IEEE C95.1-1991
(Revision of
ANSI C95.1-1982)

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 September 26, 1991

IEEE 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 by or under the direction of practitioners of the healing arts. The recommendations at 300 GHz are compatible with existing recommendations of safe exposure in the infrared frequency range (starting at 300 GHz). A rationale that describes how the recommendations were arrived at, and the factors taken into account in formulating them, is included.
Keywords: Electromagnetic fields, exposure limits, microwave, MPE, nonionizing radiation, radiation protection, RFPG, radiofrequency, safety levels.

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Foreword

(This Foreword is not a part of IEEE C95.1-1991, 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 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 C95.1-1991, IEEE Standard for Safety Levels With Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 100 GHz. (Replaces ANSI C95.1-1982).

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

ANSI C95.4-1978, American National Standard 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.

Changes in the latest revision 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.

This standard 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 data base, 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 a controlled environment under certain conditions, such as resonance, or when exposure is complicated by associated hazards like RF shock or burn.

This standard contains a detailed discussion of both the rationale and the limitations of the recommended guidelines based on the present data base.

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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. Scope and Purpose

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 Z136.1-1986 [B2].

2. Definitions and Glossary of Terms

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

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

averaging time (T_{avg}). The appropriate time period over which exposure is averaged for purposes of determining compliance with an 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}.

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

controlled environment. Controlled environments are locations 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.[1]

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.

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.

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

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

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

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

exposure. Exposure occurs whenever and wherever a person is subjected to electric, magnetic or electromagnetic fields or to contact currents other than those originating from physiological processes in the body and other natural phenomena.

exposure, partial-body. Partial-body exposure 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. *See* **RF "hot spot".**

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.

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

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).

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

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

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

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.

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

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.

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.

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

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 ohms. In particular,

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

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.

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

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.

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

radio frequency (RF). 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.

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**.

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

(1) 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
(2) 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.

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.

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.

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

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).

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).

uncontrolled environment. Uncontrolled environments are locations where there is the exposure of individuals who have no knowledge or control of their exposure. 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.

wavelength (λ). 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.

3. References

This standard shall be used in conjunction with the following documents:

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

[2] IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).

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-

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

yspace 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.[3]

Table 1
Maximum Permissible Exposure for Controlled Environments

Part A
Electromagnetic Fields*

1 Frequency Range (MHz)	2 Electric Field Strength (E) (V/m)	3 Magnetic Field Strength (H) (A/m)	4 Power Density (S) E-Field, H-Field (mW/cm^2)	5 Averaging Time $\lvert E\rvert^2$, $\lvert H\rvert^2$ or S (minutes)
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 - 3 000			f/300	6
3 000 - 15 000			10	6
15 000 - 300 000			10	616 000/$f^{1.2}$

Part B
Induced and Contact Radiofrequency Currents‡

Frequency Range	Maximum Current (mA) Through both feet	Maximum Current (mA) Through each foot	Contact
0.003 - 0.1 MHz	2 000f	1 000f	1 000f
0.1 - 100 MHz	200	100	100

f=frequency in MHz

*The exposure values in terms of electric and magnetic field strengths are the values obtained by spatially averaging values 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.

‡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.

(a) In a controlled environment, access should be restricted to limit the rms RF body current (averaged over any 1 second) and potential for RF shock or burn as follows:
   (i) 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:

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

$I = 1000f$ mA for ($0.003 < f \leq 0.1$ MHz)
$I = 100$ mA for ($0.1 < f < 100$ MHz)

(ii) For conditions of possible contact with metallic bodies, maximum RF current through an impedance equivalent to that of the human body for conditions of grasping contact [see 4.3 (1)] as measured with a contact current meter shall not exceed the following values:

$I = 1000f$ mA for ($0.003 < f \leq 0.1$ MHz)
$I = 100$ mA for ($0.1 < f < 100$ MHz)

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. Evaluation of the magnitude of the induced currents will normally require a direct measurement.

(b) The MPEs refer to exposure values obtained by spatially averaging 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 nonuni-form 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 re-laxed by reference to SAR limits in 4.2.1 by appropriate calculations or measurements.

(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 Appendix C 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:

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

A maximum of five such pulses, with a pulse-repletion period of at least 100 ms, is permitted during any period equal to the averaging time [see 4.1.1(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

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

4.1.2 MPE in Uncontrolled Environment. 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 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.

Table 2
Maximum Permissible Exposure for Uncontrolled Environments

Part A
Electromagnetic Fields*

1 Frequency Range (MHz)	2 Electric field Strength (E) (V/m)	3 Magnetic Field Strength (H) (A/m)	4 Power Density (S) E-Field, H-Field (mW/cm^2)	5 Averaging Time (minutes) $\|E\|^2$, S	 or $\|H\|^2$
0.003 - 0.1	614	163	$(100, 1\,000\,000)^\dagger$	6	6
0.1 - 1.34	614	$16.3/f$	$(100, 10\,000/f^2)^\dagger$	6	6
1.34 - 3.0	823.8/f	$16.3/f$	$(180/f^2, 10\,000/f^2)^\dagger$	$f^2/0.3$	6
3.0 - 30	823.8/f	$16.3/f$	$(180/f^2, 10\,000/f^2)^\dagger$	30	6
30 - 100	27.5	$158.3/f^{1.668}$	$(0.2, 940\,000/f^{3.336})^\dagger$	30	$0.0636 f^{1.337}$
100 - 300	27.5	0.0729	0.2	30	30
300 - 3 000			$f/1\,500$	30	
3 000 - 15 000			$f/1\,500$	$90\,000/f$	
15 000 - 300 000			10	$616\,000/f^{1.2}$	

Part B
Induced and Contact Radiofrequency Currents‡

Frequency Range	Maximum Current (mA) Through both feet	 Through each Foot	Contact
0.003 - 0.1 MHz	$900f$	$450f$	$450f$
0.1 - 100 MHz	90	45	45

f=frequency in MHz

*The exposure values in terms of electric and magnetic field strengths are the values obtained by spatially averaging values 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 frequency and are displayed on some instruments in use.

‡It should be noted that the current limits given above may not adequately protect against startle reactions caused by transient discharges when contacting an energized object. See text for additional comment.

(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 prevent the possibility of RF burns.

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

$I = 450f$ mA for $(0.003 < f \leq 0.1$ MHz)
$I = 45$ mA for $(0.1 < f < 100$ MHz)

(ii) For conditions of possible contact with metallic bodies, maximum RF current through an impedance equivalent to that of the human body for conditions of grasping contact [see 4.3(1)], as measured with a contact current meter, shall not exceed the following values:

$I = 450f$ mA for $(0.003 < f \leq 0.1$ MHz)
$I = 45$ mA for $(0.1 < f < 100$ MHz)

(b) The MPEs refer to exposure values obtained by spatially averaging 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.

(c) The MPE refers to values averaged over any 6-min to 30-min period for frequencies up to 3 000 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 Appendix C 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:

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

A maximum of five such pulses, with a pulse-repletion period of at least 100 ms, is permitted during any period equal to the averaging time [see 4.1.2(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

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

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 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.

The SARs are averaged over any 6-min 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 and 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.

At frequencies between 450 and 1 500 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.

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 and 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.

At frequencies between 100 kHz and 450 MHz, the MPE may be exceeded if the radiated power is 1.4 W or less.

At frequencies between 450 and 1 500 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

(1) 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-min or 30-min 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-min or 30-min averaging time is no longer valid, and, for purposes of determining compliance with the recommended limits discussed in 4.1(a), 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 which 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. [B10] (See Fig A6.)

(2) Generally, for frequencies less than 300 MHz, both the electric and magnetic field strengths shall be determined. For frequencies equal to or less than 30 MHz, 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).

(3) Measurements to determine adherence to the recommended MPE shall be made (with appropriate instruments) at distances 20 cm or greater from any object. See IEEE C95.3-1991 [1].

(4) Evaluation of induced RF currents will generally require a measurement, unless the exposure situation is very simple. Most exposure conditions are complex and induced currents are not amenable to analysis.

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

(a) 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.

(b) 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 (a). 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=induced RF current (A)
V=RF voltage drop across the resistor (V)
R= 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.

(c) 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 (b), 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 second. When it is desired to make an indirect measurement 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 4.47[4] 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
Relaxations for Partial Body Exposures

	Frequency in GHz	Peak Value of Mean Squared Field	Equivalent Power Density in mW/cm^2
Controlled Environment	$0.0001 \leq f < 0.3$	$< 20\overline{E}^2$ or $20\overline{H}^{2*}$	
	$0.3 < f \leq 6$		< 20
	$6 < f \leq 96$		$< 20\ (f/6)^{1/4\ddagger}$
	$96 < f \leq 300$		40
Uncontrolled Environment	$0.0001 \leq f < 0.3$	$< 20\overline{E}^2$ or $20\overline{H}^{2\dagger}$	
	$0.3 < f \leq 6$		4
	$6 < f \leq 30$		$f/1.5$ ‡
	$30 < f \leq 300$		20

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

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 deposition, averaged over the entire body mass for

[4] $(\sqrt{20})$

any 6-min period of about 144 J/kg or less. This is equivalent to an SAR of about 0.40 W/kg or less, as spatially and temporally averaged over the entire body mass.

Biological effects data that are applicable to humans for all possible combinations of frequency and modulation do not exist. Therefore, this standard has been based on the best available interpretations of the extant literature and is intended to prevent adverse effects on the functioning of the human body.

At low frequencies, the magnetic field limits have been relaxed relative to ANSI C95.1-1982 [B1]. An anatomically realistic model [B26] of a human being has been used to show that the new limits will ensure SARs less than one twentieth of those specified (i.e., 0.4 and 0.08 W/kg). This is still very conservative, but more realistic than the H-field limits in ANSI C95.1-1982 [B1].

The electric field limits at low frequencies in Table 1 are primarily dictated by the following two objectives:

(1) limiting induced currents in the ankles during free-field exposure, and
(2) lowering the probability of inducing large body currents when conducting objects are touched.

The limits on induced RF currents are based on two different considerations.

First, *in any environment*, currents are limited to a level that prevents RF burns due to excessively high current densities in small areas of tissue while the subject is free standing in high-strength fields and has contact with conductive objects in which induced currents are flowing. This level, taken from [B10, B49, B54] is 100 mA, if measured through one foot, and 200 mA if measured through both feet. A value of 100 mA is applicable to contact situations, similar to a grasping contact with the hand. These currents will not result in localized SARs in the extremities (e.g., ankles or wrists) that exceed 20 W/kg, but may be perceived if protective clothing, such as insulated gloves, is not worn.

