



IEEE Recommended Practice for Measurements and Computations of Electric, Magnetic, and Electromagnetic Fields with Respect to Human Exposure to Such Fields, 0 Hz to 300 GHz

IEEE Standards Coordinating Committee 39

Developed by the
IEEE International Committee on Electromagnetic Safety

IEEE Std C95.3™-2021
(Revision of
IEEE Std C95.3-2002 and
IEEE Std C95.3.1™-2010)

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Approved 25 March 2021

IEEE SA Standards Board

Abstract: Best practices are described for the development, validation, and application of methods for the computation and measurement of relevant metrics characterizing human exposure to electric and/or magnetic fields (collectively, electromagnetic fields) over the frequency range of 0 Hz to 300 GHz. This recommended practice is a replacement for IEEE Std C95.3™-2002 and IEEE Std C95.3.1™-2010, extensively revising the contents from those and harmonizing with IEEE Std C95.1™-2019. Detailed methodology is not described; rather, requirements for best practice are expressed through guidance and references to other documents and standards. Examples are included to clarify the guidance. This recommended practice is intended for professional users who are familiar with basic electromagnetic field theory and practice and for persons involved in specifying or implementing critical hazard assessments or surveys such as those described in IEEE Std C95.7™-2014.

Keywords: electromagnetic field computation, electromagnetic field measurements, EMF hazard assessment, EMF survey, exposure assessment, IEEE C95.3™, microwave hazard assessment, microwave survey, non-ionizing radiation, RF hazard assessment, RF survey, specific absorption rate assessment

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

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PDF: ISBN 978-1-5044-7510-5 STDGT24664
Print: ISBN 978-1-5044-7511-2 STDPD24664

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Introduction

This introduction is not part of IEEE Std C95.3-2021, IEEE Recommended Practice for Measurements and Computations of Electric, Magnetic, and Electromagnetic Fields with Respect to Human Exposure to Such Fields, 0 Hz to 300 GHz.

In 1960, the American Standards Association approved the initiation of the Radiation Hazards Standards project under the co-development of the Department of the Navy and the Institute of Electrical and Electronics Engineers, Incorporated (IEEE; called the “Institute of Radio Engineers (IRE)” at the time). 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 the “Standards Coordinating Committee 28 (SCC28)” under the development of the IEEE Standards Board. In 2001, the IEEE Standards Association Standards Board approved the name “International Committee on Electromagnetic Safety (ICES)” for SCC28 to better reflect the scope of the committee and its international membership. In accordance with the policies of the IEEE, C95 standards are issued and developed as IEEE standards and submitted to ANSI for recognition.

In June 1995, the IEEE Standards Board approved the establishment of “Standards Coordinating Committee 34 (SCC34), Product Performance Standards Relative to the Safe Use of Electromagnetic Energy.” Standards developed by SCC34 do not specify limits for human exposure to electromagnetic fields, but refer to established limits found in science-based standards such as IEEE Std C95.1™-2019, IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 0 Hz to 300 GHz.

In 2005, SCC28 and SCC34 became “Technical Committee 95” and “Technical Committee 34,” respectively, under a new IEEE Standards Coordinating Committee, SCC39, which is now called “ICES.”¹

The present scope of IEEE ICES Technical Committee 95 (TC95) 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 six TC95 Subcommittees, each of whose area of responsibility is described as follows in correspondence with its designated Subcommittee number:

- SC 1: Techniques, Procedures, Instrumentation, and Computation
- SC 2: Terminology, Units of Measurements, and Hazard Communication
- SC 3: Safety Levels with Respect to Human Exposure, 0 Hz to 3 kHz
- SC 4: Safety Levels with Respect to Human Exposure, 3 kHz to 300 GHz
- SC 5: Safety Levels with Respect to Electro-Explosive Devices
- SC 6: EMF Modeling and Dosimetry

This recommended practice was prepared by Subcommittee 1 of TC95. The present versions of TC95 standards and recommended practices are as follows:

- IEEE Std C95.1™-2019, IEEE Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 Hz to 300 GHz.

¹ 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.

- IEEE Std C95.1-2345™-2014, IEEE Standard for Military Workplaces—Force Health Protection Regarding Personnel Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 Hz to 300 GHz.
- IEEE Std C95.2™-2018, IEEE Standard for Radio-Frequency Energy and Current-Flow Symbols.
- IEEE Std C95.3™-2021, IEEE Recommended Practice for Measurements and Computations of Electric, Magnetic, and Electromagnetic Fields with Respect to Human Exposure to Such Fields, 0 Hz to 300 GHz.
- IEEE Std C95.7™-2014, IEEE Recommended Practice for Radio Frequency Safety Programs, 3 kHz to 300 GHz.²

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² The latest revisions of IEEE Std C95.1, IEEE Std C95.1-2345, IEEE Std C95.2, IEEE Std C95.3, and IEEE Std C95.7 are available at no cost (at the time of publication of this recommended practice) through the IEEE Get Program. (<https://ieeexplore.ieee.org/browse/standards/get-program/page/series?id=82>).

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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 300 GHz

1. Overview

1.1 Scope

This recommended practice describes methods for measuring and computing external electric, magnetic, and electromagnetic fields to which persons could be exposed over the frequency range of 0 Hz to 300 GHz. Instrument characteristics and the methods of calibrating such instruments, and methods for computation and measurement of the resulting fields and currents that are induced in bodies of humans exposed to these fields, are included.

1.2 Purpose

The purpose of this recommended practice is to specify techniques and instrumentation for the measurement and computation of potentially hazardous electric, magnetic, and electromagnetic fields both in the near-field and the far-field of the source. In so doing, this document incorporates and extends the specifications previously set forth in IEEE Std C95.3TM-2002 [B192] and IEEE Std C95.3.1TM-2010 [B193]. In addition to measurement and computation of exposure fields, this document includes a description of the concepts, techniques, and instruments that can be applied to the measurement and computation of the specific absorption rate or the electric field strength in organisms (including humans) and phantoms exposed to electromagnetic fields. Guidance on measurement and computation of induced current and contact current is also included.

This document is intended primarily for use by engineers, biophysicists, and other specialists who are familiar with basic electromagnetic field theory and practice, and the potential hazards associated with exposure to such fields.

1.3 Approach

The approach to this recommended practice is as follows:

- a) Updates and revises the specifications previously set forth in IEEE Std C95.3-2002 [B192] and IEEE Std C95.3.1-2010 [B193]. Replacing these two standards, this unified recommended practice covers the electromagnetic spectrum from 0 Hz to 300 GHz, consistent with IEEE Std C95.1™-2019.
- b) Is not intended to replace regulatory requirements or guidelines, or best practices that are specific to an industry or product line.
- c) Provides guidance on best practice for the development, validation, calibration, and application of methods for the computation and measurement of relevant metrics characterizing human exposure to electric and/or magnetic fields (collectively, electromagnetic fields [EMF]) over the frequency range of 0 Hz to 300 GHz both outside the body (environmental fields) and inside exposed phantoms, humans, and organisms (internal fields). It includes descriptions of the relevant concepts, techniques, methods, and instruments and references standards and other material that detail task-specific assessment methods. Similarly, it provides guidance on calibration (including pertinent references) but specific calibration methods, commonly performed by specialist calibration facilities, are not detailed.
- d) Is intended primarily for professional users (e.g., engineers, physicists, biophysicists, occupational health hygienists, instrument and calibration system developers, manufacturers) who:
 - 1) Are familiar with basic electromagnetic field theory and practice, and the potential hazards associated with human exposure to such fields,
 - 2) Are developing assessment methods targeted to their specific tasks and are required to demonstrate that those methods are consistent with best practice,
 - 3) Are involved in specifying or implementing critical hazard assessments or surveys such as those described in IEEE Std C95.7™-2014 [B194], and
 - 4) Represent regulatory agencies as well as manufacturers and operators of systems that generate EMF, such as high-voltage transmission and distribution lines, low-voltage power distribution lines, underground power distribution vaults, railway power distribution systems, radio frequency communications equipment, radar systems, electric welding systems, medical and security scanning and imaging equipment, induction and dielectric heating equipment, and domestic appliances.
- e) Complements IEEE Std C95.1-2019, without intending to lose its generality to other standards and guidelines on limiting human exposure to EMF. Such standards and guidelines have common elements so the guidance herein can be readily applied. For example, the concepts of exposure reference level (ERL) and dosimetric reference limit (DRL) that are referred to in this recommended practice are analogous to the *reference level* and *basic restriction* expressed in other standards.

1.4 Non-biological hazards from electric, magnetic, and electromagnetic fields

Hazards other than those resulting from direct biological interaction are beyond the scope of this recommended practice. However, it is possible that the computation and measurement techniques and instruments described in this recommended practice can also be applied to the evaluation of electric, magnetic, and electromagnetic field parameters relating to such hazards. Care should be taken to comply with relevant safety requirements not addressed in this recommended practice, and to apply the appropriate methods for summing field levels from multiple sources or frequencies. For example:

- The US Institute of Makers of Explosives (IME) offers safety guidance on preventing inadvertent detonation of commercial electric detonators in IME Safety Library Publication 20 [B197]; see also CENELEC technical report CLC/TR 50426:2004 [B53].
- NAVSEA OP 3565, Volume 1 [B255] describes electromagnetic radiation hazards associated with fuel and other flammable material; see also CENELEC technical report CLC/TR 50427:2004 [B55].

- Interpretation of susceptibility of medical and other devices to electromagnetic interference requires techniques beyond the scope of this document that are addressed in the electromagnetic compatibility literature and standards.

1.5 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{4,5}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they shall 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 C95.1TM-2019, IEEE Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 Hz to 300 GHz.

⁴ The word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁵ The word *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

3. Definitions, acronyms, abbreviations, frequency bands, symbols, and units

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.⁶

action level: Deprecated. *See:* **safety program initiation level.**

adverse health effect: An effect detrimental to a person's physical well-being due to exposure to an electric, magnetic, or electromagnetic field or to induced or contact currents or voltages. *See also:* **established adverse health effect.**

NOTE 1—For purposes of this recommended practice, *adverse effect* is interchangeable with *adverse health effect* or *adverse reaction*.⁷

NOTE 2—Adverse effects do not include biological effects without a harmful health effect or changes in subjective feelings of well-being.

