fields are present. The particle is moved in the direction of the field (or against it if the charge is negative), leading to the possibility of increased deposition. The various ways in which particles can become charged are described in paragraphs 64–75.

Airborne particulate pollutants

29 Particulate air pollutants arise from various sources. Some are produced within buildings where their concentrations are relatively high, but outdoors are much diluted. Others originate outdoors, but penetrate and persist within buildings to an extent that depends on their physical and chemical characteristics. In so far as most people in Britain spend the greater part of their time inside buildings, indoor concentrations of a pollutant (whether it originates indoors or outdoors) have a greater impact on cumulative personal exposures than outdoor concentrations.

Combustion products

30 In Britain, the most important source of particulate pollution in outdoor air, in both urban and rural locations, is the combustion of fossil fuels (EPAQS, 2001). Historically, coal burning in domestic fires and industrial processes generated high levels of carbonaceous smoke particles that contributed to the infamous smogs of the 19th and early-to-mid 20th centuries. However, since the Clean Air Act of 1956 and the introduction of smokeless fuels, particulate pollution from coal fires has been largely eliminated.

31 Nowadays, the main particulate pollutants in outdoor air are soots from diesel engines, and ammonium salts of sulphate and nitrate. The former comprise mainly

elemental carbon, but with a coating of low volatility hydrocarbons, including polycyclic aromatic hydrocarbons (PAHs) such as benzo[a]pyrene (BaP). The latter arise when oxides of nitrogen (principally from the exhaust of petrol engines) and sulphur (mainly from the combustion of coal and oil in power stations and of oil in industry) undergo secondary photochemical oxidation in the atmosphere, and then combine with ammonia from the excreta of farm animals. Particles from these sources have diameters that are generally less than 2.5 μm (EPAQS, 2001).

32 In the UK, concentrations of particulate pollutants in outdoor air tend to be highest next to roads, intermediate at urban locations which are not immediately next to roads, and lowest in rural areas (EPAQS, 2001). Particle emissions from road traffic are falling, and will decline further in the future, because of changes in regulations. For example, heavy diesel vehicles will require particle traps from 2006.

33 Combustion of some fossil fuels can also lead to the formation of particulate air pollutants within buildings. However, in Britain this is less important than the ingress of particles from outdoors.

Products of abrasion and dispersion

34 In addition to the fine particles that result directly or indirectly from combustion processes, coarser particles occur in outdoor air through abrasion and through dispersion of dusts and liquid droplets. Particles naturally present in the air include sodium and magnesium chlorides from sea spray; minerals from rocks, soils and surface dusts; and biological materials such as viruses, fungal spores, bacteria and pollen fragments. Human activities, particularly industrial and agricultural practices, such as quarrying, construction, demolition and ploughing, can increase the numbers of coarse particles in the air.

Radon decay products

35 The radioactive decay products of radon gas in indoor air provide a larger contribution to the radiation exposure of the UK population than any other source (Hughes, 1999). Radon-222 is produced continuously through the decay of uranium-238, which is present in varying concentrations in all rocks and soils. Radon seeps into buildings to some extent from the materials of which they are made, most of which contain traces of uranium, but more importantly in the UK, from the ground. The amount in the indoor air consequently depends mainly on the geology of the area in which the building is situated but also on features of the building which allow radon to be drawn in and the concentration to build up. Outdoors radon is rapidly dispersed and concentrations in the UK are generally low.

36 The immediate decay products of radon-222, polonium-218 to polonium-214 (see Figure 4), have short half-lives. They are all radioactive isotopes of solids and are either alpha emitters or beta–gamma emitters. Radon decay products are not gases, so they stick to surfaces that they touch, in contrast to the parent radon. The surfaces that they deposit on may be particles present in the air but may also be skin, or the linings of the airways. Radon decay products that deposit on particles are described as 'attached'. The particles to which they attach are normally in the accumulation mode (Figure 1). Unattached decay products have sizes towards the lower end of the nucleus mode, so can diffuse much more rapidly than those that are attached (Figure 3) (Porstendorfer and Reineking, 1992).

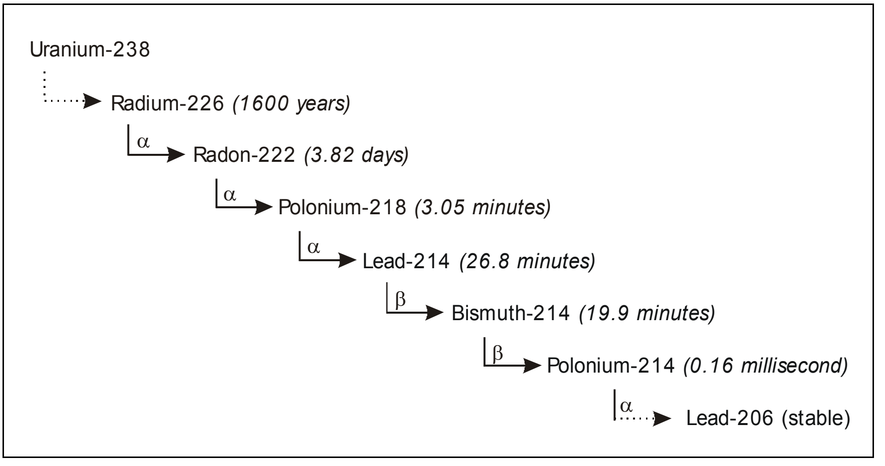


FIGURE 4
Radon-222 decay chain showing half-lives (broken lines show where isotopes have been omitted)

Environmental tobacco smoke

37 Sidestream smoke from cigarettes and other tobacco products is another source of particulate pollution indoors. In addition to elemental carbon, the particles in tobacco smoke contain a complex mixture of organic compounds and various metallic species (IARC, 2002).

Health effects of airborne particulate pollution

38 Understanding of the toxicity of particulate air pollutants comes from laboratory investigations *in vitro* and in whole animals, experimental studies in human volunteers, and clinical and epidemiological observations. The two long-term adverse health effects that have been clearly identified are cardiorespiratory disease and lung cancer. In theory, some forms of particulate pollution might also cause skin cancer. In practice, however, any effect on the risk of skin tumours appears to be negligible.

Outdoor air pollution

39 The impact of outdoor air pollution on health was first brought to wide public notice through the demonstration of a substantial rise in daily mortality during the London smog of 1952. Most of the excess deaths were from respiratory illness and, although other pollutants such as sulphur dioxide gas may also have contributed, it seems likely that particulate pollution was a major cause.

40 At that time air pollution arose almost entirely from the combustion of coal, principally in residential dwellings where it was commonly burnt in open fires. During smogs, levels of pollution were exceptionally high. How much disease was caused by chronic exposure to the lower, but still substantial, amounts of smoke that caused towns to be constantly enveloped in a visible haze was controversial. It seems likely, however, that it contributed to an increased incidence of chronic obstructive lung disease, and that PAHs such as BaP which were present on the smoke particles contributed to the risk of lung cancer. An excess of lung cancer was not clearly demonstrated in non-smokers, but up to 10% of mortality from the disease in big cities was estimated to be due to air pollution interacting with smoking (Cederlöf et al, 1978). At that time the amount of BaP in the air of big cities was commonly 30–40 ng m^{-3}, and

Pike et al (1975) reached a similar conclusion to Cederlöf et al by extrapolating from the experience of men heavily exposed to PAHs by the nature of their work.

41 Although particulate pollution from coal burning has virtually disappeared since the introduction of the Clean Air Act of 1956, and levels of particulate matter in outdoor air are now much reduced, there is strong evidence that health effects continue to occur from the particulate pollution produced by motor vehicles. It has been shown that daily fluctuations in outdoor concentrations of particulate matter (most often measured as PM_{10}, that is particles of less than 10 μm diameter) are associated with changes in morbidity and mortality from both cardiac and respiratory disease (EPAQS, 2001). The average effect on the risk of an individual is relatively small and sophisticated statistical techniques are needed to distinguish it from that of potentially confounding factors such as ambient temperature and the community prevalence of influenza. Nevertheless, the finding has been consistent across a large number of studies in different countries and, because large numbers of people are exposed to the pollution, the impact at a population level is important. Estimates made by Samet et al (2000) from observations in 20 cities in the USA suggest that the risk of death from cardiovascular and respiratory disease increases by 0.7% for each increase of $10\,\mu g\,m^{-3}$ in the PM_{10} level and that of death from all causes by 0.5%. More recent work suggests that, if anything, these figures may err on the high side (Samet et al, 2003).

42 Short-term fluctuations in mortality could arise simply because pollution caused people who were already seriously ill to die a few days earlier than they would have done otherwise. Long-term follow-up of large populations has, however, shown that a 'harvesting' effect of this sort cannot account for all the observed associations (Dockery et al, 1993; Pope et al, 1995).

43 The extent to which chronic exposure to particulate pollution of outdoor air impacts on long-term morbidity and mortality is difficult to assess because of the potentially confounding influences of people's smoking habits. However, a study of mortality in population samples from six cities in the USA with widely different levels of pollution, was able to include data on individual smoking habits. After taking smoking habits into account, the residents of the most polluted city had 37% higher mortality from cardiorespiratory disease and lung cancer than residents of the least polluted city, while mortality rates from other causes were similar (Dockery et al, 1993).

44 The pathological mechanisms underlying the health effects of particulate pollution are not yet firmly established. The impact on cardiorespiratory disease appears not to depend critically on the main chemical constituents of the particles inhaled since it is observed in locations where these differ (diesel exhaust particles dominating in some areas and nitrate and sulphate in others). Rather, evidence is accumulating that it results from inflammation triggered by oxidant damage to cells in the lung, and that a major factor in this process is the generation of free radicals by transition metals adsorbed on the surface of the particles.

45 If this is the main pathogenic mechanism, then the toxicity would be expected to lie principally in the finer fraction of particles, which have a relatively high surface area in relation to their mass. However, it has proved difficult to discriminate between the effects of different particle fractions epidemiologically, since their concentrations are usually highly correlated.

46 The excess risk of lung cancer in polluted cities is likely to derive in part from the carcinogenic activity of PAHs contained in airborne particles. However, it is unclear whether this is the only disease mechanism involved. It is probable that risk is determined by cumulative exposure to the relevant carcinogens over the course of a lifetime, in which case the main contribution to the pollution-related differences in mortality that are currently observed between cities may come from historical exposures at higher levels than now pertain.

Indoor air pollution

47 Pollution of the air outdoors penetrates into buildings and contributes at a lower level to pollution indoors. In addition, particulate pollution can arise indoors from radon decay products and from the sidestream and exhaled smoke produced by smokers.

48 The experience of workers exposed to high concentrations of radon in underground mines has established that radon decay products cause an increased risk of lung cancer, the risk produced being approximately proportional to the air concentration, except at very high levels when it is relatively less. Extrapolation from the experience of miners suggests that some 6% of all lung cancers in the UK are attributable to residential radon exposure and the studies based on direct observation of its role in houses are consistent with this. The UK has an Action Level for radon of 200 Bq m^{-3} (ten times the average concentration), above which homeowners are advised to reduce radon concentrations. Residential exposure to radon at the Action Level is estimated to carry a cumulative risk of death from lung cancer in a lifelong non-smoker to age 85 years of 1.4% as compared with 0.7% for zero exposure (Darby et al, 2001).

49 Environmental tobacco smoke within buildings has a clear effect on some special groups. Respiratory illnesses are more frequent in children whose parents smoke (Landau, 2001; Peat et al, 2001) and attacks of wheezing and breathlessness can be exacerbated in asthmatics (Leikauf, 2002). It also increases the risk of lung cancer in non-smokers to a small extent and so must be presumed to increase the risk additionally in smokers. A review by IARC (2002) estimated that the total effect of exposure to environmental tobacco smoke at home and at work is to increase the risk of lung cancer in non-smokers by some 30%.

Particulate air pollution and skin cancer

50 An elevated incidence of skin cancer has been demonstrated in various groups of workers whose skin was liable to be contaminated by soots, tars or mineral oils contaminated with PAHs. It has not, however, been recognised as an effect of air pollution by particles containing PAHs, probably because the dose to the skin from such pollution is relatively low.

51 An excess of skin cancer has also been reported in an early morbidity study of Czechoslovak uranium miners (Sevcova et al, 1978), but this cannot necessarily be attributed to radon as the miners were also exposed to high levels of arsenic, a known cause of skin cancer. Moreover very little irradiation from radon decay products penetrates to the basal layer of the skin from which skin cancers arise and the experience of people exposed to high doses of penetrating radiation indicates that any risk from domestic radon is too small to cause concern (Charles, 2001).

CORONA IONS

52 Whenever voltages of a few thousand volts or greater are present in electrical systems there is a tendency for the high electric fields that exist to cause electrical breakdown of the air by corona discharges. Here some details of the conditions required for corona discharges and their characteristics are given.

53 A simple estimate of the electric field near the point or tip of a sharp object is given by dividing the tip voltage by the tip radius. Corona discharge occurs when this local field exceeds approximately 3 MV m^{-1}, which is equivalent to 30 000 V sustained across a 1 cm gap between two large flat electrodes. Any electrons entering the field region are accelerated and gain enough energy to ionise air atoms with which they collide. The ion/electron pairs produced are then themselves accelerated and undergo collisions. Only the electron collisions are ionising and produce the avalanche breakdown process confined to the region of air adjacent to the 'corona electrode'. The corona appears as a faint filamentary discharge radiating outwards from its source. Most coronas are direct current (DC), ie sustained by either a positive or a negative electrode voltage. However, alternating current (AC) coronas are used in industry for the elimination of static electricity and also occur on power transmission lines.

54 Since positive ions and electrons differ greatly in size and mass, the character of a corona depends on the polarity of the sharp electrode. If the corona electrode is negative (negative corona), electrons are accelerated away from it and, since the field is decreasing, the discharge does not extend far. Positive ions produced in the discharge are accelerated towards the electrode and release secondary electrons upon collision. The electrons emanating from a negative corona point attach to air molecules to produce negative ions that depend on conditions but typically are species such as O^-, OH^- and O_3^- and neutral molecules such as N_2O, NO_2 and HNO_3 (Goldman et al, 1985). So a negative corona serves as a source of negative ions. Similar considerations for a positive corona electrode explain why this acts as a source of positive ions such as H^+, NO^+ and NO_2^+.

55 A single corona point can produce a current of up to a few hundred microamps, whereas a corona wire can produce a current from discrete regions on the wire surface of approximately 10 mA m^{-1}) (Cross, 1987). Commercial static eliminators usually operate at about 1 mA m^{-1} when the discharge is quite stable.

