IEEE Std C95.1, 1999 Edition
(Incorporating IEEE Std C95.1-1991 and
IEEE Std C95.1a-1998)

IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz

Sponsor

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

Approved 8 December 1998

IEEE-SA Standards Board

Abstract: IEEE C95.1-1991 gives recommendations to prevent harmful effects in human beings exposed to electromagnetic fields in the frequency range from 3 kHz to 300 GHz. The recommendations are intended to apply to exposures in controlled, as well as uncontrolled, environments. They are not intended to apply to the purposeful exposure of patients under the direction of practitioners of the healing arts. The induced and contact current limits of IEEE C95.1-1991 are modified in this edition. In addition, field strengths below which induced and contact currents do not have to be measured are specified, spatial averaging and measurement distance requirements are clarified, and more precise definitions for averaging volume and radiated power are provided.
Keywords: electromagnetic fields, exposure limits, microwave and radio frequency safety, nonionizing radiation protection, safety levels

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Introduction

(This introduction is not part of IEEE Std C95.1, 1999 Edition, IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz.)

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

Prior to 1988, C95 standards were developed by Accredited Standards Committee C95 (ASC 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 (SCC 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 SCC 28 is the

> "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 SCC 28."

The IEEE SCC 28 is responsible for this standard. There are five subcommittees concerned with

I Techniques, Procedures, and Instrumentation

II Terminology, Units of Measurements, and Hazard Communication

III Safety Levels with Respect to Human Exposure, 0–3 kHz

IV Safety Levels with Respect to Human Exposure, 3 kHz–300 GHz

V Safety Levels with Respect to Electro-Explosive Devices

Two standards, two guides, and three recommended practices have been issued. Current versions are

IEEE Std C95.1-1991 (Reaff 1997), IEEE Standard Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz. (Replaces ANSI C95.1-1982.)

ANSI C95.2-1982 (Reaff 1988), American National Standard Radio Frequency Radiation Hazard Warning Symbol.

IEEE Std C95.3-1991 (Reaff 1997), IEEE Recommended Practice for the Measurement of Potentially Hazardous Electromagnetic Fields - RF and Microwave. (Replaces ANSI C95.3-1973 and ANSI C95.5-1981.)

ANSI C95.3-1973 (Reaff 1979), American National Standard Techniques and Instrumentation for the Measurement of Potentially Hazardous Electromagnetic Fields—RF and Microwave.

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

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

ANSI C95.4-1971, American National Standard Safety Guide for the Prevention of Radio-Frequency Radiation Hazards in the Use of Electric Blasting Caps.

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Changes in the 1991 revision of C95.1 include an expanded frequency range, limits on induced body current to prevent radio-frequency (RF) shock or burn, a relaxation of limits on exposure to magnetic fields at low frequencies, and exposure limits and averaging time at high frequencies that are compatible at 300 GHz with existing infrared maximum-permissible exposure (MPE) limits. Important improvements in rules for valid measurement of electromagnetic fields have been introduced, and expanded rules for relaxing the exposure limits for the case of partial body exposure have been developed. Also, a distinction is made between controlled and uncontrolled environments relative to safe exposure limits.

IEEE C95.1-1991 prescribes MPEs to prevent biological injury from exposure to electromagnetic radiation. Revisions of the original version of this standard (ANSI C95.1-1966) were made in 1974 and major revisions of ANSI C95.1-1974 were made in 1982 to take into account the significant expansion of the database, improvements in dosimetry, and the increasing number of people in the general population exposed to RF fields. The changes in the standard included a wider frequency coverage, frequency dependence resulting from the recognition of whole-body resonance and incorporation of dosimetry. In addition to those changes, the present standard also includes a distinction between controlled and uncontrolled environments and guidelines for partial-body and near-field exposures. Exposure limits in the uncontrolled environment are lower than in the controlled environment under certain conditions, such as resonance, or when exposure is complicated by associated hazards like RF shock or burn.

IEEE C95.1-1991 contains a detailed discussion of both the rationale and the limitations of the recommended guidelines based on the present database.

IEEE C95.1-1991 was reaffirmed in 1997 and is now undergoing revision. Several issues approved by SCC 28 for the next revision were deemed sufficiently important by the committee to warrant a supplement before the entire revision is completed. IEEE C95.1a-1998 was approved as a supplement to IEEE C95.1-1991. This supplement was incorporated into the text of IEEE C95.1-1991 to create IEEE C95.1, 1999 Edition. This edition modifies the induced and grasping-contact current limits specified in IEEE C95.1-1991, specifies electric field strength below which induced and contact currents do not have to be determined, modifies measurement distance requirements, and provides more precise definitions for spatial averaging, averaging volume, and radiated power as applied to hand-held wireless devices.

