Table 4. Measured current through the finger and the test circuit representing the human body impedance for contact with a Chevrolet Cavalier wagon (metal parts, no paint).

Test subject	Ground	f = 7.3 MHz, E = 18 V m^{-1} current (mA)	f = 162 kHz, E = 6 V m^{-1} current (mA)
Female, 1.60 m (finger)	Copper plate, 1 m^2	6	0.75
	Grass	3	0.41
Male, 1.88 m (finger)	Copper plate, 1 m^2	9	—
	Grass	4	—
Test circuit	Copper plate, 1 m^2	10	1.04
Theoretical value		7.3	1.03

Table 5. Maximum estimated contact current (I) for cars, trucks, and buses in electric fields (E) recommended in the Canadian standard.

Frequency (MHz)	Exposure type	Max. E (V m^{-1})	Max. I (mA)
30–100	Occupational	20	20
	General population	10	10
20	Occupational	35	33
	General population	18	17
10	Occupational	100	80
	General population	50	40
3	Occupational	600	350
	General population	280	160

1985; Gandhi 1987). The ratio of the currents (from eqn 5) as a function of frequency is shown in Fig. 12. Short-circuit currents for objects such as cars, buses, or trucks can be estimated (Guy 1985). Then, currents through a person in finger contact with any of these objects can be estimated from eqn (5), substituting the values of $\hat{Z}$ for the test circuit shown in Fig. 3. Table 5 shows the estimated maximum contact currents (the last column) for objects such as cars, trucks, or buses for the maximum electric field strength recommended in a proposal of the Canadian exposure standard (the third column) (Stuchly 1987). It is anticipated that the contact currents for other objects are not greater than these shown in Table 5 except, possibly, for very tall objects of a relatively small surface area parallel to the ground, such as a crane.

On the basis of the field test (Table 4), it appears that the body impedance test circuit provides a viable way of evaluating the contact current. The current measured by the circuit gives the upper bound of values for people of various sizes under the worst-case conditions, i.e., for perfect contact with the object and the ground. The differences in currents through a male and a female and for two different ground conditions are in agreement with data presented earlier by Gandhi et al. (1987) and Guy (1985). The measurement results are also in agreement with the estimated current through a person assuming the car capacitance of C_o = 800 pF and the short-circuit current equal to $I_o = 1.47 \times 10^{-3}$ fE, where f is the frequency (in Hz) and E is the electric field strength (in V m^{-1}).

CONCLUSION

A measurement method and circuitry have been developed and proven simple and viable for determining contact currents between isolated metallic objects in RF

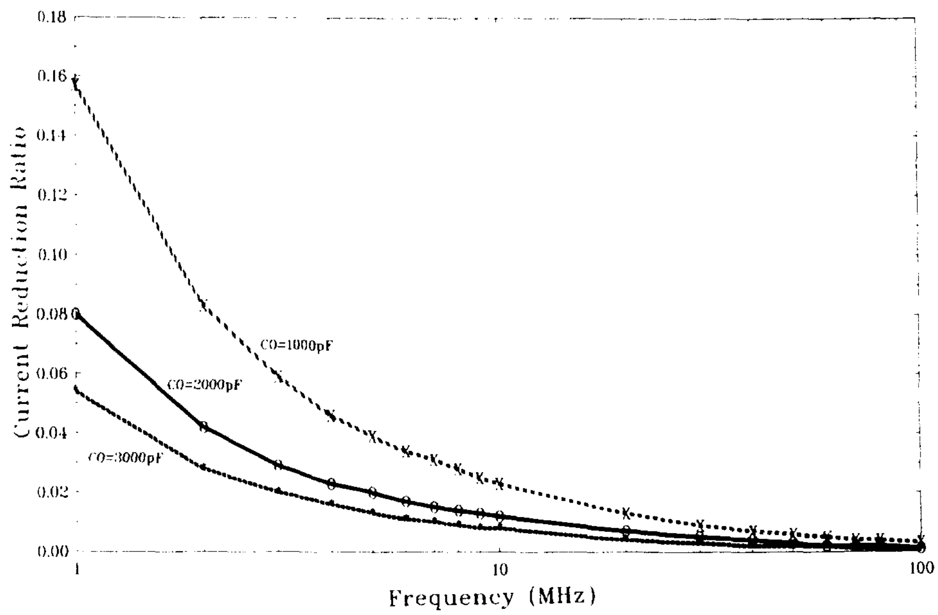

Fig. 12. Ratio of the current through the human body to the object short-circuit current for three objects having different capacitance to ground.

fields and a person who touches these objects. It should be noted that the current limits at frequencies above 100 kHz provide an exceptionally high safety margin because they prevent perception of warmth for the general population and pain due to heat for workers. However, for the conditions imposed (eqns 2 and 4), perception and pain occur only after the contact is maintained for a few minutes.

REFERENCES

Chatterjee, I.; Wu, D.; Gandhi, O. P. Human body impedance and threshold currents for perception and pain for contact hazard analysis in the VLF-MF band. IEEE Trans. Biomed. Eng. 33:486–494; 1986.

Gandhi, O. P. Basis for RFR-safety standards in the 10 kHz–50 MHz region. Brooks Airforce Base, TX: USAF School of Aerospace Medicine; Report No. USAFSAM-TR-87; 1987.

Gandhi, O. P.; Chatterjee, I.; Wu, D.; D'Andrea, J. A.; Sakamoto, K. Very low frequency (VLF) hazard study. Brooks Airforce Base, TX: USAF School of Aerospace Medicine; Report No. USAFSAM-TR-84; 1985.

Guy, A. W. Hazards of VLF electromagnetic fields. France: North Atlantic Treaty Organization; AGARD Lecture Series No. 138; 1985.

Kanai, H.; Chatterjee, I.; Gandhi, O. P. Human body impedance for electromagnetic hazard analysis in the VLF to MF band. IEEE Trans. Microwave Theory Tech. 32:763–771; 1984.

Richman, P. Computer modelling the effect of oscilloscope bandwidth on ESD waveforms, including oscillations. In: Proceedings of the IEEE International Symposium on Electromagnetic Compatibility, Wakefield, MA; New York: IEEE Press; 1985:37–41.

Stuchly, M. A. Proposed revision of the Canadian recommendations on radiofrequency-exposure protection. Health Phys. 53:649–665; 1987.

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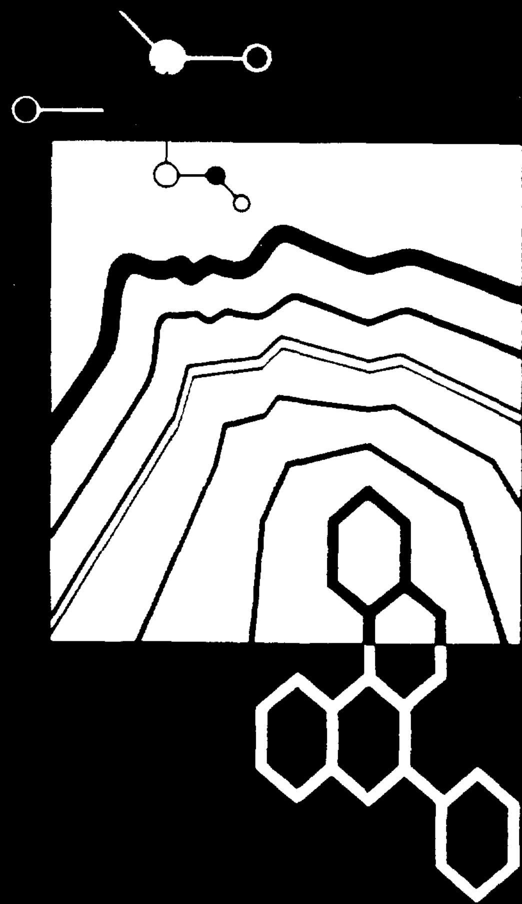

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Environmental Health Criteria 137

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NOTE TO READERS OF THE CRITERIA MONOGRAPHS

Every effort has been made to present information in the criteria monographs as accurately as possible without unduly delaying their publication. In the interest of all users of the environmental health criteria monographs, readers are kindly requested to communicate any errors that may have occurred to the Director of the International Programme on Chemical Safety, World Health Organization, Geneva, Switzerland, in order that they may be included in corrigenda, which will appear in subsequent volumes.

