NATURAL BACKGROUND AND HUMAN-MADE SOURCES AND EXPOSURE

3.1 Natural Electric and Magnetic Fields

3.1.1 Natural electric 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 typically has a fair weather strength of about 130 V m^{-1} (Dolezalek, 1979). The field strength decreases with height, with values of about 100 V m^{-1} at 100 m elevation, 45 V m^{-1} at 1 km, and less than 1 V m^{-1} at 20 km. Actual values vary widely, depending upon the local temperature, the humidity profile and the presence of ionized contaminants. Large field variations occur at ground level beneath thunderclouds, and even as thunderclouds are approaching, because the lower part of a cloud is normally negatively charged while the upper part contains a positive charge. In addition, space charge is present between the cloud and ground. As the cloud approaches, the field at ground level may first increase and then reverse, with the ground becoming positively charged. Fields of 100 V m^{-1} to 3 kV m^{-1} may be observed during this process, even in the absence of local lightning. Field reversals may take place very rapidly, within 1 min, and high field strengths may persist for the duration of the storm. Ordinary clouds, as well as thunderclouds, contain electric charge and therefore have a strong effect on the electric field at ground level. Large deviations from the fair-weather field of up to 200% are also to be expected in the presence of fog, rain, and naturally occurring small and large ions. Electric field diurnal changes can even be expected in completely fair weather. Fairly regular changes in local ionization, temperature or humidity and the resulting changes in the atmospheric electrical conductivity near the ground, as well as mechanical charge transfer by local air movements, are probably responsible for these diurnal variations.

3.1.2 Natural magnetic fields

The natural magnetic field is the sum of an internal field due to the Earth acting as a permanent magnet and an external field generated in the environment from such factors as solar activity and atmospheric processes.

The Earth's magnetic field changes continually at periods ranging from a few milliseconds to up to several million years for a field reversal. The main feature of the geomagnetic field is its close resemblance to a dipole field aligned approximately with the spin axis of the earth (Gauss, 1839). The dipole field is explained by electrical currents flowing in the core. There are significant local differences in the strength of this field, whose average magnitude varies from about 28 A m^{-1} at the equator (corresponding to a magnetic flux density of about 35 µT in a non-magnetic material such as air) to about 56 A m^{-1} over the geomagnetic poles (corresponding to about 70 µT in air). Changes of the dipole field with periods of approximately 100 years constitute the secular variation, and are explained by eddy currents located near the core boundary (Bullard, 1948). Most other changes are due to processes occurring in the ionosphere and magnetosphere, where typical magnetic field amplitudes are very small and are generally only a fraction of 1 µT.

See Table 3 for a summary of natural electric and magnetic fields.

Table 3. Natural static electric and magnetic fields

Description/activity	Field average value
Static electric field (kV/m)	
Surface (fair weather)	0.13
Altitude of 1,000 m	0.045
Approaching storm	0.1 - 3
Static magnetic field (µT)	
Magnetic equator	35
Magnetic poles	70
Atmospheric processes	< 1

3.2 Human-made fields

3.2.1 Electric fields

3.2.1.1 Power transmission

Since the late 1950's direct current has been used in several countries to efficiently transmit electricity over long distances. Voltages of up to 800 kV have been used in commercial systems. In Europe, maximum static electric field strengths of up to 20 kV m^{-1} have been recorded directly beneath a 500 kV DC transmission line, and field levels decayed only slowly with distance, to about 2 kV m^{-1} at 400 m and 1 kV m^{-1} at 800 m from the line (EC, 1996). Blondin et al. (Blondin et al., 1996) quoted average values of 13.7 kV m^{-1} and a maximum value of 23.3 kV m^{-1} beneath a Canadian ± 450 kV high voltage direct current (HVDC) line.

3.2.1.2 Transportation

Static electric fields are also produced by the many conventional electrical rail systems, including rapid transit and light rail systems that use DC electricity. Static field strengths of around 30 V m^{-1} have been reported at 5 m from the lines on 600 V DC underground systems or tramways. Static fields of up to 300 V m^{-1} can occur inside trains that operate at 1.5, 3 and 6 kV DC. In general, regardless of category, electric fields associated with transportation systems have not been reported in any great detail, nor have concerns about them been consistently expressed. Voltages are low to moderate (generally less than a few kV), energized conductors are sufficiently well separated from passengers or workers and located overhead or as a third rail and, most importantly, shielding is provided by the intervening metallic structures of the passenger and operator compartments. Excluding sources that might be carried in by occupants, electric fields within vehicles are typically highest near windows and do not exceed a few tens of V m^{-1}.