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Participants

IEEE Std C95.1-1991 was prepared by Subcommittee IV on Safety Levels with Respect to Human Exposure, 3 kHz to 300 GHz, of IEEE Standards Coordinating Committee 28, and had the following membership at the time the standard was prepared:

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IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz

1. Overview

1.1 Scope

Recommendations are made to prevent harmful effects in human beings exposed to electromagnetic fields in the frequency range from 3 kHz to 300 GHz. These recommendations are intended to apply to exposures in controlled, as well as uncontrolled, environments. These recommendations are not intended to apply to the purposeful exposure of patients by, or under the direction of, practitioners of the healing arts. The recommendations at 300 GHz are compatible with existing recommendations on safe exposure in the infrared frequency range (starting at 300 GHz). See ANSI Z136.1-1993 [B2].[1]

1.2 Purpose

This edition is meant to address certain ambiguities in IEEE Std C95.1-1991 and to reflect a more complete understanding of the effects of currents induced in the body from exposure to radio frequency (RF) electromagnetic fields or from grasping conducting objects that are exposed to RF fields.

2. References

This standard shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.

IEEE Std C95.3-1991, IEEE Recommended Practice for the Measurement of Potentially Hazardous Electromagnetic Fields—RF and Microwave.[2]

IEEE Std 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms.

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[1]The numbers in brackets correspond to those of the bibliography in Annex A.

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

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3. Definitions

For the purposes of this standard, the following terms and definitions apply. IEEE Std 100-1996 should be referenced for terms not defined in this clause.

3.1 average (temporal) power (P_{avg}): The time-averaged rate of energy transfer.

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

where

$P(t)$ is the instantaneous power,

t_1 is the initial time,

t_2 is the final time of the interval over which $P(t)$ is averaged.

3.2 averaging time (T_{avg}): The appropriate time period over which exposure is averaged for purposes of determining compliance with a maximum permissible exposure (MPE). For exposure durations less than the averaging time, the maximum exposure, *MPE*', in any time interval equal to the averaging time is found from

$$MPE' = MPE\left(\frac{T_{avg}}{T_{exp}}\right)$$

where

T_{exp} is the exposure duration in that interval expressed in the same units as T_{avg}. (Restrictions on peak power density limit T_{exp}.)

3.3 continuous exposure: Exposure for durations exceeding the corresponding averaging time. Exposure for less than the averaging time is called *short-term exposure*.

3.4 controlled environment: Location where there is exposure that may be incurred by persons who are aware of the potential for exposure as a concomitant of employment, by other cognizant persons, or as the incidental result of transient passage through areas where analysis shows the exposure levels may be above those shown in Table 2 but do not exceed those in Table 1, and where the induced currents may exceed the values in Table 2, Part B, but do not exceed the values in Table 1, Part B.[3]

3.5 duty factor: The ratio of pulse duration to the pulse period of a periodic pulse train. A duty factor of 1.0 corresponds to continuous-wave (CW) operation.

3.6 electric field strength (E): A field vector quantity that represents the force (F) on a positive test charge (q) at a point divided by the charge.

$$\boldsymbol{E} = \frac{\boldsymbol{F}}{q}$$

Electric field strength is expressed in units of volts per meter (V/m).

[3]The means for the identification of these areas is at the discretion of the operator of a source.

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3.7 energy density (electromagnetic field): The electromagnetic energy contained in an infinitesimal volume divided by that volume.

3.8 exposure: The subjection of a person to electric, magnetic, or electromagnetic fields or to contact currents other than those originating from physiological processes in the body and other natural phenomena.

3.9 exposure, partial-body: Exposure that results when RF fields are substantially nonuniform over the body. Fields that are nonuniform over volumes comparable to the human body may occur due to highly directional sources, standing-waves, re-radiating sources, or in the near field region of a radiating structure. *See* **RF "hot spot."**

3.10 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 uniform distributions of electric field strength and magnetic field strength in planes transverse to the direction of propagation.

3.11 hertz (Hz): The unit for expressing frequency, *f*. One hertz equals one cycle per second.

3.12 magnetic field strength (*H*): A field vector that is equal to the magnetic flux density divided by the permeability of the medium. Magnetic field strength is expressed in units of amperes per meter (A/m).

3.13 magnetic flux density (*B*): A field vector quantity that results in a force (***F***) that acts on a moving charge or charges. The vector product of the velocity (***v***) at which an infinitesimal unit test charge, q, is moving with ***B***, is the force that acts on the test charge divided by q.

$$\frac{\boldsymbol{F}}{q} = (\boldsymbol{v} \times \boldsymbol{B})$$

Magnetic flux density is expressed in units of tesla (T). One tesla is equal to 10^4 gauss (G).

3.14 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.

3.15 mixed frequency fields: The superposition of two or more electromagnetic fields of differing frequency.

3.16 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, but vary considerably from point to point. The near-field region is further subdivided into the reactive near-field region, which is closest to the radiating structure and that contains most or nearly all of the stored energy, and the radiating near-field region where the radiation field predominates over the reactive field, but lacks substantial plane-wave character and is complicated in structure.

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

3.17 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 $1/e$ (~36.8%) of the boundary values.

3.18 power density, average (temporal): The instantaneous power density integrated over a source repetition period.

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3.19 power density (*S*): Power per unit area normal to the direction of propagation, usually expressed in units of watts per square meter (W/m^2) or, for convenience, units such as milliwatts per square centimeter (mW/cm^2) or microwatts per square centimeter ($\mu W/cm^2$). For plane waves, power density, electric field strength (E), and magnetic field strength (H) are related by the impedance of free space, i.e., 377 Ω. In particular,

$$S = \frac{E^2}{377} = 377H^2$$

where E and H are expressed in units of V/m and A/m, respectively, and S in units of W/m^2. Although many survey instruments indicate power density units, the actual quantities measured are E or E^2 or H or H^2.

