Occupational Exposure to Electric and Magnetic Fields in the Context of the ICNIRP Guidelines

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ABSTRACT

Occupational exposures to electric and magnetic fields at sub-optical frequencies are reviewed and measurements of exposure are compared with the reference levels advised in guidelines published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP). Compliance with the reference levels ensures compliance with the underlying basic restrictions that have been advised to provide protection against the established adverse health effects of exposure. The review draws on material published in 1994 and on data obtained in more recent exposure assessments carried out by NRPB. Many of the exposure measurements that are reported complied with the relevant reference levels, however a number of devices and applications have been identified where the reference levels or basic restrictions may be approached or exceeded. Further work may be required in some areas to determine whether occupational exposures exceeding the reference levels are likely to result in non-compliance with the basic restrictions.

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EXECUTIVE SUMMARY

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) published guidelines on limits of exposure to static magnetic fields in 1994 and on limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz) in 1998. The guidelines advise basic restrictions to provide protection against the established adverse health effects of exposure. Reference levels are also given for practical exposure assessment purposes to determine whether the basic restrictions are likely to be exceeded. Compliance with the reference levels ensures compliance with the relevant basic restrictions, however the reference levels are not limits and if they are exceeded, it does not necessarily follow that the basic restrictions will also be exceeded.

A review is given of occupational exposures to electric and magnetic fields at sub-optical frequencies with regard to the ICNIRP exposure guidelines. Measurements of electric and magnetic field strength, magnetic flux density, power density and contact current are reported that have been obtained in assessments of exposure to the fields produced by electricity generating equipment, resistance welders, induction heaters, plasma discharge equipment, security and access control systems and other miscellaneous devices. The measurements are compared with the reference levels advised by ICNIRP for occupational exposure. Data published previously in NRPB Report R265 are also compared with the reference levels.

Many of the exposure measurements that are reported complied with the relevant reference levels, however a number of devices and applications have been identified where the reference levels or basic restrictions may be approached or exceeded under certain circumstances. In many cases the reference levels were exceeded only at locations of limb or extremity exposure. Reference levels have been found to be exceeded in assessments of exposure to electromagnetic fields produced by the following sources:

a Electricity generating equipment
b Resistance welders
c Tape erasers
d Crack detection equipment
e Induction heaters
f Dielectric heaters
g Plasma etchers
h Radiofrequency sputtering units
i Radiofrequency identification systems
j Electronic article surveillance equipment
k Diathermy and hyperthermia
l Broadcast and telecommunications

Further work may be required in some areas to determine whether occupational exposures exceeding the reference levels are likely to result in non-compliance with the basic restrictions. Analyses of the spatial distributions of magnetic fields produced by resistance welders, radiofrequency identification devices, electronic article surveillance equipment and other security systems would provide valuable information on exposures and would allow compliance with the basic restrictions to be investigated in greater detail. Product standards for some of these devices have been developed by the European Committee for Electrotechnical Standardization (CENELEC) and the standards incorporate protocols for assessing compliance with reference levels and basic restrictions.

CONTENTS

1 INTRODUCTION

1.1 Preamble

This report was commissioned by the Health and Safety Executive (HSE) in order to facilitate a regulatory impact assessment on non-optical sources of non-ionising radiation with regard to guidelines published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) for occupational exposure. The review of occupational exposure to electric and magnetic fields draws upon material published in 1994 and upon more recent data obtained from assessments of exposure carried out by NRPB under commercial contract. Permission to publish these data was sought from the individuals and organisations who contracted the work from NRPB under the conditions that the customers' names and equipment models included in the review remain anonymous.

HSE specifically requested that a comprehensive literature review, similar to that undertaken during the preparation of NRPB-R265, should not be carried out for this work. Consequently, the data presented arise from measurements carried out solely by NRPB and not by any other organisation. These data are necessarily selective, since the exposure assessments were carried out at the request of customers, therefore it cannot be assumed that all potential occupational exposure conditions are addressed in this document.

1.2 Background

Occupational exposure to electric and magnetic fields was reviewed by NRPB in report R265 (Allen *et al*. 1994) in order to provide data for comparison with the action levels and hazardous activities levels contained in a proposal for a Council of the European Communities (CEC) Directive on the minimum health and safety requirements regarding the exposure of workers to risks arising from physical agents (CEC 1993). The physical agents covered by the proposal included noise, mechanical vibration, optical radiation and electromagnetic fields and waves. The proposal was later amended (CEU 1994), however the revised document was published after the publication of NRPB-R265. The review carried out by NRPB considered occupational exposures to electric and magnetic fields in industry, commerce and medicine from *inter alia* broadcast, telecommunications, radar, induction heating, dielectric heating, visual display units and the transmission, distribution and use of electrical power.

ICNIRP published guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz) in 1998 (ICNIRP 1998a). The ICNIRP guidelines advise basic restrictions on exposure that differentiate between workers and the general public. Reference levels are also given for practical exposure assessment purposes to determine whether the basic restrictions are likely to be exceeded.

This review provides new data on non-optical devices and processes covered in NRPB-R265 and summarises the results of measurements for new technologies for which exposure assessments have been carried out by NRPB. The measurements previously reported and the more recent measurements are compared with the ICNIRP reference levels for occupational exposure.

1.3 Electromagnetic spectrum

The electromagnetic spectrum is divided into several regions based on the different physical properties of electromagnetic fields with different frequencies. The spectrum is bounded at zero frequency by static electric and magnetic fields. The various regions encountered as frequency increases are time-varying electromagnetic fields, radiofrequency (RF) fields and waves, microwaves, optical radiation (subdivided into infrared, visible and ultraviolet radiation), X-rays and gamma rays. This report is concerned with the sub-optical region of the spectrum, i.e. frequencies below 300 GHz.

The boundaries between neighbouring regions of the electromagnetic spectrum are defined somewhat arbitrarily and do not necessarily represent distinct qualitative changes in the nature or effects of the different categories of fields and waves etc. The term radiofrequency has historically been used to describe the frequencies that can be employed practically for wireless communications by the transmission of modulated electromagnetic waves. By convention, the term now applies to electromagnetic fields and radiation with frequencies between 3 kHz and 300 GHz. The radio spectrum, together with some lower frequencies, has been divided into ten bands by the International Telecommunications Union (ITU). Each band is a decade wide and the ITU nomenclature is given in Table 1. The ELF band is often taken to include frequencies less than 30 Hz in addition to those in the specified range. The top three bands, covering the frequency range 300 MHz to 300 GHz, are considered to define the microwave part of the spectrum. Some common sources of electromagnetic fields with sub-optical frequencies are summarised in Figure 1.

TABLE 1 ITU frequency bands for the radio spectrum

Band	Abbreviation	Frequency range
Extra high frequency	EHF	30–300 GHz
Super high frequency	SHF	3–30 GHz
Ultra high frequency	UHF	300–3000 MHz
Very high frequency	VHF	30–300 MHz
High frequency	HF	3–30 MHz
Medium frequency	MF	300–3000 kHz
Low frequency	LF	30–300 kHz
Very low frequency	VLF	3–30 kHz
Voice frequency	VF	300–3000 Hz
Extremely low frequency	ELF	30–300 Hz

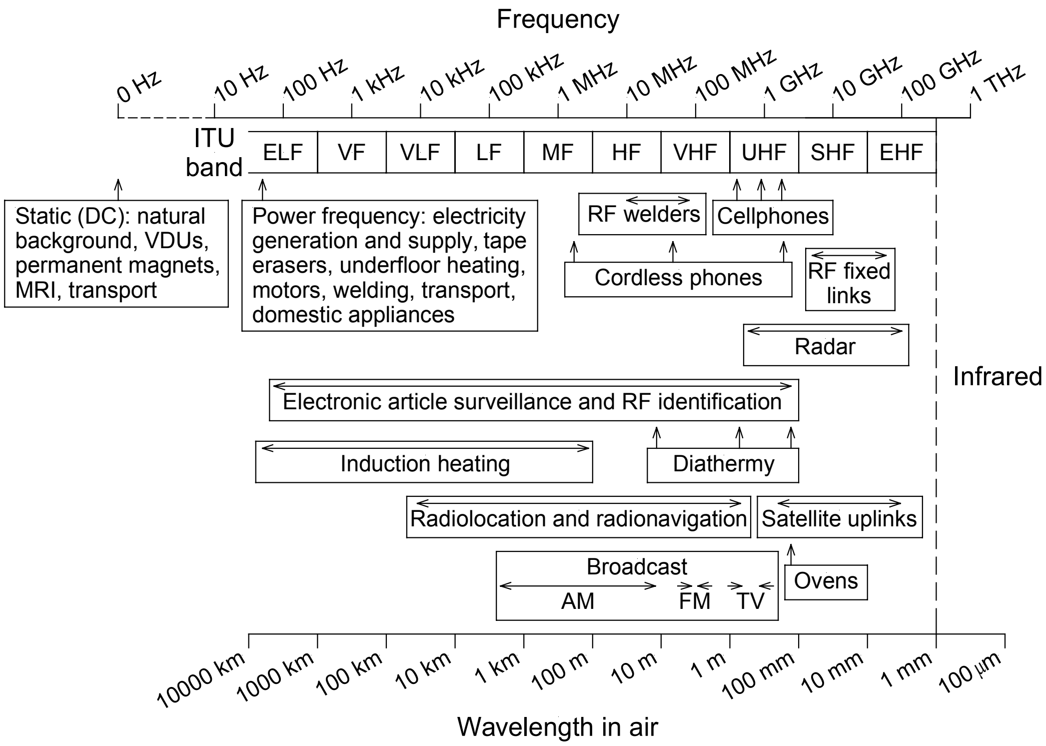

FIGURE 1 Sources of electromagnetic fields and radiation with sub-optical frequencies

1.4 Structure of review

Five main areas have been selected for inclusion in this review and these are electricity generation, resistance welding, induction heating, plasma discharge applications and security and access control. These are all areas in which NRPB has carried out a number of exposure assessments, since the publication of NRPB-R265, and a section of this review is devoted to each of them. Some additional devices, for which NRPB has carried out limited work, are included towards the end of the review as miscellaneous sources of exposure.

Tables of results have been used extensively in the review to aid clarity and to facilitate the comparison of measured field strengths and contact currents, etc. with the corresponding reference levels. In some instances the same device, or source of exposure, appears in several tables, for example where electric field strength and magnetic field strength are reported separately. In these cases the devices have been numbered consistently, for example a plasma etcher listed as Model 1 in a table of electric field strengths will also be listed as Model 1 in the corresponding table of magnetic field strengths.

Before the main body of the review, a summary is given of the guidelines advised by ICNIRP for occupational exposure. The basic restrictions and reference levels, and notes on their application, are given in Appendix A.

2 ICNIRP GUIDELINES

ICNIRP is an independent scientific organisation responsible for providing guidance and advice on the health hazards of exposure to non-ionising radiation. ICNIRP was chartered as an independent Commission in 1992 as a successor to the International Non-Ionizing Radiation Committee of the International Radiological Protection Association (IRPA/INIRC). The precursor organisation published guidelines on exposure to radiofrequency (RF) electromagnetic fields in 1988 (INIRC 1988), however these have been superseded by guidelines published by ICNIRP.

ICNIRP published guidelines on limits of exposure to static magnetic fields in 1994 (ICNIRP 1994). Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz) were published in 1998 (ICNIRP 1998a) with clarification later that same year (ICNIRP 1998b). A reference book based on the guidelines on limiting exposure to non-ionising radiation and statements on special applications was published by ICNIRP in the following year (ICNIRP 1999).

The ICNIRP guidelines are based on reviews of the science, they summarise scientific results, set out the basis for limiting exposure and recommend exposure limits. The ICNIRP exposure guidelines have been reviewed through members of the world-wide network of national IRPA-affiliated radiation protection societies and, more recently, the review process was extended to include ICNIRP’s International Partners in Non-Ionizing Radiation Protection. The International Partners of ICNIRP include the World Health Organization and the European Commission.

2.1 Basis of guidelines

The main objective of the ICNIRP guidelines is to provide protection against known adverse health effects, i.e. effects that cause detectable impairment of the health of the exposed individual or of his or her offspring. The guidelines on limits of exposure to static magnetic fields advise exposure limits that are expressed in terms of magnetic flux density. The guidelines discriminate between occupational exposures and exposures of the general public and this is reflected in the exposure limits where a distinction is made between the two groups. Observations over who might be included in the occupationally exposed population are made by ICNIRP in the guidelines. The occupational exposure limits are given in Appendix A.

The guidelines published by ICNIRP for limiting exposure to time-varying electric, magnetic and electromagnetic fields also distinguish between occupational and general public exposures. The guidelines advise basic restrictions that are based directly on established health effects and it is stated that protection against adverse health effects requires that these basic restrictions are not exceeded. Depending on frequency, the physical quantities used to specify the basic restrictions are current density, specific energy absorption rate (SAR) and power density. Power density is measured in air, outside the body, however current density and SAR are internal dosimetric quantities.

2.2 Reference levels

Current density and SAR cannot be readily measured in tissues within living people, therefore ICNIRP has introduced reference levels for practical exposure assessment purposes to determine whether the basic restrictions are likely to be exceeded. The reference levels that apply in a given exposure situation depend on frequency, whether there is the potential for indirect effects to occur, and whether the fields are pulsed. The reference levels are given in Appendix A and are expressed in terms of electric field strength, magnetic field strength (and magnetic flux density), power density, limb current, contact current and specific energy absorption (SA)*.

Compliance with the reference levels ensures compliance with the relevant basic restrictions, however the reference levels are not limits and if they are exceeded by measured or calculated values, it does not necessarily follow that the basic restrictions will also be exceeded. The guidelines state that whenever a reference level is exceeded it is necessary to test compliance with the relevant basic restriction and to determine whether additional protective measures are necessary.

The reference levels for electric and magnetic field strength and magnetic flux density are quantified as root mean square (rms) values and this allows easy comparison with measurements since most commercially available instruments display rms quantities. At frequencies up to 100 kHz the guidelines permit the derived electric fields to be increased by a factor of two under conditions in which adverse indirect effects from contact with electrically charged conductors can be excluded.

At frequencies greater than 100 kHz power density can be averaged over a time interval that depends on frequency, as specified in Appendix A. Electric and magnetic field strength may also be time averaged on a field-strength-squared basis.

At frequencies above 1 MHz, if exposure is in the far field, the electric and magnetic fields need not both be considered since the reference levels are related by the impedance of free space (E/H = 377 Ω). In this case, power

* The text of the ICNIRP guidelines treats SA values as reference levels although the values are actually given in Note 7 of Table 4 in the guidelines. This table specifies the *basic restrictions* for frequencies up to 10 GHz.

density S may be deduced from the electric field strength or the magnetic field strength alone through the expression

$$S = \frac{E^2}{377} = 377H^2. \qquad (1)$$

However, in the near field of any source the relationship between power density and field strength is not so straightforward and the contributions of the electric and magnetic field components have to be considered separately.

In addition to the rms reference levels, the guidelines advise peak values of electric and magnetic field strength and power density. It is acknowledged by ICNIRP that little information is available on the relation between biological effects and peak values of pulsed fields and it is suggested that, for frequencies exceeding 10 MHz, the equivalent plane wave power density, as averaged over the pulse width, should not exceed 1000 times the reference level. Following from this, electric and magnetic field strength should not exceed 32 times the corresponding reference levels for rms field strength. In the frequency range 100 kHz to 10 MHz, peak values for field strength are obtained by interpolation from a 1.5-fold peak at 100 kHz to the 32-fold peak at 10 MHz.