NOTE 3—Sensory perceptions *per se* are not necessarily considered adverse health effects. For example, a perception of warmth at millimeter and other wavelengths and the microwave auditory effect under the underlying special conditions are not recognized as effects to be protected against by this standard.

NOTE 4—Painful or aversive sensations are considered adverse.

amplitude modulation (AM): The variation of the amplitude of a continuous-wave signal by the amplitude of a time-varying input signal.

anechoic chamber: A room or enclosure with inside surfaces that absorb electromagnetic fields to attenuate reflections.

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

antenna array: In emission, a system of antennas coupled together for the purpose of enhancing radiation in one or more directions and reducing radiation in other directions. In reception, a system of antennas coupled together to enhance the sensitivity, or the spatial resolution compared with one single antenna.

antenna directivity: The ratio of the transmitted radio frequency radiation intensity in a specified direction to the radiation intensity averaged over all directions. *See also:* **antenna gain, antenna pattern.**

NOTE—If no direction is specified, the direction of maximum radiation intensity from the given antenna is implied.

antenna field regions: Classification of the important spatial subdivisions of an antenna's electromagnetic field. *See also:* **near-field region, far-field region.**

NOTE—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.

⁶*IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

⁷Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

antenna gain: Ratio of the radiation intensity in a given direction to the radiation intensity that would be obtained from a reference antenna.

NOTE 1—The fundamental reference antenna is the theoretical isotropic antenna.

NOTE 2—The second most popular reference antenna is a dipole.

NOTE 3—Antenna gain includes losses due to antenna inefficiency and does not include losses arising from impedance and polarization mismatches with the source and the load.

NOTE 4—If an antenna is without dissipative loss, then in any given direction its gain is equal to its directivity.

NOTE 5—If the direction is not specified, the direction of maximum radiation intensity is implied.

NOTE 6—Antenna gain as determined in the far-field region at a distance from the source that reductions in observed gain due to near-field effects are negligible; this could be at a distance greater than the commonly defined near-field to far-field boundary.

NOTE 7—If there are substantial amounts of energy in two orthogonal polarizations, the gain of an antenna is characterized independently for each polarization. To evaluate potential exposure, it is important to account for the radiated fields for two orthogonal polarizations.

NOTE 8—The gain of aperture antennas, e.g., parabolic reflectors, is usually referenced to an isotropic radiator (e.g., G_i or G_{dBi}); The gain of linear antennas, dipoles, and collinear arrays is often referenced to a half-wave dipole (e.g., G_d or G_{dBd}).

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

NOTE 1—The distribution can be expressed as a mathematical function, tabular form, or as a graphic representation.

NOTE 2—Antenna patterns are typically described as field ratios or power ratios, usually with the highest value normalized to unity (or zero dB).

NOTE 3—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.

antenna 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.

aperture (of an antenna): A physical opening through which electromagnetic energy radiates. *See also:* **effective area.**

NOTE—It might be convenient to synthesize an aperture for computational purposes. For example, for planar and aperture antennas, 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. For other types of antennas, the aperture can be defined as the longest dimension of the radiating array.

assessment: The process of making determinations and recommendations about an exposure situation, including determining the objectives of the process, determining the characteristics of the situation under consideration, identifying appropriate metrics and limits, performing the necessary evaluations, and making determinations and recommendations based on the results.

assessor: The person, or set of people, accountable for the planning, performing, interpreting, and reporting on an assessment within the scope of this recommended practice.

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

averaging area: The area over which a physical quantity is averaged for assessing compliance.

NOTE—For compliance with the ERL, the averaging area is the area over which the power density is averaged when the frequency is greater than 100 MHz, and the area over which the field strength squared is averaged when the frequency is between 100 kHz and 100 MHz.

averaging time: The time period over which exposure is averaged for purposes of comparison with the exposure reference level or dosimetric reference limit.

basic restriction (BR): Deprecated. *See:* **dosimetric reference limit**.

beamwidth: In a plane intersecting the main lobe containing the maximum gain of the antenna pattern, the angle between the two directions in which the radiated power is a defined fractional value of the maximum.

NOTE—A typical beamwidth designation is the half-power (3 dB) beamwidth.

body current: The flow of electrical current in part of a body resulting from contact with energized surfaces and/or induction from exposure to ambient fields.

combined standard uncertainty: The result of combining individual standard uncertainties affecting a measurement or prediction. *See also:* **expanded uncertainty; standard uncertainty; coverage factor**.

conductivity: A property of materials that determines the magnitude of the electric current density when an electric field is impressed on the material.

NOTE—The SI unit of conductivity is siemens per meter (S/m), the inverse of resistivity.

conform: To be in compliance with the limits of a standard while allowing for the uncertainties of the assessment method. In the context of this recommended practice, a location, a device, or a person's exposure could be found to conform, or not, with applicable exposure limits.

contact current: The current flowing through a person at the point of contact with a surface.

NOTE—In IEEE C95.1-2019 contact current is specified as either that associated with a grasping contact (area assumed to be 15 cm²) or a touch contact (area assumed to be 1 cm²).

contact voltage: For purposes of this standard, an open-circuit voltage between two conducting objects that when bridged by a human would produce contact current. *See also:* **open-circuit voltage**.

continuous wave (CW): The characteristic of a signal being an unmodulated, uninterrupted, sinusoidal electromagnetic waveform.

controlled environment: Deprecated. *See:* **exposure environment (restricted)**.

coverage factor: A multiplier that is applied to the combined standard uncertainty to obtain the expanded uncertainty. *See also:* **combined standard uncertainty; expanded uncertainty; standard uncertainty**.

NOTE— $U = k u_c$ where U is expanded uncertainty, u_c is combined standard uncertainty and k is coverage factor.

current density: The ratio of the flowing current to the cross-sectional area perpendicular to the direction of the current.

NOTE—The SI unit of current density is ampere per square meter (A/m²).

dielectric constant: *See: permittivity.*

diode: A device having two terminals and exhibiting a nonlinear voltage-current characteristic, e.g., a semiconductor device that has the asymmetrical voltage-current characteristic exemplified by a single p-n junction.

dipole (antenna): Any one of a class of antennas producing the radiation pattern approximating that of an elementary electric dipole.

displacement current: Expresses an effect of the rate of change of electric flux density, manifesting itself as a magnetic field but without a conduction current.

NOTE—Displacement current can be the current flowing through the dielectric of a capacitor or the current associated with the fringing fields that terminate on ground near the edge of parallel plate (stand-on) induced body current meters that could escape detection by the meter electronics.

dosimetric reference limit (DRL): The exposure limit based on dosimetric thresholds for established adverse health effects.

NOTE 1—DRL expressed as internal electric field strength (0 Hz to 5 MHz), specific absorption rate (100 kHz to 6 GHz), or epithelial power density (6 GHz to 300 GHz) and that provides an adequate margin of safety.

NOTE 2—DRL is defined in conjunction with specified spatial and temporal averaging requirements.

NOTE 3—DRL is equivalent to the quantity previously referred to as *basic restriction*.

dosimetry: The discipline that quantifies the relationship between external exposure quantities and internal dose and dose rate quantities. *See also: specific absorption; specific absorption rate.*

NOTE—External exposure quantities include electric field, magnetic field, and electromagnetic field (incident power density); internal quantities include internal electric field, dose, dose rate, specific absorption, specific absorption rate, and epithelial power density, respectively.

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

NOTE—A duty factor of 1.0 corresponds to continuous-wave (CW) operation.

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. *See also: antenna gain; aperture (of an antenna).*

NOTE 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.

NOTE 2—If the direction is not specified, the direction of maximum radiation intensity is implied.

NOTE 3—For a lossless and perfectly matched antenna, effective area in a given direction is given by:

$$A_e(\theta, \phi) = \frac{G_i(\theta, \phi) \lambda^2}{4\pi}$$

where

$A_e(\theta, \phi)$ is the effective area in direction (θ, ϕ)

$G_i(\theta, \phi)$ is the antenna gain with respect to an isotropic source (ratio) in the direction (θ, ϕ)

λ is the wavelength (m)

electric dipole: A pair of equal and opposite point charges separated by a distance.

NOTE—When the charges are oscillating and the separation is infinitesimal, the dipole becomes an elementary radiating electric dipole.

electric field: A fundamental component of electromagnetic (EM) waves that exists when there is a difference in potential between two points in space.

electric field strength: Force exerted by an electric field on an electric point charge divided by the electric charge.

NOTE—The SI unit for electric field strength is newton per coulomb or volt per meter ($N/C = V/m$).

electric field vector: The magnitude and direction of the force on a stationary positive unit charge. *See also:* **electric field strength**.

electromagnetic field (EMF): For the purposes of this recommended practice, any field consisting of electric and/or magnetic components, regardless of whether it is propagating (radiating) or not.

electromagnetic interference: Any electromagnetic disturbance, whether intentional or not, which interrupts, obstructs, or otherwise degrades or limits the effective performance or safe operation of an electronic or electrical device or system.

electrostimulation: Induction of a propagating action potential in excitable tissue by an applied electrical stimulus; electrical polarization of presynaptic processes leading to a change in postsynaptic cell activity.

NOTE—Electrostimulation involves excitation of nerve and/or muscle tissue.

electromagnetic unit: A physical quantity of electromagnetic energy at a single point in time and space.

environmental field: An electric, magnetic, or electromagnetic field external to the body that is measured in the absence of the body (in order not to perturb the field).

epithelial power density: The power flow through the epithelium per unit area directly under the body surface (i.e., in stratum corneum of the skin or corneal epithelium of eyes).

NOTE 1—The SI unit for epithelial power density is watt per square meter (W/m^2).