In controlled environments, various mitigative measures can be taken to reduce the probability of hazardous conditions. Such measures may include the following:

(1) protective gloves or clothing,
(2) awareness programs so that individuals are alerted to the possible presence of induced currents in conductive objects, and
(3) specific work practices that lessen the probability of exposure.

Second, for frequencies between 0.003 and 0.1 MHz, the induced current in controlled environments is limited to reduce the probability of reactions caused by induced currents that exceed the perception threshold for grasping contact with energized objects [B10]. The perception threshold is frequency dependent below 0.1 MHz and the limiting current is given by

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

In uncontrolled environments, individuals will, in general, not be aware of the presence of induced currents in various objects illuminated with RF fields. Inadvertent contact by an individual with such objects could lead to burns or startle reactions that, while not hazardous per se, could lead to an accident. To reduce the probability of such startle reactions[5], the contact current limit is based on laboratory data on perception of currents at different frequencies in humans [B10, B14]. These data indicate that perception thresholds, at any given frequency, depend on the type of contact made with the conducting object; touching contact generally results in lower current perception thresholds than grasping contact by a factor as great as ten times. Accordingly, the current limits in Table 2 are based on

[5] This does not include the startle reaction associated with spark discharges.

grasping contact and limit the current to 4.5 mA at 10 kHz. In the frequency range of 0.1-100 MHz, the current perception thresholds are related to the sensation of heating and become relatively constant with increasing frequency. In this frequency range, the contact current is limited to 45 mA.

In some environments, the transient discharge phenomenon associated with initiating or breaking contact with energized conductors can lead to easily perceived shock effects even though the steady-state current flow, after complete contact is established, is within the limits prescribed in this standard. These effects are more directly related to the energy contained in the transient discharge and, consequently, measures of the open-circuit voltage and short-circuit current on the energized object may be better indicators of the potential for momentary shock effects. Data on such phenomena have not been sufficiently developed in the technical literature to permit quantitative limits on energy transfer that are related to perception thresholds. *Users of this standard are cautioned that such phenomena can exist and, when performing hazard assessments, they should investigate the possibility of transient discharges that may be perceptible and even cause startle reactions, but that result in steady-state currents that are within the guidelines.*

Above 6.0 GHz, the exposure in human tissue is quasi-optical and the SAR exclusion rule does not apply.

At higher frequencies, above 15 GHz, it is known that penetration depth is much less than 1 cm and thermal time constants drop to seconds as the infrared range is approached. Consequently, the MPE specifies continuous functions for the field limits and averaging time as frequency increases to the upper limit of 300 GHz.

Below 0.1 MHz the SAR exclusion rule does not apply. Instead, limits on internal current density can substitute as the basis for exclusion. These limits are based on the literature on electro-stimulation at low frequencies [B8].

Exclusion criteria (4.2) to the MPE can be used in relation to fields from low-power devices such as hand-held, mobile, and marine radio transceivers. These devices may emit localized fields exceeding the MPE, but will result in a significantly lower rate of energy absorption than the whole-body averaged SARs that are allowed.

Exposures in excess of the MPEs are not necessarily harmful. However, in the absence of intended benefits (e.g., medical or lifesaving procedures), exposures above the MPE are not recommended.

6. Rationale

American National Standards Institute (ANSI) policy requires that each of its standards or guides be reviewed at five-year intervals. At the time of expiration, the standard or guide may be reaffirmed, revised, or rescinded in accord with the consensus of the reviewing body. In 1982, extensive revisions of the earlier standard were introduced by into ANSI C95.1-1982 [B1] based on improved dosimetry that defined frequency-dependent limits on fields and power density. The use of SAR as the basic dosimetric parameter permitted the formation of exclusion rules. Since 1982, Subcommittee IV has met at least once and usually twice annually to review a wide range of proposed refinements of the ANSI 1982 standard. The decision to expand the range of frequencies made it clear that quasi-static and quasi-optical considerations shall apply at the lower and higher boundary regions of the frequency range. Therefore, the applicability of SAR considerations was limited to the range from 0.1 MHz to 6.0 GHz, which includes the resonance range for human beings. Below 0.1 MHz, the data base on electro-stimulation of biological tissue plays the dominant role and the primary dosimetric parameter is internal current density. Above 6.0 GHz, the exposures are quasi-optical, and under these conditions, power density is the meaningful parameter.

In the broader resonance range, 0.1 MHz to 6.0 GHz, a primary question was the validity of the previously-adopted SAR criterion of 4 W/kg as a basis for standard setting. A total of

321 papers selected from the archival literature (Appendix A) was reviewed for biological, engineering, and statistical validity (see 6.3). It was agreed that only peer-reviewed reports of studies at SAR ≤ 10 W/kg, which had received favorable engineering and biological validation, should be considered relevant to the assessment of risk from exposure to electromagnetic fields in the resonance range. The literature review was followed by extensive deliberations of the Risk Assessment Working Group that was charged to reach agreement on an SAR at which potentially-deleterious health effects are likely to occur in human beings. A majority of the Risk Assessment Working Group agreed that the literature is still supportive of the 4 W/kg criterion. Further, the ANSI 1982 safety factor of 10 was reaffirmed by Subcommittee IV, yielding an SAR of 0.4 W/kg as the working basis for the MPE. The question then arose of the need for two tiers of MPE (as adopted by NCRP, 1986 [B52]) to distinguish occupational vs. general public exposures.

To some, it would appear attractive and logical to apply a larger, or different, safety factor to arrive at the guide for the general public. Supportive arguments claim subgroups of greater sensitivity (infants, the aged, the ill and disabled), potentially greater exposure durations (24-hr/day vs. 8-hr/day), adverse environmental conditions (excessive heat and/or humidity), voluntary vs. involuntary exposure, and psychological/emotional factors that can range from anxiety to ignorance. Non-thermal effects, such as efflux of calcium ions from brain tissues, are also mentioned as potential health hazards. The members of Subcommittee IV believe the recommended exposure levels should be safe for all, and submit as support for this conclusion the observation that no reliable scientific data exist indicating that:

(1) Certain subgroups of the population are more at risk than others
(2) Exposure duration at ANSI C95.1-1982 levels is a significant risk,
(3) Damage from exposure to electromagnetic fields is cumulative, or
(4) Nonthermal (other than shock) or modulation-specific sequelae of exposure may be meaningfully related to human health.

No verified reports exist of injury to human beings or of adverse effects on the health of human beings who have been exposed to electromagnetic fields within the limits of frequency and SAR specified by previous ANSI standards, including ANSI C95.1-1982 [B1]. In the promulgation of revised guidelines, the responsibility of the current Subcommittee IV is adherence to the scientific base of data in the determination of exposure levels that will be safe not only for personnel in the working environment, but also for the public at large. The important distinction is not the population type, but the nature of the exposure environment. When exposure is in a controlled environment, the scientifically-derived exposure limits apply. When exposure is in an uncontrolled environment, however, an extra safety factor is applied under certain conditions; these include, but are not limited to, the following:

(1) Exposure in the resonant frequency range, and
(2) Low-frequency exposure to electric fields where exposure is penetrating or complicated by associated hazards like RF shocks or burns induced by metal contacts.

As defined earlier, uncontrolled environments include the domicile and most places where the infirm, the aged, and children are likely to be. It also includes the work environment where employees are not specifically involved in the operation or use of equipment that does or may radiate significant electromagnetic energy and where there are no expectations that the exposure levels may exceed those shown in Table 2. On the other hand, controlled environments may involve exposure of the general public as well as occupational personnel, e.g., in passing through areas such as an observation platform near a transmitting tower where analyses show the exposure may be above that shown in Table 2 but is below that in Table 1. Other exposure conditions include that of the radio amateur who voluntarily and knowledgeably operates in a controlled RF environment.

At frequencies below 3 MHz, the MPEs, in terms of magnetic fields, have been relaxed to more reasonably correspond to whole-body SAR limits. On the other hand, the MPEs, in terms of E field, continue to be capped below 3 MHz in order to limit the possibility of reactions (shocks or burns) at the surface of the body that might occur in E fields of high strength, especially under conditions of spatial and temporal field concentration.

In this standard, there are extensive modifications of the averaging time for determining permissible exposure. At the upper frequencies, these rules agree with soundly-based averaging times derived from optical considerations. At the lower frequencies, new rules on induced currents have been introduced to prevent RF shock or burn upon grasping contact with an object in an RF environment. These rules supplement the limits on E and H field exposure.

This standard is thus an extension of ANSI C95.1-1982 [B1], and incorporates many refinements that will serve to make the MPEs more useful in a greater variety of exposure situations. There remain areas, however, which the standard does not cover, e.g., the possible exposure of the body to transient spark-discharge phenomena upon touching a large conducting object in an RF environment. Future research may provide the data base from which quantitative rules for preventing adverse effects from such discharges can be derived.

Research on the effects of chronic exposure and speculations on the biological significance of nonthermal interactions have not yet resulted in any meaningful basis for alteration of the standard. It remains to be seen what future research may produce for consideration at the time of the next revision of this standard.

6.1 Recognition of Whole-Body Resonance. As is true of ANSI C95.1-1982 [B1], the MPE in this standard is based on recommendations of field strengths or of plane-wave-equivalent power densities of incident fields, but these limits are based on well established findings that the body, as a whole, exhibits frequency-dependent rates of absorbing electromagnetic energy [B6, B20, B21, B25]. Whole-body-averaged SARs approach maximal values when the long axis of a body is parallel to the E-field vector and is four tenths of a wavelength of the incident field. Maximal absorption occurs at a frequency near 70 MHz for Standard Man (height = 175 cm) and results in an approximate seven-fold increase of absorption relative to that in a 2450 MHz field [B22, B27]. In consideration of this dependency, recommended MPEs of field strength have been reduced across the range of frequencies in which human bodies from infants to large adults exhibit whole-body resonance. Above 6 GHz, the absorption is quasi-optical and body resonance considerations do not apply.

6.2 Incorporation of Dosimetry. Dosimetry is the fundamental process of measuring physical quantities of energy or substances that are imparted to an absorbing body [B40, B41]. In 1972, The National Council on Radiation Protection and Measurements (NCRP) convened Scientific Committee 39 to deliberate and recommend dosimetric quantities and units applicable to electromagnetic fields [B51]. In keeping with the NCRP recommendations, in 1982 the ANSI C95 Subcommittee IV adopted the unit-mass, time-averaged rate of electromagnetic energy absorption, as specified in units of watts per kilogram (W/kg). The quantity expressed by these units is termed the specific absorption rate (SAR).