2.3 Simultaneous exposure to multiple frequency fields

The ICNIRP guidelines contain advice for determining whether, in situations of simultaneous exposure to fields of different frequencies, the exposures are additive in their effects. Summation formulae, based on the assumption of worst-case exposure conditions, are provided that distinguish between electrical stimulation effects and thermal effects arising from exposures to different frequencies.

The magnetic fields generated by some types of electrical equipment have significant harmonic content and exposure to each harmonic component should be considered additively, according to the method prescribed by ICNIRP. Since the reference levels are dependent on frequency, simultaneous exposures at multiple frequencies should be added as quotients of the reference levels. Spectral analysis allows the derivation of an *effective* reference level based on this principle that is specific to a given exposure situation (Chadwick 1998). Compliance with the guidelines can then be assessed by comparing measured magnetic flux densities with the effective reference level directly. Measurements should be made with instrumentation that has a bandwidth sufficient to encompass the frequencies of the significant harmonic components in the spectrum.

Figure 2 shows a typical waveform of magnetic flux density produced by a resistance welder under pulsed AC operation. The spectral content of the waveform, derived from a fast Fourier transform (FFT), is represented in Figure 3 where the relative contribution to the spectrum of each harmonic component is shown at the head of each column as a percentage. The rms effective reference level B_{eff} was derived for this specific exposure situation from the harmonic content using the expression

$$B_{eff} = 1 \Big/ \sum_i \frac{F_i}{B_{L,i}} \qquad (2)$$

where F_i is the fractional contribution of harmonic i to the spectrum and $B_{L,i}$ is the reference level of magnetic flux density for that harmonic. The effective reference level for the welder was evaluated at 240 μT, which is approximately half the reference level of 500 μT that applies to pure 50 Hz sinusoidal magnetic fields.

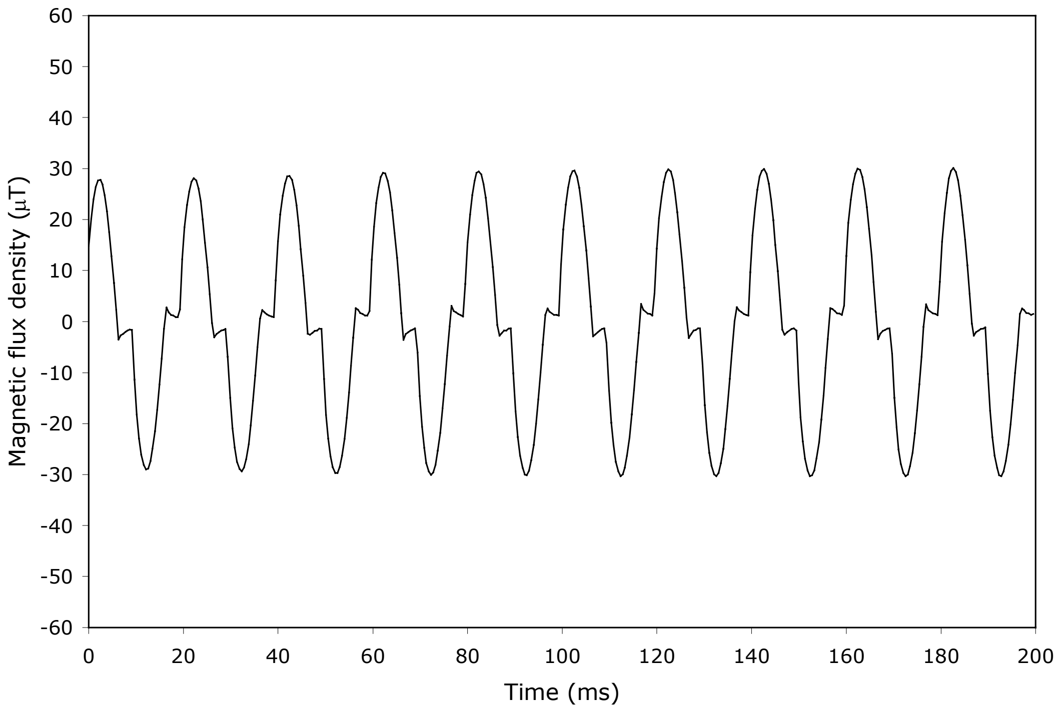

FIGURE 2 Waveform of magnetic flux density produced by a resistance welder under pulsed AC operation. The waveform contains harmonics of the fundamental 50 Hz frequency

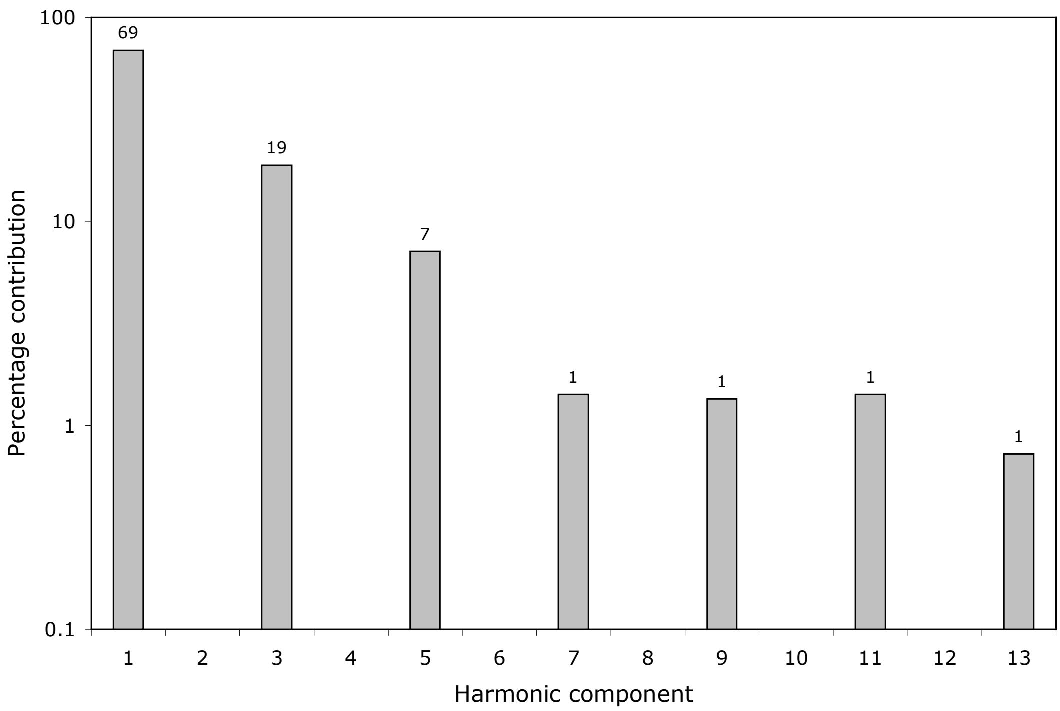

FIGURE 3 Harmonic content of the magnetic flux density waveform produced by a resistance welder under pulsed AC operation

3 ELECTRICITY GENERATION

Assessments of occupational exposure have been carried out at a number of electricity generating stations and ELF electric and magnetic fields have been investigated close to generators, transformers, substations, conductors and other associated equipment. In many cases the magnetic fields produced by these items had significant harmonic content and an effective reference level was derived specific to each exposure situation, as discussed in Section 2.3. The maximum electric field strengths measured in various environments at power stations are given in Appendix B and are displayed graphically in Figure 4. Measurements of magnetic flux density made close to certain components in the electricity generating process are also given in Appendix B and are displayed in Figure 5. The results are shown as ratios of the measured flux density to the effective reference level appropriate to each exposure situation. Consequently, the effective reference level was exceeded by any data point with ordinate greater than unity. The numbers along the abscissa axes of Figures 4 and 5 identify particular power stations and the numbering is consistent such that any individual power station is given the same identifier in both figures.

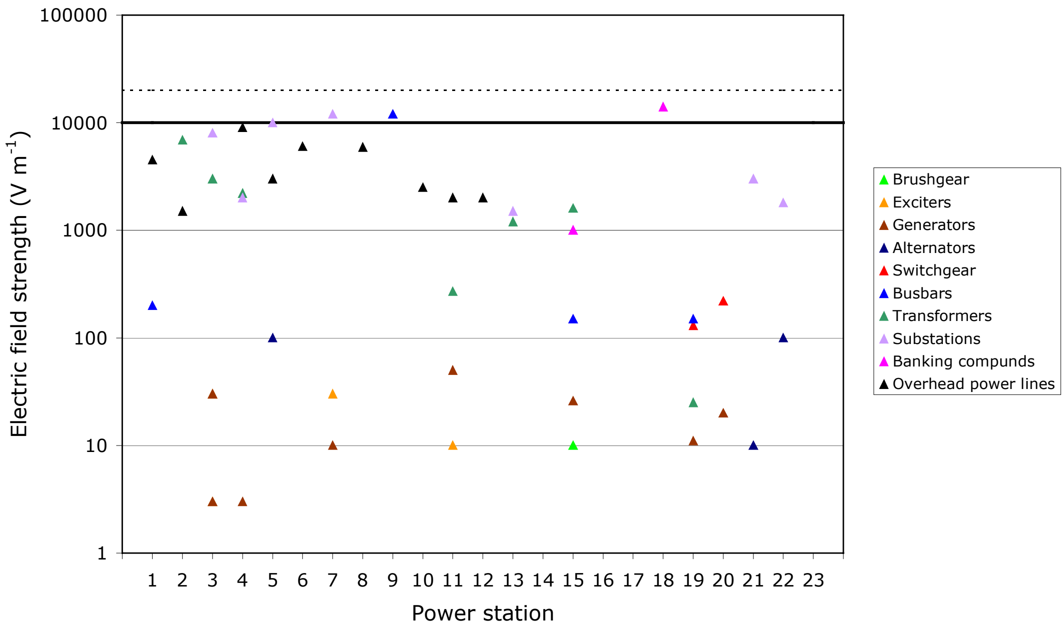

FIGURE 4 Electric field strengths from electricity generating equipment at power stations shown with the ICNIRP reference level (solid line) and the relaxed reference level that can be applied under conditions in which adverse indirect effects from contact with electrically charged conductors can be excluded (broken line)

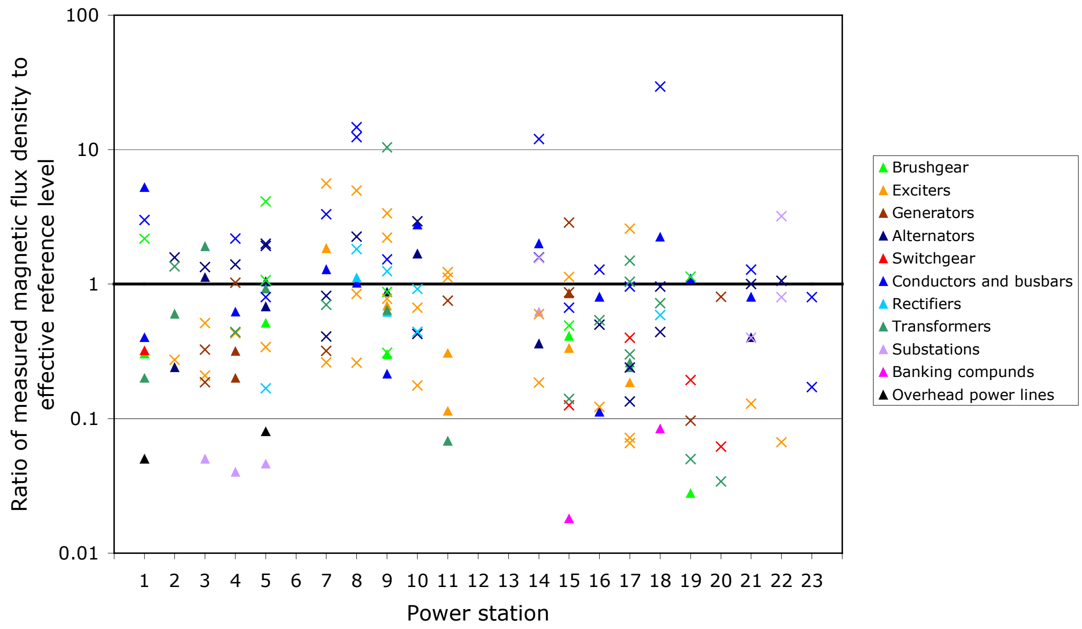

FIGURE 5 Magnetic flux densities from electricity generating equipment at power stations, expressed as a ratio of the effective ICNIRP reference level. Exposures of the head and/or torso are indicated by solid triangles; exposures of the limbs and extremities are indicated by crosses. Triangles and crosses of the same colour represent exposures produced by the same types of equipment

Most of the measurements of electric field strength shown in Figure 4 indicate compliance with the ICNIRP occupational reference level (10 kV m^{-1} at the frequency 50 Hz). However, the reference level was exceeded in a few isolated incidences at a substation, close to bus bars and beneath 400 kV conductors within a banking compound. Effects of electric charge on the surface of the body may be perceived by some people on exposure to field strengths in the region of 14 kV m^{-1}, the maximum measured value, however the basic restriction on induced current density would not be expected to be exceeded (Dimbylow 2000, NRPB 1993).

The reference level for electric field strength can be doubled under conditions in which adverse indirect effects from contact with electrically charged conductors can be excluded, as stated in Section 2.2. The electric field strengths shown in Figure 4 indicate that the relaxed value of the reference level would have been complied with wherever these conditions regarding the exclusion of adverse indirect effects were met.

Locations close to most types of equipment where the effective reference level for magnetic flux density was exceeded were usually confined to regions where parts of the body other than the limbs and extremities would not normally be exposed. In these cases the basic restriction on induced current density in tissues of the head and trunk would be unlikely to be exceeded. The measurements shown in Figure 5, and reported in Appendix B, indicate that in some instances close to exciters, alternator pits, transformers, rectifiers, bus bars and conductors, the effective reference level was exceeded at locations where the head or trunk could potentially be exposed. In these situations there exists the possibility that the basic restriction may be exceeded.

4 RESISTANCE WELDERS

Resistance welders are used in industry to fuse together two or more metal components. The workpiece is placed between two electrodes and a current is injected so that resistive heating occurs, causing the metals to coalesce. Spot welders and stitch welders employ electrodes shaped like rods to allow a weld to be made at a single point. In the case of portable spot welders the electrodes are fixed in a hand-held activation device. Micro spot welders, or ‘poke guns’, are used for thin-gauge materials and allow welding from one side only. The electrodes for seam welders are generally in the form of two counter-rotating wheels, mounted vertically, one above the other, on the front of the machine. The workpiece is passed between the two wheels and a continuous or pulsed current is injected to produce the weld.

AC welders usually operate at power frequency (50 Hz), although harmonics of the fundamental frequency can often be present. The rectification used by DC welders often results in the generation of harmonics of the power frequency and can give rise to exposures to alternating magnetic fields. In assessing exposures to magnetic fields from welders, it is normal practice to measure the harmonic content and evaluate an effective reference level for each magnetic field waveform encountered, as discussed in Section 2.3.

The results of static and time-varying magnetic flux density from a number of exposure assessments are shown in Tables 2–4. The measurement positions were generally at the same height above floor level as the welder electrodes, except for the assessments summarised in Table 4 where some measurements were made at head height. The operating conditions are assumed to be those typically found for each item of equipment unless specified otherwise.