Sources of corona ions

56 There are only a few examples of AC corona applications and phenomena. One application is the AC static eliminator which produces ions of both polarities by driving a corona point or wire with an alternating voltage. Power transmission lines (50 Hz) operating at 132, 275 and 400 kV are examples of unintentional sources of corona ions. The high voltage (HV) rails and overhead lines used to power trains (Chadwick and Lowes, 1998) may also produce some ions at times. 'Third' rail systems use a rail energised up to 750 V (DC) and are most unlikely to produce corona ions. Transient arc discharges that may occur when trains pass along a line will produce some ions but they will be rapidly lost to ground. Mainline electric systems operating with overhead lines at 25 kV, 50 Hz, are likely to produce some corona ions in wet weather but it is expected that these will be in very much lower concentrations than the ions produced by the much higher voltage power transmission lines.

57 Corona ions are only produced when the corona electric field exceeds the air breakdown threshold during the positive and negative excursions of the AC cycle (Cross, 1987). The negative and positive corona threshold fields differ slightly. At low frequency such as 50 Hz the positive and negative ions produced on alternate half cycles of voltage behave independently, as if two separate DC discharges were being switched on and off in sequence. However, some recombination of positive and negative ions will occur as the two clouds oscillate in the AC electric field. Due to the asymmetry of the discharges and the normally higher mobility of negative ions it would seem likely that there would be a surplus of negative ions, which may then drift away or be blown away from the AC corona source. There is, though, some evidence that the surfeit of ions can be negative or positive depending on corona electrode geometry and prevailing conditions.

58 Corona discharges often occur from electrodes that are at a high potential, say several thousand volts, with respect to ground. High voltage AC transmission lines are examples of this but are of course designed not to operate under corona discharge conditions because this would result in loss of power, and also produce noise that would cause complaints. The electric field value at the high voltage conductor surfaces will be large and divergent but normally not large enough to cause electrical breakdown at the conductor surfaces where the field is greatest. To ensure that lines operate below the corona threshold field, the lines are arranged in groups of either two, three or four cables (twin, triple and quad lines) with spacers holding the individual cables 30 cm or so apart. With these arrangements the mutual interaction between the individual lines in a group results in increased line capacitance so that the charge on each individual line is redistributed and reduced in magnitude. This results in a reduced electric field at the line surfaces. However, small local intensifications of the conductor surface electric field can arise at dust and dirt accumulations or at water drops sometimes causing corona discharges to occur. Also, some high voltage lines are operated above their original design voltage. This can lead to corona discharge at the separators between sets of two or four cables, unless the original separators are replaced with ones appropriate for the higher voltage. These lines are also closer to the threshold for corona discharge than lines designed for the higher voltage, so are more prone to discharge along the line or at insulator support surfaces in adverse weather conditions.

Behaviour of corona ions

59 Corona discharges produce various ionic species depending on conditions and these may be used to charge surfaces or particles in a number of industrial applications. Negative corona discharges are used to charge and precipitate flue gas particles in the electrostatic precipitators now used in many commercial chimneys, or to charge paint particles or insecticide droplets to ensure efficient deposition of material on to grounded objects or foliage. These applications use the fact that when particles are charged, they tend to deposit on to surfaces more effectively due to attractive (image) forces. If there are additional electric fields at the surface these may further increase particle deposition.

60 Whenever ions are present in the atmosphere either as a low level natural background from radiation (ultraviolet radiation, cosmic rays, etc) or at a relatively high level in a locality due to a source such as a corona discharge, then any particles such as dust or pollutant particles will become charged by ion collision and attachment. The low level natural background charging gives rise to a Maxwell-Boltzmann (M-B) charge

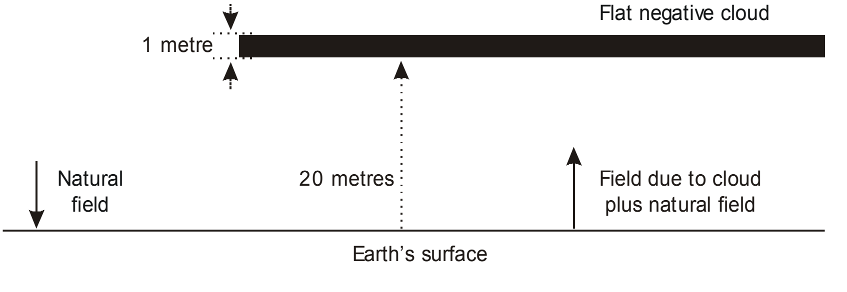
distribution in which some particles are neutral, a size-dependent fraction is positively charged and an equal fraction is negatively charged (paragraphs 65–68). Surplus ions from, say, a corona source may change the natural M-B equilibrium and bias it positively or negatively depending on the polarity of the corona ions. The very mobile clouds of surplus ions diffuse rapidly amongst the relatively immobile larger particles and attach, the process being described as diffusion charging.

61 Global thunderstorm activity delivers negative charge to the Earth leaving the atmosphere charged positively. A typical atmospheric space charge value is approximately $+10\,\mathrm{pC\,m^{-3}}$, which results in an electric field at the Earth's surface of about $-100\,\mathrm{V\,m^{-1}}$. Naturally occurring ions in the atmosphere move under this field, thus constituting a leakage current. The Earth's field depends sensitively on weather conditions and cloud cover and may vary significantly both temporally and spatially over the Earth's surface. Any local clouds or plumes of ions from, say, a power line, will change the Earth's natural field. The space charge of negative ions reduces the magnitude of the natural field and, if the space charge is sufficiently great, will reverse the field to a positive value. Positive space charge in the atmosphere increases the magnitude of the negative value of the Earth's field. Figure 5 illustrates this effect for a flat cloud of negative space charge 20 m above the Earth's surface.

62 Away from the cloud, the natural field is directed towards the Earth and has a value $E = -100\,\mathrm{V\,m^{-1}}$. The field terminates on negative charge at the Earth's surface of charge density $\sigma = \varepsilon_0 E = -8.8\ 10^{-10}\,\mathrm{C\,m^{-2}}$ (where ε_0 = permittivity of air = $8.8\ 10^{-12}\,\mathrm{F\,m^{-1}}$).

63 If the cloud is negative and reduces the natural field from $-100\,\mathrm{V\,m^{-1}}$ to zero, then the equivalent surface space charge density of the cloud as seen from the ground will be $8.8\ 10^{-10}\,\mathrm{C\,m^{-2}}$. The same is true if the cloud is positive and doubles the natural field to $-200\,\mathrm{V\,m^{-1}}$. However, as the cloud has some thickness it is the volume charge density that needs to be described. If the cloud is 1 m thick it must consist of a space charge volume density of $8.8\ 10^{-10}\,\mathrm{C\,m^{-3}}$. This corresponds to 5500 ions $\mathrm{cm^{-3}}$, if the ions have charge e, which falls to 550 ions $\mathrm{cm^{-3}}$ for a cloud 10 m thick. This simple calculation indicates that a change in the Earth's natural field of about $\pm 100\,\mathrm{V\,m^{-1}}$ shows the presence of ion densities from power lines or other sources of a few hundred or thousand ions $\mathrm{cm^{-3}}$.

FIGURE 5 *Effect of a cloud of charge on the Earth's field*



The normal convention, used here, is to designate an electric field as emanating from positive to negative charge. In some atmospheric field measurements the opposite convention is used, the normal electric field at the Earth's surface, which points downwards, being designated as positive.

Transfer of charge to particles

64 Particles in the atmosphere are invariably exposed to collisions with ions and thus acquire charge. As ions are usually relatively tiny and mobile compared to atmospheric particles, they diffuse through a particle population and frequent collisions occur. The particle charging that results is known as diffusion charging. Its efficiency is increased by the presence of an electric field and the process is then referred to as field charging. These two processes are considered briefly below. The equilibrium charge distribution of a particle population in the atmosphere obeys Maxwell-Boltzmann statistics. Although the M-B charge distribution describes well the charge on particles above about 0.5 μm in diameter, for smaller particles the charge observed may be greater than predicted (see paragraph 69). Hoppel and Frick (1986) considered ion-particle attachment coefficients. If an initially neutral population of particles (ie one with equal numbers of positive and negative charges) is exposed to an ion cloud, their net charge will increase. However, some of this increase will be due to neutralisation of the particles by ions of opposite charge. As a consequence, during initial charging, the total charge on all the particles increases more rapidly than the average magnitude of the charge per particle.

Maxwell-Boltzmann distribution

65 Over typical land surfaces approximately 10 ion pairs cm^{-3} are formed per second by natural processes. These then attach to airborne particles and recombine at a rate which leads to an equilibrium concentration of small ions (diameters of about a few nm) of 100–5000 cm^{-3} (Hinds, 1982). In calculations it is often assumed that there are about 1000 ions cm^{-3} consisting of approximately equal numbers of positive and negative species. They are assumed to be in complete thermal equilibrium with the atmosphere and so their probabilities of collision with dust or pollutant particles also present, can be calculated. The larger a dust or other particle the greater is the probability that it will become charged by collision and attachment to ions. The equilibrium charge level of a particle occurs when its charge is just sufficient to repel like charged ions diffusing towards it by Brownian motion. Since the potential energy of a particle of diameter d and charge ne at its surface is given by $n^2 e^2/4\pi \varepsilon_0 d$, the M-B distribution gives the probability of it having this charge as $p_n = a_n/\Sigma a_n$, where $a_n = \exp(-n^2 e^2/4\pi \varepsilon_0 d k_B T)$. In this equation k_B is the Boltzmann constant (1.38 10^{-23} J K^{-1}) and T is the absolute temperature (K). The table shows this for airborne particle populations of different particle sizes.

66 It is seen that over 99% of particles smaller than 0.01 μm carry no charge. For particles smaller than 0.1 μm some are uncharged and the remainder singly charged either positively or negatively in equal numbers. For particles larger than 0.1 μm the average number of charges, $\overline{n}$, per particle of diameter, d, in μm is given by $\overline{n} \cong 2.37\sqrt{d}$.

67 Given enough time and stable conditions all particles in the atmosphere would reach M-B equilibrium. The time to reach it depends on the ion density and is around 100 minutes for a density of 1000 ions cm^{-3}.

68 In practice, measured charge distributions are often asymmetrical. They may also contain larger fractions of charged particles than the predicted equilibrium M-B values. (Cohen et al, 1996). Indeed this would normally appear to be the case for very small particles for which the equilibrium fractions of even singly charged particles are small because of the large energies involved, $e^2/4\pi \varepsilon_0 d$. The laboratory studies by Cohen et al of atmospheric particles in the size range 0.01–0.5 μm showed that the charged

fractions were about 50%–100% higher than predicted by M-B theory and the fraction of size 0.125 μm having a single electronic charge was about 60% higher than expected. Kousaka et al (1983) also found that the proportion of charged particles in test particle clouds in the diameter range 0.004–0.04 μm exceeded the M-B predictions and a ratio of 0.35 : 0.65 was observed between the proportions of positively and negatively charged particles.

Numbers of electronic charges on atmospheric particles at equilibrium

Particle diameter (μm)	Average charge	Percentage of particles carrying the indicated number of charges								
		< –3	–3	–2	–1	0	+ 1	+ 2	+ 3	> + 3
0.01	0.007	–	–	–	0.3	99.3	0.3	–	–	–
0.02	0.104	–	–	–	5.2	89.6	5.2	–	–	–
0.05	0.411	–	–	0.6	19.3	60.2	19.3	0.6	–	–
0.1	0.672	–	0.3	4.4	24.1	42.6	24.1	4.4	0.3	–
0.2	1.00	0.3	2.3	9.6	22.6	30.1	22.6	9.6	2.3	0.3
0.5	1.64	4.6	6.8	12.1	17.0	19.0	17.0	12.1	6.8	4.6
1.0	2.34	11.8	8.1	10.7	12.7	13.5	12.7	10.7	8.1	11.8
2.0	3.33	20.1	7.4	8.5	9.3	9.5	9.3	8.5	7.4	20.1
5.0	5.28	29.8	5.4	5.8	6.0	6.0	6.0	5.8	5.4	29.8
10.0	7.47	35.4	4.0	4.2	4.2	4.3	4.2	4.2	4.0	35.4

Diffusion charging

69 Diffusion charging is the process described above by which particles in the atmosphere attain an equilibrium charge by exposure to naturally occurring ion pairs. It tends to be the dominant charging mechanism for particles smaller than about 0.2 μm even in the presence of an electric field when field charging might be expected to be important (Hinds, 1982). In many situations diffusion charging implies a preponderance of unipolar ions which diffuse to and attach to particles producing particle distributions with a net charge whose size depends on $N_i t$, where N_i is the ion concentration and t the exposure time.

Field charging

70 Field charging of particles is a modified form of diffusion charging whereby an electric field imposed on the charging region constrains the Brownian motion of ions to be directed along the electric field lines. In addition, due to the polarisability of particles (proportional to their permittivity, ε), particles 'attract' or distort the electric field in their immediate vicinities as shown in Figure 6.

71 The collision probability of ions with particles is thereby significantly increased by the presence of the electric field, E. For particles of a few μm in diameter and larger, field charging, say by corona ions in an electric field, is far more effective than diffusion charging and is the preferred method of charging particles in a number of industrial applications. For particular conditions and particle size there is a limiting value of charge possible (called the Pauthenier limit).

72 Figure 7 shows particle charge limiting values for $N_i t = 10^7$ ions s cm^{-3} and different charging processes. It is assumed that for field charging the field is 500 kV m^{-1}.

