

IEEE Recommended Practice for Measurements and Computations of Radio Frequency Electromagnetic Fields With Respect to Human Exposure to Such Fields, 100 kHz–300 GHz

Sponsor

**IEEE International Committee on Electromagnetic Safety
(Standards Coordinating Committee 28 on Non-Ionizing Radiation)**

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Abstract: Techniques and instrumentation for the measurement and computation of potentially hazardous electromagnetic (EM) fields both in the near field and the far field of the electromagnetic source are specified. The specifications previously set forth in IEEE Std C95.3™-1991 are extended and combined. Leakage and near-field measurements and a description of the concepts, techniques, and instruments that can be applied to the measurement of specific absorption rate (SAR) or the electric field strength in organisms (including humans) and phantoms exposed to electromagnetic fields are included. Below 100 MHz, the current flowing through the body to ground is measurable and can be used to determine the SAR and, therefore, a brief treatment of low-frequency body current measurement is included.

Keywords: electromagnetic field computation, electromagnetic field measurements, exposure assessment, non-ionizing radiation, RF/microwave hazard assessment, RF/microwave survey instruments, RF/microwave surveys, specific absorption rate (SAR) assessment

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Introduction

(This introduction is not part of IEEE Std C95.3-2002, IEEE Recommended Practice for Measurements and Computations of Radio Frequency Electromagnetic Fields with Respect to Human Exposure, 100 kHz–300 GHz.)

In 1960, the American Standards Association approved the initiation of the Radiation Hazards Standards project under the co-sponsorship of the Department of the Navy and the Institute of Electrical and Electronics Engineers.

Prior to 1988, C95 standards were developed by accredited standards committee C95, and submitted to ANSI for approval and issuance as ANSI C95 standards. Between 1988 and 1990, the committee was converted to Standards Coordinating Committee 28 under the sponsorship of the IEEE Standards Board, and in 2001, became also known as the International Committee on Electromagnetic Safety (ICES). In accordance with policies of the IEEE, C95 standards will be issued and developed as IEEE standards, as well as being submitted to ANSI for recognition.

The present scope of ICES is:

“Development of standards for the safe use of electromagnetic energy in the range of 0 Hz–300 GHz relative to the potential hazards of exposure of man, volatile materials, and explosive devices to such energy. The committee does not address infrared, visible, ultraviolet, or ionizing radiation. The committee will coordinate with other committees whose scopes are contiguous with ICES.”

IEEE International Committee on Electromagnetic Safety is responsible for this recommended practice. There are five subcommittees concerned with the following:

- I Techniques, Procedures, Instrumentation, and Computation
- II Terminology, Units of Measurements and Hazard Communication
- III Safety Levels with Respect to Human Exposure, 0–3 kHz
- IV Safety Levels with Respect to Human Exposure, 3 kHz–300 GHz
- V Safety Levels with Respect to Electro-Explosive Devices

Three standards, two recommended practices, and one guide have been issued. Current versions are as follows:

IEEE Std C95.1TM, 1999 edition, IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz–300 GHz.

IEEE Std C95.2TM-1999 IEEE Standard for Radio Frequency Energy and Current Flow Symbols. (Supersedes ANSI C95.2-1982)

IEEE Std C95.3-2002, IEEE Recommended Practice for Measurements and Computations of Radio Frequency Electromagnetic Fields with Respect to Human Exposure to such Fields, 100 kHz–300 GHz. (Supersedes IEEE Std C95.3-1991.)

IEEE Std C95.4-2002, IEEE Recommended Practice for Determining Safe Distances from Radio Frequency Transmitting Antennas When Using Electric Blasting Caps During Explosive Operations.

IEEE Std 1460TM-1996, IEEE Guide for the Measurement of Quasi-Static Magnetic and Electric Fields.

This recommended practice extends the specifications previously set forth in IEEE Std C95.3-1991. This document includes leakage and near-field measurements. Further, many contemporary RF exposure guidelines and standards, including IEEE Std C95.1-1991, recommend limits for specific absorption rate (SAR) in biological tissues and limits for induced current and contact current associated with exposure to electromagnetic fields. Therefore, this recommended practice includes a description of the concepts,

computational techniques, and measurement techniques and instrumentation that can be applied to the determination of SAR in organisms and phantoms exposed to electromagnetic fields, and a description of the instrumentation and techniques for measuring induced and contact currents. This document also discusses several methods that can be used to calibrate field-measuring instruments, instruments for measuring SAR, and instruments used for measuring induced and contact current.

This document is intended primarily for use by engineers, biophysicists, and other specialists who are familiar with basic electromagnetic (EM) field theory and practice, and the potential hazards associated with EM fields. It will be most useful to bioeffects researchers, instrument developers, and manufacturers, those developing calibration systems and standards, and individuals involved in critical hazard assessments or surveys.

Subcommittee 1 on Techniques, Procedures, Instrumentation and computation was originally organized on 7 April 1960, to establish specifications for techniques and instrumentation used in evaluating potentially hazardous radio frequency (RF) radiation. In June 1985 the scope was clarified and the purpose was extended to establish specifications for techniques and instrumentation to be used in evaluating potential RF hazards to mankind from exposure to manmade sources of EM radiation or from the exposure of volatile materials and explosive devices to such radiation. The subcommittee does not address infrared, visible, ultraviolet, or ionizing radiation

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IEEE Recommended Practice for Measurements and Computations of Radio Frequency Electromagnetic Fields With Respect to Human Exposure to Such Fields, 100 kHz–300 GHz

1. Overview

1.1 Scope

The scope of this recommended practice is to revise and develop specifications for preferred methods for measuring and computing external radio frequency electromagnetic fields to which persons may be exposed. In addition, the document will specify preferred methods for the measurement and computation of the resulting fields and currents that are induced in bodies of humans exposed to these fields over the frequency range of 100 kHz–300 GHz.

Although the scope of ICES (formerly SCC28) includes potential hazards resulting from exposure of flammable volatile materials and explosive devices to EM radiation, this document is devoted exclusively to the measurement and calculation of human exposure to electromagnetic fields. This is because the necessary specifications and definitions pertaining to fuels and explosive devices are still being developed, and there are implications that the instrumentation requirements may be substantially different from those addressed here. Nevertheless, the measurement techniques and instruments described here are applicable to the measurement of fields in the vicinity of flammable materials and explosive devices, even though exposure standards for these situations have not been established.

1.2 Purpose

The purpose of this recommended practice is to specify techniques and instrumentation for the measurement and computation of potentially hazardous electromagnetic (EM) fields both in the near field and the far field of the electromagnetic source.¹ In doing so, this document incorporates and extends the specifications previously set forth in IEEE Std C95.3TM-1991 [B136].² This recommended practice includes leakage and

¹It is beyond the scope of this recommended practice to define what constitutes a hazardous radio frequency electromagnetic field. Maximum permissible exposure guides can be found, for example, in IEEE Std C95.1-1991 or the recommendations of the International Commission on Non-Ionizing Radiation Protection [B132]. It should be kept in mind that the limits given in such documents are continually under review and are subject to change as new information becomes available.

²The numbers in brackets correspond to those in the Bibliography in Annex G.

near-field measurements. Further, IEEE Std C95.1TM-1991 and other contemporary standards and guidelines for personnel exposure include specific absorption rate (SAR) in biological tissues as a parameter to be determined. Accordingly, this document contains a description of the concepts, techniques, and instruments that can be applied to the measurement and computation of SAR or the electric field strength in organisms (including humans) and phantoms exposed to electromagnetic fields. Below approximately 100 MHz, the current flowing through the body to ground is measurable and can be used to determine the SAR, and therefore, a brief treatment of low-frequency body current measurement is also included.

This document is intended primarily for use by engineers, biophysicists, and other specialists who are familiar with basic electromagnetic (EM) field theory and practice, and the potential hazards associated with exposure to EM fields. It will probably be most useful to bioeffects researchers, instrument developers and manufacturers, those developing calibration systems and standards, and individuals involved in critical hazard assessments or surveys. Interested parties seeking a less technical document describing how to measure potentially hazardous fields may refer to NCRP Report 119 [B196]. However, the material in Clause 3, Clause 4, and Clause 5 of this document, which treats measurement problems, desirable instrument characteristics, and procedures for measuring external fields should be of value to anyone concerned with potential EM hazards.

Subcommittee 1 on Techniques, Procedures, Instrumentation, and Computation was originally organized on 7 April 1960, to establish specifications for techniques and instrumentation used in evaluating potentially hazardous radio frequency (RF) radiation. In June 1985, the scope was clarified and the purpose was extended to establish specifications for techniques and instrumentation to be used in evaluating potential RF hazards to mankind from exposure to manmade sources of EM radiation or from exposure of volatile materials and explosive devices to such radiation. It is not intended to include infrared, visible, ultraviolet, or ionizing radiation.

Although the scope of SCC-28 includes potential hazards resulting from exposure of flammable volatile materials and explosive devices to EM radiation, this document is devoted exclusively to potential hazards to personnel. This is because the necessary specifications and definitions pertaining to fuels and explosive devices are still being developed, and there are implications that the instrumentation requirements may be substantially different from those addressed here. However, the measurement techniques and instruments described here are applicable to the measurement of fields in the vicinity of flammable materials and explosive devices, even though exposure standards for these situations have not been established.

1.3 Frequency range

The techniques and instrumentation specified herein are useful for field measurements over the frequency range of approximately 100 kHz to about 100 GHz.³ No single measurement technique or instrumentation arrangement is valid over the wide frequency range covered by this recommended practice. In general, techniques and instrumentation developed for use in the frequency range below about 900 MHz apply to the measurement of both the electric and magnetic field strengths. To evaluate potentially hazardous near-field situations at frequencies below a few hundred MHz, measurement of both the electric and the magnetic field strength is required. A series of commercially available instruments has been developed for this purpose. For body currents, measurements can be made with simple, portable laboratory instruments over the frequency range of 0 to about 100 MHz. SAR can be measured using RF-transparent temperature sensors over the frequency range of 100 kHz to about 6 GHz and can be measured in phantoms using E-field probes over the frequency range of 300 MHz to about 3 GHz. Above about 6 GHz, absorption is confined to the surface of a biological system and thermographic cameras can be used to measure the surface SAR up to about 300 GHz.

³These frequency limits should not be considered rigid, but are given as a general guide. Normally, a given instrument does not abruptly become invalid at a specific frequency; rather its accuracy, sensitivity, or both, deteriorate over some frequency range until finally it is no longer usable. For example, an instrument designed for the lower frequencies may cover the entire broadcast band down to 0.5 MHz. When using a given instrument, one should be aware of its frequency limitations.

1.4 Quantities and parameters to be measured

For frequencies above 300 MHz, and for measurements performed at distances from the source greater than a^2/λ (a is the largest dimension of the effective aperture of the source, and λ is the wavelength) with a probe whose dimensions are much less than a , power density S is usually a meaningful quantity that has been widely adopted as a hazard indicator. However, power density is difficult to determine, except in cases of stationary, single-component, plane-wave fields of known polarization. In fact, no existing instrument actually measures power density directly; all measure one or more components of the electric field strength (E), or the magnetic field strength (H), or both, and then infer an equivalent power density from the far-field, plane-wave relationship $S = |E|^2 / (120\pi)$ or $120\pi |H|^2$, where E is the rms electric field strength in volts per meter, H is the rms magnetic field strength in amperes per meter, and S is the power density in watts per meter squared. In the near field, and where scattering, reflections, or multiple sources are present, the field configuration can be extremely complex and one must measure both E and H separately.⁴ In many instances, measurements will be required in the reactive or radiating near-field regions where reactive fields or standing waves exist.⁵ Under these more general conditions, the time-averaged power density is not a reliable hazard indicator, even if practical probes could be developed for its measurement. Under these complex conditions, induced current (for frequencies below about 100 MHz) and SAR (for frequencies between about 100 kHz and about 6 GHz) are the more meaningful quantities.

Because for plane waves all of the preceding parameters are simply related to power density, no loss of generality would occur with the use of these parameters for far-field measurements. As stated previously, some commercially available meters actually measure $|E|^2$ or $|H|^2$, while indicating equivalent plane-wave power density. Therefore, they do provide a valid indication of the exposure level and, hence, the potential hazard, even though they may not indicate the actual power density at the point of measurement. Because RF-hazard measurement instrumentation is currently not available to measure absolute peak values, except for pulses of RF energy of duration greater than a few milliseconds, rms values will be considered unless otherwise stated. As the state-of-the-art advances, recommendations will be extended to include absolute peak quantities. For internal dosimetry (within body tissues), the quantities used are SAR (W/kg), internal rms, and peak electric field strength (V/m), internal current (A), and current density (A/m²).