TABLE 2 Static magnetic flux densities from resistance welders

Welder	Current (kA)	Distance from electrodes (cm)	Magnetic flux density (mT)
250 kVA DC welder	14.1	5 20	30 10
High frequency DC welder*	8	– –	1† 0.2‡
Exposure limit for whole working day (time-weighted average)			200

* Direct current derived from rectification of an 800 Hz alternating supply.
† At position where the limbs could be exposed.
‡ At position where an operator would typically be situated.

All the measurements reported in Table 2 are below the ICNIRP limit on time-weighted average magnetic flux density for continuous exposure during the work day.

The data contained in Tables 3 and 4 indicate that exposures to the time-varying magnetic fields produced by some AC and DC welders can exceed the corresponding reference level. At locations where the head or trunk of the operator is exposed to magnetic flux densities in excess of the reference level, there is the possibility that the basic restriction may be exceeded. In some of these situations the magnetic fields may be highly non-uniform and the basic restriction may not be exceeded, in which case it may be possible to establish compliance with the basic restriction using a simple dosimetric assessment based on the spatial distribution of the magnetic flux density. However, it is not possible to draw general conclusions without further detailed information on the spatial distributions of magnetic fields close to resistance welders.

In some of the exposure assessments summarised in Tables 3 and 4, the reference level was exceeded only in regions close to the electrodes where the hands and arms, but usually no other parts of the body, are exposed. If the head and trunk are not exposed in these regions then the basic restriction on induced current density would be unlikely to be exceeded.

TABLE 3 Time-varying magnetic flux densities from resistance welders. Measured values are italicised where the effective reference level was exceeded

Welder	Operating conditions	Effective reference level (mT)	Distance from electrodes (cm)	Magnetic flux density (mT)
Projection welder	High power setting	0.50	15	*9*
			20	*5*
			100	*1.52*
			150	0.34
	Reduced power	0.23	15	*4.2*
			20	*0.67*
			100	*0.33*
			150	0.12
75 kVA seam welder	Nominal 65% max power	0.22	10	*6.5–8.5*
			20	*0.76*
75 kVA spot welder	Nominal 60% max power	0.25	15	*2*
			20	*0.55*
			150	0.095
3.5 kA seam welder	Continuous operating cycle	0.24	10	*8*
			20	*5*
			30	*2*
25 kVA spot welder	9.2 kA	0.22	15	*0.7*
			25	*0.33*
Spot welder	6.6 kA	0.17	15	*0.81*
			20	*0.31*
			30	0.14
Portable spot welder	6.3 kA	0.17	20	*0.19*
250 kVA DC welder	14.1 kA	0.08	15	*0.22*
			30	*0.085*
			60	0.032
High frequency DC welder*	8 kA	0.03	10	*0.16*
			15	*0.08*
Stitch welder	–	0.26	5	*1.60*
			20	*0.96*
			50	0.26

* Direct current derived from rectification of an 800 Hz alternating supply.

TABLE 4 Time-varying magnetic flux densities from resistance welders. Measured values are italicised where the effective reference level was exceeded and are given in bold where this occurred at positions of exposure of the head or torso

Welder	Effective reference level (mT)	Lateral distance from electrodes (cm)	Magnetic flux density (mT)		
			Hands	Torso	Head
Seam welder	0.21	–	*0.56*	0.20	***0.36***
Seam welder	0.26	–	*2.8*	***0.53–0.79***	–
Stitch welder	0.26	–	*7.4*	***0.49–0.64***	–
Stitch welder	0.24	–	*6.9*	***0.38–0.64***	–
Stitch welder	0.30	–	*6.6*	***0.89–1.76***	–
Stitch welder	0.25	–	*4.0*	***0.69–1.95***	–
Spot welder	0.27	5	*8.0*	–	–
		25	–	***2.7***	***1.00***
		40	–	***1.11***	***0.44***
		60	–	***0.41***	0.26
Seam welder	0.32	5	*2.6*	–	–
		35	–	***1.53***	***1.38***
		60	–	0.20	0.31
Spot welder	0.41	5	*6.5*	–	–
		30	–	***3.6***	***2.0***
		60	–	***1.7***	***1.0***
Spot welder	0.31	10	*3.8*	–	–
		30	–	***1.11***	***1.04***
		60	–	***0.82***	***0.98***
Seam welder	1.42	5	0.7	–	–
		45	–	0.13	0.13
Seam welder	2.35	5	1.5	–	–
		40	–	0.22	0.24
Spot welder	0.27	10	*2.8*	–	–
		30	–	***1.69***	***1.48***
		40	–	***0.96***	***0.48***
Micro spot welder	0.31	30	–	***0.73***	***0.34***
Spot welder	0.27	5	*3.2*	–	–
		40	–	***1.18***	***0.37***
Spot welder	0.28	5	*5.4*	–	–
		40	–	***1.37***	***0.82***
		60	–	***0.78***	***0.66***
Spot welder	0.27	5	*3.5*	–	–
		30	–	***0.91***	***0.82***
		40	–	***0.45***	***0.66***
Seam welder	0.47	5	*1.4*	–	–
		50	–	***0.57***	0.19
		70	–	0.21	0.12
Spot stitch welder	0.47	5	*2.2*	–	–
		40	–	***0.64***	0.25
Portable spot welder	0.21	5	*0.89*	–	–
		40	–	0.042	0.015
Micro spot welder	0.21	5	*1.6*	–	–
		20	–	0.19	0.017
		40	–	0.040	0.009
Micro spot welder	0.32	5	*2.6*	–	–
		20	–	***0.43***	0.025
		30	–	0.14	0.023

5 INDUCTION HEATERS

Industrial induction heating was reviewed extensively in NRPB-R265 and results from a variety of processes were reported. Results from more recent assessments of induction heaters, including some that operated at lower power levels than many of the devices reported in R265, are reviewed here since they complement the previously published data. Descriptions of the induction heaters and furnaces are given below, followed by tables summarising the measured exposure data.

The induction heater identified as Machine 1 was used in the manufacture of tools and was operated with an output power of 10 kW in continuous mode, although an intermittent mode was also available. A number of hollow-core, water cooled copper coils were available and the coil with the appropriate size and number of turns was selected depending on the dimensions of the tool to be heated. The operator generally stood 1 m away from the heater whilst RF energy was being applied to the coil.

Machines 2–5 were low-power induction heaters used to heat small metallic components. Typically a screened RF generator with an output power in the range 1–1.5 kW was used to energise one or more multi-turn, water cooled copper coils at a frequency between 2 MHz and 4.5 MHz. Access to the coils was prevented by enclosing them behind a wire mesh and polycarbonate screen.

Machines 6 and 7 were vacuum furnaces that operated at the frequency 150 Hz with a nominal output power of 1.5 MW. Machine 6 had a capacity of 5000 kg and Machine 7 had a capacity of 2500 kg. The output power of the furnaces varied over the course of a process cycle, which lasted many hours, and the results shown were the maximum magnetic flux densities obtained using a personal exposure meter worn by the operator of the equipment.

Machine 8 was a 750 kW airmelt induction furnace that operated at the frequency 1 kHz. The vertically-mounted coil was not encased and could be approached closely. Measurements of magnetic flux density were made with the furnace operating at full power.

Machine 9 was a 7.5 kW induction heater used to heat strips of steel in order to harden them. The operating frequency was 436 kHz.

Tables 5–7 contain measurements of electric field strength, magnetic flux density and contact current obtained around induction heaters, although the assessments of some machines did not include measurements of electric field strength and contact current.

TABLE 5 Electric field strengths from induction heaters. Measured values are italicised where the reference level was exceeded

Machine	Frequency (kHz)	Power (kW)	Reference level (V m^{-1})	Distance from unit (cm)	Electric field strength (V m^{-1})
1 (coil 1)	395	10	610	20 100*	100 30
1 (coil 2)	395	10	610	10 100*	300 20
2	2200	~1	277	10 30*	100 55
3	2400	~1	254	10 30*	100 55
4	3800	~1	161	10 30*	*220* 32
5	2550	~1	239	10 30*	45 <10

* Typical operator position.

TABLE 6 Magnetic flux densities from induction heaters. Measured values are italicised where the reference level was exceeded

Machine	Frequency (kHz)	Power (kW)	Reference level (μT)	Distance from unit (cm)	Magnetic flux density (μT)
1 (coil 1)	395	10	5.1	5 30 100*	*420* *18* 3.5
1 (coil 2)	395	10	5.1	5 30 100*	*480* *34* 0.8
2	2200	~1	0.91	10 30*	*6.3* <0.4
3	2400	~1	0.83	10 30*	*3.0* <0.4
4	3800	~1	0.53	10 30*	*2.9* <0.4
5	2550	~1	0.78	10 30*	*7.3* 0.5
6	0.15	1500	167	–	50
7	0.15	1500	167	–	27
8	1	750	30.7	15 100 250 500	*1700* *300* *80* 17
9	436	7.5	4.6	5 20	*74* 2.6

* Typical operator position.

TABLE 7 Contact currents from induction heaters

Machine	Frequency (kHz)	Power (kW)	Reference level (mA)	Contact current (mA)
1 (coil 1)	395	10	40	3.8
2	2200	~1	40	15
3	2400	~1	40	15
4	3800	~1	40	18
5	2550	~1	40	19

Most of the measurements reported in Table 5 complied with the ICNIRP occupational reference level for electric field strength. In the one instance where the reference level was exceeded, this was at a location closer to the induction heater than the typical operator position. It is therefore likely that the reference level would not generally have been exceeded under normal circumstances once the time averaging permitted by the guidelines was taken into account.

The data contained in Table 6 show that at the positions typically occupied by induction heater operators, where these were known, the reference levels for magnetic flux density were generally not exceeded. However, at locations closer to some of the machines the reference levels could be exceeded. For frequencies above 100 kHz the guidelines permit time averaging, based on the square of magnetic flux density, which may be invoked when investigating transient exposures. Time averaging is carried out over a six-minute period when the frequency is below 10 GHz.

No contact currents drawn from induction heaters were measured that exceeded the reference level.

6 PLASMA DISCHARGE EQUIPMENT

6.1 Plasma etchers

Plasma etchers are used in various stages of the semiconductor fabrication process to break down polymer resist, etch metals deposited on the semiconductor wafer, or assist in building up deposits on the wafer through plasma assisted chemical vapour deposition (PACVD). The technique involves the delivery of RF energy to a pair of electrodes inside an evacuated reaction vessel, in which the wafers to be etched are placed, in order to establish and maintain a plasma discharge.

Measurements of electric and magnetic field strength close to plasma etchers and PACVD equipment and measurements of contact current from the surfaces of reaction vessels have been made and the results are given in Tables 8–10. The recorded electric and magnetic field strengths are representative of the maximum values at the specified distances from the reaction vessels.

Measurements of field strength a few centimetres from the vacuum chambers represent hand exposures; exposures of the head or torso are indicated by measurements at greater distances.

TABLE 8 Electric field strengths at specified distances from the reaction vessels of plasma etchers and chemical vapour deposition equipment

Model	Frequency (MHz)	Power (kW)	Reference level ($V m^{-1}$)	Distance (cm)	Electric field strength ($V m^{-1}$)
1	13.56	–	61	10	10
2	13.56	0.74	61	10	7
3	13.56	0.8	61	5	2
4	13.56	0.2	61	5	<0.5
5	13.56	0.5	61	5	<0.5
6	0.28	0.5	610	5	<0.5
7	13.56	–	61	2.5	2.7
8	13.56	0.06	61	5	<20
9	0.375	1.5	610	5	<0.5

TABLE 9 Magnetic field strengths at specified distances from the reaction vessels of plasma etchers and chemical vapour deposition equipment. Measured values are italicised where the reference level was exceeded

Model	Frequency (MHz)	Power (kW)	Reference level ($A m^{-1}$)	Distance (cm)	Magnetic field strength ($A m^{-1}$)
1	13.56	–	0.16	5	<0.05
2	13.56	0.74	0.16	5	<0.05
3	13.56	0.8	0.16	5	<0.05
4	13.56	0.2	0.16	5 20 30	*1.54* *0.28* 0.07
5	13.56	0.5	0.16	20 30	0.16 <0.05
6	0.28	0.5	5.7	5	<0.08
7	13.56	–	0.16	2.5	0.006
8	13.56	0.06	0.16	5	<0.05
9	0.375	1.5	4.3	5	<0.08*
10	13.56	0.45	0.16	5	<0.03
11	13.56	0.1	0.16	5	<0.03
12	13.56	2	0.16	5	0.06†
13	13.56	0.4	0.16	5	<0.03
14	0.38	1	4.2	5 20	*13* 0.5
15	0.14	130	11	5 10 30	*50* 8 2

* 7.2 $A m^{-1}$ measured in small area where gas pipes enter casing.
† 1.63 $A m^{-1}$ measured around the RF feed and matching unit when the screening panels were removed.

TABLE 10 Contact currents from plasma etchers and chemical vapour deposition equipment

Model	Frequency (MHz)	Power (kW)	Reference level (mA)	Contact current (mA)
4	13.56	0.2	40	8.0
7	13.56	–	40	<1
8	13.56	0.06	40	<0.1
9	0.375	1.5	40	3.8
10	13.56	0.45	40	0.4
11	13.56	0.1	40	0.1
12	13.56	2	40	8–21
13	13.56	0.4	40	0.1
14	0.38	1	40	0.2
15	0.14	130	40	0.1

All of the measurements reported in Table 8 complied with the reference levels for electric field strength. Similarly, all the measurements of contact current, listed in Table 10, complied with the corresponding reference level.

The measurements of magnetic field strength, shown in Table 9, were not found to exceed the reference levels close to some of the plasma etchers that have been assessed. For the remainder of the devices, locations where the reference level was exceeded were generally confined to regions within a few centimetres of the reaction vessels and in no circumstances were found to occur more than a few tens of centimetres away from the vessels. For frequencies above 100 kHz the guidelines permit time averaging, based on the square of magnetic flux density, which may be invoked when investigating transient exposures. Time averaging is carried out over a six-minute period when the frequency is below 10 GHz.

The plasma etcher listed as Model 10 in the tables above incorporated two extremely low frequency magnetic field coils around the chamber. The maximum magnetic flux density at 50 Hz was measured to be 2.4 mT at a distance of 1 cm from the chamber but was reduced to 30 μT at a distance of 50 cm. The ICNIRP occupational reference level for exposure to 50 Hz magnetic fields is 500 μT.

6.2 RF Sputterers

RF sputterers are similar to plasma etchers in that the process applies coatings to components placed inside an evacuated chamber by means of a plasma discharge. Measurements of electric and magnetic field strength have been made close to the vacuum chambers and control/matching units of four sputtering units operating at the frequency 13.56 MHz, and the results are reported in Tables 11 and 12. The maximum contact currents drawn from the vacuum chambers of the sputterers are given in Table 13.

TABLE 11 Electric field strengths from 13.56 MHz RF sputtering units. Measured values are italicised where the reference level was exceeded

Model	Power (kW)	Reference level ($V\ m^{-1}$)	Distance (cm)	Electric field strength ($V\ m^{-1}$)
1	3.6	61	5 15	*150* 22
2	3.5	61	3 10 20	*280* *110* <61
3	3.5	61	3 10 30	*180* 61 <27
4	0.08	61	5	<0.5

TABLE 12 Magnetic field strengths from 13.56 MHz RF sputtering units. Measured values are italicised where the reference level was exceeded

Model	Power (kW)	Reference level ($A\ m^{-1}$)	Distance (cm)	Magnetic field strength ($A\ m^{-1}$)
1	3.6	0.16	5 15	*0.53* 0.12
2	3.5	0.16	10 30 50	>*1.10* *0.40* 0.16
3	3.5	0.16	10 30	0.16 <0.07
4	0.08	0.16	5	<0.05

TABLE 13 Contact currents drawn from 13.56 MHz RF sputtering units. Measured values are italicised where the reference level was exceeded

Model	Power (kW)	Reference level (mA)	Contact current (mA)
1	3.6	40	1.3
2	3.5	40	*125** *41*†
3	3.5	40	<5

* Grasping contact.
† Light finger contact.