3.20 power density, peak: The maximum instantaneous power density occurring when power is transmitted.

3.21 power density, plane-wave equivalent: A commonly used term associated with any electromagnetic wave, equal in magnitude to the power density of a plane wave having the same electric (E) or magnetic (H) field strength.

3.22 pulse modulated field: An electromagnetic field produced by the amplitude modulation of a continuous wave carrier by one or more pulses.

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

NOTE—Although the RF spectrum is formally defined in terms of frequency as extending from 0 to 3000 GHz, for purposes of this standard, the frequency range of interest is 3 kHz to 300 GHz.

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

3.25 RF "hot spot": A highly localized area of relatively more intense radio-frequency radiation that manifests itself in two principal ways:

a) The presence of intense electric or magnetic fields immediately adjacent to conductive objects that are immersed in lower intensity ambient fields (often referred to as re-radiation), and

b) Localized areas, not necessarily immediately close to conductive objects, in which there exists a concentration of radio-frequency fields caused by reflections and/or narrow beams produced by high-gain radiating antennas or other highly directional sources. In both cases, the fields are characterized by very rapid changes in field strength with distance.

RF hot spots are normally associated with very nonuniform exposure of the body (partial body exposure). This is *not* to be confused with an actual thermal hot spot within the absorbing body.

3.26 root-mean-square (rms): The effective value, or the value associated with joule heating, of a periodic electromagnetic wave. The rms value is obtained by taking the square root of the mean of the squared value of a function.

3.27 scattered radiation: An electromagnetic field resulting from currents induced in a secondary, conducting or dielectric object by electromagnetic waves incident on that object from one or more primary sources.

3.28 short-term exposure: Exposure for durations less than the corresponding averaging time.

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3.29 spatial average: The root mean square of the field over an area equivalent to the vertical cross section of the adult human body, as applied to the measurement of electric or magnetic fields in the assessment of whole-body exposure. The spatial average is measured by scanning (with a suitable measurement probe) a planar area equivalent to the area occupied by a standing adult human (projected area). In most instances, a simple vertical, linear scan of the fields over a 2 meter height (approximately 6 feet), through the center of the projected area, will be sufficient for determining compliance with the maximum permissible exposures (MPEs).

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

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

The specific absorption is expressed in units of joules per kilogram (J/kg).

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

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

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

3.32 uncontrolled environment: Locations where there is the exposure of individuals who have no knowledge or control of their exposure.

NOTE—The exposures may occur in living quarters or workplaces where there are no expectations that the exposure levels may exceed those shown in Table 2 and where the induced currents do not exceed those in Table 2, Part B. Transitory exposures are treated in 4.1.1.

3.33 wavelength (λ): Of a monochromatic wave, the distance between two points of corresponding phase of two consecutive cycles in the direction of propagation. The wavelength (λ) of an electromagnetic wave is related to the frequency (f) and velocity (v) by the expression $v = f\lambda$. In free space the velocity of an electromagnetic wave is equal to the speed of light, i.e., approximately 3×10^8 m/s.

4. Recommendations

4.1 Maximum permissible exposure (MPE)

4.1.1 MPE in controlled environments

For human exposure in controlled environments to electromagnetic energy at radio frequencies from 3 kHz to 300 GHz, the MPE, in terms of rms electric (E) and magnetic (H) field strengths, the equivalent plane-wave free-space power densities (S) and the induced currents (I) in the body that can be associated with exposure to such fields or contact with objects exposed to such fields, is given in Table 1 as a function of frequency. Exposure associated with a controlled environment includes exposure that may be incurred by persons who are aware of the potential for exposure as a concomitant of employment, exposure of other cognizant individuals, or exposure that is the incidental result of passage through areas where analysis shows the exposure levels may be above those shown in Table 2, but do not exceed those in Table 1, and where the induced currents may exceed the values in Table 2, Part B, but do not exceed the values in Table 1, Part B.[4]

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Table 1—Maximum permissible exposure for controlled environments*

Part A: Electromagnetic fields†				
Frequency range (MHz) **1**	**Electric field strength (*E*) (V/m)** **2**	**Magnetic field strength (*H*) (A/m)** **3**	**Power density (*S*) E-field, H-field (mW/cm^2)** **4**	**Averaging time $\|E\|^2$, $\|H\|^2$ or *S* (min)** **5**
0.003–0.1	614	163	(100, 1 000 000)‡	6
0.1–3.0	614	$16.3 / f$	$(100, 10\,000 / f^2)$‡	6
3–30	$1842 / f$	$16.3 / f$	$(900 / f^2, 10\,000 / f^2)$	6
30–100	61.4	$16.3 / f$	$(1.0, 10\,000 / f^2)$	6
100–300	61.4	0.163	1.0	6
300–3000	—	—	$f / 300$	6
3000–15 000	—	—	10	6
15 000–300 000	—	—	10	$616\,000 / f^{1.2}$
Note—*f* is the frequency in MHz.				

