2 SOURCES, MEASUREMENTS AND EXPOSURES

2.1 Electric and magnetic fields

This chapter describes the nature of electric and magnetic fields, provides information on sources and exposures, and discusses the implications for exposure assessment for epidemiology. Generation and measurement of fields in experimental laboratory settings is outside the scope of this chapter.

2.1.1 The field concept

The field concept is very general in physics and describes for each point in a region of space the specific state of a physical quantity. Although a field can be defined for almost any physical quantity, it is in common use only for those which are capable of exerting a force. The gravitational field, for example, describes the force exerted on a unit mass at each point in space. Accordingly, the electric field describes the force exerted on a unit electric charge, and the magnetic field is defined in terms of the force exerted on a moving unit charge.

Electric fields are produced by electric charges, irrespective of their state of motion. A single charge at a point produces an electric field in all directions in a pattern with spherical symmetry and infinite dimension. A line of charges (e.g. a power line) produces an electric field around the line in a pattern with cylindrical symmetry. In practice, it is not possible to have a single isolated charge or a single isolated charged object, and instead of indefinitely long field lines, they will terminate on another charge (which could be another charge already present in a conductor or could be a charge induced by the field itself in a conducting object). The overall shape of the pattern of electric field experienced at any point thus depends on the distribution of charges and of objects in the vicinity. In technical systems, electric charges are related to voltages, and not to currents or power.

Magnetic fields are produced by moving charges and thus are proportional to electric currents in a system, irrespective of the voltage used. A current flowing in any conductor, no matter how complicated the shape of the conductor, can be broken down into a series of infinitesimally small segments, joined end-to-end. The magnetic field produced by a short element of current is given by the Biot-Savart law:

$$\frac{|dH|}{dl} = \frac{i}{4\pi r^2} \sin(\varphi)$$

where dH is the element of magnetic field produced by the current element i in the conductor element dl at a position r in space, and φ is the angle between dl and r.

As long as charges and currents are static, electricity and magnetism are distinct phenomena. Time varying charge distributions however result in a coupling of electric and magnetic fields that become stronger with increasing frequency. The characteristics and interactions of electric and magnetic fields are completely described by Maxwell's equations.

In addition to the "quasi static fields" from resting and moving charges, accelerating charges produce a radiation component. At extremely low frequencies the radiating field of a source is negligible. In practical exposure situations, radiation is absolutely negligible in the ELF range. Radiation only becomes dominant at distances that are large compared to the wavelength.

The wavelength is the distance between two successive cycles of the wave. In free space it is related to the frequency by the formula wavelength = speed of light / frequency. At 50 Hz, the wavelength is very long, 6000 km (60 Hz: 5000 km). In comparison, a radio wave with a frequency of 100 kHz has a wavelength of 3 km.

2.1.2 Quantities and units

For magnetic fields, there are two different quantities: the magnetic flux density, usually designated *B*, and the magnetic field strength, usually designated *H*. The distinction between *B* and *H* becomes important for the description of magnetic fields in matter, especially for materials which have certain magnetic (ferromagnetic) properties, such as iron. Biological tissue generally has no such properties and for practical purposes, either *B* or *H* can be used to describe magnetic fields outside and inside biological tissues.

Similarly, for the description of electric fields there are also different quantities: the electric field strength *E* and the dielectric displacement *D*. *D* is not useful for the description of electric fields in biological tissue. All these parameters are vectors; vectors are denoted in italics in this Monograph (see also paragraph 3.1).

The SI unit of magnetic flux density (*B*) is the tesla (T), and of magnetic field strength (*H*) is the ampere per metre (A m^{-1}). In the absence of magnetic material, 1 μT = $4\pi\times10^{-7}$ A m^{-1}. Either *B* or *H* can be used to describe fields, but *B* (i.e. tesla) is more common and is used here. Older literature, especially American, often uses the Gauss (G): 1 μT = 10^4 G (1 μT= 10 mG).

The SI unit of the electric field strength (*E*) is volt per metre (V m^{-1}).

2.1.3 Polarization

Electric and magnetic fields are vector quantities; they are characterized by an intensity (field strength) and a direction. In static (direct current, DC) fields, direction and intensity are constant over time. A time varying (alternating current, AC) field usually has a constant direction but a variable intensity. The field oscillates in a defined direction. This is often referred to as linear polarization.

In complex exposure scenarios, fields with different vector quantities may overlap. The resultant field is the addition of the two or more field vectors. In DC fields the result is a field with a different intensity and in most cases a different orientation. In AC fields, the situation becomes more complex because the vector addition may result in a time varying orientation of the resulting field. The field vector rotates in space; with the varying intensity of AC fields, the tip of the vector traces out an ellipse in a plane. This is often referred to as elliptical or circular polarization. This situation needs to be considered with respect to field measurement.

2.1.4 Time variation, harmonics and transients

The basic AC field can be described as a sine wave over time. The peak field strength is called the amplitude and the number of wave cycles within a second is called the frequency. The most common frequencies used in the electricity system of many countries are 50 Hz and 60 Hz. When fields of more than one frequency are combined, the resultant field is no longer a sine wave when plotted against time. Depending on the parameters of the combined fields (amplitude, frequency) any time course of the resultant field can be achieved, for example a square wave or a triangular wave. Conversely, any shape waveform can be split into a number of sinusoidal components at different frequencies. The process of splitting a waveform into its component frequencies is known as Fourier analysis, and the components are called the Fourier components.

In many electrical systems, sinusoidal signals are distorted by a non-linear behaviour of the loads. This happens when the electrical properties of the system depend on the signal strength. Such distortions introduce Fourier components in addition to the fundamental frequency of the signal, which are called harmonics. Harmonics are a precise multiple of the fundamental frequency. Given a 50 Hz fundamental frequency, 100 Hz is the second harmonic, 150 Hz is the third harmonic, and so forth.

Note that the terminology used in electrical engineering is different to musical terminology: a frequency of twice the fundamental is the second harmonic to the engineer but only the first harmonic to the musician. In electrical engineering, “fundamental” and “first harmonic” are equivalent terms.

The term “harmonic” is generally used only for those components of the current or voltage with a frequency which is an integral multiple of the power frequency (and is locked into that frequency) and that are produced as part of the operation of the electricity system. These will produce harmonic frequencies in the magnetic or electric fields produced. If there are currents or voltages at other frequencies, which are not tied to the power frequency, these frequencies will also appear in the magnetic or electric fields produced.

There is a number of possible sources of such currents and voltages, particularly at frequencies rather higher than the power frequencies. With regard to exposure of the public, the main sources are the 16 2/3(20 or sometimes 15) Hz used by some electric transport systems, 400 Hz used by most aeroplanes, the screen-refresh frequencies of video display units (VDUs) (which have varied over the years with advances in computer design but is typically 50–160 Hz), and the variable frequencies increasingly used by variable-speed traction drives for trains and trams. It can be seen that these are all specific to particular situations, and, with the exception of the VDU, it would not be expected to find fields at these frequencies in normal domestic settings. In a normal domestic setting, any non-harmonic frequencies are generally negligible. There are many other sources in occupational settings related to specific industrial processes.

All the frequency components of the field so far considered are periodic: that is, although the amplitude of the field varies over time, the pattern of the variation repeats itself at fixed intervals (e.g. at 20 ms intervals for signals with a fundamental frequency of 50 Hz).

Natural and man made field sources often produce signals which are not repeated periodically but rather occur only once. The resulting time variation of the field is called transient. Over the course of a period of time, say a day, there may be a number of transients, but there is no regularity or periodicity to them, and they are sufficiently far apart to be treated as separate isolated events.

Transients accompany virtually all switching operations and are characterized by a high rate of change of the field. In fact there is a wide range of events which fit the basic definition of a transient as a non-periodic event. The characteristics of transients are numerous, which makes measurement complex.

2.1.5 Perturbations to fields, shielding

Magnetic fields are perturbed by materials that have a very high relative permeability. This effectively means they are perturbed only by ferromagnetic materials, and the most common example is iron and its compounds or alloys. An object made of such material will produce a region of enhanced field where the field enters and leaves the object, with a corresponding reduction in the field to the sides.

Shielding of ELF magnetic fields with such material is in practice only an option to protect small areas, for example VDU's from magnetic interference. Another option with only little practical relevance for field reduction purposes is the compensation of the magnetic field with a specially designed field source.

Electric fields, in contrast to magnetic fields, are readily perturbed by materials with a high relative permittivity (dielectrics) and even more significantly by conducting objects. A conducting enclosure eliminates the electric field within it. A conducting object also perturbs the field outside it, increasing it in line with the field and reducing it to the sides. At power frequencies, a metal box is effectively a perfect screen, and buildings are sufficiently conducting to reduce the electric field within them from an external source by factors of 10–100 or more.

Electric fields are particularly affected by earthed conducting objects including not just the ground, but also trees, hedges, fences, many buildings, and human beings. Any conducting object has a charge induced on it by the electric field. This induced charge itself then becomes part of the set of charges which constitutes the field. The consequence is that to determine the electric field produced by, say, a transmission line it is necessary to consider not just the positions of the conductors of the line but the position of the ground relative to them and the positions of any other conducting objects. In terms of human exposure to power lines, the main effect is that close to a vertical object that is tall compared to a person – e.g. a tree or a house – field exposure on the ground is reduced.

2.2 Sources of alternating fields

2.2.1 Electric fields

2.2.1.1 Naturally occurring fields

The natural electric field encountered above the surface of the Earth varies greatly with time and location. The primary cause of the field is the charge separation that occurs between the Earth and the ionosphere, which acts as a perfect conductor separated by air of negligible conductivity (König et al., 1981). The field near the surface in fair weather has a typical strength of about 130 V m^{-1} (Dolezalek, 1979). The strength generally depends on height, local temperature, humidity profile and the presence of ions in the atmosphere. Deviations of up to 200% from fair-weather levels have been recorded in the presence of fog or rain. Daily changes are attributed to meteorological phenomena, such as thunderstorms, which affect the rate of charge transfer between the ground and the upper atmosphere.

Variations of up to 40 kV m^{-1} occur near thunderstorms, although even in the absence of local lightning, fields can reach up to 3 kV m^{-1}. Because the dominant component usually changes very slowly, the phenomenon is often described as “electrostatic”. However a variety of processes in the atmosphere and magnetosphere produce a wide range of signals with frequencies reaching up to several megahertz. Atmospheric inversion layer phenomena produce electric fields at the lower end of the ELF range (König et al., 1981). Atmospheric fields related to lightning discharges have spectral components below 1 Hz but the largest amplitude components have frequencies between 1 and 30 kHz. Generally the range of frequencies and field strengths vary widely with geographical location, time of day and season. Characteristics of the Earth's electric field in the ELF range are summarized in Table 2. The intensity of time-varying fields related to atmospherics such as lightning between 5 Hz and 1 kHz are typically less than 0.5 V m^{-1} and amplitudes generally decrease with increasing frequency. The natural electric field strength at the power frequencies of 50 or 60 Hz is about 10^{-4} V m^{-1} (EC, 1996).

Table 2. Characteristics of the Earth's electric field in the ELF range

Frequency range (Hz)	Electric field strength ($V m^{-1}$)	Comment
0.001–5	$0.2–10^3$	Short duration pulses of magnetohydrodynamic origin
7.5–8.4 and 26–27	$0.15–0.6 \times 10^{-6}$	Quasi-sinusoidal pulses of underdetermined origin
5–1000	$10^{-4}–0.5$	Related to atmospheric changes (atmospherics)

The Earth-atmosphere system approximates electromagnetically to a three conductive layer radial shell, denoted as the Earth-ionosphere cavity, in which electromagnetic radiation is trapped. In this cavity broadband electromagnetic impulses, like those from lightning flashes, create globally the so-called Schumann resonances at frequencies 5–50 Hz (Bliokh, Nickolaenko & Filippov, 1980; Schumann, 1952; Sentman, 1987). Electric fields of up to a few tenths of a millivolt per metre can be attributed to the Schumann resonances (König et al., 1981).

2.2.1.2 Artificial fields

The dominant sources of ELF electric fields are invariably the result of human activity, in particular, the operation of power systems or the operation of mains appliances within a home.

2.2.1.2.1 Overhead power lines

The electric field at a point near a power line depends on the voltage of the line, its distance, and how close together the various charged conductors making up the line are. The radius of the conductors is also relevant. Other factors being equal, thicker conductors result in larger electric fields at ground level. In addition, electric fields are affected by conducting objects.

Electric fields are lower and fall more rapidly with distance for point symmetric systems than for others. Electric fields are lowest when the three phases are balanced and rise with the unbalance. At ground level, electric fields are highest towards the middle of a span where the sag of the conductors brings them nearest the ground and reduce towards the end of the span.

The highest electric field strength at ground level from overhead lines is typically around 10 kV m^{-1} (AGNIR, 2001b; NIEHS, 1995).

2.2.1.2.2 House wiring and appliances

The electric field produced by any source outside the home will be attenuated considerably by the structure of the home. All common building materials are sufficiently conducting to screen fields, and the ratio of the field outside to the field inside typically ranges from 10 to 100 or more (AGNIR, 2001b).

Within homes, however, there are sources of electric field just as there are sources of magnetic field. House wiring can produce electric fields, which are clearly strongest close to the wiring but which can be significant over the volume of a house as well. The electric field produced by wiring depends partly on how it is installed; wiring installed in metal trunking or conduit produces very small external fields, and the fields produced by wiring installed within walls is attenuated by an amount depending on the building materials (AGNIR, 2001b).

