



IEEE Recommended Practice for Measurements and Computations of Electric, Magnetic, and Electromagnetic Fields with Respect to Human Exposure to Such Fields, 0 Hz to 100 kHz

IEEE Standards Coordinating Committee 39

Sponsored by the
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IEEE Recommended Practice for Measurements and Computations of Electric, Magnetic, and Electromagnetic Fields with Respect to Human Exposure to Such Fields, 0 Hz to 100 kHz

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IEEE International Committee on Electromagnetic Safety

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Abstract: Techniques and instrumentation for the measurement and computation of electric, magnetic, and electromagnetic (EM) fields in the near field of an EM field source are presented in this recommended practice. Descriptions of the concepts, techniques, and instruments that can be applied to the measurement of the electric and magnetic fields and the currents induced in the human body by these fields are provided. Techniques for determining the current density and the electric field strength within the human body are discussed. This recommended practice is intended primarily for use by engineers, biophysicists, and other specialists who are familiar with basic EM field theory and practice, and the potential hazards associated with EM fields. It will be most useful to bioeffects researchers, instrumentation developers and manufacturers, those developing calibration systems and standards, and persons involved in critical hazard assessments or hazard surveys.

Keywords: contact current measurement, electric field computation, electric field measurement, electromagnetic field computation, electromagnetic field measurement, ELF/VLF/RF survey instruments, exposure assessment, induced current measurement, magnetic field computation, magnetic field measurement, nonionizing radiation, RF/ELF/VLF hazard assessment

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Introduction

This introduction is not part of IEEE Std C95.3.1-2010, IEEE Recommended Practice for Measurements and Computations of Electric, Magnetic, and Electromagnetic Fields with Respect to Human Exposure to Such Fields, 0 Hz to 100 kHz.

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, Inc. (IEEE). Prior to 1988, C95 standards were developed by Accredited Standards Committee C95, and submitted to the American National Standards Institute (ANSI) for approval and issuance as ANSI C95 standards. Between 1988 and 1990, the committee was converted to Standards Coordinating Committee 28 (SCC 28) under the sponsorship of the IEEE Standards Board. In 2001, the IEEE Standards Association Standards Board approved the name “International Committee on Electromagnetic Safety (ICES)” for SCC 28 to better reflect the scope of the committee and its international membership. In accordance with policies of the IEEE, C95 standards are issued and developed as IEEE standards, as well as submitted to ANSI for recognition.

In 2005, SCC 28 and SCC 34 became Technical Committees 95 and 34, respectively, under a new IEEE Standards Coordinating Committee (SCC), SCC 39, which is now called ICES.^a

The present scope of IEEE ICES is as follows:

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

There are five TC95 subcommittees, each of whose area of responsibility is described as follows in correspondence with its designated subcommittee number:

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

Subcommittee I of ICES Technical Committee 95 (TC95) is responsible for this recommended practice. Three standards, four recommended practices, and one guide have been issued. Present versions are as follows:

- IEEE Std C95.1TM-2005 [B55]^b
- IEEE Std C95.2TM-1999 [B56]
- IEEE Std C95.3TM-2002^c
- IEEE Std C95.3.1TM-2010
- IEEE Std C95.4TM-2002 [B57]
- IEEE Std C95.6TM-2002 [B58]
- IEEE Std C95.7TM-2005 [B59]
- IEEE Std 1460TM-1996 [B54]

^a Standards Coordinating Committees are established by the IEEE-SA Standards Board, and provide a mechanism to oversee the development of standards that are beyond the scopes of individual technical committees within IEEE's societies.

^b The numbers in brackets correspond to those of the bibliography in Annex D.

^c Information on references can be found in Clause 2.

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1. Overview

1.1 Scope

This recommended practice describes 1) methods for measuring external electric and magnetic fields and contact currents to which persons may be exposed, 2) instrument characteristics and the methods for calibrating such instruments, and 3) methods for computation and the measurement of the resulting fields and currents that are induced in bodies of humans exposed to these fields. This recommended practice is applicable over the frequency range of 0 Hz to 100 kHz.

1.2 Purpose

The purpose of this recommended practice is to describe preferred measurement techniques and computational methods that can be used to ascertain compliance with contemporary standards for human exposure to electric and magnetic fields in the frequency range of 0 Hz to 100 kHz such as

IEEE Std C95.1™-2005 [B55], IEEE Std C95.6™-2002 [B58], and similar standards.¹ 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 also be useful to bioeffects researchers, instrument developers and manufacturers, those developing calibration systems and standards, and individuals involved in critical hazard assessments or surveys.

1.3 Application

This recommended practice is not intended to replace any recommended practice or standard intended for a particular product or product family, but should be useful to regulatory agencies, manufacturers and operators of systems such as high-voltage transmission and distribution lines, underground power distribution vaults, induction motors, MRI devices, electric transportation, etc., and may also be useful in assessment of exposure from other equipment such as domestic appliances that generate and/or use EM energy, especially cookers, ovens, washing machines, tumble dryers, hair dryers and electric heaters, low-voltage power distribution lines, railway power distribution systems, electric welding and induction heating equipment, electronic security devices such as metal detectors, induction loop communications systems, and low-frequency radio communications and time-signaling transmitters that produce electric, magnetic, and EM fields in the workplace and general environment.

There are a number of other international and national standards that identify product-specific methods that also may be used, e.g., IEC 62369:2008 [B48], European standards EN 50357 [B33] and EN 50364 [B34] for electronic article surveillance (EAS) and RFID devices, and IEC 62233:2005 [B47] for appliances. The requirements of these or other national and international standards can take precedence over this document for the evaluation of human exposure from specific products and systems.

IEEE Std C95.1-2005 [B55], IEEE Std C95.6-2002 [B58], and other contemporary standards and guidelines (e.g., ICNIRP [B44]) for human exposure to electric, magnetic, and EM fields include provisions concerning induced and contact currents, internal current density, and internal electric field strength. Accordingly, this document contains a description of the concepts, techniques, and instruments that can be applied to the measurement and determination of these quantities.