The electric and magnetic field strengths reported in Tables 11 and 12 exceeded the reference levels close to some sputtering units, however this generally occurred at locations where the head and trunk would not normally be exposed. Exposures at 13.56 MHz can be time-averaged over a period of six minutes on a field-strength-squared basis. The basic restrictions on whole-body average and localised SAR would be complied with if the time-averaged field strengths do not exceed the reference levels.

The contact currents shown in Table 13 demonstrate that the reference level was exceeded on contact with the vacuum chamber of one of the sputtering units.

This suggests there may be the potential for RF burn to occur or for the reference level on limb current to be exceeded, possibly giving rise to tissue heating induced by the flow of RF current.

The sputterer listed as Model 1 in the tables above incorporated two coils that were wound around the chamber in the horizontal plane in order to allow the application of a static magnetic field. The maximum static magnetic flux density, measured 5 cm from the chamber, was 0.33 mT and was below the ICNIRP limit on time-weighted average magnetic flux density of 200 mT for continuous exposure during the work day.

6.3 Plasma torch

Measurements of electric and magnetic field strength have been made around the plasma torch assembly of a mass spectrometer system and are summarised in Table 14. The plasma torch assembly consisted of a glass cylinder containing the discharge electrodes, which was placed within a metal enclosure. A coil, coaxial with the assembly, was fed with RF excitation at the frequency 27 MHz with a normal operating power of 1.4 kW. Screening was provided by an inner and outer shield although the system could be operated without either in place.

TABLE 14 Electric and magnetic field strengths around a plasma torch. Measured values are italicised where the reference level was exceeded and are given in bold where this occurred at positions of exposure of the head or torso

Operating conditions	Region of exposure	Electric field strength (V m^{-1})	Magnetic field strength (A m^{-1})
Inner and outer shields removed	Hands Head Torso	*316* 30 30	*2.2* 0.14 ***0.25***
Inner shield in place, outer shield removed	Hands Head and torso	– <30	*0.22* <0.07
Inner and outer shields in place	All exposures	<30	<0.07
Reference level		61	0.16

The measurements reported in Table 14 indicate that exposure of the limbs could exceed the rms reference levels with one or both shields removed but exposure of the head and torso could only exceed the reference levels with both shields removed. ICNIRP advises that exposures at 27 MHz can be time averaged over a six-minute period before making a comparison with the reference levels.

7 SECURITY AND ACCESS CONTROL

A number of different types of device are used for security purposes and for controlling personal access. NRPB has made measurements of exposure to electromagnetic fields produced by metal detectors, radiofrequency identification (RFID) equipment and electronic article surveillance (EAS) systems, also known as anti-theft systems.

7.1 Metal detectors

Metal detectors are used in locations such as airports and prisons for security purposes. Two types of metal detector have been investigated by NRPB. The first type is the free-standing walk-through metal detector and the second is the hand-held metal detector. Both types of detector produce magnetic fields, although the fields from hand-held metal detectors tend to be weaker than those from walk-through devices.

7.1.1 Walk-through metal detectors

Assessments of exposure to the magnetic fields produced by two walk-through metal detectors have been carried out. The construction of both detectors was that of an archway with two vertical pillars supporting a cross-piece situated above them. One pillar housed a transmitter unit which utilised conducting coils to produce a pulsed magnetic field within the archway. The other pillar contained a receiver which employed a set of coils to detect the electric currents induced in metallic objects by the pulsed field. The magnetic field waveforms from both detectors consisted of a train of bipolar pulses and fast Fourier transforms (FFTs) of the pulses exhibited broad spectral content with an amplitude peak in the region of 1 kHz.

A technique for assessing exposures to pulsed magnetic fields has been described in an NRPB report (Chadwick 1998) and was used to analyse the measurements from the two detectors. The instantaneous current density induced in the body was determined from the rate of change of magnetic flux density associated with the pulsed waveform using Faraday's Law of electromagnetic induction. A dosimetric model was employed assuming that the induced current flows in a circular loop of tissue of radius 20 cm and of homogeneous conductivity. The spatial distribution of magnetic flux density over the vertical plane 5 cm away from the inner surface of the transmitting pillar was taken into account using simple numerical or analytical methods.

An FFT was applied to the derived waveform of current density and the resulting spectrum was normalised with respect to the basic restriction. This was necessary since the basic restriction varied over the frequency range covered by the spectral content of the pulse train. An inverse transform was then applied to yield a representation of the induced current density as a quotient of the basic restriction in the time domain. Compliance with the guidelines could then be assessed based on the instantaneous maximum exposure quotient over the duration of the pulse.

The results from the two assessments are given in Table 15 where the peak magnetic flux densities are the maximum values measured anywhere close to the transmitting pillars. The exposure quotients are expressed as percentages such that a quotient no greater than 100% indicates compliance with the basic restriction. The basic restriction on induced current density was not found to be exceeded at any location within the archway of either detector.

TABLE 15 Exposures from walk-through metal detectors

Metal detector	Peak magnetic flux density (μT)	Exposure quotient
1	94	69%
2	105	40%

7.1.2 Hand-held metal detectors

The operation of hand-held metal detectors is generally based on a coil which carries an alternating current, often at kilohertz frequencies, thus producing a magnetic field. If electrically conducting material is brought within the detection range of the device, eddy currents are produced in the material which 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.

Exposure assessments of two hand-held metal detectors have been carried out. The first detector produced a sinusoidal magnetic field with frequency 20 kHz and the ICNIRP reference level for this frequency is 30.7 μT. The maximum magnetic flux density recorded 2.5 cm from the casing of the detector was measured at 4.5 μT.

The frequency of the sinusoidal magnetic field produced by the second detector was 94 kHz and the reference level for this frequency is 21.3 μT. The maximum magnetic flux density recorded 2.5 cm from the casing of the second detector was 5.1 μT.

7.2 Radiofrequency identification

Radiofrequency product identification and personnel access control systems essentially consist of four items: a transmitter, a receiver, an antenna and a tag, or transponder. The transmitter and receiver may be combined in a single transceiver unit known as the interrogator or reader. The transmitter generates an RF signal which is emitted by the antenna. If a tag is within range, it responds with a signal that is recognised by the receiver. Tags can be active, with an internal battery, or passive, deriving power from the electromagnetic field produced by the antenna. Communication between the transceiver and the tag is generally achieved by inductive coupling, capacitive coupling or by sending and receiving electromagnetic waves. RFID applications use a wide range of frequencies from below 135 kHz to microwave frequencies in the UHF and SHF bands.

Assessments of exposure have been carried out for five RFID systems. The transceivers associated with each system emitted continuous sinusoidal signals that were fed to planar wire coil antennas. Where tags were available, these were passive devices that derived their power from the electromagnetic field produced by the antenna. The maximum vector-summed resultant magnetic flux densities measured at varying distances from the antennas are shown in Table 16. The magnetic flux densities were not materially altered when the effect of bringing a tag into the detection range of the device was investigated.

TABLE 16 Magnetic flux densities around RFID equipment. Measured values are italicised where the reference level was exceeded

Device	Frequency (kHz)	Reference level (μT)	Distance (cm)	Magnetic flux density (μT)
Card reader	120	17	7.5	*20*
			12	10
Antenna	120	17	7.5	10
Antenna	134	15	2.5	*25*
			5	7
Antenna	154	13	2.5	*15.0*
			5	5.3
			10	1.2
Card reader	4900	0.41	5	*8.4*
			10	*2.1*
			20	0.3

The measurements of magnetic flux density, reported in Table 16, exceeded the reference level close to some of the RFID equipment that was assessed. The regions where the reference level was exceeded were generally highly localised and the magnetic flux density reduced rapidly with increasing distance from the device. For frequencies above 100 kHz the guidelines permit time averaging, based on the square of magnetic flux density, which may be invoked when investigating transient exposures. Time averaging is carried out over a six-minute period when the frequency is below 10 GHz.

A numerical dosimetric analysis has been used to calculate the current density induced in a loop of human tissue, and the concomitant SAR, for the two card readers and the first two antennas listed in Table 16. The analysis was based on the spatial distribution of magnetic flux density, as outlined in Section 7.1.1. The results indicated that the basic restrictions on induced current density and SAR would not be exceeded, even under pessimistic conditions of exposure to the magnetic fields produced by the devices. These conditions assume that the torso is close to the device in the region where the field strength is greatest and that, where appropriate, the vector component of the magnetic field with the greatest magnitude is perpendicular to the front surface of the body. The maximum induced current densities evaluated for the devices were typically in the region of 10% of the basic restriction and the corresponding SARs were less than 10% of the basic restriction on whole-body average SAR.

7.3 EAS equipment

Electronic article surveillance equipment is used to prevent theft from shops and libraries etc. EAS systems essentially comprise a detection unit, a tag to be detected and sometimes a tag deactivator. The principles of operation are similar to those of metal detectors and RFID systems in that an electromagnetic field is produced over a defined volume and, if a tag that has not been deactivated or removed from the item to which it is attached enters the detection region, the resulting characteristic perturbation of the field is detected. As with RFID systems, a broad range of frequencies is used by different types of EAS equipment from sub-kilohertz frequencies to microwave frequencies.

EAS detectors typically contain two or more field-generation and detection elements which have the appearance of flat panels, loops or pillars and are positioned either side of the customer exit of the store or library, etc. At least one of the elements contains transmitter coils; the other element or elements contain receiver coils, and possibly transmitter coils too if a Helmholtz configuration is employed. Systems also exist that employ just a single antenna containing coils that are connected to the transceiver.

Tags are normally passive devices containing no internal power source, although active tags do exist. They may be durable, in which case they are removed from the goods at the customer checkout, or they may be disposable, usually in the form of adhesive patches attached to the packaging. Disposable tags used with lower frequency systems may contain a ferromagnetic strip, the magnetisation of which can be altered at the checkout. Disposable tags associated with higher frequency inductive systems typically contain a resonant element or circuit which is disabled at the checkout using a deactivator. The change in field strength resulting from bringing a tag, whether active or passive, into the vicinity of a detector is usually a small fraction of the field strength that exists in the absence of a tag.

Deactivators are generally desktop devices installed at the customer checkout. Some deactivators produce static magnetic fields which may be continuous or pulsed and which may only be generated on demand. Disposable tags containing resonant circuits may be deactivated by overloading the circuit by electromagnetic induction using a pulsed RF magnetic field at the resonant frequency. RF deactivators may operate in two modes, a detection mode and a deactivation mode. The detection mode is used for sensing the presence of a tag and the transmitted frequency is swept or stepped through the likely resonant frequency of the tag. The deactivation mode is used to disable the tag and the frequency is fixed at the resonant frequency of the tag.

Measurements of electric and magnetic field strength close to EAS equipment and of contact current from some devices have been carried out and the results are summarised in Tables 17–19. The tables also contain the relevant reference levels, including peak values in addition to rms values where appropriate. The field strength values shown in Tables 17 and 18 are the maximum ones measured at a given distance from the device. In the case of exposures to pulsed fields, the displayed field strengths are peak rms values, i.e. the rms field strengths during a pulse. The reported contact currents are the maximum values measured from any part of the device.

TABLE 17 Electric field strengths from EAS detectors and tag deactivators at specified distances from the plane of the antenna casing of each device. The detectors were dual antenna systems unless noted otherwise

Device	Frequency (MHz)	Transmission characteristics	Reference level ($V m^{-1}$)		Distance (cm)	Electric field strength ($V m^{-1}$)
			rms	peak		
Detector	7.4–9.1	Continuous, swept frequency	67–82	–	10	4.0
Detector (single antenna)	7.4–8.8	Continuous, swept frequency	69–82	–	2.5	<1
Detector	7.4–8.8	Continuous, swept frequency	69–82	–	2.5	<1
Deactivator (detection mode)	7.4–8.6	Pulsed, frequency stepped	71–82	~2100	10 20	89* 21
Deactivator (detection mode)	7.4–8.8	Continuous, swept frequency	69–82	–	2.5	<1
Deactivator (deactivation mode)	7.4–8.6	Pulsed, fixed frequency	71–82	~2100	10 20	86* 20
Deactivator (deactivation mode)	7.4–8.8	Pulsed, fixed frequency	69–82	~2100	5 10 20	190† 60 9

* Root mean square reference level complied with when time averaging taken into account due to duty factor of 0.15%.
† Root mean square reference level complied with when time averaging taken into account due to duty factor of 0.25%.

The data given in Table 17 suggest that the reference levels for electric field strength are not exceeded on exposure to the electric fields produced by EAS detectors. The rms reference level was found to be exceeded close to some tag deactivators, however these deactivators generated pulsed fields and the reference levels were complied with once the time averaging permitted by the guidelines was taken into account.

Most of the EAS detectors for which exposure assessments have been carried out operated in the HF band. Of these, the reference level for rms magnetic field strength was exceeded close to one device. The measured exposures may be time averaged on a field-strength-squared basis when investigating transient exposures, as permitted by the guidelines.

In the case of tag deactivators the reference level for rms magnetic field strength could be exceeded up to several tens of centimetres away from the antennas of some units. However these deactivators generated pulsed fields and the rms reference level was exceeded only within 10 cm of the antennas, after time averaging was taken into account. The reference level for peak magnetic field strength was also exceeded in regions within 10 cm of the antennas associated with the deactivators that produced pulsed fields.

TABLE 18 Magnetic field strengths from EAS detectors and tag deactivators at specified distances from the plane of the antenna casing of each device. The detectors were dual antenna systems unless noted otherwise. Measured values are italicised where the rms reference level was exceeded and are given in bold where the peak level was exceeded

Device	Frequency (MHz)	Transmission characteristics	Reference level (A m^{-1}) rms	Reference level (A m^{-1}) peak	Distance (cm)	Magnetic field strength (A m^{-1})
Detector*	0.001953	Pulsed, fixed frequency	24.4	–	25 100	*350* *30*
Detector	7.4–9.1	Continuous, swept frequency	0.18–0.22	–	15 20	0.09 0.06
Detector (single antenna)	7.4–8.8	Continuous, swept frequency	0.18–0.22	–	0† 10 20	*2.0* *0.39* 0.18
Detector	7.4–8.8	Continuous, swept frequency	0.18–0.22	–	15 35	0.12 0.03
Deactivator (detection mode)	7.4–8.6	Pulsed, frequency stepped	0.19–0.22	5.4–5.7	3 10 50	***12.3*** 3.1‡ 0.18
Deactivator (detection mode)	7.4–8.8	Continuous, swept frequency	0.18–0.22	–	2.5	0.12
Deactivator (deactivation mode)	7.4–8.6	Pulsed, fixed frequency	0.19–0.22	5.4–5.7	3 10 30 50	***58*** 2.7‡ 0.34‡ 0.13
Deactivator (deactivation mode)	7.4–8.8	Pulsed, fixed frequency	0.18–0.22	5.4–5.7	5 10 20	***10*** 3§ 0.8§

* It is understood that this detector was never marketed.
† In open section within frame of antenna.
‡ Root mean square reference level complied with when time averaging taken into account due to duty factor of 0.15%.
§ Root mean square reference level complied with when time averaging taken into account due to duty factor of 0.25%.