The other main source of electric fields within a home is mains appliances. Any mains appliance produces power-frequency electric fields whenever it is connected to the mains (in contrast to magnetic fields, which are produced only when current is being drawn), and appliances are often left plugged in even when not operating. The size of the electric field depends on the wiring of the appliance, and on how much of the wiring is enclosed by metal which will screen the electric field. The electric field from an appliance falls rapidly with distance from the appliance, just as the magnetic field does. The magnetic field from an appliance typically merges into the background magnetic field within a metre or two. With electric fields, except in those few homes very close to a source of high electric field, there is no background field from sources outside the home. Therefore the electric field from an appliance is still appreciable, albeit rather small, at greater distances from the appliance than is the case for magnetic fields.

Because electric fields are so easily perturbed by conducting objects, fields within the volume of a room are rarely uniform or smoothly varying. Many objects, in particular metal objects, perturb the field and can create local areas of high electric field strength.

2.2.1.2.3 Underground cables and substations

When a cable is buried underground, it still produces a magnetic field above the ground (see section 2.2.2.2.2). By contrast, a buried cable produces no electric field above ground, partly because of the screening effect of the ground itself, but mainly because underground cables practically always include a metal sheath which screens the electric field.

Substations also rarely produce significant electric fields outside their perimeter. In the case of a ground-mounted final distribution substation, this is because all the busbars and other equipment are contained either in metal cabinets and pillars or in a building, both of which screen electric fields. Higher-voltage substations are not so rigorously enclosed, but are usually surrounded by a security fence, which because it is metal again screens the electric field.

2.2.1.2.4 Electric power industry

Bracken and colleagues have characterized the electric field environment within towers of transmission lines rated between 230 and 765 kV. During various operations that include climbing the towers, electric fields may reach anywhere from 10 to 30 kV m^{-1}.These fields would not typically be oriented parallel to the body (Bracken, Senior & Dudman, 2005; Bracken, Senior & Tuominen, 2004). In some operations, such as bare hand live line work, linemen wear a conductive suit, which shields the individual from the electric field.

2.2.2 Magnetic fields

2.2.2.1 Naturally occurring fields

The Earth's magnetic field changes continually at periods ranging from a few milliseconds up to 10^{12} seconds. The broad spectrum of variation is summarized in Table 3. The main feature of the geomagnetic field is its close resemblance to a dipole field aligned approximately with the spin axis of the Earth. The dipole field is explained by electrical currents that flow in the core. The vertical component of the field reaches a maximum of about 70 µT at the magnetic poles, and approaches zero at the magnetic equator; conversely the horizontal component is close to zero at the poles and has a maximum just over 30 µT at the magnetic equator. Changes of the dipole field with periods of the order of 100 years or so constitute the secular variation, and are explained by eddy currents located near the core boundary (Bullard, 1948).

Table 3. The broad spectrum of variation in the Earth's magnetic field

Type	Period (seconds)	Typical amplitudes	Origin	Comment
Reversals Secular change	~10^{12} 10^{9}–10^{10}	100 T 10 T	Internal	Current systems in the earth
Magnetic storms Sunspot activity Storm repetition	10^{8}–10^{9} 10^{6}	hundreds nT	External	11 year period of maximum 27 day period
Diurnal Lunar	10^{5} 10^{5}	tens nT		24 hour period 25 hour period
Pulsations	10^{-1}–10^{2}	0.02–100 nT		Solar-terrestrial interaction
Cavity resonances	10^{-2}–10^{-1}	10^{-2} nT		Solar-terrestrial interaction
Atmospherics	10^{-6}–10^{0}	10^{-2} nT (ELF)		Lightning discharges

Table 4. Characteristics of the Earth's magnetic field across the ELF part of the spectrum

Nature and origin	Amplitude changes (T)	Typical frequency (Hz)	Comment
Regular solar and lunar variations	0.03–0.05 (solar) 0.005–0.006 (lunar)	10^{-5} 10^{-5}	Increases in energy during summer and towards the equator. Also increases at a period of 11 years due to sunspot activity.
Irregular disturbances, such as magnetic storms related to sunspot activity	0.8–2.4	Wide range of frequencies	Repetition after 27 day period corresponding to the sun’s rotation time on its axis.
Geomagnetic pulsations (micropulsations) related to changes in the magnetosphere	2×10^{-5}–8×10^{-2}	0.002–5 Hz	Amplitudes quoted for moderate activity at mid-latitudes.
Cavity resonances	2×10^{-5}–5×10^{-5}	5–50 Hz	Schumann resonance oscillations excited by broadband lightning discharges
Atmospherics related to lightning discharges	5×10^{-5}	< 1–2 kHz	Energy peak at 100–200 Hz. Some spectral components < 1 Hz and VLF components in the range 1–30 kHz.

The main characteristics of the Earth's magnetic field across the ELF and VLF part of the spectrum are summarized in Table 4. All of the spectrum of time variations of period shorter than the most rapid secular change have their primary cause outside the Earth, associated with processes in the ionosphere and magnetosphere (Garland, 1979). These include the regular solar and lunar daily variations upon which more irregular disturbances are superimposed. The typical solar diurnal cycle shows variations of no more than a few tens of nanoteslas depending on magnetic latitude. Large magnetic disturbances known as storms show typical variations of 0.5 μT over 72 hours and are closely related to sunspot activity and the sun’s rotation time. Geomagnetic pulsations arise from effects in the magnetosphere and typically cover the frequency range from 1 MHz to 1 Hz. At mid-latitudes during periods of moderate activity up to several tens of nanotesla can be attributed to pulsations (Allan & Pouler, 1992; Anderson, 1990).

The ELF variations arise mainly from the effects of solar activity in the ionosphere and atmospheric effects such as lightning discharges which cause resonance oscillations in the Earth-ionosphere cavity. Changes in ELF signals over 11-year and 27-day periods and circadian variations reflect the solar influences (EC, 1996). The electromagnetic fields that arise from lightning discharges, commonly known as atmospherics, have a very broad frequency range with spectral components from below 1 Hz up to a few megahertz. In the ELF range the peak intensity from lightning discharges occurs typically at 100–200 Hz. The Schumann resonances are a source of ELF magnetic fields of the order of 10^{-2} nT at frequencies of up to a few tens of hertz (König et al., 1981). The measurement of signals with frequencies below 100 Hz is extremely difficult because of the interference from man-made signals. At 50 Hz or 60 Hz the natural magnetic field is typically of the order of 10^{-6} μT (Polk, 1974).

2.2.2.2 *Artificial fields*

2.2.2.2.1 Transmission lines

Factors affecting fields

The magnetic field produced by a transmission line depends on several factors.

- The number of currents carried by the line (usually three for a single-circuit line, 6 for a two-circuit line, etc.).
- The arrangement of those currents in space, including:
  - The separation of the currents. This is usually determined by the need to avoid sparkover between adjacent conductors, including an allowance for displacement of conductors caused by wind. The separation therefore usually increases as the voltage of the line increases.
  - The relative phasing of multiple circuits. Suppose the three phases of one circuit are arranged in the order a-b-c from top to bottom. If the second circuit is similarly arranged a-b-c, the two circuits produce magnetic fields which are aligned with each other and reinforce each other. But if the second circuit is arranged in the opposite order, c-b-a, its magnetic field will be in the opposite direction and the two fields will partially cancel each other. The resultant field falls more nearly as the reciprocal of distance cubed instead of squared. This is variously known as transposed, reversed, or rotated phasing. Other arrangements of the relative phasing are clearly possible and generally produce higher fields at ground level.
- The currents carried by the line, which include:
  - the load current;
  - any out of balance currents;
- any currents carried by the earth conductor or in the ground itself;

- the height of the currents above ground: the minimum clearance allowed for a given voltage line is usually determined by the need to avoid sparkover to objects on the ground.

Higher voltage lines usually carry higher currents and have larger spacing between conductors. They therefore usually produce higher magnetic fields, even though the magnetic field itself does not depend on the voltage.

Currents in power lines vary over the course of a day, seasonally and from year to year as electricity demand varies. This affects the magnetic field both directly and also because the load carried affects the conductor temperature and hence sag and ground clearance. Lines usually operate at significantly less load than their rating, and therefore average magnetic fields encountered are usually significantly less than the theoretical maximum field a line is capable of producing.

Harmonics and transients

The nature of the electricity system and the use of electricity means that some harmonics are more prevalent than others. In particular, the third harmonic, 150 (180) Hz, is usually the strongest, and even harmonics (2nd, 4th, 6th etc.) are usually smaller than odd harmonics (3rd, 5th, 7th etc.). In many situations, harmonics are very small, perhaps a few percent or less of the fundamental. In some situations, however, particularly in buildings with certain types of apparatus, or near certain industrial users of electricity, the harmonic content can increase, and on occasion the third harmonic can be comparable in magnitude to the fundamental. In general, harmonics above the third or fifth are very small, but there are certain processes which lead to harmonics as high as the 23rd and 25th. Some harmonics occur as a result of the operation of the electricity system itself – for instance, small amounts of 11th, 13th, 23rd and 25th harmonics are produced by common types of AC-to-DC conversion equipment – but most occur as a result of the loads consumers connect to the electricity system. A particular example is dimmer switches used in lighting applications. Harmonics are regarded as undesirable on an efficiently operated electricity system. Harmonics tend to be lower in the transmission system, higher in the distribution system, and highest in final-distribution circuits and homes.

Transients also occur in electrical systems. Transients in the voltage (and hence in the electric field) are produced by the following causes.

- Lightning strikes to an overhead power line. Most lightning strikes hit the earth conductor (where one is present). If the lightning hits a phase conductor instead, or jumps across to the phase conductor having initially hit something else, a very high voltage can be applied to that phase conductor. This voltage rapidly dissipates, not least over the spark gaps which are installed partly for this very purpose.

- Switching events. When a switch in a circuit carrying a current is opened and the current is interrupted, a voltage is generated in that circuit. The voltage dissipates over a period of time determined by the electrical characteristics of the circuit. Switching surges occur whenever circuits are interrupted, so also occur in distribution systems and in homes.
- Short circuits. These can occur either between two phase conductors or from a phase conductor to earth or to an earthed conductor. Examples of how short circuits occur with overhead lines include when two phase conductor, both oscillating in the wind, clash, or when an object such as a tree or a hot-air balloon bridges the gap between a phase conductor and another conductor or the earth. With underground circuits and circuits in homes, short circuits can occur when a drill cuts the cable, or as a result of corroded insulation. Short circuits should usually result in the circuit concerned being rapidly disconnected (by the operation of a circuit breaker or by the blowing of a fuse). For the duration of the short circuit, which could be as short as 40 ms on parts of the transmission system or as long as a second on parts of the distribution system, the voltage of the circuit concerned is forced by the fault to a different value from normal.

Transients in the current (and in the resulting magnetic field) result from the following causes.

- Short circuits. For the duration of the short circuit (until either the short circuit is removed, or more usually, until the circuit is disconnected by the fuse or circuit breaker) abnormally high currents will be flowing. On the UK transmission system, the highest “fault current” that is allowed to flow is 63 kA. At lower voltages, the “fault level” (the amount of current that can flow in the event of a short circuit) is lower, but can still be many times the normal current in the circuit.
- Switching events. Transient currents can be produced when a circuit is first switched on (such currents are often called “inrush” currents which describes their nature quite well).

Some transients affect only the circuit they are generated on. More usually, they affect neighbouring circuits as well, but to a lesser extent. For instance, at high voltages, a lightning strike to a transmission circuit may cause a sufficiently large transient voltage on that circuit to cause the protection circuits to operate the circuit breaker and to disconnect the circuit. On other nearby circuits, it may cause a large transient voltage, but not large enough to cause the protection to operate. On circuits further away, the transient may still be present but may be much smaller and for practical purposes negligible. At low voltages, switching an appliance in one home may produce a transient that affects adjoining homes as well. Thus it is only transient voltages or currents which are generated close to a given point which are likely to produce significant transient electric or magnetic fields at that point.

Field levels

Transmission lines can produce maximum magnetic flux densities of up to a few tens of microteslas during peak demand, however mean levels are usually no more than a few microteslas. The magnetic flux density reduces typically to a few hundred nanotesla at distances of several tens of metres from a transmission line. The magnetic flux density decreases in lower voltage systems, mainly due to progressively smaller currents and conductor separations used.

Overhead transmission lines operate at various voltages up to 1150 kV. In the UK, the largest power lines in use operate at 400 kV with ratings up to 4 kA per circuit and a minimum ground clearance of 7.6 m. This theoretically produces up to 100 µT directly beneath the conductors. In practice, because the load is rarely the maximum and the clearance rarely the minimum, the typical field at ground level directly beneath the conductors is 5 µT. Table 5 gives more detail on the average magnetic field at various dis-

Table 5. Average magnetic field at various distances from National Grid line [a]

Distance (m)	Average field (µT)
0	4.005
50	0.520
100	0.136
200	0.034
300	0.015

[a] Source: National Grid, 2007b.

Typical values for the US at various distances, voltages, and power usage are summarized in Table 6.

Table 6. Typical magnetic field levels in µT for power transmission lines [a]

Type of line	Usage	Maximum on right-of-way	Distance from lines			
			15 m	30 m	61 m	91 m
115 kV	Average	3	0.7	0.2	0.04	0.02
	Peak	6.3	1.4	0.4	0.09	0.04
230 kV	Average	5.8	2.0	0.7	0.18	0.08
	Peak	11.8	4.0	1.5	0.36	0.16
500 kV	Average	8.7	2.9	1.3	0.32	0.14
	Peak	18.3	6.2	2.7	0.67	0.30

[a] Source: NIEHS, 1995.

tances from a typical National Grid line. These figures were calculated from one year's recorded load data and are the average for a representative sample of 43 different lines.