While this recommended practice is intended primarily for use by engineers, biophysicists, and other specialists who are familiar with basic EM field theory and practice and the potential hazards associated with exposure to electric, magnetic, and EM fields, it is also intended to be a general guidance document and should be most useful to bioeffects researchers, instrument developers and manufacturers, and those developing calibration systems and standards. It should also be useful to persons involved in critical hazard assessments or surveys. The material in Clause 4, Clause 5, and Clause 6 of this document that treats measurement problems, desirable instrument characteristics, and procedures for measuring external fields should be of direct interest to anyone concerned with potential EM exposure hazards.

The scope of IEEE ICES also includes potential hazards resulting from exposure of flammable materials and explosive devices to EM radiation. IEEE Std C95.4™-2002 [B57] provides an analysis of EM radiation phenomena that could present a potential hazard to the transportation, handling, or use of electric blasting caps or detonators in an EM environment; other documents, e.g., NAVSEA OP 3565, Volume 1 [B83] describe hazards associated with fuel and other flammable material in such environments. Although this recommended practice is devoted exclusively to methods used for the evaluation of human exposure to electric and magnetic fields, the measurement techniques and instruments described herein are also applicable to the measurement of fields in the vicinity of flammable materials and explosive devices.²

¹ The numbers in brackets correspond to those of the bibliography in Annex D.

² Equipment, including test and measurement equipment, operated in the vicinity of flammable materials, explosive devices, and explosive atmospheres may have additional safety requirements, not included in this recommended practice.

1.4 Frequency range

The techniques and instrumentation specified in this recommended practice are useful for field measurements over the frequency range of approximately 0 Hz to 100 kHz.³ In some cases a specific measurement technique or instrumentation arrangement will not be valid over the entire frequency range covered by this recommended practice.

1.5 Quantities and exposure metrics to be evaluated

1.5.1 Internal electric fields and currents

Electric fields and currents are induced in the human body when partial-body or whole-body exposures to electric or magnetic fields occur. IEEE Std C95.1-2005 [B55] and IEEE Std C95.6-2002 [B58] specify limits for these quantities, called *basic restrictions*, to protect against established adverse health effects. These basic restrictions include the *in situ* root-mean-square (rms) and peak electric field strength (V/m) and current (A). Derived values, called *maximum permissible exposure* (MPE) values (IEEE Std C95.1-2005 [B55] and IEEE Std C95.6-2002 [B58]), are specified in terms of the external electric and magnetic field strength and contact current levels that ensure that exposures conform to the basic restrictions. Other standards and guidelines have different names of their exposure limits on external electric and magnetic fields, e.g., *reference levels* (RL) (ICNIRP [B44]).

NOTE—Exceeding the MPE values does not necessarily mean that the exposures do not conform to the basic restrictions. In such cases a more detailed assessment is required to decide if the EMF exposures conform to the basic restrictions. Techniques in this recommended practice may be used for this purpose.

For best accuracy in predicting the magnitude of induced field strengths and current densities in humans, use of a representative model of the human body is required. The model position used in the exposure evaluation should be representative of the human body position and posture relative to the exposure source. Special measurement or computational techniques are then used to evaluate the induced fields, as described in the following clauses and subclauses.

For actual measurements of induced currents, a complication arises concerning the pathways through which these currents flow in a person's body. For example, when the exposure is such that the electric field is parallel to the axis of the body, the induced currents typically flow through the body or parts of the body, through the legs and the feet, to the ground or floor (i.e., whichever is the lowest potential surface in contact with the body). Instrumentation is available that 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*, typically circulate around the cross sections of the anatomy, i.e., with the greater magnitudes being at the outer periphery of the body near the surface. These circulating currents typically do not exit the body in the same fashion as do electric-field-induced currents; consequently these present an important measurement challenge. However, evaluations of induced currents should consider contributions from both electric and magnetic fields.

1.5.2 Environmental electric and magnetic fields

For the purposes of this recommended practice, *environmental fields* means electric and/or magnetic fields external to the body, and measured in the absence of the body. The MPE values in IEEE Std C95.6-2002 [B58] that are applicable over the frequency range of this recommended practice are expressed in terms of the electric field strength (E), magnetic field strength (H), or magnetic flux density (B), and induced contact

³ These frequency limits should not be considered rigid or absolute, but are intended to be used as a general guide. Normally, the measurement results obtained with a particular measurement instrument do not abruptly become invalid at a specific frequency; rather the accuracy or sensitivity of the instrument, or both, deteriorate over some frequency range until eventually it becomes no longer usable. For example, some instruments designed for power frequencies (50/60 Hz) may be used for measuring fields from induction heaters up to 1 kHz. When using a particular instrument, a user should be aware of its frequency limitations.

currents. Most measurements at frequencies below 100 kHz are made in the near field of the source, where the field configuration can be relatively complex. Usually electric and magnetic fields need to be evaluated separately because their relationship is not easily predicted as it would be in the far field where the vectors are perpendicular and their magnitudes are in proportion to the free-space wave impedance ($377\ \Omega$). For well-defined EMF sources where analysis indicates that only one type of field (electric or magnetic) is sufficient to assess conformance with a particular MPE value, only that field component needs to be measured.

1.5.3 Contact currents

Contact currents flow through the body of a person touching objects that are at a different potential than that of the person. They can range from subliminal currents to life-threatening electric shocks. In addition to safety limits in the National Electrical Code® (NEC®) (NFPA 70, 2007 Edition) [B84], IEEE Std C95.6-2002 [B58] has limits for the contact currents that result from EM induction of voltage differences in the environment. Contact currents can be measured either as currents (in amperes) passing from an object to body (usually through the hand) or as a potential difference (in volts) between two extremities (hand to foot, or hand to hand).

1.6 Types of situations covered

- Static and quasi-static electric fields
- Static and quasi-static magnetic fields

This recommended practice treats non-propagating electric and magnetic fields (static, quasi-static, and reactive fields) found in the immediate vicinity of an EMF source.⁴

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std C95.3™-2002 (Reaff 2008), 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).^{5, 6}

3. Definitions

For the purposes of this document, the following terms and definitions apply. *The IEEE Standards Dictionary: Glossary of Terms & Definitions* should be referenced for terms not defined in this clause.⁷

amplitude modulation: The process by which a continuous wave (carrier) is caused to vary in amplitude by the action of another wave containing information.