TABLE 19 Contact currents from EAS systems. The detectors were dual antenna systems unless noted otherwise

Device	Frequency (MHz)	Transmission characteristics	Reference level (mA)	Contact current (mA)
Detector	7.4–9.1	Continuous, swept frequency	40	0.03
Detector (single antenna)	7.4–8.8	Continuous, swept frequency	40	<0.1
Detector	7.4–8.8	Continuous, swept frequency	40	<0.1
Deactivator (detection mode)	7.4–8.6	Pulsed, frequency stepped	40	0.02*
Deactivator (detection mode)	7.4–8.8	Continuous, swept frequency	40	<0.1

* Peak rms current estimated to be 0.5 mA due to duty factor of 0.15%.

A numerical dosimetric analysis based on the spatial distribution of magnetic flux density has been used to calculate the current density induced in a loop of human tissue, and the concomitant SAR, for all of the devices listed in Table 18 that operated in the HF band. The procedure employed was that outlined in Section 7.1.1. The results indicated that the occupational basic restrictions on induced current density and SAR would not be exceeded, even under pessimistic conditions of exposure to the magnetic fields produced by the devices. These conditions assume that the torso is close to the device in the region where the field strength is greatest and that, where appropriate, the vector component of the magnetic field with the greatest magnitude is perpendicular to the front surface of the body, as discussed in Section 7.2.

No contact currents drawn from EAS equipment were measured that exceeded the reference level.

8 MISCELLANEOUS SOURCES

8.1 Permanent magnetisers

Measurements of magnetic flux density have been made close to a tabletop unit used to permanently magnetise small ferromagnetic components. The procedure involved placing the components in a jig and magnetising them by means of a single unipolar magnetic field pulse, produced by charging a capacitor bank and then discharging it through a coil. A trace of the magnetic flux density produced during a pulse is shown in Figure 6.

Exposures were assessed using the technique summarised in Section 7.1.1 whereby the induced current density in a circular loop of tissue is calculated. A uniform spatial distribution of the vector component of magnetic flux density perpendicular to the surface of the body with a temporal amplitude equivalent to the maximum measured amplitude was assumed for simplicity as this provides a conservative method of assessment.

The results from the assessment are given in Table 20 where the exposure quotients are expressed as percentages of the effective basic restrictions. The basic restriction was exceeded close to the magnetiser, however this was at a position where tissues in the head and trunk, to which the basic restriction applies, would not normally be exposed.

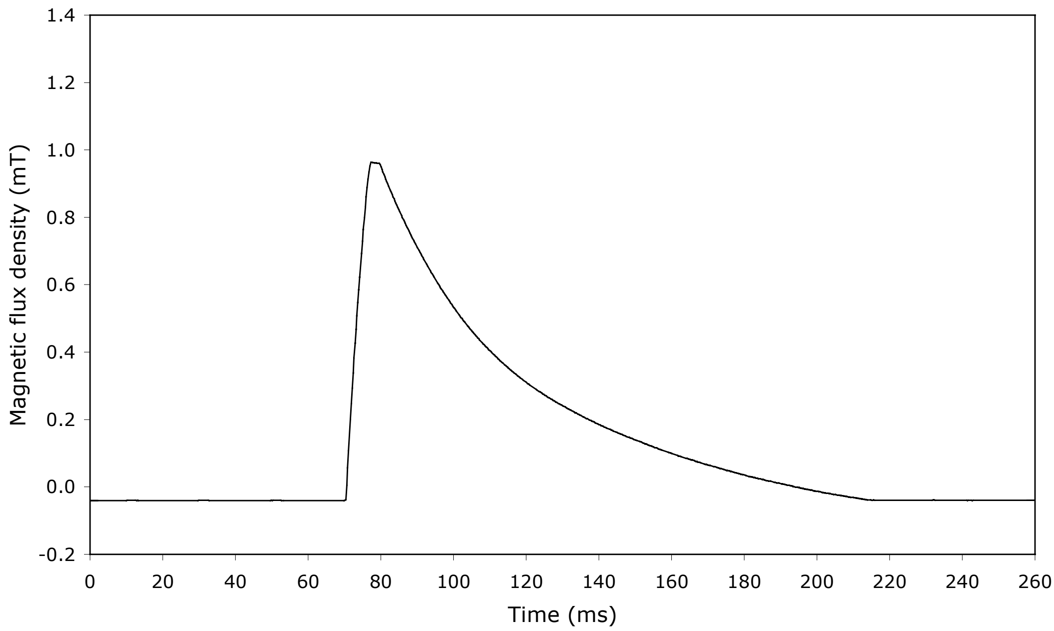

FIGURE 6 Pulse of magnetic flux density captured near a permanent magnetiser

TABLE 20 Exposures from a permanent magnetiser

Distance from jig (cm)	Peak magnetic flux density (mT)	Exposure quotient
10	7.1	200%
30	0.96	29%

8.2 Arc furnaces

Measurements of alternating magnetic flux density have been made close to two 3-electrode arc furnaces used for processing scrap metal. Effective reference levels were derived for each furnace based on the harmonic content observed in the spectra of the magnetic fields produced by the devices. In both cases the fundamental frequency was 50 Hz. The results are shown in Table 21 where the reported values are the maximum magnetic flux densities measured at specified distances from the furnaces. The effective reference level was exceeded close to one of the furnaces.

TABLE 21 Time-varying magnetic flux densities from arc furnaces. Measured values are italicised where the effective reference level was exceeded

Furnace	Power (MW)	Current (kA)	Effective reference level (μT)	Distance (m)	Magnetic flux density (μT)
1	66	54	380	1 3	*480* 300
2	12	30	440	1 2	240 130

8.3 Crack detection equipment

Crack detection equipment is used in the non-destructive testing of metallic components. The systems that have been assessed by NRPB were used to induce or inject a current into ferromagnetic workpieces. Current induction occurs through placing the workpiece inside several turns of a coil. The direct injection of current into a workpiece is achieved via electrodes at each end of the piece. In some systems the electrodes are hand-held. A ferromagnetic dye or contrast agent applied to the surface of the workpiece allows cracks, flaws or discontinuities to be observed when viewed under a suitable light source. Crack detection systems can use AC or DC supplies, although the latter generally produce a rectified current that may contain harmonics of the fundamental power frequency. The current may be delivered continuously or in pulses. Some systems incorporate a demagnetising function whereby an alternating current is gradually reduced to zero amplitude over a period of time.

It is normal practice for the harmonic content of the magnetic fields produced by AC and DC crack detection systems to be examined in an exposure assessment and for an effective reference level to be evaluated for each magnetic field waveform encountered, as discussed in Section 2.3. The results of static and time-varying magnetic flux density for two different units are shown in Tables 22 and 23. The measurements were made at the positions typically occupied by personnel whilst operating the equipment.

TABLE 22 Static magnetic flux densities from a DC crack detection system

Model	Operating mode	Current (kA)	Position	Magnetic flux density (mT)
1	Induction Injection	3.7 –	Hands Limbs Torso Head	3.2 20 5 4
Exposure limit for whole working day (time-weighted average)				200

TABLE 23 Time-varying magnetic flux densities from AC and DC crack detection systems. Measured values are italicised where the effective reference level was exceeded and are given in bold where this occurred at positions of exposure of the head or torso

Model	Type	Operating mode	Current (kA)	Effective reference level (μT)	Position	Magnetic flux density (μT)
1	DC	Induction	3.7	350	Limbs	*2300*
					Torso	***800***
					Head	300
		Injection	–	180	Hands	*350*
					Torso	8
					Head	42
2	AC	Induction	2.0	500	Hands	*3000*
					Limbs	*2050*
					Torso	***900***
					Head	390
		Injection	–	250	Hands	*1200*
					Torso	18
					Head	9

All the measured static magnetic flux densities reported in Table 22 are below the ICNIRP limit on time-weighted average magnetic flux density for continuous exposure during the work day. The time-varying magnetic flux densities reported in Table 23 indicate that, at typical operating positions, the effective reference level can be exceeded for some systems. In certain cases the reference level was exceeded only in regions close to the electrodes where the limbs, but usually no other part of the body, are exposed. In these cases the basic restriction on induced current density on tissues in the head and trunk would be unlikely to be exceeded.

Where the head or trunk of the operator is exposed to magnetic flux densities in excess of the reference level, there is the possibility that the basic restriction may be exceeded, however this may depend on the spatial distributions of the magnetic fields produced by the equipment.

8.4 Tape erasers

Tape erasers, or degaussers, typically use an ELF (usually power frequency) magnetic field to erase data stored on tapes or other magnetic media. Measurements of magnetic flux density have been made around four erasers that were used to remove information from videotapes. The maximum magnetic flux densities measured at a number of specified distances from the tape erasers are shown in Table 24.

The data shown in Table 24 indicate that the reference level can be exceeded in regions within a few tens of centimetres from certain types of tape eraser. It is unlikely that the basic restriction on induced current density in tissues of the head and trunk would be exceeded if the limbs alone are exposed in these regions.

TABLE 24 Time-varying magnetic flux densities from tape erasers. Measured values are italicised where the reference level was exceeded

Model	Description	Reference level (μT)	Distance (cm)	Magnetic flux density (μT)
1	Compact degausser	380*	7 15	*500* 300
2	Tape eraser	500	15 20	*604* 500
3	Bulk tape eraser	500	15 20	*4000* <500
4	Bulk tape eraser	500	5 20	*5000* *800*

* Effective reference level derived from spectral analysis which revealed the presence of harmonics of the 50 Hz fundamental frequency with significant components extending up to 350 Hz.

8.5 Fibre curing units

Fibre curing units are used to coat reels of optical fibre with ultraviolet (UV) curable ink. The units incorporate UV lamps which may be powered by a source of RF radiation. Assessments of exposure to electromagnetic radiation at the frequency 2.45 GHz have been carried out for three curing units. The front of each unit was enclosed within polycarbonate panels which could only be opened when the system was running at low speed and on reduced power. The maximum power densities measured close to each unit are shown in Table 25; none of the measurements exceeded the ICNIRP reference level.

TABLE 25 Power densities from fibre curing units

Model	Operating conditions	Reference level ($W\ m^{-2}$)	Power density ($W\ m^{-2}$)
1	Normal	50	<1
2	Normal	50	1.5
3	Low speed, low power; enclosure open	50	3

9 DISCUSSION

The discussion is divided into two sections. The first section discusses the impact on the conclusions of NRPB report R265 of adopting the ICNIRP guidelines. The second section discusses the exposures that have been found to exceed the ICNIRP reference levels in the more recent investigations detailed in this review.

The reference levels of electric and magnetic field strength, magnetic flux density and power density advised by ICNIRP are intended to be spatially averaged values over the entire body of the exposed individual, providing the basic restrictions on localised exposure are not exceeded. Spatial averaging has not generally been taken into account in the exposure assessments reported here, hence comparisons with the ICNIRP reference levels may be pessimistic, particularly in situations where the spatial distribution of electromagnetic fields is highly non-uniform.

9.1 Exposure data reported in NRPB-R265

The exposure data collated in NRPB report R265 are displayed in Figures 7–9 where the measured data are compared with the ICNIRP occupational reference levels.

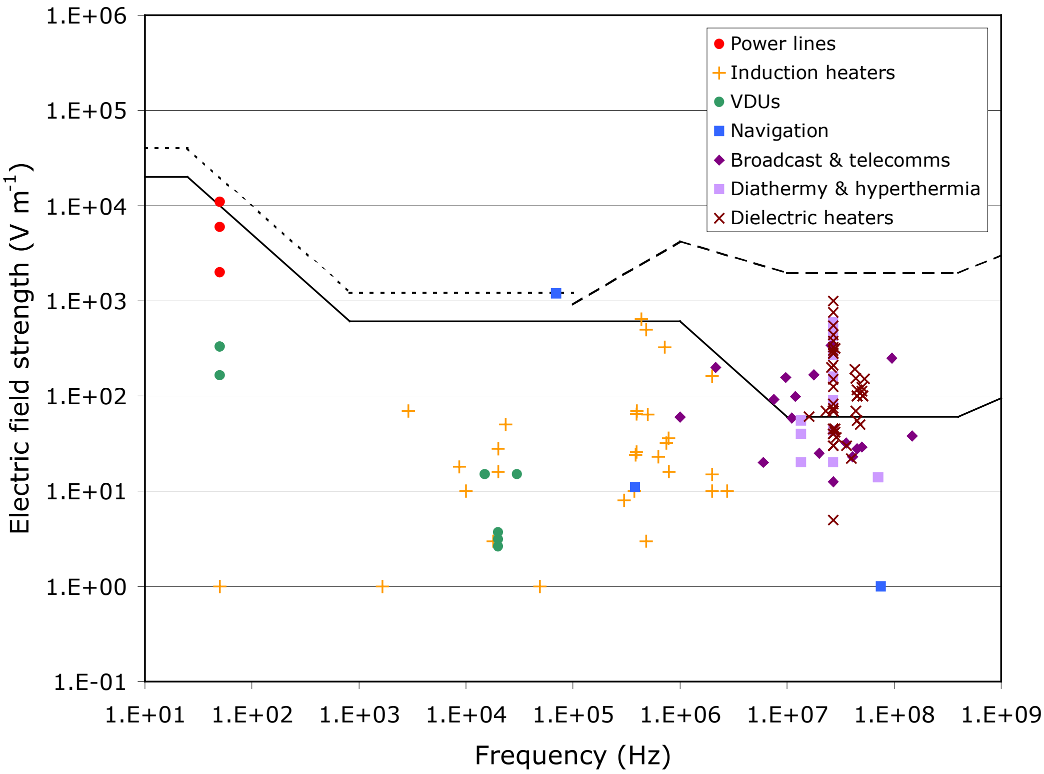

FIGURE 7 Occupational electric field exposures reported in NRPB-R265 shown with the ICNIRP reference levels for rms electric field strength (solid line) and peak electric field strength (broken line). The dotted line extending to frequencies below 100 kHz indicates the rms reference level that applies under conditions in which adverse indirect effects from contact with electrically charged conductors can be excluded

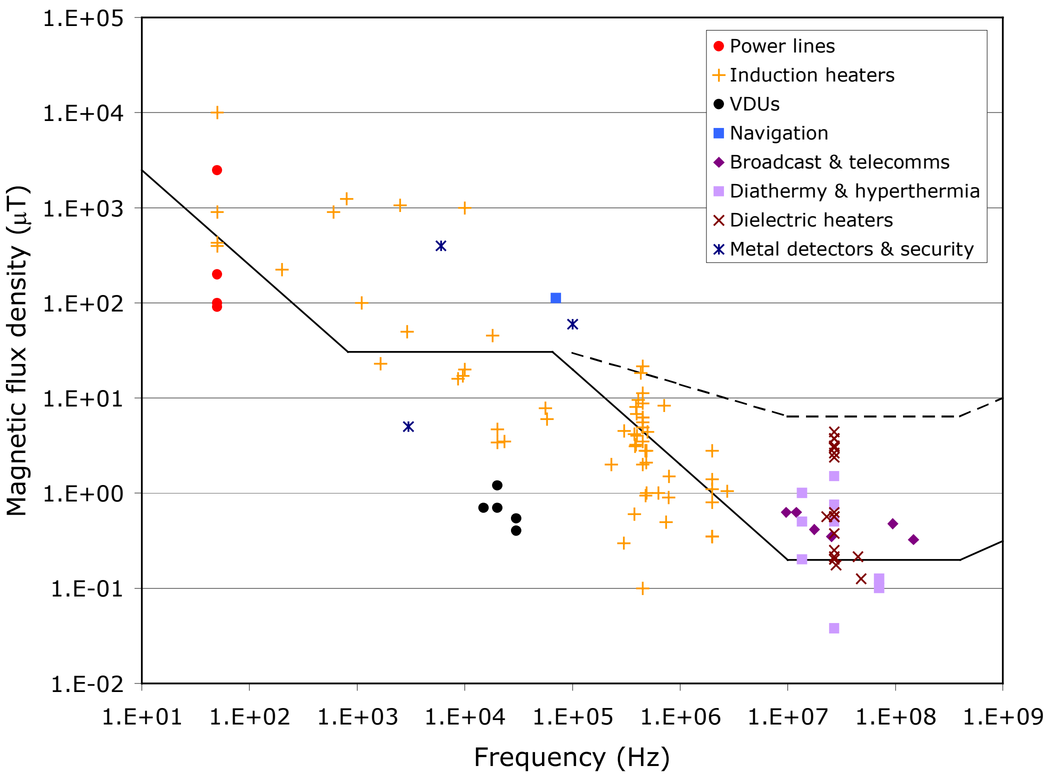

FIGURE 8 Occupational magnetic field exposures reported in NRPB-R265 shown with the ICNIRP reference levels for rms magnetic flux density (solid line) and peak magnetic flux density (broken line)

The NRPB-R265 data suggest that, in the case of electric fields, some induction heaters, dielectric heaters, broadcast and telecommunications antennas and short-wave diathermy sources give rise to exposures that might exceed the ICNIRP rms reference level. However, exposures to certain examples of the abovementioned sources will not be continuous over six-minute periods and the ICNIRP guidelines permit time averaging of electric field strength at frequencies greater than 100 kHz over a six-minute period. Field strength values are to be squared before time averaging is applied.