2.2.2.2.2 Underground cables

When a high-voltage line is placed underground, the individual conductors are insulated and can be placed closer together than with an overhead line. This tends to reduce the magnetic field produced. However, the conductors may only be 1 m below ground instead of 10 m above ground, so can be approached more closely. The net result is that to the sides of the underground cable the magnetic field is usually significantly lower than for the equivalent overhead line, but on the line of the route itself the field can be higher. Examples of fields for UK underground cables are given in Table 7.

Table 7. Examples of fields for underground cables calculated at 1 m above ground level [a]

Voltage	Specifics	Location	Load	Magnetic field in μT at distance from centreline			
				0 m	**5 m**	**10 m**	**20 m**
400 kV	trough	0.13 m spacing	maximum	83.30	7.01	1.82	0.46
and		0.3 m depth	typical	20.83	1.75	0.46	0.12
275 kV	direct	0.5 m spacing	maximum	96.17	13.05	3.58	0.92
	buried	0.9 m depth	typical	24.06	3.26	0.90	0.23
132 kV	separate cores	0.3 m spacing 1 m depth	typical	9.62	1.31	0.36	0.09
	single cable	1 m depth	typical	5.01	1.78	0.94	0.47
33 kV	single cable	0.5 m depth	typical	1.00	0.29	0.15	0.07
11 kV	single cable	0.5 m depth	typical	0.75	0.22	0.11	0.06
400 V	single cable	0.5 m depth	typical	0.50	0.14	0.07	0.04

[a] Source: National Grid, 2007a.

Depending on the voltage of the line, the various conductors can be contained within an outer sheath to form a single cable. Not only is in that case the separation of the conductors further reduced, but they are usually wound helically, which produces a further significant reduction in the magnetic field produced.

2.2.2.2.3 Distribution lines

In power system engineering, it is common to distinguish between transmission lines and distribution lines. Transmission lines are high voltage (more than a few tens of kV), usually carried on lattice steel towers or substantial metal or concrete structures, capable of carrying large currents (hundreds or sometimes thousands of amps), and used for long-distance bulk transmission of power. Distribution lines are usually lower voltage (less than a few tens of kV), more often carried on wood poles or simpler structures, designed to carry lower currents, and used for more local distribution of power, including the final distribution of power to individual homes. Distribution lines may also have a neutral conductor whereas transmission lines rarely do.

Viewed from the standpoint of production of electric and magnetic fields, the difference between transmission lines and distribution lines is one of degree rather than kind. As the voltage of a circuit reduces, generally so does the spacing of the conductors and the load. All of these factors tend to mean that as the voltage decreases, so do both the electric and magnetic fields. Thus, conceptually, a distribution line without grounding currents is no different to a transmission line, it simply produces lower fields. In practice, the main difference between transmission and distribution lines is often that distribution lines do carry grounding currents but transmission lines do not.

The situation described for transmission lines also applies for a distribution circuit where the neutral is isolated from ground for most of its length. The neutral is often connected to the earth once at or near the transformer or substation which supplies the line, but that is the only earth connection. However, it was realised in various countries that by connecting the earth to the neutral at further points along their length other than just at the transformer/substation, extra security and safety could be obtained. When this is done, the neutral is usually connected to the mass of earth itself at various points, and in some configurations, there is a combined neutral-and-earth conductor rather than separate neutral and earth conductors.

This is the basis of much distribution wiring round the world. Practical systems are more complicated than this simple description, and there are usually numerous regulations and practices associated with them. However, for the present purposes, it is sufficient to note that much distribution wiring results in the neutral conductor being earthed at various points along its length. The situation in different countries is summarized in Table 8.

Each time the neutral conductor is earthed, there is the possibility that neutral current can divert out of the line into the earth itself (or more likely, into a convenient conducting earthed utility such as a water pipe) and return to the transformer/substation by a different route altogether. As soon as any neutral current diverts out of the lines, the currents left in the line are no longer exactly balanced. This can be expressed in various ways, for instance by saying that the neutral current is no longer equal and opposite to

Table 8. Wiring practices in different countries

Country	What is known about distribution earthing practices	Source of information
Australia	Neutral is earthed at entrance to each house	Rauch et al., 1992
France	Multiple earthing should not occur	
Germany	Cities: neutral multiply earthed (optional but common). Rural: neutral not normally earthed.	Rauch et al., 1992
Japan	Multiple earthing not normal but can occur with certain motors and telecommunications equipment	Rauch et al., 1992
Norway	Multiple earthing should not occur	Vistnes et al., 1997b
UK	Multiple earthing becoming more common. Over 64% of circuits with multiple earthing.	Swanson, 1996
USA	Multiple earthing of neutral universal	Rauch et al., 1992

the zero-sequence current. The commonest and most useful way of describing the situation is to say that the line now has a net current, that is, a non-zero vector sum of all the currents flowing within the line.

Grounding currents – diverted neutral currents – flow on various conducting services, such as water pipes, and these may pass through a home. Where this happens there can be a region of elevated field within the home.

The net current clearly has a return path (all currents must flow in complete circuits). However, the return path, comprising water pipes, the ground, and maybe other distribution circuits or the same circuit further along its length, are likely to be rather distant from the line with the net current. So at any given point, for instance in a home supplied by the line, there is likely to be rather poor cancellation between the magnetic fields produced by the net current in the line and its return path. Often, it is accurate enough to calculate the magnetic field in a home based just on the net current in the distribution line supplying it, ignoring the return current altogether.

Net currents tend to be low — typically varying from a fraction of an amp to a few amps — and so these magnetic fields produced by net currents are also rather low compared to the magnetic fields produced directly underneath transmission lines. However, in homes which are distant from transmission lines (which is in fact the majority of homes in most countries), and from heavily loaded 3 phase distribution lines, there are no other significant sources of magnetic field outside the home, so it is the field produced by the net current which constitutes the dominant source of field, usually referred to as the “background field”. If the return path is distant and we are regarding the field as produced by a single net current, it falls as one over the distance from the source, so varies comparatively little over the volume of a typical home.

Note that, although the concept of a net current was introduced by reference to deliberate multiple earthing of a neutral conductor, there are two other ways net currents can arise. These are, firstly, where two adjacent distribution circuits meet and their neutral conductors are connected; and secondly, where faulty house wiring or a faulty appliance results in an unintended earth connection to the neutral (this probably occurs in 20% or more of homes in the UK and is also common in the USA). Both have the effect of allowing neutral current to divert out of the line, and thus of creating a net current. In practical situations, a net current could be created by any of these three mechanisms, or more likely by a combination of two or all three of them, and the magnetic field it produces is unaffected by which of the mechanisms produced it (Maslanyj et al., 2007).

With overhead distribution, the phase conductors are sometimes close together in a single cable. Often, however, they are not as close together as they are with underground distribution, and significant fields may arise from load currents as well as net currents. Net currents still exist, and the magnetic field is produced by both net current and the currents in the phase conductors.

The size of a net current depends on the size of the neutral current, which in turn depends on the size of the currents in the phase conductors. These vary over time, as loads are switched on and off. In fact, electricity use shows characteristic variations both diurnally and annually. Because net currents do not depend directly on loads, they do not vary over time in exactly the same way, but net currents (and hence the background magnetic fields in homes produced by them) do usually show characteristic variations over time.

Supplies to houses in the USA have two phases each at 110 V. Appliances connected at 220 V between the two phases do not contribute neutral current and therefore do not contribute to net currents. Appliances connected between one or other phase and earth do contribute to neutral current. The neutral current, and hence the net current and magnetic field, depends on the difference between the loads connected to the two phases rather than to the total load.

Another wiring source of magnetic field within homes is two-way switching of lights. If wired in orthodox fashion, no net currents are produced by two-way switched lights. However, the layout of the lighting circuits, switches and lights in a home often makes it tempting to wire the light in a way which effectively creates a loop of net current connecting the light and the two switches and enclosing part of the rest of the volume of the home. This loop of net current constitutes a source of magnetic field. Again, this source only operates when the relevant light is switched on.

Spatial distribution

EMF strength from any source diminishes as the distance from the source increases. Quite often, fields decrease with a power of the distance, depending on the configuration of the source (Kaune & Zafanella, 1992).

The field strength at any distance r is proportional to $1/r$, $1/r^2$, or $1/r^3$. The higher the power of r, the steeper the decrease of the field. When the field strength is proportional to one over the distance cubed ($1/r^3$), the field is reduced to an eighth with every doubling of the distance. Although good approximations, in practice, fields rarely follow these power laws exactly, departing from them particularly at very small distances or very large distances.

Within homes, the background field – the general level of field over the volume of the home – varies relatively little, as it usually comes from sources outside the home, and the inverse distance or inverse distance square relationship with distance does not produce great variation over a limited volume. However, superimposed on that background variation, there are local areas of higher fields, from appliances, or house wiring. The fields from such devices tend to decay at $1/r^3$.

Temporal variation

Because magnetic fields stem from currents, they vary over time as electricity demand varies over time. The relationship is not precise, as magnetic fields usually depend on net currents, which may not be precisely proportional to loads. Nonetheless, magnetic fields do show daily, weekly and annual variations. The magnetic field in a home in the UK can vary typically by a factor of 2 during the day above and below the daily average and by 25% during the year above and below the annual average.

Direct measurements of fields in the same property are available only up to about 5 years apart. Dovan et al. (Dovan, Kaune & Savitz, 1993) conducted measurements in a sample of homes from the childhood cancer study of Savitz et al. (1988) five years after they were first measured and reported a correlation of 0.7 between the spot measurements for the two periods. For longer periods, changes in fields have to be estimated from models, taking account of changes in loads, numbers of consumers, lengths of circuits, etc. Kaune et al. (1998) examined the correlation of loads over time for over one hundred transmission circuits in Sweden. The correlation decayed substantially over time (after about ten years) and thus, contemporaneous measurements are not reliable for retrospective estimation of ambient residential fields. Simple models look just at some measure of per capita consumption. Swanson (1996) developed a more sophisticated model which looks at changes in electricity systems and wiring practices as well. Even so, there are some changes which such models cannot easily take into account, so the results should be interpreted with caution. The models all suggest that average fields have increased over time, for example by a factor of 4.2 in the UK from 1949 to 1989.

Data on fields in different countries

Several authors (e.g. Kaune et al., 1994; Kaune & Zaffanella, 1994; Merchant, Renew & Swanson, 1994a; Merchant, Renew & Swanson, 1994c; Perry et al., 1981; Silva et al., 1989; UKCCSI, 2000) have found that the distribution of fields in domestic settings was approximately lognormal, and other published data also appear to exhibit this structure. It is therefore assumed here that all distributions are approximately lognormal and, thus, are better characterised by their geometric mean (GM) and geometric standard deviation (GSD) than by their arithmetic mean (AM) and standard deviation (SD). For a log-normal distribution, GM and GSD can be calculated from AM and SD using the following formulae (Swanson & Kaune, 1999):

$$\mathrm{GM} = \frac{\mathrm{AM}^2}{\sqrt{\mathrm{AM}^2 + \mathrm{SD}^2}}$$

$$\mathrm{GSD} = e^{\sqrt{\ln\left[1+\left(\frac{\mathrm{SD}}{\mathrm{AM}}\right)^2\right]}}$$

Data from various countries show, that the geometric mean of spot measurements in homes do not vary dramatically. Geometric means of the data provided range between 48 nT and 107 nT in Canada (Donnelly & Agnew, 1991; Mader et al., 1990; McBride, 1998), 60 nT in Finland (Juutilainen, 1989), 26 nT to 29 nT in Germany (Michaelis et al., 1997; Schüz et al., 2000), 29 nT in New Zealand (Dockerty et al., 1998; 1999), 37 nT to 48 nT in Sweden (Eriksson et al., 1987; Tomenius, 1986), 29 nT to 64 nT in the UK (Coghill, Steward & Philips, 1996; Merchant, Renew & Swanson, 1994c; Preece et al., 1996; UKCCSI, 1999), and 47 nT to 99 nT in the USA (Banks et al., 2002; Bracken et al., 1994; Davis, Mirick & Stevens, 2002; Kaune et al., 1987; Kaune et al., 1994; Kaune & Zaffanella, 1994; Kavet, Silva & Thornton, 1992; Linet et al., 1997; London et al., 1991; Zaffanella, 1993; Zaffanella & Kalton, 1998). There is a tendency of higher fields in countries with lower distribution voltage. These data should, however, be interpreted with care, given great differences in the evaluation conditions (e.g. number of homes included).

2.2.2.2.4 Electrical equipment, appliances, and devices

The commonest source of magnetic field within a home is not the fixed wiring of the home but mains appliances. Every mains appliance produces a magnetic field when it is drawing current (and with some appliances, the mains transformer is still connected and drawing current whenever the appliance is plugged in, regardless of whether it is switched on or not). In a typical home the magnetic field consists of the background field with “peaks” of field surrounding each appliance. Exposure to magnetic fields from home appliances can sometimes usefully be considered separately from exposure to fields due to power lines. Power lines produce relatively low-intensity, small-gradient fields that are always present throughout the home, whereas fields produced by appliances are invariably more intense, have much steeper spatial gradients, and are, for the most part, experienced only sporadically. The appropriate way of combining the two field types into a single measure of exposure depends critically on the exposure metric considered.

Magnetic fields from appliances are produced by electric current used by the devices. Currents in an appliance can often be approximated as small closed loops. Appliances of that type usually produce a comparatively small field, because any current within the appliance is balanced by a return current a comparatively short distance away. It is usually only in some appliances such as kettles, convection fires, electric blankets, that the current flows in the heating element round a reasonably large loop.

However, many appliances contain an electric motor, a transformer, or a choke or inductor. These all depend on magnetic fields for their operation: that is, they deliberately create a magnetic field inside the appliance. The magnetic field around those appliances (stray field) depends strongly on the design, which aims to keep stray fields as low as possible. If the design priorities are not efficiency but low cost, small size or low weight, the result will be an appliance that produces higher magnetic fields.