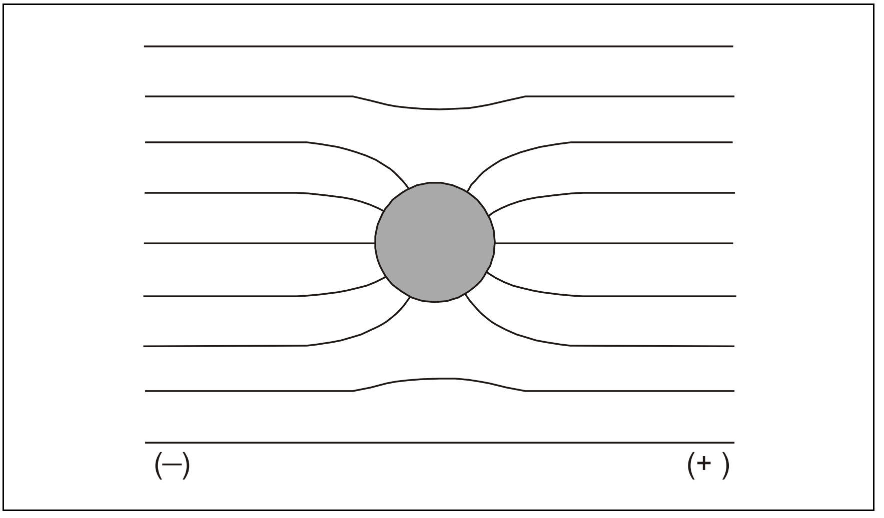


FIGURE 6 *Distorted electric field around a spherical particle*

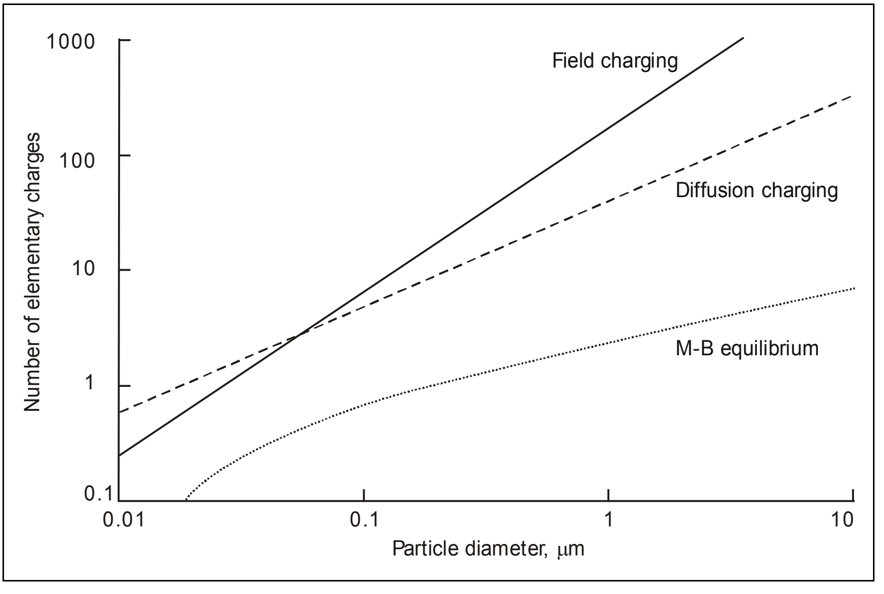


FIGURE 7 *Limiting values of charge for different charging processes*

Charging near to power lines

73 Henshaw and Fews (2001), Jeffers (2001) and Swanson and Jeffers (2002) have used existing theories to model the transfer of charge from unipolar corona ions to airborne particles. They concentrated particularly on particles of diameter 0.02 and 0.125 µm for which measurements were made by Cohen et al (1998) investigating the effect of charge on tracheobronchial deposition.

74 Henshaw and Fews (2001) calculated that for a unipolar ion density of 2500 cm^{-3} and an uncharged particle concentration of 15 000 cm^{-3}, 17% of uncharged particles in the size range 0.02–0.125 µm would ultimately acquire a charge. Since most of these would be singly charged, the average charge acquired would be about 0.17*e*. This limiting average value is referred to as the saturation charge. This can be compared with the average equilibrium charge in this range, which varies from about 0.1*e* to 0.7*e* (see the table, page 20).

75 Jeffers (2001) and Swanson and Jeffers (2002) carried out similar calculations but allowed for the fact that the plume of unipolar ions was expected to expand, partly because of repulsion between the ions (Jones and Jennings, 1977), as it moved away from the power line. This led to a decrease in the ion density and so in the charge transfer rate with distance from the power line. They estimated saturation charges of about 0.14*e* and 0.87*e* for 0.02 and 0.125 µm particles, respectively. They suggested, however, that for similar ion densities to those assumed by Henshaw and Fews (2001), the exposure time was only about one-tenth of that needed to reach saturation so that these values overestimated appreciably the charges actually acquired. They also explored transfer to particles with an M-B charge distribution and found somewhat smaller changes as expected (Swanson and Jeffers, 2002).

Experimental studies

76 Some of the earliest measurements of DC electric fields due to unipolar charge from AC power transmission lines were made by Chalmers (1952) at distances of several km from 66 and 132 kV lines. The observations were usually in fog or misty conditions. Negative fields were normally observed and were as high as 800 V m^{-1} on one occasion. Observations in fine weather generally were of low or no negative fields and Chalmers concluded that the observed negative fields were always associated with dampness. Furthermore, he concluded that wind was necessary to carry negative ions from the power lines the considerable distances over which the measurements were made. Mühleisen (1953) made similar observations up to 7 km from a 220 kV line and observed positive fields in clear weather.

77 The production of unipolar ions from high voltage direct current (HVDC) lines is readily understood and measurements on a ±400 kV test line were reported by Johnson (1983). Electric fields and ion currents were monitored in the range ±60 m laterally from the centre of the line. DC fields were found to be up to about 20 kV m^{-1}. Wind increased the field and ion current on the downwind side as expected. The electric fields and ion currents showed a large statistical variation even within the same weather conditions. The highest levels of electric field and ion current occurred during frost and the next highest in rain and fog.

78 In a second paper, Carter and Johnson (1988) measured space charge downwind of a –500 kV HVDC line. Corona sources were placed on the line to ensure a strong stable level of ions and measurements were made in the vicinity and up to 300 m downwind of the line. They identified two categories of charge carriers which they called small air ions and charged particles, which correspond to the nucleus and accumulation modes in Figure 1 (page 9). The small air ions were singly charged, positive or negative, hydrated molecular clusters having high mobilities which were typically greater than $5\ 10^{-5}\ m^2\ V^{-1}\ s^{-1}$. The charged particles had lower mobilities around $10^{-6}\ m^2\ V^{-1}\ s^{-1}$ so were moved little by electric fields but readily by the wind. They consisted of naturally occurring solid and liquid particles suspended in the atmosphere. It was observed that the small air ion density decayed rapidly with distance downwind – for example, the peak ion density of 160 000 ions cm^{-3} close to the line decayed to about 10% of this value in a downwind distance of 150 m in a wind of 8 m s^{-1}. At larger distances downwind the space charge of the cloud of airborne particles persisted with virtually no decay over the maximum measurement distance of 300 m.

79 In a theoretical paper, Cole and Jones (2002) considered how clouds of both positive and negative ions might persist for periods of up to an hour or so. Some experimental evidence for such persistent charge is reported in the literature. For example, Allen et al (1977) showed that after a succession of positive impulse sparks some of the positive ions produced persisted for five minutes, and negative ions also produced (surprisingly) at the same time appeared to persist for about an hour. Cole and Jones believed that 'the simultaneous existence of positive and negative ions at far higher densities than those found in natural background ionisation and which last for long time intervals has therefore been clearly experimentally established'. The authors considered the stability of spherical clouds of bipolar ions. They showed that when an external electric field, such as the Earth's field, is imposed on a cloud of bipolar ions there is a partial separation of charges. Equilibrium is re-established when the external field is removed. The time constant for re-establishing equilibrium may be long, ie some tens of minutes, and depends on the factor by which the ion density exceeds that of the typical ion density of the locality. As noted in paragraphs 65–68 on the M-B distribution, long time constants are to be expected under certain conditions. The time to reach M-B equilibrium can be 100 minutes or so in some circumstances.

80 Jones and Hutchinson (1977) studied ion plumes from a corona point source set up a few metres above ground and measured electric field and space charge downwind. Even though the source current was only 0.3 μA, fields of 1000 V m^{-1} or so were measured tens of metres downwind. They concluded that, for their setup, ion movement and dispersion were largely determined by wind patterns. In a second paper, Jones and Jennings (1977) studied the highly charged plumes of airborne particles (not ions) emitted from an industrial chimney stack equipped with an electrostatic precipitator. This would charge the flue gas particles negatively by corona discharges and only the fine components of the charged particles would escape into the atmosphere. Very high values of electric field were observed (5–6 kV m^{-1}). Even at 3 km downwind of the stack the electric field was 3.5 kV m^{-1}, suggesting particle concentrations equivalent to 10 000 ions cm^{-3} or more were present, assuming the cloud was 1 m thick (see paragraph 64). The fields did not decay to the normal Earth field value until the distance exceeded about 9 km. The authors concluded that significant trajectory modification could occur in light wind conditions and that image forces might cause higher ground level concentrations of charged particles than might have been expected from diffusion theory alone.

81 Swanson and Jeffers (1999) considered possible mechanisms by which power lines might affect airborne pollutant particles harmful to health. Most of their paper was devoted to particle deposition mechanisms but some important aspects of power line fields and measurements were discussed. They stated that results of DC field measurements made close to AC power lines should probably be treated with caution. Their view was that, even well away from the power lines, direct and simultaneous measurements of both the positive and negative ion densities provided more reliable values for the densities than those obtained from measurements of DC fields particularly at humidities less than 65% (Swanson and Jeffers, 2002). They presented the results of measurements of ion concentrations around different power lines in dry weather. The highest ion concentrations were found 50 m downwind of a line at Chobham with twin cables working at 400 kV, but with spacers designed for 275 kV. The measured concentrations of ions downwind of this line fluctuated rapidly, averaging around 3000 positive ions cm^{-3}, and peaking at over 6000 positive ions cm^{-3}. Around other power lines the average concentrations were 500 positive ions cm^{-3} or less, peaking at over 1000 cm^{-3}. The concentrations of negative ions were generally lower, but either positive or negative ions could predominate.

82 Fews et al (1999b) have considered the corona ions from power lines and measured the DC electric fields in the vicinity of, and especially downwind of, AC power lines. Measurements were made several hundred metres either side of 132 and 275 kV lines and up to 75 m from a 400 kV line. Twelve separate power line sites were examined, two being revisited making a total of fourteen datasets. Of these, eight cases were considered to show significant field perturbation effects and were reported in some detail. Further measurements are reported in Fews et al (2002). A common feature of all the datasets was an asymmetry in DC field between the upwind and downwind sides of the lines. This was attributed to a surplus of negative corona ions that was blown downwind of the lines giving rise to electric field values that considerably exceeded the Earth's natural field in magnitude and was of an opposite sense. The effects were particularly pronounced for one power line suggesting the corona was more severe in this case. In their first paper the authors put forward a mathematical model consisting of a negative sheet of corona charge emanating from a line and extending in the downwind direction but dropping in ion concentration with distance. This model was further refined in their second paper. By using typical parameters for the power line height and observed electric fields, the authors calculated that the area charge density required on the negative sheet of charge was $3\ 10^{10}$ electrons m^{-2}. If the sheet was assumed to have a thickness of 10 m, this area charge density corresponded to a volume charge density of 3000 electrons cm^{-3}. The authors noted, though, that this could be two or three times larger for some power lines.

Discussion

83 It is clear from experimental data that clouds of positive and/or negative ions may be produced by AC power lines and transported downwind. Ion densities of a few thousand per cubic cm are typical and they grossly perturb and indeed sometimes reverse the Earth's natural electric field. There is no doubt that the mobile negative ions attach to and thus charge pollutant particles in the atmosphere. Unfortunately, this particle-charging process is not fully understood. The reason why an AC corona discharge should normally result in a surfeit of negative ions is quite complex but is essentially due to the fact that negative ions normally have greater mobility than positive ions. A complicating factor is that in some situations, not properly defined, HVAC power lines produce a surfeit of positive ions. Furthermore, no matter which ion polarity dominates in any particular power line situation, the perturbation to the Earth's electric field should be symmetrically disposed either side of the line in still weather conditions. Such symmetry has not been reported in experimental measurements, probably due to shortcomings in the techniques used so far and the fact that significant temporal variations of field occur at specific locations.

84 It is not possible to calculate accurately the levels of charge that pollutant particles acquire near to HV power lines. The nature of pollutant particles depends on location, although for the purposes of calculation a typical pollutant population may be specified, together with an assumed particle size distribution. How such particles may charge near to a power line depends on their initial charge, ie whether or not an M-B distribution of charge is established. There is evidence that in some situations this is not the case particularly for small particles. To charge by diffusion, the dominant process for typical pollutant particles, the particles must pass through the ion plume adjacent to the power lines. Some particles will charge more than others and some will not be charged at all because of the range of possible trajectories and exposure times. With various assumptions, Henshaw and Fews (2001) calculated that 17% of particles in the size range 0.020–0.125 μm would acquire a charge of one electron. Using somewhat different assumptions, Swanson and Jeffers (2002) obtained rather larger values but emphasised that these (and presumably therefore those of Henshaw and Fews) are all saturation values and that the time for which the particles are exposed may be an order of magnitude smaller than that needed to reach saturation. Therefore, the actual values could well be smaller. They also noted that if the initial particles have some charge then the change in charge will be smaller than that calculated for uncharged particles. In addition, turbulence was not included in these calculations. This would seem likely to disperse the ions in the plume and so could further reduce these values. It is noted that the average charges on particles near to the ground would be somewhat smaller than these and closer to the M-B values, although it seems unlikely that this reduction would be significant since the times for the particles to reach the ground should mostly be small compared with the equilibrium times.

85 It is concluded that the values by which the average charge on pollutant particles increase are inevitably uncertain because of the difficulties of defining the conditions to which they are exposed. Nevertheless it seems likely that the pollutant particles downwind of a power line in corona and out of doors do have somewhat larger average charges on them as a result of corona discharge.

86 The situation indoors is potentially even more complex and variable than that outdoors. Airborne pollutant particles indoors result from entry of the outdoor particles through open windows and doors and/or cracks around closed windows and doors (Liu and Nazaroff, 2003). There may, however, also be indoor sources of pollution such as tobacco smoke, fires and gas burners, as well as radon which mainly comes through cracks and joints in the floor. So in some cases the pollutant concentration indoors may be significantly larger than that outdoors. Corona ions (and pollutant particles charged by them) would readily enter open windows and doors. However, they would tend to plate out to some extent if they were entering through a crack or joint and their concentrations indoors seem likely to be less than those outdoors. So the increase in average charge of pollutant particles resulting from corona ions should be less indoors than out, particularly if the particles are mainly of indoor origin, and will be further reduced since many of these particles will be deposited on other surfaces. It is concluded that the effect of corona ions on lung deposition will be less indoors than out, although this reduction will be offset to some degree in situations where the concentration of pollutant particles is substantially greater indoors because of indoor sources.

Summary

87 High voltage AC power lines may produce clouds of negative or positive ions that are readily blown downwind. Negative ions are more often produced especially in fog or misty conditions. The ion clouds significantly perturb the Earth's natural electric field and measurements of the perturbed field can be used to calculate the ion densities of the clouds or plumes. The ion clouds charge pollutant particles when they encounter them. Calculating the levels of particle charge that result is only possible if simplifying assumptions are made so there could be appreciable uncertainties in the values obtained in this way. Nevertheless, it seems likely that the pollutant particles downwind of a power line in corona and out of doors do have somewhat larger average charges on them as a result of corona discharge. The effect indoors on pollutant particles of *outdoor* origin is probably somewhat less since it seems likely that some preferential deposition of charged particles will occur on the surfaces of small apertures through which some of the air enters the building, and on indoor surfaces. The effect indoors on pollutant particles of *indoor* origin is probably considerably less, because there would be greater deposition of corona ions during entry through small apertures.

INHALATION OF PARTICLES

88 The extent to which particles deposit in each part of the respiratory tract depends on the processes outlined in paragraphs 24–28, and also on the size and shape of the airways, and the pattern of air flow within them. Physiologically there are two main parts: the 'deep lung' where oxygen and carbon dioxide are exchanged with the blood (technically known as the alveolar or pulmonary region); and the conducting airways of the head and tracheobronchial tree, which bring air to the deep lungs and act as an air cleaner and conditioner.