1.5 Types of situations covered

This recommended practice is intended for use in situations typified by the following.

1.5.1 External fields

- a) Leakage fields
- b) Radiation fields
- c) Reactive fields

Leakage fields are generally interpreted as those resulting from the unintentional emission of RF energy, whereas radiation fields are generally interpreted as those resulting from equipment designed to intentionally radiate EM energy. Reactive fields are present in the immediate vicinity of sources of both leakage and radiation fields and tend to be stronger near radiators of small dimensions with respect to wavelength. Multipath interference due to the scattering and reflection of energy from objects or conducting surfaces is an additional complicating factor and is present to some degree in most situations. Accurate measurements should include procedures for estimating or avoiding multipath effects and near-field measurement errors. Some useful techniques for measurements in multipath environments are given in Clause 6 (see 6.3.2 and 6.3.3).

⁴For well-defined sources where analysis indicates that only one field component is sufficient to show compliance with a particular maximum permissible exposure (MPE) level or radio frequency protection guide (RFPG), only that component need be measured.

⁵See definitions in Clause 3.

1.5.2 Specific absorption rate (SAR)

The need for SAR measurements within models of exposed personnel is twofold. First, over the frequency range where SAR is meaningful (approximately 100 kHz–6 GHz), it is the underlying basis for the maximum permissible exposure (MPE) values found in many contemporary RF safety standards and guidelines, including those of IEEE Std C95.1-1991. That is, the MPEs in terms of the external fields, induced current, and induced current density are derived from the basic dosimetric quantity SAR over its meaningful frequency range [B55]. The external field strength MPEs in many RF exposure guidelines and standards, e.g., IEEE Std C95.1-1991, ICNIRP [B132], limit the whole-body-averaged SAR to 0.4 and 0.08 W/kg for the controlled and uncontrolled environments, respectively. Compliance with such standards and guidelines is assured if the whole-body-averaged SAR and specific local (or spatial-peak) SAR criteria, e.g., 8 W/kg and 1.6 W/kg in any gram of tissue in the shape of a cube, are met, even if the field strength MPEs are exceeded. Generally, accepted SAR measurement methods [B55], [B195] include the measurement of the rate of temperature rise within the exposed object or the measurement of the internal electric field strength. The temperature rise may be characterized by a whole-body-averaged (calorimetric) measurement, a point measurement (via a thermometer implanted in the object being exposed), or thermographic camera analyses of bisected phantom models and animal carcasses that have been exposed to large RF fields. The internal electric field strength may be measured with an implantable E-field probe or may be computed using sophisticated numerical methods.⁶

The second need for determining SAR is that even under far-field plane-wave exposure conditions, the SAR varies widely with frequency, polarization, and spatial location within an object. The determination of the SAR provides a much-needed insight into the spatial distribution of absorbed energy, particularly with respect to different organs of the exposed subject.

1.5.3 Induced and contact current

Internal currents are induced in humans when partial or whole-body exposures to RF fields occur. The issue of induced body currents generally becomes a consideration at lower frequencies, typically below 100 MHz, and especially below 30 MHz. Most often, the evaluation of excessive induced body current occurs in the near-field region of the RF source. For greatest accuracy in predicting the magnitude of these induced currents in humans, use of a full size model is required. The model is placed in the near-field region of the source in question, simulating the position, posture, and size of the potentially exposed individual. Then, special measurement techniques are used to evaluate the RF-induced currents. A complication associated with evaluating the magnitude of induced RF current relates to pathways through which these currents flow in the body. For example, when the exposure is such that the electric field is parallel to the axis of the body, the induced currents flow through the body, or parts of the body, commonly through the legs and the feet to the ground or floor (whichever is the lowest potential surface in contact with the body). The use of instrumentation, which is in effect placed in series with the body and ground, can provide a measure of these electric field induced currents. In the case of magnetic field exposure, however, the currents that are induced in the body, called eddy currents, most commonly circulate about the cross sections of the anatomy, with the greater magnitudes being at the outer periphery of the body, near the surface. These circulating currents tend not to exit the body in the same fashion as electric field induced currents and, consequently, represent a major measurement challenge. Assessments of induced currents should, however, give consideration to both electric and magnetic field contributions.

2. References

This recommended practice shall be used in conjunction with the following publication. When the following specification is superseded by an approved revision, the revision shall apply.⁷

⁶Protocols for determining the peak spatial-average SAR induced by specific products, e.g., hand-held radio transceivers used for personal wireless communications, are developed by IEEE Standards Coordinating Committee 34.

IEEE Std C95.1™, 1999 edition, IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz–300 GHz.⁸

3. Definitions

For the purposes of this recommended practice, the following terms and definitions apply.

3.1 amplitude modulated average power output: The radio frequency power delivered to the transmitter output terminals averaged over a modulation cycle.

3.2 anechoic chamber: A room or enclosure in which reflections of electromagnetic waves from the boundary surfaces have relatively small values.

3.3 antenna: A device designed for radiating (or receiving) electromagnetic energy.

3.4 antenna aperture: A surface, near or on an antenna, on which it is convenient to make assumptions regarding field values for the purpose of computing fields at external points.

NOTE—The aperture is often taken as that portion of a plane surface near the antenna, perpendicular to the direction of maximum radiation, through which the major part of the radiation passes.

3.5 antenna array: A system of antennas coupled together for the purpose of enhancing radiation in one or more directions and reducing radiation in other directions.

3.6 antenna directivity: The ratio of the transmitted radio frequency radiation intensity in a specified direction to the radiation intensity averaged over all directions.

NOTE—The average radiation intensity is equal to the power radiated by the antenna divided by 4π .

3.7 antenna effective aperture or effective area: In a given direction, the ratio of the power available at the terminals of a receiving antenna to the power density of a plane wave incident on the antenna from that direction; the wave being polarization-matched to the antenna.

NOTES

1—A plane wave of given power density and from a given direction is polarization-matched to an antenna if its polarization is that which results in maximum power at the antenna terminals.

2—The (total) effective aperture of an antenna may be decomposed into the sum of two partial effective apertures referred to two specified, orthogonal polarizations, respectively.

3—For a lossless and perfectly matched antenna, effective area in a given direction is equal to the square of the operating wavelength, times the gain in that direction, divided by 4π .

3.8 antenna field regions: Classification of the important spatial subdivisions of an antenna's electromagnetic field. The subdivisions, at non-uniquely defined distances from the antenna, include the reactive near-field region adjacent to the antenna, the radiating near-field region (for large antennas commonly referred to as the Fresnel region), a transition zone, and furthestmost, the far-field region, also known as the Fraunhofer region. *See also: near-field region and far-field region.*

⁷The IEEE standards or products referred to in Clause 2 are trademarks owned by the Institute of Electrical and Electronics Engineers, Incorporated.

⁸IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

3.9 antenna gain (absolute gain in a given direction): The ratio of the radiation intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna was radiated isotropically.

NOTES

1—Gain does not include losses arising from impedance and polarization mismatches.

2—The radiation intensity corresponding to the isotropically radiated power is equal to the power accepted by the antenna divided by 4π .

3—If an antenna is without dissipative loss, then in any given direction, its gain is equal to its directivity.

4—If the direction is not specified, the direction of maximum radiation intensity is implied.

5—The term “absolute gain” is used in those instances where added emphasis is required to distinguish gain from relative gain, for example, absolute gain measurements.

3.10 antenna gain, partial (for a given polarization): In a given direction, that part of the radiation intensity corresponding to a given polarization, divided by the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically.

NOTES

1—The (total) gain of an antenna, in a specified direction, is the sum of the partial gains for any two orthogonal polarizations.

2—The gain of aperture antennas, e.g., parabolic reflectors, is usually referenced to an isotropic radiator; The gain of linear antennas, dipoles, and colinear arrays is usually referenced to a half-wave dipole.

3.11 antenna lobe: A part of the antenna radiation pattern between adjacent minima.

3.12 antenna pattern: The spatial distribution of a quantity that characterizes the electromagnetic fields radiated by an antenna.

NOTES

1—The distribution can be expressed as a mathematical function or as a graphic representation.

2—The quantities that are most often used to characterize the radiation from an antenna are proportional to, or equal to, power density, radiation intensity, directivity, phase, polarization, and field strength.

3—The spatial distribution of the EM field characteristics over any surface is also an antenna pattern.

4—When the amplitude or relative amplitude of a specified component of the electric field vector is plotted graphically, it is called the amplitude pattern, field pattern, or voltage pattern. When the square of the amplitude or relative amplitude is plotted, it is called a power pattern.

3.13 antenna terminal impedance or driving-point impedance: The ratio of complex voltage to complex current at the terminals of a transmitting antenna, or the ratio of the open-circuit voltage to the short-circuit current at the terminals of a receiving antenna.

3.14 athermal effect (nonthermal effect): Any effect of electromagnetic energy absorption not associated with or dependent on the production of heat or a measurable rise in temperature.

3.15 attenuation: A general term, expressed as a ratio, used to denote a decrease in magnitude of a field quantity in the transmission from one point to another.

NOTE—The attenuation may be expressed as a ratio or, by extension of the term, in decibels.

3.16 average power ($\bar{P}$): The time-averaged rate of energy transfer:

$$\bar{P} = \frac{1}{t_2 - t_1} \left(\int_{t_1}^{t_2} P(t) dt \right)$$

3.17 average power density: The instantaneous power density integrated over a specific time duration. The time duration could be source related, e.g., the source repetition period, or use related, e.g., the averaging time specified in exposure guidelines. Average power density is expressed in units of watts per square meter (W/m^2).

NOTE—In speaking of average power density in general, it is necessary to distinguish between the spatial average (at a given instant) and the time average (at a given point).

3.18 backward scatter: Energy directed (scattered) into the rear hemisphere with respect to the direction of incident energy.

3.19 bolometer: A device capable of absorbing radiant energy and of using the heat so developed to change its electrical resistance, thus indicating the amount of energy absorbed.

3.20 conductivity: The ratio of the conduction-current density in a medium to the electric field strength. The unit of conductivity is siemens per meter (S/m).

3.21 dielectric constant: *See:* **permittivity**.

3.22 diode: A semiconductor device having two terminals and exhibiting a nonlinear voltage-current characteristic; in more restricted usage, a semiconductor device that has the asymmetrical voltage-current characteristic exemplified by a single p-n junction.

3.23 dipole: **(A)** Any one of a class of antennas producing the radiation pattern approximating that of an elementary electric dipole. **(B)** A linear radiator, usually fed in the center, producing a maximum of radiation in the plane normal to its axis. The length specified is the overall length.

NOTE—Common usage considers a dipole antenna to be a metal radiating structure that supports a line-current distribution similar to that of a thin straight wire, a half-wavelength long, so energized that the current has a node only at each end.

3.24 driving-point impedance: *See:* **antenna terminal impedance**.

3.25 duty cycle: Deprecated. *See also:* **duty factor**.

3.26 duty factor: The ratio of the pulse duration to the pulse period of a periodic pulse train.

3.27 duty ratio: The ratio of average to peak pulse power.

3.28 effective aperture: *See:* **antenna effective aperture**.

3.29 effective area: *See:* **antenna effective aperture**.

3.30 electric dipole: A pair of equal and opposite charges separated by an infinitesimal distance. When the charges are oscillating, the dipole becomes an elementary radiating electric dipole.

3.31 electric field (general): A vector field of electric field strength or of electric flux density.

NOTE—The term is also used to denote a region in which such vector fields have a significant magnitude.

3.32 electric field strength (E): (A) (General): At a given point, the magnitude (modulus) of the vector limit of the quotient of the force that a small stationary charge at that point will experience, by virtue of its charge, to the charge as the charge approaches zero in a macroscopic sense. (B) (Signal-transmission system): The magnitude of the potential gradient in an electric field expressed in units of potential difference per unit length in the direction of the gradient. (C) (Radio wave propagation): The magnitude of the electric field vector. The electric field strength is expressed in units of volts per meter (V/m).

3.33 electric field vector: The force on a stationary positive charge per unit charge.

NOTE—This may be measured either in newtons/coulomb or in volts/meter. This term is sometimes called the electric field intensity, but such use of the word intensity is deprecated, because intensity connotes power in optics and radiation.

3.34 electrical length: The length of any electrical conductor, such as an antenna or transmission line, expressed in wavelengths, radians, or degrees.