*See Figure E.1 and Figure E.2 for graphical depictions of MPEs.
†The exposure values in terms of electric and magnetic field strengths are the mean values obtained by spatially averaging the squares of the fields over an area equivalent to the vertical cross section of the human body (projected area).
‡These plane-wave equivalent power density values, although not appropriate for near-field conditions, are commonly used as a convenient comparison with MPEs at higher frequencies and are displayed on some instruments in use.

Part B: Induced and contact radio frequency currents*			
Frequency range (MHz)	**Maximum current (mA)**		**Contact**
	Through both feet	**Through each foot**	
0.003–0.1	$2000 f$	$1000 f$	$1000 f$
0.1–100	200	100	100
Note—*f* is the frequency in MHz.			

*It should be noted that the current limits given above may not adequately protect against startle reactions and burns caused by transient discharges when contacting an energized object. (See text for additional comment and see Figure E.3 for a graphical depiction.)

a) In a controlled environment, access should be restricted to limit the rms RF body current (averaged over the appropriate averaging time) as follows:
   1) For freestanding individuals (no contact with metallic objects), RF current induced in the human body, as measured through each foot, should not exceed the following values:

[4]The means for the identification of these areas is at the discretion of the operator of a source.

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$\bar{I} = 1000f$ mA (for $0.003 < f \leq 0.1$ MHz)

where

$\bar{I}$ is the average over any 1 second period,

f is the frequency in MHz.

$\tilde{I} = 100$ mA (for $0.1 < f < 100$ MHz) subject to a ceiling limit of 500 mA

where

$\tilde{I}$ is the rms current during any 6 minute period.

2) For conditions of possible contact with metallic bodies, where making or breaking the contact does not result in any momentary spark discharge or high skin-surface current density causing startle reaction, pain, burns, or other skin injury, maximum RF currents through an impedance equivalent to that of the human body for conditions of grasping contact [see item (a) of 4.3] as measured with a contact current meter shall not exceed the following values:

$\bar{I} = 1000f$ mA (for $0.003 < f \leq 0.1$ MHz)

where

$\bar{I}$ is the average over any 1 second period,

f is the frequency in MHz.

$\tilde{I} = 100$ mA (for $0.1 < f < 100$ MHz) subject to a ceiling limit of 500 mA

where $\tilde{I}$ is the rms current during any 6 minute period.

$$\bar{I} \equiv \frac{1}{T}\int_0^T |I|\ \mathrm{dt} \qquad (f \leq 100\ \mathrm{kHz},\ T = 1\ \mathrm{s})$$

and

$$\tilde{I} \equiv \left[\frac{1}{T}\int_0^T I^2\ \mathrm{dt}\right]^{\frac{1}{2}} \qquad (f > 100\ \mathrm{kHz},\ T = 360\ \mathrm{s})$$

The means for complying with this current limit can be determined by the user of the MPE as appropriate. The use of protective gloves, the prohibition of metallic objects, or training of personnel may be sufficient to assure compliance with this aspect of the MPE in controlled environments.

3) Induced current measurements are not required if the spatially averaged electric field strength does not exceed the MPE at frequencies of 0.45 MHz or less and does not exceed the limits shown in Figure E.6 at frequencies greater than 0.45 MHz.

b) The MPEs refer to exposure values obtained by spatially averaging the squares of the fields over an area equivalent to the vertical cross section of the human body (projected area). In the case of partial-body exposure, the MPEs can be relaxed as described in 4.4. In nonuniform fields, spatial peak values of field strengths may exceed the MPEs if the spatially averaged value remains within the specified limits. The MPEs may also be relaxed by reference to SAR limits in 4.2.1 by appropriate calculations or measurements.

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c) The MPE refers to values averaged over any 6 minute period for frequencies less than 15 GHz and over shorter periods for higher frequencies down to 10 s at 300 GHz, as indicated in Table 1.

d) For near-field exposures at frequencies less than 300 MHz, the applicable MPE is in terms of rms electric and magnetic field strength, as given in Table 1, columns 2 and 3. For convenience, the MPE may be expressed as equivalent plane-wave power density, given in Table 1, column 4.

e) For mixed or broadband fields at a number of frequencies for which there are different values of the MPE, the fraction of the MPE [in terms of E^2, H^2, or power density (S)] incurred within each frequency interval should be determined and the sum of all such fractions should not exceed unity. See Annex D for an example of how this is accomplished.

In a similar manner, for mixed or broadband induced currents at a number of frequencies for which there are different values of the MPE, the fraction of the induced current limits (in terms of I^2) incurred within each frequency interval should be determined, and the sum of all such fractions should not exceed unity.

f) For exposures to pulsed radio frequency fields, in the range of 0.1 to 300 000 MHz, the peak (temporal) value of the MPE in terms of E field is 100 kV/m.

g) For exposures to pulsed radio frequency fields of pulse durations less than 100 milliseconds and frequencies in the range of 0.1 to 300 000 MHz, the MPE, in terms of peak power density for a single pulse, is given by the MPE (Table 1, E-field equivalent power density) multiplied by the averaging time in seconds and divided by 5 times the pulse width in seconds. That is

$$Peak\ MPE = \frac{MPE \times Avg\ Time\ (\text{seconds})}{5 \times Pulsewidth\ (\text{seconds})}$$