Deposition in the respiratory tract

89 The nasal passage has a small cross-sectional area, and the air velocity is high. There are sharp bends at the front and back, which promote deposition by impaction. In between, the nasal passage is narrow and convoluted (Figure 8), enabling deposition by diffusion to take place. The nose acts as an efficient filter for very small and for large (coarse mode) particles. Deposition in the mouth is broadly similar to that in the nose, but has been less well characterised. It would be expected to more variable (eg depending on how wide the mouth is open), but generally lower than in the nose at all particle sizes (ICRP, 1994; Cheng, 2003).

90 The trachea divides into the two main bronchi, which in turn subdivide, and so on. There are about 20 such divisions, known as 'generations', through which air flows successively to some 300 million air sacs or alveoli, which have a total surface area for gas exchange about equal to that of a tennis court. At each division the daughter airways are smaller but, because there are more of them, their total cross-sectional area is greater, and so the air velocity decreases with depth. Thus impaction is important in the first few airways, but decreases, giving way to sedimentation.

91 In the deep lung the air moves very slowly, and deposition occurs through sedimentation and diffusion. However, many particles are filtered out before they reach this region.

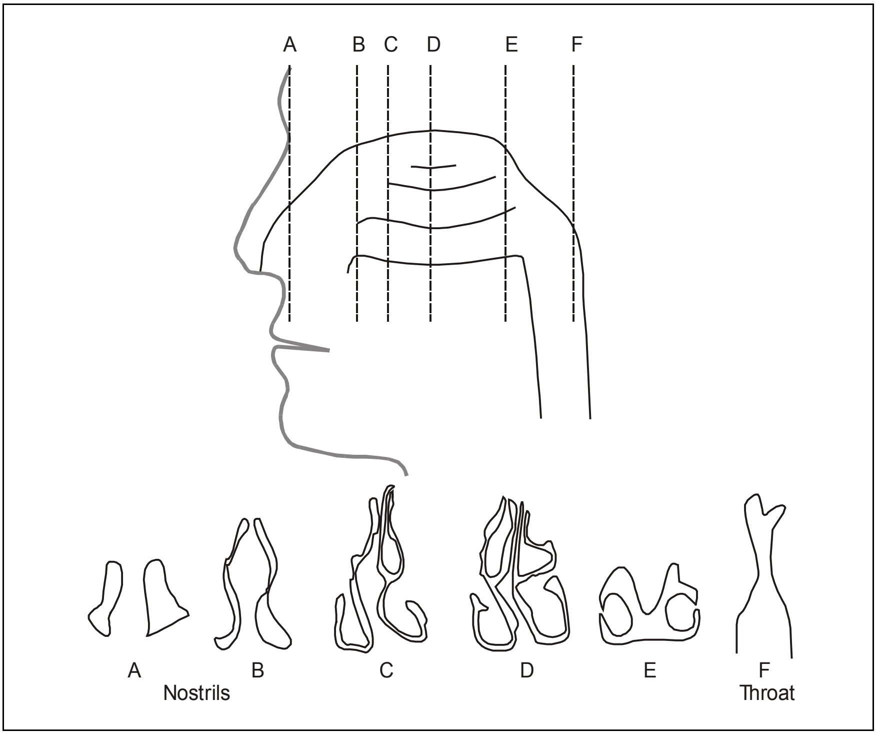


FIGURE 8 *Cross-sections through the nasal passage (based on Häußermann et al, in press)*

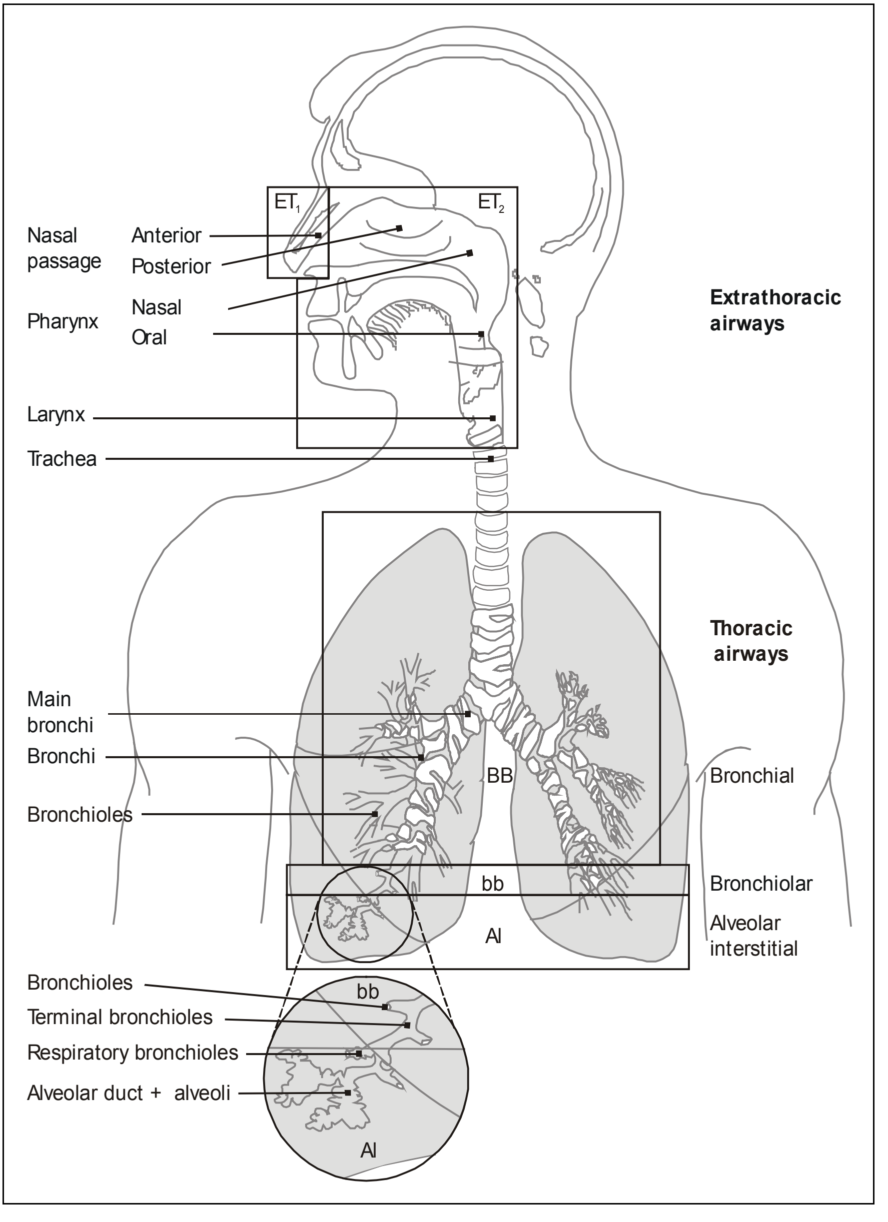
92 Sophisticated models have been developed over several decades to calculate the fraction of inhaled material that deposits in each part of the respiratory tract according to particle size and the subject's size and breathing pattern. The models use a combination of experimental data (results of experiments with volunteers and with physical models of airways) and mathematical analysis based on knowledge of the geometry of the airways, the patterns of flow within them, and the forces on the particles (outlined in paragraphs 24–28 above). They were originally developed mainly because of concerns about possible health hazards of inhaled particles, which were likely to depend on where the particles deposited in the respiratory tract. More recently there has been added impetus because of the increasing use of inhaled particles to deliver drugs to parts of the respiratory tract, particularly for treatment of lung diseases.

93 One of the most widely used models is the Human Respiratory Tract Model (HRTM) developed by a task group of the International Commission on Radiological Protection (ICRP, 1994). In the HRTM the respiratory tract is divided into the thoracic airways (the airways within the chest, ie the lungs) and the extrathoracic airways (ET, the airways in the head and neck). These, in turn, are divided into regions (Figure 9).

(a) The extrathoracic airways are divided into ET_1, the front part of the nose, and ET_2, which consists of the rest of the nasal and oral passages, the pharynx and larynx.

(b) The thoracic regions are bronchial (BB: the trachea and bronchi – the next 8 airway generations); bronchiolar (bb: airway generations 9–15, having diameters smaller than about 2 mm), and alveolar-interstitial (AI: the gas exchange region).

FIGURE 9
Respiratory tract regions defined in the HRTM (based on ICRP, 1994)



94 Figure 10 shows particle deposition calculated using software that implements the HRTM (Jarvis et al, 1996). For simplicity, deposition in both ET_1 and ET_2 have been combined (extrathoracic), and deposition in both BB and bb have been combined (T-B, tracheobronchial). The smallest particles (0.001 μm) diffuse very rapidly (see Figure 3, page 10) and mainly deposit in the extrathoracic airways (the nose). As their size increases, the particles diffuse less rapidly and more penetrate, first to the T-B, and then to the deep lung. As the size increases further, more particles are exhaled, and

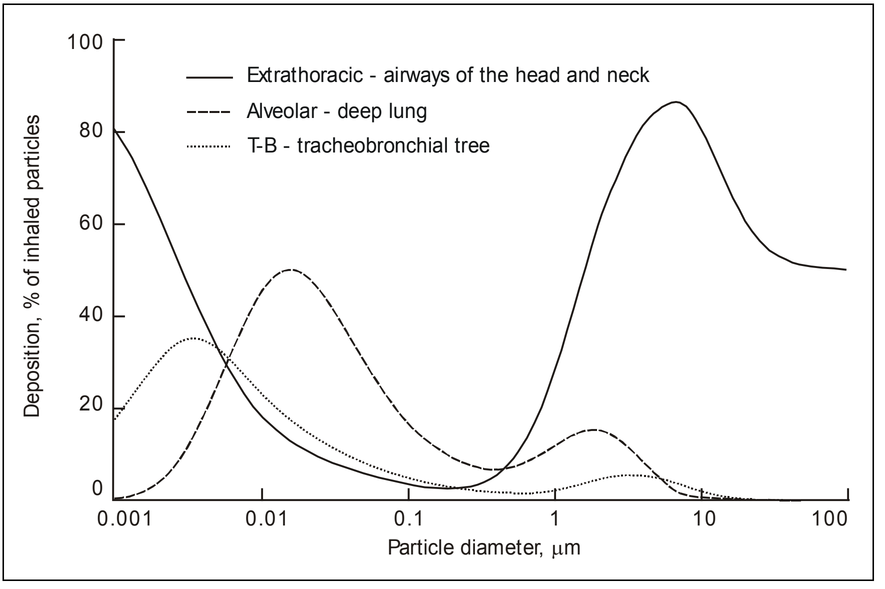


FIGURE 10 *Particle deposition in the respiratory tract for unit density spheres inhaled by an adult male averaged over 24 hours, calculated using the HRTM*

deposition reaches a minimum around 0.5 µm. Beyond this, sedimentation and impaction become increasingly important and deposition increases, especially in the nose. The fall in extrathoracic deposition between about 5 and 50 µm results from an inertial effect known as 'inhalability'. Such large particles do not always follow the air into the nose and mouth.

95 Figure 11 also shows particle deposition calculated with the HRTM, but for different combinations of regions, which might be relevant to atmospheric pollutants. Thus 'Lungs' are a combination of T-B and alveoli, which would be relevant to an agent that affected the lungs, or was absorbed into blood from the lungs much more readily than from the gut. 'Lungs + ET_2' also includes the nasal and oral passages (except the front of the nose), the pharynx and larynx. In the HRTM it is assumed that some absorption to blood occurs in ET_2, and also that material deposited in ET_2 is cleared to the throat and swallowed. Thus 'Lungs + ET_2' could be relevant to pollutants whose toxic effects depend on the amount absorbed into blood, and which are absorbed to a similar extent from both lungs and the gut. For completeness, 'Total' deposition is also shown (including the front of the nose, ET_1), although in the HRTM it is assumed that no absorption to blood occurs in ET_1, and material deposited in it is removed by nose-blowing, and is not swallowed. For particles smaller than 0.01 µm or larger than a few µm, most inhaled particles deposit in the respiratory tract, and a high proportion of them in the nose. However, for particles in the range 0.1–1 µm, only 10%–20% of inhaled particles deposit, mostly in the lungs.

96 Electrostatic charge effects are not addressed specifically in the HRTM. Where possible, the model is based on data from experiments using test particles. These particles are often highly charged when produced, so steps are usually taken to bring the charges into equilibrium before they are inhaled. Thus they represent particles with equilibrium charge, rather than uncharged particles.

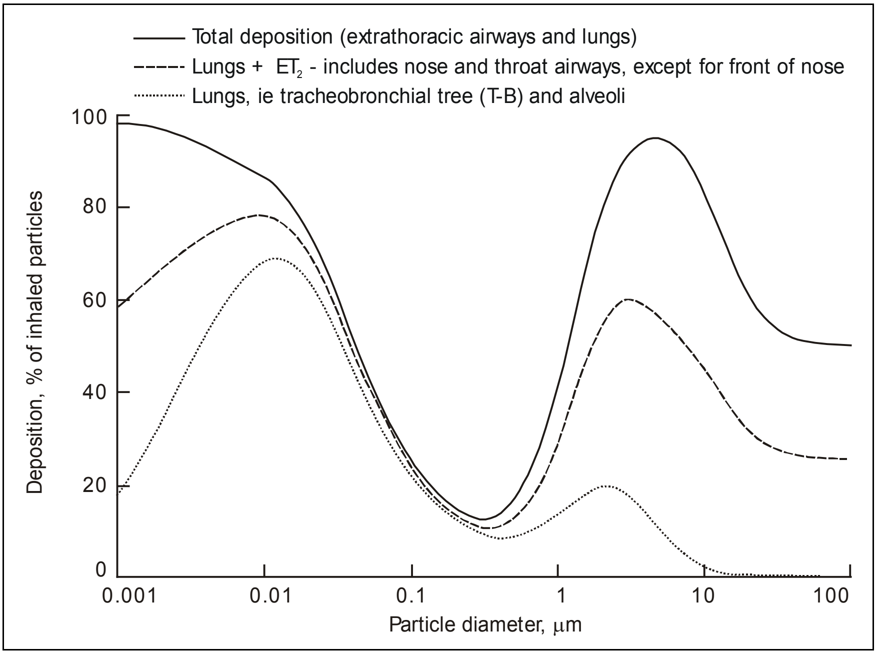


FIGURE 11 *Particle deposition in the respiratory tract for unit density spheres inhaled by an adult male averaged over 24 hours, calculated using the HRTM*

Deposition of charged particles in the respiratory tract

97 There are two mechanisms that increase the deposition of charged particles, compared to uncharged particles: space charge and image charge.