Formally defined, the SAR is the time rate at which radio-frequency electromagnetic energy is imparted to an element of mass of a biological body. The SAR is applicable to any tissue or organ of interest (that is, can be applied to any macroscopic element of mass) or, as utilized in ANSI C95.1-1982 [B1], is expressed as a whole-body average. Ideally, anatomical distributions of SARs would be used explicitly to formulate a guide in recognition that absorption of electromagnetic energy from even the most uniform field can result in highly variable anatomical depositions of energy. It has been established [B31, B34, B35] through thermographic analyses of models of rats and man, and cadavers of rabbits, that spatial peak SAR values can exceed a whole-body average value by more than a factor of 20. Comparable findings have been reported [B27]. However, several factors preclude explicit use of peak SAR, such as the following:

(1) The availability of data on distributive SARs is limited, and
(2) SAR distributions are highly variable, since they depend on wavelength, polarization, and zone of the incident field, as well as on the mass and momentary geometry of the biological body.

The number of the possible SAR distributions approaches infinity. It is recognized, however, that a whole-body averaged SAR is the mean of a distribution, the high side of which is an envelope of electrical hotspots. These range from the mean value to the peak value, and when integrated with localized SARs of less than the mean value, are equal to the whole-body average. Moreover, for any given orientation of a given species in a given field, the correlation between the magnitude of a whole-body-averaged SAR and that of any lower or higher part-body SAR approaches unity. That is, if the power density of an incident electromagnetic field is increased, then the relative increase of the whole-body SAR will be directly proportional to the increase of any part-body SAR. Because of the invariable presence of electrical hotspots in the irradiated body and the inherent correlation between magnitudes of whole-body and part-body SARs, a biological effect induced by a localized SAR that is well above the whole-body average will be reflected to some extent by that average. The predictive utility of the correlation between part and whole has long served clinical and experimental medicine in which a whole-body, unit-mass dosimetry underlies therapeutic administration of pharmacological agents.

There are situations, however, where the implicit use of peak SAR provides a practical means for determining compliance with the MPEs. These situations correspond to exposure to nonuniform fields and partial body exposures. For example, the MPEs in Tables 1 and 2 are based on uniform field exposure and limit the whole-body averaged SAR, over the frequency range where SAR is meaningful (from approximately 3 MHz to 6 GHz for E-field exposure), to 0.4 W/kg for exposures in controlled environments and 0.08 W/kg for exposures in uncontrolled environments. As indicated above, implicit in these MPEs is the assumption that the spatial peak SARs may exceed the whole-body averaged values by a factor of more than 20 times. Since most exposures are not to uniform fields, a method has been derived, based on the demonstrated peak to whole-body averaged SAR ratio of 20, for equating nonuniform field exposure and partial body exposure to an equivalent uniform field exposure. This is used in this standard to allow relaxation of power density limits for partial body exposure, except in the case of the eyes and the testes.

The equivalent uniform field is obtained from a spatial average of the actual exposure field over a projected area equal to or greater than that of the exposed human. Measurements of the spatial average can be made using standard off-the-shelf instruments and devices such as data loggers. However, some situations may exist where the spatially-averaged value of a nonuniform field complies with Tables 1 or 2, but the peak value of the field corresponds to a partial-body exposure that could produce peak SARs exceeding 20 times the maximum whole-body average value. Simple, partial-body exposure analyses have indicated that peak SARs may be kept within desired limits if the peak mean squared field strengths do not exceed 20 times the maximum allowed spatial average values (Table 1) at frequencies below 300 MHz or 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 for frequencies between 6 GHz and 96 GHz (f is in GHz) and 40 mW/cm^2 at frequencies above 96 GHz for exposures in controlled environments. Similarly, for exposures in uncontrolled environments, the peak value of the mean squared field strengths should not exceed 20 times the allowed spatial average values (Table 2) at frequencies below 300 MHz, nor the equivalent power density of 4 mW/cm^2 at frequencies between 300 MHz and 6 GHz, $(f/1.5)$ mW/cm^2 at frequencies between 6 and 30 GHz (f is in GHz), and 20 mW/cm^2 for frequencies above 30 GHz (see Table 3). These analyses are based on the following two models:

(1) exposure of a planar layer of tissue where the average SAR is calculated in 1 g of tissue in the shape of a cube below the surface;
(2) exposure of a triple layered (fat-muscle-bone) cylindrical arm model with the E field both perpendicular and parallel to the axis of the cylinder. (The results of the analyses where the E field is parallel to the axis of the cylinder are valid only where the arm model is equal or greater than one half wavelength.) The overall results of these analyses support the recommended peak exposure values as worst-case levels.

The planar model was based on an analysis described in [B42], and the cylindrical models were derived and discussed [B38, B41].

The rules for relaxation of exposure limits for partial-body exposure do not apply for exposure of the eyes and testes, but the SAR exclusion rules (see 4.2.1 and 4.2.2) can still be used to show conformance to the standard, despite localized power density limits above the specified whole-body average.

6.3 Data Base. The literature on RF bioeffects comprises many thousands of papers on all aspects of the subject presented in various scientific journals, reports, and symposia. From that large data base, the Literature Surveillance Working Group selected the initial list of 321 papers shown in Appendix A (listed in alphabetical order by first author) as representative of the current state of knowledge on the many RF bioeffects topics.

A prime criterion governing this first selection was peer review before publication. Presentations at recent scientific symposia or abstracts thereof were excluded from consideration (with few exceptions) under the assumption that either more complete, peer-reviewed accounts of such studies will appear subsequently or will not be published at all (perhaps because the study was flawed or the investigators were not able to reproduce their results). Other selection criteria were publication date, with greater emphasis given to more recent publications on each topic; possible significance of findings (positive or negative) to human health; and relevance to concerns expressed by citizen groups. Although many of the selections were published after the issuance of ANSI C95.1-1982 [B1], earlier papers regarded as seminal or of current interest were also included. The list was based on a cut-off publication date of December, 1985, with the proviso that later papers would be added if their findings could significantly affect the MPEs. Several papers published after 1985 on shock and burn from electromagnetic fields and on peak power, per se, were added to the list.

The Subcommittee IV Working Groups on Engineering Validation and Biological Validation then used the criteria described in 6.4 and 6.5 to assess the papers on the list. Those that fulfilled the acceptance criteria of these two working groups were further evaluated by the Risk Assessment Working Group. (See Fig A7 for a flow chart of the literature review process.) Appendix B is the final list of 120 papers comprising the data base for IEEE C95.1-1991.

6.4 Assessment Criteria. The absorption and distribution of electromagnetic energy in the body are very complex phenomena that depend on the mass, shape, and size of the body, the orientation of the body with respect to the field vectors, and the electrical properties of both the body and the environment. Other variables that may play a substantial role in possible biological effects are those that characterize the environment (e.g., ambient temperature, air velocity, relative humidity, and body insulation) and those that characterize the individual (e.g., age, gender, activity level, debilitation, or disease). Because innumerable factors may interact to determine the specific biological outcome of an exposure to electromagnetic fields, any protection guide shall consider maximal amplification of biological effects as a result of field-body interactions, environmental conditions, and physiological variables.

To assess positive reports of the biological effects of exposure to electromagnetic fields, Subcommittee IV emphasized studies that had generated evidence of debilitation or morbidity during both chronic and acute exposure. While it is generally agreed that measurements of the responses of human beings are the most pertinent to the establishment of guidelines for exposure to any noxious environment, few data of this type exist; most human studies are epidemiological or clinical in nature. As was the case for ANSI C95.1-1982 [B1], IEEE Subcommittee IV has had to turn to data collected on subhuman species, fully realizing that the small mass, limited physiological capacity, and unusual body dimensions of most furred laboratory animals strongly influence not only the SAR at any given frequency but also the character and magnitude of biological response. It is important to realize that not only is there an uncertainty inherent in measurements of the responses of animals, but extrapolation of these measurements to human beings may be difficult.

Despite the greatly expanded database since ANSI C95.1-1982 [B1], most reports of biological effects have embodied acute exposures at relatively few frequencies. An extensive review of the literature revealed once again that the most sensitive measures of potentially harmful biological effects were based on the disruption of ongoing behavior associated with an increase of body temperature in the presence of electromagnetic fields [B16, B17, B18, B19]. Because of the paucity of reliable data on chronic exposures, IEEE Subcommittee IV focused on evidence of behavioral disruption under acute exposures, even disruption of a transient and fully reversible nature. The disruption of a highly demanding operant task is a statistically reliable endpoint that is associated with whole-body SARs in a narrow range between 3.2 and 8.4 W/kg, despite considerable differences in carrier frequency (400 MHz to 5.8 GHz), species (rodents to rhesus monkeys), and exposure parameters (near- and far-field, multipath and planewave, CW- and pulse-modulated). In contrast, the time-averaged power densities associated with these thresholds of disruption ranged (by calculation or measurement) from 8 to 140 mW/cm^2.

During the assessment procedure, classifications of findings were made without prejudgment of mechanisms of effects. Studies such as those indicating effects, in vitro, on cell function were considered transient and reversible with no detrimental health effects. IEEE Subcommittee IV's intent was to protect exposed human beings from harm by any mechanism, including those arising from excessive elevations of body temperature. After the list of relevant peer-reviewed papers had been compiled by the Literature Surveillance Working Group (see 6.3), each report was evaluated in detail by the Engineering Validation and Biological Validation Working Groups. Three subgroups constituted the Engineering Validation Working Group. These were divided according to frequency as follows:

(1) Below 3 MHz,
(2) 3 to 300 MHz, and
(3) 300 MHz and above.

Fourteen subgroups constituted the Biological Validation Working Group, comprising scientists and experts in the following disciplines:

(1) Behavior, (2) Biorhythms, (3) Cardiovasculature, (4) Central Nervous System, (5) Development and Teratology, (6) Endocrinology, (7) Visual Systems, (8) Genetics, (9) Modulation (RF), (10) Hematology-Immunology, (11) Metabolism-Thermoregulation, (12) Oncology, (13) Combined Effects, and (14) Physiology.

