



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

Sponsored by the
IEEE International Committee on Electromagnetic Safety (SCC39)

IEEE
3 Park Avenue
New York, NY 10016-5997, USA
19 April 2006

IEEE Std C95.1™-2005
(Revision of IEEE Std C95.1-1991)

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

Sponsor

IEEE International Committee on Electromagnetic Safety (SCC39)

Approved 3 October 2005

IEEE-SA Standards Board

Recognized as an American National Standard

Abstract: Recommendations to protect against harmful effects in human beings exposed to electromagnetic fields in the frequency range from 3 kHz to 300 GHz are provided in this standard. These recommendations are intended to apply in controlled environments and for general population exposure. These recommendations are not intended to apply to the exposure of patients by or under the direction of physicians and medical professionals.

Keywords: basic restriction (BR), maximum permissible exposure (MPE), radio frequency (RF), RF exposure, RF safety, specific absorption rate (SAR)

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

Copyright © 2006 by the Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 19 April 2006. Printed in the United States of America.

IEEE is a registered trademark in the U.S. Patent & Trademark Office, owned by the Institute of Electrical and Electronics Engineers, Incorporated.

Print: ISBN 0-7381-4834-2 SH95389
PDF: ISBN 0-7381-4835-0 SS95389

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

IEEE Standards documents are developed within the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association (IEEE-SA) Standards Board. The IEEE develops its standards through a consensus development process, approved by the American National Standards Institute, which brings together volunteers representing varied viewpoints and interests to achieve the final product. Volunteers are not necessarily members of the Institute and serve without compensation. While the IEEE administers the process and establishes rules to promote fairness in the consensus development process, the IEEE does not independently evaluate, test, or verify the accuracy of any of the information contained in its standards.

Use of an IEEE Standard is wholly voluntary. The IEEE disclaims liability for any personal injury, property or other damage, of any nature whatsoever, whether special, indirect, consequential, or compensatory, directly or indirectly resulting from the publication, use of, or reliance upon this, or any other IEEE Standard document.

The IEEE does not warrant or represent the accuracy or content of the material contained herein, and expressly disclaims any express or implied warranty, including any implied warranty of merchantability or fitness for a specific purpose, or that the use of the material contained herein is free from patent infringement. IEEE Standards documents are supplied “**AS IS.**”

The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE Standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard. Every IEEE Standard is subjected to review at least every five years for revision or reaffirmation. When a document is more than five years old and has not been reaffirmed, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE Standard.

In publishing and making this document available, the IEEE is not suggesting or rendering professional or other services for, or on behalf of, any person or entity. Nor is the IEEE undertaking to perform any duty owed by any other person or entity to another. Any person utilizing this, and any other IEEE Standards document, should rely upon the advice of a competent professional in determining the exercise of reasonable care in any given circumstances.

Interpretations: Occasionally questions may arise regarding the meaning of portions of standards as they relate to specific applications. When the need for interpretations is brought to the attention of IEEE, the Institute will initiate action to prepare appropriate responses. Since IEEE Standards represent a consensus of concerned interests, it is important to ensure that any interpretation has also received the concurrence of a balance of interests. For this reason, IEEE and the members of its societies and Standards Coordinating Committees are not able to provide an instant response to interpretation requests except in those cases where the matter has previously received formal consideration. At lectures, symposia, seminars, or educational courses, an individual presenting information on IEEE standards shall make it clear that his or her views should be considered the personal views of that individual rather than the formal position, explanation, or interpretation of the IEEE.

Comments for revision of IEEE Standards are welcome from any interested party, regardless of membership affiliation with IEEE. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments. Comments on standards and requests for interpretations should be addressed to:

Secretary, IEEE-SA Standards Board
445 Hoes Lane
Piscataway, NJ 08854
USA

NOTE—Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken with respect to the existence or validity of any patent rights in connection therewith. The IEEE shall not be responsible for identifying patents for which a license may be required by an IEEE standard or for conducting inquiries into the legal validity or scope of those patents that are brought to its attention.