⁴For purposes of this recommended practice, *EMF* means *electric and magnetic fields* (see 3.1).

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⁷*The IEEE Standards Dictionary: Glossary of Terms & Definitions* is available at <http://shop.ieee.org/>.

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

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

averaging distance: The distance over which the internal electric field is averaged when determining conformance with basic restrictions.

averaging time: The appropriate time period over which exposure is averaged for purposes of determining conformance with a maximum permissible exposure (MPE) or reference level (RL).

axial cross section: A cross section of the body taken in a plane perpendicular to its long axis.

axial exposure: Exposure by an electric or magnetic field perpendicular to the axial cross section.

basic restrictions: Limitations on the internal electric fields, current, and current density that protect against known adverse health effects with an acceptable safety factor.

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).

conform: A person's EMF exposures are within the safety limits from an applicable standard while allowing for the uncertainties of the exposure assessment method. *Syn:* **conformance assessment; conformity assessment.**

coverage factor: Factor (k) that multiplies the standard uncertainty (u) or relative standard uncertainty (u_r), giving an interval that may be expected to encompass a large fraction (usually 95%), of the distribution of values that could reasonably be attributed to the true exposure metric. *See also:* **relative standard uncertainty, standard uncertainty.**

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

diode: A device having two terminals and exhibiting a nonlinear voltage-current characteristic; commonly, a semiconductor device that has the asymmetrical voltage-current characteristic typical of a single p-n junction.

dipole (antenna): **(A)** Any one of a class of antennas producing the radiation pattern approximating that of an elementary electric dipole. **(B)** A receiving sensor loaded in the center.

distortion factor (DF): The ratio of the rms value of the harmonic content to the root-mean-square (rms) value of the fundamental quantity, expressed as a percentage of the fundamental.

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

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

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

electric dipole: A pair of equal and opposite charges separated by an infinitesimal distance.

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.⁸

electric field strength (*E*): At a given point in space and time, *E* is force ΔF on a positive test charge ΔQ in the limit as the charge approaches zero, i.e.,

$$E = \lim_{\Delta Q \rightarrow 0} \frac{\Delta F}{\Delta Q}$$

Electric field strength may be measured either in newton per coulomb or in volt per meter (V/m).

NOTE—This term is sometimes called the *electric field intensity*, but such use of the word intensity is deprecated, since intensity connotes power in optics and radiation.

electric field vector: Electric field strength as a vector quantity with direction and magnitude. *See also:* **electric field strength.**

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/m²).

electromagnetic (EM) field: The mutually coupled time-varying electric and magnetic fields that transmits energy through space. This term is sometimes used incorrectly, instead of *electric and magnetic fields* or *EMF*.

NOTE—See **EMF** in 3.1.

electromagnetic (EM) radiation: The propagation of energy through space in the form of EM fields.

NOTE—Not intended to describe propagation along waveguides and other transmission lines.

environmental field: An electric or magnetic field external to the body measured in the absence of the body.

exposure metric: A single number derived from an exposure that varies over time, space, and frequency for the purposes of predicting health risks in epidemiology or other studies or for expressing exposure limits. *Syn:* **metric.**

finite difference time domain (FDTD) method: The FDTD method is a numerical algorithm for solving Maxwell's differential equations of electromagnetic (EM) 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.

finite element method (FEM): A class of numerical algorithms for solving Maxwell's differential equations of electromagnetic (EM) field interactions. Discrete Differential Forms (DDF), which are finite element basis functions defined on a mesh, are utilized in the FEM.

NOTE—A *mesh* is a subdivision of the region into polyhedrons. The most common are triangles in two dimensions and tetrahedrons in three dimensions.

⁸ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

fundamental frequency: The frequency in a complex waveform with the greatest amplitude, and the principal frequency of a sinusoidal waveform. In the case of unmodulated sinusoidal waveforms, it is the lowest frequency of a harmonic series or Fourier representation of the periodic quantity. *Syn:* **primary frequency**.

NOTE—For fields associated with modern electrical power systems, the fundamental frequency is 60 Hz in most of the Americas, 50 Hz in most of the rest of world, and 400 Hz on airplanes and submarines. Other frequencies were used in the early years of electric power and still are in use, e.g., for traction systems.

grasping contact: An electrical connection with a large energized conductor made by firmly holding the conductor in the hand.

NOTE—In this recommended practice, a contact area of 15 cm² is assumed for such contact.

harmonic: A Fourier component of a signal or vector field whose frequency is an integral multiple of the fundamental frequency.

in situ electric (magnetic) field: *See:* **internal electric (magnetic) field**.

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

internal electric (magnetic) field: The electric (magnetic) field within biological tissue in its normal anatomical position.

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

isotropic: Having the same properties in all directions.

isotropic probe: A sensing probe capable of radiating or receiving equally well in all directions, and equally responsive to all polarizations of electric and/or magnetic fields.

lower uncertainty limit (LUL): A lower bound of a measurement incorporating all sources of bias and random uncertainty so that the true value of a stated exposure metric is greater in 95% of repeat measurements. Also known as the *lower confidence limit* (LCL) when it includes only random uncertainties and omits uncorrected biases. *See also:* **upper uncertainty limit**.

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

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.