NOTE—When expressed in angular units, it is distance in wavelengths multiplied by 2π to give radians, or by 360 to give degrees.

3.35 electric flux density (displacement): A vector equal to the product of the electric field strength and the permittivity of the medium. In an anisotropic medium, the permittivity is a function of direction; hence, the electric flux density is not necessarily in the same direction as the electric field strength. Electric flux density can be considered as a surface charge density and is expressed in units of coulombs per square meter (C/m^2).

3.36 electromagnetic field: Electromagnetic phenomena expressed in scalar or vector functions of space and time.

3.37 electromagnetic radiation: The propagation of energy in the form of electromagnetic waves through space. (Not intended to describe propagation along waveguides and other transmission lines.)

3.38 equivalent plane-wave power density: The normalized value of the square of the electric or the magnetic field strength at a point in the near field of a radiating source. The value is expressed in W/m^2 and is computed as follows:

$$S = |E|^2 / (120\pi) = |H|^2 \times 120\pi$$

3.39 far-field region: That region of the field of an antenna where the angular field distribution is essentially independent of the distance from the antenna. In this region (also called the free-space region), the field has a predominantly plane wave character, i.e., locally, very uniform distributions of electric field strength and magnetic field strength in planes transverse to the direction of propagation. For larger antennas especially, the far-field region is also referred to as the Fraunhofer region.

3.40 finite difference time domain (FDTD) method: The FDTD method is a numerical algorithm for solving Maxwell's differential equations of electromagnetic field interactions in the time domain by discretizing the problem space into unit cells where the space and time derivatives of the electric and magnetic fields are directly approximated by simple, second-order accurate central-difference equations.

3.41 half-power beamwidth: In a plane containing the direction of the maximum lobe of the antenna pattern, the angle between the two directions in which the radiated power is one-half the maximum value of the lobe.

3.42 heat capacity: The amount of heat necessary to raise the temperature of a given mass of a substance one degree. Heat capacity is expressed in joules per kg kelvin (J/kg K) or joules per kg degree Celsius (J/kg °C).

3.43 horn antenna: An antenna consisting of a waveguide section whose cross-sectional area increases toward the open end that is the aperture through which electromagnetic energy is radiated or received.

3.44 horn radiator: *See:* horn antenna.

3.45 incident wave: A wave, traveling through a medium, in a specified direction, which impinges on a discontinuity or a medium of different propagation characteristics.

3.46 insertion loss: The loss resulting from the insertion of a component in a transmission system. It is the ratio of the power delivered to the load when connected to the generator, to the power delivered to the load when the component is inserted. Insertion loss is usually expressed in decibels.

3.47 internal body current: The current that is induced in a biological subject that is exposed to low-frequency radio frequency fields.

3.48 intrinsic impedance (of free space): The ratio of the electric field strength to the magnetic field strength of a propagating electromagnetic wave. The intrinsic impedance of a plane wave in free space is equal to $1.20\pi \Omega$ (approximately 377Ω).

3.49 ionizing radiation: Any electromagnetic or particulate radiation capable of producing ions directly or indirectly in its passage through matter. Examples are X-rays and gamma rays.

3.50 isotropic: Having the same properties in all directions.

3.51 isotropic antenna: An antenna capable of radiating or receiving equally well in all directions, and equally responsive to all polarizations of electric and/or magnetic fields.

NOTE—In the case of transmitting coherent electromagnetic waves, an isotropic antenna does not exist physically, but represents a convenient reference antenna for expressing directional properties of an actual transmitting antenna.

3.52 loss tangent: The ratio of the imaginary component of the complex permittivity of a material to the real component of the complex permittivity.

3.53 magnetic dipole: A magnetic field moment caused by current flowing in an infinitesimally small loop. When the current is oscillating, the dipole becomes an elementary radiating magnetic dipole.

3.54 magnetic field strength (H): The magnitude of the magnetic field vector, expressed in units of amperes per meter (A/m).

3.55 magnetic field vector: A field vector that is equal to the ratio of the magnetic flux density to the permeability, expressed in units of amperes per meter (A/m).

3.56 magnetic flux density (magnetic induction): The vector quantity $\vec{B}$ producing a torque $\vec{T}$ (in Newton meters) on a plane current loop in accordance with the relation $\vec{T} = LA\vec{n} \times \vec{B}$, where $\vec{n}$ is the positive unit

vector normal to the loop, A is its area in m^2 , and I is the loop current in amperes. Magnetic flux density is expressed in units of Teslas (T), formerly webers per square meter.

NOTE—The tesla is often defined as equal to a weber per square meter (Wb/m^2), but as can be seen from the above equation for T , the tesla is also equal to a newton per ampere meter ($\text{N}/\text{A} \cdot \text{m}$).

3.57 maximum normalized field strength: The value of the maximum spatial electric field strength E or the maximum spatial magnetic field strength H under a set of specific near-field exposure conditions (in a prescribed volume of space) that is equal to the corresponding value of E or H associated with a plane wave of given power density.

NOTE—The maximum normalized field strength concept is used to aid in the assessment of the relationship between exposure of an object to external near-fields and the resulting internal SAR.

3.58 maximum permissible exposure (MPE): The rms and peak electric and magnetic field strengths, their squares or the plane-wave equivalent power densities associated with these fields and the induced and contact currents to which a person may be exposed without harmful effect and with an acceptable safety factor. In some guidelines, they are referred to as investigation levels or reference levels.

3.59 microwaves: A term used rather loosely to signify radio waves in the frequency range from about 300 MHz upward.

3.60 modulation: The process, or result of the process, whereby some characteristic of one wave is varied in accordance with another wave or signal.

NOTE—For the purpose of this recommended practice, continuous wave (CW) operation is considered to be a special form of modulation, that is, zero modulation.

3.61 multipath error: The error caused by the reception of a composite signal that arrives via two or more different paths.

3.62 multipath transmission (radio propagation): The propagation phenomenon that results in signals reaching the receiving antenna by two or more paths.

3.63 near-field region: A region in the field of an antenna, located near the antenna, in which the electric and magnetic fields do not have a substantially plane-wave character, but vary considerably from point to point. The term is only vaguely defined and has different meanings for large and small antennas. It is further subdivided into the reactive near-field region, which is closest to the antenna and contains most or nearly all of the stored energy associated with the field of the antenna, and the radiating near-field region. If the antenna has a maximum overall dimension that is not large compared with the wavelength, the radiating near-field region may not exist. For antennas large in terms of wavelength, the radiating near-field region is sometimes referred to as the Fresnel region on the basis of analogy to optical terminology.

NOTE—For most antennas, the outer boundary of the reactive near-field region is commonly taken to exist at a distance of one-half wavelength from the antenna surface.

3.64 nonionizing radiation: Any electromagnetic radiation incapable of producing ions directly or indirectly. Microwaves and radio frequency energy are forms of nonionizing radiation.

3.65 nonthermal effect: *See:* athermal effect.

3.66 parabolic antenna: An antenna consisting of a parabolic reflector and a source at or near its focus.

3.67 passive or parasitic re-radiator: Electrically conducting structures that, when illuminated by a primary radio frequency source or ambient electromagnetic fields, act as a secondary radiating source

because of currents induced in the structure. In some cases, re-radiators can produce localized electromagnetic fields significantly more intense than the fields at the location of the re-radiator that are associated with the prime source.

3.68 peak power density: The maximum instantaneous power density occurring during the interval when power is transmitted.

3.69 peak power output: In a modulated carrier system, the output power averaged over a carrier cycle, at the maximum amplitude that can occur with any combination of signals to be transmitted.

3.70 peak pulse amplitude: The maximum absolute peak value of a pulse excluding those parts considered to be unwanted, such as spikes, provided that the energy is small (5% or less) compared with the total energy at the pulse.

NOTE—Where such excursions are made, it is desirable that the amplitude chosen be illustrated pictorially.

3.71 peak spatial-average specific absorption rate (SAR): The maximum local SAR averaged over a specified volume or mass, e.g., any 1 g or 10 g of tissue in the shape of a cube. SAR is expressed in units of watts per kilogram (W/kg).

3.72 penetration depth: For a plane electromagnetic wave incident on the boundary of a medium, the distance from the boundary into the medium along the direction of propagation in the medium, at which the field strengths of the wave have been reduced to 1/e of their boundary values. Penetration depth is expressed in meters (m).

3.73 permittivity (complex): The ratio of the electric flux density in a medium to the electric field strength at a point. The permittivity of biological tissues is frequency dependent. Permittivity is expressed in units of farad per meter (F/m).

3.74 polarization (radiated wave): That property of a radiated electromagnetic wave describing the time-varying direction and amplitude of the electric field vector; specifically, the figure traced as a function of time by the extremity of the E-field vector at a fixed location in space, as observed along the direction of propagation.

NOTE—In general, the figure is elliptical and it is traced in a clockwise or counterclockwise sense. The commonly referenced circular and linear polarizations are obtained when the ellipse becomes a circle or a straight line, respectively. Clockwise sense rotation of the electric vector is designated right-hand polarization and counterclockwise sense rotation is designated left-hand polarization.

3.75 power: A physical quantity describing the rate of delivery or transmission of energy. In this document, power will refer to radio frequency power with units of watts (W).

3.76 power density: Power per unit area normal to the direction of propagation, usually expressed in watts per meter squared (W/m^2) or, traditionally, mW/cm^2 . *See also:* **Poynting vector**.

NOTE— $10 \text{ W/m}^2 = 1 \text{ mW/cm}^2$

3.77 power gain: Of an amplifying device, the ratio of the radio frequency power delivered to a specified load impedance to the radio frequency power absorbed by its input. *See also:* **antenna gain**.

NOTE—Power gain is usually expressed in decibels.

3.78 power level: At any point in a transmission system, the ratio of the power at that point to some arbitrary amount of power chosen as a reference. This ratio is usually expressed as decibels referred to 1 mW (dBm) or decibels referred to 1 W (dBW).

3.79 Poynting vector: A vector $\bar{P}$, defined as the vector product of the electric and magnetic field vectors at the point in question, that is, $\bar{P} = \bar{E} \times \bar{H}$.

NOTE— $\bar{P}$ is expressed in units of watts per square meter and, for a uniform plane wave, represents the electromagnetic energy flow per unit area per unit time across a given surface element.

3.80 probe: A minimally perturbing device used for measuring a component of a radio frequency field in a medium. A probe contains the following components:

- a) An electrically small (in the medium) sensor (or sensors) for detecting the radio frequency field component of interest
- b) A means for converting the RF signal to a proportional dc or slowly varying ac signal
- c) A balanced high-impedance resistive transmission line to extract the rectified signal

3.81 probe antenna-length: The maximum physical dimension of the sensing element, e.g., dipole or loop of an electric or magnetic field probe, respectively, or the dimension of the largest sensing element in a multiple array.

3.82 pulse repetition frequency (PRF): In a pulse-modulated radio frequency system using recurrent pulses, the number of pulses per unit of time.

3.83 pulse repetition rate: *See:* pulse repetition frequency.

3.84 pulsed radio frequency (PRF): A continuous-wave radio frequency carrier signal that is amplitude-modulated at a known PRF with a controlled duty factor.

3.85 radar: A system that radiates pulsed or frequency-modulated electromagnetic waves and utilizes the reflection of such waves from distant objects to determine their existence and/or position.

NOTE—The name is derived from initial letters of the expression “radio detection and ranging.”

3.86 radiation intensity: In a given direction, the power radiated from an antenna per unit solid angle in that direction. The units are watts per steradian (W/sr).

3.87 radio beam: Radiowaves whose energy is essentially confined within a relatively small angle in at least one plane.

3.88 radio frequency (RF): The frequency in the portion of the electromagnetic spectrum that is between the audio-frequency portion and the infrared portion.

NOTE—The present practicable limits of radio frequency are roughly 10 kHz–300 GHz. Within this frequency range, electromagnetic radiation may be detected and amplified as an electric current at the wave frequency.

3.89 radio frequency protection guide (RFPG): Deprecated. *See:* maximum permissible exposure (MPE).

3.90 radio frequency radiation hazard meter (monitor): An instrument that is capable of measuring spatially localized electric and/or magnetic field strengths under near- and far-field conditions. The instrument consists of a sensor with an antenna suitable for the wavelength under study, plus a means for transmitting information from the sensor to a suitable field strength indicator.

3.91 reactive field: Electric and magnetic fields surrounding an antenna or other electromagnetic devices that result in storage rather than propagation of electromagnetic energy.