Authorization to photocopy portions of any individual standard for internal or personal use is granted by the Institute of Electrical and Electronics Engineers, Inc., provided that the appropriate fee is paid to Copyright Clearance Center. To arrange for payment of licensing fee, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; +1 978 750 8400. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center. Authorization to photocopy portions of any individual standard for internal or personal use is granted by the Institute of Electrical and Electronics Engineers, Inc., provided that the appropriate fee is paid to Copyright Clearance Center. To arrange for payment of licensing fee, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; +1 978 750 8400. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Introduction

This introduction is not part of IEEE Std C95.1-2005, 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, Inc. Prior to 1988, C95 standards were developed by Accredited Standards Committee C95, and submitted to the American National Standards Institute (ANSI) for approval and issuance as ANSI C95 standards. Between 1988 and 1990, the committee was converted to Standards Coordinating Committee 28 (SCC 28) under the sponsorship of the IEEE Standards Board. In 2001, the IEEE Standards Association Standards Board approved the name “International Committee on Electromagnetic Safety (ICES)” for SCC 28 to better reflect the scope of the committee and its international membership. In accordance with policies of the IEEE, C95 standards are issued and developed as IEEE standards, as well as submitted to ANSI for recognition.

In 2005, SCC 28 and SCC 34 became Technical Committees 95 and 34, respectively, under a new committee, SCC 39, which is now called ICES.

The present scope of IEEE ICES is as follows:

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

Subcommittee 4 of ICES Technical Committee 95 (TC95) is responsible for this standard. There are five TC95 subcommittees, each of whose area of responsibility is described below in correspondence with its designated subcommittee number:

- 1) Techniques, Procedures, and Instrumentation;
- 2) Terminology, Units of Measurements and Hazard Communication;
- 3) Safety Levels with Respect to Human Exposure, 0-3 kHz;
- 4) Safety Levels with Respect to Human Exposure, 3 kHz-300 GHz;
- 5) Safety Levels with Respect to Electro-Explosive Devices.

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

IEEE Std 1460TM-1996 (R2002), IEEE Guide for the Measurement of Quasi-Static Magnetic and Electric Fields.

IEEE Std C95.1TM-2005, IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz.

NOTE—The recommendations in this standard protect against scientifically established adverse health effects in human beings resulting from exposure to radio frequency electromagnetic fields in the frequency range of 3 kHz to 300 GHz. Other effects that have been reported in the literature but have not been confirmed or could not be related to human health have been considered and are discussed in Annex B and Annex C of this standard.

IEEE Std C95.2TM-1999 (R2005), IEEE Standard for Radio-Frequency Energy and Current Flow Symbols.

IEEE Std C95.3TM-2002, Recommended Practice for Measurements and Computations of Radio Frequency Electromagnetic Fields with Respect to Human Exposure to Such Fields, 100 kHz-300 GHz.

IEEE Std C95.4TM-2002, IEEE Recommended Practice for Determining Safe Distances from Radio Frequency Transmitting Antennas When Using Electric Blasting Caps During Explosive Operations.

IEEE Std C95.6TM-2002, IEEE Standard for Safety Levels With Respect to Human Exposure to Electromagnetic Fields, 0-3 kHz.

IEEE Std C95.7TM-2005, IEEE Recommended Practice for Radio Frequency Safety Programs, 3 kHz to 300 GHz.

Notice to users

Errata

Errata, if any, for this and all other standards can be accessed at the following URL: <http://standards.ieee.org/reading/ieee/updates/errata/index.html>. Users are encouraged to check this URL for errata periodically.

Interpretations

Current interpretations can be accessed at the following URL: <http://standards.ieee.org/reading/ieee/interp/index.html>.

Participants

This standard was prepared by Subcommittee 4 (Safety Levels with Respect to Human Exposure, 3 kHz-300 GHz) of IEEE ICES SCC 28 (now ICES TC-95). The following persons contributed to the development of this standard:

Chung-Kwang Chou, *Co-Chair*
John D'Andrea, *Co-Chair*
Ronald Petersen, *Secretary*

Eleanor Adair
Max Ammann
Vitas Anderson
Edward Aslan
Tadeusz Babij
William Bailey
Quirino Balzano
David Baron
Howard Bassen
John Bergeron
David Black
Dennis Blick
Ralf Bodemann
Aviva Brecher
Jerrold Bushberg
Philip Chadwick
Kazuhiku Chikamoto
Robert Cleveland
Jules Cohen
Roger Coghill
Robert Curtis
Howard Cyr
John DeFrank
Abiy Desta
David Dini
Thanh Dovan
Gregor Durrenberger
Amnon Duvdevany
Joe Elder
Linda Erdreich
Alice Fahy-Elwood
David Fichtenberg