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

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). *See also:* **magnetic field strength**.

magnetic flux density (magnetic induction) (*B*): The vector quantity *B* producing a torque *T* (in newton meter) on a plane current loop in accordance with the relation $\mathbf{B} = IA(\hat{\mathbf{n}} \times \mathbf{B})$, where $\hat{\mathbf{n}}$ is the positive unit vector normal to the loop, *A* is its area (in units of meter squared) and *I* is the loop current (in units of ampere). Magnetic flux density is expressed in units of tesla (T), formerly weber per square meter.

maximum permissible exposure (MPE): The root-mean-square (rms) 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 as set by incorporating an acceptable safety factor below hazardous levels. *See also:* **reference level.**

NOTE—Non-compliance with the MPEs does not mean that the basic restrictions have been exceeded. If an exposure is proven to be below the basic restrictions, the MPE can be exceeded. MPEs are closely comparable to *reference levels*, *derived limits*, and *investigation levels* as used in exposure standards and exposure guidelines prepared by various organizations, and can have indistinguishable meanings and applications.

maximum root-mean-square (rms) component: The rms component of an EMF vector in the direction that results in the maximum value. Mathematically, the maximum rms component is defined as follows:

$$G_{\max} = \sqrt{\frac{1}{T} \int_0^T (\hat{\mathbf{n}}_{\max} \cdot \mathbf{G}(t))^2 dt}$$

where T is the averaging time, $\mathbf{G}(t)$ is a time-dependent EMF vector, and $\hat{\mathbf{n}}_{\max}$ is a unit vector pointing in the direction that maximizes the expression. For a single-frequency, elliptically polarized field, $\hat{\mathbf{n}}_{\max}$ is aligned with the ellipse's major axis, and $G_{\max}$ is the ellipse's semi-major axis divided by $\sqrt{2}$.

mean: The arithmetic average of a series of measurements or other data.

median: The value within a statistical distribution at which 50% of data are above and below.

modulation: Alteration of the waveform of a time-varying electric current, electric field, magnetic field, or electromagnetic (EM) field by impressing another waveform or signal in order to change the original amplitude, frequency, or phase

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.

near-field region: For a device or object that produces electromagnetic (EM) fields, the near-field region is that region closest to the device where the following applies: 1) The electric and magnetic fields vary considerably from point to point; 2) The ratio of the electric to magnetic fields is not a constant, but varies from point to point; 3) The stored energy associated with the fields predominates over the energy that is radiated.

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

non-uniform field: A field that is not constant in amplitude, direction, or relative phase over the dimensions of the body or body part under consideration. In the case of electric fields, the term is often applied to an environmental field disturbed by the presence of the body.

normal load current: The maximum current in an electric power transmission line under conditions that exclude outages or other emergency operating conditions.

open-circuit voltage: The potential difference between two conducting objects without a current load being applied to the objects.

passive or parasitic re-radiator: An electrically conducting structure located in the radiation field of a primary source of radio frequency (RF) electromagnetic (EM) fields that acts as a secondary radiating source because of RF currents induced in the structure. In some cases, re-radiators can produce localized EM fields significantly more intense than the co-located fields associated with the prime source. *See also:* **re-radiated fields.**

peak power density: The maximum instantaneous power density occurring during the interval when power is transmitted. Power density is expressed in units of watts per square meter (W/m^2).

NOTE— $1 \text{ W}/\text{m}^2 = 0.1 \text{ mW}/\text{cm}^2$.

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.

peak pulse amplitude: The maximum absolute peak value of a pulse excluding spurious elements, such as spikes, provided that the spurious energy is small (5% or less) compared with the total energy in the pulse.

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

peak vector magnitude: The greatest magnitude of a vector quantity at a single point in space over an observation time of at least one period.

permittivity (complex): The ratio of the electric flux density in a medium to the electric field strength at a point. Complex permittivity (ϵ^*) is expressed as

$$\epsilon^* = \epsilon_0(\epsilon' - j\epsilon'') = \epsilon_0\left(\epsilon' - j\frac{\sigma}{\omega\epsilon_0}\right)$$

where ϵ_0 is the permittivity of free space (8.854×10^{-12} farads per meter), ϵ' is the dielectric constant, or real part of the complex relative permittivity, ϵ'' is the imaginary part of the relative complex permittivity, σ is the conductivity of the medium, and ω is the angular frequency in radian.

personal monitor: A portable device that can be worn on the body to measure, record, or analyze one or more components of an electric or magnetic field for purposes of exposure assessment.

polarization: That property of periodic electric or magnetic field describing the figure traced over one cycle by the extremity of the field vector at a fixed location in space.

NOTE—For a single-frequency field, the figure is in general elliptical. The commonly referenced circular and linear polarizations are obtained when the ellipse becomes a circle or a straight line, respectively. For multi-frequency fields, the polarization can have an arbitrary shape in the time domain. In the frequency domain, the field is composed of a sum of elliptically polarized components with variable phases and orientations with respect to each other.

power: A physical quantity describing the rate of delivery or transmission of energy. Power is measured in units of watt (W).

power gain: Of an amplifying device, the ratio of the radio frequency (RF) power delivered to a specified load impedance to the RF power absorbed by its input.

NOTE—Power gain is usually expressed in decibels (dB).

probe: A minimally perturbing device that contains an electrically small (in the medium) sensor (or sensors) for detecting and measuring a component of an electromagnetic (EM) field in air or a dielectric medium.

probe sensor-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, i.e., the tip-to-tip dimension of a simple dipole or the diameter of a loop sensor. *Syn:* **probe-antenna length; probe length.**

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

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

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

quasi-static electric (magnetic) field: A field of interest whose wavelength is much longer than the specific distance from its source or any re-radiator that creates this field.

NOTE—Quasi-static electric and magnetic fields from any source are decoupled from each other. Therefore, eliminating the quasi-static electric field will not affect the quasi-static magnetic field.

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

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

reference level (RL): The exposure field and contact current values derived or estimated from the basic restrictions, i.e., induced electric field and current density. *See also:* **maximum permissible exposure.**

relative standard uncertainty (u_r): The standard uncertainty divided by the mean. May also be expressed as a percentage (% u_r). Also known as the *relative standard deviation* or *coefficient of variation*. *See also:* **standard uncertainty.**

re-radiated fields: An electromagnetic (EM) field resulting from currents induced in an object, usually a conductor, by incident EM energy from one or more primary radiating structures. Re-radiated fields are sometimes called *reflected* or, more correctly *scattered fields*. The scattering object is sometimes called a *parasitic re-radiator* or *secondary radiator*. *See also:* **passive or parasitic re-radiator; scattering.**

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.