NOTE 2—In this recommended practice, the epithelial power density just inside the body surface is employed to define local dosimetric reference limits at frequencies greater than 6 GHz.

established adverse health effect: An effect detrimental to the health of a person due to exposure to an electric, magnetic, or electromagnetic field, or to induced or contact currents, with the following characteristics:

- It is supported by the weight of the evidence of that effect in studies published in the scientific literature.
- The effect has been demonstrated by independent laboratories.
- There is consensus in the scientific community that the effect occurs for the specified exposure conditions.

See also: **adverse health effect**.

established adverse reaction: *See:* **established adverse health effect**.

evaluation: The process of quantifying human exposure to electromagnetic field (EMF) by employing exposure metrics using measurement and/or computation, including consideration of uncertainty, and making necessary adjustments to normalize the result.

expanded uncertainty: An interval expected to encompass a large fraction (usually 95%), of the distribution of values that could reasonably be attributed to the true value of a measurement or computation. *See also:* **combined standard uncertainty; coverage factor; standard uncertainty.**

NOTE—expanded uncertainty is the result of multiplying the combined standard uncertainty by the coverage factor.

exposure: The state of being in the presence of electric, magnetic, or electromagnetic fields, or in contact with a current or voltage source.

exposure environment: A defined area that is characterized by the maximum potential exposure that could occur within it.

- a) **restricted environment:** An environment in which exposure can result in exceeding the unrestricted environment dosimetric reference limit.

NOTE 1—Implementation of an effective safety program (such as per IEEE Std C95.7-2014 for the radio frequency range) is to help prevent persons being exposed above the DRL or ERL for the restricted environment.

NOTE 2—In some documents, exposure in restricted environments is referred to as “upper tier” or “controlled environment” or “occupational exposure.”

NOTE 3—Members of the general public are not permitted in restricted environments unless they become subject to the applicable safety program, at which time they are no longer considered members of the “general public.”

- b) **unrestricted environment:** An environment in which exposure does not result in exceeding the dosimetric reference limit that marks the safety program initiation level, and which serves as an exposure limit for the general public. *See also:* **general public.**

NOTE 1—The exposures can occur in living quarters or workplaces where there are no expectations that the DRL or ERL for unrestricted environments would be exceeded and where the induced currents or contact currents do not exceed the limits for unrestricted environments.

NOTE 2—In some documents, the unrestricted environment is referred to as a “lower tier” or an “uncontrolled environment” or a “general public exposure.”

exposure limit: A threshold such as a dosimetric reference limit (DRL) or exposure reference limit (ERL) including, when applicable, frequency dependency and spatial and temporal aspects (e.g., averaging).

NOTE— EL_f is the numerical value of the exposure limit at frequency f .

exposure metric: *See:* **metric.**

exposure ratio: The ratio of the exposure value to the corresponding dosimetric reference limit (DRL) or exposure reference limit (ERL) at the frequency of interest. *See also:* **total exposure ratio.**

NOTE—When multiple exposure ratios are summed, the frequency dependency of the applicable DRL or ERL is preserved.

exposure reference level (ERL): The maximum exposure level relative to ambient electric and/or magnetic field strength or power density, induced and/or contact current, or contact voltage.

NOTE 1—ERLs provide an adequate margin of safety against established adverse health effects.

NOTE 2—The ERL is expressed using the metric appropriate to the frequency and temporal characteristics of the exposure under consideration.

NOTE 3—ERLs are derived from DRLs (internal electric field, specific absorption rate, or epithelial power density).

NOTE 4—For the purposes of this standard, an ERL may be exceeded if it can be demonstrated that the corresponding DRL is not exceeded.

NOTE 5—The ERLs and DRLs for contact current are the same.

NOTE 6—In some documents, ERLs are called reference levels, derived limits, permissible exposure limits, maximum permissible exposure values, action levels, or investigation levels.

exposure value: The result of a measurement or computation of the electromagnetic energy reported in the SI units relevant to the exposure metric being implemented and scaled to represent the applicable reference conditions.

NOTE 1—Used in the calculation of the exposure ratio.

NOTE 2—The exposure value incorporates all the criteria required to compare a result with an applicable DRL or ERL.

far-field (region): The region where the angular field distribution is essentially independent of distance from the source.

NOTE—In the far-field 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 large antennas especially, the far-field region is also referred to as the “Fraunhofer region.”

finite difference time domain (FDTD) method: 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.

finite element method (FEM): A class of numerical algorithms for solving Maxwell’s differential equations of electromagnetic field interactions.

NOTE—The FEM uses Discrete Differential Forms (DDF), which are finite element basis functions defined on a mesh.

general public: All members of the human population who have no knowledge or control of their exposure and are, consequently, not permitted in a restricted environment. The unrestricted environment exposure limit applies to the general public. *See also:* **exposure environment (unrestricted).**

NOTE 1—The general public includes, but is not limited to, children, pregnant women, people with impaired thermoregulatory systems, and persons using medications that can result in poor thermoregulatory system performance.

NOTE 2—Some documents and regulations use the similar term “general population.”

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

NOTE—In IEEE Std C95.1-2019, a contact area of 15 cm² is assumed.

grip tetanus: A condition where an electrical stimulus causes the hand to “freeze” its grip on an object. The threshold of grip tetanus is also called the let-go current. *See also:* **let-go current.**

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

hazard: An intrinsic property or condition that has the potential to cause an adverse health effect.

hazard meter (monitor): An instrument that can measure spatially localized electric and/or magnetic field strengths under near-field and far-field conditions. The instrument consists of a sensor suitable for the wavelength under study with a means for transmitting information from the sensor to a suitable indicator.

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.

incident energy density: For purposes of this recommended practice, the quantity of energy per unit area that impinges on the body surface.

NOTE—The SI unit for incident energy density is joule per square meter (J/m^2).

incident power density: For purposes of this recommended practice, the quantity of power per unit area that impinges on the body surface. *See also:* **power density**.

NOTE 1—The SI unit for incident power density is watt per square meter (W/m^2).

NOTE 2—In this recommended practice, the incident power density just outside the body surface is employed to define local exposure reference levels at frequencies greater than 6 GHz.

induced current: Electric current flowing in the body of a person in a freestanding condition due to an electromagnetic field.

induction: The act of generating an electric or a magnetic field in a conducting medium caused by the action of a time-varying external (environmental) electric or magnetic field.

internal: Within a biological tissue in its normal anatomical position.

NOTE 1—Typically used to qualify an electric field (strength), a magnetic field (strength), a current, or an assessment.

NOTE 2—IEEE Std C95.1-2019 uses the term *in situ* to mean within a biological tissue in its normal anatomical position; in other standards and guidelines the term “in-situ,” “in situ,” or “*in situ*” is used to describe evaluations made onsite rather than in a laboratory or test facility.

isotropic antenna: An ideal lossless antenna capable of radiating (or receiving) uniformly in all directions in three-dimensional space, as well as equally well in all polarizations.

isotropic probe: *See:* **probe**.

let-go current: The current level above which involuntary muscular contraction prevents release of a grip on an energized conductor. *See also:* **grip tetanus**.

NOTE 1—“Let-go current” is the preferred term but is often used interchangeably with “can’t let go current” or “lock-on current.”

NOTE 2—“Let-go” has occasionally been used for the threshold for withdrawal from an aversive stimulus.

limb: An entire leg or arm.

lobe: A three-dimensional section of the radiation pattern of a directional electromagnetic field (EMF) source, bounded by one or more pattern nulls or by regions of diminished field strength.

NOTE—The main lobe of an antenna is the lobe which exhibits the greatest antenna gain.

local exposure: An exposure condition in which a limited portion of the body is subject to most of the incident energy and is usually the result of 1) the source being located very close to the body or 2) a highly concentrated region of energy associated with contact with an energized conductor exposed to environmental fields.

low-level fields: Electromagnetic fields in the frequency range 0 Hz to 300 GHz that produce induced internal electric fields, specific absorption rate, or epithelial power density at or below the corresponding dosimetric reference limits.

magnetic field: A fundamental component of electromagnetic waves produced by a moving electric charge.

magnetic field strength: The magnitude of the magnetic field vector.

NOTE 1—The SI unit of magnetic field strength is ampere per meter (A/m).

NOTE 2—In air and simple (nonmagnetic) media, the magnetic field strength H is related to the magnetic flux density B by: $B = H \mu$, where μ is the permeability of the medium.

magnetic field vector: A field vector that is equal to the ratio of the magnetic flux density to the permeability.

NOTE—The SI unit of magnetic field vector is ampere per meter (A/m).

magnetic flux density: A vector quantity that determines the force on a moving charge or charges (electric current).

NOTE 1—The SI unit of magnetic flux density is tesla (T).

NOTE 2—In air and simple (nonmagnetic) media, the magnetic flux density B is related to the magnetic field strength H by $B = H \mu$, where μ is the permeability of the medium.

NOTE 3—One gauss (deprecated unit) equals 10^{-4} T. Similarly, 1 mG = 0.1 μ T.

maximum permissible exposure (MPE): Deprecated. *See:* **exposure reference level**.

maximum root-mean-square (rms) component: The rms component of an electromagnetic field (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

$\hat{\mathbf{n}}_{\max}$ is a unit vector pointing in the direction that maximizes the expression

NOTE—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 numerical values.

median: The value within a statistical distribution at which 50% of values are greater than and 50% are less than.

median threshold: The threshold value within a statistical distribution at which 50% of subjects have greater thresholds and 50% have lesser thresholds.

metric: a standard of measure.

NOTE—In this recommended practice, the term metric is used generally with respect to the various measures involved in making exposure assessments. Specifically, an exposure metric is one that incorporates all the criteria required to compare a result against an applicable exposure limit. An exposure metric is the result of combining various contributing metrics such as measured or computed physical quantity, time-averaging, spatial-averaging, and waveform dynamics.

microwave: An informal term that signifies radio frequencies in the range from about 300 MHz to 300 GHz.

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 operation is considered to be a special form of modulation, that is, no modulation.

near-field (region): A region, generally in proximity to an antenna or other radiating structure, in which the electric and magnetic fields do not have a substantially plane-wave character and vary considerably from point to point.