(a) *Space charge* (or mutual repulsion) effects apply because particles carrying the same charge repel each other. It is considered only to be important for situations in which the particle concentration is high, and is unlikely to be significant for inhaled atmospheric particles.
(b) *Image charge* effects apply to individual particles. The charge on a particle causes it to be attracted to a conducting surface as if there were an equal and opposite charge at an equal distance below the surface (like an 'image' of an object in a mirror). The force on the particle does not depend on whether the charge is positive or negative or on the particle concentration, but it increases the nearer the particle is to the surface.

The force on a charged particle increases with the strength of the electric field and the charge on the particle. The effect that the force has on the particle, however, depends on the particle's mobility. The motion of the particle is opposed by viscous drag, which increases with the diameter of the particle. Hence, as for diffusion, the effect of a given charge decreases with increasing particle size.

98 The general effect of an increase in the rate of deposition in the respiratory tract due to particle charge can be seen by reference to Figures 10 and 11:

(a) For very small or very large particles (<0.01 or >1 μm), deposition in the nose is high, and deposition in the lungs is low because few particles penetrate the nose to reach the lungs. Since most particles that reach the lungs deposit there, any increase in nasal deposition due to electrostatic charge will tend to reduce deposition in the lungs.

(b) For particles of intermediate size an increase in deposition due to charge will tend to increase deposition in the lungs, especially in the smallest airways, ie the deep lung.

99 The effect of electrostatic charge on increasing respiratory tract deposition has been recognised for some time. There have been a number of experimental studies: in human volunteers (Fry, 1970; Melandri et al, 1983; Prodi and Mularoni, 1985), experimental animals (Ferin et al, 1983), and in models of the bronchial tree (Chan et al, 1978; Chan and Yu, 1982; Cohen et al, 1995, 1998). Melandri et al (1983) made lung deposition measurements on volunteers, and their data showed that the minimum charge per particle needed to increase deposition was 9*e* for 0.3 μm particles and more than about 20*e* for 0.6 and 1.0 μm particles. The most recent of these experimental studies (Cohen et al, 1998) is also of particular interest because a significant effect of charge was found for deposition of small particles in a model of a human trachea and bronchi (about six generations, down to 3 mm diameter airways). Deposition of 0.02 and 0.125 μm particles with a single charge was two to three times greater than that of particles with equilibrium distribution of charge, and five to six times greater than for particles with no charge. It is highly desirable to obtain confirmation of these results *in vivo*, in view of the difficulties of simulating the relevant conditions in a model system.

100 There have also been a number of theoretical studies of the effect of electrostatic charge on respiratory tract deposition (Ingham, 1981; Yu, 1985; Hashish et al, 1988; Hashish, 1989; Bailey et al, 1998). In particular, Yu assessed the minimum charge per particle needed for image charge to increase deposition significantly (when sedimentation is the dominant mechanism): for 0.3 and 1 μm particles, these are about 10*e* and 50*e*, respectively, far above the equilibrium number of charges that occur at these sizes (see the table, page 20) or to be expected from charging by corona ions in the atmosphere. Bailey et al (1998) considered how the natural charge on airborne particles could be increased significantly by, for example, corona or induction charging to levels, which although well below the maximum possible, could cause significant increases in the lung deposition of inhaled particles. By choosing parameters such as particle size, charge and breathing rate, some control of particle deposition could be achieved. The authors concluded that the charging of particles could be utilised to give better control of drug delivery or to increase the trapping of pollutant particles in the upper airways.

101 Many airborne particles produced in workplaces result from dispersion of material, so they can be charged above equilibrium levels, and this could result in higher lung deposition for workers close to the source, and to problems with air sampling. A symposium on the subject of 'Static Electrification of Airborne Dusts: Occupational and Industrial Hygiene Considerations' was held in 1984. According to John and Vincent (1985) in their overview of the symposium: '... for isometric dusts in normal circumstances it is concluded that electric charge effects will have no significant effect on lung deposition, and in turn, on health risk'. (Isometric dusts are those with similar lengths in all three dimensions. This includes most dusts except fibres and platelets.) They also concluded that there were some special circumstances, eg electrostatic spraying of paints and pesticides, where particles are so highly charged that there could be increased lung deposition, and that for fibrous dusts such as asbestos, electrostatic charge effects could be important.

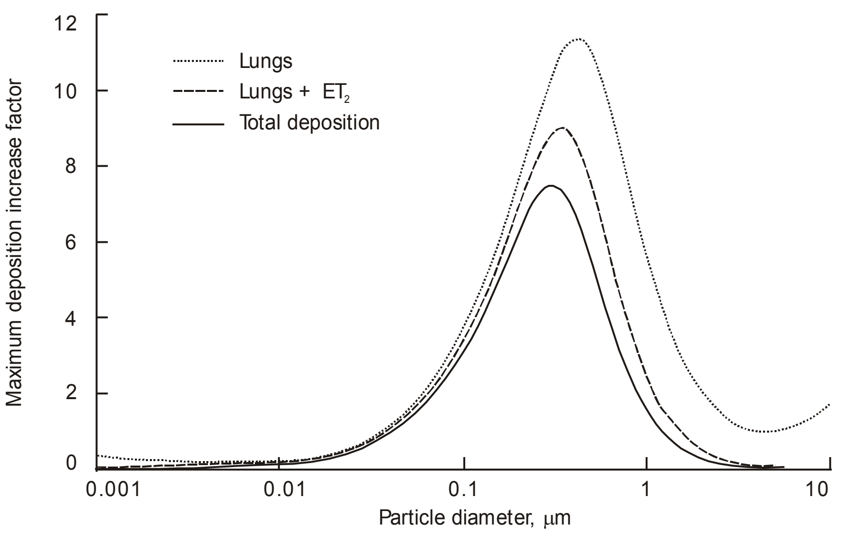
102 A more recent review was published by Cohen et al (1996). They noted that increased deposition from electrostatic charge effects has been observed in animal and human studies. For particles larger than about 1 μm, for which lung deposition is relatively high, and results from impaction and sedimentation, there appears to be good agreement between theory and experiment. Effects of charge are observed but at high levels of charge that are unlikely to occur in the environment, and only in unusual circumstances in the workplace. For submicron particles (less than 1 μm in diameter), that deposit mainly by diffusion, and for which lung deposition is low, the effect of charge can be important. Their experiments showed greater deposition of particles with a single charge than predicted by theory (Cohen et al, 1995). They also noted that, in practice, the fraction of charged submicron particles in the atmosphere can be greater than predicted by the M-B equilibrium (see paragraphs 65–68). They therefore emphasised the need to take account of charge effects when modelling the deposition of submicron particles, and the need for further experimental studies of the effect of charge on deposition in the human lung of such particles.

103 Assessing how much greater deposition in the lungs will be for particles with greater than normal charge is thus possible in principle, but difficult in practice. As mentioned above, larger particles can carry more charge, but the effect of a certain charge is greater for smaller particles. There appears to be a discrepancy between the limited experimental data and current theory for submicron particles. Assessing the effect on deposition of a given pollutant would be even more difficult, because it would require knowledge of the size distribution of the particles with which the pollutant is associated, as well as knowledge (or assessment) of the distribution of charges on particles of different sizes in various situations (eg rural or urban, and near or remote from power lines).

104 Detailed modelling of the effect of electrostatic charge on particle deposition in the size range of interest would form a substantial research project in itself. However, an assessment can be made of the maximum effect that particle charge could have (Figure 12). For simplicity, total deposition in the respiratory tract is considered first. As shown in Figure 11, for very small (less than 0.01 μm diameter) and very large (greater than 5 μm diameter) particles, deposition is close to 100% (the drop to about 50% between 5 and 50 μm results from inhalability: not all the particles present in the inhaled air actually enter the nose). Hence there is little scope to increase deposition of those particles that are inhaled. However, total deposition reaches a minimum of about 13% at about 0.3 μm. Thus if the particles were charged sufficiently, there is the potential to increase total deposition by at most a factor of 100%/13% = 7.7.

105 Deposition in the lungs of very small and very large particles is determined by the fraction of inhaled particles that pass through the extrathoracic airways: most of the particles that enter the lungs deposit anyway, so there is no scope to increase lung deposition. Instead, the effect of charge would be to increase deposition in the extrathoracic airways and reduce lung deposition. However, deposition in both the extrathoracic airways and lungs is low between about 0.1 and 1 μm, and there is potential for charge effects to increase lung deposition significantly in that size range. Lung deposition reaches a minimum of about 8.5% at about 0.4 μm, where extrathoracic deposition is also low. Thus if the particles were charged sufficiently, there is the potential to increase lung deposition by at most a factor of about 100%/8.5% = 12. For deposition in 'Lungs + ET_2', which could be relevant to pollutants whose toxic effects depend on the amount absorbed into blood, the pattern is intermediate between the two, with the maximum potential increase by a factor of about nine at about 0.35 μm.

106 Thus there is potential for electrostatic charge effects to increase total respiratory tract deposition and lung deposition by a large factor, about three- to ten-fold, over a limited size range, essentially between about 0.1 and 1 μm, where deposition is normally low. This size range does, however, correspond to the accumulation mode of the ambient atmospheric particle distribution (Figure 1, page 9). However, as discussed below, in practice any increase in deposition due to charge from corona ions is likely to be much smaller. There is potential for electrostatic charge effects to increase lung deposition by a smaller factor over a wider range of sizes (see Figure 12).



For particles smaller than about 0.01 μm or larger than about 5 μm total deposition in the respiratory tract is close to 100% and therefore there is little scope to increase deposition. Total deposition in the respiratory tract falls to its lowest value of about 13% at about 0.3 μm. Thus there is scope to increase total deposition by a factor of 100%/13% = 7.7 at that size. In practice, the effect of electrostatic charge will be lower than this maximum factor for various reasons, as described in the text.

FIGURE 12 *Scope for increasing deposition of unit density spheres in the respiratory tract (deposition conditions and combinations of regions as in Figure 11)*

107 The analysis and discussion in the previous paragraphs are based on the assumption that the size of the particles suspended in the air does not change within the respiratory tract, as assumed in the HRTM deposition model. However, particles in the ambient air, including pollutant particles, may well have water-soluble components. If so they can absorb water in the high relative humidity (close to 100%) of the respiratory tract and grow in size significantly (a factor of two or more), a phenomenon known as hygroscopic growth. The effect of this on deposition depends on the initial particle size and the rate of growth, and is not easy to calculate even for particles of known size and composition. (The issue is discussed in ICRP (1994), but a version of the HRTM incorporating hygroscopic growth does not appear to have been implemented.) Particles in the ambient air will have wide ranges of both size and composition. Consideration of Figures 10 and 11 suggests that moderate growth of particles in the approximate range 0.01–0.1 μm diameter will reduce lung deposition compared to that of non-hygroscopic particles. Thus in this size range there is greater potential for electrostatic charge to increase lung deposition. However, growth of particles in the approximate range 0.1–1 μm (where the potential for electrostatic charge effects is greatest: see Figure 12) will increase lung deposition compared to that of non-hygroscopic particles and reduce the potential for electrostatic charge to increase lung deposition. It therefore seems likely that for a cloud of particles with a range of hygroscopic growth rates, the effect of hygroscopic growth will be to 'smooth out' the potential effect of electrostatic charge as a function of size (Figure 12).

Discussion

108 It is emphasised that the factors derived above by which deposition could be increased are theoretical maxima. As noted, it is not possible at this time to make a reliable assessment of the increases that could occur in practice. There do not appear to be available human *in vivo* data, nor a validated model that enables the effect of charge on respiratory tract deposition in the relevant size range (below about 0.3 μm) to be calculated. If such a model were available, its application to a particular situation would also require information about:

(a) distributions of size and hygroscopic growth rate of the pollutant particles,
(b) distribution of charge on the pollutant particles as a function of their size.

However, adequate information on these is not available.

109 In view of these uncertainties, the amount by which electrostatic charge effects resulting from corona produced by a particular power line will increase deposition of any specific pollutant particles is not known. All that is known is that it must be less than the maximum possible increase of about ten (Figure 12). However, the maximum possible increase in lung deposition resulting from corona will not occur because of several factors, as follows.

(a) The extent to which the pollutant is charged – as noted above, it is considered very unlikely that particles larger than about 0.3 μm would be charged sufficiently to result in significantly increased lung deposition.
(b) The size distribution of the pollutant particles – the particles formed by any process generally have a wide size distribution, typically about two-thirds of the particles have sizes within a factor of two to three of the central (median) value. Therefore, in a 'worst case', where the central value of the pollutant size distribution was about 0.4 μm (the size for which the maximum potential for increased deposition occurs), about one-third of the particles will be smaller than 0.15 μm or larger than 1 μm. Hence the average maximum increase would be nearer seven than ten. However, if the central value were larger or smaller than 0.4 μm, then the maximum increase would be further reduced.

(c) Increased deposition in the extrathoracic airways could reduce the amount reaching the lungs.
(d) Hygroscopic growth of particles of approximately 0.4 μm diameter (where the potential for electrostatic charge effects is greatest) will increase lung deposition compared to that of non-hygroscopic particles and therefore reduce the potential for electrostatic charge to increase lung deposition.

110 The effect on deposition of a pollutant for any individual will be lower still, because he or she will only be exposed to corona-charged particles for some of the time. To be exposed, there needs to have been corona formation, and the right weather conditions for highly charged particles to be brought to ground level where the individual is located. Continuous corona from power lines does not occur frequently in populated areas, because the accompanying noise would cause complaints. However, it is possible that corona ions from some distance away could be blown on to residential areas. The PAH air concentrations in urban areas are typically three to four times those in rural areas, so any effect of corona ions on pollutant intake there could be significant. It would, though, be difficult to distinguish any increase due to corona charge from normal variations in pollutant concentration.

111 In paragraphs 73–75 it was noted that, using certain assumptions, Henshaw and Fews (2001) calculated that about 17% of particles with diameters between 0.020 and 0.125 μm would become charged. They suggested that exposure of people to these charged particles would occur whether they were indoors or outdoors, as only the very small particles (around 0.001 μm diameter) were removed from air when it entered buildings. Using the results of Cohen et al (1996, 1998) that singly charged particles had two to three times higher deposition in the lungs than charge-neutralised particles, they further calculated that people living downwind of power lines might have 20%–60% more particles deposited in their lungs than those upwind, assuming only modest particle charging by corona ions.

112 In the light of the review above, some increase in lung deposition of particles of these sizes is likely in some circumstances as a result of charging by corona ions. However, there is neither a suitable model available nor adequate information about the distributions of particle size and charge, to enable reliable estimates to be made of the size of any increase.

Summary

113 The deposition of particles in the human respiratory tract has been studied extensively both experimentally and theoretically. Current models such as the ICRP Human Respiratory Tract Model (HRTM) enable the fraction of inhaled particles that is deposited in each region of the respiratory tract to be calculated, according to the size distribution of the inhaled particles and the breathing pattern and age of the subject.