NOTE—In this recommended practice, 90% of the final value is assumed.

resultant: A metric for an EMF vector $G(t)$ defined by

$$\sqrt{G_{x, \text{rms}}^2 + G_{y, \text{rms}}^2 + G_{z, \text{rms}}^2}$$

where $G_{x, \text{rms}}$, $G_{y, \text{rms}}$, and $G_{z, \text{rms}}$ are the root-mean-square (rms) components of the field measured simultaneously or sequentially in three orthogonal directions at a single point in space. If the field is either static or periodic over the time when the three components are measured (i.e., constant peak magnitude, frequency composition, polarization and spatial orientation), the resultant equals the rms vector magnitude. *See:* **rms vector magnitude.** *See also:* **maximum root-mean-square (rms) component; rms (EMF) vector magnitude.**

rms (EMF) vector magnitude: The root-mean-square (rms) of the magnitude of an EMF vector.

root-mean-square (rms): The measure of average effect determined from the function:

$$\sqrt{\frac{1}{T} \int_0^T v(t)^2 dt}$$

where a signal $v(t)$ is measured over an averaging time T .

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

screening method: A simple method for measuring EMF exposures in order to determine whether more accurate methods are needed to achieve conformity with the applicable safety limits. *Syn:* **screening measurements.**

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.

spatial average: As applied to the measurement of electric or magnetic fields for the assessment of whole-body exposure means the root-mean-square (rms) value, i.e., rms value 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. Averages can also be taken over the effective volume occupied by the person.

standard uncertainty (u): The standard deviation associated with a measurement that characterizes the dispersion of values that occurs upon making repeated measurements under nearly identical conditions.

touch contact: A contact of small area made between the human body and an energized conductor.

NOTE—In this recommended practice, a contact area of 1 cm² is the assumed touch contact area.

uncertainty factor: A factor incorporating all sources of bias and random uncertainty that multiplies a measurement in order to enclose the true value of the specified measurement for 95% of repeat measurements.

uniform field: A field that is constant in amplitude, direction, and relative phase over the dimensions of the body or body part under consideration. In the case of electric fields, the definition applies to an environmental field undisturbed by the presence of the body.

upper uncertainty limit (UUL): An upper bound of a measurement incorporating all sources of bias and random uncertainty so that the true value of a stated measurement is less in 95% of repeat measurements. Also known as the *upper confidence limit* (UCL) when it includes only random uncertainties and omits uncorrected biases. *See also:* **lower uncertainty limit.**

vector magnitude: The length of an EMF vector. In Cartesian coordinates, the magnitude of a vector G equals

$$\sqrt{G_x^2 + G_y^2 + G_z^2}$$

where G_x , G_y , G_z are the components of the vector. *See also:* **rms (EMF) vector magnitude.**

3.1 Special terms

EMF: For the purposes of this recommended practice, EMF means electric and magnetic fields [although it also may mean a propagating electromagnetic (EM) field in other contexts]. As used here, it means low-frequency fields (<100 kHz) where the relationship between electric and magnetic fields is not mutually determined and the impedance that relates propagation fields is not defined.

4. Basic issues in measuring electric and magnetic fields for use in exposure assessments (0 Hz to 100 kHz)

4.1 Introduction

In the frequency range up to 100 kHz, the common basis for protection is to limit the effects of electrostimulation of cells and/or tissues of human nervous systems, the cardiac system, and other biological systems, caused by induced electric fields, currents, or current densities within tissues and/or organs of the human body. In addition, for environmental electric fields, protection against indirect effects resulting from spark discharges, and touch and/or contact currents is necessary.

The MPE values and other EMF exposure limits found in contemporary standards and guidelines are derived from the basic restrictions, e.g., the internal electric field (E_i). The basic restrictions provide a more fundamental evaluation of exposure but are difficult or impossible to measure directly, so calculation and numerical modeling methods are required. The basic restrictions (E_i) may be calculated with induction models, including computer modeling methods when external field characteristics and the electrical properties of the relevant tissue are known (see Clause 7).

In practice, measurement or computation of the external environmental fields is often used for purposes of exposure assessment because measurement of the internal fields (basic restrictions) is impossible and their computation difficult. For exposure assessment purposes, these external environmental fields are compared with the MPE values in standards such as IEEE Std C95.1-2005 [B55] and IEEE Std C95.6-2002 [B58], or the corresponding quantities of other standards and guidelines that have been derived from the basic restrictions. Conformance with the MPEs ensures conformance to the basic restrictions. In contrast, exceeding the MPEs does not necessarily mean that the basic restrictions have been infringed.

This clause discusses the concepts and issues associated with measurements of the environmental fields for use in assessments of human exposure, or other purposes. For EMF exposure levels close to the MPEs, an accurate evaluation may require of the operator a thorough understanding of electromagnetism, specialized instruments, and/or software. Subclause 4.2 discusses the issues that EMF specialists need to consider for accurate measurements for any EMF environment. However, simple methods and basic instrumentation can be adequate for assessing exposure to the fields associated with common EMF sources. Subclause 4.3 describes simple screening measurements that occupational and environmental health generalists can use to determine whether a specialist is needed. These measurement methods can also be used to assess exposures to electric and magnetic fields at levels far below the MPEs, e.g., for the evaluation of control measures, epidemiology studies, investigations of reported health hazards, and other research.

4.2 Considerations for exposure assessments of electric and magnetic fields

4.2.1 Characteristics of environmental EMF (0 Hz to 100 kHz)

The characteristics of electric fields (E) and magnetic fields (either H or B) that are important for the purposes of comparison with the MPEs found in contemporary standards and guidelines are as follows:

- Continuous wave (CW), pulsed or pulsed-modulated fields
- Frequency spectrum (single frequency, harmonics, rectified sine waves, complex waveforms)
- Polarization (linear, elliptical, circular, or multi-frequency—see Figure 1)
- Variability over a person's body and over time
- Intensity (rms or peak, vector component or magnitude)

In cases where environmental fields are spatially, temporally, and spectrally uniform, measurements can be carried out with simple methods and basic instrumentation. However, when dealing with sources that produce fields with atypical or non-uniform characteristics, care must be taken when comparisons are made with the MPEs. Such characteristics include the following:

- Nonlinear polarization
- Multiple-frequency sources
- Spatially and temporally non-uniform fields
- Non-sinusoidal or fields with high-harmonic content

Because electric and magnetic fields are multi-dimensional quantities, safety standards define *exposure metrics*, which are functions for converting the time-varying EMF vectors into a single number for comparison with the MPEs. In the 0 Hz to 100 kHz range, important metrics are the *rms vector magnitude* and the *peak vector magnitude*, which are measured over the averaging time specified by the standard. For the elliptically polarized, sinusoidal fields produced by three-phase transmission lines and similar EMF sources, another metric related to the exposure guidelines is the *maximum rms component*, which lies along the major axis of the elliptical trace of the field vector (see Figure 1).