DEDICATION

This monograph is dedicated to:

Professor Przemyslaw A. Czerski, a charter member of International Non-ionizing Radiation Committee, who died on 15 April 1990 in Silver Spring, MD (USA). He was a pioneer investigator into the effects of non-ionizing radiation on biosystems and the assessment of the potential hazards associated with such exposure. As a fervent promoter of international cooperation, Professor Czerski played an active part in the establishment of the International Non-Ionizing Radiation Committee and in the development of its activities. His broad scientific knowledge and his tireless energy made him a major contributor to the present publication.

PREFACE

The International Radiation Protection Association (IRPA) initiated activities concerned with non-ionizing radiation by forming a Working Group on Non-Ionizing Radiation in 1974. This Working Group later became the International Non-Ionizing Radiation Committee (IRPA/INIRC), at the IRPA meeting held in Paris in 1977. The IRPA/INIRC reviews the scientific literature on non-ionizing radiation and makes assessments of the health risks of human exposure to such radiation. On the basis of Environmental Health Criteria monographs, developed in conjunction with the World Health Organization, Division of Environmental Health, the IRPA/INIRC recommends guidelines on exposure limits, drafts codes of safe practice, and works in conjunction with other international organizations to promote safety and standardization in the non-ionizing radiation field.

A WHO/IRPA Task Group to review the final draft of the Environmental Health Criteria on Electromagnetic Fields (300 Hz-300 GHz) met at the WHO Collaborating Centre for NIR in Ottawa, Canada, from 22 to 26 October 1990. Dr A.J. Liston, Assistant Deputy Minister, Health Protection Branch, opened the meeting on behalf of the Minister for Health and Welfare Canada. Mr J.R. Hickman, Director General, Environmental Health Directorate, welcomed the participants. The support of Health and Welfare Canada and the local organization by the Environmental Health Directorate are gratefully acknowledged.

The first draft of this publication was compiled by Professor J. Bernhardt, Professor P. Czerski, Professor M. Grandolfo, Dr A. McKinlay, Dr M. Repacholi, Dr R. Saunders, Professor J. Stolwijk, and Dr M. Stuchly. An editorial group comprising Professor J. Bernhardt, Professor P. Czerski, Professor M. Grandolfo, Mr C. Hicks, Dr A. McKinlay, Dr R. Saunders, Mr D. Sliney, Professor J. Stolwijk, and Dr M. Swicord met at the US Army Environmental Hygiene Agency, Edgewood, MD, in February 1990 to revise the draft. A second editorial group comprising Professor J. Bernhardt, Mme A. Duchêne, Dr A. McKinlay (Chairman), Professor B. Knave, Dr R. Saunders, and Dr M. Stuchly met at the National Radiological Protection Board, Didcot, United Kingdom, in May 1990 to collate and incorporate the comments received by IPCS Focal

Points, IRPA Associate Societies, and individual experts. Dr M. Repacholi was responsible for the scientific editing of the text and Mrs M.O. Head of Oxford for the language editing.

This publication comprises a review of the data on the effects of electromagnetic field exposure on biological systems pertinent to the evaluation of human health risks. The purpose of the document is to provide an overview of the known biological effects of electromagnetic fields in the frequency range 300 Hz to 300 GHz, to identify gaps in this knowledge so that direction for further research can be given, and to provide information for health authorities, regulatory, and similar agencies on the possible effects of electromagnetic field exposure on human health, so that guidance can be given on the assessment of risks from occupational and general population exposure.

Most radiofrequency (RF) field standards are based on the premise that there exists a threshold specific absorption rate (SAR) of RF energy (for frequencies above about 1 MHz) of 1-4 W/kg, above which there is increasing likelihood of adverse health effects. Below about 1 MHz, standards are based on induced currents in the body, causing shocks and burns. The purpose of updating the original Environmental Health Criteria monograph on radio frequency (WHO, 1981) is not only to provide a description of more completely developed RF dosimetry in humans, but to critically review more recent scientific literature, to determine if the threshold SAR on which standards are based is still valid. With the frequency range covered by the document extended down to 300 Hz, more emphasis is placed on induced currents and other possible mechanisms of interaction.

In conducting the literature review, earlier reports are not necessarily included, since these were reviewed in UNEP/WHO/IRPA (1981). Every effort has been made to distinguish clearly between biological effects that have been established and those that have been reported as preliminary or isolated results, or as hypotheses proposed to explain observed results. The conclusions of this document are based on peer reviewed and established knowledge of interactions of electromagnetic fields with biological systems.

Subjects reviewed include: the physical characteristics of electromagnetic fields; measurement techniques; applications of electromagnetic fields and sources of exposure; mechanisms of interaction; biological effects; and guidance on the development of protective measures, such as regulations or safe-use guidelines.

Health agencies and regulatory authorities are encouraged to set up and develop programmes that ensure that the maximum benefit occurs with the lowest exposure. It is hoped that this criteria document will provide useful information for the development of national protection measures against electromagnetic fields, as well as serving as a reliable basis for such reports as environmental impact statements necessary for proposed electromagnetic field emission facilities.

The WHO Regional Office for Europe has published a second edition of the book entitled *Nonionizing radiation protection*, which includes a chapter on radiofrequency radiation (Suess & Benwell-Morison, 1989).

1. SUMMARY AND RECOMMENDATIONS FOR FURTHER STUDIES

1.1 Summary

1.1.1 Physical characteristics in relation to biological effects

This monograph is concerned with the health effects of electromagnetic fields in the frequency range of 300 Hz-300 GHz, which includes the radiofrequency (RF) range (100 kHz-300 GHz) covered in the earlier publication (WHO, 1981). For simplicity, RF is the term used in this document for electromagnetic fields of frequency 300 Hz-300 GHz. Within these frequencies are microwaves, having frequencies of between 300 MHz and 300 GHz.

Exposure levels in the microwave range are usually described in terms of "power density" and are normally reported in watt per square metre (W/m^2), or milliwatt or microwatts per square metre (mW/m^2, $\mu W/m^2$). However, close to RF sources with longer wavelengths, the values of both the electric (V/m) and magnetic (A/m) field strengths are necessary to describe the field.

Exposure conditions can be altered considerably by the presence of objects, the degree of perturbation depending on their size, shape, orientation in the field, and electrical properties. Very complex field distributions can occur, both inside and outside biological systems exposed to electromagnetic fields. Refraction within these systems can focus the transmitted energy resulting in markedly non-uniform fields and energy deposition. Different energy absorption rates can result in thermal gradients causing biological effects that may be generated locally, difficult to anticipate, and perhaps unique. The geometry and electrical properties of biological systems will also be determining factors in the magnitude and distribution of induced currents at frequencies below the microwave range.

When electromagnetic fields pass from one medium to another, they can be reflected, refracted, transmitted, or absorbed, depending on the conductivity of the exposed object and the frequency of the field. Absorbed RF energy can be converted to other forms of energy and cause interference with the functioning of the living system. Most of this energy is converted into heat. However, not all electromagnetic field effects can be explained in terms of the biophysical mechanisms of energy absorption and conversion to heat. At frequencies below about 100 kHz, it has been demonstrated that induced electric fields can stimulate nervous tissue. At the microscopic level, other interactions leading to perturbations in complex macromolecular biological systems (cell membranes, subcellular structures) have been postulated.