114 There have been a number of experimental and theoretical studies of the effect of electrostatic charge on deposition in the respiratory tract. Increased deposition results from image charge forces. The effect increases with increasing number of units of charge on a particle, but decreases with increasing particle size. There is consensus that for particles larger than about 0.3 μm, charge is unlikely to have a significant effect on lung deposition. However, for smaller particles, there are no human *in vivo* data available. Measurements from one study using a model (hollow cast) of human bronchial airways suggest that at about 0.1 μm a single unit of charge increases lung deposition by a factor of about three, which is more than predicted by current theory. Hence there does not seem to be a suitably validated model for predicting the effect of charge on deposition of submicron particles.

115 The HRTM does not address electrostatic charge explicitly. It was, however, used here to assess the potential for charge to increase lung deposition. The maximum by which deposition can be increased was calculated by comparing the number of particles that enter the lungs with the number that deposit there in the absence of charge effects. This showed that for very small (less than about 0.01 μm) and large particles (greater than about 5 μm), lung deposition is limited by deposition in the extrathoracic (ET) airways: most particles that reach the lungs deposit anyway. The effect of charge would therefore be to increase ET deposition and reduce lung deposition. In the size range about 0.1–1 μm, where lung deposition is normally low (about 10%) there is potential to increase lung deposition by a large factor, a theoretical maximum of three to ten, depending on size. This size range corresponds to the accumulation mode of the ambient atmospheric particle distribution (Figure 1, page 9). In any practical situation the effect of charge on deposition of a pollutant will be less than this theoretical maximum because of a number of factors, including the extent to which the pollutant particles are charged, the size distribution of the pollutant particles, increased deposition in the ET airways, and hygroscopic growth. Thus, as noted above, particles larger than 0.3 μm diameter are unlikely to carry a sufficient number of units of charge for lung deposition to be affected. The effect on exposure of individuals will be lower still because of their 'occupancy' factor: the fraction of the time to which they are exposed to particles charged by corona ions.

116 Henshaw and Fews (2001) calculated that people downwind of power lines might have 20%–60% more particles deposited in their lungs than those upwind. In the light of the review carried out, it is considered that some increase in lung deposition of particles of these sizes is likely as a result of charging by corona ions. However, it appears that there is neither a suitable model available nor information about the distributions of particle size and charge, to enable reliable estimates to be made of the size of any increase.

DEPOSITION OF PARTICLES ON SKIN

Mechanisms of deposition

117 High voltage power lines may increase the deposition of particles on surfaces in two ways:

(a) by causing airborne particles downwind of the power line to become electrically charged, and so more likely to deposit on surfaces by electrostatic effects,

(b) by causing charged airborne particles passing underneath power lines to oscillate up and down in the electric field so increasing the probability of impact.

118 It is assumed that all foliage, people, buildings and wooden structures are effectively grounded; the normal humidity in the UK ensures that surfaces are sufficiently conducting. Hence, any charges settling on such surfaces are rapidly dissipated so that the surfaces remain at ground potential. The surfaces which receive the increased deposition will include the clothing, hair and exposed skin of people. The particles depositing on clothing and hair are unlikely to have any significant effect on health. Those depositing on exposed skin could, if their quantity is sufficient and their nature harmful, have effects on health.

119 In order to understand what effect power lines could have on deposition rates of pollutants, it is necessary to consider first deposition in the absence of fields from power lines. This occurs by several mechanisms, as discussed in paragraphs 24–28.

(a) Large particles gradually settle out of the air under the force of gravity, a process known as sedimentation.
(b) Particles diffuse through the air, even if there is no air flow. If they touch a surface, they will generally stick to it. Small particles diffuse more rapidly than large ones. If the air is still, the air close to a surface becomes depleted in particles as they deposit, so the rate of deposition slows down unless the air is disturbed.
(c) If the air is turbulent because of wind or movement of people or objects such as traffic, then particles may be thrown against surfaces and impact on them. Turbulence also replaces the air close to surfaces with fresh air: if the air close to a surface has become depleted in particles, turbulence brings more particles close to the surface, allowing deposition of particles by diffusion to resume.
(d) Charged particles are more likely to deposit on surfaces because of electrostatic effects.

120 If the pollutants are radon decay products, the deposition leads to surface activity on the skin. The amount of activity deposited depends on the concentration of radon gas and on the local conditions, such as wind speed. Published estimates of deposition rates have usually been based on indoor conditions. Although radon gas concentrations are generally a factor of five higher indoors than outdoors, deposition rates of the decay products can be about ten times higher outdoors than indoors. This is mainly because of turbulence but is also affected by the fact that for a given radon concentration there are typically twice as many decay products in outdoor air as there are in indoor air.

121 Because of these factors, estimates of the deposition rate of decay products need to take into account the relative amounts of time spent indoors and outdoors, which vary from individual to individual. The total deposition indoors and outdoors would be roughly equal for someone who spends ten times as much time indoors as outdoors.

122 The short-lived radon decay products which are deposited are polonium-218, lead-214 and bismuth-214. More atoms of bismuth-214 and lead-214 compared with polonium-218 are deposited on the skin because of their longer half-lives (about 20 and 30 minutes compared with 3 minutes) and all three nuclides decay into polonium-214 (Figure 4, page 13). For alpha-particle irradiation of the skin, the nuclide of most concern is therefore polonium-214.

Deposition downwind of power lines

123 As discussed in paragraphs 73–75, corona discharges from power lines can result in airborne particles downwind from power lines becoming electrically charged, and so having an increased probability of depositing in the respiratory tract if they are inhaled. The principal mechanism that causes the increase in deposition is the production of an image charge in a conducting surface. The same effect will lead to increased deposition of charged particles on exposed skin. The increase will be mainly of small particles because of the greater inertia of large particles.

124 Cohen et al (1998) found a significant effect of charge on deposition of small particles in a model of a human trachea and bronchi down to 3 mm diameter airways. Deposition of 0.02 and 0.125 μm particles with a single charge was two to three times greater than that of particles with equilibrium distribution of charge, and five to six times greater than for particles with no charge. The residence time of particles in the respiratory tract is likely to be longer than the time that particles in outdoor air remain close to the skin, so the increase in deposition of the fraction of the particles that are charged will probably be less than the factor found by Cohen et al. Miles (1986) found that a wind speed of 1 m s^{-1} was sufficient to cause an increase in the rate of deposition of radon decay products on a surface by a factor of two to eight, and an electrostatic charge on a surface could increase the deposition of decay products by up to a factor of two hundred. The mean wind speed in the UK is more than 1 m s^{-1} and the increased deposition by wind will apply to particles whether or not they are charged. Although the extent of electrostatic charging is likely to be less outside buildings than inside, the increase in skin deposition of particles downwind of power lines caused by corona discharge is likely to be much smaller than increases caused by wind.

Deposition under power lines

125 Particles which are electrically charged oscillate with a frequency of 50 Hz along the electric fields produced by the power lines. The distance over which particles oscillate depends on the strength of the field which is usually greatest immediately underneath the line. However, field directions and strengths can be altered by objects in the field and are, for example, normally perpendicular to a conducting object such as a human body. Field strengths are particularly high around pointed conductors. If the oscillation of a particle makes it hit a surface, it will generally stick.

126 Oscillation of particles in the electric field causes people underneath or near power lines in the open air to have increased numbers of such particles deposited on their clothing and skin compared with the numbers deposited away from the line. Power lines do not cause increased deposition indoors because buildings and other objects screen the electric field. Henshaw et al (1996a,b) considered whether such electric fields could cause increased deposition within the respiratory tract. They calculated that the field is a factor of 10 000 lower inside the body than outside, but nevertheless suggested that this might have an effect on unattached radon decay products. Stather et al (1996) pointed out that the unattached decay products mainly deposit in the upper airways, so any increase in internal deposition would probably reduce lung deposition. Since lung deposition is the parameter of interest in estimating risk from radon decay products, this effect would tend to decrease risk marginally. Both papers agreed that internal fields were too small to affect the deposition of particles larger than the nucleus mode. The nucleus mode of the particle size distribution contains a negligible proportion of the total mass of particles, so any increase in deposition of these sizes would not significantly affect the mass of any pollutants deposited. In cases where it is the number of particles deposited that causes a health effect, the analysis by Henshaw et al (1996a,b) might suggest a marginal increase in detriment if deposition in the upper respiratory tract was as harmful as deposition in the lungs. The analysis by Stather et al (1996) would suggest no increase in risk.

127 The maximum value of the AC electric field directly under a 400 kV line at minimum clearance is 10 kV m^{-1}. This is rarely achieved in practice; it is more typically less than 5 kV m^{-1}, and drops to 100 V m^{-1} at 50 m either side. The oscillation amplitude is proportional to the charge on the particle, to its mobility and to the magnitude of the field. Because the human body is a conductor, the field directly above a human head under a power line is increased by a factor of approximately 18 to a typical value of 90 kV m^{-1}. The mobility, and hence the oscillation amplitude, is strongly dependent on the size of the particle. Very small particles (a few thousandths of a μm in diameter or less) can oscillate up to 7 cm (peak-to-peak) in a typical perturbed field of 90 kV m^{-1}. However, this falls by a factor of more than 10 000 to about 5 μm oscillation for 0.2 μm particles (Fews et al, 1999a; Henshaw and Fews, 2001). This would suggest that increased deposition of charged particles under power lines should fall rapidly with diameter and become negligible for diameters greater than about 0.05 μm. Since the smaller particles carry an extremely small proportion of the total mass of chemical pollutants in the air, the effects of power line fields should have a very small effect on the deposition of chemical pollutants. Radon decay products, however, may contain a significant proportion of their radioactivity in ultrafine airborne particles.

128 Oscillation of very small charged particles in the electric field, and their deposition on surfaces, causes the layer of air within a few centimetres of a surface to become depleted in these particles. However, air movement can rapidly replace this depleted layer with air containing more of these particles. The AC field and air movement can therefore interact to produce much more deposition than either effect would cause separately.

129 Fews et al (1999a) noted, though, that correlating deposition solely with oscillation amplitude neglected the effect of turbulence. They argued that if the air in a layer next to a surface were turbulent, quite small oscillations could bring particles into the turbulent layer and the mixing that would then occur would lead to their deposition on the surface. If this were the case, increased deposition under power lines could also occur for particles greater than 0.1 μm and so could also lead to significant effects for chemical pollutants. This will be discussed further in paragraphs 131–138.

130 Fews et al (1999a) also investigated experimentally the deposition of airborne particles on earthed metal spheres underneath power lines. They used sensitive etched track detectors that measured the numbers of alpha particles attached to radon decay products. The alpha particles from polonium-218 and polonium-214 have different energies and this allowed the detectors to distinguish the number of particles deposited that were attached to polonium-218 from those deposited after this had decayed but before the polonium-214 had decayed. From Figure 4 (page 13) it can be seen that polonium-218 would have had around four minutes for attachment and then deposition to have taken place. Polonium-218 tracks could come from decay products initially deposited as polonium-218, lead-214 or bismuth-214, and could have an hour or more to attach to aerosols before being deposited. Fews et al estimated that a significant fraction would have diameters in the range 0.001–0.004 μm. However, the second set had appreciably more time to grow and most of them were estimated to have diameters greater than 0.1 μm. The deposition was greater than that away from power lines by around 2.4 for the smaller particles (those with polonium-218 attached) but was also significant, 1.2, for the larger particles (those with polonium-214 attached). Henshaw and Fews (2001) have suggested that polonium-214 deposition in these experiments resulted from wet deposition. The details of this process are not clear. This is an important point, since the evidence of increased deposition of polonium-214 appears to be the only indicator that deposition of larger particles may be increased. Further experimental research is needed to clarify this issue.

Effects of turbulence on deposition

131 The flow of air can be laminar or turbulent depending on the velocity of the flow and the particular geometry. To illustrate this, the flow along a smooth cylindrical tube is considered. If the flow is laminar, a small particle moves in a straight line parallel to the axis. However if the flow is turbulent, the particle still moves along the tube but also moves sideways in a random and fluctuating way. So turbulence produces a large degree of mixing of particles that enter the tube in different positions. The flow is laminar at low velocities but becomes turbulent when the velocity reaches a critical value. This occurs when a dimensionless parameter called the Reynolds number exceeds about 2300. For air this corresponds to an average flow velocity of about $0.035/d$ m s^{-1} (where d is the tube diameter). Similar transitions occur for flow above a flat smooth surface or round a sphere. The Reynolds numbers are, however, much larger in these cases, about $5\ 10^5$ and 10^6, respectively. These correspond to velocities of about $8/d$ m s^{-1}, where d is now the length of the plate in the direction of the flow, and $16/d$ m s^{-1}, where d is the diameter of the sphere. The critical Reynolds numbers and hence the velocities can, however, be reduced appreciably by surface roughness.

132 It is not surprising therefore that the flow above the Earth's surface is complex and changeable. There is a *turbulent surface layer*, extending to tens of metres above the surface, which is characterised by intense, small-scale turbulence generated by the surface roughness and convection. Beneath this surface layer two other layers can be distinguished whose dimensions are dictated by the dimensions of surface elements. There is a *roughness layer,* whose thickness can be as much as three times the height of the surface elements. In this zone the flow is highly irregular, being strongly affected by the nature of individual roughness features, eg buildings, hedges, trees and crops. Finally, directly in contact with the surface, there is the *laminar boundary layer*. This is the non-turbulent layer, at most a few mm thick and normally thinner, that adheres to all surfaces and establishes a buffer between the surface and the more freely diffusive environment above.

133 Figure 13 shows what happens in a very simple situation. This will give some insight into what happens in the very complicated flow of air over the Earth's surface. There is a steady air flow from the left over a flat plate. A laminar boundary layer forms at the leading edge of the flat plate and grows in thickness with distance. Eventually at some critical combination of velocity, distance and kinematic viscosity (viscosity divided by density) the flow breaks down into turbulent flow. This is characterised by a haphazard jumble of eddies, vortices, etc. A residual boundary layer normally still remains (the viscous sublayer of Figure 13). Its thickness is determined by the roughness of the surface and the wind speed and, over smooth surfaces and at high wind speeds, it can become very thin and, temporarily, may even be absent. The presence of a non-turbulent sublayer can substantially reduce particle deposition (eg Quarini and Greenfield, 1998) since the only particle mixing within it takes place by diffusion.