For multi-frequency and pulsed fields, the exposure guidelines establish limits based on a sum rule for the Fourier components, as shown in Equation (1):

$$\sum_i \frac{A_i}{MPE_i} \leq 1 \quad (1)$$

where A_i is the rms vector magnitude or maximum rms component of the i -th Fourier component, and MPE_i is the MPE value for frequency f_i . IEEE Std C95.6-2002 [B58] offers two other metrics for multi-frequency fields: the *peak vector magnitudes* of the internal electric field (E_i) and the time derivative of the magnetic field (dB/dt).

Two statistics are recommended in IEEE Std C95.6-2002 [B58] for combining multiple measurements taken over the area equivalent to that of a person's body. For electric fields, the average of the chosen metric is used for comparison with the MPE; for magnetic fields, the maximum is used, which implies that a single measurement would suffice if the field is spatially uniform, but measurements at multiple locations are clearly needed to demonstrate uniformity.

Finally, the temporal variability of the field affects the sampling strategy used for measurements for assessing exposure. A single time point can be adequate if it represents the maximum power of the EMF source and the person's closest proximity. If these maximal conditions are not reliably known, multiple measurements over time, and possibly personal monitoring, will be needed to determine the maximum exposure.

Strategies for selecting exposure metrics are discussed further in 4.2.4, measurement considerations are discussed in 4.2.2, and the role of measurement uncertainty in EMF conformity decisions is described in 4.2.3.

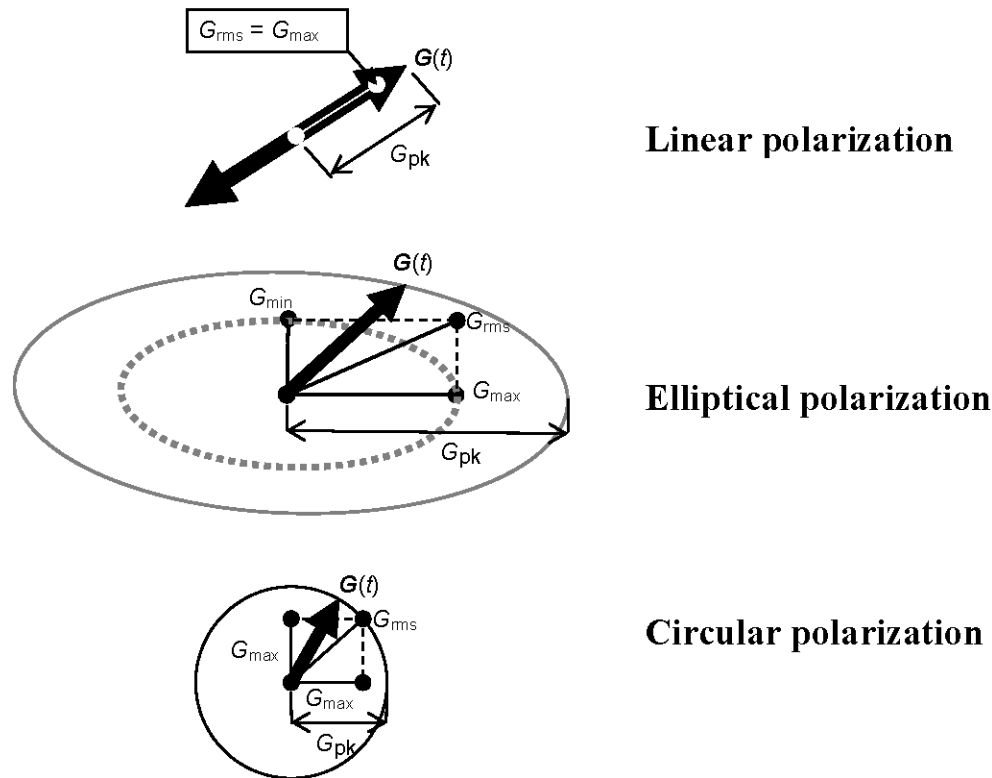


Figure 1—Vector traces of the polarizations with single-frequency electric or magnetic field $G(t)$, showing the rms vector magnitude (G_{rms}), the maximum (G_{max}) and minimum (G_{min}) rms components, and the peak magnitude (G_{pk})

4.2.2 Measurement considerations for purposes of comparisons with the MPEs

The MPE values depend on the frequency and/or waveform of the field because they are fundamental variables in the coupling mechanisms with body tissues. Therefore, the frequency of the field must be determined, preferably by measurement but at least from reliable specifications of the EMF source. A frequency meter with the correct bandwidth is often adequate, but care should be taken that the correct phenomena are being measured when simple equipment is used.

At frequencies below 100 kHz, exposures are usually in the near field (i.e., non-radiating) where electric and magnetic fields are independent and need to be measured separately. For well-defined sources, where analysis indicates that one field is much closer to the applicable MPE, only that field needs to be measured for purposes of conformity assessment.

Although, for measurements of environmental electric and magnetic fields, it is unlikely that a single instrument will cover the entire frequency of this recommended practice [0 Hz (dc) to 100 kHz], the instrumentation must cover the frequency range of the fields produced by a source under test. In the event that broadband instruments are used, the bandwidth of the instrumentation must cover the range of frequencies produced by the source.

Some measuring instrumentation may have a frequency dependent response that correlates with the MPEs. In order to fully characterize the exposure conditions, it may be necessary to use several instruments including a broadband meter, oscilloscope, or spectrum analyzer. If more than one instrument is used, care

must be taken to ensure that the ranges of the instruments do not overlap, resulting in an over-evaluation of the levels.