3.2.1.3 Other

The main cause of man-made static electric fields in the environment is charge separation as a result of friction. Charge potentials of several kilovolts can be accumulated by walking on non-conductive carpets, producing field strengths near the body in the range 10 - 500 kV m^{-1} (EC, 1996). Visual display units (VDUs) produce static electric fields, the strength depending on humidity, the grounding conditions of the screen, and the electric potential between the VDU and the operator. Electric field strengths in the range 100 - 300 kV m^{-1} have been measured at 5 cm from screens, typically falling to 10 - 20 kV m^{-1} at 30 cm. A grounded electrically conductive surface on the outside of a VDU screen can significantly reduce the field strength to levels of a few hundred volts per metre at a distance of a few centimetres (AGNIR, 1994). The handling and treating of plastics can produce static field strengths near the body of up to several hundred kilovolts per metre (EC, 1996).

See Table 4 for a summary of human-made electric fields.

Table 4. Human-made static electric field in a variety of situations

Description/activity	Static electric field Average value (kV m^{-1})	Static electric field Maximum value (kV m^{-1})
Walking on non-conductive carpets[a]	10 - 500	
Video display terminals[b]		
5 cm from screen	100 - 300	
30 cm	10 - 20	
Plastic welding and moulding	100 - 300	
DC electric transmission lines[a]		176.3
500 kV (directly below)	20	
at 400 m	2	
at 800 m	1	
Electrical railway system[c]		
600 V (at 5m)	0.03	
15 - 6 kV (inside)	0.3	

[a] (EC, 1996); [b] (AGNIR, 1994); [c] (ICNIRP, 2003)

3.2.2 Magnetic fields

There may be man-made magnetic fields of significantly higher strength that are superimposed on the Earth's magnetic field.

3.2.2.1 Transportation

Dietrich and Jacobs (Dietrich & Jacobs, 1999) in the USA have reported static magnetic field levels in a range of transport environments. In general, electrified railway systems produce some of the largest static field levels encountered by the general public. Magnetic flux densities of up to 1 mT have been reported inside Italian high-speed trains operating at 30 kV DC at a maximum speed of 250 km/h (Grandolfo, 1989). Modern magnetic levitation (MagLev) systems use very high fields (around 1 T) directly on the rails. However fields inside the trains vary between 50 µT and 1 - 2 mT, depending on the design. Static fields up to several tens of microtesla have been reported inside trams operating at 500 A DC (EC, 1996).

See Table 5 or a summary of magnetic fields in transportation systems.

Table 5. Static field magnetic flux densities (µT) measured in US and European transportation systems.

Mode of transport	Static magnetic field Average value (µT)	Static magnetic field Range of values (µT)
Ferry boat (diesel powered)[b]	55.9	47.6 - 67.9
Escalator[b]	57.6	30.9 - 84.9
Moving walkway[b]	61.7	23.6 - 121.8
Conventional cars, light trucks and buses[c]	33.9	2.7 - 87.5
Electric cars & light trucks[c]		
Test facility	40.8	10.6 - 104.4
Test track	38.8	12.5 - 104.1
Electric shuttle bus	37.4	15.1 - 61.0
Shuttle Tram (AC)[b]	48.6	24.3 - 73.4
Commuter Train (AC)[d]	53.8	19.4 - 196.9
US railway system		
25 Hz version	60.6	176.3
60 Hz version	63.0	103.9
Non-Electrified	56.9	103.3
New Jersey Long Branch	73.4	101.6
TGV-A	54.5	96.2
UK railway system[e]		
London underground		
Driver's cabin		200
Passenger car – floor level		100 - 2,000
Suburban & mainline railways		
Passengers		25
Equipment car		2,000
German Transrapid MagLev System[f]		
TR07	61.1	111.0
TR08 – passenger location	46.2	108.4

TR08 – platform (1 m from car)	52.9	71.8
Japan Railways developmental MagLev system[g]		
4 m outside guideway	190	
8 m under bridge section	20	
Inside passenger cabin		80 - 1060
Between passenger cars		60 - 1330

[a] Dietrich and Jacobs (Dietrich & Jacobs, 1999) on behalf of US Department of Transportation, Federal Railroad Administration DOT-VNTSC-FRA-02-11

[b] Measured at a height of 3 feet (0.9m)

[c] Average of all sensor positions (i.e. driver and passenger head, waist and ankle)

[d] Includes all locations and sensor positions (head, waist & ankle)

[e] Chadwick and Lowes (Chadwick & Lowes, 1998)

[f] Experimental vehicles

[g] (IEEJ - Institute of Electrical Engineers of Japan, 1998)

3.2.2.2 Industry

Static fields formed by rectifying an intense alternating current are used in several industrial processes, including gas welding and the production of aluminium and chlorine.