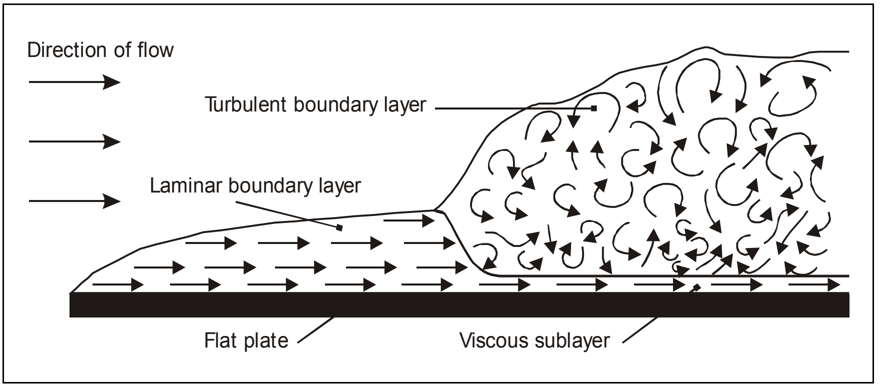


FIGURE 13 *Laminar and turbulent flow across a flat plate*

134 Such a sublayer will usually exist adjacent to all surfaces. However, in real situations, three-dimensional surfaces are being dealt with and the resulting flows are complex and strongly dependent on the characteristics of the surface elements, including their shape and flexibility and the number, size and shape of any obstacles on the surface. In addition, the situation is dynamic because of changes in wind direction and strength and movements of the object itself. In the case of human beings they are likely to move frequently and even if the body is nearly stationary, the head may be moving.

135 To summarise briefly, the flow of air over the Earth's surface is complex. The details of the flow over an object such as the human body are complicated and depend on the conditions. However, in general, there is usually a thin boundary layer, at most a few mm thick, in which the flow is laminar. Above this the air flow will be turbulent and will resemble the turbulent boundary layer of Figure 13. Beyond that turbulence on a larger scale, dictated by the gross features of the landscape, sets in.

136 As noted in paragraphs 125–130, Fews et al (1999a) modelled the deposition of airborne particles on to surfaces underneath power lines The surfaces were assumed to be those of a sphere whose diameter, 20 cm, was chosen to provide a rough description of a head. The model is one-dimensional and attempts to take account of

(a) atmospheric diffusion,
(b) oscillation in the AC field,
(c) the effect of the Earth's DC field,
(d) gravitational settling,
(e) attraction to the surface by image charges.

The particles were assumed to have an M-B distribution of charge and, close to the surface, the turbulent diffusivity, D_T, was assumed to take the form $D_T = K_2\, r^n$, where K_2 is the diffusion constant near to the deposition surface and r is the distance in spherical geometry; calculations were made for $n = 1.5$, 2.0 and 3.0. For each value of n, the value of K_2 was set so that the velocity of deposition of ultrafine particles was 0.01 m s^{-1} outdoors. The value $n = 2.0$ gave the most physically sensible results (similar conclusions were obtained by Crump and Seinfeld (1981) and by Mayya and Sapra (1997)). The authors concluded that, using physically reasonable parameters, it was possible to account for the increased deposition under power lines found experimentally for both ultrafine particles and, more significantly, for particles of 0.2 μm diameter.

137 Swanson and Jeffers (2000, 2002) have commented on both the model used by Fews et al (1999a) and on their experiments. They did not disagree with the form of the model but suggested that the values for the various parameters used were not appropriate for the physical situation. Overall they agreed that the model gave sensible predictions for ultrafine particles but questioned the velocities of deposition predicted for the larger ones. They argued that since the oscillation amplitude of the larger particles due to the AC field was very small compared with the movements due to turbulence it could have very little effect on the deposition. They also suggested that by not including the effects of inertial impaction, which became increasingly important for particles greater than 1 μm, the Fews et al model underestimated the effect of turbulence on the larger particles. They also pointed out that Figure 7 of Fews et al (1999b) appeared to give rates of gravitational settling of 10 μm particles that differed by about an order of magnitude from those given by standard models.

138 Swanson and Jeffers (1999) expressed concern that values obtained by Fews et al for increased deposition under power lines may have been affected by the design of the experimental arrangement. These comments referred to the initial experimental arrangement used by Fews et al (1999a). Swanson and Jeffers (2000) also pointed out that the detectors used in the later experimental arrangement by Fews et al had dimensions that were significant compared with the radii of the spheres on which they were mounted, so that they would create, in the wind, a complex mix of laminar, turbulent, separated and re-circulating flows over the surface. The Advisory Group noted, however, that photographs of the spheres and detectors show that they were no more irregular than the human head so that the flows around the surface might be very roughly comparable. The experimental arrangement does, though, differ significantly from the smooth spheres assumed by the theoretical model.

Summary

139 It is likely that there will be a small increase in skin deposition of airborne particles downwind of power lines caused by corona discharge. The increase will be mainly of small particles and so any adverse health effects are likely to come from increased surface activity from radon decay products rather than surface effects from chemical pollutants. The change in deposition of radon decay products on skin is also very sensitive to the electrostatic charge on the skin and the wind speed over it. It seems likely that, even downwind of power lines, these last two variations will be much larger than the increases from corona ions.

140 There is experimental evidence supported by theoretical analysis (Fews et al, 1999a) that the deposition of particles of sizes associated both with radon decay products and with chemical pollutants are somewhat larger directly underneath power lines. The increase is around 2.4 for radon decay products and still significant, around 1.2, for chemical pollutants. The increased deposition is attributable to the increase in impact rate and therefore deposition rate of the naturally charged particles in the oscillating electric fields. The oscillation amplitude decreases rapidly with the mass of the particle. Since the mass of chemical pollutants is mostly associated with larger particles, the increased deposition of these would be insignificant in still air. Fews et al calculated, however, that this was not the case when the air flow was turbulent.

141 This view is not wholly shared by Swanson and Jeffers (2002). They accepted that increased deposition of radon decay products would occur under power lines. However,

they attributed the increased deposition observed of larger particles, and therefore likely increased deposition of chemical pollutants, to the design of the experiments. They also attributed the theoretically predicted increased deposition of larger particles to the parametric values and analytical expressions used by Fews et al (1999a).

HEALTH IMPLICATIONS OF INCREASED PARTICLE DEPOSITION NEAR POWER LINES

142 The main health hazards of airborne particulate pollutants are cardiorespiratory disease and lung cancer. There is strong evidence that the risk of cardiorespiratory disease is increased by inhalation of particles generated outdoors, mainly from motor vehicle exhaust, and of environmental tobacco smoke produced within buildings. The risk of lung cancer is increased by particulate pollution in outdoor air, and by radon decay products and environmental tobacco smoke in buildings. The potential impact of corona ions will depend on the extent to which they increase the dose of relevant pollutants to target tissues in the body.

Cardiorespiratory disease and particulate pollution in outdoor air

143 Although levels of particulate pollution in outdoor air are clearly associated with mortality and morbidity from cardiorespiratory disease, the exposure of most people, and particularly that of vulnerable groups such as the elderly and infirm, is determined largely by penetration of the pollutants into buildings. The effect appears to depend on particles that reach the lung, and not those that deposit in the upper airways. Moreover, recent research suggests that it is mediated by oxidant species adsorbed on the surface of the particles, in which case the toxicity will reside largely in the finer fractions (ie those with diameters less than 1.0 μm) that have a relatively high surface area for a given mass (see Figure 1, page 9). In theory, for particles with a diameter of 0.1–1.0 μm, there is scope for corona ions to increase lung deposition by a factor of about seven (see Figure 12, page 33), although below a diameter of 0.1 μm, deposition is unlikely to be more than doubled. In practice, the effect is likely to be much smaller than this because of factors such as incomplete charging of particles, hygroscopic growth, and increased deposition in the upper airways (paragraphs 108–112). Furthermore, charged particles are liable to be selectively deposited when entering buildings through cracks around doors and windows. As emphasised above, because of the complexity and variability of the phenomena involved it is not possible to make a reliable assessment of the increase that would occur in any situation, but it seems unlikely that, even in the worst case, corona ions would more than double the relevant dose to the lung. To assess the potential 'worst-case' implications for health, the effect of an arbitrary doubling of lung deposition is considered below.

144 The current national air quality standard for particulate pollution in outdoor air (measured as a running 24 hour average of PM_{10}) is 50 μg m^{-3}. On the basis of the estimate made by Samet et al (2000) (see paragraph 41), a doubling of the dose to the lung at this level of exposure might increase an individual's risk of cardiorespiratory death by a factor of 0.7% x 50/10 = 3.5%. However, when averaged over a longer period, the effects of corona ions on individual risk would be much smaller than this because on most days pollution levels will be lower than 50 μg m^{-3}, and the direction and speed of the wind will vary. The average impact at a population level would be far lower because only a small proportion of people live in areas of high particulate pollution that are also close to sources of corona ions.

145 Risks of this magnitude would be far too small to be demonstrable in even the largest epidemiological studies. To put them in context they are substantially smaller than the risk of mortality from coronary heart disease that has been estimated for non-smokers exposed to environmental tobacco smoke (Steenland et al, 1996).

Lung cancer and particulate pollution in outdoor air

146 The risk of lung cancer from particulate pollution in outdoor air arises from cumulative exposure to PAHs and possibly other pollutants, not all of which are in the particulate phase. It is unclear exactly how the contribution to risk from PM_{10} is distributed across the different size fractions of particles, but the maximum increase in lung deposition of particulate carcinogens at any time, because of corona ions, is unlikely to be more than three- or four-fold, and probably less. The average effect should be much smaller than this because ionisation will not always be maximal, people do not spend all of their time downwind from a source of corona ions, and concentrations of charged particles will normally be attenuated within buildings. In view of this relatively small average effect, the fact that not all carcinogenic pollutants in outdoor air occur in the particulate phase, and the small contribution that current levels of outdoor air pollution are likely to make to an individual's risk of lung cancer, any additional risk from an effect of corona ions will probably be small. In public health terms, the proportionate impact will be far lower because only a small fraction of the general population live or work close to sources of corona ions.

Lung cancer and radon decay products

147 The risk of cancer from radon decay products in indoor air relates to cumulative exposure of the lung to these pollutants, which are present in both the accumulation and nucleus modes (Figure 1). Other internal body tissues receive doses that are only a small fraction (less than 1%) of the dose to the lung (Stather et al, 1996). In theory, the presence of corona ions on occasion might increase lung deposition of particles in the accumulation mode (see Figure 12), but the effect on particles in the nucleus mode might well be to increase deposition in the extrathoracic airways and thereby reduce the amount reaching the lungs and so deposition in the lungs (Stather et al, 1996). Moreover, for the same reasoning as applied to carcinogens in outdoor air, effects averaged over time will be much lower. Again, therefore, any impact on an individual's risk of lung cancer is likely to be relatively small – perhaps a small percentage increase or decrease in the excess risk that would normally occur from radon decay products. (As noted in paragraph 48, about 6% of lung cancers in the UK may be attributable to radon exposure.)

Environmental tobacco smoke

148 Some of the health risks from environmental tobacco smoke may be attributable to its gaseous components rather than to smoke particles. As with radon decay products, the effects of corona ions on exposure to the latter will be reduced to the extent that not all particles will be charged, and that charged particles will be selectively deposited when entering buildings. The risk of lung cancer from environmental tobacco smoke depends on cumulative exposure, and therefore the proportionate impact of corona ions will depend on their average effect over time. It seems unlikely that they would add much to the 30% elevation of risk from environmental tobacco smoke that has been estimated for non-smokers (IARC, 2002).

149 Where an effect of environmental tobacco smoke depends on short-term exposures (this might apply to exacerbations of asthma) and particulate components of the smoke contribute importantly, the proportionate impact of corona ions could be higher, but the excess risk is unlikely to be more than doubled, and this would apply only on days when levels of corona ions were at a maximum.

Skin cancer

150 As described in paragraphs 38, 50 and 51, any risk of skin tumours from particular air pollution appears to be negligible. Therefore, corona ions would not be expected to impact materially on the risk of such tumours.

OVERALL SUMMARY AND CONCLUSIONS

Production of corona ions

151 Whenever high voltages are present in electrical systems there is the possibility that the high electric fields that exist close to conductors may cause electrical breakdown of the surrounding air; an effect known as corona discharge. Corona discharges often occur from electrodes that are at a potential of several thousand volts with respect to ground. DC and AC high voltage transmission lines are examples of this, but are of course designed not to operate under corona discharge conditions because this would result in loss of power, and also produce noise that would cause complaints. However, small local intensification of the electric field at the conductor surfaces can arise at dust and dirt accumulations or at water drops causing corona discharges to occur. In addition, some power lines are operated at higher voltages than their design values.

152 As a consequence of corona discharges, high voltage AC power lines may produce clouds of negative or positive ions that are readily blown downwind. An increase of charge density downwind of power lines is well established and can be measured at distances up to several kilometres. The ion clouds charge pollutant particles that pass through them. These particles will already carry some charge because of the naturally occurring ions that exist in the atmosphere but it seems likely that in some regions this will be increased even at ground level as a result of corona discharge. Calculating this increase as a function of particle size is possible but only if a number of simplifying assumptions are made. The effects indoors, where the majority of people spend most of their time, are probably somewhat less than outdoors – for example, because of deposition of corona ions on the surfaces of small apertures through which some air enters buildings. The presence of corona ions could influence the uptake of pollutants by increasing their deposition in the lung or on the skin.

Inhalation of pollutant particles

153 People may be exposed to these more highly charged pollutant particles and the effect of electrostatic charge on increasing respiratory tract deposition has been recognised for some time. The deposition of particles in the human respiratory tract has been studied extensively both experimentally and theoretically. Current models such as the ICRP Human Respiratory Tract Model (HRTM) enable the fraction of inhaled particles that is deposited in each region of the respiratory tract to be calculated, according to the size distribution of the inhaled particles and the breathing pattern and age of the subject.

154 There have been a number of experimental and theoretical studies of the effect of electrostatic charge on deposition in the respiratory tract. Increased deposition results from image charge forces. The effect increases with increasing number of units of charge on a particle, but decreases with increasing particle size. There is consensus that for particles larger than about 0.3 μm, charge is unlikely to have a significant effect on lung deposition. However, for smaller particles, there are no human *in vivo* data available. Measurements from one study using a model of human bronchial airways suggest that at about 0.1 μm a single unit of charge increases lung deposition by a factor of about three, which is more than predicted by current theory. Hence there does not seem to be a suitably validated model for predicting the effect of charge on deposition of submicron particles.

155 The HRTM does not address explicitly the effects of electrostatic charge. It has, however, been used in this report to assess the potential for charge to increase lung deposition. This was done by comparing the number of particles that enter the lungs with the number that deposit there in the absence of any charge effects. For very small (less than about 0.01 μm) and large particles (greater than about 5 μm), lung deposition is limited by deposition in the nose and upper airways (the extrathoracic airways, ET): most particles that reach the lungs deposit anyway. The effect of charge would therefore be to increase ET deposition and reduce lung deposition. In the size range about 0.1–1 μm, where lung deposition is normally low (about 10%), there is potential to increase lung deposition by a large factor, a theoretical maximum of about three to ten, depending on particle size. This size range does, however, correspond to a major fraction of the normal ambient atmospheric particle distribution. In any practical situation the effect of charge on deposition of a pollutant will be less than this theoretical maximum because of factors including the extent to which the pollutant particles are charged, the size distribution of the pollutant particles, hygroscopic growth, and increased deposition in the ET airways. Thus, as noted above, particles larger than 0.3 μm diameter are unlikely to carry a sufficient number of units of charge for lung deposition to be affected.