For single-frequency fields, the polarization helps determine the most accurate metric for use when assessing conformance with the MPEs and, therefore, the most practical instrument and measurement procedure. EMF sources powered by single-phase electricity usually generate linearly polarized fields. With a three-phase power line, linear polarization is also encountered by a person who is much closer to one phase than the other two, as in bare-hands work on high-voltage transmission lines. EMF sources with three-phase electric power generally create nonlinear polarization, as do multi-frequency sources.

For magnetic fields, the polarization can be confirmed with a three-axis digital waveform capture (DWC) instrument, or a single-axis gaussmeter. DWC instruments measure the polarization exactly as the axial ratio $= B_{\min} / B_{\max}$ (see Figure 1). With a single-axis gaussmeter, the probe must be rotated to determine if $B_{\min} = 0$ (i.e., linear polarization). First, study the geometry of the source to determine the plane of polarization of the magnetic field, using the principle that magnetic fields are always perpendicular to a conductor. For a power line, the plane of polarization is therefore perpendicular to the line. For a solenoid, the plane of polarization lies along the radius of the coil. If the field is zero at probe orientations perpendicular to the maximum direction, the field is linearly polarized.

When spectral information is required, e.g., for comparing measurements with frequency dependent MPEs, the measurements shall be performed using instrumentation capable of measuring relevant frequency domain and time domain characteristics of the signal. In the case of time domain measurements, it may also be necessary to determine the frequency content for comparisons with the MPEs. It may also be necessary to sum the field strength at each frequency in accordance with the appropriate MPE [see Equation (1)].⁹ In cases of multi-frequency evaluations, it is not necessary to include all the low-level spectral components, such as those of low-energy spikes and minor modulation components representing less than 5% of the total energy or spectral size relative to the fundamental or carrier frequency.

For screening measurements where less accuracy is needed (see 4.3), an rms meter with a three-axis (isotropic) probe can be used instead of measuring the frequency spectrum and the polarization. If the frequency of the field is known from the specifications of the source, an accurate measurement of the rms vector magnitude is reasonably accurate for purposes of comparisons with the MPEs for single-frequency fields. Depending on the method of signal processing (see 5.2.2), the resultant reported by these isotropic rms meters can equal the rms vector magnitude of the field being measured. In addition, the rms vector magnitude can be easily measured for multi-frequency and pulsed fields, but is only an approximate measure of the multi-frequency metrics specified in IEEE Std C95.6-2002 [B58] and other relevant standards and guidelines. It also is necessary to consider the frequency range of the fields, e.g., when time averaging of exposure is allowed, and it may be necessary to calculate the instantaneous maximum field strength for comparison with MPEs for pulsed sources.

Electric field measurements of the unperturbed field strengths are necessary because the presence of the human body can significantly affect the results. In this case, the instrumentation should be mounted on a non-conductive support. It may also be appropriate to use a fiber-optic coupled remote readout unit (or similar means of distancing the body of the operator) for some electric field measurements. Because people do not perturb magnetic fields, they are preferably measured during common exposure conditions.

If control of the source under test is possible, the power should be set to maximum or adjusted according to the manufacturer's set-up instructions. The unit under test should be located at sufficient distance from nearby objects, so that the electric field is not disturbed.

In addition, considerations need be given to the following:

- Measurement requirements: both electric and magnetic fields

⁹ In cases where the exposure standards or guidelines contain their own summation formulae or requirements, these take precedence over those in 4.2.2.

- Frequency bandwidth of instrumentation, probes, and sensors
- Overall measurement uncertainty
- Separate instrument for static or dc electric and magnetic fields

4.2.3 Measurement uncertainty and conformity decisions

Measurement uncertainty as well as uncertainties in calculations of such exposures may need to be considered in deciding whether exposures conform to the applicable safety standards, for example when a regulatory or accreditation agency has such requirements. General methods for handling uncertainty are given in ISO/IEC Guide 98-3:2008 [B62].¹⁰ This subclause provides an alternative method that focuses on the large asymmetric biases that can result from the choice of an EMF exposure metric.

Uncertainty in EMF measurement consists of random errors and systematic biases of an instrument, plus the bias of the metric relative to the definition of the basic restriction and MPE. Bias is particularly an issue in cases where measurements use approximate metrics, such as the rms vector magnitude for magnetic fields with harmonics. Calculations may also contain errors due to uncertainties in input parameters (such as current levels) and approximations in the mathematical techniques. Practitioners should first determine the bias in their EMF evaluations relative to the metric specified in the standard (the “true” value).¹¹ The percent bias $\% \Delta_m$ in an evaluation of a metric X is defined as shown in Equation (2):

$$\% \Delta_m = 100 \% \frac{X_{\text{metric}} - X_{\text{true}}}{X_{\text{true}}} \quad (2)$$

The bias due to an inexact metric, X_{metric} , is usually a range of values that depends on the environmental parameters, like the polarization or the frequency spectrum.

As an example, Annex C derives the possible biases in measurements of the rms vector magnitude of magnetic fields (B_{rms}) for fields with harmonics. In this situation, a “true” metric for comparison with the MPE (IEEE Std C95.6-2002 [B58] or other guidelines) is the harmonic sum rule [Equation (1)]. For the MPE, the rms vector magnitude can have percent biases ranging from –1% to –20% for the harmonic distortion commonly found in homes and workplaces, while other extremely low frequency (ELF) standards have biases from –4% to –49% (Annex C). With this negative bias, measurements of the rms vector magnitude can be less than the MPE while the harmonic sum rule (the true metric) exceeds it.