A maximum of five such pulses, with a pulse-repetition period of at least 100 ms, is permitted during any period equal to the averaging time [see item (c) of 4.1.1]. If there are more than five pulses during any period equal to the averaging time, or if the pulse durations are greater than 100 ms, normal averaging-time calculations apply, except that during any 100 ms period, the energy density is limited per the above formula, viz

$$\Sigma Peak\ MPE \times Pulsewidth\ (\text{seconds}) = \frac{MPE \times Avg\ Time\ (\text{seconds})}{5}$$

4.1.2 MPE in uncontrolled environments

For human exposure in uncontrolled environments to electromagnetic energy at radio frequencies from 3 kHz to 300 GHz, the MPE, in terms of rms electric (E) and magnetic (H) field strengths, the equivalent plane-wave free-space power densities (S) and the induced currents (I) in the body that can be associated with exposure to such fields or contact with objects exposed to such fields are given in Table 2 as a function of frequency.

Exposure associated with an uncontrolled environment is the exposure of individuals who have no knowledge or control of their exposure. The exposure may occur in living quarters or workplaces where there are no expectations that the exposure levels may exceed those shown in Table 2, and where the induced currents do not exceed those in Table 2, Part B. Transitory exposures are treated in 4.1.1.

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Table 2—Maximum permissible exposure for uncontrolled environments*

Part A: Electromagnetic Fields†					
Frequency range (MHz) **1**	**Electric field strength (E) (V/m)** **2**	**Magnetic field strength (*H*) (A/m)** **3**	**Power density (*S*) E-field, H-field (mW/cm^2)** **4**	**Averaging time $\|E\|^2$, *S* or $\|H\|^2$ (min)** **5**	
0.003–0.1	614	163	(100, 1 000 000)‡	6	6
0.1–1.34	614	$16.3 / f$	$(100, 10\,000 / f^2)$‡	6	6
1.34–3.0	$823.8 / f$	$16.3 / f$	$(180 / f^2, 10\,000 / f^2)$	$f^2 / 0.3$	6
3.0–30	$823.8 / f$	$16.3 / f$	$(180 / f^2, 10\,000 / f^2)$	30	6
30–100	27.5	$158.3 / f^{1.668}$	$(0.2, 940\,000 / f^{3.336}$	30	$0.0636\, f^{1.337}$
100–300	27.5	0.0729	0.2	30	30
300–3000	—	—	$f / 1500$	30	
3000–15 000	—	—	$f / 1500$	$90\,000 / f$	
15 000–300 000			10	$616\,000 / f^{1.2}$	
NOTE—*f* is the frequency in MHz.					

*See Figure E.1 and Figure E.4 for graphical depictions of MPEs.
†The exposure values in terms of electric and magnetic field strengths are the mean values obtained by spatially averaging the squares of the fields over an area equivalent to the vertical cross section of the human body (projected area).
‡These plane-wave equivalent power density values, although not appropriate for near-field conditions, are commonly used as a convenient comparison with MPEs at higher frequencies and are displayed on some instruments in use.

Part B: Induced and contact radio frequency currents*			
Frequency range (MHz)	**Maximum current (mA)**		**Contact**
	Through both feet	**Through each foot**	
0.003–0.1	$900\, f$	$450\, f$	$450\, f$
0.1–100	90	45	45
NOTE—*f* is the frequency in MHz.			

*It should be noted that the current limits given above may not adequately protect against startle reactions and burns caused by transient discharges when contacting an energized object. (See text for additional comment and see Figure E.5 for a graphical depiction.)

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a) In uncontrolled environments, where individuals unfamiliar with the phenomenon of induced RF currents may have access, it is recommended that precautions be taken to limit induced currents to values not normally perceptible to individuals, as well as to prevent the possibility of RF burns.

1) For freestanding individuals (no contact with metallic objects), RF current induced in the human body, as measured through each foot, should not exceed the following values:

$\bar{I} = 450f$ mA (for $0.003 < f \leq 0.1$ MHz)

where

$\bar{I}$ is the average over any 1 second period,

f is the frequency in MHz.

$\tilde{I} = 45$ mA (for $0.1 < f < 100$ MHz) subject to a ceiling limit of 220 mA

where $\tilde{I}$ is the rms current during any 6 minute period.

2) For conditions of possible contact with metallic bodies, where making or breaking the contact does not result in any momentary spark discharge or high skin-surface current density causing startle reaction, pain, burns, or other skin injury, maximum RF currents through an impedance equivalent to that of the human body for conditions of grasping contact [see item (a) of 4.3] as measured with a contact current meter shall not exceed the following values:

$\bar{I} = 450f$ mA (for $0.003 < f \leq 0.1$ MHz)

where

$\bar{I}$ is the average over any 1 second period,

f is the frequency in MHz.