Only those reports with adequate dosimetry were judged acceptable. The relevance of each of these reports to standards setting was evaluated, as were the scientific quality and originality of the data, reliability, and evidence of adverse effects. The evaluation stressed thresholds of adverse effects and the extent to which the findings had been verified in independent investigations. Reports embodying questionable statistical methods were evaluated further by a Statistical Evaluation Working Group. The acceptable reports were then funnelled to the Risk Assessment Working Group for an evaluation of the implied risk for human beings.

A majority of the Risk Assessment Working Group agreed that the literature is still supportive of the 4 W/kg criterion and that whole-body SARs below 4 W/kg were not associated with effects that demonstrably constitute a hazard for humans. Because the threshold for disruption of ongoing behavior in nonhuman primates always exceeded a whole-body SAR of 3.2 to 4 W/kg [B15, B17, B18, B19], the latter value has again been adopted as the working threshold for unfavorable biological effects in human beings in the frequency range from 100 kHz to 300 GHz. In terms of human metabolic heat production, 4 W/kg represents a moderate activity level (e.g., housecleaning or driving a truck) and falls well within the normal range of human thermoregulation.

At frequencies between 3 kHz and 100 kHz other mechanisms, such as electro-stimulation of excitable cells, become important. Since the SAR corresponding to thresholds for excitable cell stimulation decreases almost directly as the square of frequency (from above 8 W/kg at 100 kHz to approximately 0.01 W/kg at 3 kHz), a constant SAR cannot be used as a basis for the guidelines below 100 kHz. The thresholds for these biological effects have been quantified in terms of current density in [B8]. A peak current density of $35.0f$ mA/cm^2 (where f is in MHz), is below the reported thresholds for cell stimulation. This limit is used as the basis for the magnetic field guidelines and exclusions for controlled environments, described in Section 5, for the 3 kHz to 100 kHz frequency range. Exclusions for the uncontrolled environment require a lower peak current density limit of $15.7f$ for consistency with the larger safety factor employed for exposures in that group.

6.5 Safety Factors. The concept of a "safety factor" may be intuitively evident to all; yet, it deserves a closer examination. Considered literally, the expression "safety" (condition of being safe; freedom from danger or hazard) "factor" (agent, contributor to effect, element when multiplied by another form a product) means the agent or multiplier producing freedom from hazard. The development of a safety factor presupposes the following:

(1) the identification of the hazard, and
(2) the selection of the multiplier needed to produce freedom from the hazard.

In practice, the better the hazards involved are understood, the better the process. If, as in engineering practice, the phenomenon is catastrophic failure of a material or system under specified stress, and the failures follow a defined distribution about an average value, then it is possible to define a factor applied to the mean for which the probability of catastrophe is known with a specified degree of confidence. Biological hazards commonly pose special difficulties to the formulation of safety factors. For some phenomena, such as ionizing radiation carcinogenesis, the majority view is that the proper form of the dose response curve is linear or linear-quadratic through zero; hence, there is no safety factor at all. For some phenomena the threshold concept may be accepted, but the distribution of responses is inadequately known to formulate a moderately precise factor or margin of safety. The interested reader is referred to [B13] for a review that is both scholarly and pragmatic on the nature and use of inference guidelines for risk management. Particularly noteworthy is the explicit recognition of the need to distinguish between "science" and "science policy" in the formulation of guidelines.

One effect of lack of knowledge is to foster "conservative" assumptions. Not uncommonly, there may be layers, often unidentified, of such assumptions with each layer contributing to the approach to "safety." This is true for ANSI C.95.1-1982 [B1]. The previous standard explicitly invoked a safety factor of 10 on the threshold of 4 W/kg whole-body average SAR, but incorporated numerous "conservative assumptions" or implicit contributions toward "safety." The list (not comprehensive) includes:

(1) the threshold selected itself (evidence of behavioral disruption) is not a defined hazard; rather it was assumed that chronic exposure under such conditions constitutes a health hazard;

(2) the direct extrapolation from animal to man, arguably, is a conservative assumption given the demonstrably superb thermoregulation of man compared to the reference species;
(3) the selection of the far-field, E-polarized "worst case" exposure as the reference condition (the SAR decreases markedly for other polarizations); and
(4) the incorporation in one contour of the resonance frequencies for all size humans (the SAR falls off markedly for frequencies below resonance).

The collective impact of these "conservative" assumptions is to provide a degree of safety or freedom from hazard for a given human over time and space much greater than is implied by the explicit safety factor of ten. In the context of human thermoregulation, the impact of exposure to 0.4 W/kg is practically indistinguishable from the impact of normal ambient temperature variation, exposure to the sun, exercise, etc. The effect of (3) and (4) above greatly reduces the likelihood that the exposure of a given human to the fields permitted under the standard will produce a whole body average SAR of 0.4 W/kg, except at that individual's resonant frequency, oriented for E-polarization in the far-field.

For this present revision, IEEE Subcommittee IV concluded that an additional safety factor is justified only in an uncontrolled environment and then only for exposures that are penetrating or associated with complicating factors like effects from contacting metal objects. At high frequencies where exposure is quasi-optical or for exposure to low-frequency magnetic fields, where the safety factor is already very conservative, there is no need for an extra safety factor, even in an uncontrolled environment.

In summary, the use of a safety factor presupposes the selection of a threshold for a hazard. The existing MPEs are based on the threshold for behavioral disruption with acute (short-term) exposures of experimental animals. The threshold selected was 4 W/kg and the explicit safety factor of 10 or more was applied to obtain a maximum permitted SAR (whole body average) of 0.4 W/kg. In addition to this explicit safety factor, the MPE contains multiple conservative assumptions that constitute implicit or hidden contributions to a less precise but much greater margin of safety. An extra safety factor is justified only for some exposures in an uncontrolled environment.

It is true that safety factor has a clear meaning only if the bioeffects of electromagnetic energy exhibit thresholds. There is no scientific evidence that contradicts this basic assumption.

6.6 Measurement Procedures. Exposure to RF radiation below 3 MHz, and particularly below 100 kHz, requires special consideration and treatment. Practical experience has shown that prevention of electrical shock can be a significant safety consideration. The principal concern arises from the induction of RF currents in conductive objects that are immersed in ambient RF fields. These induced currents may flow through the body of an individual who contacts them. The amount of current that will flow through the body of a person depends on how well the individual is electrically grounded and the impedance between the current source and the individual [B28, B30]. Low-frequency fields can cause potentially hazardous electric currents to flow in capacitive objects such as vehicles, fencing, metal roofing and other supporting metallic cables like guy wires and other ungrounded conducting objects, including the human body, when these objects become adequately grounded [B24, B28]. RF exposures at low frequencies, even at very low field strengths, can cause high values of electrically induced current to flow from large conducting objects to a grounded individual. But, because of the very wide variety of conducting objects in the environment and the diverse opportunities for humans to contact these objects, it is impractical to specify numerical electromagnetic field strength limits that prevent all possible shock and RF burn effects.

The values of electric field strength given in Table 1 could produce a value of about 550-610 mA to flow to ground in a standing adult at 3 MHz. Such a current is significantly above the level of 100 mA normally taken as the threshold for RF burns for small contact (current conduction) areas. Thus, while this standard specifies maximum exposure field strengths, it is recommended that in those cases where such shock and RF-burn conditions may exist, action be taken to prevent their occurrence.

In particular, in conditions where the potential for RF burns exists, mitigation measures should be taken to reduce the induced currents through each foot to below 100 mA for $f > 0.1$ MHz and below $1000f$ mA for $0.003 < f \leq 0.1$ MHz. Possible methods for reducing currents include restricting area access and reduction in source power, shielding and other engineering methods.

Generally, the requirement to measure both electric and magnetic fields below 300 MHz derives from a consideration of the spatial variation in electric and magnetic field strengths commonly found in reflective environments that produce standing-wave exposure fields. In reflective field environments, the two fields are typically out of phase with one another; i.e., the electric and magnetic field strengths will not exhibit maxima at the same point in space relative to the reflective surface. Where the electric field strength is at a peak value, the magnetic field strength may be at a relative minimum value, and vice versa. If the maximum value of a given field parameter determined over the volume of space occupied by the body is used in determining compliance with the MPE, it is important to verify that a true maximum in the given field parameter has been measured. For example, at very-high-frequencies, with wavelengths of approximately a meter and the fields originating from an elevated antenna, the ground reflected fields will oscillate through successive maxima and minima (spaced apart by one-half wavelength) as a function of height above ground.

In this case, it will be found that the plane-wave equivalent power densities, based on the peak electric and magnetic fields, are comparable to one another, even though they occur at different points above the ground plane [B24]. Where measurements of only one of the field parameters are to be made, for example the electric field strength, *because of the relatively short wavelength compared with the size of the human body*, this single measurement would be sufficient to assure that both fields are within the recommended limits over the space that might normally be accessible. As the frequency of the exposure field decreases and the wavelength increases, the distance between the standing wave field maxima will correspondingly increase. At some point, this distance will exceed the range accessible to an individual performing the RF field measurement. Consequently, verifying that one has measured a peak in one of the reflected field distributions will become impossible under normal conditions; i.e., the peak in the field will occur at a height above ground or a distance away from the exposure area that cannot be readily reached. When this is the case, it is possible that while one field component may have relatively low field strength, the other component may possess a relatively high field strength. Should measurements be made of only one of the field components, and this component was of lower strength and within the MPE limits, and its spatial peak could not be verified because of its unreachable location, it is possible that the unmeasured field component might, in fact, be in excess of the MPE. Clearly, at low frequencies, below approximately 30 MHz (wavelength of 10 m), measurement of only one field component could lead to erroneous conclusions as to compliance with the MPE. Accordingly, below 30 MHz, both electric and magnetic fields shall be determined to evaluate compliance of exposure fields with the MPE. Between 30 and 300 MHz it may be possible through analyses to show that measurement of only one of the two fields is sufficient to determine compliance with the MPEs.

In exposure situations where the distribution of field strengths or plane-wave equivalent power densities is substantially non-uniform over the body (partial-body exposure), for frequencies less than 300 MHz, determination of compliance with the MPE field limits may be determined by a spatial average of the exposure fields over the plane occupied by the body but in the absence of the body, where feasible. Nonuniform fields are commonly encountered in reflective conditions such as standing wave fields produced by reflection of fields from the earth or other reflective surfaces. Averaging may be accomplished through the use of real-time data-logging equipment [B58], or via manually obtained point measurements.

For practical measures of compliance with the standard, the average of a series of ten field strength measurements performed in a vertical line with uniform spacing starting at ground level up to a height of 2 m shall be deemed sufficient. In practice, this means that field strength measurements shall be made at heights above ground separated by 20 cm. Additional field strength data, for example, as obtained through the use of data-logging or spatial averaging equipment, obtained at smaller spacings than 20 cm is acceptable and will provide more detail on the spatial distribution of the fields.