1.1.2 Sources and exposure

1.1.2.1 Community

In comprehensive community surveys of background levels of electromagnetic fields in the USA, a median exposure of the order of 50 $\mu W/m^2$ was found. Very high frequency broadcasts were identified as the main contributors to ambient electromagnetic fields. No more than 1% of the population was exposed to ambient power densities in excess of 10 mW/m^2. Exposure in the immediate vicinity (at a distance of the order of one half wavelength of the incident fields) of transmitting facilities, can be higher, and can be enhanced by nearby conducting objects. Such conditions should be evaluated for each specific situation.

1.1.2.2 Home

RF sources in the home include microwave ovens, induction heating stoves, burglar alarms, video display units (VDUs), and television receivers. Leakage from microwave ovens can be up to 1.5 W/m^2 at 0.3 m and 0.15 W/m^2 at a distance of 1 metre. Exposure to radiation from domestic appliances is best limited by design and by monitoring at the point of manufacture.

1.1.2.3 Workplace

Dielectric heaters for wood fabrication and the sealing of plastics, induction heaters for the heating of metals, and video display units, are widely used in a variety of occupational settings. VDUs create electric and magnetic fields at frequencies in the 15-35 kHz range and frequencies modulated in the ELF range. Personnel working on, or near, broadcasting towers or antennas can be exposed to substantial fields of up to 1 kV/m and 5 A/m, respectively. Workers

near radar installations can be exposed to substantial peak power densities, if they are in the RF beam a few metres from radar antennas (up to tens of MW/m^2). Usually, the average power density in the vicinity of air traffic control radars, for example, is of the order of 0.03-0.8 W/m^2.

In the occupational environment, the protection of workers is best assured by referring to the emission specifications for individual items of equipment, and, where necessary, by monitoring and surveillance using appropriate instrumentation.

A special case of exposure occurs in the medical environment with the use of diathermy treatments for pain and inflammation in body tissues. Diathermy operators are likely to be exposed occupationally to stray radiation at relatively high levels, which can be reduced by appropriate shielding or machine design. Field strengths of 300 V/m and 1 A/m at 10 cm from the applicators have been measured. Similarly, surgeons using electrosurgical devices operating at frequencies near 27 MHz may be exposed to levels above recommended limits. These field strengths decline very rapidly with increasing distance from the applicators.

Most magnetic resonance imaging (MRI) systems use static magnetic fields with flux densities of up to 2 T, low-frequency gradient fields up to 20 T/s, and RF fields in the 1-100 MHz frequency range. Although power deposition in the patient can be substantial, staff exposures are much lower and are determined by equipment characteristics.

1.1.3 Biological effects

Electromagnetic fields in the frequency range of 300 Hz-300 GHz interact with human and other animal systems through direct and indirect pathways. Indirect interactions are important at frequencies below 100 MHz, but are specific to particular situations. When metallic objects (such as automobiles, fences) in an electromagnetic field have electrical charges induced in them, they can be discharged when a body comes into contact with the charged object. Such discharges can cause local current densities capable of shock and burns.

A major interaction mechanism is through the currents induced in tissues, so effects are dependent on frequency, wave shape, and intensity. For frequencies below approximately 100 kHz, the interactions with nervous system tissue are of interest, because of their increased sensitivity to induced currents. Above 100 kHz, the nervous tissue becomes less sensitive to direct stimulation by electromagnetic fields and the thermalization of energy becomes the major mechanism of interaction.

There is evidence from a number of studies that weak-field interactions also exist. Different mechanisms for such interactions have been postulated, but the precise mechanism(s) has not been elucidated. These weak-field interactions result from exposure to RF fields, amplitude modulated at lower frequencies.

1.1.4 Laboratory studies

Many of the biological effects of acute exposure to electromagnetic fields are consistent with responses to induced heating, resulting either in rises in tissue or body temperature of about 1 °C or more, or in responses to minimizing the total heat load. Most responses have been reported at specific absorption rates (SARs) above about 1-2 W/kg in different animal species exposed under various environmental conditions. The animal (particularly primate) data indicate the types of responses that are likely to occur in humans subjected to a sufficient heat load. However, direct quantitative extrapolation to humans is difficult, given species differences in responses in general, and in thermoregulatory ability, in particular.

The most sensitive animal responses to heat loads are thermoregulatory adjustments, such as reduced metabolic heat production and vasodilation, with thresholds ranging between about 0.5-5 W/kg, depending on environmental conditions. However, these reactions form part of the natural repertoire of thermoregulatory responses that serve to maintain normal body temperatures.

Transient effects seen in exposed animals, which are consistent with responses to increases in body temperature of 1 °C or more (and/or SARs in excess of about 2 W/kg in primates and rats), include reduced performance of learned tasks and increased plasma

corticosteroid levels. Other heat-related effects include temporary haematopoietic and immune responses, possibly due to elevated corticosteroid levels. The most consistent effects observed are reduced levels of circulating lymphocytes, increased levels of neutrophils, and altered natural killer cell and macrophage function. An increase in the primary antibody response of B-lymphocytes has also been reported. Cardiovascular changes consistent with increased heat load, such as an increased heart rate and cardiac output, have been observed, together with a reduction in the effect of drugs, such as barbiturates, the action of which can be altered by circulatory changes.

Most animal data indicate that implantation and the development of the embryo and fetus are unlikely to be affected by exposures that increase maternal body temperature by less than 1 °C. Above these temperatures, adverse effects, such as growth retardation and post-natal changes in behaviour, may occur, with more severe effects occurring at higher maternal temperatures.

Most animal data suggest that low RF exposures that do not raise body temperatures above the normal physiological range are not mutagenic: Such exposures will not result in somatic mutation or hereditary effects. There is much less information describing the effects of long-term, low-level exposures. However, so far, it does not appear that any long-term effects result from exposures below thermally significant levels. The animal data indicate that male fertility is unlikely to be affected by long-term exposure to levels insufficient to raise the temperature of the body and testes.

Cataracts were not induced in rabbits exposed at 100 W/m^2 for 6 months, or in primates exposed at 1.5 kW/m^2 for over 3 months.

A study of 100 rats, exposed for most of their lifetime to about 0.4 W/kg, did not show any increased incidence of non-neoplastic lesions or total neoplasias compared with control animals; longevity was similar in both groups. There were differences in the overall incidence of primary malignancies, but these could not necessarily be attributed to the irradiation.

The possibility that exposure to RF fields might influence the process of carcinogenesis is of particular concern. So far, there is no definite evidence that irradiation does have an effect, but there is clearly a need for further studies to be carried out. Many experimental data indicate that RF fields are not mutagenic, and so they are unlikely to act as initiators of carcinogenesis; in the few studies carried out, the search has mainly been for evidence of an enhancement of the effect of a known carcinogen. Long-term exposure of mice at 2-8 W/kg resulted in an increase in the progression of spontaneous mammary tumours, and of skin tumours in animals treated dermally with a chemical carcinogen.

In vitro studies have revealed enhanced cell transformation rates after RF exposure at 4.4 W/kg (alone or combined with X-radiation) followed by treatment with a chemical promoter. The latter data have not always been consistent between studies. It is clear, however, that studies relevant to carcinogenesis need replicating and extending further.