$\tilde{I} = 45$ mA (for $0.1 < f < 100$ MHz) subject to a ceiling limit of 220 mA

where $\tilde{I}$ is the rms current during any 6 minute period.

$$\bar{I} \equiv \frac{1}{T}\int_0^T |I|\ \mathrm{dt} \qquad (f \leq 100\ \mathrm{kHz},\ T = 1\ \mathrm{s})$$

and

$$\tilde{I} \equiv \left[\frac{1}{T}\int_0^T I^2\ \mathrm{dt}\right]^{\frac{1}{2}} \qquad (f > 100\ \mathrm{kHz},\ T = 360\ \mathrm{s})$$

3) Induced current measurements are not required if the spatially averaged electric field strength does not exceed the MPE at frequencies of 0.20 MHz or less and does not exceed the limits shown in Figure E.7 at frequencies greater than 0.20 MHz.

b) The MPEs refer to exposure values obtained by spatially averaging the squares of the fields over an area equivalent to the vertical cross section of the human body (projected area). In the case of partial-body exposure, the limits can be relaxed, as described in 4.4. In nonuniform fields, spatial peak values of field strengths may exceed the MPEs if the spatial average value remains within the specified limits. The MPEs may also be relaxed by reference to SAR limits in 4.2.1 by appropriate calculation or measurement.

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c) The MPE refers to values averaged over any 6 minute to 30 minute period for frequencies up to 3000 MHz, and over shorter periods for higher frequencies, down to 10 s at 300 GHz, as indicated in Table 2.

d) For near-field exposures at frequencies less than 300 MHz, the applicable MPE is in terms of rms electric and magnetic field strength, as given in Table 2, columns 2 and 3. For convenience, the MPE may be expressed as equivalent plane-wave power density, given in Table 2, column 4.

e) For mixed or broadband fields at a number of frequencies for which there are different values of the MPE, the fraction of the MPE [in terms of E^2, H^2, or power density (S)] incurred within each frequency interval should be determined, and the sum of all such fractions should not exceed unity. See Annex D for an example of how this is accomplished.

In a similar manner, for mixed or broadband induced currents at a number of frequencies for which there are different values of the MPE, the fraction of the induced current limits (in terms of I^2) incurred within each frequency interval should be determined, and the sum of all such fractions should not exceed unity.

f) For exposures to pulsed radio frequency fields in the range of 0.1 to 300 000 MHz, the peak (temporal) value of the MPE, in terms of E field, is 100 kV/m.

g) For exposures to pulsed radio frequency fields of pulse durations less than 100 ms, and frequencies in the range of 0.1 to 300 000 MHz, the MPE, in terms of peak power density for a single pulse, is given by the MPE (Table 2, E-field equivalent power density), multiplied by the averaging time in seconds, and divided by 5 times the pulse width in seconds. That is

$$Peak\ MPE = \frac{MPE \times Avg\ Time\ (\text{seconds})}{5 \times Pulsewidth\ (\text{seconds})}$$

A maximum of five such pulses, with a pulse-repetition period of at least 100 ms, is permitted during any period equal to the averaging time [see item (c)]. If there are more than five pulses during any period equal to the averaging time, or if the pulse durations are greater than 100 ms, normal averaging-time calculations apply, except that during any 100 ms period, the energy density is limited per the above formula, viz

$$\Sigma Peak\ MPE \times Pulsewidth\ (\text{seconds}) = \frac{MPE \times Avg\ Time\ (\text{seconds})}{5}$$

4.2 Exclusions

4.2.1 Controlled environment

At frequencies between 100 kHz and 6 GHz, the MPE in controlled environments for electromagnetic field strengths may be exceeded if

a) The exposure conditions can be shown, by appropriate techniques, to produce specific absorption rates (SARs) below 0.4 W/kg as averaged over the whole-body and spatial peak SAR, not exceeding 8 W/kg as averaged over any 1 g of tissue (defined as a tissue volume in the shape of a cube), except for the hands, wrists, feet and ankles where the spatial peak SAR shall not exceed 20 W/kg, as averaged over any 10 g of tissue (defined as a tissue volume in the shape of a cube); and

b) The induced currents in the body conform with the MPE in Table 1, Part B.

Recognition must be given to regions of the body where a 1 or 10 cm^3 volume would contain a mass significantly less than 1 or 10 g, respectively, because of enclosed voids (air). For these regions, the absorbed power should be divided by the actual mass within that volume to obtain the spatial peak SARs.

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The SARs are averaged over any 6 minute interval. Above 6 GHz, the relaxation of the MPE under partial body exposure conditions is permitted (see 4.4).

At frequencies between 0.003 and 0.1 MHz the SAR exclusion rule, stated above, does not apply. However, the MPE in controlled environments can still be exceeded if it can be shown that the peak rms current density, as averaged over any 1 cm^2 area of tissue in 1 s does not exceed $35f$ mA/cm^2, where f is the frequency in MHz.

4.2.1.1 Low-power devices: controlled environment

This exclusion, consistent with the provision of 4.2.1, pertains to devices that emit RF energy under the control of an aware user. This exclusion addresses exposure of the user. For such devices, the exposure of other persons in the immediate vicinity of the user will meet the exclusion criterion for the uncontrolled environment. (See 4.2.2.)

At frequencies between 100 kHz and 450 MHz, the MPE may be exceeded if the radiated power is 7 W or less. In this subclause,*radiated power* means the power radiated into free space in the absence of any nearby objects.

At frequencies between 450 and 1500 MHz, the MPE may be exceeded if the radiated power is $7(450/f)$ W or less where f is the frequency in MHz.