3.92 reflected wave: A wave in a medium produced by reflections from objects or discontinuities in the medium or from a boundary of a different medium.

3.93 re-radiated field: An electromagnetic field resulting from currents induced in a secondary, predominantly conducting object by electromagnetic waves incident on that object from one or more primary radiating structures or antennas. Re-radiated fields are sometimes called “reflected” or, more correctly “scattered fields.” The scattering object is sometimes called a “re-radiator” or “secondary radiator.” *See also:* **re-radiator.**

3.94 response time: The time required for a field-measuring instrument to reach some specified percentage of the final value after being placed in the field to be measured. In this document, 90% of the final value is assumed.

3.95 separation distance: As applied to the measurement of electric and magnetic fields, separation distance means the distance between a source and the nearest point on the probe sensing elements.

3.96 scattering: The process that causes waves incident on discontinuities or boundaries of media to be changed in direction, frequency, phase, or polarization.

3.97 skin depth: *See:* **penetration depth.**

3.98 spatial average: As applied to the measurement of electric or magnetic fields for the assessment of whole-body exposure means the root mean square of the field over an area equivalent to the vertical cross section of the adult human body. The spatial average can be measured by scanning (with a suitable measurement probe) a planar area equivalent to the area occupied by a standing adult human (projected area). In most instances, a simple vertical, linear scan of the fields over a 2 m height will be sufficient.

3.99 specific absorption rate (SAR): The time derivative (rate) of the incremental energy (dW) absorbed by (dissipated in) an incremental mass (dm) contained in a volume element (dV) of a given density (ρ).

$$SAR = \frac{d}{dt} \left(\frac{dW}{dm} \right) = \frac{d}{dt} \left(\frac{dW}{\rho dV} \right)$$

SAR is expressed in units of watts per kilogram (W/kg).

NOTES

1—SAR can be related to the electric field at a point by

$$SAR = \frac{\sigma |E|^2}{\rho}$$

Where

- σ is the conductivity of the tissue (S/m),
- ρ is the mass density of the tissue (kg/m³),
- E is the rms electric field strength (V/m).

2—SAR can be related to the increase in temperature at a point by

$$SAR = \frac{c \Delta T}{\Delta t}$$

Where

- ΔT is the change in temperature (°C),
- Δt is the duration of exposure (seconds),
- c is the specific heat capacity (J/kg °C).

This assumes that measurements are made under “ideal” non-thermodynamic circumstances, i.e., no heat loss by thermal diffusion, heat radiation, or thermoregulation (blood flow, sweating, etc.).

3.100 specific heat capacity: *See:* **heat capacity.**

3.101 standing wave: A spatially periodic or repeating field pattern of amplitude maxima and minima that is generated by two equal-wavelength propagating waves traveling in different directions. For any component of the field, the ratio of the amplitude at one point to that at any other point does not vary with time.

3.102 standing wave ratio: The ratio of maximum field strength to minimum field strength along the direction of propagation of two waves traveling in opposite directions on a transmission line.

3.103 thermocouple: A pair of dissimilar conductors so joined at two points that an electromotive force is developed by the thermoelectric effect when the junctions are at different temperatures.

3.104 waveguide: An enclosed system capable of guiding electromagnetic waves from one place to another. A waveguide usually consists of a hollow metallic tube or a solid dielectric material.

3.105 waveguide component: A device designed to be connected at specified ports in a waveguide system.

4. Measurement problems associated with RF hazard assessment

4.1 Characteristics of RF EM radiation

4.1.1 Parameters determined by the source

Sources of EM radiation have widely different characteristics that impose a requirement for versatility on the monitoring equipment. Pertinent characteristics are the following:

- a) *Modulation*—The specific characteristics of the signal in both the time and frequency domains.
- b) *Radiation pattern*—In the near field, patterns change with distance from the source, whereas in the far field, no significant change with distance occurs. At any given point in space, the field strength continually changes if either mechanical or electronic scanning techniques are used.
- c) *Frequency*—Energy may be present over several decades of frequency and may be predominately associated with either the E- or H-fields.
- d) *Polarization*—In the far field of a single radiating source, only one polarization exists over a broad physical area (vertical linear, horizontal linear, elliptical, or circular). However, in the near field, any one of these polarizations may exist at any given point, and the polarization changes with small variations in location from the RF source.

4.1.2 Interference patterns

In any environment where RF measurements are to be made, field strength will commonly vary with position. Such variability is caused by interference patterns produced by the combining of energy received directly from the source(s) and reflections (or re-radiation) from natural or manmade objects (multi-path radiation). Because the phase of the reflected signal can be at any angle with respect to that of the direct signal, the effect of the reflection can enhance or diminish the signal strength that would be found at the measuring location in the absence of a reflected signal. The distances between maxima and minima are a function of wavelength, and so they may vary from a fraction of a centimeter to many meters. At locations with emitters operating at various frequencies, the field strength pattern is likely to be particularly complex.

Scanning sources, such as radars and other sources that operate intermittently, introduce time variations with their own interference patterns. Planning of measurement programs should take into account both spatial and

time variations. That need is important from both the viewpoints of collecting all data pertinent to the objective and ensuring that personnel are protected from excessive exposure.

4.1.3 Radiation leakage

Radiation leakage from electronic equipment presents special problems because the source of energy may not be clearly defined *a priori*. It could emanate from a crack in a shielding cabinet or from poorly joined or non-shielded connecting cables or sections of waveguide. The polarization of the EM field and the location of the leak are not generally known. This is a special case of the general near-field situation, and the same problems can exist for all near-field measurements, whether the emitted fields are intentional or accidental. Whereas RF antennas (dipoles, horns) include structures intentionally designed to radiate or receive EM energy efficiently, devices designed to process materials with RF energy (RF-dielectric and induction heaters, electrosurgical devices, and arc welders) are not intentionally designed to radiate, but may contain structures that can function as antennas. Workers operating such equipment can receive very intense exposures because of their proximity to these radiating elements.

A completely general theoretical treatment of the leakage problem is very difficult and is beyond the scope of this recommended practice. The survey techniques differ from those associated with the radiation fields from antennas. In the leakage case, the location of the source is generally found by trial and error. A nondirectional, nonpolarized “isotropic” detector is generally desirable in order to probe in the immediate vicinity of the equipment where directive pickup antennas would give inaccurate readings because of their inability to respond to multipath signals and because of inaccurately known gain-reduction factors in their near field. However, at microwave frequencies, a somewhat directive system consisting of a small horn or waveguide probe, thermistor, attenuator, and power meter is easy to assemble, and may be useful for locating a source of leakage when accurate knowledge of the level is not required. However, both the vertical and horizontal polarization components should be measured separately by rotating the probe 90° about its axis.

In the case of leakage sources that produce highly nonuniform exposure of personnel, measurements of induced currents may be a more accurate indicator of exposure than the magnitude of the electric and magnetic field strengths. Induced currents provide a measure of the capacitive coupling between the source and a nearby individual that field strength alone cannot. For example, in a case where the hands are exposed to particularly strong EM fields, the induced current flowing in the fingers, hands, and wrists may become the limiting factor, when interpreted in terms of the resulting SAR.

4.1.4 Reactive near field

The reactive near field is the region close to the radiation source where energy storage fields are important. In this region of space immediately surrounding the leakage source or antenna, reactive components of the field predominate over the radiating near-field and radiating far-field components. Reactive fields can be inductive (low E/H ratio) or capacitive (high E/H ratio) in nature, and either field component can dominate. The characteristics of reactive fields relate to the inductance and capacitance of the radiating structure. Part of the associated electromagnetic energy is stored; i.e., it is not propagated beyond the near-field region. This stored energy is transferred periodically between the radiating structure and the near field. Although the extent of the reactive region varies for different equipment, the practical outer limit is of the order of a few wavelengths. For example, at a distance of between two and three wavelengths from an ideal dipole, all reactive components are less than 10% of the radiating components. Although the reactive components do not contribute to the net flow of radiated energy, they can couple into biological or other material and, thus, affect energy absorption. Consequently, for many hazard assessments, it is important that the reactive fields be measured using the appropriate instrumentation and measurement techniques (see 6.3). Furthermore, both the electric and the magnetic fields should be measured to fully evaluate the hazard potential, because both contribute to the induced SAR in biological objects [B170].

4.1.5 Passive, parasitic, or secondary re-radiators

Conducting objects that are illuminated by RF energy, either in the near or the far field of a primary source, are termed passive or parasitic re-radiators. High E- and/or H-fields (with respect to ambient RF fields) can usually be measured in close proximity to a re-radiator. These are generally reactive fields that decay rapidly with distance, as discussed in 4.1.4. A passive re-radiator can theoretically and physically be replaced by an equivalent transmitting antenna (reciprocity) because an antenna has the same field pattern whether it is transmitting or receiving. The magnitude of the near and far fields produced by a re-radiator depends on the RF currents induced on it by the primary source. The size and orientation (with respect to the primary source) also determine the magnitude of the induced currents and, hence, the local fields.

Examples of passive re-radiators are electrically large, linear, metal objects, such as flag poles, metal sign posts, and electrical house wiring. Closed loops, such as metallic automobile steering wheels and metal window frames are examples of a second type of re-radiator. Large metal surfaces, such as metal fences, metal signs, and the walls of metallic buildings are examples of a third type of re-radiator. Each individual re-radiator has a unique scattering cross section that determines the amount of energy intercepted from an ambient RF field. The scattering cross section of any single object is dependent on the frequency and polarization of the incident radiation and the physical configuration of the object. Resonances and focusing at specific frequencies may occur in a given object that results in significantly enhanced re-radiated fields.

There are virtually no data in the literature that relate to the SAR induced in a person exposed to the near fields of a passive re-radiator. In spite of this fact, near-field theory, antenna theory, and published dosimetric data associated with active radiators can be utilized to draw some general conclusions. Potential hazards to personnel due to passive re-radiators are “reduced” or “enhanced” with respect to exposure to plane waves of equal maximum normalized field strength. Caution should be exercised when interpreting so-called, localized “hot spots” caused by re-radiating objects because the amount of energy that may be coupled to an individual contacting the re-radiator may be very small, despite the existence of relatively high-surface field strengths. This subject is discussed further in 6.6.

4.1.6 Other considerations

In the near field, three orthogonal components of the electric field with arbitrary relative phases and amplitudes exist. Similarly, there are three orthogonal components of the magnetic field with arbitrary phases and amplitudes. The electric field is elliptically polarized in an arbitrary plane, and the magnetic field, in general, is elliptically polarized in another plane. Consequently, in the near field, measurements of the phase and amplitude of each of the three components of the electric (magnetic) field generally do not provide sufficient information to determine the magnetic (electric) field at the same point. Thus, use of instruments capable of measuring either the electric or the magnetic field and that respond simultaneously to all polarizations is desirable. Field measurement devices utilizing three orthogonal dipoles or loops that detect the amplitude, but not the phase of the electric or magnetic field, cannot provide complete information about the elliptically polarized field. Specifically, the maximum instantaneous field vector is not measured with these types of devices. Only an averaged total field strength is measured, with the averaging occurring over one cycle of the oscillation of the field (the carrier frequency). Currently available hazard instrumentation does not provide both phase and amplitude measurement capability. This means that power density is not actually measured under these circumstances even when power density is the quantity displayed, but is only inferred from measurements of $|E|^2$ and $|H|^2$.

An RF radiation monitoring instrument can respond to pulsed fields in an entirely different manner than it responds to CW fields. For low-duty factor pulsed fields, the instrument may become a peak detector and produce meter indications that exceed the actual, time-averaged field values by factors of 10 dB–20 dB.

When characterizing potentially hazardous EM fields, a distinction should be recognized between emission levels and exposure levels. An emission standard specifies the maximum field strength or power density at a specified (usually small) distance from an emitting source; an exposure standard generally specifies the

maximum field strength or power density to which personnel should be exposed as a function of exposure duration. In most cases where an emission standard applies, the sources are small apertures, e.g., localized leakage around the periphery of a microwave oven door. In these situations, the radiated fields follow approximately an inverse-square law reduction of power density with distance or an inverse dependence of field strength with distance. Such inverse-distance dependence has been verified for leakage emission from microwave ovens for distances of 5 cm to about 1 m. The inverse-square relationship may not apply, however, close to an electrically large aperture.

In general, the maximum level of exposure to personnel will not be equivalent to the measured emission level of a source of RF energy. Furthermore, the exposure area will generally decrease as one approaches the source. Thus, as the source is approached, a plane should be scanned by personnel surveying a leakage field to determine the location of the localized leakage radiation beam.