Two additional measurements lie above the reference level for rms electric field strength in Figure 7 and these are due to a high-voltage power line and an LF navigation system with a frequency of about 70 kHz. NRPB-R265 identifies the latter as an unusual and rare exposure condition that is unlikely to involve more than a few maintenance workers. Both measurements would comply with the reference level under conditions in which adverse indirect effects from contact with electrically charged conductors can be excluded.

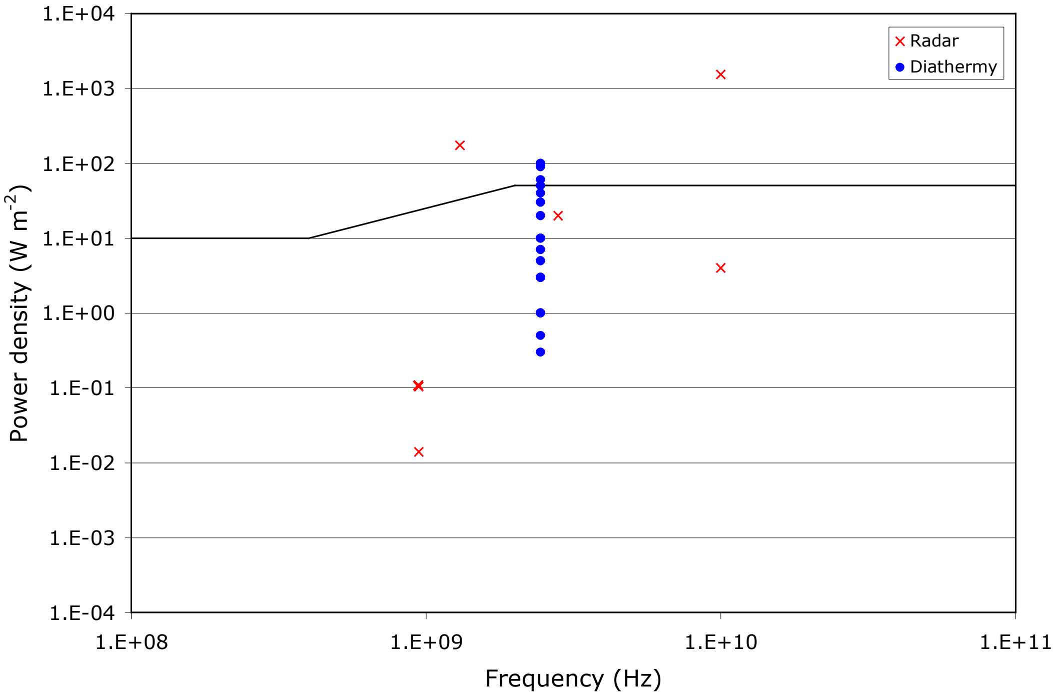

FIGURE 9 Occupational power density exposures reported in NRPB-R265 shown with the ICNIRP reference level for equivalent plane wave power density (solid line). Power densities from exposure to radar are shown as mean values. The guidelines suggest that the peak equivalent plane wave power density, as averaged over the pulse width, does not exceed 1000 times the reference level

In the case of magnetic fields, the NRPB-R265 data suggest that the ICNIRP rms reference level might be exceeded on exposure to some induction heaters, dielectric heaters, broadcast and telecommunications antennas, security systems, short-wave diathermy and hyperthermia sources and the LF navigation system discussed above.

Many of the sources that give rise to exposures to magnetic fields exceeding the rms reference level operate at frequencies greater than 100 kHz. At these frequencies time averaging can be applied in the same way that it can for exposures to electric fields, i.e. the square of magnetic field strength, or magnetic flux density, is averaged over a six-minute period. Figure 8 suggests that exposures to frequencies above 100 kHz that exceed the peak reference level are likely to be uncommon.

Exposures to microwave sources are shown on the graph of power density in Figure 9 and the two categories of source identified are radar and microwave diathermy. The measurements indicate that power densities were usually below the ICNIRP reference level, although there is the potential for this level to be exceeded if the main beam of certain radar systems can be approached close to the source. There is also the possibility that power densities from microwave diathermy may exceed the reference level under certain exposure conditions.

Time averaging of exposures is carried out in a straightforward manner by taking the average power density over the period of time specified by ICNIRP for the frequency of interest.

Much of the discussion in NRPB-R265 on sources and exposures is valid here. For example many sources operate at frequencies above 10 MHz where time-averaging of whole-body and localised SAR is allowed over a period of six minutes when comparing exposures with the basic restrictions. The low duty factors of dielectric heaters and some telecommunications systems can lower the time-averaged exposures considerably with respect to the instantaneous maximum exposures. Working practices may also reduce time-averaged exposures, for example at broadcast sites there may be procedures designed to prevent prolonged exposure close to feeders or antenna arrays associated with high-power transmitters.

In some situations the spatial distributions of electric and magnetic fields may be highly non-uniform so that SARs averaged over the whole body or parts of the body may be lower than those that would be expected to occur under uniform exposure to the local maximum field strength. This might be the case, for example, close to some antennas used in security and access control devices.

9.2 New exposure data

The exposure data contained within this review are summarised in Figures 10–12 where measured electric field strengths, magnetic flux densities and contact currents are compared with the ICNIRP occupational reference levels. The data shown are generally maximum rms values for each device or application, although separate values are given representative of limb exposure and whole-body exposure where these are different.

9.2.1 Electric fields

All the sources of exposure with frequencies less than 100 kHz for which measurements of electric field strength were included in this review were associated with the electricity generation industry. A few of the measurements summarised in Figure 10 exceeded the reference level for 50 Hz and the highest recorded electric field strength was 14 kV m^{-1}. Exposure to electric field strengths exceeding the reference level may result in stress due to the perception and annoyance of surface charge effects and other indirect effects. However, it is expected that even the strongest fields reported in this review would not be sufficient to cause the basic restriction on induced current density to be exceeded since all the measured field strengths would comply with the reference level under conditions in which adverse indirect effects from contact with electrically charged conductors can be excluded.

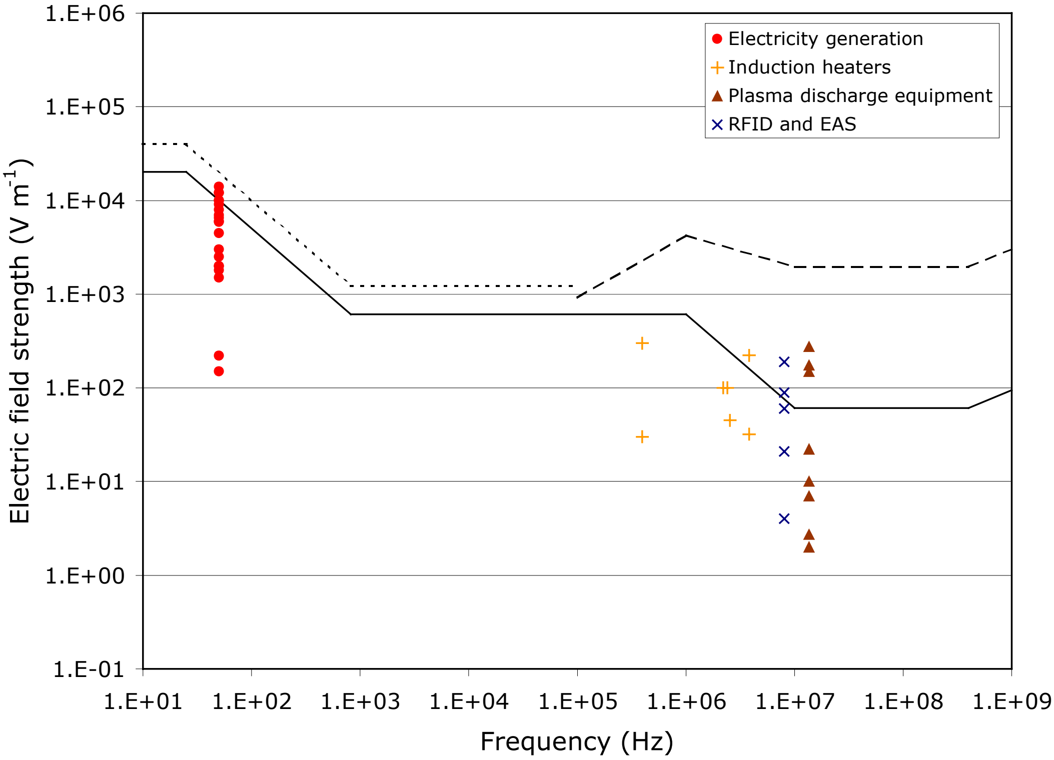

FIGURE 10 Occupational electric field exposures shown with the ICNIRP reference levels for rms electric field strength (solid line) and peak electric field strength (broken line). The dotted line extending to frequencies below 100 kHz indicates the rms reference level that applies under conditions in which adverse indirect effects from contact with electrically charged conductors can be excluded

At frequencies greater than 100 kHz the ICNIRP reference level for rms electric field strength was exceeded by a single measurement close to an induction heater and by measurements from RF sputtering units and EAS tag deactivators. The reference level for peak field strength was not exceeded by any exposure measurements. The EAS tag deactivators that have been assessed transmitted pulses with a low duty cycle, consequently the reference levels were not exceeded after the time averaging permitted by the guidelines was taken into account. The isolated instance where the reference level was exceeded near an induction heater was at a location closer to the heater than the typical operator position, therefore the time-averaged exposure would be unlikely to exceed the reference level under normal circumstances. The electric field strengths that exceeded the reference level close to some sputtering units occurred at locations where the head and trunk would not normally be exposed. Again, these exposures can be averaged over time so transient exposures exceeding the reference level are permitted under the conditions specified in the guidelines.

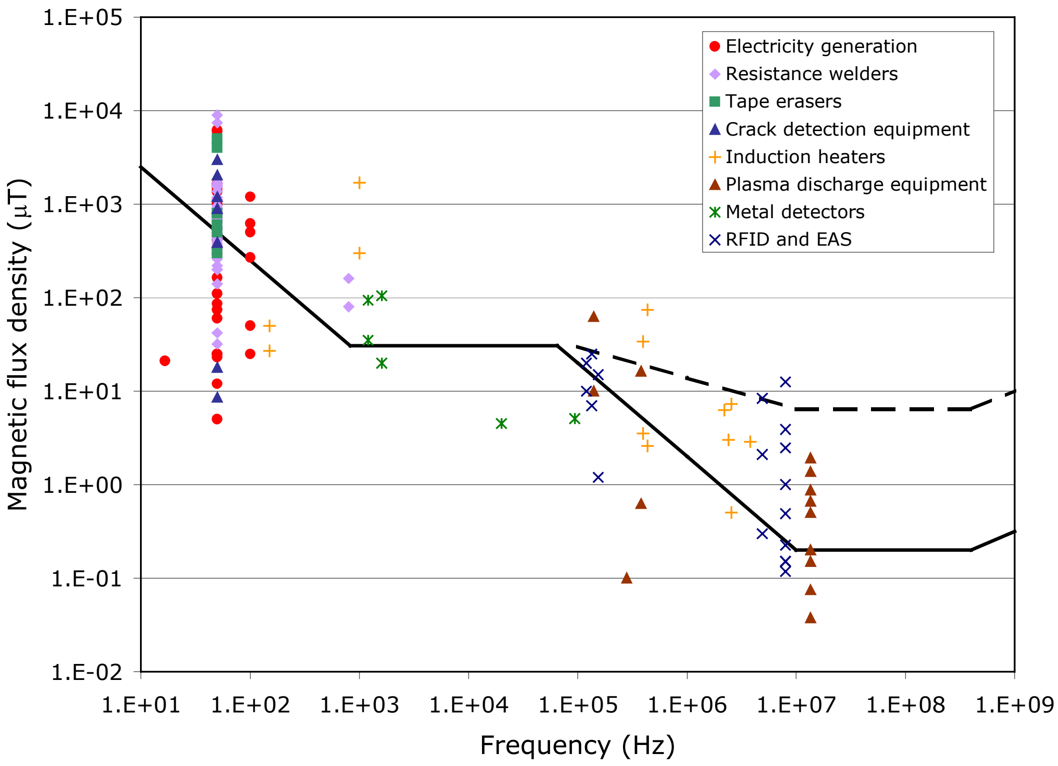

FIGURE 11 Occupational magnetic field exposures shown with the ICNIRP reference levels for rms magnetic flux density (solid line) and peak magnetic flux density (broken line)

9.2.2 Magnetic fields

9.2.2.1 Frequencies below 100 kHz

The magnetic flux densities shown in Figure 11 indicate that the ICNIRP occupational reference level is exceeded by a number of devices and applications. Averaging of exposure over time is not permitted for frequencies below 100 kHz and the reference level was found to be exceeded by electricity generation equipment, tape erasers, crack detection equipment, resistance welders, an induction heater and metal detectors.

Locations close to electricity generating equipment where the effective reference level for magnetic flux density was exceeded were sometimes confined to highly localised regions where parts of the body other than the limbs and extremities would not normally be exposed. In these cases the basic restriction on induced current density in tissues of the head and trunk would be unlikely to be exceeded. However, there is the possibility that the basic restriction may be exceeded at locations where the head or trunk of a worker could be exposed to magnetic flux densities exceeding the reference level. Preventing access to these locations by administrative procedures or controls would provide protection in these instances.