Kenneth Foster
Om Gandhi
David George
Kenneth Gettman
Margaret Glaser
George Goldberg
Gregory Gorsuch
Arthur Guy
Donald Haes
Konstantinos Halkiotis
Wayne Hammer
James Hatfield
Janet Healer
Donald Heirman
Louis Heynick*
William Hurt
Michel Israel
Veronica Ivans
Sheila Johnston
Kenneth Joyner
Shaiela Kandel
Kimberly Kanter
Jolanta Karpowicz
B Jon Klauenberg
Niels Kuster
Sakari Lang
John Leonowich
Dariusz Leszczynski
James Lin
Gregory Lotz
Edward Mantiplay
Patrick Mason
Raymond McKenzie

Tom McManus
Martin Meltz
Joeseeph Morrissey
Michael Murphy
Robert Needy
John Osepchuk
Russell Owen
Peter Polson
Kenneth Proctor
J Patrick Reilly
Brad Roberts
Terence Rybak
Theodoros Samaras
Veli Santomaa
William Scanlon
Asher Sheppard
David Sliney
Mays Swicord
John Tattersall
Richard Tell
Thomas Tenforde
Paul Testagrossa
Artnarong Thansandote
Santi Tofani
Don Umbdenstock
Eric van Rongen
Arthur Varanelli
Robert Weller
Louis Williams
Richard Woods
Done-Sik Yoo
Marvin Ziskin

*Deceased

The following members of the individual balloting committee voted on this standard. Balloters may have voted for approval, disapproval, or abstention.

Eleanor Adair
Max Ammann
Reza Arefi
Quirino Balzano
David Baron
Howard Bassen
John Bergeron
Dennis Blick
Ralf Bodemann
Aviva Brecher
Jerrold Bushberg
Chung-Kwang Chou
Robert Cleveland
Jules Cohen
John D'Andrea
John DeFrank
Guru Dutt Dhingra
David Dini
David Fichtenberg

Kenneth Foster
Kenneth Gettman
Margaret (Marne) Glaser
Arthur W. Guy
Donald Haes
Edward Hare
James Hatfield
Philip Hopkinson
Masateru Ikehata
Veronica Ivans
Sheila Johnston
Kenneth Joyner
Efthymios Karabetsos
Joseph L. Koepfinger
Sakari Lang
John Leonowich
Arthur Light
Martin L. Meltz
Abdul Mousa

Michael Murphy
Michael Newman
John Osepchuk
Ron Petersen
Peter Polson
Vikram Punj
J Patrick Reilly
Markus Riederer
Ervin Root
Veli Santomaa
William Scanlon
Asher Sheppard
Mays Swicord
Richard Tell
Paul Testagrossa
Artnarong Thansandote
Arthur Varanelli
Dale Watts
Louis Williams
Donald W. Zipse

The following persons were members of ICES SCC 28 (now ICES TC-95) at the time this standard was approved:

Ronald Petersen, *Chair*
Ralf Bodemann, *Vice Chair*
Eleanor Adair, *Secretary*

Melvin Altman
Max Amann
Vitas Anderson
Edward Aslan
Quirino Balzano
David Baron
Howard Bassen
John Bavin
Pascale Bellier
John Bergeron
David Black
Denis Blick
Aviva Brecher
Jerrold Bushberg
Philip Chadwick
Scott Chesnick
Huai Chiang
Stephen Chiusano
Chung-Kwang Chou
Robert Cleveland
Roger Coghill
Jules Cohen
Robert Curtis
James Daly
John D'Andrea
Linda deJager
John DeFrank
John deLorge
David Dini
Guglielmo d'Inzeo
Thanh Dovan
Gregor Durrenberger
Leon DuToit
Linda Erdreich
Stewart Fastman
William Feero
Kenneth Foster
Peter Gajsek
Om Gandhi
Robert Gardner

David George
Martino Grandolfo
Arthur Guy
Donald Haes
Konstantinos Halkiotis
Robert Hanna
Edward Hare
James Hatfield
Donald Heirman
Paul Heroux
Louis Heynick*
Jeff Holley
Masatero Ikehata
Michel Israel
Veronica Ivans
Kent Jaffa
Sheila Johnston
Kenneth Joyner
Shaiela Kandel
Efthymios Karabetsos
Raymond Kemp
Nam Kim
James King
B Jon Klauenberg
George Koban
Joeseph Koepfinger
Niels Kuster
Anthony LaMastra
Sakari Lang
John Leonowich
Dariusz Leszczynski
James Lin
Constantine Maletskos
Nisakorn Manatrakul
Patrick Mason
Stewart Maurer
Tom McManus
James McNamee
Martin Meltz
Noel Montgomery