A substantial body of data exists describing biological responses to amplitude-modulated RF or microwave fields at SARs too low to involve any response to heating. In some studies, effects have been reported after exposure at SARs of less than 0.01 W/kg, occurring within modulation frequency "windows" (usually between 1-100 Hz) and sometimes within power density "windows"; similar results have been reported at frequencies within the voice frequency (VF) range (300 Hz-3 kHz). Changes have been reported in: the electroencephalograms of cats and rabbits; calcium ion mobility in brain tissue *in vitro*, and *in vivo*; lymphocyte cytotoxicity *in vitro*; and activity of an enzyme involved in cell growth and division. Some of these responses have been difficult to confirm, and their physiological consequences are not clear. However, any toxicological investigations should be based on tests carried out at appropriate levels of exposure. It is important that these studies be confirmed and that the health implications, if any, for exposed people, are determined. Of particular importance would be studies that link extremely low frequency, amplitude-modulated, RF or microwave interactions at the cell surface with changes in DNA synthesis or transcription. It is worth noting that this interaction implies a "demodulation" of the RF signal at the cell membrane.

1.1.5 Human studies

There are relatively few studies that address directly the effects of acute or long-term exposures of humans to RF fields. In studies

in the laboratory, cutaneous perception of fields in the 2-10 GHz range has been reported. Thresholds for just noticeable warming have been reported at power densities of 270 W/m^2 - 2000 W/m^2, depending on the area irradiated (13-100 cm^2) and the duration of exposure (1-180 s). When human volunteers are exposed to SARs of 4 W/kg for 15-20 minutes their average body temperature rises by 0.2-0.5 °C, which is quite acceptable in healthy people. The impact that this added thermal load would have on thermoregulatory impaired individuals in environments that minimize the perspiration-based cooling mechanisms is not known.

The few epidemiological studies that have been carried out on populations exposed to RF fields have failed to produce significant associations between such exposures and outcomes of shortened life span, or excesses in particular causes of death, except for an increased incidence of death from cancer, where chemical exposure may have been a confounder. In some studies, there was no increase in the incidence of premature deliveries or congenital malformations, while other studies produced indications that there was an association between the level of exposure and adverse pregnancy outcome. Such studies tend to suffer from poor exposure assessment and poor ascertainment and determination of other risk factors.

1.1.6 Health hazard assessment

The following categories of health hazard have been identified in an overall assessment of the health hazards associated with RF exposures.

1.1.6.1 Thermal effects

The deposition of RF energy in the human body tends to increase the body temperature. During exercise, the metabolic heat production can reach levels of 3-5 W/kg. In normal thermal environments, an SAR of 1-4 W/kg for 30 minutes produces average body temperature increases of less than 1 °C for healthy adults. Thus, an occupational RF guideline of 0.4 W/kg SAR leaves a margin of protection against complications due to thermally unfavourable environmental conditions. For the general population, which includes sensitive subpopulations, such as infants and the elderly, an SAR of 0.08 W/kg would provide an adequate further margin of safety against adverse thermal effects from RF fields.

1.1.6.2 *Pulsed fields*

It has been shown, under a number of conditions, that the thresholds for biological effects at frequencies above several hundred MHz are decreased when the energy is delivered in short (1-10 μs) pulses. For example, auditory effects occur when pulses of less than 30 μs duration deliver more than 400 mJ/m^2 per pulse. A safe limit for such pulses cannot be identified on the basis of available evidence.

1.1.6.3 *Amplitude-modulated RF fields*

The effects described for this type of field at the cellular, tissue, and organ levels cannot be related to adverse health effects. No dose-effect relationships can be formulated that demonstrate threshold levels; thus, the available information cannot lead to specific recommendations.

1.1.6.4 *RF field effects on tumour induction and promotion*

It is not possible, from the reports of the effects of RF exposure in certain cell lines, on cell transformation, enzyme activity, and tumour incidence and progression in animals, to conclude that RF exposure has any effect on the incidence of cancer in humans, or, that specific recommendations are necessary to limit such fields to reduce cancer risks.

1.1.6.5 *RF-induced current densities*

In the frequency range of 300 Hz-100 kHz, the induction of fields and current densities in excitable tissues is the most important mechanism for hazard assessment. The thresholds for the stimulation of nerve and muscle tissue are strongly dependent on frequency, ranging from 0.1-1 A/m^2 at 300 Hz to about 10-100 A/m^2 at 100 kHz. However, with regard to other effects, reported to occur below these thresholds, there is not sufficient information available to make specific recommendations.

1.1.6.6 *RF contact shocks and burns*

Conducting objects in an RF field can become electrically charged. When a person touches a charged object or approaches it closely, a substantial current can flow between the object and the person. Depending on the frequency, the electric field strength, the size and the shape of the object,and the cross-sectional area of contact, the resulting current can cause shock through stimulation of peripheral nerves. If the current is strong enough, burns can result. Protective measures include the elimination or enclosure of conductive objects in strong RF fields, or the limiting of physical access.

1.1.7 *Exposure standards*

1.1.7.1 *Basic exposure limits*

To protect workers and the general population from the possible health effects of exposure to electromagnetic fields, basic exposure limits have been determined on the basis of knowledge of biological effects. Different scientific bases were used to develop the limits for frequencies above and below about 1 MHz. Above 1 MHz, biological effects on animals were studied to determine the lowest value of the whole body average SAR that caused detrimental health effects in animals. This value was found to be in the 3-4 W/kg range.

The vast majority of results pertained to exposures in the low GHz region. Thus, to determine the effects at lower frequencies requires an assumption concerning the frequency dependence of the biological response. Since the observed bioeffects in the 1-4 W/kg range are believed to be thermal, the SAR threshold was assumed to be independent of frequency. It was considered that exposure of humans to 4 W/kg for 30 minutes would result in a body temperature rise of less than 1 °C. This body temperature rise is considered acceptable.

A safety factor of 10 is introduced, in order to allow for unfavourable, thermal, environmental, and possible long-term effects, and other variables, thus arriving at a basic limit of 0.4 W/kg. An additional safety factor should be introduced for the general population, which includes persons with different sensitivities to RF exposure. A basic limit of 0.08 W/kg, corresponding to a further safety factor of 5, is generally recommended for the public at large.

Derived limits of exposure are given in Tables 34 and 35 of this publication.

The limitations for the whole body average SAR are not sufficiently restrictive, since the distribution of the absorbed energy in the human body can be very inhomogeneous and dependent on the RF exposure conditions. In partial body exposure situations, depending on frequency, the absorbed energy can be concentrated in a limited amount of tissue, even though the whole body average SAR is restricted to less than 0.4 W/kg. Therefore, additional basic limits of 2 W/100 g are recommended in any other part of the body, in order to avoid excessive local temperature elevations. The eye may need special consideration.

At frequencies below about 1 MHz, exposure limits are selected that will prevent stimulation of nerve and muscle cells. Basic exposure limits refer to current densities induced within body tissues. Exposure limits should have a sufficiently large safety factor to restrict the current density to 10 mA/m^2 at 300 Hz. This is the same order of magnitude as natural body currents. Above 300 Hz, the current density necessary for excitation of nervous tissue increases with frequency, until a frequency is reached at which thermal effects dominate. For frequencies around 2-3 MHz, the basic limit for current density is equivalent to the limit for the peak SAR of 1 W/100g. Since SAR or induced current density values cannot be measured easily in practical exposure situations, exposure limits in terms of conveniently measurable quantities must be derived from basic limits. These "derived limits" indicate the acceptable limits in terms of the measured and/or calculated field parameters that allow compliance with the basic limits.

1.1.7.2 *Occupational exposure limits*

The occupationally-exposed populations consist of adults exposed under controlled conditions, who are aware of the occupational risks. Because of the wide frequency range addressed in this publication, a single limit number for occupational exposure is not possible. Recommended derived occupational limits in the frequency range 100 kHz to 300 GHz are provided in Table 34. A conservative approach is recommended for pulsed fields where electric and magnetic field strengths are limited to 32 times the values given in Table 34, as averaged over the pulse width, and the power density

is limited to a value of 1000 times the corresponding value in Table 34, as averaged over the pulse width.

1.1.7.3 *Exposure limits for the general population*

The general population includes persons of different age groups, different states of health, and pregnant women. The possibility that the developing fetus could be particularly susceptible to exposure to RF deserves special consideration.