The concept of spatial averaging of field strengths is based on the finding that whole-body SARs are related more to the average field strength over the body dimensions than to the peak value at one specific point [B9]. Although it is recognized that additional research is needed to more accurately relate nonuniform field exposures to SARs, the assumption that the whole-body SAR in an individual exposed to nonuniform RF fields is related to the peak value of fields is unnecessarily conservative.

When the wavelength becomes sufficiently small, it is possible that electromagnetic fields can become relatively focused over areas that are small compared to the body dimensions. This is obvious for microwave frequencies above perhaps a few GHz. In this case, limited areas of the body could be exposed to very high power densities, resulting in inadvisable temperature elevations, while the average exposure for the body as a whole might be well within the MPE limits (see 6.2).

Measurements to determine adherence to the recommended MPEs should take into account the fact that several factors influence the response of measurement probes to the field which exists at any given point in space. These factors include the following:

(1) variation of probe impedance with proximity to nearby reflective surfaces,
(2) capacitive coupling between the probe and the field source, and
(3) nonuniform illumination of the sensing elements that make up the probe (for example, the three orthogonal elements that comprise an isotropic, broadband electric field probe) [B39, B55, B56, B57].

The influence of each of these factors, which can result in erroneous measurements of field strengths, can be eliminated by maintaining an adequate separation distance between the probe elements and the field source. Accordingly, measurements should be made at a distance equal to three-probe dimensions between the surface of the nearest probe element and any object or 20 cm, whichever is greater.

In the performance of measurements for determining compliance with the MPE, it is not uncommon to encounter RF hot spots. RF hot spots usually exhibit locally enhanced field conditions near to (within a few probe diameters of) RF sources, conductive surfaces, or objects that act as parasitic sources. The associated electric and/or magnetic fields vary extremely rapidly in radial directions away from the source over dimensions equal to a few probe diameters. Although these highly localized fields can often be extremely intense, their capacity to cause high SARs in tissue is usually significantly reduced when compared to plane waves having the same intensity [B3, B7]. One way of viewing this is to consider the total RF energy that is available in the incident fields if the reradiating object were not there. In general, the reradiated fields cannot contain more energy than was contained in the incident fields [B59]. Obviously, large focusing surfaces could conceivably collect sufficient amounts of incident energy to produce a concentration at a specific point, but this generally occurs only in the microwave frequency range.

SARs that are smaller than might be expected on the basis of the local field strength are partially a function of the field impedances normally associated with hot spots [B50]. For example, very high impedance fields (i.e., high values of E/H) cannot deliver RF energy to nearby absorptive tissues as effectively as lower field impedances. Thus, in these near-field situations involving RF fields with ratios of E to H that are significantly different from plane waves (E/H = 377 ohms), assessment of the resulting SARs in exposed tissues is complicated by the fact that our present state of knowledge does not permit accurately relating such fields to SAR. The determination of this SAR requires either internal field measurements in the tissue [B53] or a thermographic method, neither of which is currently practical for humans, or the measurement of induced tissue-currents that may be related to local SARs through knowledge of tissue geometries and electrical parameters.

Contact currents associated with individuals contacting objects that are exposed to ambient RF fields have been investigated [B54]. A common finding is that conductive objects, when immersed in relatively weak ambient RF fields with strengths less than the applicable MPE, can exhibit locally strong surface fields which may exceed the MPE in the immediate region of the surface of the object. While these surface fields might imply that the MPE is exceeded, measurements of the contact currents that result when touching the object can often be used to determine local SARs in the tissue that are less than the SAR limits inherent to the MPE. Thus, often high-strength surface fields common to reradiating objects do not imply that the MPE SAR limits are exceeded.

6.7 Shock and Burn Hazards. Shock and burn hazards from electric field exposures are mitigated by imposing limits on the magnitude of the rms current (averaged over a 1-second period) allowed to flow from an exposed subject to ground or a conducting object. Maximum current limits are preferable to electric field limits for preventing shocks and burns, since maximum induced current levels are a function of the size, shape, and impedance to ground of the contacted object, as well as the uniformity of the exposure field, presence of nearby objects, and type of footwear and clothing worn by the exposed subject.

The current limits specified in Table 1, Part B, and Table 2, Part B, and current density limits for the basis of the exclusions in 4.2, have been set below the threshold for shock perception and cell stimulation in the exposed subject. The current density limits for the uncontrolled environment are reduced to account for the increase in the safety factor adopted for those conditions. The specified limits are also below thresholds for the production of burns from direct contact with metal objects. It should be noted, however, that the specified levels of current provide protection from shock or burn *only* under conditions of direct contact and *do not* protect against spark discharge phenomena associated with making or breaking contact with conducting objects. The perception threshold of spark discharge is a complicated function of many variables. These include frequency, induced open-circuit voltage and capacitance between the conducting object and exposed person, temperature, speed of making or breaking contact, bodily location where contact is made, and other variables. Although much quantitative research has helped to solve this problem for 60-Hz electric field exposures, insufficient archival data exist to formulate MPEs for exposures at other frequencies.

6.8 Averaging Time. Averaging time is the appropriate time period over which exposure ($|E|^2$, $|H|^2$ or S) is averaged, for the purpose of determining compliance with the standard. Because the present revision of the standard introduces many refinements, it is necessary to permit averaging time, as well as the limits on E, H or S, to be frequency-dependent. This permits the transition from values of minutes for averaging time in the resonance range, to values of seconds for the averaging time suitable at infrared frequencies. This transition appropriately reflects the frequency-dependent change in thermal time constant that characterizes the heating of the whole or part of the human body by exposure to radiofrequency energy. At low frequencies, frequency-dependence in averaging time is used to permit a continuous transition between an MPE that is identical for controlled and uncontrolled environments (below 1.34 MHz), to the existence of two different MPEs in the resonance range. Here, the lower MPEs for the uncontrolled environment are tempered by a longer averaging time to allow for transient exposures. The rules always insure, however, that the SA in an uncontrolled environment will be less than or equal to the corresponding SA permitted in a controlled environment, even in the transition range where either or both of the field limits and averaging time are frequency-dependent.

The reduction of the averaging time with increasing frequency precludes high SARs for short periods (seconds) in decreasingly thin layers of skin and subcutaneous tissue that otherwise could result in skin burns. Since the penetration depth at frequencies above 30 GHz is similar to that at visible and near infrared wavelengths, the literature for skin burn thresholds for optical radiation is expected to be applicable. Thus, the averaging time (10 s) and MPE (10 mW/cm^2), at 300 GHz, are consistent with the averaging time and MPE, at a wavelength of 1 mm, specified in ANSI Z136.1-1986 [B2]. These MPEs are derived from the biological database for skin burns and apply to irradiation of large areas (greater than 1000 cm^2).

In uncontrolled environments, the appropriate averaging time for exposure to electric fields (Table 2) is 0.5 hr. (30 min) for frequencies between 3 MHz and 3 GHz. For frequencies between 15 GHz and 300 GHz, the appropriate averaging time is given by the formula $T_{avg} = 616\ 000/f^{1.2}$ where f is the frequency in MHz. Between 3 and 15 GHz the averaging time follows the function $T_{avg} = 90\ 000/f$. The increased averaging time addresses typical expected transient exposures to E fields in uncontrolled environments. Since the MPE in Table 2 is 1/5 of the MPE in Table 1, the maximum SA over the averaging time of each MPE is the same for E field exposures. For exposure times less than the averaging time in Table 1, the two MPEs are identical. Below 1.34 MHz, the averaging time is the same (6 minutes) for either a controlled or uncontrolled environment.

For exposures to low-frequency magnetic fields where the limits are the same for both controlled and uncontrolled environments, the averaging time is the same, i.e., 6 minutes. However, the averaging time changes to 30 min above the transition region 30-100 MHz. Above 100 MHz, power density becomes a meaningful exposure parameter and the associated E and H field limits must be consistent with plane-wave equivalence. Below 30 MHz, however, E and H field exposures can occur separately, and the respective MPEs follow different rules of frequency dependence because of the important difference in the nature of potential bioeffects. H fields heat biologic tissue and induce internal currents less effectively than E fields.

The application of the MPEs at low frequencies assures that induced currents are prevented or limited by measures other than imposition of field limits. Since the time averaging of induced currents is over a period of one second, the likelihood of permitted exposures to E or H fields greatly exceeding the long term limits is small and restricted to special situations.

6.9 Peak Power Exposure. Peak power limits are provided to prevent unintentionally high exposure and to preclude high SA for decreasingly short widths of RF pulses. For some time, it has been recognized that the lack of such consideration in the standard has allowed the peak power density to rise arbitrarily, as long as average power density met the standard.

Furthermore, under exposure to pulsed fields it is advisable to be conservative in view of some uncertainty about the value of spatial peak SAR, which could be over twenty times the spatially-averaged SAR. Under pulsed conditions (less than 100 ms pulses), the allowable MPE as averaged over any 100 ms is reduced by a factor of five times.

For a single pulse, this is equivalent to reducing the maximum permissible peak power density by a factor of five times below the value that normal time averaging would permit. A maximum of five such pulses are permitted during any period equal to the averaging time. If there are more than five pulses in any period equal to the averaging time, normal time-averaging will further reduce the permissible peak power density.

The limits on peak power are the values obtained by consideration of a well-established scientific base of data that includes the auditory effect in humans and radio-frequency energy-induced unconsciousness in rats [B11, B33, B36, B45, B46, B47, B48, B49]. The limit on SA associated with the reduced averaging time [4.1.1(g) and 4.1.2(g)] is conservative relative to RF-induced unconsciousness and is well above the threshold for auditory effect. The latter is clearly not deleterious. For example, in the microwave range for exposures to a single pulse, the SA over any six-minute period is limited to 28.8 J/kg (spatial average) and 576 J/kg (spatial peak), assuming a ratio of twenty to one between peak and average.

For low frequencies and short pulses, the more conservative limit of 100 kV/m [4.1.1(f)] takes precedence over the SA limit [4.1.1(g)]. For high frequencies and longer pulses, the SA limit [4.1.1(g)] is more conservative than the 100 kV/m limit [4.1.1(f)]. The recommendation for a peak E-field limit of 100 kV/m is based on the necessity to cap the allowable field below levels at which air breakdown or spark discharges occur. The level chosen is ultraconservative in this regard, and represents an absorbed energy which is also more conservative than the continuous-wave limit over pulse lengths for which it is intended. This conservatism is prudent in light of the relative sparseness of studies for very-short high-intensity exposures. Such studies as do exist are reassuring that this level is indeed far below the threshold for adverse effects.