Michael Moore
Amitabha Mukopadhyay
Michael Murphy
David Nelson
Kwan-Hoong Ng
John Osepchuk
Andrei Pakhomov
William Paul
Bertil Persson
Paolo Ravazzani
J Patrick Reilly
Michael Repacholi
Brad Roberts
Ervin Root
Theodoros Samaras
Veli Santomaa
Herman Schwan*
Willaim Scanlon
Asher Sheppard
Jon Sirugo
Jan Stolwijk
Mays Swicord
Stanislaw Szmigielski
Rosa Tang
John Tattersall
Richard Tell
Thomas Tenforde
Artnarong Thansandote
Gyorgy Thuroczy
Tammy Utteridge
Eric van Rongen
Arthur Varanelli
Femme-Michel
Wagenaar
Joe Wiart
Louis Williams
Done-Sik Yoo
Donald Zipse
Marvin Ziskin

*Deceased

When the IEEE-SA Standards Board approved this standard on 3 October 2005, it had the following membership:

Steve M. Mills, *Chair*
Richard H. Hulett, *Vice Chair*
Don Wright, *Past Chair*
Judith Gorman, *Secretary*

Mark D. Bowman
Dennis B. Brophy
Joseph Bruder
Richard Cox
Bob Davis
Julian Forster*
Joanna N. Guenin
Mark S. Halpin
Raymond Hapeman

William B. Hopf
Lowell G. Johnson
Herman Koch
Joseph L. Koepfinger*
David J. Law
Daleep C. Mohla
Paul Nikolic

T. W. Olsen
Glenn Parsons
Ronald C. Petersen
Gary S. Robinson
Frank Stone
Malcolm V. Thaden
Richard L. Townsend
Joe D. Watson
Howard L. Wolfman

*Member Emeritus

Also included are the following nonvoting IEEE-SA Standards Board liaisons:

Satish K. Aggarwal, *NRC Representative*
Richard DeBlasio, *DOE Representative*
Alan H. Cookson, *NIST Representative*

Mike Fisher
IEEE Standards Project Editor

Contents

1.	Overview.....	1
1.1	Scope.....	1
1.2	Purpose.....	1
1.3	Introduction.....	2
2.	References.....	4
3.	Definitions, acronyms, abbreviations, and letter symbols.....	4
3.1	Definitions	4
3.2	Abbreviations.....	12
3.3	Letter symbols for quantities	13
3.4	Unit symbols.....	14
4.	Recommendations.....	14
4.1	Basic restrictions (BRs) and maximum permissible exposures (MPEs) for 3 kHz – 5 MHz....	14
4.2	BRs and MPEs for frequencies between 100 kHz and 3 GHz.....	20
4.3	BRs for frequencies between 3 GHz and 300 GHz	23
4.4	MPEs for frequencies between 100 kHz and 300 GHz	23
4.5	Suggested limit for contact voltage to protect against RF burns	28
4.6	Relaxation of the power density MPEs for localized exposures	28
4.7	Assessing compliance with this standard.....	28
4.8	RF safety programs.....	29
	Annex A (informative) Approach to revision of IEEE Std C95.1, 1999 Edition	30
	Annex B (informative) Identification of levels of RF exposure responsible for adverse effects: summary of the literature	34
	Annex C (informative) Rationale	78
	Annex D (informative) Practical applications—examples	140
	Annex E (informative) Glossary.....	150
	Annex F (informative) Literature database.....	152
	Annex G (informative) Bibliography	228

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

1. Overview

1.1 Scope

Recommendations are made to protect against established adverse health effects in human beings associated with exposure to electric, magnetic and electromagnetic fields in the frequency range of 3 kHz to 300 GHz. The recommendations are expressed in terms of basic restrictions (BRs) and maximum permissible exposure (MPE) values. The BRs are limits on internal fields, specific absorption rate (SAR), and current density; the MPEs, which are derived from the BRs, are limits on external fields and induced and contact current. The recommendations, which protect against effects associated with electrostimulation and tissue and whole-body heating, are intended to apply to all human exposures except for exposure of patients by, or under the direction of, physicians and medical professionals. These recommendations are not intended for the purpose of preventing interference with medical and other devices that may exhibit susceptibility to radio frequency (RF) fields. The recommendations at 300 GHz are compatible with existing recommendations for safe exposure in the infrared frequency range, which begins at 300 GHz, cf., ANSI Z136.1-2000 [B7]¹, ICNIRP guidelines [B63], and IEC 60825-1 [B65]. IEEE Std C95.6-2002² is the applicable standard for use at frequencies below 3 kHz.