Exposure limits for the general population should be lower than those for occupational exposure. For example, recommended derived limits in the frequency range of 100 kHz-300 GHz are provided in Table 35, which are generally a factor of 5 lower than the occupational limits.

1.1.7.4 *Implementation of standards*

The implementation of RF field occupational and public health protection standards necessitates the allocation of responsibility for measurements of field intensity and interpretation of results, and the establishment of detailed field protection safety codes and guides for safe use, which indicate, where appropriate, ways and means of reducing exposure.

1.1.8 *Protective measures*

Protective measures include workplace surveillance (exposure surveys), engineering controls, administrative controls, personal protection, and medical surveillance. Where surveys of RF fields indicate levels of exposure in the workplace in excess of limits recommended for the general population, workplace surveillance should be conducted. Where surveys of RF fields in the workplace indicate levels of exposure in excess of recommended limits, action should be taken to protect workers. In the first instance, engineering controls should be applied, where possible, to reduce emissions to acceptable levels. Such controls include good safety design and, where necessary, the use of interlocks or similar protection devices.

Administrative controls, such as limitation of access and the use of audible and visible warnings, should be used in conjunction with engineering controls. The use of personal protection (protective clothing), though useful under certain circumstances, should be regarded as a last resort to ensure the safety of the worker. Wherever possible, priority should be given to engineering and administrative controls. Where workers could be expected to incur exposures in excess of the limits applicable to the general population, consideration should be given to providing appropriate medical surveillance.

Prevention of health hazards related to RF fields also necessitates the establishment and implementation of rules to ensure: (*a*) the prevention of interference with safety and medical electronic equipment and devices (including cardiac pacemakers); (*b*) the prevention of detonation of electroexplosive devices (detonators); and (*c*) the prevention of fires and explosions due to the ignition of flammable material from sparks caused by induced fields.

1.2 Recommendations for further studies

1.2.1 Introduction

There are concerns about the possible effects of RF fields in the areas of promotion and progression of cancer, of reproductive failures, such as spontaneous abortions and congenital malformations, and of effects on central nervous system function. Knowledge in all these areas is inadequate to determine whether such effects exist, and therefore, there is no rational basis for recommendations to protect the general population from possible adverse effects.

Future research efforts in the areas of weak-interaction mechanisms on the one hand, and studies of effects on carcinogenesis and reproduction in animals and humans on the other hand, should be coordinated to a high degree. This coordination can be brought about by focusing funding on research proposals of a multidisciplinary and multi-institutional nature. Studies on RF field effects could well be coordinated with similar programmes addressing ELF (50/60 Hz) field effects. A high priority should be placed on research that emphasizes causal relationships and dose-effect thresholds and coefficients.

The following is a list of priority areas identified by the Task Group as needing further study.

1.2.2 Pulsed fields

There is a major deficiency in the understanding of the effects of pulsed fields in which very high peak power densities occur, separated by periods of zero power. Only a few isolated reports of pulsed field effects are available and it is not possible to identify either the frequency or the peak power domain of importance. Data to assess human health hazard in terms of pulse peak power, repetition frequency, pulse length, and the frequency of the RF in the pulse, are urgently needed in view of the widening application of systems employing high power pulses, (mostly radar), and involving both occupational and general population exposures.

1.2.3 Cancer, reproduction, and nervous system studies

There is increasing concern about the possibility that RF exposure may play a role in the causation or promotion of cancer, specifically of the blood forming organs or in the CNS. Similar uncertainties surround possible effects on reproduction, such as increased rates of spontaneous abortion and of congenital malformations.

Effects of RF exposure on CNS function, with resulting changes in cognitive function, are also surrounded by uncertainties. In view of the potential importance of these interactions and the disruptive effects of the uncertainty on society, a high priority should be placed on research in this area. It is important that research efforts be coordinated to clarify rather than increase the level of uncertainty. Research on possible mechanisms, such as weak-field interactions, should be closely coordinated with appropriately designed animal toxicology studies and with human epidemiology.

1.2.4 Weak-field interactions

Very few people are exposed to thermally significant levels of RF; the vast majority of exposures occur at levels at which weak-field interactions would be the only possible source of any adverse health response. A substantial amount of experimental evidence implicates responses to amplitude-modulated RF fields, which show frequency and amplitude windows; some responses are dependent on co-exposure to physical and chemical agents. Establishing the significance of effects for human health and their dose-response relationships is of paramount importance. Studies are necessary that identify biophysical mechanisms of interaction and that extend the animal and human studies, in order to identify health risks.

1.2.5 Epidemiology

Epidemiological studies on the association between cancer and adverse reproductive outcomes and RF fields are made difficult by a number of factors:

- Most members of any population are exposed to levels of RF that are orders of magnitude below thermally significant levels.

- It is very difficult to establish RF exposure in individuals over a meaningful period of time.

- Control of major confounders is very difficult.

Some, but not all, of the sources of difficulties can be overcome by a suitably designed and implemented case-control study. Such studies are in progress and being planned to study childhood cancer and any effects of ELF fields. It is important that such studies evaluate any exposures to RF radiation.

2. PHYSICAL CHARACTERISTICS

2.1 Introduction

The study of the biological effects of electromagnetic fields is multidisciplinary; it draws from physics, engineering, mathematics, biology, chemistry, medicine, and environmental health. For this reason, background information has been included in this publication that may appear elementary to some readers, but is essential for those from a different discipline. Much of the confusion and the controversies that exist in the field today arise from individuals of one discipline not fully appreciating the basic facts or theories of another.

In this section, the aim is to summarize briefly the basic physical characteristics of electric, magnetic, and electromagnetic fields in the frequency range 300 Hz-300 GHz. The corresponding wavelengths extend from 1000 km to 1 mm. At low frequencies (below about 10 MHz) and for near-field conditions (see section 4), the electric (E) and magnetic (H) fields must be treated separately.

The quantum energies at these frequencies are extremely small and are not capable of altering the molecular structure or breaking any molecular bonds. The maximum quantum energy (at 300 GHz) is 1.2 millielectronvolts (meV), while disruption of the weakest hydrogen bond requires 80 meV; for comparison, the thermal motion energy at 30 °C is 26 meV.

Although there are other definitions of the radiofrequency (RF) spectrum, its use in this document covers 300 Hz-300 GHz. The region between 300 MHz and 300 GHz is called microwaves (MW).

2.2 Electric field

Electric charges exert forces on each other. It is convenient to introduce the concept of an electric field to describe this interaction. Thus, a system of electric charges produces an electric field at all points in space and any other charge placed in the field will experience a force because of its presence. The electric field is denoted by **E** and is a vector quantity, which means that it has both a magnitude and a direction. The force, **F**, exerted on a point (infinitely small) body containing a net positive charge q placed in an electric field **E** is given by:

$$\mathbf{F} = q\mathbf{E} \quad \text{(Equation 2.1)}$$

Various units of the electric field strength are in use; the SI unit is newton per coulomb (N/C). It is frequently easier and more useful to measure the electric potential, V, rather than the force and charge. This is because the potential is much less dependent on the physical geometry of a given system (e.g., location and sizes of conductors).

The potential difference V between two points in an electric field E is defined by $V = W/q$, where W is the work done by the field in moving a charge q between the two points. The work done is $W = Fd$, where d is the separation between the two points; or using equation 2-1, $W = qEd$. From $V = W/q$, it follows that:

$$E = V/d \quad \text{(Equation 2.2)}$$

In practice, the unit of volt per metre (V/m) is used for the electric field strength.