The next step in the treatment of measurement uncertainty is to determine the accuracy of the meter from the manufacturer’s specifications, calibration data, and/or independent tests. The random errors can be expressed as the standard uncertainty $u(X)$, or the relative standard uncertainty, i.e., $\%u_r(X) = 100\% u(X) / \text{Mean}(X)$. Any uncorrected bias in the instrument relative to its specified metric $\% \Delta_i$ is expressed as shown in Equation (3):

$$\% \Delta_i = 100 \% \frac{X_{\text{measurement}} - X_{\text{metric}}}{X_{\text{metric}}} \quad (3)$$

With ELF magnetic fields, the largest and most important instrument bias occurs with three-axis gaussmeters that calculate the resultant from serial measurements of the magnetic field components with a multiplexing rate slower than changes in the environmental fields (see 5.2.2). In the only field trial of a serial-measuring gaussmeter side-by-side with a DWC monitor, the reported instrumental biases in the

¹⁰ Further details on measurement uncertainty and conformance decisions are provided by numerous documents, including UKAS LAB34 [B107], UKAS M3003 [B106], CISPR 16-4-1:2003 [B21], and Bartley and Lidén [B8]

¹¹ When estimating uncertainty for EMF measurements using the GUM approach, additional efforts may be needed concerning how to handle the bias component; see e.g., O’Donnell and Hibbert [B88], ASME PTC 19.1:2005 [B6].

resultant versus the rms vector magnitude in personal monitoring were as much as –68% in rapidly varying fields (McDevitt et al. [B72]).

Such uncorrected instrumental bias $\% \Delta_i$ should be combined with the bias of the metric $\% \Delta_m$ to give the total bias, as shown in Equation (4):

$$\begin{aligned} \% \Delta &\equiv 100\% \frac{X_{\text{measurement}} - X_{\text{true}}}{X_{\text{true}}} \\ &= \% \Delta_i + \% \Delta_m + (\% \Delta_i \% \Delta_m) / (100\%) \end{aligned} \quad (4)$$

Because both the instrumental and metric biases vary with environmental factors such as the frequency spectrum, bounds to their variability should be determined, resulting in minimum and maximum values for the total bias. When serial-measuring gaussmeters are used in fields with harmonics, the total biases in the resultant versus the sum rule method for the MPE ranges from $\% \Delta_{\min} = -74\%$ to $\% \Delta_{\max} = -1\%$.

The large asymmetric range of biases possible in EMF measurements should be considered in deciding whether exposure measurements conform to the MPE. Following the methods of NIOSH Publication No. 77-173 [B85], one-sided uncertainty limits may be used in conformance decisions with large biases for which upper and lower bounds can be estimated. For the most conservative determination that an exposure conforms to the MPEs, the upper uncertainty limit (UUL) on the measurement results should be used, as given by Equation (5):

$$\text{UUL} = X \left(\frac{100\% + k \% u_r(X)}{100\% + \% \Delta_{\max}} \right) \quad (5)$$

where k is the coverage factor for a stated probability of assurance in the decision (usually 95%). A common value for the coverage factor in one-tailed hypothesis tests is 1.645, the 95th percentile of the standard normal distribution. If repeat measurements are not normally distributed, other error distributions will result in different values for the coverage factor (ISO/IEC Guide 98:2008 [B62]).

To evaluate whether the exposure truly exceeds the MPEs, the lower uncertainty limit (LUL) should be used, as given by Equation (6):¹²

$$\text{LUL} = X \left(\frac{100\% - k \% u_r(X)}{100\% + \% \Delta_{\max}} \right) \quad (6)$$

If more than one measurement has been taken of the site, consult an occupational health statistics text, e.g., NIOSH Publication No. 77-173 [B85] or ISO/IEC Guide 98:2008 [B62], for methods to calculate the uncertainty limits.

For the approach described in the preceding paragraphs, the hypothesis tests that follow from these confidence limits are:

- UUL < MPE: Implies that potential exposures are below the MPEs. If this is not the case, more accurate measurements should be made or the internal electric fields should be calculated in order to determine conformity with the basic restrictions in an applicable standard.
- LUL > MPE: Implies that potential exposures are above the MPEs and some action should be taken to achieve conformity.

¹² Different regulatory domains, guidelines, and/or standards may have different ways of accounting for uncertainty when determining compliance with a limit, for example, a shared-risk approach as described in ITU-R Recommendation M.1545 [B64].

- $LUL < MPE < UUL$: Implies the measurements are not accurate enough to decide whether or not the MPEs are exceeded. In this case, more accurate measurements and/or metrics are needed when a conformity decision is needed.

Since these conformity decisions depend on the exposure metric, the next subclause develops strategies for selecting optimal metrics based on these concepts.

Other strategies to account for measurement uncertainty include assuming generous uncertainty limits when doing screening measurements (see 4.3). To ensure the rms vector magnitude is truly less than the exposure limit, the upper uncertainty factor [i.e., the quantity in parentheses in Equation (5)] should accommodate the most extreme values for all sources of uncertainty. For magnetic fields in underground distribution vaults, as analyzed in Annex C, an uncertainty factor of 3 should be adequate for demonstrating conformance with the relevant standards by using meters with no instrumental bias. For instruments with bias in measuring the rms vector magnitude, an uncertainty factor of 10 should be sufficient with underground vaults and similar ac sources. For EMF sources with greater distortion, e.g., dc welders, larger uncertainty factors are probably required to minimize erroneous decisions based on screening measurements, but more research is needed to determine their values.

4.2.4 Selecting an EMF exposure metric by its uncertainty and practicality

Selecting an exposure metric from among the many specified by safety standards and guidelines may be challenging. The metrics vary both in their ease of measurement and their accuracy when used in predicting conformity with the basic restrictions on the internal electric fields or current densities.

This subclause discusses efficient strategies for selecting metrics. The basic approach is to start with screening measurements of the more convenient metrics with methods that seek the maximum exposure (see 4.3). If the initial results suggest that the applicable exposure limit may be exceeded (using uncertainty limits as discussed in 4.2.3), then more accurate metrics and/or dosimetry calculations (see Clause 7) can be used to support a conformity decision.

A full implementation of this strategy requires accurate estimates of metric bias relative to the basic restriction for all the field characteristics discussed in 4.2.1. Subclause 4.2.3 and Annex C describe an example of a bias calculation for two metrics and a single EMF source. However, the comprehensive bias determinations needed to guide practitioners for dealing with all EMF sources clearly requires more research. Nonetheless, the assumptions required to predict the maximum internal electric field in the brain or other organ (as specified by the basic restrictions) from a measurement of a metric allows for their ranking in order of increasing bias, as shown in Table 1.