1.2 Purpose

The purpose of this standard is to provide exposure limits to protect against established adverse effects to human health induced by exposure to RF electric, magnetic and electromagnetic fields over the frequency range of 3 kHz to 300 GHz.

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

²Information on references can be found in Clause 2.

1.3 Introduction

This standard is a revision of IEEE Std C95.1, 1999 Edition [B70] and IEEE Std C95.1b-2004 [B71]. The recommendations to protect against established adverse health effects from RF exposures have been made on the basis of a comprehensive review of the scientific data. In revising the standard, findings of studies published between 1950 and December 2003³ were considered, including those studies that involve low level exposures where increases in temperature could not be measured or were not expected. New insights gained from improved experimental and numerical methods and a better understanding of the effects of acute and chronic RF electromagnetic field exposures of animals and humans are included. A lack of credible scientific and medical reports showing adverse health effects for RF exposures at or below similar exposure limits in past standards supports the protective nature of the exposure limits. This standard includes guidance on the necessity of an RF safety program.

This standard presents two separate sets of rules to limit human exposure to electric fields, magnetic fields, and electromagnetic fields, and to induced and contact currents, in order to protect against established adverse health effects identified in the reviewed studies that are associated with exposure to such fields and currents. Specifically, in the frequency range of 3 kHz to 5 MHz, the rules minimize adverse effects associated with electrostimulation; in the frequency range of 100 kHz to 300 GHz, the rules protect against adverse health effects associated with heating. In the transition region of 0.1 to 5 MHz, each of the two sets of rules must be applied. In this transition region the rules based on heating will be more restrictive for long-term exposures to continuous wave (CW) fields, while the rules based on the effects of electrostimulation will be more restrictive for short-term exposure, e.g., short isolated pulses of low duty factor. The rules and the exposure limits incorporate safety factors that account for uncertainties and that provide a margin of safety for all. (See Annex C.6 for the derivation and detailed aspects of the safety factors.) The safety factors are conservative so that exposures that exceed the BR or MPE are not necessarily harmful. The safety factors incorporated in the MPEs are generally greater than the safety factors in the BRs. Thus, it is possible to exceed an MPE while still complying with the BRs.

Two tiers of exposure limits have been established. The upper tier, which is protective for all with an acceptable margin of safety, applies to exposure of persons in controlled environments. While the weight of scientific evidence supports the conclusion that there is no measurable risk associated with RF exposures below the upper tier of this standard, it is scientifically impossible to prove absolute safety (the null hypothesis) of any physical agent. Thus the lower tier, with an additional safety factor, recognizes public concerns and also supports the process of harmonization with other standards, e.g., the NCRP recommendations [B95] and the ICNIRP guidelines [B62]. The lower tier also defines the action level above which implementation of an RF safety program is recommended. The BRs and MPEs of the lower tier may also be used for the general public to address concerns of continuous, long-term exposure of all individuals.

These exposure limits are intended to apply to all people, with the exception of patients undergoing a procedure for medical diagnosis or treatment. This exemption is provided under the expectation that the medical staff is appropriately trained in minimizing the risk of RF hazards concomitant with the provision of a recognized benefit from the exposure. Likewise, this standard does not apply to exposure of informed volunteers in medical or scientific research studies, subject to approval by Institutional Review Boards for the Use of Human Subjects, nor is it intended to prevent interference with medical and other devices that may exhibit susceptibility to RF energy⁴.

³Although the literature cutoff date was December 2003, several papers published in 2004 and 2005 were included.

⁴While the issue of RF emissions from wireless transmitters causing electromagnetic interference (EMI) with medical devices is outside the scope of the current standard, there are several relevant standards that the reader is directed to that recommend immunity levels for external medical devices, e.g., IEC 60601-1 [B66] and IEC 60601-1-2 [B67], as well as implantable medical devices e.g., ANSI/AAMI PC69-2000 [B5]. ISO TC215 Technical Report 21073 [B75] offers guidance for the use and operation of mobile wireless transmitters within healthcare facilities.