4.2 Summary of the measurement problem

4.2.1 Time and spatial averaging

4.2.1.1 Time averaging

Many contemporary guidelines and standards, including IEEE Std C95.1-1991, specify the maximum permissible values of the RF field strength or power density as averaged over a specified averaging time, e.g., any continuous 6 min or 30 min interval. The time-averaging provision permits exposures that exceed the MPEs for continuous exposure when the exposure duration is less than the averaging time. For example, if the MPE is 10 W/m² (1 mW/cm²) averaged over any 6-min period, the time-averaging provision permits exposures that exceed 10 W/m² provided the following is met:

$$S(\text{W/m}^2) \times t(\text{min}) = 60 \text{ W min/m}^2$$

$$t \leq 6 \text{ min}$$

Thus, for example, if the exposure duration is only 3 minutes in any 6-minute period, a maximum power density of 20 W/m² is permitted.

Figure 1 illustrates the application of the time-averaging provision of the MPEs. In Figure 1(a), the time-averaged exposure value is 60 W-min/m² in both periods 1 and 2. During the remainder of the illustrated 6-min periods, no exposure is allowed in order to keep the time-averaged value from exceeding 60 W min/m² (6 mW min/cm²). In reality, RF exposures usually vary continuously with time due to source characteristics or movement of the individual within the RF exposure field. This is represented by Figure 1(b), where the area under the curve within any 6-min window of time does not exceed 60 W min/m². The time-averaging feature of the MPE may introduce substantial complications in determination of compliance, depending on the particular exposure situation. For example, although the time-averaged MPE is not exceeded for either period 1 or period 2 in Figure 1(a), the MPE is exceeded for the 6-min period beginning at 3 min in period 1 and ending at 3 min in period 2. Assessing time-averaged RF exposures in some complex environments may be accomplished accurately only through the use of instrumentation designed to acquire and average the real-time variations in the measured field strengths [B17]. Such measurements may be performed with portable datalogging devices adapted to the averaging time of the MPE [B249], which can provide a “sliding” average over the appropriate averaging time. In less complicated exposure environments, such as when the RF exposure is intermittent but not otherwise varying in level, a datalogger used in conjunction with a broadband RF field-strength meter may suffice for determining the time-averaged exposure values.

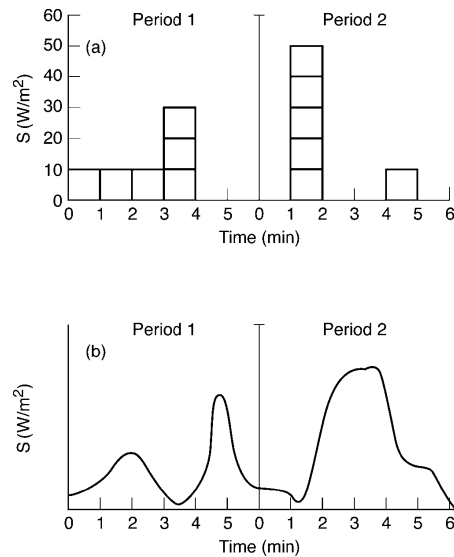


Figure 1—Application of 6-minute time averaging

4.2.1.2 Spatial averaging

The assessment of RF fields that vary substantially with location requires the fields to be spatially averaged in order to specify whole-body-average exposure levels. As applied to the measurement of electric or magnetic fields in the assessment of whole-body exposure, spatial average means the root mean square of the field over an area equivalent to the vertical cross section of the adult human body. The spatial average can be measured by scanning (with a suitable measurement probe) a planar area equivalent to the area occupied by a standing adult human (projected area). In most instances, a simple vertical, linear scan of the fields over a 2 m height through the center of the projected area will be sufficient. In this case, the same approach employed for the measurement of time-averaged exposure levels may be used successfully. For example, Tell [B249] describes a measurement technique using a data-logging device wherein a uniform velocity scan is performed over a linear distance equivalent to the height of an adult human. The resulting value, averaged over the total scanning time, is equivalent to the spatial average of the RF field. Commercially available RF survey meters have provisions for integrated data logging and spatial and time averaging. These instruments offer this capability in smaller packages than previously attainable with separate data logging devices connected to a basic field meter. Spatial averaging of the exposure fields provides a more meaningful description of the exposure, particularly in areas where extremely localized and high-intensity fields may exist, but where only limited exposure of the body actually occurs.

In addition to a straight line linear spatial average, RF exposure fields may be (1) averaged over the projected area of the body or (2) averaged as a volumetric average over the space within which individuals have access. Each of these methods has advantages and disadvantages, and the results in a given situation may differ. When averaging over the actual projected area of the body, the projected area of the body varies with height and the nonuniform fields are weighted accordingly; i.e., the RF fields are not linearly averaged. For example, the projected area of the head represents a relatively small area relative to its vertical extension compared with the torso over an equal vertical dimension. Thus, in cases where the fields may be maximum near the location of the head, and relatively small over the rest of the body, the projected area average will result in a smaller value than would occur via simple linear averaging. However, for fields that are highly variable with spatial maxima in the region of the torso and lower body, the use of projected area averaging may produce higher spatial averages than simple linear averaging. The outcome of the spatial averaging process will also be dependent on the spatial characteristics of the RF fields in relation to the posture of the exposed subject.

The use of spatial volumetric field averaging provides a relatively convenient approach for characterizing RF fields at antenna sites that occupy large areas. In this case, fields are measured by walking about the site moving the RF measurement probe in an up and down oscillatory motion with the probe being moved from near the ground to approximately head height. Combined with walking, this approach permits the probe to sweep out a volume of space and produces a volumetric average that may more realistically represent the typical exposure of individuals in the area than other averaging methods and may be more realistically related to whole-body SAR.

The choice of the most appropriate method for assessing RF exposure relative to whole-body-average SAR should be made by the individual performing the field investigation. With any of the above methods, it may prove useful to determine the relationship between the average value and the spatial peak value of the RF fields measured. Such a relationship may be useful for estimating the average field from simple probing for spatial peak fields. This relationship will be dependent on the frequency of the fields because this will dictate the spatial distance between field minima and maxima caused by reflections.

Preliminary, unpublished data suggest that spatially averaged fields may range between approximately 40% and 60% of the spatial peak field values at VHF and UHF broadcast antenna sites. Individuals performing RF surveys should develop information on these relationships and include such data in field survey reports as well as an explanation for why the specific measurement method was chosen.

Tell [B253] has evaluated the differences between these two methods of spatial averaging for vertical colinear type antennas, common to the type used for paging and other wireless communications services. In an analysis of an 800 MHz band antenna with alternative mounting heights of 0 m, 1.2 m, and 1.83 m, it was found that with the simulated head height configuration, the projected area averaging resulted in an averaged power density almost 29% less than linear averaging.⁹ But, for field distributions producing larger fields only slightly higher in elevation, the reduction was determined to be nominally less, about 8% and 1%, respectively. However, for the field distributions of the colinear antennas with 0 m and 1.83 m mounting heights, the projected area approach actually resulted in slightly higher values for the spatially averaged power density, being 7% and 15% greater, respectively.

This finding is not surprising based on the considerably complex situation of reflected fields encountered at telecommunications antenna sites. If the power density of the local field is relatively high in the regions of the trunk of the body, the increased projected area of the body throughout the trunk can result in weighted power densities that are actually greater than if the fields were simply linearly averaged. On the other hand, it is clear that basing spatial averaging on the body's projected area can result, in some cases (especially with highly localized fields), in notably lower values of exposure. Although IEEE Std C95.1-1991 specifies MPEs in terms of spatial averages based on projected areas, the practical complication that this presents for compliance studies is recognized in Clause 6 of the standard, yielding to the acceptability of performing linear averaging. Individuals involved in compliance studies of telecommunications sites should be aware of the possible differences that either technique can have on the results.

4.2.2 External field measurement problems

The EM environment is determined by many factors including the following:

- a) The direction of energy propagation from the sources
- b) The directions, distances, and relative orientations of the sources and prominent features of the physical environment with respect to the field point
- c) The polarization, frequency, type of modulation, and power of the sources

⁹0 m, 1.2 m, and 1.83 m= 0 ft, 4 ft, and 6 ft)

The variable nature of these factors and their effects on the resulting EM field should be understood to successfully design and operate instruments that measure the EM environment, and to obtain sufficient data to ensure personnel safety.

In general, the character of the near field of an RF source is composed of both reactive and radiation components that exhibit both spatial and temporal variations. These variations will be functions of the physical environment, as well as the properties of the RF source. As a result of the extremely wide variety of possible situations, each of which could be essentially unique, the calculation of near-field intensities for each situation is generally not practical due to the complex nature of near fields. Hence, one should usually rely on measurements. The following material is applicable to both near-field and far-field external fields and SAR measurement applications.

4.2.3 Limitations in the use of near-field instruments

An undesirable situation often arises when a hazard survey is performed using isotropic survey instruments when attempts are made to assess the degree of hazard using only field strength data taken in the near field of a radiating RF source or a passive re-radiating object. The surveyor measures a high field strength that decays rapidly as the probe is moved away from the source. At distance of a few centimeters, the measured field strength may exceed the applicable MPE expressed in units of far-field electric or magnetic field strength or equivalent plane wave power density. However, the coupling of these localized RF fields to any absorbing object (such as a person) may not exceed the SAR value upon which the MPE was based. The possibilities for estimating RF absorption using only external field measurements are discussed in Clause 6 (see 6.6). However, the estimate will often be so inexact that it is useless to attempt to determine the degree of potential risk using external field measurements.

One such situation is the high E-field strength near the tip of the monopole antenna of a hand-held transmitter operating at a wavelength that has similar dimensions as the human head. Very high field strengths (relative to contemporary MPEs) can be measured but only within a few centimeters of the antenna tip. It can be shown that RF absorption may indeed be high if a person's head is placed a few centimeters from the antenna tip, but it is not possible to predict the local SAR in the head using only the measured external field strength. This and many other situations should be assessed through the use of SAR measurements (dosimetry) or induced current measurements in realistic models of the part of the anatomy that is immersed in the local high fields. The use of dosimetric analysis via physical or mathematical models is a well-accepted technique in ionizing radiation health physics and tools and models to perform RF dosimetry are also commercially available. These dosimetric techniques should be used as the principal means for hazard assessment under circumstances where the risk or the economic scale of an RF exposure issue make the relatively high cost and complexity of the dosimetric techniques worthwhile. Such techniques are discussed in detail in this document to enable persons responsible for RF hazard assessment to utilize the available dosimetric technology.

4.2.4 In- and out-of-band interference in RF hazard meters, including cable pickup

In-band interference associated with RF pickup in the cable connecting the probe with the readout of an RF hazard meter often occurs. Errors of as great as 10 dB can occur at frequencies below a few MHz in improperly designed instruments. See 5.4 for more detailed information.

Out-of-band performance of RF radiation hazard monitors becomes increasingly important in areas where multiple signals are present. When illuminated only by frequencies within its designated band, a monitor may provide accurate measurement results; signals outside this band, however, may produce uncalibrated meter responses giving rise to false characterization of the fields actually present. In the case of frequencies higher than the upper usable frequency, erroneously high responses associated with the probe structure generally produce this form of error. For frequencies below the operating band, the instrument response to the reactive field, or a scalar potential field, may produce false indications [B181]. This type of error can be minimized by avoiding measurements close to energized low-frequency elements, where capacitive coupling

to the survey instrument may produce this type of false response. Techniques developed for 60 Hz field strength measurements, e.g., IEEE Std 1460™-1996 [B135], where the potential effects are canceled [B188] can, in some situations, be utilized to correct for this error. The effect of low-frequency interference can be determined at the measurement site using the technique described in 6.3.5.

4.2.5 Effects of sensor size and measurement distance

When an isotropic, near-field probe is used to make RF measurements close to an RF radiator, or near a reflecting or re-radiating object, several types of errors arise. The errors can readily exceed many decibels if the following effects are not avoided.