6.10 Exclusions and Relaxation of Limits for Partial Body Exposure. Under certain conditions, the only practical way to cope with the problems of exposures to nonuniform fields and low-power devices is by means of exclusion clauses that allow the local incident field strengths (and the plane-wave equivalent power density, where applicable) to exceed the general MPE.

The exclusions are based on the following considerations:

(1) The general provisions of the standard should not be violated. The whole-body averaged SAR during localized exposure should be limited to 0.4 W/kg and 0.08 W/kg for, respectively, controlled and uncontrolled environments. Previous studies have shown that peak SARs in a biological body can be 10 to 20 times higher than the average SAR [B37]. If the peak value of the mean-squared field strengths and the equivalent power densities are in accordance with the provision of 4.4, then the general provisions of the MPE will not be violated under conditions of partial body exposure or exposure to non-uniform fields.

(2) Laboratory studies have shown that it is unlikely for devices such as low-power handheld radios (where the radiating structure is not maintained 2.5 cm or less from the body) to expose the user in excess of the exclusion criterion for the controlled environment (4.2.1), or other persons in the immediate vicinity of the user in excess of the criterion for the uncontrolled environment (4.2.2), if the radiated power is 7 W or less at frequencies between 100 kHz and 450 MHz, and 7(450/*f*) W or less at frequencies between 450 and 1 500 MHz [B4, B5, B12]. Further, these studies have also shown that similar devices will not expose the user in excess of the exclusion criterion for the uncontrolled environment (4.2.2) if the radiated power is 1.4 W or less at frequencies between 100 kHz and 450 MHz, and 1.4(450/*f*) W or less at frequencies between 450 and 1 500 MHz.

Therefore, these exclusions have been included in this standard to allow the pertinent MPE to be exceeded if it can be shown that:

(i) the SAR averaged over the whole-body and over the appropriate averaging time does not exceed 0.4 W/kg and 0.08 W/kg for, respectively, exposure in controlled and uncontrolled environments and;

(ii) the spatial peak value of the SAR averaged over any 1 g of tissue (defined as a tissue volume in the shape of a cube) and over the appropriate averaging time does not exceed 8 W/kg (controlled environment) or 1.6 W/kg (uncontrolled environment) in the body,and over any 10 g of tissue (defined as a tissue volume in the shape of a cube) and over the appropriate averaging time does not exceed 20 W/kg (controlled environment) or 4 W/kg (uncontrolled environment) in wrists, ankles, hands and feet. The

20 W/kg limit for the wrists and ankles allows higher absorptions in the soft tissues produced by the induced currents specified in Table 1 flowing in these bony, narrow cross-sectional areas. Considerations that mitigate these higher permitted local SARs include relatively high surface-to-volume ratios for these parts of the body, the common experience of relatively large temperature excursions of these parts that normally occur without apparent adverse effects, and the lack of critical function when compared to vital organs.

It is also recognized that, in some cases, it may be difficult to determine whether a particular RF exposure would meet these absorption criteria, and, therefore, could be done only in a laboratory setting or by an appropriate scientific body. In many cases, however, the determination could be made with an appropriate source material, e.g., dosimetry handbooks [B22]. Detailed measurements of the field distribution over the volume of the human body and spatial averaging over the same volume could, in some instances, be used to verify compliance with the relaxation of limits for partial body exposure. In the case of the eyes and testes, direct relaxation of power density limits is not permitted. However, the SAR exclusion rules still apply.

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Appendix A
Final List of Papers Comprising Data Base

(The following Appendixes are not a part of IEEE C95.1-1991, IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHZ to 300 GHz, but are included for information only.)

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Appendix B
Final List of Papers Reviewed for IEEE C95.1-1991

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Appendix C
Exposure Calculations for Multiple Sources

When a number of sources at different frequencies, and/or broadband sources contribute to the total exposure, it becomes necessary to weigh each contribution relative to the MPE in accordance with the provisions of 4.1.1 (e) and 4.1.2 (e). To comply with the MPE, the fraction of the MPE in terms of E^2, H^2 (or power density) incurred within each frequency interval should be determined and the sum of all such fractions should not exceed unity. The following example illustrates this:

Measurements were made in a controlled environment at a point near several induction heaters (IH) and dielectric heaters (DH). The values below present the electric and magnetic field strengths as averaged over an area equivalent to the vertical cross section of an adult.

Source	Frequency (MHz)	Electric Field Strength (V/m)	Magnetic Field Strength (A/m)	Duty Factor (%)
DH_1	27.5	90	0.1	20
DH_2	7.5	283	0.2	60
DH_3	3.5	592	0.4	45
IH_1	0.400	15	8	100
IH_2	0.900	21	4	100
IH_3	8.035	30	0.2	100

In order to ensure compliance with the MPE for a controlled environment, the sum of the ratios of the time averaged squares of the measured electric field strength to the corresponding squares of the MPE, and the sum of the ratios of the time averaged squares of the measured magnetic field strength to the corresponding squares of the MPE, should not exceed unity. That is:

$$\sum_{i=1}^{n} \frac{E_i^2}{MPE_i^2} \leq 1$$

and

$$\sum_{i=1}^{n} \frac{H_i^2}{MPE_i^2} \leq 1$$

Applying this to the data above yields

$$\sum_{i=1}^{n} \frac{E_i^2}{MPE_i^2} = \frac{0.2(90)^2}{67^2} + \frac{0.6(283)^2}{246^2} + \frac{0.45(592)^2}{526^2} + \frac{15^2}{614^2} + \frac{21^2}{614^2} + \frac{30^2}{230^2} = 1.74 > 1$$

$$\sum_{i=1}^{n} \frac{H_i^2}{MPE_i^2} = \frac{0.2(0.1)^2}{(0.6)^2} + \frac{0.6(0.2)^2}{(2.2)^2} + \frac{0.45(0.4)^2}{(4.7)^2} + \frac{8^2}{(40.8)^2} + \frac{4^2}{(18.1)^2} + \frac{0.2^2}{(2.0)^2} = 0.11 < 1$$

In order to comply with the provisions of the MPE, both summation must be less than unity. Although the summation in terms of magnetic field strength is less than unity, the summation in terms of electric field strength exceeds unity and, therefore, the MPE for controlled environment is exceeded.