Thus higher fields are often produced by small and cheap transformers (e.g. mains adaptors, transistor radios) and small, cheap and compact motors (e.g. mains razors, electric can openers). A survey of 57 mains appliances conducted for National Grid in 1992 (Swanson, 1996) found that the field produced by an appliance was, on average, independent of the power consumed by the appliance.

Whether it is produced directly by the currents or indirectly by leakage field from a transformer or motor, the magnetic field produced by an appliance usually falls as one over the distance cubed. In consequence, magnetic fields from appliances tend to be significant only close to the appliance itself. More than a metre or two away, they have usually become so small that they have effectively merged into the background field. Very close to an appliance, the fields can rise to quite high levels; hundreds of microteslas on the surface of many mains radios, and over a millitesla on the surface of some mains razors. Exactly how high the field rises depends not just on the size of the field produced by the source (motor or transformer) inside the appliance, but also on how close the source can be approached. This depends on where within the volume of the appliance the source is located.

Examples of the field levels likely to be encountered at short distances from various appliances are presented in Table 9.

Table 9. Examples of magnetic flux densities from 50 and 60 Hz domestic electrical appliances [a]

	Source	**Magnetic flux densities (T)**			
		60 Hz at 30 cm [b]		**50 Hz at 50 cm** [c]	
		Median	**Range** [d]	**Computed field**	**SD**
Bathroom	Hair dryers	1	bg***–7	0.12	0.1
	Electric shavers	2	bg–10	0.84	
	Electric showers			0.44	0.75
	Shaver socket			1.24	0.27
Kitchen	Blenders	1	0.5–2	0.97	1.05
	Can openers	15	4–30	1.33	1.33
	Coffee makers	bg	bg–0.1	0.06	0.07
	Dishwashers	1	0.6–3	0.8	0.46
	Food processors	0.6	0.5–2	0.23	0.23
	Microwave ovens	0.4	0.1–20	1.66	0.63
	Mixers	1	0.5–10	0.69	0.69
	Electric ovens	0.4	0.1–0.5	0.39	0.23
	Refrigerators	0.2	bg–2	0.05	0.03
	Freezers			0.04	0.02
	Toasters	0.3	bg–0.7	0.09	0.08
	Electric knives			0.12	0.05
	Liquidisers			0.29	0.35
	Kettle			0.26	0.11
	Extractor fan			0.5	0.93
	Cooker hood			0.26	0.10
	Hobs			0.08	0.05
Laundry/Utility	Clothes dryers	0.2	bg–0.3	0.34	0.42
	Washing machines	0.7	0.1–3	0.96	0.56
	Irons	0.1	0.1–0.3	0.03	0.02
	Portable heaters	2	0.1–4	0.22	0.18
	Vacuum cleaners	6	2–20	0.78	0.74
	Central heating boiler			0.27	0.26
	Central heating timer			0.14	0. 17
Living room	TVs	0.7	bg–2	0.26	0.11
	VCRs			0.06	0.05
	Fish tank pumps			0.32	0.09
	Tuners/tape players	bg	bg–0.1	0.24	

Table 9. Continued.

	Audio systems			0.08	0.14
	Radios			0.06	0.04
	Bedroom				
	Clock alarm	0-50		0.05	0.05
Office	Air cleaners	3.5	2–5		
	Copy machines	2	0.2–4		
	Fax machines	bg	bg–0.2		
	Fluorescent lights	0.6	bg–3		
	VDUs	0.5	0.2–0.6	0.14	0.07
Tools	Battery chargers	0.3	0.2-0.4		
	Drills	3	2-4		
	Power saws	4	0.9-30		
Miscellaneous	Central heating pump			0.51	0.47
	Burglar alarm			0.18	0.11

[a] Source: ICNIRP, 2003.

[b] Source: EPA, 1992.

[c] Source: Preece et al., 1997.

[d] bg: background.

Preece et al. (1997) assessed broadband magnetic fields at various distances from domestic appliances in use in the United Kingdom. The magnetic fields were calculated from a mathematical model fitted to actual measurements made on the numbers of appliances. They reported that few appliances generated fields in excess of 0.2 μT at 1 meter distance: microwave cookers 0.37 ± 0.14 μT; washing machines 0.27 ± 0.14 μT; dishwashers 0.23 ± 0.13 μT; some electric showers 0.11 ± 0.25 μT and can openers 0.20 ± 0.21 μT.

Gauger (1984) and Zaffanella & Kalton (1998) reported narrow band and broadband data, respectively, for the USA. In Gauger's analysis of hand held hair dryers, at 3 cm from their surfaces, magnetic felds of about 6, 15, and 22 μT were produced for three types of hair dryers. Zaffanella (1993) found that at a distance of 27 cm from digital and analog clocks/clock radios, the median fields were 0.13 μT and 1.5 μT for digital and analog clocks, respectively. Preece et al. (1997) also measured the magnetic fields produced by hair dryers and electric clocks. At distances of 5 and 50 cm from hair dryers field measurements were 17 and 0.12 μT, respectively, and from electric clocks 5.0 and 0.04 μT, respectively.

Florig & Hoburg (1990) characterized fields from electric blankets, using a three-dimensional computer model; maximum, minimum, and volume-average fields within human forms were presented as a function of blanket type and geometric factors such as body size, body-blanket separation, and lateral body position. They reported that when blankets are heating, typical flux densities range from a few tenths of microtesla on the side of the body farthest from the blanket to a few tens of microtesla on the side closest to the blanket. Wilson et al. (1996) used spot measurements made in the home and in the laboratory. They reported that the average magnetic fields from electric blankets to which the whole body is exposed are between 1 and 3T. More recently, from eight-hour measurements, Lee et al. (2000) estimated that the time-weighted average magnetic field exposures from overnight use of electric blankets ranged between 0.1 and 2T.

It should be noted that many appliances produce a wide range of harmonics. The interpretation of results from broad band measurements can be misleading, if the spectral content of the fields is not known. Another problem with the interpretation of field measurements from appliances may result from the huge spatial and temporal variability of the fields.

2.2.2.2.5 Distribution substations and transformers

Overhead lines and underground cables at whatever voltage usually terminate at substations. All substations usually contain apparatus to perform similar functions: transforming, switching metering and monitoring. Substations range from large complexes several hundred metres in extent at one end of the scale to simple pole-mounted transformers at the other end of the scale. One feature they all have in common is that members of the general public are excluded from most of the functional regions of the substation, either by a perimeter fence or enclosure (for ground-based substations) or by the height of the pole (for pole-mounted substations).

Although substations vary in their complexity and size, the principles which determine the magnetic fields they produce are common. Firstly, in all substations, there are a number of components which produce a negligible magnetic field outside the confines of the substation. These include the transformers, virtually all switches and circuit breakers, and virtually all metering and monitoring equipment. Secondly, in many cases the largest fields in publicly accessible regions are produced by the overhead lines and underground cables running in and out of the substation. Thirdly, all substations contain a system of conductors (often referred to as ‘busbars’) which connect the various components within it, and these busbars usually constitute the main source of magnetic field within the substation producing appreciable field outside.

The size of the currents and the separation of the busbars are both larger in higher-voltage substations than in lower-voltage ones. However, the perimeter fence also tends to be further away from the busbars in higher-voltage substations. Therefore, the resulting field to which the public can be exposed can be somewhat greater at higher-voltage substations than at lower-voltage ones. In both cases, the magnetic field falls very rapidly with distance from the substation.

Typical values in the United Kingdom for substations of 275 and 400 kV at the perimeter fence is 10 µT, and 1.6 µT for an 11 kV substation. Renew, Male & Maddock found the mean field at the substation boundary, measured at about 0.5 m above ground level, to be 1.6 µT (range: 0.3–10.4 µT) (Renew, Male & Maddock, 1990). They also found (for the 19 substations where the background field was low enough to enable this measurement to be made) the mean distance at which the field at the substation boundary was halved to be 1.4 m (range: 0.6–2.0 m). NRPB has performed similar measurements on 27 substations in the UK with similar findings (Maslanyj, 1996). The mean field at the substation boundary was 1.1 µT, with a field of 0.2 µT at between 0–1.5 m from the boundary and a field of 0.05 µT at between 1–5 m.

2.2.2.2.6 Transport

Dietrich & Jacobs (1999) have reported magnetic fields associated with various transportation systems across a range of frequencies. AC currents of several hundred amperes are commonly used in electric railway systems, and magnetic fields are highly variable with time, the maxima often occurring during braking and acceleration. Up to a few millitesla can be generated near motor equipment, and up to a few tens of microteslas elsewhere on the trains (Table 10). Elevated ELF exposure levels also occur in the areas adjacent to electrified rail lines. Peak magnetic flux densities up to a few tens of microteslas have been recorded on the platform of a local city railway line (EC, 1996). Magnetic flux densities of a few microteslas were measured at 5 m from the line reducing to a microtesla or so at 10 m. In France, measurements inside a high-speed train and at a distance of 10 m outside the train showed peak values around 6 to 7 µT during high-speed drive (Gourdon, 1993). In a Swedish study (Anger, Berglund & Hansson Mild, 1997) field values in the driver cabinet range from a few to over 100 µT with mean values for a working day between a few to up to tens of microteslas depending on the engine. Some UK results are summarized in Table 10.

The magnetic fields encountered in electrified rail systems vary considerably because of the large variety of possible arrangements of power supply and traction. Many of the conventional rail systems use DC traction motors and AC power supplies with frequencies of 16 2/3 Hz or 50 Hz AC power in Europe and 25 Hz or 60 Hz in North America. Such systems often rely on pulse rectification either carried out on board or prior to supply and this gives rise to a significant alternating component in the static or quasi–static magnetic fields from the traction components of the trains (Chadwick & Lowes, 1998). Major sources of static and alternating magnetic fields are the smoothing and line filter inductors and not the motors themselves, which are designed to minimise flux leakage. Alternatively where DC supplies are used, voltage choppers are used to control the power by switching the power supply on and off regularly. Recently AC motors have become more common with the advances in high capacity solid-state technologies. When the required frequency differs from that of the supply frequency, converters are used to supply the correct frequency, or inverters are used when the power supply is DC (Muc, 2001).

Table 10. Alternating magnetic fields from UK electrified rail systems [a]

System and Source	AC magnetic flux density	Frequency	Comments
London underground	Up to 20 T	100 Hz	In the driver's cab; arising from traction components and on board smoothing inductors
Suburban trains			
750 DC Electric	Up to 1 mT	100 Hz	Floor level
Motor Units	16–64 T	100 Hz	In passenger car at table height
	16-48 T	100 Hz	Outside train on platform
Mainline trains			
Electric Motor Units	Up to 15 mT	100 Hz	Floor level above inductor
Mainline trains			
Locomotives	Up to 2.5 mT	100 Hz	0.5 m above floor in equipment car
	5–50 T	50 Hz	In passenger coaches

[a] Source: Allen et al., 1994; Chadwick & Lowes, 1998.

Train drivers and railway workers incur higher exposures than passengers because they often work closer to important sources. Nordenson et al. (2001) reported that engine drivers were exposed to 16 2/3 Hz magnetic fields ranging from a few to more than 100 µT. Hamalainen et al. (1999) reported magnetic fields ranging in frequency from 10 Hz to 2 kHz measured in local and long distance electrified trains in Finland where roughly more than half of the rail network is electrified with 50 Hz. Average levels to which workers and passengers were exposed varied by a factor of 1000 (0.3–290 µT for passengers and 10–6000 µT for workers). On Swedish trains, Nordenson et al. (2001) found values ranging from 25 to 120 µT for power-frequency fields in the driver's cabin, depending on the type (age and model) of locomotive. Typical daily average exposures were in the range of 2–15 µT.

Wenzl (1997) reported measurements on a 25 Hz AC electrified portion of the Northeast Rail Corridor in Maryland and Pennsylvania. Averages for workers were found to range between 0.3 and 1.8 µT , although 60 Hz and 100 Hz fields were also present from transmission lines suspended above the railway catenaries and from the railway safety communications and signalling system respectively. Chadwick & Lowes (1998) reported flux densities of up to 15 mT modulated at 100 Hz at floor level on British Electric Motor Units and 100 Hz fields of up to 2.5 mT in mainline locomotives (Table 10).

Other forms of transport, such as aeroplanes and electrified road vehicles are also expected to increase exposure, but have not been investigated extensively. Other possible ELF exposures associated with transport are discussed in 2.2.2.2.8.

2.2.2.2.7 Heating

The magnetic fields associated with underfloor heating systems depend on the configuration and depth of the cables, and the current flowing in them (Allen et al., 1994). Typically magnetic flux densities of up to a few microtesla can occur at floor level falling to a few tenths of a microtesla at 1 m above the floor. Systems operating at commercial premises can give up to a few hundred microtesla at floor level falling to a few tens of microtesla at 1 m above the floor. Many systems only draw current overnight, relying on off-peak electricity, and the heat capacity of the floor to provide warmth during the day.

2.2.2.2.8 Miscellaneous sources of ELF fields (other than power frequencies)

ELF magnetic fields are also generated in the home by petrol engine-powered devices such as lawnmowers, strimmers and chainsaws. Personal localised exposures of up to a few hundred microteslas can result when using such equipment (EC, 1996).

The pulsating battery current in the mobile phone generates a low-frequency nonsinusoidal magnetic field in the vicinity of the phone (Jokela, Puranen & Sihvonen, 2004). The time course is approximately a square wave with a pulse cycle similar to the radiation pattern of the phone (pulse width 0.7 to 1 ms with a repetition period of 4.6 ms). As the current drawn by the phones investigated (seven different types) was up to 3 A and the devices are used very close to the brain (approximately 10 mm), the field may exceed 50 μT.

