

IEEE Recommended Practice for the Measurement of Potentially Hazardous Electromagnetic Fields—RF and Microwave

Sponsor

IEEE Standards Coordinating Committee 28, on Non-Ionizing Radiation Hazards

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Abstract: IEEE Std C95.3-1991 specifies techniques and instrumentation for the measurement of potentially hazardous electromagnetic fields. The recommendations apply to hazards to personnel. However, the measurement techniques and instruments described are also applicable to the measurement of fields in the neighborhood of flammable materials and explosive devices, even though exposure standards for these situations have not been established.

Keywords: Electromagnetic fields, RF fields, microwave fields, potentially hazardous fields, RF/microwave survey instruments, SAR measurement, RF hazard determination, RF/microwave instrumentation, RF/microwave instrumentation calibration

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Foreword

(This foreword is not a part of IEEE C95.3-1991, IEEE Recommended Practice for the Measurement of Potentially Hazardous Electromagnetic Fields—RF and Microwave.)

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

Prior to 1988, C95 standards were developed by an accredited standards committee C95, and submitted to ANSI for approval and issuance as ANSI C95 standards. Between 1988 and 1990, the committee was converted to Standards Coordinating Committee 28 under the sponsorship of the IEEE Standards Board. In accordance with policies of the IEEE, C95 standards will be issued and developed as IEEE standards, as well as being submitted to ANSI for recognition.

The present scope of IEEE SCC28 is:

“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 SCC28.”

The IEEE Standards Coordinating Committee 28 is responsible for the present revision. There are five subcommittees concerned with:

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

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

IEEE Std C95.1-1991, IEEE Standard for Safety Levels With Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz.

ANSI C95.2-1981, American National Standard Radio Frequency Radiation Hazard Warning Symbol; Reaffirmed in 1989.

ANSI C95.3-1973, IEEE Standard Techniques and Instrumentation for the Measurement of Potentially Hazardous Electromagnetic Radiation at Microwave Frequencies. Reaffirmed in 1979.

IEEE Std C95.3-1991, IEEE Standard Recommended Practice for the Measurement of Potentially Hazardous Electromagnetic Fields—RF and Microwave (replaces ANSI C95.3-1979 and ANSI C95.5-1981).

ANSI C95.4-1978, American National Safety Guide for the Prevention of Radio-Frequency Radiation Hazards in the Use of Electric Blasting Caps.

ANSI C95.5-1981, American National Standard Recommended Practice for the Measurement of Hazardous Electromagnetic Fields—RF and Microwave.

This recommended practice combines and extends the specifications previously set forth in ANSI C95.3-1973 and C95.5-1981. This document includes leakage and near-field measurements and covers lower frequencies than the previous documents. Further, the IEEE Std C95.1-1991, IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz, includes specific absorption rate (SAR) in biological tissues and induced current and contact current associated with exposure to electromagnetic fields as parameters to be measured. Therefore, this recommended practice includes a description of the concepts, techniques and instrumentation that can be applied to the determination of SAR in organisms exposed to electromagnetic fields, and a description of the instrumentation and techniques for measuring induced body current and contact current.

This recommended practice is primarily intended for use by engineers, biophysicists and other specialists who are familiar with electromagnetic (EM) field theory and practice, and the potential hazards associated with exposure to EM fields. It will be especially useful to bioeffects researchers, instrument developers and manufacturers, those developing calibration systems and standards, and individuals involved in critical hazard assessments or surveys. However, the material in Sections 3, 4, and 5 of this document that treats measurement problems, desirable instrument characteristics, and procedures for measuring external fields should be of interest to anyone concerned with EM hazards.

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IEEE Recommended Practice for the Measurement of Potentially Hazardous Electromagnetic Fields—RF and Microwave

1. Scope

1.1 Purpose

The purpose of this recommended practice is to specify techniques and instrumentation for the measurement of potentially hazardous electromagnetic (EM) fields¹ both in the near field and far field of the electromagnetic source. In doing so, this document combines and extends the specifications previously set forth in ANSI C95.3-1973 , and ANSI C95.5-1981 [B2], [B3]. This recommended practice includes leakage and near-field measurements and covers lower frequencies than the two earlier documents. Further, IEEE Std C95.1-1991 [1]² personnel exposure standard includes specific absorption rate (SAR) in biological tissues as a parameter to be measured. Therefore, this document contains a description of the concepts, techniques, and instruments that can be applied to the measurement of SAR or the electric field strength in organisms (including humans) exposed to electromagnetic fields. Below 100 MHz, the current flowing through the body to ground is measurable and can be used to determine the SAR and, therefore, a brief treatment of the low-frequency body current measurement is also included.