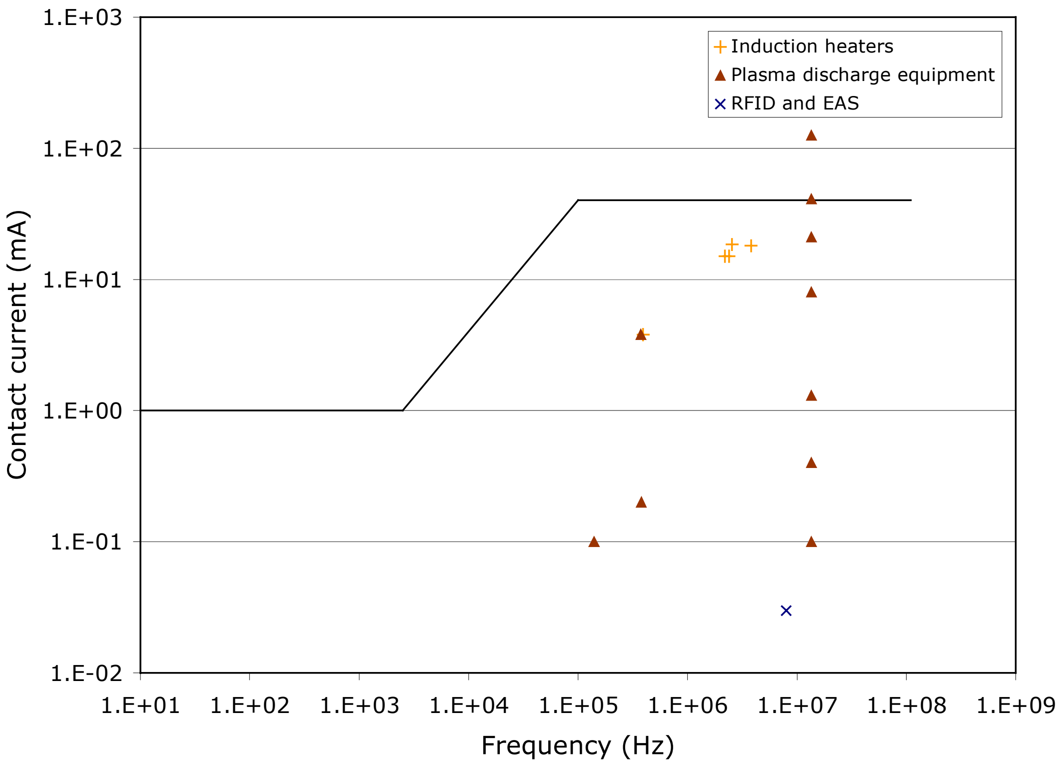

FIGURE 12 Occupational contact current exposures shown with the ICNIRP reference level (solid line)

Assessments of exposure to magnetic fields produced by resistance welders, induction heaters, crack detection systems and tape erasers demonstrated that the reference level could be exceeded at the normal operator positions near certain machines. In some cases the reference level was exceeded only in highly localised regions where parts of the body other than the hands and arms would not normally be exposed. In these cases, as above, the basic restriction on induced current density on tissues in the head and trunk would be unlikely to be exceeded. Where the head or trunk of the operator is exposed to magnetic flux densities in excess of the reference level, there is the possibility that the basic restriction may be exceeded. A lack of detailed information on typical spatial distributions of magnetic fields prevents general conclusions being drawn on the likelihood of the basic restriction being complied with in cases where the reference level is exceeded.

The two metal detectors, close to which the reference level was found to be exceeded, were isolated examples and it is not possible to conclude whether or not the devices assessed were representative of the range of equipment operating at kilohertz frequencies. In both cases the current density induced in a 20 cm loop of homogeneous human tissue was determined from the rate of change of magnetic flux density measured in the assessments, taking into account the spatial distributions of the magnetic fields. The analyses suggested that the basic restriction on induced current density would not be exceeded at any position of exposure.

9.2.2.2 Frequencies greater than 100 kHz

At frequencies greater than 100 kHz the ICNIRP reference level for rms magnetic flux density was exceeded by measurements close to induction heaters, plasma etchers, RF sputtering units, RFID systems and EAS equipment. The reference level for peak magnetic flux density was also exceeded under certain circumstances on exposure to a minority of the devices assessed. The ICNIRP guidelines permit time averaging, based on the square of magnetic flux density, which may be invoked when investigating transient exposures or exposures to pulsed fields where the measured values do not exceed the peak reference level.

Exposure to magnetic fields produced by induction heaters generally exceeded the rms reference level only at locations closer to the devices than the typical operating positions. Consequently it is unlikely that the time-averaged exposures would exceed the reference level under normal operating conditions.

Measurements of magnetic field strength exceeded the rms reference level close to the reaction vessels of some of the plasma etchers and RF sputtering units that have been assessed. However the locations where the reference level was exceeded were generally confined to highly localised regions where the head and trunk of operators would not normally be exposed.

Measurements of magnetic field strength close to some RFID equipment and EAS detectors operating at frequencies above 100 kHz exceeded the rms reference level, however this generally occurred only in highly localised regions and the magnetic flux density was found to reduce rapidly with increasing distance from the devices. The measured exposures may be time averaged on a field-strength-squared basis when investigating transient exposures. The reference level for rms magnetic field strength could be exceeded up to several tens of centimetres away from EAS tag deactivators, however the deactivators generated pulsed fields and the reference levels were generally only exceeded much closer to the devices once the time averaging permitted by the guidelines was taken into account.

A numerical dosimetric analysis based on the spatial distribution of magnetic field strength has been used to calculate the current density induced in a loop of human tissue, and the concomitant SAR, for many of the RFID and EAS devices for which exposure assessments have been carried out. The results indicated that the occupational basic restrictions on induced current density and SAR would not be exceeded, even under pessimistic conditions of exposure to the magnetic fields produced by the devices. Protocols for assessing compliance with the ICNIRP guidelines for RFID and EAS devices have been developed by the European Committee for Electrotechnical Standardization (CENELEC 2001a, 2001b).

9.2.3 Contact currents

The measurements of contact current are summarised in Figure 12 and the reference level was exceeded only on contact with the vacuum chamber of one of the sputtering units that was assessed. In situations where the contact current reference level is exceeded there may be the potential for RF burn to occur or for the reference level on limb current to be exceeded, possibly giving rise to tissue heating induced by the flow of RF current.

10 CONCLUSIONS

A review has been given of the results from assessments of exposure to the electric and magnetic fields produced by a variety of sources over a broad spectrum of sub-optical frequencies. The review is based on work undertaken by NRPB since publication of NRPB-R265 in 1994. The assessments were largely carried out under commercial contract to companies and other organisations who requested the work. Consequently there may be devices and applications that give rise to significant occupational exposures to electromagnetic fields that have not been included in the review. Moreover, the reported results should not necessarily be considered representative of all actual and potential exposures to the fields produced by all examples of the types of device and application covered by the review. Notwithstanding the above, a number of areas have been identified where the reference levels or basic restrictions advised in the ICNIRP guidelines may be approached or exceeded.

The guidelines published by ICNIRP for occupational exposure to time-varying electric, magnetic and electromagnetic fields advise basic restrictions that are based directly on established health effects. The physical quantities used to specify the basic restrictions are, depending on frequency: induced current density, specific energy absorption rate (SAR) and power density. ICNIRP has introduced reference levels for practical exposure assessment purposes to determine whether the basic restrictions are likely to be exceeded. The reference levels that apply in a given exposure situation depend on frequency, whether there is the potential for indirect effects to occur and whether the fields are pulsed. The reference levels are expressed in terms of electric field strength, magnetic field strength (and magnetic flux density), power density, limb current, contact current and specific energy absorption (SA).

The main devices and applications close to which reference levels were found to be exceeded in at least some of the assessments reviewed in NRPB-R265 and in this report are listed below with additional comments based on measurements carried out by NRPB. It should be noted that occupational exposures to the devices listed do not necessarily exceed the reference levels under all circumstances, but that measurements have been recorded where the reference levels were exceeded in some instances.

Electricity generating equipment	Head and trunk exposed in excess of the reference level for magnetic flux density near certain types of equipment. Basic restriction on induced current density not expected to be exceeded on exposures to electric fields.
Resistance welders	Potential for basic restriction to be exceeded may depend on operator position and spatial distribution of magnetic field.
Tape erasers	Potential for basic restriction to be exceeded may depend on operator position and spatial distribution of magnetic field.
Crack detection equipment	Potential for basic restriction to be exceeded may depend on operator position and spatial distribution of magnetic field.
Induction heaters	Potential for exceeding reference levels likely to depend on operator position. Time averaging can be applied for frequencies at or above 100 kHz.
Dielectric heaters	Basic restrictions may not necessarily be exceeded where reference levels are exceeded due to non-uniform fields and low duty factors.
Plasma etchers	Head and trunk not normally exposed in excess of reference levels. Time averaging can be applied.
RF sputtering units	Head and trunk not normally exposed in excess of reference levels. Time averaging can be applied.
RFID	Time averaging can be applied for frequencies at or above 100 kHz. Basic restrictions have not been exceeded in simple dosimetric assessments.
EAS equipment	Time averaging can be applied for frequencies at or above 100 kHz. Basic restrictions have not been exceeded in simple dosimetric assessments of devices operating in the HF band.
Diathermy and hyperthermia	Potential for exceeding reference levels likely to depend on operator position. Time averaging can be applied.
Broadcast and telecommunications	Time averaging can be applied for frequencies at or above 100 kHz.

The ICNIRP guidelines state that compliance with the reference levels ensures compliance with the relevant basic restrictions, however the reference levels are not limits and if they are exceeded by measured or calculated values, it does not necessarily follow that the basic restrictions will be exceeded. In many of the exposure assessments carried out by NRPB it is likely that the basic restrictions would not have been exceeded even though the reference levels were exceeded and this has been confirmed in some assessments of RFID and EAS equipment. There are several reasons for this and they are outlined below.

Firstly the reference levels of electric and magnetic field strength, magnetic flux density and power density are intended to be spatially averaged values over the entire body of the exposed individual, providing the basic restrictions on localised exposure are not exceeded. Many of the fields produced by the above devices exhibit considerable spatial variation, therefore the current density and SAR induced in the body under realistic conditions may be less than those that would be induced assuming the whole body was exposed uniformly to the maximum field strength measured at a point in space.

Secondly at frequencies below 100 kHz the prime consideration is the basic restriction on induced current density which applies to tissues of the head and trunk. If the only parts of the body exposed to field strengths exceeding the reference level are the limbs and extremities then it is likely that the basic restriction would not be exceeded.

Thirdly at frequencies above 100 kHz the rms reference levels may be time averaged, providing the peak reference levels are not exceeded. Consequently the effective exposures may be reduced if they are transient or due to pulsed fields.

Further work may be required in some areas to determine whether occupational exposures exceeding the reference levels are likely to result in non-compliance with the basic restrictions. Analyses of the spatial distributions of magnetic fields produced by resistance welders, RFID devices, EAS equipment and other security systems would provide valuable information on exposures and would allow compliance with the basic restrictions to be investigated in greater detail. Product standards for some of these devices have been developed by the European Committee for Electrotechnical Standardization (CENELEC) and the standards incorporate protocols for assessing compliance with reference levels and basic restrictions.

11 ACKNOWLEDGEMENTS

Many of the data reported in this review were obtained in assessments of exposure carried out under commercial contract. The author is grateful to the various individuals and organisations who gave permission for their data to be published in this report.

The measurements reported in this review were obtained in surveys carried out by past and present NRPB staff, to all of whom the author is grateful.

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APPENDIX A

ICNIRP GUIDELINES FOR OCCUPATIONAL EXPOSURE

In developing exposure guidelines, ICNIRP has reviewed studies of exposed human populations, biological studies and the dosimetry of electric and magnetic fields (ICNIRP 1994, 1998a). The exposure limits and basic restrictions advised by ICNIRP for occupational exposure are given in Tables A1 and A2. The limits specified in Table A1 have been set for exposure to a homogeneous field. For inhomogeneous static magnetic fields, the average magnetic flux density must be measured over an area of 100 cm^2.

TABLE A1 Occupational limits of exposure to static magnetic fields

Exposure characteristics	Magnetic flux density (T)
Whole working day (time-weighted average)	0.2
Ceiling value	2
Limbs	5

Notes

(a) Caution: People with cardiac pacemakers and other implanted electrically activated devices, or with ferromagnetic implants, may not be adequately protected by the limits given here. The majority of cardiac pacemakers are unlikely to be affected from exposure to fields below 0.5 mT. People with some ferromagnetic implants or electrically activated devices (other than cardiac pacemakers) may be affected by fields above a few mT.

(b) When magnetic flux densities exceed 3 mT, precautions should be taken to prevent hazards from flying metallic objects.

ICNIRP's response to questions and comments on the guidelines contained several points of clarification relating to the basic restrictions (ICNIRP 1998b). These included a statement on the averaging mass specified for the restrictions on localised SAR to the effect that the 10 g of tissue is intended to be a mass of contiguous tissue with nearly homogeneous electrical properties. The response also states that the basic restriction of 10 mA m^{-2} is intended to protect against acute exposure effects on central nervous system tissues in the head and trunk of the body, with a safety factor of 10. ICNIRP recognised that this basic restriction may permit higher current densities in body tissues other than the central nervous system under the same exposure conditions.

TABLE A2 Basic restrictions for occupational exposure to time-varying electric, magnetic and electromagnetic fields with frequencies up to 300 GHz

Frequency range	Current density for head and trunk (mA m^{-2}) (rms)	Whole body average SAR (W kg^{-1})	Localised SAR (head and trunk) (W kg^{-1})	Localised SAR (limbs) (W kg^{-1})	Power density (W m^{-2})
up to 1 Hz	40	–	–	–	–
1–4 Hz	40/*f*	–	–	–	–
4 Hz – 1 kHz	10	–	–	–	–
1–100 kHz	*f*/100	–	–	–	–
100 kHz – 10 MHz	*f*/100	0.4	10	20	–
10 MHz – 10 GHz	–	0.4	10	20	–
10–300 GHz	–	–	–	–	50

Notes

(a) *f* is the frequency in hertz.

(b) Because of electrical inhomogeneity of the body, current densities should be averaged over a cross-section of 1 cm^2 perpendicular to the current direction.

(c) For frequencies up to 100 kHz, peak current density values can be obtained by multiplying the rms value by √2 (~1.414). For pulses of duration t_p the equivalent frequency to apply in the basic restrictions should be calculated as $f = 1/(2t_p)$.

(d) For frequencies up to 100 kHz and for pulsed magnetic fields, the maximum current density associated with the pulses can be calculated from the rise/fall times and the maximum rate of change of magnetic flux density. The induced current density can then be compared with the appropriate basic restriction.

(e) All SAR values are to be averaged over any 6 minute period.

(f) Localised SAR averaging mass is any 10 g of contiguous tissue; the maximum SAR so obtained should be the value used for the estimation of exposure.

(g) For pulses of duration t_p the equivalent frequency to apply in the basic restrictions should be calculated as $f = 1/(2t_p)$. Additionally, for pulsed exposures in the frequency range 0.3 to 10 GHz and for localised exposure of the head, in order to limit or avoid auditory effects caused by thermoelastic expansion, an additional basic restriction is recommended. This is that the SA should not exceed 10 mJ kg^{-1} for workers [and 2 mJ kg^{-1} for the general public], averaged over 10 g tissue.