Occupational exposure to ELF electric and magnetic fields from video display units (VDUs) has recently received attention. VDUs produce both power-frequency fields and higher-frequency fields ranging from about 50 Hz up to 50 kHz (NIEHS, 1998). Sandström et al. (1993) measured magnetic fields from VDUs in 150 offices and found that rms values measured at 50 cm from the screen ranged up to 1.2 μT (mean: 0.21 μT) in the ELF range (0–3 kHz) and up to 142 nT (mean: 23 nT) in the VLF range (3–30 kHz).

Cars are another source of ELF magnetic field exposure. Vedholm (1996) measured the field in 7 different cars (two of them with the battery underneath the back seat or in the trunk), engines running idle. In the left front seat the magnetic field, at various ELF frequencies ranged from 0.05 to 3.9 μT and in the left back seat from 0.02 to 3.8 μT. The highest values where parts of the body are likely to be were found at the left ankle at the left front seat, 0.24–13 μT. The higher values were found in cars with the battery located underneath the back seat or in the trunk.

Another source of ELF magnetic fields result from the steel belts in car tires that are permanently magnetized. Depending on the speed of the car, this may cause magnetic fields in the frequency range below 20 Hz. The field has a fundamental frequency determined by the speed (rotation rate of the tire) and a high harmonic content. At the tread fields can exceed 500 μT and on the seats the maximum is approximately 2 μT (Milham, Hatfield & Tell, 1999).

2.2.2.2.9 Occupational exposure in the electric power industry

Strong magnetic fields are encountered mainly in close proximity to high currents (Maddock, 1992). In the electric power industry, high currents are found in overhead lines and underground cables, and in busbars in power stations and substations. The busbars close to generators in power stations can carry currents up to 20 times higher than those typically carried by the 400-kV transmission system (Merchant, Renew & Swanson, 1994b).

Exposure to the strong fields produced by these currents can occur either as a direct result of the job, e.g. a lineman or cable splicer, or as a result of work location, e.g. when office workers are located on a power station or substation site. It should be noted that job categories may include workers with very different exposures, e.g. linemen working on live or dead circuits. Therefore, although reporting magnetic-field exposure by job category is useful, a complete understanding of exposure requires a knowledge of the activities or tasks and the location as well as measurements made by personal exposure meters.

The average magnetic fields to which workers are exposed for various jobs in the electric power industry have been reported as follows: 0.18–1.72 μT for workers in power stations, 0.8–1.4 μT for workers in substations, 0.03–4.57μT for workers on lines and cables and 0.2–18.48 μT for electricians (AGNIR, 2001b; NIEHS, 1998).

2.2.2.2.10 Other occupational sources

Exposure to magnetic fields varies greatly across occupations. The use of personal dosimeters has enabled exposure to be measured for particular types of job.

Measurements by the National Institute for Occupational Safety and Health (NIOSH) in various industries are summarized in Table 11 (NIOSH, 1996).

In some cases the variability is large. This indicates that there are instances in which workers in these categories are exposed to far stronger fields than the means listed here.

Floderus et al. (1993) investigated sets of measurements made at 1015 different workplaces. This study covered 169 different job categories, and participants wore the dosimeters for a mean duration of 6.8 h. The most common measurement was 0.05 μT and measurements above 1 μT were rare.

Table 11. Magnetic flux densities from equipment in various industries [a]

Industry	Source	ELF magnetic flux density (T)	Comments	Other frequencies
Manufacturing	Electrical resistance heater	600–1400	Tool exposures measured at operator's chest	VLF
	Induction heater	1–46		
	Hand-held grinder	300		
	Grinder	11		
	Lathe, drill press etc	0.1–0.4		
Electrogalvanizing	Rectification	200–460	Rectified DC current (with an ELF ripple) galvanized metal parts	Static fields
	Outdoor electric line and substation	10–170		
Aluminum refining	Aluminum pot rooms	0.34–3	Highly-rectified DC current (with an ELF ripple) refines aluminum	Static field
	Rectification room	30–330		Static field
Steel foundry	Ladle refinery, electrodes active	17–130	Highest ELF field was at the chair of control room operator	ULF from ladle's magnetic stirrer
	Electrodes inactive	0.06–0.37		
	Electrogalvanizing unit	0.2–110		VLF
Television broadcasting	Video cameras (studio and minocam)	0.72–2.4	Measured at 30 cm	VLF
	Video tape degaussers	16–330		
	Light control centres	0.1–30		
	Studios and newsrooms	0.2–0.5	Walk-through surveys	

Table 11. Continued.

Telecommunications	Relay switching racks	0.15–3.2	Measured 5-7 cm from relays	Static fields and ULF-ELF transients
	Switching rooms (relay and electronic switches)	0.01–130	Walk-through survey	Static fields and ULF-ELF transients
	Underground phone vault	0.3–0.5	Walk-through survey	Static fields and ULF-ELF transients
Hospitals	Intensive care unit	0.01–22	Measured at nurse's chest position	VLF
	Post anaesthesia care unit	0.01–2.4		VLF
	Magnetic resonance imaging	0.05–28	Measured at technician's work locations	Static, VLF and RF
Government offices	Desk work locations	0.01–0.7	Peaks due to laser printers	
	Desks near power centre	1.8-5		
	Power cables in floor	1.5–17		
	Computer centre	0.04–0.66		
	Desktop cooling fan	100	Appliances measured at 15 cm	
	Other office appliances	1–20		
	Building power supplies	2.5–180		

[a] Source: (NIOSH, 1996).

2.2.2.2.11 Arc and spot welding

In arc welding, metal parts are fused together by the energy of a plasma arc struck between two electrodes or between one electrode and the metal to be welded. A power-frequency current usually produces the arc but higher frequencies may be used in addition to strike or to maintain the arc. A feature of arc welding is that the insulated welding cable, which can carry currents of hundreds of amperes, can touch the body of the operator. Magnetic flux densities in excess of 1 mT have been measured at the surface of a welding cable and 100 μT close to the power supply (Allen et al., 1994).

Stuchly & Lecuyer (1989) surveyed the exposure of arc welders to magnetic fields and determined the exposure at 10 cm from the head, chest, waist, gonads, hands and legs. Whilst it is possible for the hand to be exposed to fields in excess of 1 mT, the trunk is typically exposed to several hundred microtesla. Once the arc has been struck, these welders work with comparatively low voltages and this is reflected in the electric field strengths measured; i.e. up to a few tens of volts per metre (AGNIR, 2001b).

Bowman et al. (1988) measured exposure for a tungsten-inert gas welder of up to 90 µT. Similar measurements reported by the National Radiological Protection Board indicate magnetic flux densities of up to 100 µT close to the power supply, 1 mT at the surface of the welding cable and at the surface of the power supply and 100–200 µT at the operator position (AGNIR, 2001b). London et al. (1994) reported the average workday exposure of 22 welders and flame cutters to be much lower (1.95 µT).

2.2.2.2.12 Induction furnaces

Electrically conducting materials such as metals and crystals can be heated as a consequence of eddy current losses induced by alternating magnetic fields. Typical applications include drying, bonding, zone refining, melting, surface hardening, annealing, tempering, brazing and welding. The main sources of electromagnetic fields in induction heaters are the power supply, the high frequency transformer and the induction heater coil, and the product being processed. The latter is positioned within a coil, which acts like a primary winding of a transformer. This coil generates magnetic fields that transfer power to the load, which behaves like a single turn short-circuited secondary winding.

The frequency determines the penetration of the field, a lower frequency being used for volume heating and a higher frequency for surface heating. For example frequencies of a few tens of hertz are used for heating copper billets prior to forging, whereas frequencies of a few megahertz are used for sealing bottle tops. The heating coils range in size depending on the application. Small single turn devices of a few centimetres diameter are used for localised heating of a product, and large multi-turn systems of 1 or 2 m diameter are used in furnaces capable of melting several tons of iron. Power requirements also depend on the application, and range from about 1 kW for small items to several megawatt for induction furnaces (Allen et al., 1994).

Studies of magnetic flux densities in the vicinity of induction furnaces and equipment heaters have shown that operators may have some of the highest maximum exposure levels found in industry (Table 12). Typical maximum flux densities for induction heaters operating at frequencies up to 10 kHz are presented in Table 13. Somewhat higher levels of 1–60 mT have been reported in Sweden (Lövsund, Öberg & Nilsson, 1982), at distances of 0.1–1 m.

Table 12. Maximum exposures to power frequency magnetic flux densities in the workplace [a]

Workplace	Occupation / source	Magnetic flux density (μT)
Industry	Induction workers	10^4
	Railway workers	10^3
	Power industry	10^3
	Arc welders	10^2
Office	Tape erasers	10^2
	VDUs	1
General	Underfloor heating	10
	Electric motors	10

[a] Source: Allen et al., 1994.

Table 13. Examples of magnetic fields produced by induction heaters operating up to 10 kHz [a]

Machine	Input power	Frequency	Position	Maximum magnetic flux density (μT)
Copper billet heater	Up to 6 MW	50 Hz	1 m from coil line	540
Steel billet heater	~ 800 kW	1.1 kHz	1 m from coil	125
Axle induction hardener	140 kW	1.65 kHz	Operator position	29
Copper tube annealer	600 kW	2.9 kHz	0.5 m from coil	375
Chain normalisers	20 kW	8.7–10 kHz	0.5 m from coils	25

[a] Source: Allen et al., 1994.

Electric field strengths in the vicinity of induction heaters that operate in the frequency range of interest are usually no more than several volts per metre.

2.2.2.2.13 Induction cooking equipment

Originally induction cooking equipment was restricted largely to commercial catering environments where three phase power supplies were available; however, single phase domestic varieties are now common (IEC, 2000). Induction cooking hobs normally operate at frequencies of a few tens of kilohertz. In domestic environments a frequency of over 20 kHz is necessary to avoid pan noise and below 50 kHz to have a maximum efficiency and comply with electromagnetic compatibility product standards. Powers normally range between 1–3 kW used for domestic appliances and 5–10 kW for commercial equipment. Under worst-case exposure conditions, corresponding to poor coupling between the coil and pan, maximum magnetic flux densities are usually less than a few microtesla at a few tens of centimetres from the front edge of the hobs. Electric field strengths are usually no more than a few tens of volt per metre because the appliances do not use high voltage electricity. Usually the fundamental frequency induction dominates the magnetic field; however, some models produce harmonic components comparable in magnitude to that of the fundamental (Allen et al., 1994).

2.2.2.2.14 Security and access control systems

A number of devices generate electromagnetic fields for security purposes and for controlling personal access. These include metal detectors, radiofrequency identification (RFID) equipment and electronic article surveillance (EAS) systems, also known as anti-theft systems. RFID and EAS equipment use a broad range of frequencies, ranging from sub-kilohertz frequencies to microwave frequencies.

Metal detectors

Metal detectors are used for security, e.g. at airports. The two main types are the free-standing walk-through systems and the hand-held detectors. Walk-through detectors usually consist of two columns, one which houses the transmitter unit and uses conducting coils to produce a pulsed magnetic field, and the other which contains a receiver which employs a set of coils to detect the electric currents induced in metallic objects by the pulsed field. The magnetic field waveforms from both detectors consist of a train of bipolar pulses and fast Fourier transforms (FFTs) of the pulses exhibit broad spectral content with an amplitude peak in the region of 1 kHz. Peak magnetic fields are usually a few tens of microtesla (Cooper, 2002).

Hand-held detectors normally contain a coil, which carries an alternating current, at frequencies of a few tens of kilohertz. If electrically conducting material is brought within the detection range of the device, eddy currents are produced in the material that disturb the configuration of the magnetic field. The corresponding change in the behaviour of the coil, which may be resonant, can then be detected by the instrument.

The magnetic fields from hand-held metal detectors tend to be weaker and more localised than those from walk-through devices. The maximum magnetic flux density encountered near the casing is typically a few microtesla (Cooper, 2002).

Electronic access and security systems (EAS)

EAS systems use electromagnetic fields to prevent unauthorised removal of items from shops, libraries and supermarkets and are even used in hospitals to stop abduction of babies. The detection panels are the most significant source of electromagnetic fields. The tags or labels serve only to cause a slight perturbation of the fields in the detection systems and are usually passive in the sense that they do not contain any power source, although they may contain a small number of electronic components such as diodes.

The third component of EAS systems is known as “deactivators”. These are used to “switch off” disposable tags or to remove re-usable tags. The deactivator fields are usually higher in absolute amplitude than the main detection fields, though they are confined to a small region.

There are two main types of EAS system that operate within the ELF-VLF range. Both use inductive fields, so the field is almost completely magnetic in nature, and the field propagation is negligible (ICNIRP, 2002; IEC, 2000).

The electromagnetic (EM) type operates at frequencies of 20 Hz–20 kHz and detects harmonics in the detection field that are set up during the non-linear magnetisation of the magnetically soft tag. The magnetic flux density at the point midway through panels normally placed 1–3 m apart is from a few tens of microtesla up to about 100 μT. Typical field strengths fall as the operating frequency rises and some systems use more than one frequency simultaneously.

The resonant acousto-magnetic (AM) type operates at typical frequencies around 60 kHz, and detects the ringing of the tag’s magnetic field caused by an element that resonates in the presence of a specific frequency pulsed magnetic field that occurs in the detection zone.

Some examples of maximum magnetic flux densities inside EAS gates are reported in Table 14.