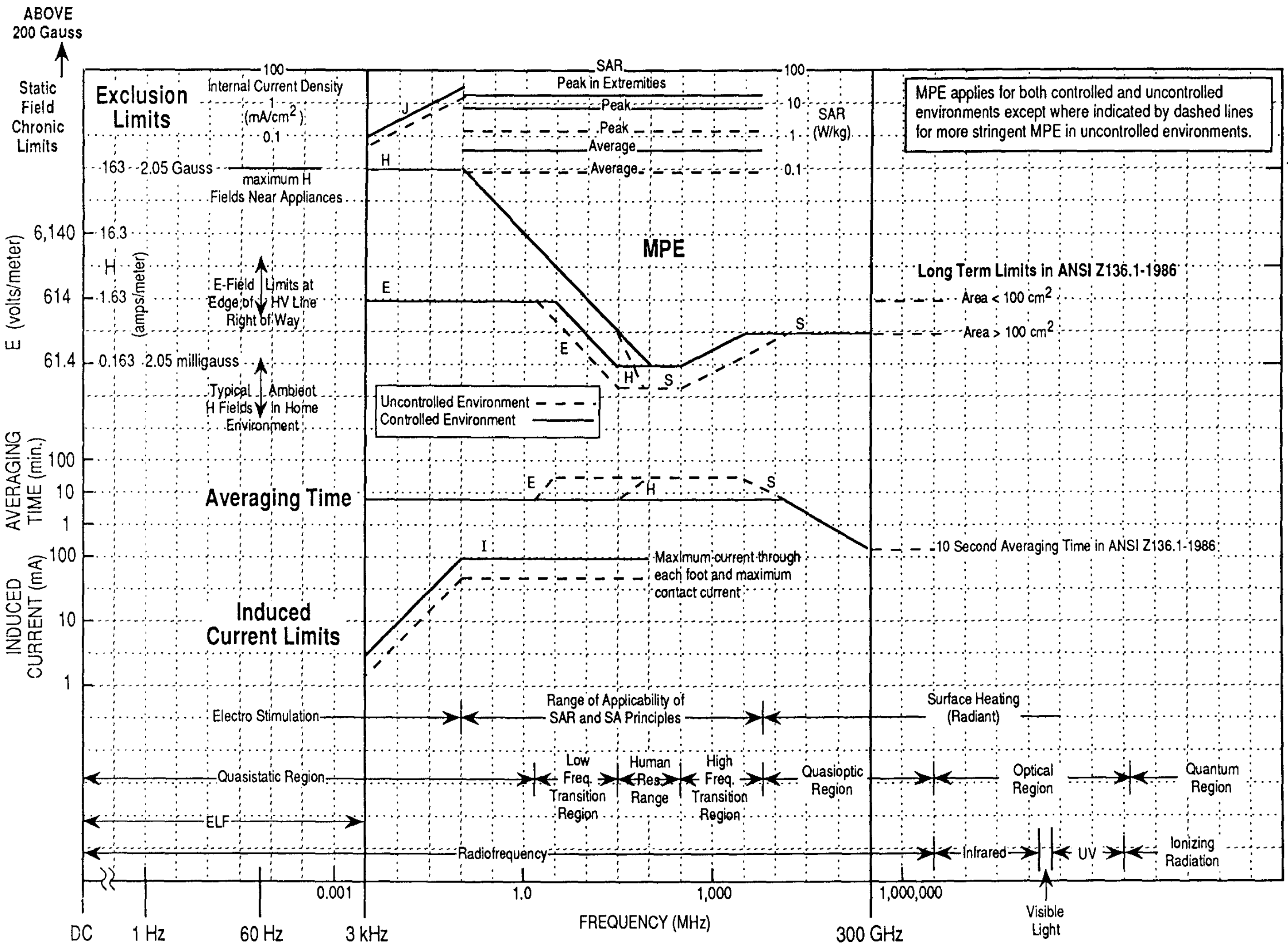


Fig A1
Capsule Guide to the Standard

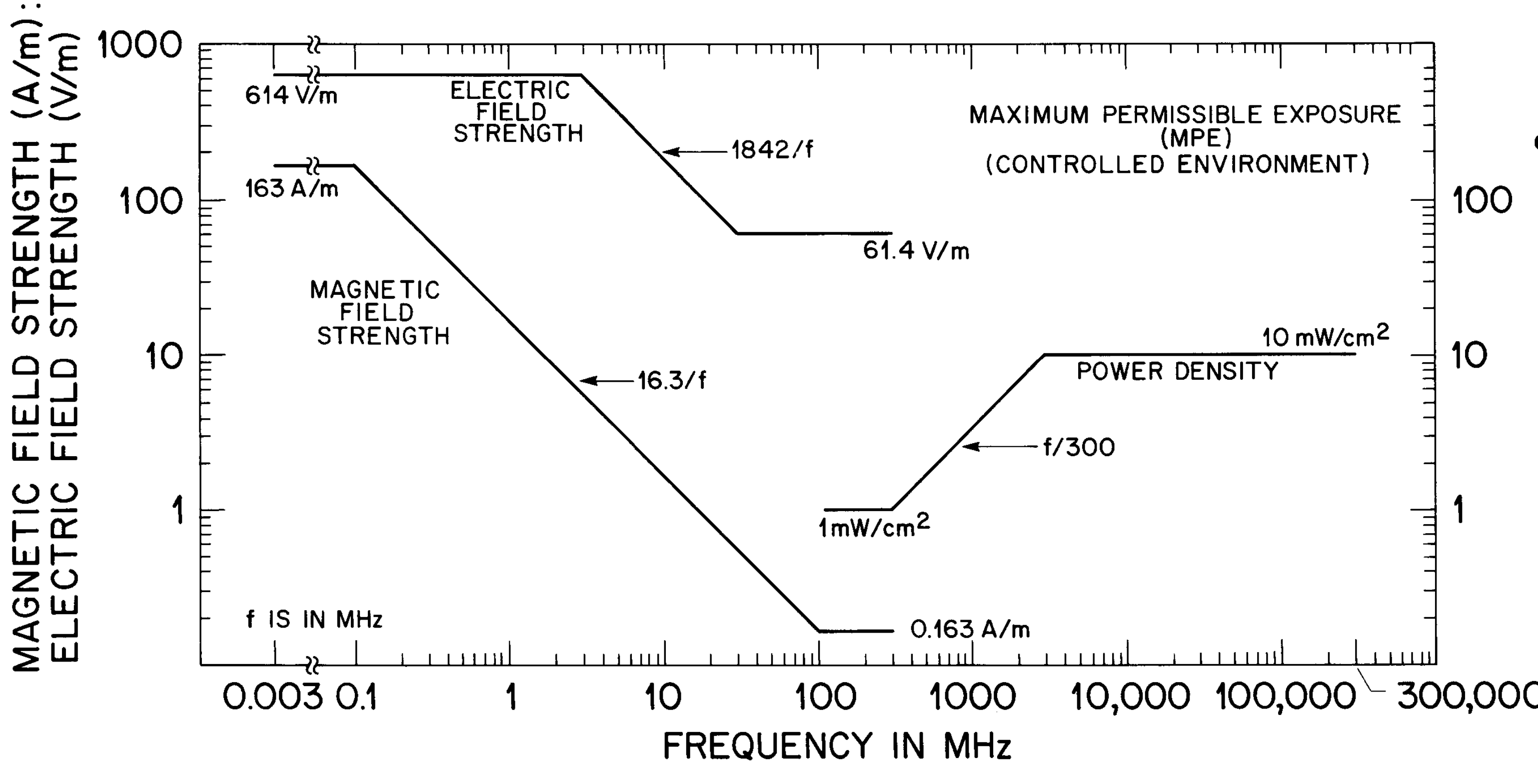


Fig A2
Graphic Representation of Maximum Permissible Exposure in Terms of Fields and Power Density for a Controlled Environment.

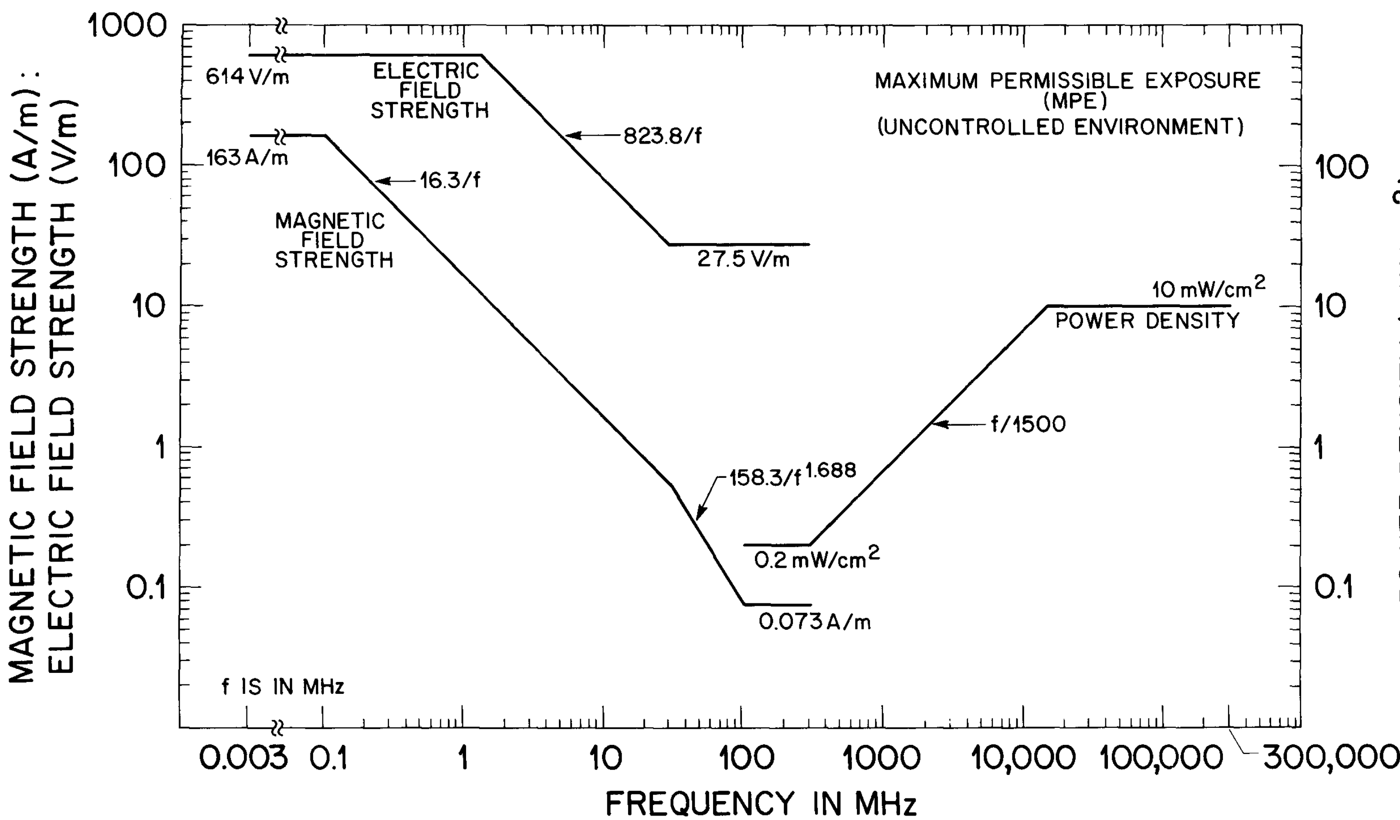


Fig A3
Graphic Representation of Maximum Permissible Exposure in Terms of Fields and Power Density for an Uncontrolled Environment.

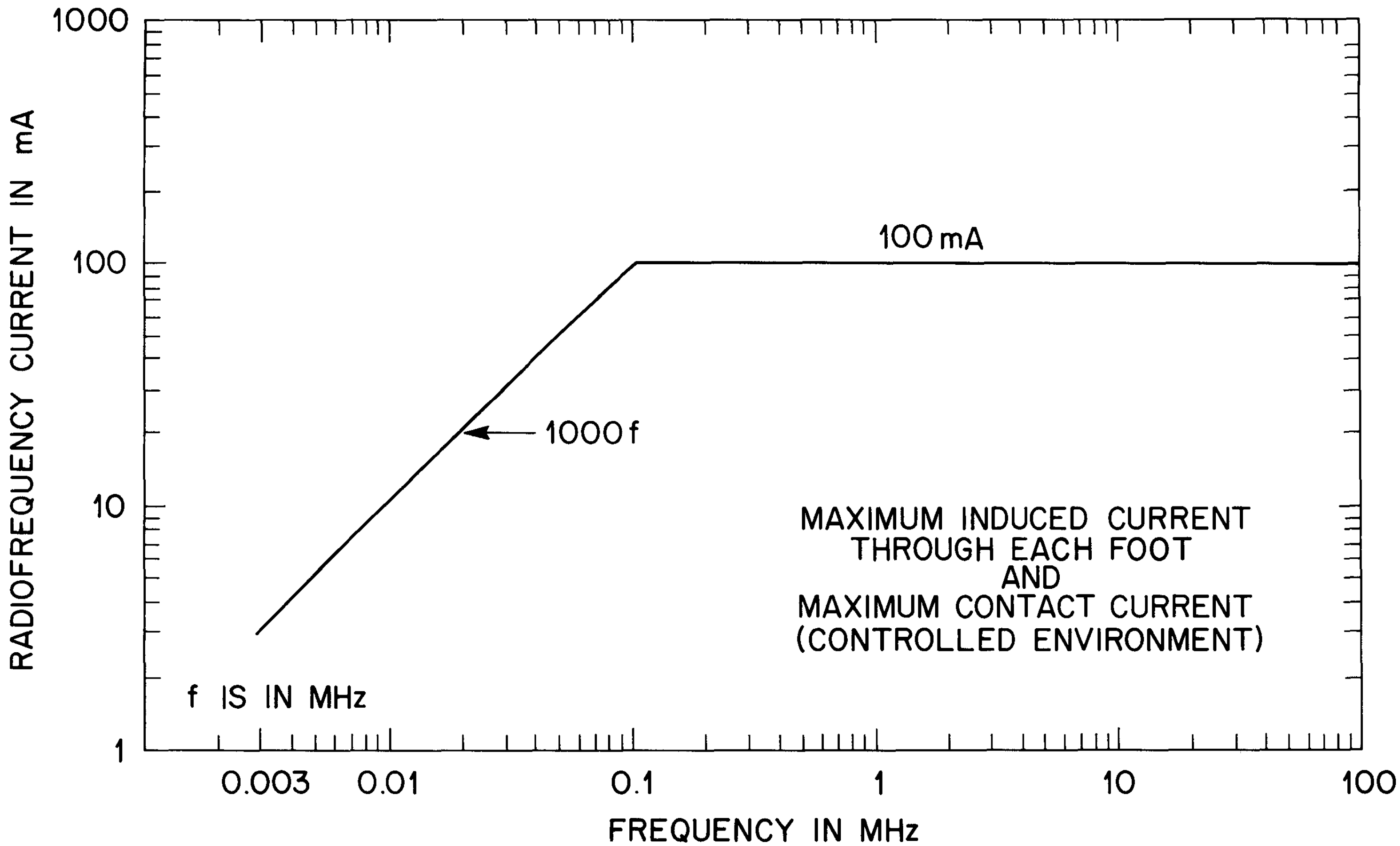


Fig A4
Graphic Representation of Maximum Permissible Exposure in Terms of Induced Current for a Controlled Environment