This exclusion does not apply to devices with the radiating structure maintained within 2.5 cm of the body.

4.2.2 Uncontrolled environments

At frequencies between 100 kHz and 6 GHz, the MPE in uncontrolled environments for electromagnetic field strengths may be exceeded if

a) The exposure conditions can be shown by appropriate techniques to produce SARs below 0.08 W/kg, as averaged over the whole body, and spatial peak SAR values not exceeding 1.6 W/kg, as averaged over any 1 g of tissue (defined as a tissue volume in the shape of a cube), except for the hands, wrists, feet, and ankles where the spatial peak SAR shall not exceed 4 W/kg, as averaged over any 10 g of tissue (defined as a tissue volume in the shape of a cube); and

b) The induced currents in the body conform with the MPE in Table 2, Part B.

Recognition must be given to regions of the body where a 1 or 10 cm^3 volume would contain a mass significantly less than 1 or 10 g, respectively, because of enclosed voids (air). For these regions, the absorbed power should be divided by the actual mass within that volume to obtain the spatial peak SARs.

The averaging time for SARs is as indicated in Table 2. Above 6 GHz, the relaxation of the MPE under partial body exposure conditions is permitted (see 4.4).

At frequencies between 0.003 and 0.1 MHz, the SAR exclusion rule does not apply. However, the MPE in uncontrolled environments can still be exceeded if it can be shown that the peak rms current density, as averaged over any 1 cm^2 area of tissue in 1 s, does not exceed $15.7f$ mA/cm^2, where f is the frequency in MHz.

4.2.2.1 Low-power devices: uncontrolled environment

This exclusion, consistent with the provisions of 4.2.2, pertains to devices that emit RF energy without control or knowledge of the user.

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At frequencies between 100 kHz and 450 MHz, the MPE may be exceeded if the radiated power is 1.4 W or less. In this subclause, *radiated power* means the power radiated into free space in the absence of any nearby objects.

At frequencies between 450 and 1500 MHz, the MPE may be exceeded if the radiated power is $1.4(450/f)$ W or less where f is the frequency in MHz.

This exclusion does not apply to devices with the radiating structure maintained within 2.5 cm of the body.

4.3 Measurements

a) For both pulsed and non-pulsed fields at frequencies below 300 MHz, the power density, the square of the field strengths and the SARs, as applicable, are averaged over any 6 minute or 30 minute period. The time-averaged values should not exceed those given in Table 1, Part A and Table 2, Part A, or the exclusions in 4.2. Note that the averaging time is a function of frequency above 15 GHz for a controlled environment and is a function of frequency between 1.34 and 3.0 MHz, and above 3 GHz for an uncontrolled environment. (The averaging time is also a function of frequency between 30 and 300 MHz for exposure to magnetic fields.)

   In the case of induced currents, where RF shock or burn may be possible because of access to conductive structures, a 6 minute or 30 minute averaging time is no longer valid, and, for purposes of determining compliance with the recommended limits discussed in item (a) of 4.1.1 and item (a) of 4.1.2, the currents should be measured with an instrument having an averaging time no greater than 1 s. Induced body currents should be measured by determining the RF current flowing to ground through the feet of the individual. Contact currents should be measured by determining the RF current through the hand in contact with the ungrounded surface. The use of instrumentation that can simulate the impedance of the human body at the frequency of the current may be used to assess the maximum expected current that would flow if a person were to come into contact with an energized object. (See Chatterjee et al. [B10] and Figure E.8.)

b) Generally, for frequencies less than 300 MHz, both the electric and magnetic field strengths shall be determined. For frequencies of 30 MHz or less, this can *only* be accomplished by independent measurement of both the electric and magnetic field strengths; for frequencies between 30 and 300 MHz, it may be possible, through analysis, to show that measurement of only one of the two fields, not both, is sufficient for determining compliance with the MPE. For frequencies above 300 MHz, only one field component need be measured (generally E).

c) Measurements to determine compliance with the recommended MPE of this standard shall be made (with appropriate instruments) at distances of 5 cm from any generating device and its associated attachments. Measurements shall be made no closer than 20 cm from re-radiating (passive or scattering) objects.

   If determination of compliance with the recommended MPEs of this standard requires measurements to be made at a distance of 5 cm from any generating device and its associated attachments, both E- and H-field measurements may be necessary. If suitable instrumentation for such objects is not available, compliance with the exclusion conditions of 4.2 is necessary. If measurements (with appropriate instruments) at distances of 5 cm from any generating device and its associated attachments are in compliance with the recommended MPE, the MPE may be exceeded at distances closer than 5 cm from the radiating source. (See IEEE Std C95.3-1991.)

d) Evaluation of induced RF currents will generally require a measurement unless the exposure situation is very simple or the E field can be shown to be no greater than the percent of the MPEs set forth in item (a)(3) of 4.1.1 or item (a)(3) of 4.1.2, as appropriate.