- a) *Field gradients*—Measurement data can be distorted when using an isotropic “near-field probe” to map steep spatial gradients close to the radiating elements of an RF emitter (an antenna or an unintentional radiator). These gradients may cause the amplitude of the field being measured to vary significantly over the volume of space occupied by the probe’s antennas. This introduces measurement errors due to spatial averaging. This problem imposes limits on the maximum size of the array antennas or sensors in the probe. Also, a minimum distance exists where accurate measurements can be made of the near field, for a given probe size.
- b) *Interaction of an active source with the probe*—Coupling of reactive near fields to the measurement probe can result in erroneously high measured values when a near-field probe is used in proximity to an active radiator or a passive re-radiator. The degree of probe interaction (or coupling) is a function of the size of the probe’s antennas (or sensors) and the separation distance between the RF source and the probe.
- c) *Probe-antenna loading effects from nearby objects*—When the probe is close to a reflecting object or re-radiator, a probe-loading error is produced. This effect alters the “source impedance” of the probe’s antennas and changes the equivalent electrical circuit of each antenna and its respective detector. For a given type of detector, this loading error is dependent on the size of the antenna, the distance to the reflecting object and the frequency of the field being measured.

4.3 SAR measurement problems

The measurement of SAR in exposed biological subjects at radio frequencies is a challenging task, both under near- and far-field exposure conditions. In the far-field case, internal fields are highly dependent on the size, shape, orientation (with respect to polarization), and composition (complex permittivity) of the object. In a sphere (such as the human head) or cylinder (such as the arm or leg), resonances may occur, causing large gradients in the internal field-strength distribution [B124] with focal points, or hot spots, occurring near the center of the sphere and standing waves throughout the volume of the exposed object. However, the SAR on the “front” surface of the sphere will typically be high, and it is usually the maximum value of local SAR. Under localized (partial body) near-field exposure conditions, the internal fields decay exponentially with distance from the exposed external surface. The rate of decay depends on the conductivity of the tissue. Thus, the determination of SAR is easier for this class of near-field exposure, compared with far-field exposure, because the internal fields are confined primarily to the volume directly adjacent to the exposure aperture of the apparatus [B124]. In both the near- and far-field cases, internal regions with differing permittivities create reflections and standing waves and, thus, complicate the measurement problem [B141]. Also, when the whole body of a person or laboratory animal is exposed to plane-wave or near-field RF energy, localized regions deep within can be heated selectively. The resulting intense, local “hot spots” are due to resonant conditions existing in these localized regions where the local SAR (E^2) may exceed the average whole-body SAR by a factor of 100 [B87], [B240].

4.3.1 SAR measurement accuracy and limitations

The local SAR values and the SAR distribution in biological objects cannot be measured without producing relatively large measurement uncertainties, regardless of the instrumentation used. Under ideal plane-wave

exposure conditions, the maximum local (point) SAR can be up to 100 times greater than the whole-body-averaged SAR [B236]. Thermodynamic factors and large gradients in the internal E-fields increase the magnitude of the SAR measurement error whether it is measured with thermal instrumentation or with implantable E-field probes. A measurement uncertainty of about ± 1 –2 dB is usually the best that can be achieved when attempting to determine the maximum and minimum internal EM fields or the SAR that exists anywhere within an irradiated biological object. Calorimetric measurements of the whole-body-averaged SAR can be performed with absolute accuracy and precision that is better than 10% [B210]. However, the whole-body-averaged SAR, as well as the local SAR at various points in an exposed object varies significantly as the position of the object is changed with respect to the exposure-field vectors. Therefore, measured SAR data should be expressed with realistic precision (no more than two significant figures) and the limits of uncertainty of the SAR measurement should be stated explicitly.

4.4 Induced current measurement problems

Measurements of induced body currents are at present practically restricted to determining the induced currents caused by electric fields (see 1.5.3). The measurement of induced currents is discussed in Deno [B67], Gandhi *et al.* [B91], Guy and Chou [B108], Hill and Walsh [B123], and Tell [B248]. In practice, a current measuring device is placed in series with the feet or hands and the current that then flows to earth or some other grounded surface is measured. A method for determining the current induced in the arms of tower climbers has been described [B74] in which a broadband, thermocouple type RF milliammeter is used. A narrowband measurement technique in which the RF voltage (that is proportional to the current flowing in the body) developed across a low-impedance resistor is measured with a high sensitivity tunable receiver is discussed in Tell *et al.* [B254]. By using this method, the currents induced at different exposure frequencies can be distinguished. The use of clamp-on type RF current transformers is an alternative method for measuring induced or contact currents.

5. Instrumentation

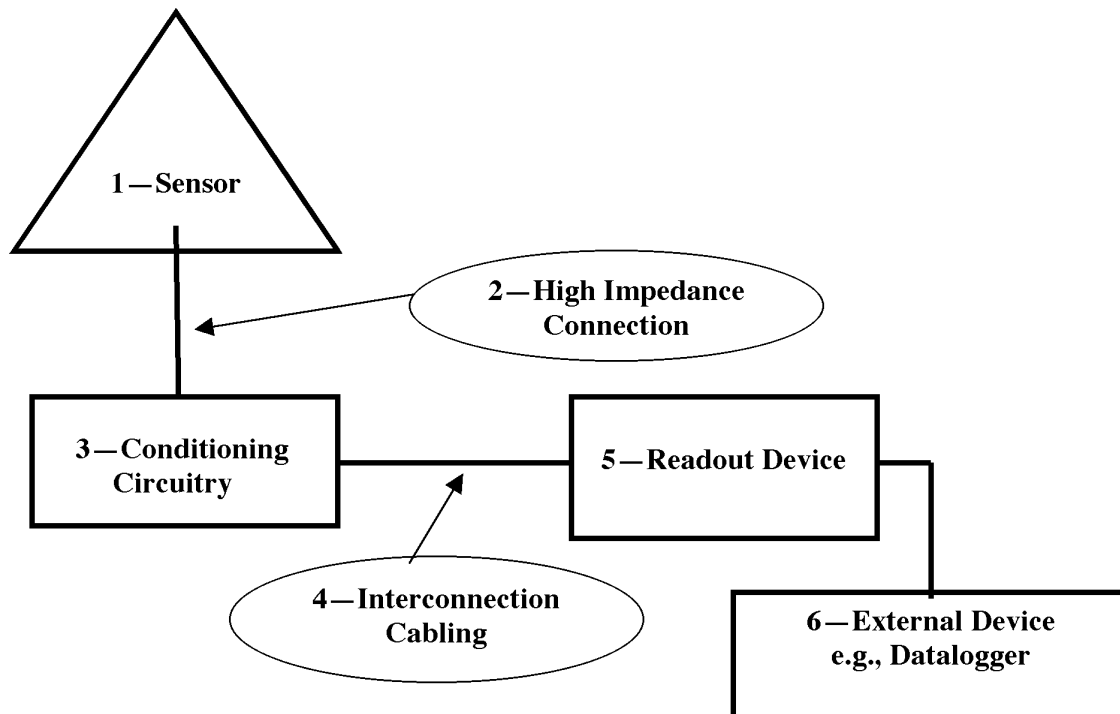
5.1 Instrumentation for external field measurements

5.1.1 RF survey instruments

RF radiation hazard meters (monitors, survey instruments) are usually the preferred means for measurement and assessment of potential RF hazards. As shown in Figure 2, an RF survey instrument can be divided into three basic parts: probe (sensor), leads, and metering instrumentation. The probe consists of an antenna in combination with a sensor or detector. The design and characteristics of the probe determine to the greatest extent the performance and application of the unit. The detected output from a probe with a flat frequency response is a direct measure of the EM-field strength. One exception is the specially designed hazard probe that has a frequency-shaped response that conforms to a particular MPE (see 5.4.6); i.e., the detected output is appropriately weighted at each frequency. The “leads” refer to that part of the instrument that carries the detected signal to the metering instrumentation. To accomplish this without causing perturbation of the field, the leads may take the form of high-resistance wires, or if they are metallic, they should be carefully oriented so as to minimize coupling with the field. They may also take the form of an optical fiber [B30], [B32], [B266]. Metering instrumentation includes signal-conditioning circuitry and display devices.

To make meaningful near-field measurements, the following conditions should be satisfied:

- a) The probe should respond to a particular electromagnetic field parameter and not have spurious responses (for example, it should respond to the E-field with no spurious H-field response).
- b) The dimensions of the probe sensor in its surrounding medium should be much less than a wavelength at the highest operating frequency.



1—*Sensor*: Generates an electrical signal proportional to field strength or the square of field strength.

2—*High impedance connection*: Minimizes interaction between the field and the connection circuit, i.e., isolates the sensor from the conditioning and readout circuitry.

3—*Conditioning circuitry*: Provides signal conditioning, which may include filtering, amplification, digitizing, etc. The sensor, high impedance connection, and conditioning circuitry, in combination, is often referred to as the “probe.” The conditioning circuitry may also be combined with the readout device.

4—*Interconnection cabling*: Connects the conditioning circuitry with readout and can be an optical connection for increased electromagnetic isolation between the probe/sensor and readout/surveyor or may be a conductive cable.

5—*Readout device*: A digital or analog readout to display field strength information. The readout device may include logging, averaging, or other data conditioning capabilities. With suitable interconnection modules, the readout device may be a PC (computer).

6—*External device*: The readout may connect through a conductive or optical fiber cable to a remote readout or data collection (logging) device.

Figure 2—Basic components of any RF survey instrument

- c) The probe should not produce significant scattering of the incident electromagnetic fields
- d) The probe response should be isotropic (independent of orientation), nondirectional, and nonpolarized. A probe with a nonisotropic response is useful if the polarization of the measured quantity (E or H) is known, or if some provision is made to rotate the probe to find the orientation for maximum output.
- e) The leads from the sensor to the meter should not interact significantly with the field or conduct RF current from the field to the sensor.

5.2 Desirable electrical performance characteristics

5.2.1 Power supply

The instrument should employ a self-contained power supply that is isolated from external fields by appropriate shielding and filter decoupling. If batteries are used, provision should be made for indicating their condition. The instrument should be capable of at least 8 hours of operation within its rated accuracy before battery replacement or recharging becomes necessary.

5.2.2 Polarization

The combination of probe antennas should be responsive to all polarization components of the EM field. This performance may be accomplished either by inherent design using multiple dipoles or loops or by physical rotation of a single antenna about its axis.

5.2.3 Quantities and units

For the assessment of potential hazards to personnel, the instrument should indicate one or more of the following parameters [B260]:

- a) Average “equivalent plane-wave” power density in watts per square meter (W/m^2) or milliwatts per square centimeter (mW/cm^2)
- b) Mean-squared electric field strength in volts squared per square meter (V^2/m^2)
- c) Mean-squared magnetic field strength in amperes squared per square meter (A^2/m^2)
- d) Field strength in amperes per meter (A/m) or volts per meter (V/m)

Average power density (W/m^2 or mW/cm^2) is displayed by some survey meters intended for use primarily above 300 MHz; such meters are often used in near-field and reactive-field regions where true power density is neither measurable nor the most meaningful quantity (E^2 or H^2 are preferred). Some instruments indicate “equivalent plane-wave” power density as derived from the field quantity being measured. Instruments having a probe with a shaped frequency response should read in terms of “percent of exposure limit” based on the MPE of interest, e.g., IEEE Std C95.1-1991.

5.2.4 Range

An adequate dynamic range for instruments with a shaped frequency-response is -10 dB to $+5$ dB (10% to 300%) relative to 100% of the exposure limit, as defined by the MPE. For flat frequency response probes, the minimum recommended dynamic range of the instrument is 10 dB below the lowest value and 5 dB above the highest value of the MPE. Either a single logarithmic range or a number of linear ranges can be used to obtain the desired dynamic range.

5.2.5 Recorder output

The instrument should be equipped with a recorder output or other means that will enable the measurement of potentially hazardous fields without endangering the operator, and will facilitate spatial and time averaging. Alternative provisions to avoid endangering the operator may be extension cables between the probe and the meter or a maximum-hold mode of operation where the maximum measured value is maintained until the instrument is re-zeroed by the operator.

5.2.6 Shielding

The instrument housing and antenna cables should provide adequate shielding to ensure that the measurement uncertainty remains within stated limits when the instrumentation portion or accessory cables

(that may act as unintended receiving elements) are exposed to the same field strength as the probe. This shielding should be effective under conditions in which the maximum coupling or “pickup” occurs for the unintentional receiving elements.

5.2.7 Modulation

The instrument should indicate rms parameters, independent of any modulation. However, it is permissible to have a detector or indicator time-constant switch for the CW and amplitude-modulated continuous-wave (AM-CW) modes. Also, the instrument should be capable of averaging the narrowest pulse-modulated envelope of a noncontinuous wave field that is expected to be encountered by the surveyor.

5.2.8 Static electricity

The instrument should not indicate false levels due to a response to static electric charges. These static charges are often induced on the probe of the survey instrument, or on the system being surveyed, e.g., cathode-ray tube displays. As an example, when making measurements during windy conditions and/or low humidity, static charge on the operator can influence the readings of the survey instrument.