NOTE 1—The near-field region is further subdivided into the reactive near-field region, which is closest to the radiating structure and contains most or nearly all of the stored energy, and the radiating near-field region where the radiating field predominates over the reactive field but lacks substantial plane-wave character and is complicated in structure.

NOTE 2—For most antennas, the outer boundary of the reactive near-field region is commonly taken to exist at $\lambda/2\pi$ from an electrically short antenna (e.g., half-wave dipole) where λ is the wavelength. For electrically large antennas, the radiating near-field region extends out to a distance from the antennas approximately equal to $2D^2/\lambda$, where D is the largest dimension of the antenna.

non-uniform field: A field that is not constant in amplitude, direction, and relative phase over the dimensions of the body or body part under consideration.

NOTE—In the case of electric fields, the definition applies to an environmental field that can be non-uniform when unperturbed by the presence of the body.

open-circuit voltage: The difference in potential between two conducting objects without a current flow between the objects.

NOTE—Also described as the difference in potential under a “no load” condition.

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

parasitic reradiator: *See:* reradiated field.

partial-body exposure: *See:* local exposure.

peak field: The instantaneous value of a time-varying electric or magnetic field when at its maximum value.

peak power density: The maximum spatial and/or temporal power density in a propagating wave.

NOTE—The SI unit of peak power density is watt per square meter (W/m²).

peak spatial-average SAR: *See: specific absorption rate—peak spatial-average.*

permittivity (complex): The ratio of the electric flux density in a medium to the electric field strength at a point.

NOTE—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 vacuum (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
- ω is the angular frequency in radians per second

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.

phantom: A physical or computational model with defined shape, size, and electrical properties used to evaluate internal field strengths or currents.

pinna: The largely cartilaginous projecting portion of the outer ear consisting of the helix, lobule, and anti-helix.

plane wave: An electromagnetic wave characterized by mutually orthogonal electric and magnetic fields that are related by the free-space wave impedance η_0 .

NOTE—For plane waves, power density (S), the electric field strength (E), and the magnetic field strength (H) exhibit the following relationship: $S = E^2/\eta_0$ or $S = \eta_0 H^2$, where S is in W/m², E is in V/m, and H is in A/m.

plane-wave-equivalent power density: The calculated power density of an electromagnetic wave that is equal in magnitude to the power density of a plane wave having the same electric field strength or magnetic field strength. *Syn: equivalent-plane-wave power density.*

NOTE 1—The SI unit of plane-wave-equivalent power density is watt per square meter (W/m²).

NOTE 2—Plane-wave-equivalent power density is computed as follows:

$$S_E = \frac{|E|^2}{\eta_0} \text{ W/m}^2 \quad \text{or} \quad S_H = \eta_0 |H|^2 \text{ W/m}^2$$

where $|E|$ and $|H|$ are the root-mean-square values of the electric- and magnetic field strengths, respectively, and η_0 is the wave impedance of a plane wave in a vacuum.

polarization (electromagnetic): The locus of the tip of the electric or magnetic field vector observed over time at a fixed point.

NOTE—The polarization of radiating electromagnetic waves is conventionally taken as the polarization of the electric field component.

power: A physical quantity describing the rate of delivery or transmission of energy.

NOTE—The SI unit of power is watt (W).

power density: Electromagnetic power per unit area crossing a surface of interest. *See also:* **plane-wave-equivalent power density.**

NOTE 1—The SI unit of power density is watt per square meter (W/m²).

NOTE 2—The surface of interest is frequently chosen to be orthogonal to the electromagnetic wave direction of propagation.

NOTE 3—For an arbitrary time-dependent signal waveform, the instantaneous power density point value is

$$S(t) = \mathcal{E}(t) \times \mathcal{H}(t) \cdot \hat{\mathbf{n}}$$

where

$\hat{\mathbf{n}}$ is the unit-vector normal to the surface of interest

$\mathcal{E}(t)$ is the instantaneous electric field intensity vector

$\mathcal{H}(t)$ is the instantaneous magnetic field intensity vector

t is the time variable

NOTE 3—For a periodic time-dependent signal waveform, the time-averaged power density point value is

$$S_T = \frac{1}{T} \int_{t_0}^{t_0+T} S(t) dt$$

where T is the waveform period and t_0 is any arbitrary time.

NOTE 4—For a time-harmonic signal waveform, the time-averaged power density point value is

$$S = \frac{1}{2} \Re(\mathbf{E} \times \mathbf{H}^*) \cdot \hat{\mathbf{n}}$$

where $\Re$ is the real-value operator, $\mathbf{E}$ is the complex electric field point value, $\mathbf{H}$ is the complex magnetic field point value, and the superscript * represents complex conjugation.

NOTE 5—The instantaneous electric and magnetic field intensity vectors depend on their respective complex fields as follows:

$$\mathcal{E}(t) = \Re(\mathbf{E}e^{j\omega t}), \quad \mathcal{H}(t) = \Re(\mathbf{H}e^{j\omega t})$$

where $\omega = 2\pi f$ is the waveform radian frequency, having defined f as the waveform frequency and $j = \sqrt{-1}$ as the imaginary unit.

power level: At any point in a system, the ratio of the power at that point to some arbitrary amount of power chosen as a reference.

NOTE—power level is often expressed as decibels referred to 1 mW (dBm) or decibels referred to 1 W (dBW).

probe: A measurement device that minimally perturbs the measurand while providing an output signal that is suitable for display or recording and has a defined relationship to the measured physical quantity.

NOTE 1—Field probes are used for measuring one or more electric and/or magnetic field components of an EMF and typically include one or more electrically small (in the medium in which it is used) sensors.

NOTE 2—Temperature probes are used to measure the temperature in a medium while minimally perturbing the EMF if present.

NOTE 3—A probe typically includes a transmission line, often in the form of a balanced high-impedance resistive lead or an optical fiber connection, to connect the (rectified) signal to processing stages.

projected area: The maximum cross-sectional area of the exposed portion of the body normal to the direction of propagation.

pulse repetition frequency: In pulse-modulated systems using recurrent pulses, the number of pulses per unit of time (s).

pulse width: The time interval between the points on the leading and trailing edges at which the instantaneous value bears a specified relation to the maximum instantaneous value of the pulse, usually the time interval between the half-power points of the pulse.

quasi-static electric (magnetic) field: A time-varying electric (magnetic) field whose spatial distribution can be described with low error using static or low-frequency approximations to Maxwell's equations.

NOTE 1—Quasi-static electric and magnetic fields are approximately decoupled from one another and can often be evaluated separately with low error.

NOTE 2—Quasi-static electric (magnetic) fields occur when the largest dimension of the evaluated domain is substantially smaller than the wavelength of the frequency under consideration.

radio frequency (RF): A frequency between approximately 3 kHz and 300 GHz.

RF burn: An injury that has occurred when contact with, or spark discharge from, an RF energized conductor results in painful heating of tissue commensurate with visible skin damage and is usually accompanied by an involuntary withdrawal.

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

reference condition: Established factors, including decision rules, reference state and applicable exposure reference level (ERL) and dosimetric reference limit (DRL), that, when applied, obtain an assessment that fulfills its purpose and is repeatable.

reference state: The characteristics of the electromagnetic field (EMF) source(s) and the exposure environment that are being compared with the applicable exposure limits.

NOTE—The reference state is established by normalizing the actual conditions observed to the conditions intended for comparison.

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.

relative phase: The phase angle of a sinusoidal waveform relative to the phase angle of another waveform measured at a different point within the conductive medium or with respect to a stated reference waveform.

reradiated 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 sources.

NOTE—Reradiated fields are sometimes called “reflected” or more correctly “scattered fields.” The scattering object, sometimes called a “reradiator,” “secondary radiator,” or “parasitic radiator,” can be a source of contact currents.

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.

restricted environment: *See:* **exposure environment (restricted).**

resultant: A metric for an electromagnetic field (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. *See:* **root-mean-square, vector magnitude**. *See also:* **maximum root-mean-square (rms) component**.

NOTE—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.

rheobase: The minimum electric field amplitude capable of initiating neural excitation as observed in a strength-frequency (S-F) or strength-duration (S-D) relationship (applicable to a stimulus phase duration that is long in comparison with the strength-duration time constant).

NOTE 1—The unit for rheobase is volt per meter (V/m).

NOTE 2—Also applied to the minimum plateau in an S-F relationship for electrostimulation.

risk: The likelihood or probability that a person will be harmed by a hazard.

root-mean-square (rms) value (of a periodic function): The square root of the arithmetic mean of a sequence of squared values extracted from measurements or other data.

NOTE—For a time-varying function G with a period T , the rms value of G is

$$G_{\text{rms}} = \sqrt{\frac{1}{T} \int_a^{a+T} G^2 dt}$$

where a is any value of time t .

root-sum-square (rss): The square root of the sum of a sequence of squared values.

safety program: An organized system of policies, procedures, practices, and plans designed to help ensure compliance with exposure limits associated with electric, magnetic, and electromagnetic fields; contact voltage; and contact and induced currents.

NOTE—A safety program typically includes awareness training, implementation of protective measures such as signage, and the use of personal protective equipment, incident response, periodic evaluation of program effectiveness, and assigned responsibilities for implementing the program similar to the elements described in IEEE Std C95.7-2014 for the radio frequency range.

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

scattered radiation: *See:* **reradiated field.**

screening: A simple method for measuring or computing electromagnetic field (EMF) exposures to determine whether more precise methods are needed to verify conformity with the applicable safety limits.

short-term exposure: Exposure for a duration less than the corresponding averaging time.

spark discharge: An arc delivering current through a conductive channel of ionized gas formed in the gap between two electrodes when the potential gradient is enough to cause dielectric breakdown of the gas (e.g., air).

spatial average: A method for averaging field strength, field strength squared, or power density over a specified line, area or volume.

spatial maximum: The maximum point value of a spatially distributed parameter.

specific absorption: The quotient (SA) of the incremental energy (dW) absorbed by (dissipated in) an incremental mass (dm) contained in a volume (dV) of a given mass density (ρ).

$$SA = \frac{dW}{dm} = \frac{dW}{\rho dV}$$

NOTE—The SI unit of specific absorption is joule per kilogram (J/kg).