This document is intended primarily for use by engineers, biophysicists, and other specialists who are familiar with basic electromagnetic (EM) field theory and practice, and the potential hazards associated with EM fields. It will probably be most useful to bioeffects researchers, instrument developers and manufacturers, those developing calibration systems and standards, and individuals involved in critical hazard assessments or surveys. Interested parties looking for a less technical document describing how to measure potentially hazardous fields may refer to the report of NCRP SC-78 [B96]. However, the material in Sections 3, 4, and 5 of this document that treats measurement problems, desirable instrument characteristics, and procedures for measuring external fields should be of value to anyone concerned with EM hazards.

¹It is beyond the scope of this recommended practice to define what constitutes a hazardous nonionizing electromagnetic field. For the present U.S. Maximum Permissible Exposure Guide, refer to IEEE Std C95.1-1991 . It should be kept in mind that the limits given in these documents are under review and are subject to change as new information becomes available.

²The numbers in brackets correspond to those of the references listed in 1.5 or 1.6.

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

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

1.2 Frequency Range

The techniques and instrumentation specified herein are useful over the frequency range of *approximately* 300 kHz to 100 GHz.³ This frequency range is an extension of that specified in ANSI C95.3-1973 [B2], which pertains only to microwave frequencies, and of that specified in ANSI C95.5-1981 [B3], which extends from 1 MHz to 100 GHz. No single measurement technique or instrumentation arrangement is valid over the wide frequency range covered by this recommended practice. In general, measurement techniques and instrumentation developed for use in the frequency range above about 300 MHz only measure the electric field strength. Magnetic field strength measurements are, however, required to evaluate near field hazardous situations at frequencies below 30 MHz. Here, measurement of both the electric and the magnetic field strength is required within one wavelength of the source. A series of commercially available instruments has been developed for this purpose. For body currents, measurements can be made with simple, portable laboratory instruments over the frequency range of 0 to about 100 MHz. SAR can be measured using RF-transparent temperature sensors over the frequency range of 0 to about 10 GHz. Above this frequency, energy absorption is confined to the surface of a biological system. Thermographic cameras can be used to measure the surface SAR up to about 300 GHz.

1.3 Quantities and Parameters to be Measured

For frequencies above 300 MHz, and for measurements performed at distances from the source greater than a^2/λ with a probe whose dimensions are much less than a , power density (W) is usually a meaningful quantity that has been widely adopted as a hazard indicator (a is the largest dimension of the *effective aperture* of the source, and λ is the wavelength). However, power density is difficult to determine, except in cases of stationary, single-component, plane-wave fields of known polarization. In fact, no existing instrument actually measures power density directly; all measure one or more components of the electric field strength (E), or the magnetic field strength (H), or both, and then infer an equivalent power density from the far-field, plane-wave relationship $W = |E|^2/377$ or $|H|^2 \times 377$ where E is the RMS electric field strength in volts per meter, H is the RMS magnetic field strength in amperes per meter, and W is the power density in watts per meter squared. In the near field, and where scattering, reflections or multiple sources are present, the field configuration can be extremely complex and one must measure both E and H separately.⁴

In many instances, measurements will be required in the reactive or radiating near-field regions⁵ where reactive fields or standing waves exist. Under these more general conditions, the time-average power density is not a reliable hazard

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

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

⁵See definitions in Section 2.

indicator, even if practical probes could be developed for measuring power density. Insofar as hazards are due to energy absorption, the parameters $|E|^2$ and $|H|^2$, or the corresponding energy densities $U_E = (1/2)(\epsilon'|E|^2)$ and $U_H = (1/2)(\mu'|H|^2)$ are more reliable indicators of potential hazards [B124]. Here ϵ' and μ' are, respectively, the real parts of the permittivity ϵ and permeability μ , of the medium, and $|E|$ and $|H|$ are the RMS magnitudes of the electric and magnetic field vectors. The units of energy density are J/m^3 . The advantage of energy density is that the intensities of the electric fields, magnetic fields, and electromagnetic fields can all be expressed in the same units, and energy absorption is conceptually easier to relate to units of energy per unit volume than to $|E|^2$ or $|H|^2$.