5.2.9 Response to other radiation

The specified accuracy of the instrument should include effects of exposure to ionizing radiation, artificial light, sunlight, or corona discharge.

5.2.10 Response time

The response time is generally defined as the time required for the instrument to reach 90% of its final value when exposed to a step function of CW RF energy. The user should know the response time. Multiple operator-selectable response times are desirable with a fast response time no greater than 1 s.

5.2.11 Special functions

It is desirable that the instrument is provided with one or more of the following functions:

- a) A maximum-hold function that indicates the maximum reading during the measurement period.
- b) An audio signal function that is proportional to the measured field strength and/or an audible indication that a preset level has been exceeded.
- c) A data-logging function that can provide an average, maximum, and minimum value of the field quantity being measured. These data are stored for later utilization. This feature could also provide a real-time average of the measured fields with an averaging time specified by the user, e.g., 6 min. This average value should be updated every few seconds, providing the user with an indication of the behavior of spatial or time varying fields.
- d) A time-averaging function with relatively long time constants (of the order of minutes) that, for a flat-frequency response probe, averages the measured quantity over a known time period. The output of a probe with an appropriately shaped frequency-response, averaged over an appropriate period, e.g., 6 min, is a direct measure of that portion of the corresponding current MPE.
- e) Analog or digital interfacing capability with a personal computer or other data-acquisition equipment, including the appropriate software.

5.2.12 Stability

The instrument should exhibit stability sufficient to permit accurate measurements of the RF exposure fields over periods of time that are consistent with the times normally required for the particular measurement. In practice, the instrument should be capable of operating for 10 min–30 min without the need for re-zeroing

the meter (in the absence of RF radiation) on the range necessary for the measurement. Automatic electronic zero-circuitry can be used to avoid the requirement of shielding the sensitive probe from ambient RF fields during the zeroing process. Automatic zeroing is desirable, particularly when performing RF surveys in difficult environments such as on communications/broadcast towers, where an RF-free location may not be available or where a surveyor, climbing a tower, may not be able to move freely or have the use of both hands to reset the zero level of the instrument. The instrument should be insensitive to thermal variations within the range of normally encountered temperature extremes. The instrument specifications should state the maximum zero drift for each range.

5.2.13 Accuracy and precision considerations

The instrument should be provided with calibration data that permit the user to assess the maximum uncertainty in determining RF field strength or power density when using the instrument in various types of fields of different frequencies. Calibration data should also include the sensitivity of the instrument to frequencies beyond the intended useful range (out-of-band response). A meter sensitive to out-of-band fields should not be used in an environment where such fields may be present at other than negligible levels. Absolute field strength calibration uncertainties (accuracy) of no greater than ± 1 dB are desirable but difficult to achieve. Uncertainties of ± 2 dB or even greater may be acceptable if the levels are well below the limits of the MPE, but as the MPE is approached, measurement uncertainty becomes of greater importance. In any event, the uncertainty factor should be known and included in the measurement report. The instrument specifications should address the instrument's ability to respond to amplitude modulated (AM) fields, such as pulsed radar signals, as well as a multiplicity of signals that might simultaneously illuminate the sensing probe (see 5.4). The instrument readout should permit resolution (precision) of the measured field strength to within 5% of the full-scale value or less.

5.3 Desirable physical characteristics

5.3.1 Portability

The instrument should be portable to permit convenient operation under restrictive conditions (e.g., climbing a tower).

5.3.2 Weight

The weight should be kept as low as is practicable in keeping with current engineering technologies.

5.3.3 Volume

The volume should be as small as is practicable and convenient for hand-held operation (see 5.3.1).

5.3.4 Dependence on temperature, humidity, and pressure

Specified accuracy of the instrument should include the effects of temperature, humidity, and pressure variations, and the operating ranges for these parameters should be indicated.

5.3.5 Durability

The indicating meter and other system components should be rugged enough to withstand vibration and shock resulting from transport. A carrying case is desirable.

5.3.6 Readability

The meter dial markings should be large enough to be easily read at arm's length. The reading corresponding to the applicable protection guide should appear within the central one-third of the full scale reading of the dial if the readout is of the analog type. If more than one range of sensitivity is provided, the full-scale value of the selected range should be indicated, and the units of interest should be readily interpretable. In any case, the analog or digital readout should provide a clear indication of the units being displayed.

5.3.7 Ease of adjustment

The instrument should have a minimum number of controls. They should be clearly labeled as to their functions. There should be no requirements for moving two controls at the same time. For mechanical meter movements, the electrical zero point should be coincident or upscale from the mechanical zero of the indicating meter.

5.3.8 Ease of use

Complicated operating procedures should be avoided. An average technician should be able to make accurate measurements with only the information supplied in the instruction manual.

5.4 Instrument types for external field measurements

The instruments described in the following clauses are limited to those types that can provide reasonable accuracy in both near-field and far-field situations. Instruments that have large scattering areas (in terms of wavelength) are not included here.

5.4.1 Diode rectifier-based instruments

In these instruments, single or multiple diodes terminate small antennas. Multiple diodes and linearly polarized antenna elements arranged in suitable configurations can be used to sum all field components and enable measurements to be made independent of polarization and direction of incidence. A minimum of three elements in an orthogonal arrangement is required for an isotropic instrument that can be used in any orientation with respect to the field.

Some units now in use employ a single diode in combination with an electrically short dipole or small loop antenna. These instruments respond to only one field component and, consequently, should be oriented to read the maximum value, a process that can be tedious and time consuming. Such instruments are, however, useful for measuring individual field components.

A crossed-dipole or multiple dipoles arranged in a single plane will respond correctly to signals arbitrarily polarized in the plane of the sensor, but not to the total field. Such units should be oriented so that the resultant (maximum) field vector is in the plane of the sensor.

Two-dimensional H-field probes, which consist of two concentric orthogonal loops with diameters of 5.4 and 5.5 mm directly loaded with diodes [B224], are commercially available. The resistive lines have been realized using thick-film technology enabling excellent decoupling of the lines from the loop with a filter. The loops are not resistively loaded; i.e., the detected signal is directly proportional to the square of the frequency (when the diode operates in the square-law region). Although this makes the probe unsuitable for measuring broadband fields, it provides a higher sensitivity and better accuracy for narrow-band signals of known frequency. The sensitivity is of the order of 1 A/m at 1 GHz decreasing to 0.1 A/m at 100 MHz. Such probes can be used to measure surface currents on conductors if held orthogonal to the surface. Single-axis probes with a loop diameter of 3 mm and frequency range of 100 MHz–2 GHz have also been developed and

are commercially available. Fiber optic H-field sensors are currently being studied, but probes based on this approach are not known to be available commercially.

Diode instruments are basically nonlinear with respect to power density or field strength. At low levels, the rectified voltage is proportional to power density, or the square of E (or H). At higher levels, the rectified voltage becomes directly proportional to E (or H) [B147]. This change in characteristic requires the range of operation of the diode to be restricted to low levels to provide a true indication of total power density. When the diodes are operated at higher levels, the output voltages of the individual elements are required to be modified (generally squared) prior to their summation. When diode instruments are used in pulsed fields, they usually change from an average to a peak-detecting device, and hence, measurement errors may be large in fields of high peak to average ratio. The exception is when saturation of the diode takes place at very high peak field strengths or when circuitry is added to minimize the effects. Such linearization of the square-law response can be very effective for the measurement of single frequency fields, but may introduce errors when subjected to multiple frequency fields. The instrument manufacturer should provide information about the true rms response of the probe over its range of operation.

Two errors are associated with measurements made with any diode-based probe. The first error arises with the use of any electrically short dipole antenna with a diode load and an RF filter transmission line. This is the multiple-source, multiple-frequency error [B214] that is typically 1–3 dB, but in some circumstances can exceed 10 dB. The second error arises from an effect discussed in 5.4.2. This is due to the fact that typical high-resistance signal-carrying leads act as a more efficient antenna at low frequencies, e.g., 540 kHz–1700 kHz used for AM broadcasting, than the short dipoles in the probes. Alignment of the leads with the E-field can result in erroneous measurements.

Schottky (metal barrier) diodes, in general, exhibit some photovoltaic effect. Beamlead hybrid types exhibit this effect to a much greater extent and may produce erroneous readings when illuminated by sunlight or strong incandescent light. Therefore, optically opaque encapsulation is required to eliminate this effect.

When adapted to broadband operation, the upper frequency range of a diode-based E-field instrument is presently above 26 GHz [B128], [B150], the low-frequency limit is below 400 kHz, and the burn-out level can be in the thousands of W/m^2 range.

Diode detectors, depending on design, may exhibit a marked dependence on ambient temperature. Variations in output with ambient temperature will typically be less than 0.05 dB per degree Celsius. Diode units also may be modulation sensitive if the square-law region is exceeded, resulting in errors dependent on the form of modulation.

5.4.2 Active antenna

It is difficult to make accurate, broadband E- and H-field probes that cover the long-wavelength (above about 100 m, i.e., frequencies below about 3 MHz) region, using the conventional means cited above. This is due to the fact that the source-impedance of an electrically small (10 cm) dipole antenna is extremely high, and the sensitivity of a small (5–10 cm diameter) loop antenna is very low. In order to provide a dipole probe with a flat frequency response and adequate sensitivity, the load impedance of the detector and the high-impedance lead in combination should be greater than the antenna (source) impedance. One solution is to provide a high-impedance RF buffer amplifier that is connected directly to a monopole or loop antenna and that acts as the load. This is accomplished by placing the amplifier and battery in a metal enclosure that serves as a cubical “ground plane” or asymmetric dipole element. In commercially available units, the size of this cube is small enough (10–15 cm on a side) so as to not unduly perturb the field under test or the receiving pattern of the device [B197]. This is practical for frequencies between 10 kHz and several hundred MHz. Commercially available magnetic and electric field probes, using active electronics, operate at frequencies as low as 60 Hz [B60].

A second problem associated with probes without active electronics is that of isolating the signal-carrying leads from the antenna/detector combination. This problem may become severe below about 100 MHz, and particularly below 10 MHz. This is due to the fact that the typical high-resistance signal-carrying leads serve as a low-pass filter, and their ability to separate the low-frequency detected signal from the RF field being measured becomes more difficult as the two frequencies approach each other. This results in excessive sensitivity and poor antenna patterns in passive probes. Finally, at frequencies above about 300 MHz, when “free-space” or uniform irradiation conditions exist, both the sensor and the metal enclosure of the survey instrument can be exposed to similar levels of RF [B147] and scattering from the enclosure to the sensor (probe) can cause significant measurement errors.

Active electronic probes eliminate the use of such leads entirely by including the visual display (readout) with the metal box containing the active electronics. Instruments are available commercially that use a fiber-optic data link to connect the box containing the active electronics (located at the base of the probe) to a remote readout.

5.4.3 Displacement current sensors

In addition to short dipoles and monopoles, a form of parallel plate capacitor, called a displacement-current sensor [B107], can be used to measure electric fields normal to its surface or normal to any large conducting surface. An example of an instrument designed primarily for measuring fields associated with video display terminals, is based on the displacement-current sensor concept [B133]. The sensor is a double-sided circuit board 30 cm in diameter. On one side, the front, an annular ring electrically isolates a smaller circular area. The smaller area, approximately 10 cm in diameter, is the active area; the larger annular ring serves as a guard ring to eliminate errors associated with fringing fields. The smaller area is connected through an integrator (an operational amplifier with capacitive feedback) to the backplane of the sensor, which serves as a reference ground. When a time varying electric field is normally incident on the front surface of the device, the induced surface charge produces a current that flows to the backplane through the integrator circuit. This current, called a displacement current because it is proportional to the time derivative of the electric displacement, is also proportional to the time derivative of the incident electric field strength. Integration of the displacement current results in a voltage at the output of the operational amplifier that is directly proportional to the incident electric field strength (and the cross-sectional area of the smaller circular area). The output of the operational amplifier drives a true rms-voltmeter located within a shielded electronics package. The electronics package, which contains a microprocessor, digital readout, and an optical fiber telemetry system for remote monitoring, is mounted to the edge of the sensor. Displacement-current sensors are typically used at frequencies in the LF and VLF regions, e.g., from dc to a few hundred kHz, but they may be used effectively at frequencies as high as a few hundred MHz.