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

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

NOTE 1—The SI unit of specific absorption rate is watt per kilogram (W/kg).

NOTE 2—The SAR can be related to the electric field at a point in the body by:

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

where

σ is the conductivity of the tissue (S/m)

ρ is the density of the tissue (kg/m³)

E is the root-mean-square (rms) electric field strength in tissue (V/m)

NOTE 3—SAR can be related to the initial rate of rise in temperature at a point by:

$$SAR = \frac{c \Delta T}{\Delta t} \Big|_{t=0}$$

where

- ΔT is the change in temperature (°C)
- Δt is the duration of exposure (s)
- c is the specific heat capacity (J/[kg °C])

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

specific absorption rate—peak spatial-average (psSAR): The maximum local SAR averaged over a specified volume or mass (e.g., any 10 g of tissue in the shape of a cube).

NOTE—The SI unit of specific absorption rate—peak spatial-average is watt per kilogram (W/kg).

specific absorption rate—whole-body-average (WBA SAR): The SAR averaged over the entire mass of the body.

NOTE—The SI unit of specific absorption rate—whole-body-average is watt per kilogram (W/kg).

standard uncertainty: The standard deviation associated with the result of a measurement or computation that characterizes the expected dispersion of values around that result.

standing wave: A spatially periodic or repeating series of amplitude maxima and minima that is generated by two propagating waves of equal wavelength traveling in opposite 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.

static field (electric or magnetic): A non-time-varying field created by a fixed difference in potential (or flow of direct current) between two points (or a magnetic pole).

thermal effects: Changes associated with heating of the whole body or an affected region sufficient to induce a biological effect.

NOTE—Established adverse health effects are associated with whole-body heating at levels that usually increase core temperature by approximately 1 °C or more.

thermal load: The imposition of additional heat to a body that can be maintained in stasis by thermal diffusion, radiation, or thermoregulation, or can exceed the capacity of these functions and cause unwanted temperature rise.

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.

total exposure ratio: The sum of a set of exposure ratios employed to characterize a total (potential) electromagnetic field (EMF) exposure in relation to a corresponding exposure limit considering that the total exposure ratio incorporates all relevant frequency, temporal and spatial components necessary to maintain consistency with the corresponding exposure metric.

NOTE—If the total exposure ratio exceeds unity, then the evaluated exposure condition exceeds the corresponding exposure limit.

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

NOTE—In IEEE Std C95.1-2019, a contact area of 1 cm² is the assumed touch contact area.

uncertainty: A measure of the dispersion of the values attributed to a measured or computed result, within which the true value is likely to lie.

uncertainty allowance: An upper limit, on the expanded uncertainty of a measured or computed result, beyond which the result shall be increased so as to limit the likelihood of the actual result exceeding the specified limit.

NOTE—An uncertainty allowance is typically applied in the context of a compliance assessment based on shared risk.

uniform field: A field that is constant in amplitude, direction, and relative phase over the dimensions of the body or body part under consideration.

NOTE—In the case of ambient electric fields, the uniformity of an external field is assessed in the presence of any permanent structures and fixtures but without the presence of any human bodies that would disturb the field. In the case of induced internal fields, the definition applies to an electric field that results in a constant difference in potential across the axonal nodes of an unmyelinated nerve fiber.

unrestricted environment: *See:* **exposure environment (unrestricted).**

vector magnitude: The length of a 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 (complex) components of the vector.

See also: **root-mean-square.**

voxel: A three-dimensional (volumetric) computational element.

waveform: The variation of an electrical amplitude with time.

NOTE—For internal assessments, the term *waveform* refers to values at sites within the biological medium.

wave impedance (of plane wave in a vacuum): The ratio of the electric field strength to the magnetic field strength of a propagating electromagnetic wave.

NOTE 1—The SI unit for wave impedance is ohm (Ω).

NOTE 2—According to the National Institute of Standards and Technology (NIST) (USA), The intrinsic impedance of a plane wave in a vacuum (η_0) is 376.730313461 Ω . This exact value of η_0 [derived as the square root of the ratio of vacuum permeability (μ_0) to vacuum permittivity (ϵ_0)] is approximately 377 Ω when rounded to the nearest integer, which is also coincidentally approximately $120\pi \Omega$. Some literature uses rounding to, for example, $\eta_0 \approx 376.73 \Omega$.

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.

whole-body exposure: The case in which the projected area of the entire body is exposed to the incident fields.

3.2 Acronyms and abbreviations

AAMI	Association for the Advancement of Medical Instrumentation
AM	amplitude modulated
ANSI	American National Standards Institute
CI	coverage interval
CW	continuous wave
DRL	dosimetric reference limit
EIRP	effective isotropic radiated power
EMF	electromagnetic field
ERL	exposure reference level
ERP	effective radiated power (dipole reference)
FDTD	finite-difference time-domain
ICES	International Committee on Electromagnetic Safety
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEC	International Electrotechnical Commission
IME	Institute of Makers of Explosives
ISO	International Organization for Standardization
MIMO	multiple input, multiple output
MRI	magnetic resonance imaging
NCRP	National Council on Radiation Protection and Measurements
NGMN	Next Generation Mobile Networks Alliance
RF	radio frequency
RFI	radio frequency interference
RFID	radio frequency identification
rms	root-mean-square
rss	root-sum-square
SEP	source-environment plane
SI	Système International d'Unités (international system of units)
TPO	transmitter power output
WBA	whole-body average

3.3 Frequency bands

ELF	extremely low frequency (0 Hz to 3 kHz)
VLF	very low frequency (3 kHz to 30 kHz)
LF	low frequency (30 kHz to 300 kHz)
MF	medium frequency (0.3 MHz to 3 MHz)
HF	high frequency (3 MHz to 30 MHz)
VHF	very high frequency (30 MHz to 300 MHz)
UHF	ultra high frequency (300 MHz to 3 GHz)
SHF	super high frequency (3 GHz to 30 GHz)
EHF	extremely high frequency (30 GHz to 300 GHz) ⁸

⁸ Per ITU Radio Regulations (2016), for the EHF frequency range, the corresponding metric subdivision is known as “millimetre waves.”

3.4 Letter and mathematical symbols for quantities

a	largest electrical dimension of an antenna element or array
a	semi-span of an uncertainty distribution
a, b	semi-major and semi-minor axes of elliptical representation of exposed body part
A_i	magnitude of the i^{th} Fourier component of a waveform
B	magnetic flux density, expressed in tesla (T)
$\dot{B}_0$	rheobase time-rate-of-change of flux density (dB_0/dt) in a strength-duration or strength-frequency relationship
$\dot{B}$	time rate of change of magnetic flux density, dB/dt , expressed in tesla per second (T/s)
$\dot{B}_p$	peak allowable limit on the time derivative of flux density
c	specific heat capacity
d	distance between antenna and point of interest
d	divisor used to calculate the standard uncertainty (depends on the probability distribution of the uncertainty)
DRL	dosimetric reference limit
E	electric field strength expressed in volt per meter (V/m)
E_i	internal electric field strength (V/m)
EL	exposure limit
EMU	electromagnetic unit
ERL	exposure reference level
ER	exposure ratio
EV	exposure value
f	frequency expressed in hertz (Hz)
f_c	upper transition frequency in a strength-frequency relation (Hz)
f_i	frequency of the i^{th} Fourier component of a waveform (Hz)
G	gain (of an antenna), by field ratio or by power ratio (dB) with respect to a reference
$G_{(\theta, \phi)}$	far-field antenna gain in direction, spherical coordinates θ, ϕ (power ratio to isotropic).
h	height of a standing person, expressed in meter (m)
H	magnetic field strength, expressed in ampere per meter (A/m)
I	current, expressed in ampere (A)
I_i	induced current, expressed in ampere (A)
I_c	contact current, expressed in ampere (A)
J	current density, expressed in ampere per square meter (A/m ²)
k	coverage factor
P	power, expressed in watt (W)
$P(t)$	instantaneous power (at time t), expressed in watt (W)
P_T	power radiated by the antenna (W)
prf	pulse repetition frequency expressed in pulses per second (pps), or, informally, (Hz)
$psSAR$	specific absorption rate—peak spatial-average, expressed in watt per kilogram (W/kg)
$\bar{P}$	average power (temporal), expressed in watt (W)
q	charge, expressed in coulomb (C)
ρ	mass density, expressed in kilogram per cubic meter (kg/m ³)
SA	specific absorption, expressed in joule per kilogram (J/kg)
SAR	specific absorption rate, expressed in watt per kilogram (W/kg)

S	power density, expressed in watt per square meter (W/m^2)
S_E	plane-wave-equivalent power density value based on the electric field strength (W/m^2)
S_{epi}	epithelial power density (W/m^2)
S_H	plane-wave-equivalent power density value based on the magnetic field strength (W/m^2)
S_{FF}	far-field power density (W/m^2)
T_{avg}	averaging time (s)
TER	total exposure ratio
u	standard uncertainty
u_c	combined standard uncertainty
U	expanded uncertainty
U_0	uncertainty allowance
U_{up}	uncertainty upper bound
V_{oc}	open circuit voltage (V)
W	energy, expressed in joule (J)
W_{lp}	local incident energy density (per pulse), expressed in joule per square meter (J/m^2)
W_p	incident energy density, expressed in joule per square meter (J/m^2)
$WBA\ SAR$	specific absorption rate—whole-body-average, expressed in watt per kilogram (W/kg)
σ	conductivity, expressed in siemens per meter (S/m)
ϵ_0	electric permittivity of a vacuum ($\epsilon_0 = 8.85 \times 10^{-12} \text{ F/m}$)
ϵ_r	relative permittivity
η	wave impedance, expressed in ohm (Ω)
η_0	wave impedance of a plane wave in a vacuum ($\eta_0 \approx 377 \Omega$ [see 3.1])
λ	wavelength, expressed in meter (m)
μ	magnetic permeability, expressed in henry per meter (H/m)
μ_0	magnetic permeability in a vacuum or in air ($\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$)
τ	pulse width (s)
τ_c	transition duration in a strength-duration relationship, expressed in second (s)
τ_h	time constant of the leakage of charge applied to a human subject (s)

3.5 Unit symbols

A	ampere
C	coulomb
$^{\circ}\text{C}$	degree Celsius
cm	centimeter (10^{-2} m)
dB	decibel
F	farad
g	gram
G	gauss
GHz	gigahertz (10^9 Hz)
H	henry
h	hour
Hz	hertz
J	joule

kg	kilogram
kHz	kilohertz (10^3 Hz)
m	meter
mm	millimeter (10^{-3} m)
m ²	square meter
MHz	megahertz (10^6 Hz)
min	minute
N	newton
Ω	ohm
S	siemens
s	second
T	tesla
V	volt
W	watt

4. Quick start guide

4.1 Context

This recommended practice considers the evaluation and assessment of human exposure to electric, magnetic, and electromagnetic fields (collectively, EMF). It provides guidance on what constitutes best practice for the assessment of human exposure to electromagnetic fields. Figure 1 presents key contributors to the management of human exposure and shows that this recommended practice should be regarded as a complement to existing information rather than an alternative.