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

1.4 Types of Situations Covered

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

1.4.1 External Fields

- 1) Leakage fields
- 2) Radiation fields
- 3) Reactive fields

Leakage situations are generally interpreted as those involving the unintentional emission of RF energy, whereas radiation situations are generally interpreted as those involving equipment designed to intentionally radiate EM energy. Reactive fields are present in the immediate vicinity of the sources of both leakage and radiation fields and tend to be stronger near radiators of small dimensions with respect to wavelength. Multipath interference due to the scattering and reflection of energy from objects or conducting surfaces is an additional complicating factor and is nearly always present to some degree in all of the above situations. Accurate measurements should include procedures for estimating or avoiding multipath effects and near-field measurement errors. Some useful techniques for measurements in multipath environments are given in 4.5.1, 5.3.2, and 5.3.3.

1.4.2 Specific Absorption Rate (SAR).

The need for SAR measurements within models of exposed personnel is twofold. First, SAR is the underlying basis for many recent radio frequency protection guides (RFPGs), including those of IEEE Std C95.1-1991 [1]. It is reasoned that the true initiator of biological effects is the internal electric field strength that leads to the concept of SAR. IEEE Std C95.1-1991 [1] external field strength exposure limits (RFPG) are based on a whole-body-averaged SAR of 0.4 W/kg. In addition, a local (or spatial-peak) SAR of less than 8 W/kg in any gram of tissue in the shape of a cube, is a criterion for exclusion from the RFPG. Generally, accepted methods of measurement of SAR [B97] include the measurement of the rate of temperature rise within the exposed object or the measurement of the internal electric field strength. The temperature rise may be characterized by a whole-body-averaged (calorimetric) measurement, a point measurement (via a thermometer implanted in the body being exposed), or thermographic camera analyses of bisected phantom models that have been exposed to large RF fields. The internal electric field strength may be measured with an implantable E-field probe.

The second need for measuring SAR is that even under far-field plane-wave exposure conditions, the SAR varies widely with frequency and spatial location within an object. Therefore, the measurement of the SAR provides a much-needed

insight into the spatial distribution of absorbed energy, and hence, the true nature of the potential hazard with respect to different organs of the exposed subject.

1.4.3 Measurement Problems for Internal Body Currents

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

1.5 References

This recommended practice should be used in conjunction with the following documents:

- [1] IEEE Std C95.1-1991, IEEE Standard for Safety Levels With Respect to Human Exposure to Radiofrequency Electromagnetic Fields, 3 kHz to 300 GHz.⁶
- [2] IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).
- [3] ANSI/IME 20-1978, Safety Guide for the Prevention of Radio Frequency Radiation Hazards on the Use of Blasting Caps.⁷

1.6 Bibliography

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⁶IEEE publications are available from the Institute of Electrical and Electronics Engineers, Inc., Service Center, 445 Hoes Lane, Piscataway, NJ 08854-1331, U.S.A.

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2. Definitions

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

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

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

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

NOTE — (1) The average radiation intensity is equal to the power radiated by the antenna divided by 4π .

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

NOTES:

- 1 — A plane wave of given power density and from a given direction is polarization-matched to an antenna if its polarization is that which results in maximum power at the antenna terminals.
- 2 — The (total) effective aperture of an antenna may be decomposed into the sum of two partial effective apertures referred to two specified, orthogonal polarizations, respectively.
- 3 — For a lossless and perfectly matched antenna, effective area in a given direction is equal to the square of the operating wavelength, times the gain in that direction, divided by 4π .

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

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

NOTES:

- 1 — Gain does not include losses arising from impedance and polarization mismatches.
- 2 — The radiation intensity corresponding to the isotropically radiated power is equal to the power accepted by the antenna divided by 4π .
- 3 — If an antenna is without dissipative loss, then in any given direction, its gain is equal to its directivity.
- 4 — If the direction is not specified, the direction of maximum radiation intensity is implied.

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

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

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

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

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

NOTES:

- 1 — The distribution can be expressed as a mathematical function or as a graphic representation.
- 2 — The quantities that are most often used to characterize the radiation from an antenna are proportional to or equal to, power density, radiation intensity, directivity, phase, polarization and field strength.
- 3 — The spatial distribution of the EM field characteristics over any surface is also an antenna pattern.
- 4 — When the amplitude or relative amplitude of a specified component of the electric field vector is plotted graphically, it is called the amplitude pattern, field pattern or voltage pattern. When the square of the amplitude or relative amplitude is plotted, it is called a power pattern.

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

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

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

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

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

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

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

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

average power density: The instantaneous power density integrated over a source repetition period.