(h) Power densities are to be averaged over any 20 cm^2 of exposed area and any $68/f^{1.05}$ minute period (where *f* is the frequency in gigahertz) to compensate for progressively shorter penetration depth as the frequency increases.

(i) Spatial maximum power densities, averaged over 1 cm^2, should not exceed 20 times the value above.

Reference levels for electric and magnetic field strength, magnetic flux density, power density and induced current flowing through the limbs have been derived from the basic restrictions by mathematical modelling and by extrapolation from the results of laboratory investigations at specific frequencies. They are given for the condition of maximum coupling of the field to the exposed individual. The reference levels of external quantities are intended to be spatially averaged values over the entire body of the exposed individual, providing the basic restrictions on localised exposure are not exceeded. Reference levels for contact current have been provided above which caution must be exercised to avoid shock and burn hazards. The reference levels advised by ICNIRP for occupational exposure are given in Tables A3 and A4.

For the specific case of exposures at frequencies up to 100 kHz, the derived electric fields can be increased by a factor of two under conditions in which adverse indirect effects from contact with electrically charged conductors can be excluded.

TABLE A3 Reference levels for occupational exposure to time-varying electric and magnetic fields (unperturbed rms values)

Frequency range	Electric field strength, E ($V\ m^{-1}$)	Magnetic field strength, H ($A\ m^{-1}$)	Magnetic flux density, B (μT)	Equivalent plane wave power density, S_{eq} ($W\ m^{-2}$)
up to 1 Hz	–	163 000	200 000	–
1–8 Hz	20 000	$163\ 000/f^2$	$200\ 000/f^2$	–
8–25 Hz	20 000	$20\ 000/f$	$25\ 000/f$	–
0.025–0.82 kHz	$500/f$	$20/f$	$25/f$	–
0.82–65 kHz	610	24.4	30.7	–
0.065–1 MHz	610	$1.6/f$	$2.0/f$	–
1–10 MHz	$610/f$	$1.6/f$	$2.0/f$	–
10–400 MHz	61	0.16	0.2	10
400–2000 MHz	$3f^{1/2}$	$0.008f^{1/2}$	$0.01f^{1/2}$	$f/40$
2–300 GHz	137	0.36	0.45	50

Notes

(a) f as indicated in the frequency range column.

(b) Provided that basic restrictions are met and adverse indirect effects can be excluded, field strength values can be exceeded.

(c) For frequencies between 100 kHz and 10 GHz, S_{eq}, E^2, H^2 and B^2, are to be averaged over any 6 minute period.

(d) For peak values at frequencies up to 100 kHz see Table A2, note (c).

(e) Between 100 kHz and 10 MHz, peak values for the field strengths are obtained by interpolation from the 1.5-fold peak at 100 kHz to the 32-fold peak at 10 MHz. For frequencies exceeding 10 MHz it is suggested that the peak equivalent plane wave power density, as averaged over the pulse width, does not exceed 1000 times the S_{eq} restrictions, or that the field strength does not exceed 32 times the field strength exposure levels given in the table.

(f) For frequencies exceeding 10 GHz, S_{eq}, E^2, H^2 and B^2 are to be averaged over any $68/f^{1.05}$ minute period (where f is the frequency in gigahertz).

(g) No electric field value is provided for frequencies <1 Hz, which are effectively static electric fields. Electric shock from low impedance sources is prevented by established electrical safety procedures for such equipment.

TABLE A4 Occupational reference levels for current induced in any limb at frequencies between 10 and 110 MHz and for time-varying contact currents from conductive objects

Frequency range	Limb current (mA)	Maximum contact current (mA)
up to 2.5 kHz	–	1.0
2.5–100 kHz	–	$0.4f$
100 kHz – 10 MHz	–	40
10–110 MHz	100	40

Notes

(a) f is the frequency in kHz.

(b) For compliance with the basic restriction on localised SAR, the square root of the time-averaged value of the square of the induced current over any 6 minute period forms the basis of the reference level.

The guidelines specify peak values of electric and magnetic field strength and magnetic flux density that apply at frequencies greater than 100 kHz. Between 100 kHz and 10 MHz the peak values are obtained by interpolation from the

1.5-fold peak at 100 kHz to the 32-fold peak at 10 MHz. An interpolation factor has been published by the Council of the European Union which has suggested that the peak reference levels are obtained by multiplying the corresponding rms reference levels by 10^a where $a = 0.665 \log(f/10^5) + 0.176$ and f is the frequency in hertz (CEU 1999).

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APPENDIX B

ELECTRIC FIELD STRENGTHS AND MAGNETIC FLUX DENSITIES MEASURED AT ELECTRICITY GENERATING STATIONS

The maximum electric field strengths measured in various environments at power stations are given in Table B1. Measurements of magnetic flux density made close to certain components in the electricity generating process are given in Tables B2–B5. The numbers in the first column of each of the tables identify particular power stations and the numbering is consistent such that any individual power station retains the same identifier throughout all the tables.

TABLE B1 Electric field strengths from electricity generating equipment at power stations. The reference level is 10 kV m^{-1} unless noted otherwise. Measured values are italicised where the reference level was exceeded

Power station	Type	Source	Electric field strength (V m^{-1})
1	Coal-fired	Brushgear Busbars Overhead power lines	<100* 200* 4500
2	Coal-fired	Transformer Overhead power lines	6900 1500
3	Coal-fired	Permanent magnet generator Pilot exciter Main exciter Generator Transformer Substation	30 3 30 3 3000 8000
4	Coal-fired	AC generator Transformer Substation Overhead power lines	3 2200 2000 9000
5	Coal-fired	Alternator Overhead power lines Substation	100 3000 10000
6	Coal-fired	HV chamber Overhead power lines	1000 6000
7	Coal-fired	Generator Main exciter Substation	10 30 *12000*
8	Coal-fired	Overhead power lines	5900
9	Coal-fired	Bus bars	*12000*
10	Coal-fired	Overhead power lines	2500
11	Oil-fired	AVR panels Pilot exciter Generator and bus bars Transformer Power lines	20* 10* 50 270 2000
12	Oil-fired	Overhead power lines	2000
13	Oil-fired	Transformer Substation	1200 1500
15	Combined cycle gas turbine	Exciter brushgear Bus bars Generator Transformers Banking compound	10 150 26 1600 10000
16	Combined cycle gas turbine	Switchgear yard	6500
18	Combined cycle gas turbine	Banking compound	*14000*
19	Hydro-electric	Generator Switchgear Bus bars Transformer	11 130 150 25
20	Hydro-electric	Generator Switchgear	20 220
21	Hydro-electric	Alternator Substation	10 3000
22	Hydro-electric	Alternator Substation	100 1800

* Reference level is 5000 V m^{-1} due to 100 Hz frequency.

TABLE B2 Magnetic flux densities from brushgear and exciters at power stations. Measured values are italicised where the effective reference level was exceeded and are given in bold where this occurred at positions of potential exposure of the head or torso

Power station	Type	Source	Effective reference level (μT)	Extent of exposure	Magnetic flux density (μT)
1	Coal-fired	Brushgear	230	Extremities	*500*
				Whole body	70
2	Coal-fired	Permanent magnet pilot exciter	270	Extremities	74
3	Coal-fired	Pilot exciter	430	Extremities	90
		Main exciter	390	Limbs	200
4	Coal-fired	DC generator exciter	440	Limbs	190
5	Coal-fired	Exciter brushgear	150	Extremities	*620*
				Whole body	77
		Pilot exciter	240	Limbs	82
		Rotor brushgear	140	Extremities	*150*
				Whole body	<50
7	Coal-fired	Pilot exciter	420	Extremities	110
		Main exciter	250	Extremities	*1400*
				Torso	***460***
8	Coal-fired	Pilot exciter	165	Extremities	43
		Main exciter	165	Extremities	*820*
				Limbs	140
9	Coal-fired	Pilot exciter	45	Extremities	*100*
				Limbs	35
		Main exciter	160	Extremities	*540*
				Torso	110
		Main exciter brushgear	160	Limbs	140
				Torso	48
10	Coal-fired	Pilot exciter	340	Limbs	60
		Main exciter	270	Extremities	180
11	Oil-fired	Pilot exciter	220	Extremities	*270*
				Head	25
		Main exciter	170	Extremities	*190*
				Head	52
14	Gas turbine	Permanent magnet pilot exciter	210	Extremities	39
		Main exciter	500	Extremities	300
15	Combined cycle gas turbine	Exciter brushgear	150	Extremities	74
		Exciter	150	Limbs	*170*
				Torso	50
		Rotor earth brushgear	390	Whole body	160
16	Combined cycle gas turbine	Exciter	310	Limbs	38
17	Combined cycle gas turbine	Excitation cubicles	54	Extremities	*140*
				Whole body	10
		Exciter (steam turbine)	500	Extremities	36
		Exciter (gas turbine)	350	Extremities	23
21	Hydro-electric	Main exciter	310	Extremities	40
22	Hydro-electric	Main exciter	180	Extremities	12

TABLE B3 Magnetic flux densities from generators and alternators at power stations. Measured values are italicised where the effective reference level was exceeded and are given in bold where this occurred at positions of potential exposure of the head or torso

Power station	Type	Source or location	Effective reference level (μT)	Extent of exposure	Magnetic flux density (μT)
2	Coal-fired	Alternator	500	Extremities	*790*
				Whole body	120
3	Coal-fired	Permanent magnet generator	430	Extremities	140
		Generator	500	Extremities	93
		Alternator pit	500	Limbs	*670*
				Head	***560***
4	Coal-fired	DC generator	500	Whole body	100
		AC generator	380	Extremities	*390*
				Torso	120
		Outside alternator pit	500	Extremities	*700*
5	Coal-fired	Alternator	500	Limbs	*1000*
				Torso	340
		Outside alternator pit	500	Limbs	*960*
				Torso	***520***
7	Coal-fired	Generator	440	Extremities	140
		Alternator	440	Extremities	180
		Alternator pit	500	Extremities	410
8	Coal-fired	Alternator	500	Extremities	*1130*
			500	Whole body	<100
9	Coal-fired	Permanent magnet generator	340	Limbs	<50
		Alternator brushgear	230	Limbs	71
		Alternator	470	Head	410
10	Coal-fired	Alternator	470	Extremities	200
		Alternator pit	340	Limbs	*1000*
				Torso	***570***
11	Oil-fired	Generator	450	Extremities	340
14	Gas turbine	Alternator	500	Extremities	*790*
				Torso	180
15	Combined cycle gas turbine	Generator (gas turbine)	380	Extremities	330
		Generator (steam turbine)	470	Extremities	*1350*
				Whole body	400
16	Combined cycle gas turbine	Alternator	500	Limbs	250
17	Combined cycle gas turbine	Alternator (steam turbine)	500	Extremities	67
		Alternator (gas turbine)	500	Extremities	120
18	Combined cycle gas turbine	Alternator (steam turbine)	500	Extremities	220
		Alternator (gas turbine)	500	Extremities	480
19	Hydro-electric	Generator	310	Extremities	30
		Alternator brushgear	360	Extremities	*410*
				Whole body	10
20	Hydro-electric	Generator	360	Extremities	290
21	Hydro-electric	Alternator	500	Extremities	500
				Whole body	200
22	Hydro-electric	Alternator	500	Extremities	*530*
				Whole body	<200

TABLE B4 Magnetic flux densities from rectifiers, transformers and substations at power stations. Measured values are italicised where the effective reference level was exceeded and are given in bold where this occurred at positions of potential exposure of the head or torso

Power station	Type	Source	Effective reference level (μT)	Extent of exposure	Magnetic flux density (μT)
1	Coal-fired	Transformer	500	Whole body	100
2	Coal-fired	Unit transformer	500	Extremities Whole body	*680* 300
3	Coal-fired	Unit transformer	500	Torso	***950***
		Substation	500	Whole body	25
4	Coal-fired	Generator transformer	500	Extremities	220
		Substation	500	Whole body	20
5	Coal-fired	Rectifiers	280	Limbs	47
		Voltage transformer	500	Head	460
		Substation	500	Whole body	23
7	Coal-fired	Generator transformer	500	Extremities	350
8	Coal-fired	Rectifiers	170	Extremities Torso	*310* ***190***
9	Coal-fired	Rectifiers	120	Extremities Whole body	*150* 74
		Generator transformer	500	Extremities Torso	*5200* 320
10	Coal-fired	Rectifiers	270	Limbs	120
		Rectifier isolators	250	Limbs	230
11	Oil-fired	Generator transformer	500	Whole body	34
14	Gas turbine	Substation switchroom	500	Extremities Head	*780* 310
15	Combined cycle gas turbine	Generator transformer	500	Extremities	70
16	Combined cycle gas turbine	Generator transformer	500	Limbs	270
17	Combined cycle gas turbine	VT transformer cubicle	500	Limbs	150
		Generator transformer (steam turbine)	500	Extremities Whole body	*750* 130
		Generator transformer (gas turbine)	500	Extremities Whole body	*520* 120
18	Combined cycle gas turbine	Rectifier cabinet	170	Extremities	100
		Unit transformer	500	Extremities	360
19	Hydro-electric	Generator transformer	500	Extremities	25
20	Hydro-electric	Earth isolation transformer	500	Extremities	17
21	Hydro-electric	33 kV substation	500	Limbs	200
22	Hydro-electric	33 kV substation	500	Extremities Limbs	*1600* 400

TABLE B5 Magnetic flux densities from conductors, bus bars, switchgear and overhead power lines at power stations. Measured values are italicised where the effective reference level was exceeded and are given in bold where this occurred at positions of potential exposure of the head or torso

Power station	Type	Source or location	Effective reference level (μT)	Extent of exposure	Magnetic flux density (μT)
1	Coal-fired	Exciter bus bars	230	Torso	***1200***
		Switchgear	500	Whole body	160
		415 V conductors	500	Extremities	*1500*
				Torso	200
		Power lines	500	Torso	25
4	Coal-fired	Generator conductors	500	Limbs	*1090*
				Torso	310
		275 kV power lines	500	Whole body	5
5	Coal-fired	Generator bus bars	500	Limbs	400
		400 kV power lines	500	Whole body	40
7	Coal-fired	Alternator conductors	500	Extremities	*1650*
				Torso	***640***
8	Coal-fired	Excitation conductors	170	Extremities	*2500*
		Main conductors	500	Extremities	*6200*
				Head	***510***
9	Coal-fired	Main exciter conductors	210	Limbs	*320*
				Torso	45
10	Coal-fired	Main conductors	500	Head	***1380***
14	Gas turbine	11 kV main conductors	500	Extremities	*6000*
				Head	***1000***
15	Combined cycle gas turbine	Exciter bus bars	150	Extremities	100
		Switchgear	500	Extremities	63
		400 kV banking compound	500	Whole body	9
16	Combined cycle gas turbine	Main conductors	500	Head	56
		Transformer conductors	500	Limbs	*640*
				Whole body	400
17	Combined cycle gas turbine	Main conductors	500	Extremities	480
		HV switchgear room	500	Extremities	200
18	Combined cycle gas turbine	Phase conductors	170	Extremities	*5000*
				Whole body	***380***
		400 kV banking compound	500	Whole body	42
19	Hydro-electric	415 V bus bars	310	Head	***340***
		Switchgear	310	Extremities	60
20	Hydro-electric	Switchgear	500	Limbs	31
21	Hydro-electric	Generator cables	500	Limbs	*640*
				Whole body	400
23	Wind farm	Main conductors	500	Extremities	86
		690 V phase conductors	200	Extremities	160
		Underground conductors	500	Whole body	<0.4