The science and engineering literature records the detailed knowledge of electromagnetics and the interaction of EMF with human beings. The exposure guidelines (in standards such as IEEE Std C95.1-2019) record the conclusions from reviewing that literature and provide guidelines on limiting human exposure to EMF. Regulations provide the legal requirements, within their jurisdiction, for control of human exposure to EMF. The range of product standards offer detailed assessment methodologies to evaluate the human exposure to EMF arising from certain sources.

This recommended practice considers the contributors to EMF exposure management and provides guidance on how to set up and perform reliable, traceable, repeatable, high-quality assessments. It includes recommendations on how to develop, execute, and document appropriate assessment methodology and capabilities consistent with best practice including the implementation of detailed methodologies described in product standards.

Throughout this recommended practice there are many references to the wider literature to provide important depth and detail. There are several international and national standards that identify assessment techniques that may be used. Indeed, these standards continue to be developed and extended to meet technical innovations so inevitably there will be many such standards that are not listed in this recommended practice and that will offer valuable guidance on specific assessments. Best practice therefore requires an ongoing process of learning and updating that should be continued beyond the publication date of this recommended practice.

This recommended practice complements the IEEE Std C95.1-2019 and IEEE Std C95.1-2345-2014 [B191] exposure standards (see Annex A), however the practices herein can be adapted to other guidelines and regulatory requirements.

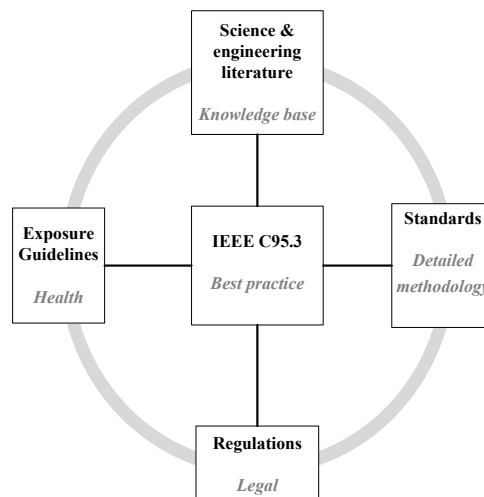


Figure 1—Management of human exposure to EMF

4.2 General requirements

This recommended practice is designed to enable professional users to develop targeted methods and demonstrate that those methods, and the professional user's application of those methods, are consistent with best practice. By meeting the following requirements, an assessment may be stated to be consistent with this recommended practice:

- a) The assessor shall have the necessary skills, knowledge and understanding to prepare for, perform, report on, and explain all aspects of the assessment.
- b) Due consideration shall be given to the safety of the assessor and bystanders during the evaluation of potential human exposure to EMFs (see Annex H). This should include preliminary estimation of the anticipated exposure conditions (see Table D.1).
- c) The assessment task shall be clearly specified, planned, and executed in a manner that achieves its objectives (see Clause 5, Annex A).
- d) Measurement instruments shall be fit for purpose and have a valid calibration that is traceable to a national standard and is appropriate for the relevant use (see Clause 5, Annex B, Annex C).
- e) Computational tools shall be fit for purpose and appropriately validated for the relevant use (see Clause 5, Annex D).
- f) Assessment results shall be qualified by appropriate information on instrument settings, computational assumptions, and post-processing (e.g., spatial or temporal averaging, extrapolation to unmeasured conditions) (see Clause 5, Annex B, Annex C, Annex D).
- g) Assessments shall be accompanied by a statement of estimated uncertainty (see Clause 5, Annex E).
- h) Records of the assessment process shall be retained by or on behalf of the assessor and shall contain relevant information (see Clause 5).

In this recommended practice, the term “evaluation” relates to the determination of the magnitude of one or more metrics of (potential) human exposure to EMFs; determined through measurement and/or computation, including due consideration of uncertainty and any scaling relevant to the intended purpose. The term “assessment” in addition includes interpretation of the determined values, for example in the context of conformity with a specified requirement. For simplicity, the term “assessor” is used for the person or persons undertaking any related task.

4.3 How to use this recommended practice

Table 1 shows the structure of this recommended practice.

The practical use of this recommended practice will depend on the reader's requirement. A few use examples are:

- a) *Getting up to speed on EMF assessment:* Understanding the context of EMF management in Clause 1 is a good start. Clause 4 provides context. Clause 5 process, and Annex A provide a background on relevant EMF exposure metrics. Annex B and Annex C provide background on measurement. Annex D gives a basic understanding of computation. Annex E provides context for estimating uncertainty in assessments and how decision rules may be applied when comparing with a limit. Annex F examples help illustrate some aspects of guidance. For specific applications, Annex G provides a cross reference for specific applications to key standards with abstracts to help determine if they will indeed fulfill the reader's needs. Guidance on identifying and mitigating hazards while working onsite are addressed in Annex H. For a researcher, Annex I identifies areas where further work might help develop best practice and Annex J is the Bibliography.
- b) *Performing a specific assessment:* Understanding the Clause 5 guidance should help structure the planning and execution of an assessment. The guidance in Annex A through Annex D offers additional detail, especially with specific references to the literature and advice on critical issues. Annex G helps identify relevant detailed assessment standards – including abstracts, and also highlight likely critical considerations for the assessment. Annex F examples should assist in clarifying issues that might arise and how to address them.
- c) *Establishing or extending an EMF test facility:* Clause 5 offers guidance on how to approach any assessment task. Referenced information in the annexes augment the guidance. Depending on the anticipated scope of work, the reader should determine relevant detailed references using Annex G. Clause 6 offers guidance on validation of new test equipment, computation tools and methods to commission them into active assessment service.
- d) *Auditing a test facility:* As technology develops, even an experienced test facility should benefit periodically from a review of their operating practices. Checking the test facility processes against the guidance in Clause 5 should help assure the facility continues to apply best practice.
- e) *Quality reference:* Since this recommended practice defines best practice for the assessment of human exposure to EMF (with respect to health hazards), it should be useful as a reference for agreements between the assessor and their clients.

Table 1—Brief overview of contents

Clause 1 Overview	Provides the scope and purpose.
Clause 2 Normative references	The key references that are essential to this document.
Clause 3 Definitions, acronyms, abbreviations	Terms and abbreviations used in this document.
Clause 4 Quick start guide	Requirements for an assessment to be consistent with this recommended practice. How to use this document.
Clause 5 Defining the exposure assessment approach	The assessment protocol describing the complete process from analyzing the specific task, how the assessment is to be performed through to delivering the final report.
Clause 6 Commissioning a new assessment capability	The process to commission new measurement instruments, computation tools and assessment methods.
Annex A Metrics associated with assessing exposure to electric, magnetic, and electromagnetic fields	Overview of metrics relevant to the assessment of human exposure to electric, magnetic, and electromagnetic fields (EMF).
Annex B Instrumentation	Information on the components of measurement systems.
Annex C Measurement process	Information on various measurement procedures that might be followed to investigate and characterize potential exposure metrics.
Annex D Computational techniques	Guidance on selecting and implementing computation techniques.
Annex E Uncertainty	Guidance on estimating the uncertainty of assessments and options for comparing with exposure limits.
Annex F Case examples	Worked example assessments illustrating best practices.
Annex G Guidance on methodology and reference documents	Abstracts of referenced documents that offer guidance relevant to EMF exposure assessment for specific use cases.
Annex H Managing safety of onsite tasks	Identifies several hazards that might be relevant to onsite working.
Annex I Items for further study	Items identified as justifying further study in future revisions.
Annex J Bibliography	Extensive references.