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

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

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

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

conductivity: The ratio of the electric field strength in a medium to the conduction-current density.

dielectric constant: See: **permittivity**

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

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

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

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

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

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

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

effective aperture: See: **antenna effective aperture**

effective area: See: **antenna effective aperture**

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

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

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

electric field strength (E):

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

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

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

electric flux density (displacement): A vector equal to the product of the electric field strength and the permittivity of the medium. In an anisotropic medium, the permittivity is a function of direction; hence, the electric flux density is not necessarily in the same direction as the electric field strength. Electric flux density can be considered as a surface charge density and is expressed in units of coulombs per square meter (C/m²).

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

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

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

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

energy density (electromagnetic field): The EM field energy contained in a given infinitesimal volume divided by that volume. Energy density is expressed in units of joules per cubic meter (J/m³).

NOTES:

- 1 — The term energy density may be used with modifiers such as instantaneous, maximum, and peak.
- 2 — In speaking of average energy density in general, it is necessary to distinguish between the space average (at a given instant) and the time average (at a given point).

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

$$W = |E|^2/377 = |H|^2 \times 377$$

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

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.

horn radiator: *See:* **horn antenna**

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

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

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

intrinsic impedance (of free space): The ratio of the electric field strength to the magnetic field strength of a propagating electromagnetic wave. The intrinsic impedance of a plane wave in free space is approximately 377 ohms.

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

isotropic: Having the same properties in all directions.

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

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

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

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

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

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

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

magnetic flux density (magnetic induction): The vector quantity D_{CL132} producing a torque T_{macr} ; (in Joules) on a plane current loop in accordance with the relation $D_{CL133} = I A D_{CL134} \times D_{CL132}$, where D_{CL134} is the positive unit vector normal to the loop, A is its area in m^2 and I is its current in amperes. Magnetic flux density is expressed in units of tesla (T), formerly webers per square meter.

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

NOTE — The Maximum Normalized Field Strength concept is used to aid in the assessment of the relationship between exposure of an object to external near-fields and the resulting internal SAR.

maximum permissible exposure (MPE): The RMS and peak electric and magnetic field strengths, their squares or the plane-wave equivalent power densities associated with these fields and the induced and contact currents to which a person may be exposed without harmful effect and with an acceptable safety factor. *See:* **radio frequency protection guide**

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

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

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

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

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

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

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

nonthermal effect: *See:* **athermal effect**

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

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

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

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

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

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

permittivity (complex): The properties of a dielectric material or biological tissues, which are frequency dependent.

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

NOTE — In general, the figure is elliptical and it is traced in a clockwise or counterclockwise sense. The commonly referenced circular and linear polarizations are obtained when the ellipse becomes a circle or a straight line, respectively. Clockwise

sense rotation of the electric vector is designated right-hand polarization and counterclockwise sense rotation is designated left-hand polarization.

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

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

power gain: Of an amplifying device, the ratio of the RF power delivered to a specified load impedance to the RF power absorbed by its input. Of an antenna, *see:* **antenna gain**

NOTE — Power gain is usually expressed in decibels.

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

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

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

probe-length (probe antenna-length): The maximum physical dimension of the antenna of a near-field probe, or the dimension of the largest antenna in a multiple array.

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

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

pulsed RF: A continuous-wave RF carrier signal that is amplitude-modulated at a known PRF with a controlled duty factor.

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

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

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

radio frequency protection guide (RFPG): The RMS electric and magnetic field strength, their squares, or the plane-wave equivalent power density associated with these fields to which a person may be exposed without harmful effect. *See:* **maximum permissible exposure**

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

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

radio frequency (RF): A frequency that is useful for radio transmission.

NOTE — The present practicable limits of radio frequency are roughly 10 kHz to 300 GHz.

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

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.

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 structures or antennas.

Reradiated fields are sometimes called “reflected” or, more correctly “scattered fields.” The scattering object is sometimes called a “reradiator” or “secondary radiator.” See: **reradiator**

reradiator, passive or parasitic: Electrically conducting structures that, when illuminated by a primary RF source or ambient electromagnetic fields, act as a secondary radiating source because of currents induced in the structure. In some cases, reradiators can produce localized EM fields significantly more intense than the fields at the location of the reradiator that are associated with the prime source.

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.

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

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

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

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

NOTES:

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

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

where:

σ = conductivity of the tissue (S/m)
 ρ = mass density of the tissue (kg/m³)
 E = Total RMS electric field strength (V/m)

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

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

where:

ΔT = change in temperature (°C)
 Δt = duration of exposure (seconds)
 c = specific heat capacity (J kg⁻¹ degree C⁻¹)

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

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

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

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.

time averaged power density: The average power density integrated over the longest source period. This period can be as a result of rotational or directional characteristics of the source. Units of this quantity are W/m².