Electric fields exert forces on charged particles. In an electrically conductive material, such as living tissue, these forces will set charges into motion to cause an electric current to flow. This current is frequently specified by the current density, **J**, the magnitude of which is equal to the current flowing through a unit surface perpendicular to its direction. The SI unit of current density is ampere per square metre (A/m^2). **J** is directly proportional to **E** in a wide variety of materials. Thus:

$$\mathbf{J} = \sigma\mathbf{E} \quad \text{(Equation 2.3)}$$

where the constant of proportionality σ is called the electrical conductivity of the medium. The unit of σ is siemens per metre (S/m).

2.3 Magnetic field

The fundamental vector quantities describing a magnetic field are the magnetic field strength **H** and the magnetic flux density **B** (also called the magnetic induction).

Magnetic fields, like electric fields, are produced by electric charges, but only when these charges are in motion. Magnetic fields exert forces on other charges but, again, only on charges that are in motion.

The magnitude of the force F acting on an electric charge q moving with a velocity **v** in the direction perpendicular to a magnetic field of flux density **B** is given by:

$$F = qvB \quad \text{(Equation 2.4)}$$

where the direction of **F** is perpendicular to both those of **v** and **B**. If, instead, the direction of **v** were parallel to **B**, then **F** would be zero. This illustrates an important characteristic of a magnetic field: it does no physical work, because the force, called the Lorentz force, generated by its interaction with a moving charge is always perpendicular to the direction of motion. The basic unit of the magnetic flux density can be deduced from Equation 2.4 to be newton second per coulomb metre [N s/C m]. According to the International System of Units (SI), this unit is called the tesla (T). In the literature, both mks and cgs units are also used to express flux density values. The conversion between the gauss (G), the cgs unit of flux density, and the tesla is $1\ T = 10^4\ G$.

The magnetic field strength **H** is the force with which the field acts on an element of current situated at a particular point. The value of **H** is measured in ampere per metre (A/m).

The magnetic flux density **B**, rather than the magnetic field strength, **H** (where $B = \mu H$), is used to describe the magnetic field generated by currents that flow in conductors. The value of μ (the magnetic permeability) is determined by the properties of the medium.

For most biological materials, the permeability μ is equal to μ_0, the value of permeability of free space (air) (1.257×10^{-6} H/m). Thus, for biological materials, the values of **B** and **H** are related by the constant μ_0.

2.4 Waves and radiation

Maxwell's equations form the theoretical foundation for all classical electromagnetic field theory. These equations are very powerful, but for complex systems, such as biological bodies, they are difficult to solve.

One class of their solutions results in wave descriptions of the electric and magnetic fields. When the source charges or currents oscillate and the frequency of oscillation is high enough, the **E** and **H** fields produced by these sources will radiate from them. A convenient and commonly used description of this radiation is wave propagation.

The basic ideas of wave propagation are illustrated in Fig. 1. The distance from one ascending, or descending, node to the next is defined as the wavelength, and is usually denoted by λ.

The wavelength and the frequency (the number of waves that pass a given point in unit time), denoted by f, are related and determine the characteristics of electromagnetic radiation. Frequency is the more fundamental quantity and for a given frequency, the wavelength depends on the velocity of propagation and, therefore, on the properties of the medium through which the radiation passes.

The wavelength normally quoted is that in a vacuum or in air, the difference being insignificant. However, the wavelength can change significantly when the wave passes through other media. The linking parameter with frequency is the speed of light as expressed in Equation 2.5 ($v = 3 \times 10^8$ m/s in air):

$$\lambda = v/f \qquad \text{(Equation 2.5)}$$

When RF traverses biological material, its speed is reduced and its wavelength becomes shorter than in air.

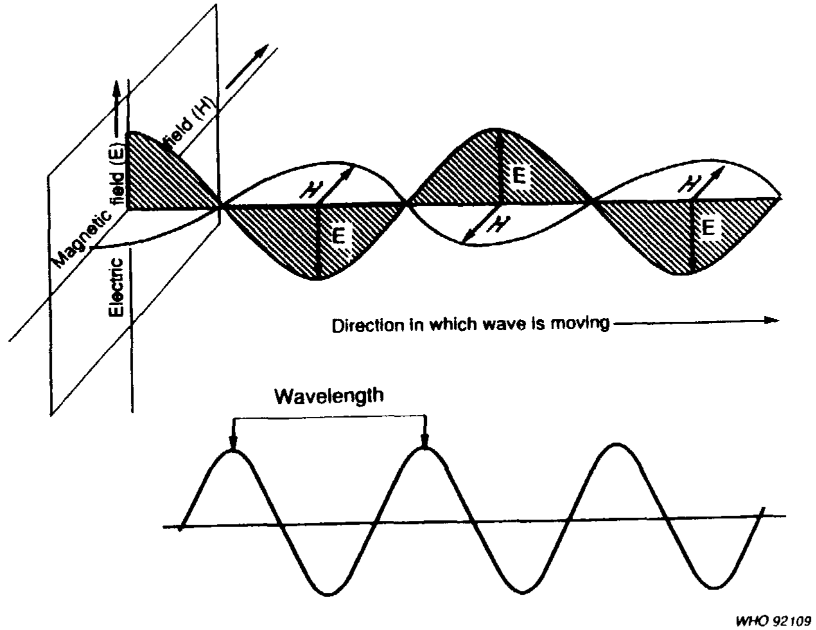

Fig. 1. An electromagnetic monochromatic wave. Electromagnetic waves consist of electrical and magnetic forces that move in consistent wave-like patterns at right angles to each other for far-field propagation, but at varying angles in the near-field.

Two idealizations of wave propagation are commonly used: spherical waves and plane waves (Stuchly, 1983; Grandolfo & Vecchia, 1988). A spherical wave is a good approximation to some electromagnetic waves that occur. Their wavefronts have spherical surfaces and each crest and trough has a spherical surface. On every spherical surface, the **E** and **H** fields are constant. The wavefronts propagate radially outwards from the source and **E** and **H** are both tangential to the spherical surfaces.

A plane wave is another model that approximately represents some electromagnetic waves. Plane waves have characteristics similar to spherical waves because, at points far from the source, the curvature of the spherical wavefronts is so small that they appear to be almost planar.

The defining characteristics of a plane wave are:

(*a*) E, H, and the direction of propagation are all mutually perpendicular.

(*b*) The quotient E/H is constant and is called the wave impedance. For free space E/H = 377 Ω. For other media and for sinusoidal steady-state fields, the wave impedance includes losses in the medium in which the wave is travelling.

(*c*) Both E and H vary as 1/r, where r is the distance from the source.

In RF plane wave propagation (far-field), the power crossing a unit area normal to the direction of wave propagation is usually designated by the symbol S. When the electric and magnetic field strengths are expressed in V/m and A/m, respectively, S represents their product, which yields VA/m^2, i.e., W/m^2 (watts per square metre).

In free space, electromagnetic waves spread uniformly in all directions from a theoretical point (isotropic) source. As the distance from the point source increases, the area of the wavefront surface increases as a square of the distance, so that the source power is spread over a larger area.

As power density S corresponds also to the quotient of the total radiated power and the spherical surface area enclosing the source, it is inversely proportional to the square of the distance from the source, and can be expressed as:

$$S = P/4\pi r^2 \quad \text{(Equation 2.6)}$$

where P is the total radiated power and r is the distance from the source.

In the case of plane waves, frequently called far-field conditions, the power density can be derived from $E^2/377$ or from $377\ H^2$ (see Table 1). Therefore, in many practical applications only the E field or the H field needs to be measured when the point of measurement

is at least one wavelength from the source. In this case, measurement of E makes possible the determination of H and vice-versa.