Aluminium is produced by the electrolytic reduction of alumina in Soderberg reduction cells or ‘pots’. The workers involved in this operation are called ‘potroom’ or ‘potline’ workers and are exposed to static magnetic fields. Measurements at eleven factories in France (Mur et al., 1998) found that the fields near the pots were ~ 4 - 30 mT, but the workers were generally exposed to < 20 mT. Measurements at a Norwegian plant (Moen et al., 1996) showed a maximum level of 63 mT, but results were otherwise similar to Mur et al. (1998). This corresponds to measurements made in a Californian aluminium production test facility, where magnetic fields up to 57 mT were determined by Tenforde (1986a).

There are many different electric arc welding processes involving direct alternating or pulsed current that produce magnetic fields. Metal inert gas (MIG) or metal active gas (MAG) welding produce static magnetic field strengths up to 5 mT at the distance of 1 cm from the welding cables (Skotte & Hjollund, 1997). Static magnetic field strength in MIG/MAG welding is roughly one order of magnitude higher than the ELF magnetic field.

3.2.2.3 Magnetic resonance imaging (MRI)

MRI systems have proliferated in recent years and there are currently many thousands worldwide. The technique utilizes a strong homogeneous static magnetic field, much smaller time-varying gradient magnetic fields, and radiofrequency radiation. The static magnetic field is generated by permanent magnets, superconducting magnets and combinations thereof in the range of 0.2 - 3 T for systems for routine clinical use. In research applications, higher magnetic fields of up to 9.4 T are used for whole body patient scanning. The stray magnetic fields around the magnets for MRI studies are well defined and can be minimized in the shielded magnet versions – unfortunately very few surveys have been published. Stuchly and Lecuyer (1987) mapped the static fields around four MRI machines (the units ranged from 0.15 - 1.9 T). Magnetic flux densities of up to about 1 T were measured close to the magnet, but these had dropped to less than 30 mT at 2 m. Measurements at the operator console position were less than 5 mT. Nevertheless, the operator will be exposed to magnetic flux density up to the maximum field strength of the magnet, which still exists just outside the bore of the magnets. Apart from the static magnetic field, the other parameters likely to be important for static magnetic field effects are the gradient field, $\partial B/\partial z$, and the 'force product' given by $B(\partial B/\partial z)$. Typical values of the gradient field and force product for a 4 T system are 2.8 T m^{-1} and 8.8 T^2 m^{-1} (Schenck et al., 1992) and 7.9 T m^{-1} and 42.9 T^2 m^{-1} for a 8 T system (Kangarlu & Robitaille, 2000).

Modern applications for the MRI systems include the use of the system in the operating theatre for interventional applications. The magnetic field strength of these systems varies from low field open (vertical field) systems, 0.2 - 0.6 T, up to medium or high field cylindrical (horizontal field) systems, 0.5 - 1.5 T. These systems have openings between the poles so theatre staff can access patients. Peak static field exposures may approach or even exceed the static field for the scanner. Force products (see section 6.1) for such designs may be higher than for solenoidal designs at the same field strength. Systems are also being introduced whereby the patient can be transported from the MRI system into an X-ray system and vice versa, using one patient table positioning device. In this way, both imaging modalities can be used for optimal diagnosis and treatment of the patient. Such systems typically operate at 1.5 T and above. However, workers will generally not be closer than the magnet opening and magnetic field exposures are not likely to exceed the rated field strength. For actively shielded magnets, the peak force product may occur close to the magnet opening. Appropriate controls to limit exposure of theatre staff are still being developed. Medical applications with the potential of using fields up to 10 T and higher are also being developed (Simon & Szumowski, 1992; Polk et al., 1996; Gowland, 2005).

A new medical system that applies strong static (inhomogeneous) magnetic fields has been recently introduced. The system, referred to as the ‘magnetic navigator system’ applies an inhomogeneous 0.5 T static magnetic field to navigate the ferromagnetic tip of a catheter under X-ray control to the correct anatomical position in a patient’s body.