5.4.4 Electro-optical (photonic) sensors

This type of electromagnetic field sensor utilizes a nonmetallic, passive sensing element (electro-optic modulator) with a very broadband response (dc to 20 GHz) that converts electromagnetic field strength information to instantaneous modulation of a laser beam. The laser energy is transmitted via fiber optics to a modulator. The modulator impresses amplitude modulation on the laser beam, in proportion to the instantaneous amplitude of the RF electromagnetic field to which the modulator is exposed. The amplitude-modulated laser beam is then carried from the modulator to a photodetector that converts the modulated optical beam to an electrical signal that represents the instantaneous amplitude of the RF field strength.

The above system has been used with electrically small dipoles [B31], [B185], [B186] as an electric field sensor, as well as without antenna elements (where the electro-optic modulator serves as the E-field sensor) [B193]. In addition, conventional antennas can be connected to a commercially available electro-optic modulator via a short lead, to provide a nonmetallic, passive RF link to the antenna [B266].

5.4.5 Thermocouple

Thermocouple-type radiation monitors generally utilize thin-film thermocouples as the detection elements, with parts of the film performing the function of the antenna element. These units exhibit extremely good adherence to square-law characteristics in that the dc output from the thermocouple is proportional to the square of the electric field strength. These units, while relatively independent of ambient temperature, are generally less stable than diode type detectors. Hot and cold junctions of the couple are in close proximity to reduce the drift due to the gradient in temperature. Variation in sensitivity is of the order of 0.1% per degree Celsius. The major limitation of the element is the burnout level, which in terms of average values may be about three times full scale. The full-scale ratings depend on the basic probe sensitivity. The utilization of thin resistive films provides very broad bandwidth.

Some commercial probes arrange alternate hot and cold thermocouple junctions in a continuous series in a linear arrangement to form a dipole or in a circular arrangement to form a loop. If any single thermocouple junction fails because the probe is subjected to fields well in excess of the maximum rating of the probe, the probe will be nonusable.

Some thermocouple devices utilize dual modes of operation for extreme bandwidth. They may function as a linear resistive dipole at frequencies typically below 18 GHz [B11], [B14], [B127], and as a traveling wave or phase effect antenna above 18 GHz. Such devices have an upper frequency limit that exceeds 95 GHz [B231].

5.4.6 Shaped frequency response

Contemporary MPEs are frequency dependent, and they require determination of the ratio of the exposure field to the corresponding MPE incurred within each frequency interval. In order to comply with the MPE, the sum of such fractions must not exceed unity. Probes containing dipole–diode elements separately or in conjunction with thermocouple elements have been designed to have a sensitivity versus frequency characteristic that is the inverse of specific MPEs [B13]. This allows the summation and weighting of multiple-frequency signals in conformance with frequency-dependent MPEs. The resultant readout for this equipment is usually expressed as a “Percent of the Standard.” The probes are tailored to specific MPEs such as those specified in IEEE Std C95.1-1991.

Shaped frequency response probes may cover only a portion of the frequency range of typical MPEs. Additional probes may be used to complement each other and provide a wider measurement range. When complementary probes are used, it is necessary that their out-of-band performance is well defined; preferably, the instrument should be insensitive to out-of-band signals. Overlapping of frequency bands will also add to the uncertainty of the measurement.

5.4.7 Combined electric and magnetic field probes

Probes described in 5.4.1 through 5.4.6 have utilized one probe to measure the electric field and a second, separate probe to measure the magnetic field. In the near field of an RF source, the relative values of E and H vary considerably with respect to one another and as a function of distance from the source. Also, under typical usage situations, potentially hazardous fields may change rapidly with time. Both of these factors present practical measurement problems. For example, in order to measure both electric and magnetic field strengths that vary over time and space, an E-field probe and an H-field probe should be placed at exactly the same point, at exactly the same time. If done sequentially, the fields under study may change during the finite time that elapses between the performance of successive measurements resulting in a measurement uncertainty.

Instruments for simultaneous and mutually independent measurement of RF electric and magnetic field strengths have been developed [B19], [B20], [B69], [B148]. A broadband isotropic probe system for measuring the E- and H-fields simultaneously can be produced with a set of three mutually orthogonal

dipole elements and a set of three mutually orthogonal loops that are physically located within the same very small (compared with wavelength) volume (Figure 3). Each antenna has associated circuitry comprising a detector and an optional frequency-response-shaping filter to provide a frequency response that is flat over the desired frequency range. The lengths of the dipoles are kept electrically short so that the fields are not perturbed and the diameters of the loops are kept electrically small so that the E-field pickup of the loops will be negligible. Mutual coupling between any of the probe elements is also minimized by the use of electrically small antennas. Detectors based on the use of square law operated diodes or thermocouples are used to provide a signal to the electronic circuits, which include an arrangement for analog or digital summing and data processing. An analog or digital display, data-logger, and/or recorder can be incorporated as the final stages of this system. If three loop antennas are arranged with a common center, an isotropic response is achieved [B16]. Probes of this type are commercially available.

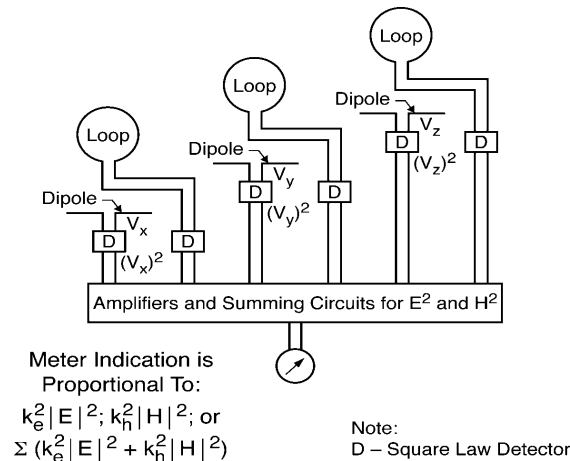


Figure 3—Schematic representation of three-dimensional isotropic E/H probe

5.4.8 Personal monitors

Personal monitors are typically small, portable broadband detectors, suitable for attachment to workers' clothing, which are equipped with an alarm feature for alerting the wearer to the presence of high-level RF fields that may approach the MPE of interest. Some personal monitors provide an alarm with an adjustable or preset threshold, e.g., 50% of the applicable MPE [B251]. In the region between 1–100 GHz, resistive thermoelectric dipoles are used as sensors with a background of lossy material to reduce the effect of scattering from the body. Electrically short dipoles with diode detectors as sensors may cover a portion of this range.

In the frequency range of 3–1000 MHz, the sensors respond to the magnetic and/or electric fields. Although magnetic field sensors are less susceptible to the effects of scattering from the body, various techniques may be employed with E-field monitors to reduce their susceptibility to these effects.

In the range of 0.1–30 MHz, surface charge detection is used and the monitors, therefore, respond to the radial fields which predominate near re-radiators in this frequency range. Personal monitors may incorporate sensors for both electric and magnetic fields and some contain frequency dependent sensors that automatically weight the detected RF fields in accordance with frequency-dependent RF exposure limits. This feature makes them especially useful in multiple frequency environments such as broadcast and wireless telecommunications antenna sites.

Because personal monitors respond to the RF fields at the position where the monitor is located on the body, some care should be used in its placement and interpreting exposure during an alarm condition. For example, wearing a belt mounted personal monitor when the predominant exposure is at eye level may not

provide sufficient warning of excessive exposure. Conversely, when used in non-uniform RF field environments, such as VHF and UHF broadcast facilities, an alarm condition may be a very conservative indication of potential excessive exposure since the MPEs of several exposure standards/guidelines are based on spatial averages over the projected area of the body. Encountering fields that trigger the alarm at one point in space may not ultimately lead to whole-body-average exposures exceeding the MPE value. Use of personal monitors can form a valuable component of an RF safety program, but a description of their use should be an integral part of any RF safety training program.

5.5 External field measuring instruments

5.5.1 Calibration methods

Reliable calibration of the various instruments used for measuring EM fields is essential to ensure safety of personnel, to assure compliance with exposure criteria and regulations, and to provide a basis for comparing the results of RF hazard or RF field-calibration research that has been performed by two or more independent groups and laboratories. Existing calibration methods are based on the premise that a known field strength can be established through measurement, calculation, or a combination of both. The device to be calibrated is placed in this standard field, and the meter indication is compared with the known field value. There are three basic approaches for producing a standard calibrating field, as follows:

- a) The free-space standard-field method
- b) Guided wave methods
- c) The standard-probe or transfer-standard method

The most widely used techniques are described in the following subclauses. The choice of technique will depend on the type and size of the probe, frequency range, available facilities and equipment, and the accuracy requirements [B149], [B165], [B194]. Refer to IEEE Std 1309™-1996 [B134] for further information on calibration methods, techniques, and typical grades of calibration used in EMC applications.

NOTE—The RF output of the generator used in all of the following methods should be free of harmonics; i.e., the harmonics should be at least 20 dB below the fundamental frequency. A low-pass filter can be placed on the output port of the generator to accomplish this.

5.5.1.1 Free-space standard field method

There are several variations of this method, but the objective is to establish a known calibration field in free space. The most common experimental arrangement for use at microwave frequencies is shown in Figure 4. The power density S at a point on the axis at a distance d from a transmitting antenna is given by the Friis free-space transmission formula

$$S = \frac{P_T G}{4\pi d^2} \quad (1)$$

Where

- P_T is the net power delivered to the antenna,
- G is the effective antenna gain with respect to an isotropic antenna

The gain is normally determined in advance, and P_T and d are measured as part of the regular calibration procedure.

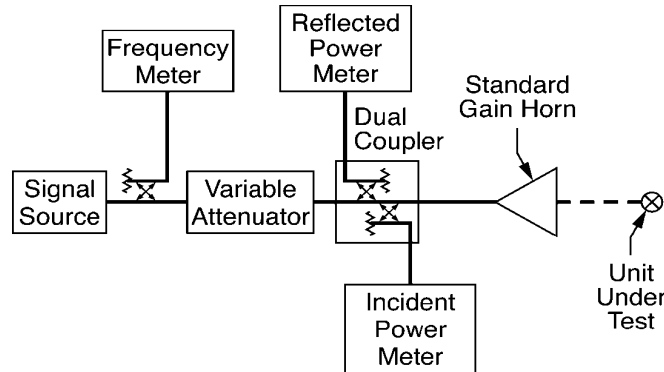


Figure 4—Free-space standard-field calibration method

The most convenient method for determining P_T is by means of a dual directional coupler, as indicated in Figure 4. The incident power P_i and the reflected power P_r are monitored at the coupler sidearms, and P_T is obtained from the relationship

$$P_T = P_i - P_r$$

High-quality, broadband couplers are available, along with methods for calibrating and using them to determine P_T [B37], [B72], [B73], [B129], [B130]. The methods cited are for calibrating power meters, but the same techniques can be applied to antennas if corrections are made for impedance mismatch effects. The method of Bramall [B37] allows the use of a low-power, calibrated bolometer to provide accurate determination of high transmitted power levels. P_T can be determined to within 1% or 2% if mismatch corrections are included (as they should be for accurate measurements).¹⁰ One way of accounting for mismatch effects utilizes the power-equation technique [B72], [B73], which also permits use of directional couplers that are not restricted in terms of directivity and do not require precision connectors. The power-equation technique and cascaded-coupler method were combined [B29] for the precise determination of transmitted absolute power from an antenna used to calibrate near-field instruments.

Alternatively, modern automatic network analyzers with built-in microprocessors for real-time correction of system errors may be used to determine P_r as well as P_T/P_r . All components used in the system being calibrated should use precision connectors and coaxial-to-waveguide adapters. This includes the high-power coaxial and waveguide directional couplers and adapters that are used during actual generation of far-field calibrated power densities.

The foregoing assumes that the device being calibrated is sufficiently small and far enough away from the transmitting antenna that the amount of energy reflected back into the transmitting system is insignificant. If this condition cannot be met, it is possible to obtain a correction for the effect of the reflected energy by varying d , observing the (approximately) sinusoidal variations in P_r , and then averaging P_r over at least one full cycle.

5.5.1.1.1 Sources of error

The principal sources of error in the free-space method are multipath interference, reflections from metallic or dielectric objects used for measuring the fields in the calibrating system, and uncertainties in the antenna gain determination. Multipath effects are often overlooked, but every calibrating facility will have some scattering associated with the walls, equipment, and even dielectric probe-support structures. They may

¹⁰The uncertainties stated here are intended to include all known, significant sources of error and correspond roughly to 95% confidence limits. However, uncertainties quoted from the published literature should be interpreted as indicated in the original articles.