156 The effect on exposure of individuals will be lower still because of their 'occupancy' factor: the fraction of the time to which they are exposed to particles charged by corona ions. Henshaw and Fews (2001) have calculated that people downwind of power lines in corona might have 20%–60% more particles deposited in their lungs than those upwind. This estimate is for people exposed out of doors to pollutant particles which originate out of doors. When outdoor air enters houses, many of the pollutant particles will be carried with it (Liu and Nazaroff, 2003), so a similar effect would be expected indoors. The effects of corona ions on lung deposition of particles which originate indoors will be substantially less. There are substantial difficulties in the way of modelling such effects, making all such estimates very uncertain. Furthermore, since wind directions vary, the excess for any one group of people would be lower, but more groups will be affected, than if the wind direction was constant.

157 The increase in pollutant deposition in the lungs seems likely to be highest in areas of the country downwind of power lines where there are high levels of airborne particulate pollution and also where the power lines are continuously in corona. The latter is most likely where the power lines were designed for a lower voltage and have not been upgraded. Because of the high rate of production of corona ions in such situations, it seems likely that there will be a significant increase in charge per particle, even when the particle concentration is high.

158 The information reviewed suggests that some increase in lung deposition of pollutant particles seems likely as a result of charging by corona ions. Even if the effect of the corona ions were to cause all the particles to be deposited, the increase in lung deposition cannot be more than a factor of ten. In practice, though, the increase seems likely to be appreciably less and it is noted that Henshaw and Fews (2001) estimated it to be 20%–60%. Such estimates are, however, inherently imprecise since they depend on the use of an approximate model and on assumptions about the experimental conditions (the distributions of particle size and charge) which are not well known and not readily obtainable. The effects of external electric fields on deposition of particles in the respiratory tract, if any, are likely to be very small (paragraph 126).

Deposition on the skin

159 The additional charges on particles downwind of power lines could also lead to increased deposition on exposed skin. However, any increase in deposition is likely to be much smaller than increases caused by wind.

160 There is experimental evidence (Fews et al, 1999a) supported by theoretical analysis that the deposition of both radon decay products and chemical pollutants on surfaces are somewhat larger under power lines. The increase is considered to be around a factor of 2.4 for radon decay products and to be still significant, around 1.2, for chemical pollutants. This is attributed to the increase in deposition of the naturally charged particles produced by the oscillating electric fields together with turbulent air flow over the skin. The electric fields are screened by the walls and roofs of buildings. Hence any significant increase of deposition would only occur outdoors. The deposition of radon decay products would vary much less from place to place than that of chemical pollutants, whose deposition would be greater in towns, near industrial sources and next to major roads.

161 There are different views of the extent of increased deposition on exposed skin under power lines. Thus Swanson and Jeffers (2002) accepted that increased deposition of radon decay products would occur. However, they attributed the increased deposition of larger particles observed experimentally and predicted theoretically to the design of the experiments and to the parametric values and analytical expressions used by Fews et al (1999a).

162 These disparate views about changes in skin deposition under power lines cannot be resolved without further experimental measurements. It is possible that the differences in the theoretical analysis might be reduced by further work. However, the physical situation is very complicated and it seems unlikely that it can be modelled with sufficient accuracy to provide reliable information in the foreseeable future.

Implications for health

163 The main health hazards of airborne particulate pollutants are cardiorespiratory disease and lung cancer. There is strong evidence that the risk of cardiorespiratory disease is increased by inhalation of particles generated outdoors, mainly from motor vehicle exhaust, and of environmental tobacco smoke produced within buildings. The risk of lung cancer is increased by particulate pollution in outdoor air, and by radon decay products and environmental tobacco smoke in buildings. Any health risks from the deposition of environmental particulate air pollutants on the skin appear to be negligible.

164 The potential impact of corona ions on health will depend on the extent to which they increase the dose of relevant pollutants to target tissues in the body. It is not possible to estimate the impact precisely, because of uncertainties about:

(a) the extent to which corona effects increase the charge on particles of different sizes, particularly within buildings,
(b) the exact impact of this charging on the deposition of particles in the lungs and other parts of the respiratory tract,
(c) the dose–response relation for adverse health outcomes in relation to different size fractions of particle.

However, it seems unlikely that corona ions would have more than a small effect on the long-term health risks associated with particulate air pollutants, even in the individuals who are most affected. In public health terms, the proportionate impact will be even lower because only a small fraction of the general population live or work close to sources of corona ions.

RECOMMENDATIONS FOR FURTHER RESEARCH

165 The possible implications for health of the mechanisms discussed in this report do not provide a strong case for further research in this area. It is concluded, therefore, that it is not appropriate for an epidemiological study to be carried out. If, however, it were felt to be desirable to reduce some of the uncertainties in the analysis of the mechanisms for increased deposition, this could be done through the following studies.

(a) Experimental study of the charge and size distributions of airborne particles upwind and downwind of power lines – the technique recently developed by Fews et al (2003) may be of value in such a study.
(b) Studies of deposition of charged particles under power lines – any such study should include laboratory and outdoor studies to allow investigation to be made of the dependence on size and air flow.
(c) Experimental study of the effect of electrostatic charge on lung deposition for particles in the size range 0.005–1 μm – the study should include *in vivo* measurements.
(d) Development of a theoretical model to calculate the effect of electrostatic charge on lung deposition for particles in the size range 0.005–1 μm – any such study should be validated by comparison with the results of the experimental study.

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Glossary

Accumulation mode Airborne particles of diameter between about 0.1 and 1.0 μm that are formed by the agglomeration or coagulation of smaller particles, and condensation on to such particles.

Aerodynamic equivalent diameter For an airborne particle, this is the diameter of a sphere of unit density that has the same settling velocity.

Aerosol Technical term for a cloud of airborne particles. The term is more commonly used to describe the spray of droplets from a pressurised can and has not been used in this document to avoid possible confusion.

AI Alveolar-interstitial region of the human respiratory tract model (HRTM) which includes the gas-exchange region of the lungs (see alveoli).

Airway generation The trachea subdivides into the two main bronchi which in turn subdivide and so on. Each subdivision is known as a generation. In the human lung, there are usually two daughter airways of similar diameter.

Alpha particle (α) An alpha particle, which is the nucleus of a helium atom and so consists of two protons and two neutrons, may be emitted during radioactive decay.

Alveoli Tiny airspaces deep in the lung with a total surface area of tens of square metres, where exchange of gases between air and blood takes place.

Avalanche breakdown In a strong electric field, the electrons released when an atom is ionised may acquire sufficient energy to ionise other atoms and so on. This can result in a rapid increase in the discharge from a high voltage electrode. The effect is referred to as avalanche breakdown.

BaP (benzo[a]pyrene) A polycyclic aromatic hydrocarbon (PAH) which carries a significant hazard to human health.

Beta particle (β) An electron emitted during radioactive decay.

Bronchi In the HRTM, the bronchial region (BB) consists of the trachea and the next eight airway generations.

Bronchioles In the HRTM, the bronchiolar region (bb) consists of the airways (with diameters smaller than about 2 mm) between the bronchi and the alveoli.

Brownian motion The random movement of airborne particles resulting from constant bombardment by air molecules.

Coarse mode Airborne particles of diameter greater than about 1.0 μm. They are mostly formed by the breaking up of larger objects or resuspension into the air of deposited particles.

Condensation Formation of liquid or solid particles from vapours present in the air or by reactions between gases.

Corona discharge Transfer of charge associated with the ionisation of air near to sharp metallic points when they are raised to a high voltage.

Corona ions Positive or negative ions formed during corona discharge.

Coulombic force Electrostatic force between two charges or the electrostatic force on a charged particle in an electric field.

Decay chain Series of decay products resulting from a long-lived radioactive atom (nucleus). It includes the products which result from the fact that some atoms (nuclei) can decay in more than one way.

Decay product Atom (nucleus) resulting from the decay of a radioactive atom (nucleus). The decay product may also be radioactive and the term is also used to include all the atoms (nuclei) formed in a decay chain.

Dielectric Non-conducting material.

Diffusion Constant bombardment of airborne particles by air molecules causes them to move randomly (Brownian motion). This random movement causes them to move away from their original position, a process known as diffusion.

Diffusion charging Process by which airborne particles can become charged, as a result of diffusion, by exposure to naturally occurring ions in the atmosphere.

Diffusivity (D) Constant that determines the rate at which particles diffuse. If the concentration, c, of particles varies with distance, x, the net mass flow of particles per unit area per second is the product of D and the concentration gradient (dc/dx). The diffusivity is also known as the coefficient of diffusion.

Discharge Loss of charge from an object due to conduction.

Electric field The electrostatic force on a charge, q, is written as Eq, where E is called the electric field.

Electrical breakdown Dielectrics are normally only insulating at electric fields less than some critical value. When this value is reached, the dielectric starts to conduct, a process known as electrical breakdown.

Electrode A metal plate.

Electron An elementary charged particle. An atom contains a nucleus made up of protons and neutrons together with a number of electrons. The proton charge is equal and opposite to the electron charge so a neutral atom has the same number of protons and electrons.

Equivalent diameter The equivalent diameter of an irregularly shaped particle is the diameter of a sphere with the same property (mass, volume, etc).

Equivalent volume diameter The equivalent volume diameter of an irregularly shaped particle is the diameter of a sphere with the same volume.

ET_1 and ET_2 In the HRTM, the extrathoracic airways (ET) are divided into ET_1, the front of the nose, from which particles are removed by nose-blowing and there is taken to be no uptake to blood, and ET_2, the rest of ET, from which particles are cleared to the throat and swallowed, and where there is some uptake to blood.

Etched track detector Passive detector that records the tracks of alpha particles.

Exposure time (t) Time for which a set of airborne particles has been exposed to the ions present.

Extrathoracic airways (ET) Defined in the HRTM as the airways of the head and neck (nose, mouth, pharynx and larynx).

Field charging A modified form of diffusion charging that occurs when an electric field is present.

Gamma radiation (γ) A photon (quantum) of electromagnetic radiation that may be emitted from the nucleus of an atom during radioactive decay.

Gravitational sedimentation Movement of airborne particles vertically downwards in response to gravity.

Half-life Time for half the number of atoms (nuclei) in a sample of radioactive atoms (nuclei) to decay.

HRTM Human Respiratory Tract Model adopted by ICRP (1994).

Hygroscopic growth Inhaled particles that have water-soluble components can absorb water in the high relative humidity (close to 100%) of the respiratory tract. Depending on their composition, they may grow in size significantly and rapidly, a phenomenon known as hygroscopic growth.

IARC International Agency for Research on Cancer.

ICRP International Commission on Radiological Protection.

Image charge A charge near to the surface of an uncharged material experiences an attractive electrostatic force. It is often convenient to consider the force as being due to another charge rather than to the material. This imaginary charge is called the image charge.

Image force Electrostatic force between a charge and a conducting surface, the strength of which is due to an equal and opposite charge at an equal distance behind the surface.

Inertial impaction In general, viscous drag causes particles to move in the same direction as the air flow. However, if the air flow changes direction as it does, for example, in a curved tube, the particle tends to follow its original direction because of its inertia and this may cause it to strike the tube wall on the outer side of the bend. This process is called inertial impaction.

Ion Atom or molecule that has lost or gained one or more electrons.

Ionise Remove or add one or more electrons from a neutral atom or molecule.

Isotope Chemical elements can have several isotopes. The isotopes are chemically identical but their nuclei contain different numbers of neutrons and, if radioactive, will have different radioactive properties.

Kinematic viscosity Viscosity of a fluid (gas or liquid) divided by its density.

Laminar boundary layer Layer of laminar flow next to a surface.

Laminar flow Flow without turbulence.

Maxwell-Boltzmann (M-B) charge distribution A charge distribution describes what proportion of particles have positive or negative charges 0, 1e, 2e, etc. An M-B charge distribution is the equilibrium distribution that a set of airborne particles would eventually be expected to reach given constant conditions (ion density, etc).

Mobility Constant velocity reached by a charged particle in an electric field of 1 V m^{-1}.

n Number of electronic charges on an airborne particle.

$\overline{n}$ Average number of electronic charges on an airborne particle.

Nucleus mode Airborne particles of diameter less than about 0.01 μm mostly formed by vapour condensation or chemical reactions between gases.

PAH Polycyclic aromatic hydrocarbons often produced in industrial processes, etc. Many PAHs are known to be carcinogenic.

Permittivity Amount by which an electric field is reduced by the polarisability of a dielectric.

PM_{10} Airborne particles (particulate matter) with aerodynamic diameters less than 10 μm.

Polarisability When an electric field is applied to a dielectric material the electrons in each atom (molecule) are moved slightly relative to the nucleus and the dielectric is said to be polarised. The size of the effect is called the polarisability. The polarisation provides an electric field opposite in direction to that of the applied field.

Radon (Rn) Radon-222 is a radioactive gas with a half-life of 3.82 days. It is a decay product of the long-lived uranium isotope uranium-238. (The numbers 222, 238, etc, denote the total number of protons and neutrons in the nucleus.)

Radon decay products The most important decay products of radon in relation to health are the radioactive polonium isotopes polonium-218 and polonium-214. Since radon gas is present in air at very low concentrations, traces of polonium isotopes are formed and deposited in the respiratory system. The numbers 214, 218, etc, denote the total number of protons and neutrons in the nucleus.

Respiratory system The body's system by which carbon dioxide in the blood is exchanged with oxygen in the air. It consists of many millions of alveoli, deep in the lungs where gas-exchange takes place, and the series of airways or tubes between the nostrils and lips, and the alveoli, including the bronchial tree.

Reynolds number Dimensionless number that determines the critical velocity at which flow becomes turbulent. The number equals the product of the flow velocity and a length characteristic of the system (tube diameter, sphere diameter, etc) divided by the kinematic viscosity of the fluid.

Roughness layer A region of irregular but essentially laminar flow. The irregularity is normally caused by the presence of buildings, trees, etc.

Settling velocity The constant velocity a particle reaches when the accelerating force due to gravity is balanced by viscous drag.

Space charge The net charge present in a region.

Space charge density The space charge present per unit volume.

T-B The tracheobrochial region or bronchial tree. This is subdivided in the HRTM into bronchi (BB) and bronchioles (bb).

Terminal velocity See settling velocity.

Turbulence Confused motion containing eddies, vortices, etc.

Turbulent diffusion Diffusion that is taking place in turbulent air.

Turbulent layer Layer of air in which the flow is turbulent.

Viscosity When an object moves through a fluid (gas or liquid) it experiences a frictional force. The size of the force is determined by a property of the fluid know as its viscosity.

Viscous drag Frictional force experienced by an object moving through a fluid (gas or liquid).