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Induced currents may be measured by one or more of the following three methods:

1) *RF thermocouple-type ammeter measurements*. These devices, employing thermocouple elements for the measurement of RF currents, offer true rms detection and may be inserted directly in series with the conduction path for the current flow into the body, or exiting the body. While simple in design and use, thermocouple type ammeters have very limited tolerance for overload currents that can destroy the thermocouple element.
2) *Voltage measurements*. The induced current may also be determined by measuring the RF voltage developed across a noninductive resistor that is connected in series with the current path, as in item (d)(1). Either a broadband type of voltmeter, suitable for the frequency of the current, or a narrowband, tunable voltmeter in the form of a tuned receiver may be used to determine the voltage. The current is determined from the relation

   $I = V/R$

   where

   I is the induced RF current (A),

   V is the RF voltage drop across the resistor (V),

   R is the impedance of the resistor (Ω).

   Various forms of circuits making use of this basic method may be used for purposes of measuring the magnitude of the RF current flowing from the body to ground, including the use of parallel plate electrodes connected with a resistive element upon which an individual may stand. Commercial instruments with a flat frequency response between 3 kHz and 100 MHz are beginning to become available for this purpose, as are instruments with shoe-insertable sensors for personnel mobility.

3) *RF current transformer (current probe) measurements*. RF current transformers are of the clamp-on type or the fixed window type. Either type may be used to measure the RF current flowing in a conductor. The current transformer consists of a toroidally wound transformer in which the current-carrying conductor is typically placed in the window of the device and acts as the primary for the transformer. Current transformers may be used to determine the current flowing in a parallel plate electrode arrangement, as described in item (d)(2), or in conjunction with a conductive rod probe assembly to determine contact currents that might be experienced by a person touching an object exposed to RF fields. Generally, the current transformer requires some form of instrument to detect the output voltage from the transformer and subsequently, the current that flows through the window of the transformer.

In each of the three methods, it may be possible to insert an impedance equivalent to the human body at the frequency of interest that would permit a measurement of the induced current, without the current actually flowing in the body until after the evaluation of its magnitude.

In any of these methods, caution shall be exercised in the selection of the exact device for the measurement, since its frequency dependence will affect the measurement result. For example, thermocouple detectors used in some RF ammeters exhibit variations in their response to different frequencies (commonly becoming less efficient at higher frequencies), and current transformer performance characteristics are a compromise between sensitivity and bandwidth.

The meters, associated circuitry, and methodology shall be appropriate for the particular frequency and the meters shall have an averaging time no greater than 1 s. When it is desired to make an indirect measurement

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of the current that might actually flow in a human, use of an antenna or phantom model may prove helpful. In this case, the phantom dipole moment, surface area, and contact impedance should be equivalent to those of the simulated subject.

4.4 Relaxation of power density limits for partial body exposures

The following relaxation of power density limits is allowed for exposure of all parts of the body except the eyes and the testes.

Compliance with the MPE of Tables 1 and 2 is determined from spatial averages of power density or the mean squared electric and magnetic field strengths over an area equivalent to the vertical cross section of the human body (projected area) at a distance no closer than 20 cm from any object. For exposures in controlled environments, the peak value of the mean squared field strength should not exceed 20 times the square of the allowed spatially averaged values (Table 1) at frequencies below 300 MHz, and should not exceed the equivalent power density of 20 mW/cm^2 at frequencies between 300 MHz and 6 GHz, 20 $(f/6)^{1/4}$ mW/cm^2 at frequencies between 6 and 96 GHz (f is in GHz), and 40 mW/cm^2 at frequencies above 96 GHz. Similarly, for exposures in uncontrolled environments, the peak value of the mean squared field strengths should not exceed 20 times the square of the allowed spatially averaged values (Table 2) at frequencies below 300 MHz, or the equivalent power density of 4 mW/cm^2 for f between 300 MHz and 6 GHz, $(f/1.5)$ mW/cm^2 for frequencies between 6 GHz and 30 GHz (f is in GHz), and 20 mW/cm^2 at frequencies above 30 GHz. At frequencies below 300 MHz, the equivalent maximum rms field strengths should not exceed $\sqrt{20}$ times the maximum allowed spatially averaged values of E and H shown in Tables 1 and 2 (see 6.10). The relaxation for partial-body exposure is summarized in Table 3.

Table 3—Relaxation for partial body exposures

	Frequency (GHz)	Peak value of mean squared field	Equivalent power density (mW/cm^2)
Controlled environment	$0.0001 \le f < 0.3$	$< 20\ \bar{E}^2$ or $20\ \bar{H}^{2\,*}$	
	$0.3 < f \le 6$		< 20
	$6 < f \le 96$		$< 20\ (f/6)^{1/4\,\dagger}$
	$96 < f \le 300$		40
Uncontrolled environment	$0.0001 \le f < 0.3$	$< 20\ \bar{E}^2$ or $20\ \bar{H}^{2\,\ddagger}$	
	$0.3 < f \le 6$		4
	$6 < f \le 30$		$f/1.5^{\dagger}$
	$30 < f \le 300$		20

* $\bar{E}$ and $\bar{H}$ are the spatially averaged values from Table 1.
† f in GHz
‡ $\bar{E}$ and $\bar{H}$ are the spatially averaged values from Table 2.

5. Explanation

Exposure to electromagnetic fields in the resonance frequency range under consideration is but one of several sources of energy input to the human body. The MPE in a controlled environment results in energy dep-

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