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

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

3. The Measurement Problems of Radio Frequency (RF) Hazard Determination

3.1 Characteristics of RF Electromagnetic (EM) Radiation

3.1.1 Parameters Determined by the Source

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

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

3.1.2 Interference Patterns

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

Scanning sources, such as radars and other sources that operate intermittently, introduce time variations with their own interference patterns. Planning of measurement programs should take into account both spatial and time variabilities. That need is important from both the viewpoints of collecting all data pertinent to the objective and ensuring that the personnel are protected from excessive exposure.

3.1.3 Radiation Leakage

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

A completely general theoretical treatment of the leakage problem is very difficult and is beyond the scope of this recommended practice. The survey techniques differ from those associated with the radiation fields from antennas. In the leakage case, the location of the source is generally found by trial and error. A nondirectional, nonpolarized “isotropic” detector is generally desirable in order to probe in the immediate vicinity of the equipment where directive

pickup antennas would give inaccurate readings because of their inability to respond to multi-path signals and because of inaccurately known gain-reduction factors in their near field. However, at microwave frequencies, a somewhat directive system consisting of a small horn or waveguide probe, thermistor, attenuator, and power meter is easy to assemble, and may be useful for locating a source of leakage when accurate knowledge of the level is not required. However, both the vertical and horizontal polarization components should be measured separately by rotating the probe 90° about its axis of propagation.

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

3.1.4 Reactive Near Field

The reactive near field is the region close to the radiation source where energy storage fields are important. In this region of space immediately surrounding the leakage source or antenna, reactive components of the field predominate over the radiating near-field and radiating far-field components. Reactive fields can be inductive (low E/H ratio) or capacitive (high E/H ratio) in nature, and either type of field can predominate. The characteristics of reactive fields relate to the inductance and capacitance of the radiating structure. Part of the associated electromagnetic energy is stored, i.e., it is not propagated beyond the near-field region. This stored energy is transferred periodically between the radiating structure and the near field. Although the extent of the reactive region varies for different equipment, the practical outer limit is of the order of a few wavelengths. For example, at a distance of between two and three wavelengths from an ideal dipole, all reactive components are less than 10% of the radiating components. Although the reactive components do not contribute to the net flow of radiated energy, they can couple into biological or other material, and thus affect energy absorption. Consequently, for many hazard assessments it is important that the reactive fields be measured using the appropriate instrumentation and measurement techniques (see 5.3). Furthermore, both the electric and the magnetic fields should be measured to fully evaluate the hazard, since both contribute to the induced SAR in biological objects [B88].

3.1.5 Passive, Parasitic or Secondary Reradiators

Conducting objects that are illuminated by RF energy, either in the near or the far field of a primary source, are termed passive or parasitic reradiators. High E- and/or H-fields (with respect to ambient RF fields) can usually be measured in close proximity to a reradiator. These are generally reactive fields that decay rapidly with distance, as discussed in 3.1.4. A passive reradiator can theoretically and physically be replaced by an equivalent transmitting antenna (reciprocity) because an antenna has the same field pattern whether it is transmitting or receiving. The magnitude of the near and far fields produced by a reradiator depends on the RF currents induced in it by the primary source. The size and orientation (with respect to the primary source) also determine the magnitude of the induced currents and, hence, the local fields.

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

There are virtually no data in the literature that relate to the SAR induced in a person exposed to the near fields of a passive reradiator. In spite of this fact, near-field theory, antenna theory, and published dosimetric data associated with active radiators can be utilized to draw some general conclusions. Personnel hazards due to passive reradiators are

“reduced” or “enhanced” with respect to exposure to plane waves of equal maximum normalized field strength. Caution should be exercised when interpreting so-called, localized “hot spots” caused by reradiating objects since the amount of energy that may be coupled to an individual contacting the radiator may be very small, despite the existence of relatively high-surface field strengths. Further discussion of this subject appears in 5.6.

3.1.6 Other Considerations

In the near field, three orthogonal components of the electric field with arbitrary relative phases and amplitudes exist. Similarly, there are three orthogonal components of the magnetic field with arbitrary phases and amplitudes.