Table 1. Comparison of power densities in the more commonly used units for free-space, far-field conditions (Note: values have been rounded to one or two significant figures, based on the relationships above)

W/m^2	mW/cm^2	$\mu W/cm^2$	V/m	A/m
10^{-2}	10^{-3}	1	2	$5\ 10^{-3}$
10^{-1}	10^{-2}	10	6	$1.5\ 10^{-2}$
1	10^{-1}	10^2	20	$5\ 10^{-2}$
10	1	10^3	60	$1.5\ 10^{-1}$
10^2	10	10^4	$2\ 10^2$	$5\ 10^{-1}$
10^3	10^2	10^5	$6\ 10^2$	1.5
10^4	10^3	10^6	$2\ 10^3$	5

The region close to a source is called the near-field. In the near-field, the E and H fields are not necessarily perpendicular; in fact, they are not always conveniently characterized by waves. They are often nonpropagating in nature and are sometimes referred to as fringing fields, reactive near-fields, or evanescent modes. Near-fields often vary rapidly with distance; the inverse square law of the dependence with distance does not apply, and the impedance (E/H) may differ from 377 Ω. Objects located near sources may strongly affect the nature of the fields. For example, placing a probe near a source to measure the fields may change the characteristics of the fields considerably (Dumansky et al., 1986).

When RF fields are incident on a conductive object, RF currents are induced in the object. These currents produce surface fields that are highly localized to the object and are often referred to as RF hot spots. RF hot spots are better characterized as electric and magnetic fields rather than radiation, since, for many conditions, the fields leading to the hot spot never propagate away from the object. At higher frequencies, the electric and magnetic fields maintain an approximately constant relationship in propagating waves. In general, the lower the frequency, the less coupled the fields become. This is particularly so when the wavelength is very large with respect to the physical size of the source. In practice, the fields of concern from a hazard perspective will be near-fields at frequencies below about 1 MHz.

3. NATURAL BACKGROUND AND HUMAN-MADE FIELDS

3.1 General

In the last few decades, the use of devices that emit electromagnetic fields has increased considerably. This proliferation has been accompanied by an increased concern about possible health effects of exposure to these fields (Grandolfo et al., 1983; Repacholi, 1988; Shandala & Zvinyatskovski, 1988, Franceschetti et al., 1989). As a result, throughout the world, many organizations, both governmental and nongovernmental, have established safety standards or guidelines for exposure (see section 10).

Electromagnetic devices already in use and the continuous addition of new sources result in the expansion to new frequencies in the spectrum and the increasing presence of RF fields. Comprehensive data on existing emission systems, and evaluation of present levels of exposure, are essential for the assessment of potential radiation hazards (Repacholi, 1983a; Shandala et al., 1983; Savin, 1986; Stuchly & Mild, 1987).

In this section, sources of electromagnetic fields, both natural and human-made, in the 300 Hz-300 GHz frequency range are surveyed. The human-made electromagnetic environment consists of fields that are produced either intentionally or as by-products of the use of other devices.

Human-made sources in the spectrum considered here, however, produce local field levels many orders of magnitude above the natural background. Therefore, for the practical purposes of hazard assessment, the electromagnetic fields on the earth's surface arise from human-made sources. According to the treaty of the International Telecommunications Union (ITU, 1981), the electromagnetic spectrum up to 3 THz is subdivided into 12 frequency bands. These bands are designated by numbers as shown in Table 2; only the bands referred to in this publication are given.

3.2 Natural background

The natural electromagnetic environment originates from processes such as discharges in the earth's atmosphere (terrestrial sources) or in the sun and deep space (extra-terrestrial sources).

Table 2. Frequency bands of the electromagnetic spectrum in the frequency range 300 Hz-300 GHz [a]

Band number	Frequency range subdivision	Metric	Description and symbol
3	0.3 to 3 kHz	-	voice frequency (VF)
4	3 to 30 kHz	myriametric	very low frequency (VLF)
5	30 to 300 kHz	kilometric	low frequency (LF)
6	0.3 to 3 MHz	hectometric	medium frequency (MF)
7	3 to 30 MHz	decametric	high frequency (HF)
8	30 to 300 MHz	metric	very high frequency (VHF)
9	0.3 to 3 GHz	decimetric	ultra high frequency (UHF)
10	3 to 30 GHz	centimetric	super high frequency (SHF)
11	30 to 300 GHz	millimetric	extremely high frequency (EHF)

[a] From: ITU (1981).

3.2.1 *Atmospheric fields*

Atmospheric fields of frequencies of less than 30 MHz originate predominantly from thunderstorms. Their strengths and range of frequencies vary widely with geographical location, time of day, and season. Some of these variations are systematic and some are random. Overall, atmospheric fields have an emission spectrum with the largest amplitude components having frequencies of between 2 and 30 kHz. Generally, the atmospheric field level decreases with increasing frequency. The geographical dependence is such that the highest levels are observed in equatorial areas and the lowest in polar areas.

3.2.2 Terrestrial emissions

The earth emits electromagnetic radiation (black-body radiation), as do all media, at a temperature T that is different from that at absolute zero. In the RF range, the black-body radiation follows the Rayleigh-Jeans law and the thermal noise from the earth (T about 300 K) is 0.003 W/m^2 (0.3 μW/cm^2), when integrated up to 300 GHz (Repacholi 1983).

The human body also emits electromagnetic fields at frequencies of up to 300 GHz at a power density of approximately 0.003 W/m^2. For a total body surface area of about 1.8 m^2, the total radiated power is approximately 0.0054 W.

3.2.3 Extraterrestrial fields

The atmosphere, ionosphere, and magnetosphere of the earth shield it from extra-terrestrial sources of nonionizing electromagnetic energy. Electromagnetic waves that are able to penetrate this shield are limited to two frequency windows, one optical and the other encompassing radiowaves of frequencies from about 10 MHz to 37.5 GHz. The short-wave boundary of the RF-window is due to energy absorption by molecules contained in the atmosphere (primarily O_2 and H_2O), whereas the long-wave boundary is related to the shielding action of the ionosphere.

RF radiation of cosmic origin observed with earth satellites ranges in magnitude from 1.8 $\times$ 10^{-20} W/m^2/Hz at 200 kHz to 8 $\times$ 10^{-20} W/m^2/Hz at 10 MHz (Struzak, 1982).

There are three main types of solar emission. The first is the so-called background, which is the constant component of the emission observed during periods of low solar activity. The second is the component that displays long-term changes, associated with variations in the number of sunspots. Its main contribution is in the frequency range from 500 MHz to 10 GHz. The third type of emission arises from isolated radio flares or radio emission bursts. The intensity of such emission can exceed the average intensity of the quiet radiation by a factor of one thousand or more; its duration varies from seconds to hours.

Natural sources of lesser intensity also exist and include the moon, Jupiter, Cassiopeia-A, the universal thermal background radiation at 3 K, hydrogen emissions from ionized clouds, line emissions from neutral hydrogen, the OH radical and, most recently observed, from ammonia.

3.3 Human-made sources

3.3.1 General

Radio and television transmitters are examples of human-made RF sources that intentionally produce electromagnetic emissions for telecommunication purposes. At frequencies of 3 kHz-3 MHz, normal service coverage is provided by ground-wave propagation. At VLF, propagation over distances of thousands of km is possible using this method. At LF and MF, during night-time, reflections from the ionosphere make propagation up to 2000 km possible with little attenuation. At HF, other propagation modes are also possible. At frequencies of 30 MHz-30 GHz, service coverage is provided by line-of-sight (short paths), diffraction (intermediate paths), or by forward scattering (long paths) propagation.

Broadcasting systems vary greatly in terms of their design. This diversity results in somewhat different approaches in evaluating human exposure and potential problems. The situations are significantly different for workers and for the general population. In the case of some workers, such as those maintaining equipment on broadcasting towers, there is a potential for exposure to strong RF fields. Workers may also be exposed to strong fields in the close vicinity of towers and particularly broadcasting antennas in the VLF, LF, and MF. In contrast, it is rare for the general population to be exposed to strong RF fields from broadcasting. However, there is simultaneous exposure to more than one source.