Table 14. Examples of peak magnetic flux densities within magnetic type EAS gates

Type	Frequency (waveform [a])	Magnetic flux density (μT)	Distance from transmitter (cm)
Electromagnetic (EM)	73 Hz (SCW)	146	31.5
	219 Hz (SCW)	122	36
	230 Hz (SCW)	93	42
	535.7 Hz (SCW)	72	36
	6.25 kHz (SCW)	39	45
	5 kHz / 7.5 kHz (CW)	43	48.5
	1 kHz (PMS)	100	41
	6.25 kHz (CW)	58	25.7
Acoustomagnetic (AM)	58 kHz (PMS)	65	36
	58 kHz (PMS)	17.4	62.5
	58 kHz (CW)	52	37.2

[a] CW = Continuous Wave, SCW = Sinusoidal Continuous Wave, PMS = Pulsed Modulated Sinusoid.

Members of the public receive transient exposure to the main detection field because of the method of use of EAS systems; workers receive longer-term whole body exposure to lower amplitude fields outside the detection system and transient localised exposures from the deactivators.

2.2.2.2.15 Sewing machines

Hansen et al. (2000) reported higher-than-background magnetic fields near industrial sewing machines, because of proximity to motors, with field strengths ranging from 0.32–11.1 μT at a position corresponding approximately to the sternum of the operator. The average exposure for six workers working a full work-shift in the garment industry ranged from 0.21–3.20 μT. A more extensive study of the personal exposures of 34 workers using sewing machines reported exposures (Kelsh et al., 2003) at the waist, where the mean 60-Hz magnetic field was 0.9 μT with a range between 0.07–3.7 μT.

2.3 Assessment of exposure

2.3.1 General considerations

Electric and magnetic fields are complex and can be characterized by many different physical parameters. Some of these parameters are discussed more fully in section 2.1. In general, they include transients, harmonic content, peak values and time above thresholds, as well as average levels. It is not known which of these parameters or what combination of parameters, if any, are relevant for the induction of health effects. If there were a known biophysical mechanism of interaction for e.g. carcinogenesis, it would be possible to identify the critical parameters of exposure, including relevant timing of exposure. However, in the absence of a generally accepted mechanism, most exposure assessments in epidemiological studies are based on a time-weighted average of the field, a measure that is also related to some, but not all field characteristics (Zaffanella & Kalton, 1998).

The physical characteristics of electric and magnetic fields have been described in detail in section 2.1. Some of the characteristics of exposure to electric and magnetic fields which make exposure assessment for the purposes of epidemiological studies particularly difficult are listed below.

- *Prevalence of exposure*. Everyone in the population is exposed to some degree to ELF electric and magnetic fields and therefore exposure assessment can only separate the more from the less exposed individuals, as opposed to separating individuals who are exposed from those who are not.
- *Inability of subjects to identify exposure.* Exposure to electric and magnetic fields, whilst ubiquitous, is usually not detectable by the exposed person nor memorable, and hence epidemiological studies cannot rely solely on questionnaire data to characterize past exposures adequately.

- *Lack of clear contrast between "high" and "low" exposure*. The difference between the average field strengths to which "highly exposed" and "less highly exposed" individuals in a population are subjected is not great. The typical average magnetic fields in homes appear to be about 0.05–0.1 µT. Pooled analyses of childhood leukaemia and magnetic fields, such as that by Ahlbom etal. (2000), have used 0.4 µT as a high-exposure category. Therefore, an exposure assessment method has to separate reliably exposures which may differ by factors of only 2 or 4. Even in most of the occupational settings considered to entail "high exposures" the average fields measured are only one order of magnitude higher than those measured in residential settings (Kheifets et al., 1995).
- *Variability of exposure over time*: *short-term*. Fields (particularly magnetic fields) vary over time-scales of seconds or longer. Assessing a person's exposure over any period involves using a single summary figure for a highly variable quantity.
- *Variability of exposure over time: long-term*. Fields are also likely to vary over time-scales of seasons and years. With the exception of historical data on loads carried by high-voltage power lines, data on such variation are rare. Therefore, when a person's exposure at some period in the past is assessed from data collected later, an assumption has to be made. The usual assumption is that the exposure has not changed. Some authors (e.g. Jackson, 1992; Petridou et al., 1993; Swanson, 1996) have estimated the variations of exposure over time from available data, for example, on electricity consumption. These apply to population averages and are unlikely to be accurate for individuals.
- *Variability of exposure over space*. Magnetic fields vary over the volume of, for example, a building so that, as people move around, they may experience fields of varying intensity. Personal exposure monitoring captures this, but other assessment methods generally do not.

People are exposed to fields in different settings, such as at home, at school, at work, while travelling and outdoors. Current understanding of the contributions to exposure from different sources and in different settings is limited. Most studies make exposure assessments within a single environment, typically at home for residential studies and at work for occupational studies. Some recent studies have included measures of exposure from more than one setting (e.g. Feychting, Forssen & Floderus, 1997; Forssén et al., 2000; UKCCSI, 1999).

In epidemiological studies, the distribution of exposures in a population has consequences for the statistical power of the study. Most populations are characterized by an approximately log-normal distribution with a heavy preponderance of low-level exposure and much less high-level exposure. Pilot studies of exposure distribution are important for developing effective study designs.

Since most epidemiological studies have investigated magnetic rather than electric fields, the next six sections will deal with aspects of magnetic field exposure and section 2.3.7 with electric field exposure.

2.3.2 Assessing residential exposure to magnetic fields: methods not involving measurement

2.3.2.1 Distance

The simplest possible way of assessing exposure is to record proximity to a facility (such as a power line or a substation) which is likely to be a source of field. This does provide a very crude measure of exposure to both electric and magnetic fields from that source, but takes no account of other sources or of how the fields vary with distance from the source (which is different for different sources). Distances reported by study subjects rather than measured by the investigators tend to be unreliable. Recently over half of the time-averaged magnetic field exposures above 0.4 μT in the UKCCS were attributable to sources other than high-voltage power lines (Maslanyj et al., 2007).

2.3.2.2 Wire code

Wire coding is a non-intrusive method of classifying dwellings on the basis of their distance from visible electrical installations and the characteristics of these installations. This method does not take account of exposure from sources within the home. Wertheimer & Leeper (1979) devised a simple set of rules to classify residences with respect to their potential for having a higher-than-usual exposure to magnetic fields. Their assumptions were simple:

- the field strength decreases with distance from the source;
- current flowing in power lines decreases at every pole from which “service drop” wires deliver power to houses;
- if both thick and thin conductors are used for lines carrying power at a given voltage, and more than one conductor is present, it is reasonable to assume that more and thicker conductors are required to carry greater currents; and
- when lines are buried in a conduit or a trench, their contribution to exposure can be neglected. This is because buried cables are placed close together and the fields produced by currents flowing from and back to the source cancel each other much more effectively than when they are spaced apart on a cross beam on a pole (see section 2.2.2.2.2).

Wertheimer & Leeper (1979) used these four criteria to define two and later four (Wertheimer & Leeper, 1982), then five (Savitz et al., 1988) classes of home: VHCC (very high current configuration), OHCC (ordinary high current configuration), OLCC (ordinary low current configuration), VLCC (very low current configuration) and UG (underground, i.e. buried). The houses with the higher classifications were assumed to have stronger background fields than those with lower classifications. According to this classification scheme, residences more than 40 m from power lines were considered to be not exposed to magnetic fields.

Wire coding, in the original form developed by Wertheimer and Leeper, has been used in a number of studies. The ranges of measurements by wire code category for five substantial data sets – the control groups from the Savitz et al. (1988) and London et al. (1991) studies, the HVTRC survey (Zaffanella, 1993), the EMDEX Residential Project (Bracken et al., 1994) and the NCI study (Tarone et al., 1998) – indicate a positive relationship between the mean of the distributions and the wire code (i.e. higher averages are seen for higher wire code categories), but there is a large overlap among the various categories.

Kheifets, Kavet & Sussman (1997) evaluated relationships between wire codes and measured fields in the data sets available to them (EMDEX; HVTRC and London). The relationships were quite similar across data sets; thus only selected examples are presented below. Log-transformed spot measurement data for all 782 single and duplex residences and for all wire codes, except VLCC, from the HVTRC survey, were distributed log-normally. The data indicate a 10th-to-90th percentile interval of about an order of magnitude for all the wire codes, considerable overlap in the field range across wire codes (as mentioned above), equivalent fields for UG and VLCC (which are sometimes grouped as referent categories), and a trend of increasing field with wire code. For this data, wire code explains 14.5% of the total variance in the log of the spot-measured fields (Kheifets, Kavet & Sussman, 1997).

There are many reasons for a discordance between wire codes and measurement classifications (for simplicity, a dichotomous classification scheme is used). For example, while number and thickness of wires reflect the total current carrying capacity of a system of wires, this does not take into account differences in geometry, phasing schemes in multi-circuit systems that enhance field cancellation, and actual loading patterns. Thus high wire code homes may actually have relatively low fields. Similarly, low wire code homes may exhibit high readings due to high field levels from non-power line sources, or from very heavily loaded external sources. Data available to date shows that the “high wire code–low measurement” situation is far more prevalent than the “low wire code–high measurement” circumstance.

While wire codes explain little of the variance of measured residential magnetic fields, they are useful in identifying homes with potentially high magnetic fields. In particular, the majority of homes with high interior measurements fell into the VHCC category. And although most of the misclassification occurs from homes in high wire code categories having low measurements, the VHCC category still performs reasonably well in excluding homes with low measurements (Kheifets, Kavet & Sussman, 1997).

The concept of wire coding has been shown to be a usable crude surrogate even when tailored to local wiring practices. For example, the correlation between wiring code and measured magnetic fields in homes in the Savitz et al. (1988) study accounted for only 16% of the variance in the measured field values. Rankin et al. (2002) report that wire code predicts < 21% of the variance in magnetic field measurements. The wire code is overall an imperfect surrogate for magnetic field exposure in a variety of environments. In general, wire codes have been used only in North American studies, as their applicability is limited in other countries, where power drops to homes are mostly underground.

2.3.2.3 Calculated historical fields

Feychting & Ahlbom (1993) carried out a case–control study nested in a cohort of residents living in homes within 300 m of power lines in Sweden. The geometry of the conductors on the power line, the distance of the houses from the power lines and historical records of currents, were all available. This special situation allowed the investigators to calculate the fields to which the subjects' homes were exposed at various times (e.g. prior to diagnosis) (Kheifets et al., 1997).

The common elements between wire coding and the calculation model used by Feychting & Ahlbom (1993) are the reliance on the basic physical principles that the field increases with the current and decreases with the distance from the power line, and the fact that both neglect magnetic-field sources other than visible power lines. There is, however, one important difference: in the Wertheimer and Leeper code, the line type and thickness are a measure of the potential current carrying capacity of the line. In the Feychting & Ahlbom (1993) study, the approximate yearly average current was obtained from utility records; thus the question of temporal stability of the estimated fields did not even arise: assessment carried out for different times, using different load figures, yielded different estimates.

The approach of Feychting & Ahlbom (1993) has been used in various Nordic countries and elsewhere, although the likely accuracy of the calculations has varied depending in part on the completeness and precision of the available information on historical load. The necessary assumption that other sources of field are negligible is reasonable only for subjects relatively close to high-voltage power lines. The validity of the assumption also depends on details such as the definition of the population chosen for the study and the size of average fields from other sources to which the relevant population is exposed.

There is some evidence from Feychting & Ahlbom (1993) that their approach may work better for single-family homes than for apartments. When Feychting & Ahlbom (1993) validated their method by comparing calculations of present-day fields with present-day measurements, they found that virtually all homes with a measured field < 0.2 μT, whether single-family or apartments, were correctly classified by their calculations. However, for homes with a measured field > 0.2 µT, the calculations were able to classify correctly 85% of single-family homes, but only half of the apartments.

The difference between historical calculations and contemporary measurements was also evaluated by Feychting & Ahlbom (1993) who found that calculations using contemporary current loads resulted in a 45% increase in the fraction of single-family homes estimated to have a field > 0.2 µT, compared with calculations based on historical data. If these calculations of historical fields do accurately reflect exposure, this implies that present-day spot measurements overestimate the number of exposed homes in the past.

When fields are calculated from transmission lines and then used as an estimate of the exposure of a person, the assumption is made that fields from other sources are negligible. Close to the transmission line where the field from the line is high, it would be rare for other (principally distribution) sources to produce as high a field, and this is a valid assumption. As the distance from the power line is increased (or equivalently as the threshold between exposed and non-exposed is lowered), the assumption becomes less valid, and misclassification will result. An example of this can be seen in the Feychting & Ahlbom (1993) study where it has been observed that there is substantial calculation error by comparing their contemporary calculations and measurements (Jaffa, Kim & Aldrich, 2000). This error was more pronounced in the lower exposure categories (Feychting & Ahlbom, 2000). These calculation errors in the lower exposure categories are likely the result of not including the field contribution from local sources, which make a greater contribution to exposures at larger distances from transmission lines. This error can negate the value of estimating historical exposures such that contemporary measurements can be a more reliable metric for effect estimates (Jaffa, 2001; Maslanyj et al., 2007; Mezei & Kheifets, 2001).

2.3.3 Assessing residential exposure to magnetic fields using measurements

Following the publication of the Wertheimer & Leeper (1979; 1982) studies, doubt was cast on the reported association between cancer and electrical wiring configurations on the grounds that exposure had not been measured. Consequently, many of the later studies included measurements of various types.

All measurements have the advantage that they capture exposure from whatever sources are present, and do not depend on prior identification of sources, as wire codes and calculated fields do. Furthermore, because measurements can classify fields on a continuous scale rather than in a limited number of categories, they provide greater scope for investigating different thresholds and exposure–response relationships.