3.2.2.4 Research and energy technologies

Large superconducting magnets are used in a variety of research applications including:

- Particle accelerators like the LEP (Large Electron Positron Collider) at CERN in Geneva that can consist of thousands of magnets, including large superconducting magnets.
- Thermonuclear fusion research requires large magnets (~ 4 T) for plasma containment. Worldwide efforts in fusion research are now being combined in an international project currently under design, but which will include the largest tokamak (chamber in which a plasma is heated and confined by magnetic fields) ever constructed.
- Magnetohydrodynamic research involving superconducting magnets of up to 5 T.
- Bubble chambers for subatomic particle detection, which have largely been replaced by different detectors, such as the multiwire chamber.
- Nuclear magnetic resonance (NMR) spectroscopy, used to obtain physical and chemical properties of molecules, can involve the use of large superconducting magnets (12 - 22 T).

See Table 6 for typical static magnetic fields in industrial, research and medical environments.

Table 6. Major technologies involving the use of large static magnetic fields, and corresponding exposure levels

Procedures	Static magnetic field Typical value (mT)
Energy technologies[g]	
Thermonuclear fusion reactors	
Hot cell areas	45
Accessible areas	5
Outside reactor site	0.1
Magnetohydrodynamic systems	10 (at about 50 m)
	0.1 (at distances greater than 250 m)
Superconducting magnet energy storage systems	50 (max) at accessible locations
Superconducting generators and transmission lines	< 0.1 (projected)
Research facilities	
Bubble chambers[g, h]	600 - 1,500 (for several minutes during changes of film cassettes)
Superconducting spectrometers[a, h]	1,000 at operator-accessible locations
Particle accelerators[a]	Exposure only during maintenance
Isotope separation units[a]	1 (typical) and 50 (occasionally)
Nuclear Magnetic Resonance	2,000 (24 cm radially from 18.8 T magnet)
	600 (52 cm radially from 18.8 T magnet)
Industry	
Aluminium production[e,f,h]	up to 100 in accessible locations < 20 (generally)
Electrolytic processes[a]	10 (average) and 50 (maximum)
Magnet production[a]	0.3 - 0.5 (chest and head) & 2 - 5 (hands)
Welding[b]	5 (submerged arc)
	0.9 - 1.9 (MIG/MAG)
	5 (1 cm from cables – MIG/MAG)

Heavy manufacturing industries[c]	< 0.13 (maximum value)
Medicine[a]	
Magnetic resonance imaging and spectroscopy	0.5 (unshielded I T magnet at 10 m)
	0.5 (unshielded 2 T magnet at 13 m)
MRI[d]	850 (next to 1.9 T unit)
	< 30 at 2 m
	0.5-< 5 at operator console
	~ 1,000 next to a shielded 4 T system

[a] (ICNIRP, 1996)
[b] (Skotte & Hjollund, 1997)
[c] (Bowman & Methner, 2000)
[d] (Stuchly & Lecuyer, 1987)
[e] (Moen et al., 1996)
[f] (Mur et al., 1998)
[g] (Stuchly, 1986)
[h] (Tenforde, 1986a)

3.2.2.5 Other

Variations of up to 20% in the Earth's static magnetic field have been observed both within and between homes (Swanson, 1994). These observations point to steel construction materials as important contributors to local field variation in homes. Static magnetic field sources within homes otherwise tend to be small and only generate high levels very locally.

Steel-belted radial tyres are magnetic and produce static and low-frequency alternating magnetic fields in the passenger compartments of cars. Milham et al. (1999) measured static fields of about 150 µT 10 mm from a tyre. At 50 km/h, the static magnetic field measured within the car did not exceed about 0.01 µT.

Headphones and telephone speakers produce magnetic flux densities of 0.3 - 1.0 mT at their surfaces (EC, 1996). The static magnetic fields from battery-powered devices are very small compared with the natural background. Magnetic plasters, blankets and mattresses for alleged therapeutic properties have surface magnetic flux densities of about 50 mT, but these decay quickly within a few millimetres or so (EC, 1996). Small bar magnets can produce 1 - 10 mT magnetic flux densities within a centimetre of the magnet.

High voltage DC transmission lines produce magnetic fields of up to a few tens of microtesla. Bracken (1979) reported 22 μT under a 500 kV line. For an underground transmission line buried at 1.4 m and carrying a maximum current of about 1 kA, the maximum field was less than 10 μT at ground level (Hassenzahl et al., 1978). These are still relatively uncommon sources of exposure.