Some insight on the levels of exposure of the general population may be gained from data collected in the USA, indicating that, in large cities, the median exposure level is about 50 μW/m^2 (Tell & Mantiply, 1980). SAR values ranging from 0.05 to 0.3 μW/kg are expected in the frequency range 170-800 MHz.

There are also human-made sources of electromagnetic fields used for non-communication purposes, in industry (I), science (S), and medicine (M). ISM applications are intended to transport and concentrate electromagnetic energy in a restricted working area to produce physical, chemical, and/or biological effects.

The frequency bands for ISM applications designated by the ITU are shown in Table 3. However, in individual countries, different and/or additional frequencies may be designated for use by ISM equipment (ITU, 1981; Metaxas & Meredith, 1983).

Table 3. Centre frequencies and frequency bands agreed internationally and assigned for ISM applications [a]

Centre frequency	Frequency bands	Area permitted
70 kHz	60-80 kHz	USSR
6.780 MHz 13.560 MHz	6.765-6.795 MHz 13.553-13.567 MHz	subject to agreement worldwide
27.120 MHz	26.957-27.283 MHz	worldwide
40.68 MHz	40.66-40.70 MHz	worldwide
42;49;56;61;66 MHz	~ 0.2%	United Kingdom
84;168 MHz 433.92 MHz	~ 0.005% 433.05-434.79 MHz	United Kingdom, Austria, Liechtenstein, The Netherlands, Portugal, Switzerland W. Germany Yugoslavia
896 MHz	886-906 MHz	United Kingdom
915 MHz	902-928 MHz	North and South America
2.375 GHz	2.325-2.425 GHz	Albania, Bulgaria, Czechoslovakia, Hungary, Romania, and USSR
2.45 GHz	2.4-2.5 GHz	worldwide, except where 2.375 GHz is used
3.39 GHz	3.37-3.41 GHz	The Netherlands
5.8 GHz 6.78 GHz	5.724-5.875 GHz 6.74-6.82 GHz	worldwide The Netherlands
24.125 GHz 40.68 GHz	24.0-24.05 GHz 40.43-40.92 GHz	worldwide United Kingdom
61.25 GHz 122.5 GHz 245 GHz	61.0-61.5 GHz 122-123 GHz 244-246 GHz	subject to agreement subject to agreement subject to agreement

[a] Adapted from: ITU (1981) and Metaxus & Meredith (1983).

Because of unavoidable imperfections in the construction, production, and use of ISM equipment, and of fundamental physical laws, there is always unintentional leakage of electromagnetic energy from such equipment. As a result, each ISM generator acts as an unintentional source producing signals capable of causing harmful effects, depending upon the amount of leakage.

To date, the total number of ISM installations in the world is estimated at 120 million (Struzak, 1985). The number of ISM generators constantly increases at a rate of about 3-7% per year. With such growth, the number of ISM generators expected by the year 2000 will be 2-4 times greater than it is now.

ISM equipment is usually designed at minimum cost, and, typically, is reduced to the essentials necessary for operation. Frequency stability and spectral purity of the power delivered to the work piece are not normally major objectives. In almost every case, the work piece is strongly coupled to the oscillator/amplifier, and since the electromagnetic characteristics of the material change during the work cycle, the magnitude, phase, and frequency of the radiation may be affected by these changes.

Electromagnetic energy leaks from ISM equipment mainly from the applicator and associated leads (e.g., RF heaters and sealers), the oscillator body/cabinet, and also from surrounding structures in which RF currents are induced. The amount of energy radiated from the applicator and associated leads depends on the particular arrangement of the devices and the work piece, which together act like an antenna the radiation efficiency of which is usually very low. However, the radiated power may be considerable if the nominal power is high.

Stray fields are also associated with currents flowing over the surface of the body/cabinet and over the surrounding structures. The equipment acts as a complex antenna system consisting of coupled radiating surface elements resonating at some unspecified frequencies. Often all the power and control wires are situated close to RF power circuits with no shielding. As a result, a considerable amount of RF energy may be fed into these leads and is conducted outwards at a distance and then reradiated.

Table 4 T; pical applications of equipment generating electromagnetic fields in the range 300 Hz-300 GHz

Frequency	Wavelength	Typical applications
0.3-3 kHz	1000-100 km	Broadcast modulation, medical applications, electric furnaces, induction heating, hardening, soldering, melting, refining
3-30 kHz	100-10 km	Very long range communications, radio navigation, broadcast modulation, medical applications, induction heating, hardening, soldering, melting, refining, VDUs
30-300 kHz	10-1 km	Radionavigation, marine and aeronautical communications, long-range communications, radiolocation, VDUs, electro-erosion treatment, induction heating and melting of metals, power inverters
0.3-3 MHz	1 km-100 m	Communications, radionavigation, marine radiophone, amateur radio, industrial RF equipment, AM broadcasting, RF excited arc welders, sealing for packaging, production of semiconductor material, medical applications
3-30 MHz	100-10 m	Citizen band, amateur radio broadcasting, international communications, medical diathermy, magnetic resonance imaging, dielectric heating, wood drying and gluing, plasma heating
30-300 MHz	10-1 m	Police, fire, amateur FM, VHF-TV, diathermy, emergency medical radio, air traffic control, magnetic resonance imaging, dielectric heating, plastic welding, food processing, plasma heating, particle separation
0.3-3 GHz	100-10 cm	Microwave point to point, amateur, taxi, police, fire, radar, citizen band, radionavigation, UHF-TV, microwave ovens, medical diathermy, food processing, material manufacture, insecticide, plasma heating, particle acceleration
3-30 GHz	10-1 cm	Radar, satellite communications, amateur, fire, taxi, airborne weather radar, police, microwave relay, anti-intruder alarms, plasma heating, thermonuclear fusion experiments
30-300 GHz	10-1 mm	Radar, satellite communications, microwave relay, radionavigation, amateur radio

Typical uses of equipment generating electromagnetic fields in the frequency range 300 Hz-300 GHz are shown in Table 4.

3.3.2 Environment, home, and public premises

A comprehensive evaluation of general population exposure to RF has been performed by the USA Environmental Protection Agency (Tell& Mantiply, 1980). Broadcasting services, particularly those usingthe VHF and UHF bands, have been identified as the main sources of ambient RF fields (Karachev & Bitkin, 1985). Measurements performed in 15 large cities in the USA led to the conclusions that the median exposure level was 50 $\mu W/m^2$ and that approximately 1% of the population studied was potentially exposed to levels greater than 10 mW/m^2.

The presence of conducting objects can give rise to field strengths higher than those expected from theoretical considerations, since they act as diffracting elements for the electromagnetic fields. Consequently, the presence of such objects in the near-field zone of radio stations makes the area between the radiator and the object potentially more hazardous and indicates that problems of safety should be considered carefully (Bernardi et al., 1981).

Although measurements as well as theory indicate that there is no high-level exposure from broadcasting stations, the existence of limited areas of relatively high irradiation close to the sources should be checked (Dumansky et al., 1985a). Such situations can exist in proximity to very powerful, ground-level transmitters. In several cases, urban areas are served locally by low-power, in-town repeaters. These are placed, for convenience, on the top of tall buildings; unless properly designed, this creates the possibility of stray fields in a densely populated area directly below the RF source. A typical, high-power, MF transmitter can have a carrier power of 100 kW, plus up to 50 kW in the sidebands of the propagated field. This is an example of how high field strengths can occur in a space open to the public.

Although a broadcasting station's property is usually fenced to keep out unauthorized individuals, the fence may be close to the tower base and people may be able to get as close as a few tens of metres or less from the antenna. Because the wavelengths involved are so long, a near-field exposure situation may exist and a field strength considerably greater than the theoretical ground-wave field strength is to be expected (Bini et al., 1980).