2.3.3.1 Spot measurements in the home

The simplest form of measurement is a reading made at a point in time at one place in a home. To capture spatial variations of field, some studies have made multiple spot measurements at different places in or around the home. In an attempt to differentiate between fields arising from sources inside and outside the home, some studies have made spot measurements under "low-power" (all appliances turned off) and "high-power" (all appliances turned on) conditions. Neither of these alternatives truly represents the usual exposure conditions in a home, although the low-power conditions are closer to the typical conditions.

The major drawback of spot measurements is their inability to capture temporal variations. As with all measurements, spot measurements can assess only contemporary exposure, and can yield no information about historical exposure, which is an intrinsic requirement for retrospective studies of cancer risk. An additional problem of spot measurements is that they give only an approximation even for the contemporary field, because of short-term temporal variation of fields, and unless repeated throughout the year do not reflect seasonal variations.

A number of authors have compared the time-stability of spot measurements over periods of up to five years (reviewed in Kheifets et al., 1997; UKCCSI, 2000). The correlation coefficients reported were from 0.7–0.9, but even correlation coefficients this high may result in significant misclassification (Neutra & Del Pizzo, 1996).

2.3.3.2 Longer-term measurements in homes

Because spot measurements capture short-term temporal variability poorly, many studies have measured fields at one or more locations for longer periods, usually 24–48h, most commonly in a child's bedroom, which is an improvement on spot measurements. Comparisons of measurements have found only a poor-to-fair agreement between long-term and short-term measurements. This was mainly because short-term increases in fields caused by appliances or indoor wiring do not affect the average field measured over many hours (Schüz et al., 2000).

Measurements over 24–48 h cannot account for longer-term temporal variations. One study (UKCCSI, 1999) attempted to adjust for longer-term variation by making 48-h measurements, and then, for subjects close to high-voltage power lines, modifying the measurements by calculating the fields using historical load data. In a study in Germany, Schüz et al. (2001) identified the source of elevated fields by multiple measurements, and attempted to classify these sources as to the likelihood of their being stable over time. Before beginning the largest study in the USA (Linet et al., 1997), a pilot study was conducted (Friedman et al., 1996) to establish the proportion of their time children of various ages spent in different parts of the home. These estimates were used to weight the individual room measurements in the main study (Linet et al., 1997) for the time-weighted average measure. In addition, the pilot study documented that magnetic fields in dwellings rather than schools accounted for most of the variability in children's exposure to magnetic fields.

Table 15. Exposure distribution of the arithmetic mean based on exposure of controls in a case-control study or all respondents in an exposure survey

Country	Authors	Study type	Measurement	Magnetic field category (μT)				N
				≤ 0.1	> 0.1– ≤ 0.2	> 0.2– ≤ 0.3	> 0.3	
Belgium	Decat, Van den Heuvel & Mulpas, 2005	Exposure survey	24-hr personal	81.9%	11.5%	1.6%	5.1%	251
Canada	McBride et al., 1999[a]	Case-control	48-hr personal	59.0%	29.2%	8.5%	3.3%	329
Germany	Michaelis et al., 1998	Case-control	24-hr bedroom	89.9%	7.0%	1.7%	1.4%	414
	Brix et al., 2001	Exposure survey	24-hr personal	73.6%	17.8%	4.1%	4.5%	1952
	Schüz et al., 2001[b]	Case-control	24-hr bedroom	93.0%	5.6%	0.9%	0.5%	1301
Japan	Kabuto et al.,2006[b]	Case-control	7-day home	89.9%	6.0%	2.5%	1.6%	603
Korea	Yang, Ju & Myung, 2004	Exposure survey	24-hr personal	64.0%	24.2%	4.0%	7.8%	409
UK	UKCCSI, 1999[b]	Case-control	48-hr home	92.3%	5.8%	1.2%	0.8%	2226
USA	London et al., 1991[a]	Case-control	24-hr bedroom	69.2%	19.6%	4.2%	7.0%	143
	Linet et al., 1997	Case-control	24-hr bedroom	65.7%	23.2%	6.6%	4.5%	620
	Zaffanella & Kalton, 1998	Exposure survey	24-hr personal	64.2%	21.1%	7.8%	4.2%	995
	Zaffanella, 1993	Exposure survey	24-hr home	72.3%	17.5%	5.6%	4.6%	987

[a] Based on the distribution for pooled analysis reported by Greenland et al., 2000.

[b] Given exposure categories: < 0.1, 0.1–< 0.2, 0.2–< 0.4, > 0.4 μT; approximated categories in the table by applying the ratios of exposures in the high categories of the EMF Rapid Survey (Zaffanella & Kalton, 1998).

Five extensive exposure surveys have been conducted to evaluate ELF exposures of the general population (Brix et al., 2001; Decat, Van den Heuvel & Mulpas, 2005; Yang, Ju & Myung, 2004; Zaffanella, 1993; Zaffanella & Kalton, 1998). As indicated in Tables 15 and 16, these surveys generally estimate that approximately 4–5% had mean exposures above 0.3 µT, with the exception of Korea where 7.8% had mean exposures above 0.3 µT (Kheifets, Afifi & Shimkhada, 2006). Only 1–2% have median exposures in excess of 0.4 µT.

Estimating exposures using the control-exposures from case-control studies allows a look at a broader spectrum of countries and results in a range of 0.5–7.0 % having mean exposures greater than 0.3? µT and 0.4–3.3% having median exposures above 0.4 µT. Two countries, the USA and Germany, had both exposure surveys and case-control studies. In the USA, the mean exposures were virtually equal from the two methods but for the case-control median eight estimates were less than the survey median estimates. In Germany, the case-control mean exposure estimates were substantially smaller than the survey estimates (median estimates were not available for the case-control study), which could be due to regional differences and the inclusion of occupational exposures in the survey estimates. In some studies, the exposure distribution for 0.2–0.3 µT and 0.3–0.4 µT had to be estimated since only data for the 0.2–0.4 µT intervals were given; the ratio from the EMF Rapid Survey from the USA was used to calculate these estimates.

Table 16. Exposure distribution of the geometric mean based on exposure of controls in a case-control study or all respondents in an exposure survey

Country	Authors	Study type	Measurement	Magnetic field category (µT)				N
				≤ 0.1	> 0.1–≤ 0.2	> 0.2–≤ 0.4	> 0.4	
Belgium	Decat, Van den Heuvel & Mulpas, 2005	Exposure survey	24-hr personal	91.9%	4.1%	2.8%	1.2%	251
Canada	McBride et al., 1999[a]	Case-control	48-hr personal	70.7%	17.4%	8.6%	3.3%	304
Germany	Michaelis et al., 1998[a]	Case-control	24-hr bedroom	92.9%	5.1%	1.5%	0.5%	409
UK	UKCCSI, 1999[a]	Case-control	48-hr home	94.4%	4.1%	1.2%	0.4%	2224
USA	Zaffanella & Kalton, 1998	Exposure survey	24-hr personal	72.6%	17.6%	7.5%	2.3%	995
	Linet et al., 1997[a]	Case-control	24-hr bedroom	72.8%	17.9%	8.3%	0.9%	530

[a] Based on the distribution for pooled analysis reported by Ahlbom et al., 2000.

2.3.3.3 Personal exposure monitoring

Monitoring the personal exposure of a subject by a meter worn on the body is attractive because it captures exposure to fields from all sources and at all places the individual encounters. Because all sources are included, the average fields measured tend to be higher than those derived from spot or long-term measurements in homes. However, the use of personal exposure monitoring in case–control studies could be problematic, due to age- or disease-related changes in behaviour. The latter could introduce differential misclassification in exposure estimates. However, personal exposure monitoring can be used to validate other types of measurements or estimates.

Table 17 summarizes results from studies which have measured the personal exposure of representative samples of people in different countries. Geometric mean and geometric standard deviation are given on the assumption of log-normal distributions.

Table 17. Summary of measurements of residential personal exposure [a]

Authors	Area	Sample type	Measurement type	Time of year	Sample size	Type of statistics [b]	Geometric mean (nT)	Geometric standard deviation
Donnelly & Agnew, 1991	Toronto, Canada	Utility employees, contacts, and general public, chosen for variety of exposure environments	Roughly 48 h, single axis	June–October	31	Children at home (D)	117	2.98
						Adults at home (D)	133	2.80
Skotte, 1994	Denmark	From industry. Homes near power lines excluded for this analysis.	Personal exposure, 24 h		298 (includes some duplication)	“Non-work” (P)	50	2.08
Brix et al., 2001	Bavaria, Germany	Volunteers recruited for exposure assessment	Personal exposure, 24 h		1952	(U)	6.4	2.41
Vistnes et al., 1997a	Suburb of Oslo, Norway	Children from two schools. This analysis only of homes > 275 m from power line	Personal exposure, 24 h		6	At home (P,A)	15	2.40

Table 17. Continued

Merchant, Renew & Swanson, 1994a	England and Wales, UK	Volunteers from electricity industry. HV lines excluded for this analysis	3–7 days	Spread over year	204	At home (P,F)	54	2.05
Preece et al., 1996	Avon, UK	Random selection from mothers with surviving children	24 h	Dec–May	44	(A)	42	2.65
Kavet, Silva & Thornton, 1992	Maine, USA	Random-digit dialing; adults	24 h	June/ August	15	At home (D)	134	1.80
Zaffanella & Kalton, 1998	USA	Random-digit dialling	24 h personal measurement (bedroom & home)		994	(D)	92	1.36
Bracken et al., 1994	USA	Employees of EPRI member utilities, weighted to random samples of wire codes	24 h		396	At home, not in bed (F)	111	1.88
Kaune et al., 1994	Washing-ton DC, USA	Children of volunteers from NCI and private daycare facility, overhead wiring	24 h	Spring	29	Residential (P)	96	2.38
Kaune & Zaffanella, 1994	California and Mass., USA	Children from volunteers from industry, chosen for variety of distribution arrangements	24 h		31	(P)	96	2.45

[a] Source: Swanson & Kaune, 1999.

[b] P = geometric statistics are given in Swanson & Kaune, 1999; A = calculated from arithmetic statistics given in Swanson & Kaune, 1999 using the equations given in Section 2.2.2.2.3 Distribution lines, subsection Data on fields in different countries; D =calculated from data given in Swanson & Kaune, 1999; F = fitted to statistics given in Swanson & Kaune, 1999 using least-squares procedure; U = calculated from unpublished data.

Table 18. Comparisons of personal exposure and background fields

Country	Authors	Subjects	Sample size	Personal exposures: geometric mean (nT)	Long-term background field: geometric mean (nT)	Ratio personal exposure / background
USA	Kavet, Silva & Thornton, 1992	Adults, at home	15	134	58	2.3
	Bracken et al., 1994	Adults, at home, not in bed	396	111	74	1.5
	Kaune et al., 1994	Children, residential	29	96	99	1.0
	Kaune & Zaffanella, 1994	Children	31	96	67	1.4
Canada	Donnelly & Agnew, 1991	Children, at home	31	117	107	1.1
		Adults, at home	31	133		1.2
UK	Merchant, Renew & Swanson, 1994a	Adults, at home	204	54	37	1.5
	Preece et al., 1996	Adults	44	42	29	1.5

In general, personal-exposure measurements are higher than fields measured away from appliances, largely because of the extra contributions of appliances and any other sources within the home. Seven studies that include both personal exposure measurements and long-term measurements of fields away from appliances in the homes of the subjects are compared in Table 18. The ratio of average personal exposure to average field away from appliances varies from 1.0 to 2.3, with an average of 1.44. This shows the relative magnitude of short-term exposure to appliances emitting relatively high magnetic fields compared with background exposure. There may be a tendency for the ratio to be smaller for children than for adults, but it would be unwise to draw firm conclusions from these limited data.

2.3.4 Assessing exposure to magnetic fields from appliances

Only little is known about the magnitude and distribution of EMF exposures from appliances. The contribution to overall exposure by appliances depends, among other things, on the type of appliance, its age, its distance from the person using it, and the pattern and duration of use. The assessment of appliance use in epidemiological studies has generally relied on questionnaires, sometimes answered by proxies such as other household members (Mills et al., 2000). These questionnaires ascertain some (but not usually all) of these facts, and are subject to recall bias. It is not known how well data from even the best questionnaire approximate to the actual exposure. Mezei et al. (2001) reported that questionnaire-based information on appliance use, even when focused on use within the last year, has limited value in estimating personal exposure to magnetic fields. Limited attempts have been made (e.g. UKCCSI, 1999) to include some measurements as well as questionnaire data.

According to Mader & Peralta (1992), appliances are not a significant source of whole-body exposure, but they may be the dominant source of exposure of extremities. Delpizzo (1990) suggested that common domestic electrical appliances were responsible for an exposure comparable to that from power lines. Recently, Mezei et al. (2001) showed that computers contributed appreciablyto overall exposure while other appliances each contributed less than 2%. Most of the time, a low contribution was the result of infrequent and short duration of appliance use. When limited to only those subjects who actually used certain appliances, the analysis showed that computers (16%) and cellular phones (21%) could contribute appreciablyto total daily exposure.

Because exposure to magnetic fields from appliances tends to be short-term and intermittent, the appropriate method for combining assessments of exposure from different appliances and chronic exposure from other sources would be particularly dependent on assumptions made about exposure metrics. Such methods have yet to be developed.

2.3.5 Assessing exposure at schools

Exposure to ELF electric and magnetic fields while at school seldom represents a major fraction of a child’s total exposure.

A study involving 79 schools in Canada took a total of 43009 measurements of 60-Hz magnetic fields (141–1543 per school) (Sun et al., 1995). Only 7.8% of all the fields measured were above 0.2 μT. For individual schools, the average magnetic field was 0.08 μT (SD: 0.06 μT). In the analysis by use of room, only typing rooms had magnetic fields that were above 0.2 μT. Hallways and corridors were above 0.1 μT and all other room types were below 0.1 μT. The percentage of classrooms above 0.2 μT was not reported. Magnetic fields above 0.2 μT were mostly associated with wires in the floor or ceiling, proximity to a room containing electrical appliances or movable sources of magnetic fields such as electric typewriters, computers and overhead projectors. Eight of the 79 schools were situated near high-voltage power lines. The survey showed no clear difference in overall magnetic field strength between the schools and domestic environments.