5. Defining the exposure assessment approach

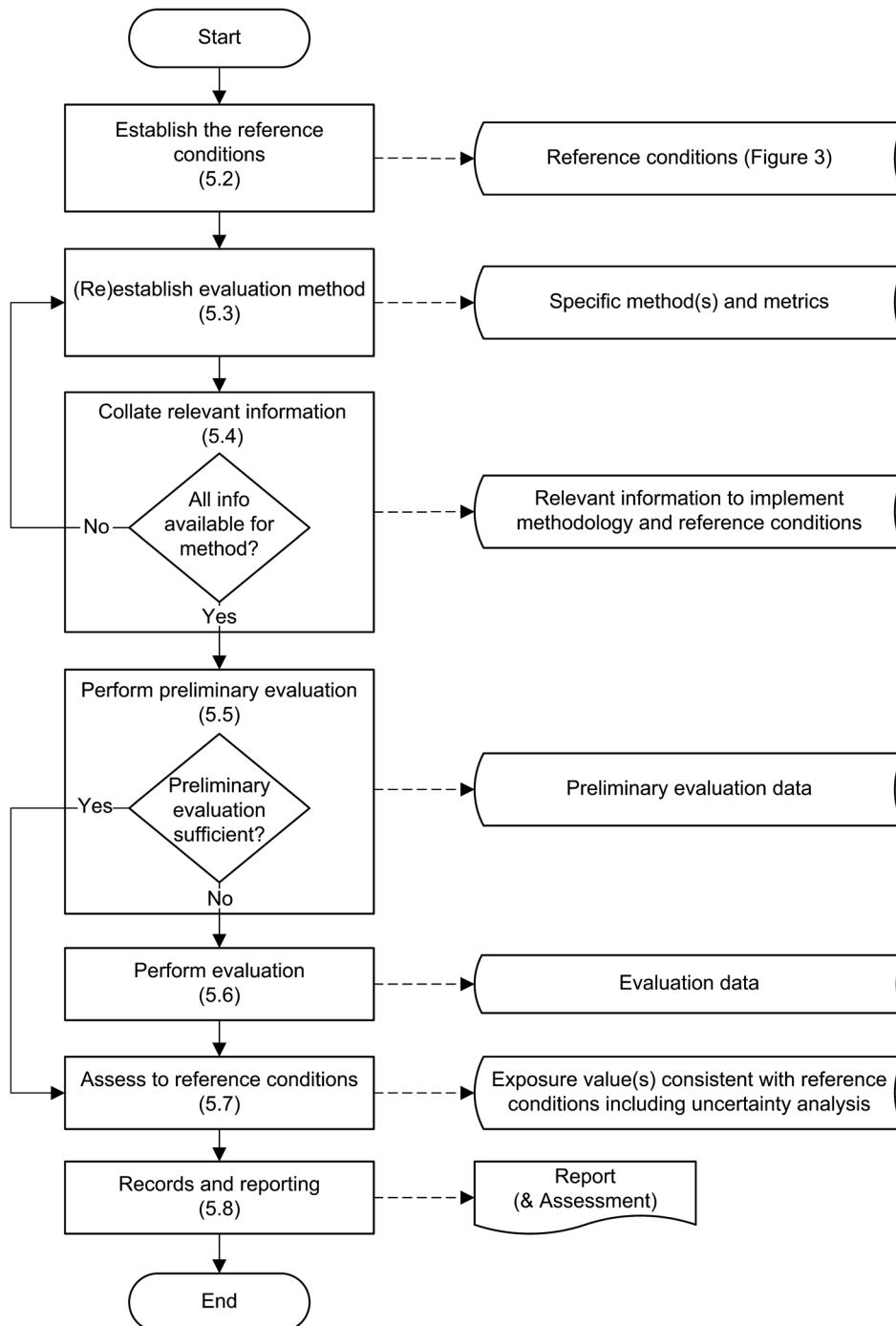
5.1 The assessment protocol

In this clause, guidance is provided on the process to specify assessment protocols that are consistent with best practice in this field; an overview of this process is presented in Figure 2.

An assessment protocol describes the complete process from analyzing the specific task to specify how the assessment is to be performed through to delivering the final report. It is important to understand why a specific assessment is required since the purpose might affect the selection of evaluation methods, their execution and the analysis and presentation of the resulting assessment.

Typically, several steps might be required to complete an assessment task; these may include measurement and/or computation. Assessing human exposure to electric, magnetic, and electromagnetic fields (collectively EMF) involves many metrics for the frequency range covered in this recommended practice (see Annex A). A protocol may therefore include multiple methods.

To improve productivity and efficiency, the assessor may consider developing a library of protocols and constituent methods relevant to the assessor's work and the available test equipment and computational facilities. The process in Figure 2 may therefore be simplified to establish the task-specific requirements for similar new tasks, provided the applicability of each library protocol is critically reviewed, and adjustments made, to maintain best practice for each new situation.



NOTE 1— The solid lines signify a process step described in Clause 5.

NOTE 2— The dotted lines signify information resulting from the respective process step.

Figure 2—Establishing the assessment protocol

5.2 Establishing the reference conditions

Human exposure to EMF varies considerably according to a range of factors. These factors should be specified so that an assessment is repeatable and can fulfill its intended purpose. In this recommended practice, this set of factors is termed the reference conditions (Figure 3).

The reference conditions might constrain the validity of the assessment to those conditions, or they might mean that the assessment is valid under all conditions, even including conditions that are unlikely to ever be attained. The reference conditions for the assessment should be specified at the outset considering at least the following:

- a) The relevant exposure limit considering all parameters associated with the EMF physical quantity (time averaging, spatial averaging, duration, restricted or unrestricted, etc.; see Annex A).
- b) The reference state—e.g., maximum possible power capability, specified percentile of the cumulative distribution function of the actual in-service power, mean in service power (over a specified time period and/or beam area), special combinations to evaluate different modes of operation. The reference state derived from statistics should be determined to be valid for the specific assessment to account for variations between assessment cases.

NOTE—The reference state of a communication base station is commonly selected to be the theoretical maximum power of the final amplifiers. An alternative approach is to use an operational maximum (e.g., 95th percentile) power that is selected by an analysis of the network's (or site's) operation over time and determining the statistical distribution of the operating power of the source over a selected interval. Statistics can also be used in the assessment of multiple input, multiple output (MIMO) systems (Matalatala et al. [B243]). The variations between individual sites might differ from an overall network average so statistically derived reference states need to be justified case by case.

- c) The decision rule for comparison with relevant exposure limit (see 5.7.3).
- d) Population variability—For assessment against DRL, the exposure value might be influenced by the values of body parameters (e.g., height and weight) that vary across the population. The evaluation methods should consider such variation and record how this is accounted for in the assessment. (For example, for the evaluation of specific absorption rate (SAR) with respect to a population, the variability of relevant parameters for that population may be accounted for in the design of test phantoms and computer models by selecting appropriate phantom shapes and body simulant dielectric properties.)
- e) Positioning of device—For laboratory tests or computer modeling to be repeatable, critical device positioning might need to be specified (e.g., against head, against body, front of face, etc.).
- f) Key technical constraints specific to the method—e.g., requirements for inclusion of reflections, interpretation of significance of contributions from low-level sources.

The reference conditions typically depend upon the purpose of the exposure evaluation task, i.e., what it is intended to achieve. Common evaluation purposes are:

- 1) Product compliance: A device or system (typically in the form of small equipment) is to be evaluated to establish whether, when operated in specified ways, it might result in human exposure to EMF above specified limits. This type of assessment is commonly performed in a test facility. The reference conditions should be specified to give a conservative assessment, i.e., giving a high confidence that the exposure is not exceeded.
- 2) Location compliance: One or more sources of EMF are operational (or planned) and the task is to determine whether human exposure to EMF will be below the specified limits with a given confidence (for a stated set of conditions) in specific locations. The reference conditions typically will be conservative, but the level of conservatism might depend on the probability, extent, and consequence of rare exceedance situations. This might be associated with for example:

- i) Pre installation/market design to establish where an EMF safety program (e.g., IEEE Std C95.7-2014 [B194]) could need to establish controls or signage.
- ii) Post market surveillance checks that relevant exposure limits are not exceeded in the proximity of operational EMF sources.
- 3) Actual EMF exposure: This is where the task is to quantify human exposure to EMF, for specific situations apart from determining compliance with the limits. These evaluations might be for, e.g., medical surveillance, evaluation of control measures or as part of a research task, population studies, legal forensics, etc. The reference conditions should reflect the intended purpose.

Note that regulators may specify constraints on any of the reference conditions and evaluation methodology.

Note also that the reference conditions might constrain the evaluation techniques available. For example, if the reference condition for the evaluation of exposures to low frequency magnetic fields near a transmission line is to determine the maximum possible exposure, then this is not achievable by measurements unless it is possible to derive the exposure under the worst-case condition from the known line loading at the time of measurement. Therefore, an assessment of the maximum possible exposure is likely to involve calculation.

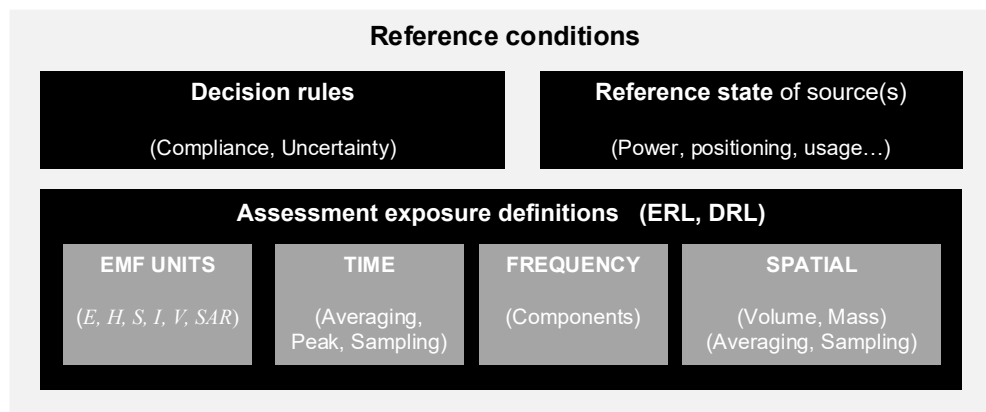


Figure 3—Reference conditions

5.3 Establishing the evaluation methods

5.3.1 Approach to establishing the evaluation method

Evaluation in this standard may be performed by measurement and/or computation. Table A.1 presents the relevant exposure metrics according to frequency range (and limiting health hazard) as specified by IEEE Std C95.1-2019. The exposure metrics are used to find the most relevant information in Annex B (Instrumentation), Annex C (Measurements), Annex D (Computation), Annex F (Case studies), and Annex G (Reference material).

A simple method may also be established where it is considered useful to perform a preliminary evaluation to estimate exposure at potentially relevant locations or where a simple evaluation may be all that is needed to satisfy the task purpose (e.g., low power device or a location at a suitable distance from a source).