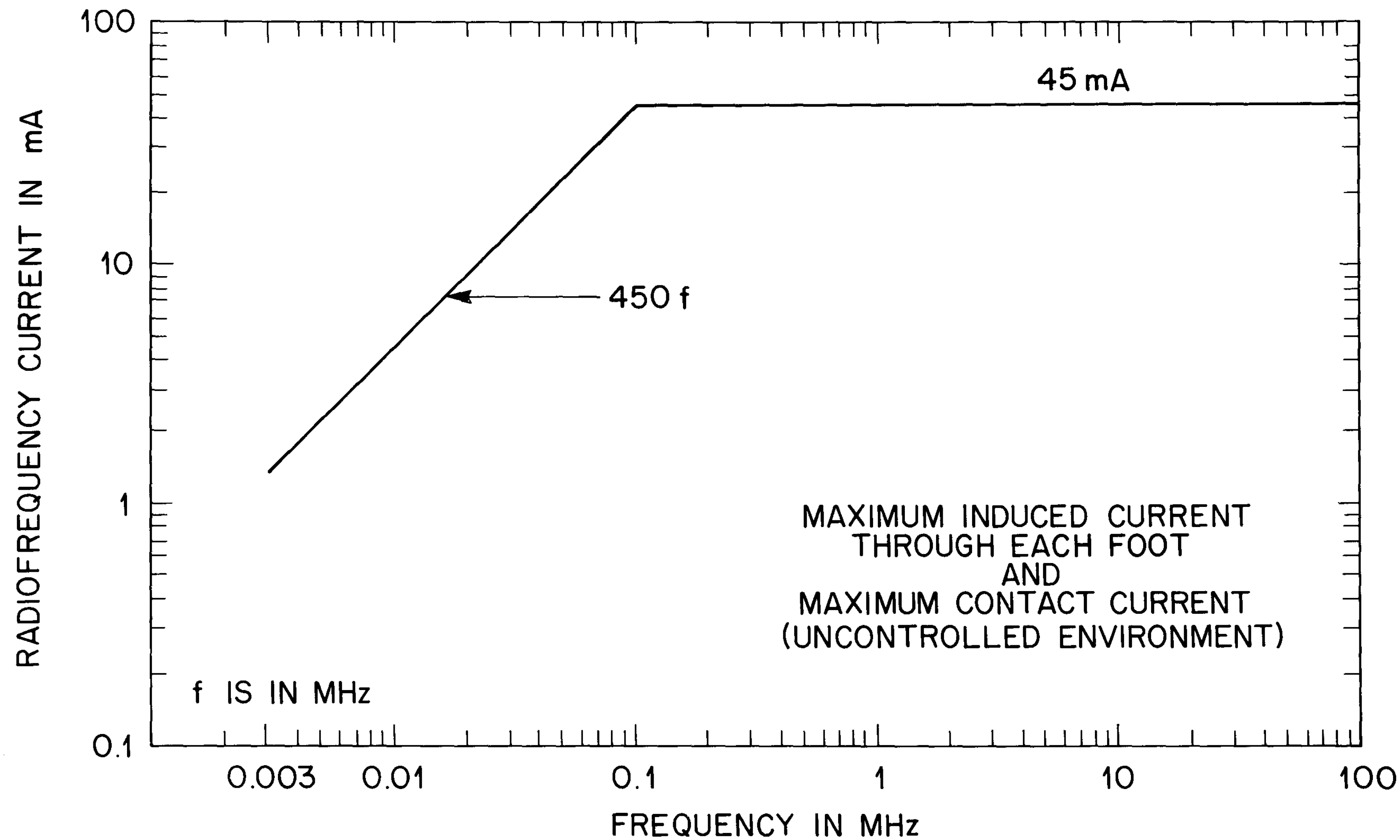
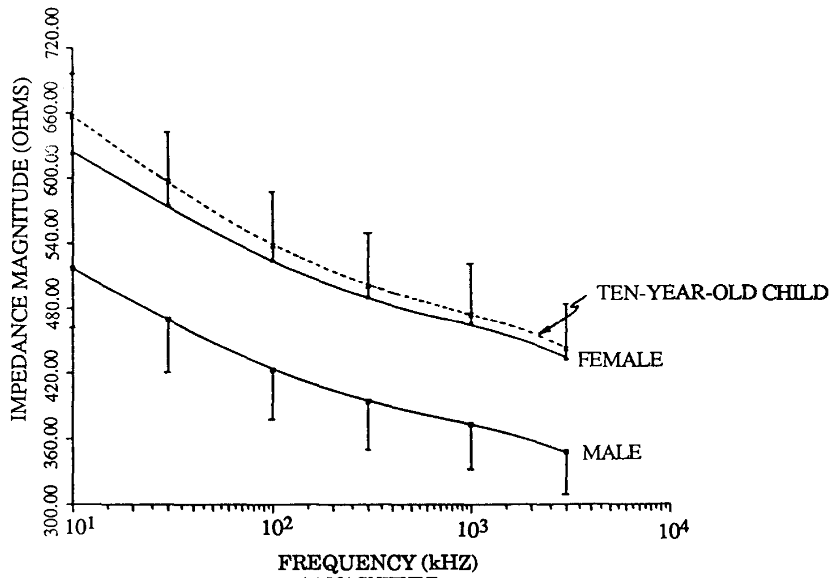
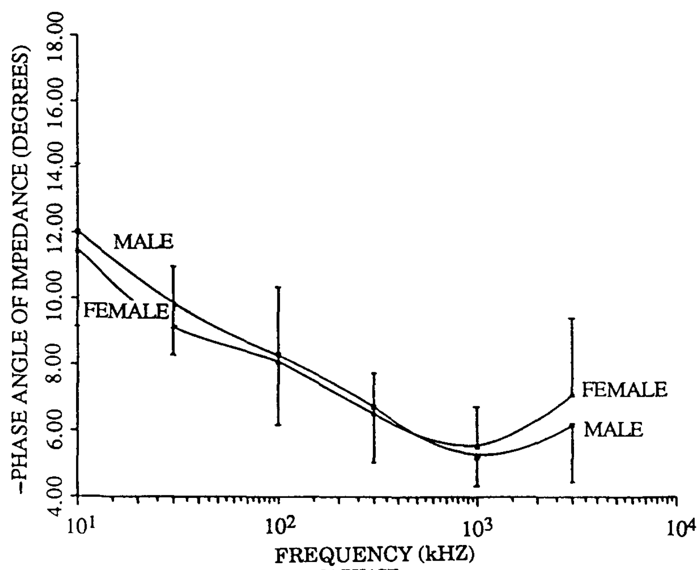


Fig A5
Graphic Representation of Maximum Permissible Exposure in Terms of Induced Current for an Uncontrolled Environment.



(a) MAGNITUDE



(b) PHASE

[From Chatterjee et al. (1986)]

Fig A6
Average Body Impedance of Adult Males (N=197), Adult Females (N=170), and Ten-year-old Children (dashed line) for Grasping Contact: (a) magnitude, and (b) phase

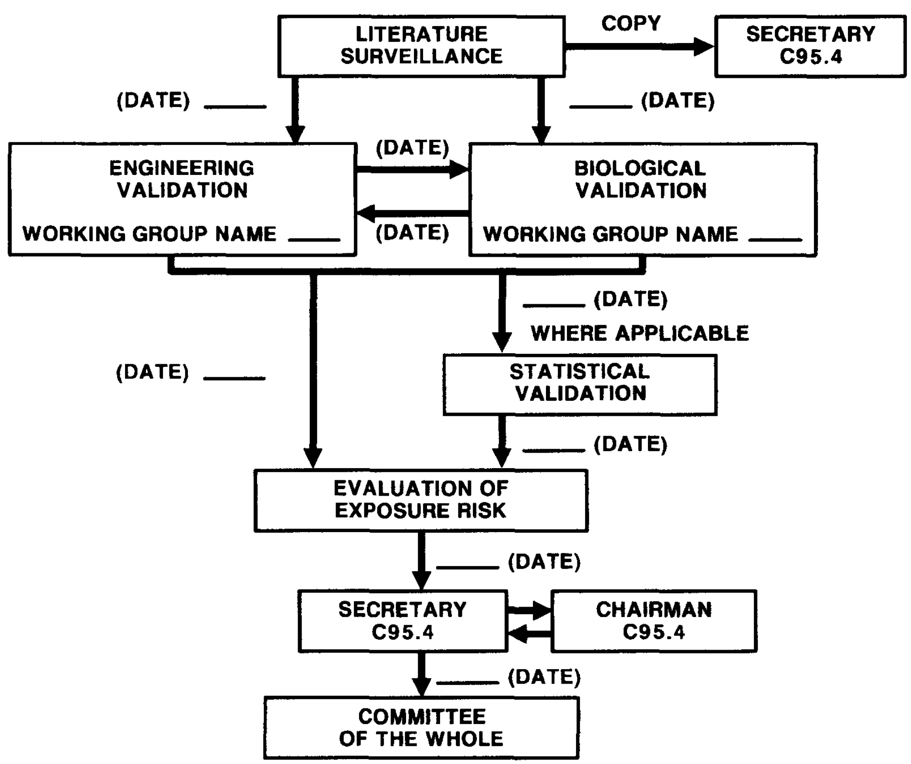


Fig A7
IEEE Standards Coordinating Committee 28 Flow Chart