Kaune et al. (1994) measured power-frequency magnetic fields in homes and in the schools and daycare centres of 29 children. Ten public shools, six private schools and one daycare centre were included in the study. In general, the magnetic field strengths measured in schools and daycare centres were smaller and less variable than those measured in residential settings.

The UKCCSI (1999) carried out an epidemiological study of children in which measurements were made in schools as well as homes. Only three of 4452 children aged 0–14 years who spent 15 or more hours per week at school during the winter, had an average exposure during the year above 0.2 µT as a result of exposure at school.

2.3.6 Assessing non-occupational exposure to magnetic fields: discussion

One crucial question in case-control studies in general, and of magnetic fields and childhood cancer in particular, is how to span time. By definition, all exposures of interest in these studies are historical. Thus, measurements, wire codes, and historic models are only surrogates for the critical exposure, which occurred at some unknown time in the past. The question is then, what is a better surrogate for historic exposure: wire codes, area measurements or personal exposure? Each method has distinct advantages. Wire codes are relatively simple categorical scales that are thought to be stable over time. This method allows magnetic fields to be estimated without resident participation, thus reducing potential bias due to non-participation and maximizing study size. Measured fields, on the other hand, are more appealing because they can account for all sources within the residence and entail fewer implicit assumptions. However, one would expect measurements taken soon after diagnosis to be better surrogates than measurements taken long after diagnosis. Although it is generally considered that such long term measurements are the best available estimate of average magnetic field exposure, wire codes may be better indicators of high historical exposure because they may be less biased, and may produce less misclassification and measurement error. This might be especially true when one has to estimate exposure that has occurred several years to decades in the past. Epidemiological studies with personal measurements are yet to be completed. However, in case-control settings personal measurements could be problematic due to age or disease-related changes in behavior and thus, exposure.

Epidemiological studies that estimated the historical exposures of subjects to magnetic fields from power lines by calculations did not usually report using documented computer programs or publish the details of the computation algorithms, e.g. Olsen, Nielsen & Schulgen (1993), Verkasalo et al. (1993; 1996), Feychting & Ahlbom (1994), Tynes & Haldorsen (1997), though others, e.g. UKCCSI (2000), did. However, for exposure assessment in these studies, it is important to consider how accurate the calculations are in a specific study when interpreting results. For example in the seminal Feychting & Ahlbom study (1993), the calculation error (contemporary calculations vs. contemporary measurements) is greater than any advantage that might have been gained by estimating exposure at the time of diagnosis with historical calculations. As a result, contemporary spot measurements appear to provide better estimates of historical exposures in this study (Jaffa, Kim & Aldrich, 2000).

2.3.7 Assessing occupational exposure to magnetic fields

Following Wertheimer and Leeper's report of an association between residential magnetic fields and childhood leukaemia, Milham (1982; 1985a; 1985b) noted an association between cancer and some occupations (often subsequently called the "electrical occupations") intuitively expected to involve proximity to sources of electric and magnetic fields. However, classification based on job title is a very coarse surrogate. Critics (Guenel et al., 1993; Loomis & Savitz, 1990; Theriault et al., 1994) have pointed out that, for example, many electrical engineers are basically office workers and that many electricians work on disconnected wiring.

Much less is known about exposures in non-electrical occupations. Little data, if any, is available for many jobs and industrial environments. Of note in the few surveys conducted are high exposures among railway engine drivers (about 4 μT) and seamstresses (about 3 μT). The best information on work exposures is available in a survey conducted by Zaffannela (Zaffanella & Kalton, 1998). The survey included 525 workers employed in a variety of occupations (Table 19).

Table 19. Parameters of the distributions of average magnetic field during work for different types of occupations [a]

Description	Sample size	Mean (μT)	Standard deviation (μT)	Geometric mean (μT)	Geometric standard deviation
Managerial and professional speciality occupations	204	0.164	0.282	0.099	2.47
Technical, sales, and administrative supports occupation	166	0.158	0.167	0.109	2.03
(Protective, food, health, cleaning, and personal) service occupations	71	0.274	0.442	0.159	2.55
Farming, forestry, and fishing occupations	19	0.091	0.141	0.045	2.97
Precision production, craft, and repair occupations, and operators, fabricators, and laborers	128	0.173	0.415	0.089	2.80
Electrical occupations [b]	16	0.215	0.162	0.161	2.25

[a] Source: Zaffanella & Kalton, 1998.

[b] As classified by Milham (1982; 1985a; 1985b): electronic technicians, radio and telegraph operators, electricians, linemen (power and telephone), television and radio repairmen, power station operators, aluminium workers, welders and flame cutters, motion picture projectionists, electrical enigineers and subway motormen.

The largest geometric mean (0.161 µT) for magnetic field exposure during work occurred in electrical occupations. Service occupations followed at 0.159 µT. Technical, sales, and administrative support positions had a geometric mean of 0.109 µT; managerial and professional specialty occupations, 0.099 µT; and precision production, craft and repair work, operation, fabrication, and labor, 0.089 µT. At 0.045 µT, farming, forestry, and fishing occupations had the lowest geometric mean. Work exposures were often significantly higher and more variable than other exposures: people spent significantly more time, for example, in fields exceeding 1.6 µT at work than at home. Nevertheless, average work exposures for the general population are low, with only 4% exposed to magnetic fields above 0.5 µT.

Intuitive classification of occupations by investigators can be improved upon by taking account of judgements made by appropriate experts (e.g. Loomis et al., 1994), and by making measurements in occupational groups (e.g. Bowman et al., 1988).

A study by Forssén et al. (2004) provides a first attempt to comprehensively evaluate occupational magnetic field exposure assessment among women. The results for the work-site environments are presented in Table 20. “Large scale kitchens” and “Shops and stores” are both environments with high exposure.

Table 20. Exposures to extremely low frequency magnetic fields by occupational environment [a]

Environment	Sample size	Arithmetic/geometric means (arithmetic standard deviations) (µT)		Proportion of time spent at exposure level (n)			
		Time-weighted average	Maximum	< 0.1 µT	0.1–0.2 µT	0.2–0.3 µT	≥ 0.3 µT
Health care	67	0.11 / 0.10 (0.07)	2.62 / 2.10 (1.90)	66% (29)	20% (18)	8% (10)	7% (10)
Hospitals	27	0.09 / 0.08 (0.05)	3.01 / 2.37 (2.26)	77% (21)	13% (14)	6% (8)	4% (6)
Elsewhere	40	0.13 / 0.11 (0.08)	2.35 / 1.94 (1.58)	59% (31)	24% (20)	9% (11)	9% (12)
Schools and childcare	55	0.15 / 0.12 (0.10)	5.41 / 2.12 (16.49)	62% (27)	20% (16)	8% (8)	10% (12)
Large scale kitchens	34	0.38 / 0.28 (0.43)	5.97 / 4.67 (4.55)	30% (27)	20% (11)	15% (12)	36% (27)
Offices	127	0.16 / 0.12 (0.13)	2.41 / 1.73 (2.32)	55% (38)	25% (26)	9% (14)	12% (22)
Shops and stores	33	0.31 / 0.26 (0.17)	5.84 / 2.55 (18.21)	26% (29)	17% (13)	17% (13)	40% (30)

[a] Source: Forssén et al., 2004.

A further improvement is a systematic measurement programme to characterize exposure in a range of jobs corresponding as closely as possible to those of the subjects in a study, thus creating a “job-exposure matrix”, which links measurement data to job titles.

Forssén et al. (2004) constructed a job-exposure matrix for women. Analysis of the exposure distribution in the female working population showed that about 16% of the women are highly exposed (0.20 µT). However, only 5% would be classified as such if the job-exposure matrix for men (Floderus, Persson & Stenlund, 1996) was used (Table 21). Furthermore, only 20% of the women with high exposure would be correctly classified as highly exposed by the job-exposure matrix for men. Using the job-exposure matrix for men in an epidemiological study that involves women would hence cause not only loss of power but could also dilute any effects through misclassification of the exposure.

Table 21. Distribution of exposure in the population of women gainfully employed in Stockholm County 1980 by using job-exposure matrices (JEM)

	Pecentage of women exposed	
Geometric mean of time-weighted average (µT)	**JEM for women** [a]	**JEM for men** [b]
≤ 0.10	21.4	7.2
0.11–0.20	48.3	47.4
0.21–0.30	13.7	4.4
> 0.30	3.0	1.0
Missing	13.6	40.0

[a] Source: Forssén et al., 2004.

[b] Source: Floderus, Persson & Stenlund, 1996.

Despite the improvements in exposure assessment, the ability to explain exposure variability in complex occupational environments remains poor. Job titles alone explain only a small proportion of exposure variability. A consideration of the work environment and of the tasks undertaken by workers in a specific occupation leads to a more precise estimate (Kelsh, Kheifets & Smith, 2000). Harrington et al. (2001) have taken this approach one stage further by combining job information with historical information not only on the environment in general but on specific power stations and substations. The within-worker and between-worker variability which account for most of the variation are not captured using these assessments.

In addition to the need for correct classification of jobs, the quality of occupational exposure assessment depends on the details of work history available to the investigators. The crudest assessments are based on a single job (e.g. as mentioned on a death certificate). This assessment can be improved by identifying the job held for the longest period, or even better, by obtaining a complete job history which would allow for the calculation of the subject’s cumulative exposure over his professional career, often expressed in µT–years.

2.3.8 Assessing exposure to electric fields

Assessment of exposure to electric fields is generally more difficult and less well developed than the assessment of exposure to magnetic fields. All of the difficulties encountered in assessment of exposure to magnetic fields discussed above also apply to electric fields. In addition, electric fields are easily perturbed by any conducting object, including the human body.Although most studies that have assessed electric fields have attempted to assess the unperturbed field, the very presence of subjects in an environment means that they are not being exposed to an “unperturbed field”.

Because electric fields are perturbed by the body, the concept of personal exposure is difficult to define, and readings taken with a meter attached to the body are likely to be dominated by local perturbations affected by the precise location of the meter on the body.

A number of electric and magnetic field exposure studies have included measurements of electric fields within homes. Some of these consisted of wearing personal exposure meters for periods of 24 or 48 hours, while others consisted of spot measurements within specific rooms. The majority of studies were epidemiological studies, although one compared homes near to a power line to homes at a considerable distance from any power lines.

In each of the studies data are presented for controls as well as for the cases. A comparison has been made between the measurements for the controls in different studies. Green et al. (1999a) performed continuous monitoring and reported that the average electric field exposure at home for controls was below 16 V m^{-1} for 90% of the group. London et al. (1991) and Savitz et al. (1988) performed spot measurements in the centre of the controls’ sitting rooms. London et al. reported a mean of 7.98 V m^{-1} and Savitz et al. reported a median below 9 V m^{-1}. A number of other studies involved monitoring of electric fields over a 24 or 48 hour period. McBride et al. (1999) carried out 48-h personal exposure monitoring, reporting a median exposure for controls of 12.2 V m^{-1}. However no distinction was made between exposure at home and away from home. Studies by Dockerty et al. (1998) and Kaune et al. (1987) performed 24-h monitoring within specific rooms of the home. Both monitored electric field within the sitting room, while the Dockerty et al. study also monitored electric field levels within the bedroom. The study by Dockerty et al. reported arithmetic means less than 10.75 V m^{-1} in at least 60% of the homes, regardless of the room, while Kaune et al. reported a mean value of 33 V m^{-1} across the homes investigated. Kaune et al. reported higher levels that other studies reported to date. Levallois et al. (1995) carried out 24-h monitoring of the electric fields in homes both near to a 735 kV line, and distant to any overhead lines. For those homes distant to power lines, a geometric mean electric field of 14 V

m^{-1} was reported. Finally, Skinner et al. (2002) made measurements in several locations in the home with geometric means around 10 V m^{-1}.

2.3.9 *Exposure assessment: conclusions*

Electric and magnetic fields exist wherever electricity is generated, transmitted or distributed in power lines or cables, or used in electrical appliances. Since the use of electricity is an integral part of our modern lifestyle, these fields are ubiquitous in our environment.

Residential exposure to power frequency magnetic fields does not vary dramatically across the world. The geometric mean magnetic field in homes ranges between 0.025 and 0.07 µT in Europe and 0.055 and 0.11 µT in the USA. The mean values of electric field in the home are in the range of several tens of volts per metre. In the vicinity of certain appliances, the instantaneous magnetic-field values can be as much as a few hundred microtesla. Near power lines, magnetic fields reach approximately 20 µT and electric fields up to several thousand volts per metre.

Few children have time-averaged exposures to residential 50 or 60 Hz magnetic fields in excess of the levels associated with an increased incidence of childhood leukaemia. Approximately 1% to 4 % have mean exposures above 0.3 µT and only 1% to 2% have median exposures in excess of 0.4 µT.

Occupational exposure, although predominantly to power-frequency fields, may also include contributions from other frequencies. The average magnetic field exposures in the workplace have been found to be higher in “electrical occupations” than in other occupations such as office work, ranging from 0.4–0.6 µT for electricians and electrical engineers to approximately 1.0 µT for power line workers, with the highest exposures for welders, railway engine drivers and sewing machine operators (above 3 µT). The maximum magnetic field exposures in the workplace can reach up to approximately 10 mT and this is invariably associated with the presence of conductors carrying high currents. In the electrical supply industry, workers may be exposed to electric fields up to 30 kV m^{-1}.