The electric field is elliptically polarized in an arbitrary plane and the magnetic field, in general, is elliptically polarized in another plane. Consequently, in the near field, measurements of the phase and amplitude of each of the three components of the electric (magnetic) field generally provide no information about the magnetic (electric) field at the same point. Thus, use of instruments capable of measuring either the electric or the magnetic field, and that respond simultaneously to all polarizations is indicated. Field measurement devices utilizing three orthogonal dipoles or loops that detect the amplitude, but not the phase of the electric or magnetic field, cannot provide complete information about the elliptically polarized field. Specifically, the maximum instantaneous field vector is not measured with these types of devices. Only an *averaged* total field strength is measured, with the averaging occurring over one cycle of the oscillation of the field (the carrier frequency). Currently available hazard instrumentation does not provide both phase and amplitude measurement capability. This means that power density is not actually measured under these circumstances even when power density is the measure displayed, but is only inferred from measurements of $|E|^2$ and $|H|^2$.

When characterizing hazardous EM fields, a distinction should be recognized between emission levels and exposure levels. An emission standard specifies the maximum field strength or power density at a specified (usually small) distance from an emitting source; an exposure standard generally specifies the maximum field strength or power density to which personnel should be exposed as a function of exposure duration. In most cases where an emission standard applies, the sources are small apertures, e.g., localized leakage around the periphery of a microwave oven door. In these situations the radiated fields follow approximately an inverse-square law reduction of power density with distance or an inverse dependence of field strength with distance. Such inverse-distance dependence has been verified for leakage emission from microwave ovens for distances of 5 cm to several feet. The rapid decay from permissible emission levels to acceptable exposure levels at a distance of several feet from the typical microwave oven may not apply if the leakage source consists of a large radiating aperture (for example, a *leaking* viewing window).

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

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

3.2 Summary of the Measurement Problem

3.2.1 External Field Measurement Problems

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

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

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

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

3.2.2 Problems of Time and Spatial Averaging

Many RFPGs⁸, including that of IEEE Std C95.1-1991 [1], specify the maximum permissible values of the RF field strength or power density as averaged over a specified averaging time, e.g., any continuous 6-min interval. If, for example, RF exposure in the VHF band is considered, a maximum time-averaged power density of 1 mW/cm² is permitted. The time-averaging provision of the RFPG permits higher exposure values if the exposure time is reduced to less than 6 min. Another way of expressing this is:

$$W \text{ (mW/cm}^2\text{)} \cdot t \text{ (min)} \leq 6 \text{ mW} \cdot \text{min/cm}^2$$

Thus, for example, if the exposure duration is only 3 min, a maximum power density of 2 mW/cm² is permitted. Figure 3.1 illustrates the application of the time-averaging provision of the RFPG. In Fig 3.1a the time-averaged exposure value is 6 mW-min/cm² in both periods 1 and 2. During the remainder of the illustrated 6-min period, no exposure is allowed in order to keep the time-averaged value from exceeding 6 mW-min/cm². In reality, RF exposures usually vary continuously with time due to source characteristics or movement of the individual within the RF exposure field. This is represented by Fig 3.1b, where the area under the curve within any 6-min window of time does not exceed 6 mW-min/cm². The time-averaging feature of the RFPG may introduce substantial complications in determination of compliance, depending upon the particular exposure situation. Assessing time-averaged RF exposures in some complex environments may be accomplished accurately only through the use of instrumentation designed to acquire and average the real-time variations in the measured field strengths [B10]. Such measurements may be performed with portable datalogging devices adapted to the averaging time of the RFPG [B120]. In less complicated exposure environments, such as when the RF exposure is intermittent, but not otherwise varying in level, the use of strip-chart recorders connected to the recorder output of a broadband RF field-strength meter may suffice for determining the time-averaged exposure values.

The assessment of RF fields that vary substantially with location also presents a problem when attempting to specify whole-body average exposure levels. In this case, the same approach employed for the measurement of time-averaged exposure levels may be used successfully. For example, [B120] describes a measurement technique using a data-logging device wherein a uniform velocity scan is performed for a vertical planar scan of space and the resulting value of RF exposure, averaged over the total planar scanning time is equivalent to the spatial average of the RF field. The use of spatial averaging of fields provides a more meaningful description of the exposure, particularly in areas where extremely localized and high intensity fields may exist, but where only limited exposure of the body actually occurs.

⁸Radio frequency protection guide (RFPG), used in ANSI C95.1-1982 to describe exposure limits of field strengths and equivalent power density, was changed to *maximum permissible exposure* (MPE) in IEEE Std C95.1-1991, the revision of ANSI C95.1-1982.