5.3.2 Specify the method requirements

5.3.2.1 General approach

Assessment tasks are characterized into the following three general approaches:

- Onsite: This covers cases (e.g., assessment of an installation) where exposure is being evaluated at a specified location or area with one or more sources of EMF. Typically, the assessor has limited or no control of these sources.
- Laboratory: This covers cases (e.g., approval of an equipment under test) where typically the equipment under test and the test environment are both subject to control of the assessor. It includes cases where the EMF exposure is being actively controlled as part of a scientific study. Commonly the evaluation is performed at a specialized test facility.
- Computation: This covers cases where the relevant parameters are determined, and the exposure is estimated by calculation.

Tasks characterized as onsite or laboratory typically imply using measurement while computation implies use of calculations or modeling.

5.3.2.2 Establishing the frequency range of interest

The criteria for inclusion or exclusion of EMF sources within the task should be recorded. For example, the project requirements might call for “specified EMF source(s),” “sources within a specified frequency range,” “sources within a specified physical boundary,” “frequency component field strengths above a stated threshold,” etc.

It should be noted that per some standards and regulations, any source that contributes less than 5% of the relevant limit may be disregarded (see IEC 62232:2017 [B168]). If such criteria are applied, the influence on uncertainty from excluding such exposure contributions should be estimated and considered in the assessment.

If the task definition gives wide bounds for the frequency range (e.g., 100 kHz to 300 GHz), then the frequency range for detailed investigation may be further restricted based on a preliminary study or documentation to identify the frequencies of relevant sources of EMF.

5.3.2.3 Establishing the exposure metrics of interest

Exposure metrics are defined by the selected exposure limits. See Table A.1 for the IEEE Std C95.1-2019 reference sorted by frequency and EMF physical quantity.

When defining the reference conditions, it shall be determined which exposure limits are applicable, based on the frequencies, spatial aspects, and waveform temporal characteristics of the situation under consideration. The selected exposure limit establishes the exposure metric, which includes the EMF physical quantity, temporal and spatial aspects, and frequency sensitivity. While the term “exposure limit” is defined as e.g., DRL or ERL, the quantity EL is a numerical value of an exposure limit obtained from a selected table of DRLs or ERLs. Once the exposure limit is selected, one or more EL_f are calculated for each applicable frequency (f) being evaluated. The EMF physical quantity for the selected exposure limit is defined by its unit of measure. In some cases, there are options for the type of EMF to be evaluated, (such as electric field strength, magnetic field strength or power density), from which a selection should be made. In other cases, more than one type (e.g., electric field strength and magnetic field strength) might be required to be evaluated. Exposure metrics also specify other factors required to perform a complete evaluation. The waveform characteristics (e.g., pulsed or non-sinusoidal EMFs) influence which exposure limits are applicable (see ICNIRP 2003 [B157]), requiring the determination of the characteristics of the waveform(s) under consideration. Exposure metrics might also have spatial or time-average elements. These elements affect how measurements are performed, or how pre/post-processing is implemented to complete the exposure metric evaluation. Proper selection of metric and method is important for efficiently obtaining accurate results.

Individual assessments will vary, and all details of the exposure assessment, reference conditions, evaluation purpose, methods and reporting should be considered during selection of appropriate exposure metrics. Initially, the necessary exposure metrics are determined by the exposure limits that are applicable to the situation. Selecting an exposure metric from among the many specified by safety standards, regulations, or guidelines is challenging. The metrics vary both in their ease of measurement and their precedence when used in judging conformity with the exposure limit. In some cases, there is a choice of exposure metric or of evaluation methodology or of both.

At minimum, the following items should be considered when selecting metrics:

- a) *Simplicity*: DRLs are specified considering electric and magnetic fields inside the human body. Such internal fields are not generally accessible, are not practical to measure directly, and their computation requires application of advanced computation methods and careful interpretation. ERLs are established to simplify verifying conformity with the corresponding DRL. Therefore, assessments with respect to DRL tend to be substantially more complex than with respect to ERL and impractical outside a test facility.
- b) *Reducing the volume close to a source in which a human might be exposed above the limit*: A more involved assessment with respect to a DRL may demonstrate a smaller volume of non-conformity than can be demonstrated using the ERL. DRL metrics take precedence over ERL metrics because ERLs are conservatively derived from the DRLs, which establish the exposure limits in IEEE Std C95.1-2019. In some cases, if a situation is found slightly out of conformity using the ERL, it may be found conformant following a DRL assessment. The evaluation report should outline the reasons for selecting DRL vs. ERL metrics for the assessment and describe the risks and benefits of the recommended choice compared with the alternatives.
- c) *Local and whole-body exposure assessment*: For cases where the source is low power and physically small in relation to the human body, it is likely that the exposure ratio at small source-to-body separations for localized DRL or ERL is higher than for the exposure ratio with respect to whole body DRL or ERL.

- d) *Environmental assessments*:⁹ Measurement or computation of the metrics for environmental fields unperturbed by the human body is often used for purposes of exposure assessment due the practical difficulties in evaluating the DRL metric within the body described in the preceding paragraph. ERLs refer to EMFs measured in the absence of the human body (but usually in locations where it is anticipated that people can access).
- e) *Source characteristics*: The waveform characteristics of the EMF are also relevant to the exposure assessment. EMF exposure is shaped by source characteristics such as antenna patterns, duty factors, modulation, operational cycles, automatic power control, and other factors.
- f) *Frequency range*: The frequency range of interest should be specified to encompass all sources relevant to the evaluation purpose (see 5.2). The frequency range of interest should be determined, preferably by measurement but at least from reliable specifications of the EMF source(s).
- g) *Established Purpose*: The scope of the assessment might be influenced by its purpose. For example, the requirement might be to evaluate only occupational exposure conditions, applying specific regulatory or corporate-policy criteria, evaluating a new installation or device, verifying a prior assessment to provide a more precise evaluation in light of a recent event, etc.

For further information on metrics, see Annex A wherein Table A.1 presents an overview of the exposure limits specified in IEEE Std C95.1-2019 and their relevant exposure metrics.

5.3.2.4 Method uncertainty

An excellent EMF exposure measurement would be both true (close to the real value) and precise (very low spread in the values found by repeated measurements). Collectively, we refer to the trueness and precision as the accuracy of the measurement; neither are perfectly achievable. For example, the calibration of any meter indicates the measurement will not be absolutely true. In conjunction with the other variables in the measurement process the result will be subject to some uncertainty (some of which would be stated on the calibration certificate and in the equipment specifications). The meter response might also have drifted since calibration. Other factors (variations in response with temperature, frequency, and modulation of the EMF source, etc.) also contribute to diminishing accuracy. Correction factors may be applied (to account for known biases in the response) to bring the result closer to the real value, but these factors are themselves subject to some uncertainty and so might decrease the precision. (Such correction factors are best applied when they make a material difference in reducing the combined uncertainty.) When using the measurement instrument, the user relies on information about the uncertainties in these quantities provided by the manufacturer, calibration laboratory and other sources, to determine the combined uncertainty in the result (see Annex E).

Potential exposure estimations using computation methods are also subject to uncertainty. Assumptions about the environment characteristics are necessarily imperfect, as are the computation methods applied to the model (see Annex D).

In practice, for most EMF evaluations, the true value is unknown. Uncertainty is a way to express confidence that the unknown true value lies within a range of values around the indicated value.

Through careful use of an instrument, or application of computational methods, and understanding the factors that affect the accuracy (trueness and precision) of the result, the evaluation can often be refined to reduce uncertainty. This might come at the cost of requiring a longer time to perform the measurement or requiring more sophisticated equipment. The equivalent for a computational evaluation would be adjusting the computation parameters, or providing greater resolution for them, perhaps at the cost of requiring a longer computation time.

⁹ The term “environmental assessment” is used herein in the context of the EMF exposure assessment process. It is not to be confused with the “environmental assessment” process that might be triggered in the USA for facilities not in compliance with environmental regulations.

Depending on the purpose of the EMF assessment and the chosen decision rule (for checking compliance or non-compliance with a limit, see E.5) methods and assumptions may be selected that:

- a) Provide a result that is the best estimate (most likely value) of the measurand (for example, for an environmental assessment, or to test for compliance or non-compliance using the shared-risk approach described in E.5.2);
- b) Have an inherent bias so that the result is higher than the most likely value (for example, when the purpose is to provide a conservative test of compliance with a limit); and
- c) Have an inherent bias so that the result is lower than the most likely value (for example, when the purpose is to provide a conservative test of non-compliance with a limit).

See Table 2 for a summary of this discussion.

If the purpose is to provide a conservative assessment of compliance or non-compliance, a simplified evaluation approach might be appropriate when it is expected that there is ample margin between the actual condition and the applicable limit. For example:

- 1) To provide a conservative test of compliance with a limit, start with screening measurements or computations using methods that err on the side of overstating the maximum exposure. In a measurement survey, scanning a region with an instrument to identify the spatial maximum field value may be sufficient if these spatial peak values comply with the spatial-average limit.
- 2) In a computation, apply simple assumptions that provide results systematically higher than the most likely values (such as assuming continuous transmission for a transmitter that normally operates intermittently).

If the results from a simple evaluation suggest that the limit might be exceeded, then more accurate methods of assessing against an ERL, or assessing against a DRL, may be used to refine the assessment.

If the purpose is to audit a previous evaluation and any inferences made from the results (for example, about compliance or non-compliance with limits), ideally the re-evaluation method (including any biases) should provide greater certainty in the result than the original evaluation.

In general, the evaluation method chosen should be capable of fulfilling the stated purpose as simply as possible, bearing in mind any specific regulatory or operational requirements. This might involve trade-offs between the time to complete or the cost of the assessment and the accuracy of the result: if necessary, these should be discussed with the stakeholders in the process to reach a consensus on the procedure.

See also Annex C on measurement technique, Annex D on computation methods, and Annex E on uncertainty.

In practice, assessors often rely on a favored set of equipment and computation methods. If the task is beyond the available capabilities, the assessor should establish that the client understands the limitations or can be guided towards alternative approaches.