1.3.1 Safety factor and margin of safety

Below 100 kHz, the effect being minimized is aversive or painful electrostimulation. Because the predominant interaction mechanisms are different above and below 100 kHz, the nature of and the rationale for the safety factors differ. At low frequencies, electrostimulation has a characteristic response time that is much less than one second and exposures are assessed in terms of instantaneous fields or currents. The estimated safety factor in terms of currents or fields is between 3 and 10 (10–20 dB) in the worst case even though for many situations and people the safety factor is considerably greater. An upper tier, which is applicable to exposures in controlled environments, incorporates a smaller safety factor approaching a minimum of unity, even though in most cases the safety factor is considerably greater. A margin of safety near unity, equivalent to no margin of safety, is justified for the upper tier MPEs below 100 kHz for the following reasons: a) the maximum electrostimulation that might occur at the upper tier has no lasting adverse effect, b) the requirement of an RF safety program, and c) the general awareness of workers in occupational situations. A greater margin of safety is provided in the lower tier for frequencies below 100 kHz.

Above 100 kHz there can be a sensation of heating, which is not considered adverse. The limits in this standard may not prevent such thermal sensations; they are designed to protect against adverse health effects resulting from tissue heating, the only established adverse effect of exposure to RF energy at frequencies above 100 kHz. Above 100 kHz, exposures are assessed with reference to an averaging time that varies with frequency and at some frequencies depends on the tier designation (action level and controlled environment). The frequency 100 kHz nominally represents a “thermal crossover” below which electrostimulation effects dominate, and above which thermal effects dominate for continuous wave exposure. However, for pulsed waveforms, especially those of a low duty factor, the thermal crossover can extend to much higher frequencies (in the megahertz region). This standard contains criteria to protect against adverse electrostimulation effects for pulsed waveforms having fundamental frequencies above 100 kHz.

For short duration exposures (less than the averaging time) the BRs and MPEs are related to energy, i.e., specific absorption (SA) or energy density. It is possible, however, to continue to use the BRs and MPEs expressed in power terms, specific absorption rate (SAR), or power density or equivalent fields, recognizing their time dependence. In this case the adverse effect to be protected against is tissue damage that can result from excessive heating. For exposure durations considerably greater than the averaging time, the effect to be protected against is that shown to be the most sensitive to RF exposure, behavioral disruption observed in animals and extrapolated to humans.

The safety factor for whole-body exposure durations greater than the averaging time has been estimated to be in the range of 10 to 50 in power (10 to 17 dB) for the upper tier BRs or MPEs. The corresponding BRs and MPEs of the lower tier incorporate an additional safety factor of 5 relative to the upper tier, i.e., an additional 7 dB. The safety factors for special exposure measures, such as peak (short pulse) limits and contact and induced currents in the limbs, are often related to the safety factors incorporated in the BRs or MPEs for fields. This factor is generally of the order of at least 10 dB.

1.3.2 RF risk assessment and RF safety programs

Throughout the RF spectrum to which this standard is applicable, the MPEs apply to *exposure of individuals*. Areas wherein intense RF fields exist (that exceed the MPEs) would be an exposure issue only when individuals have access to those areas and may become exposed. Hence, compliance with this standard is to be determined by assessing whether persons may be exposed to RF fields exceeding the MPEs and not necessarily by whether RF fields simply exceed the MPEs. This standard recommends that when and where there may be access to RF fields, currents, and/or voltages that exceed the lower tier MPEs (action levels), exposures are to be controlled through the implementation of an RF safety program, as described in IEEE Std C95.7-2005. Application of an RF safety program results in various control measures that can be taken to reduce the probability of a person's exposure exceeding the BRs and MPEs of the upper tier.

2. References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std C95.3TM-2002, IEEE Recommended Practice for Measurements and Computations of Radio Frequency Electromagnetic Fields with Respect to Human Exposure to Such Fields, 100 kHz–300 GHz.^{5, 6}

IEEE Std C95.6TM-2002, IEEE Standard for Safety Levels With Respect to Human Exposure to Electromagnetic Fields, 0 to 3 kHz.

IEEE Std C95.7TM-2005, IEEE Recommended Practice for Radio Frequency Safety Programs, 3 kHz to 300 GHz.

3. Definitions, acronyms, abbreviations, and letter symbols

3.1 Definitions

For the purposes of this standard, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms* [B72], should be referenced for terms not defined in this clause. For the convenience of the reader, terms used in this standard that are defined in *The Authoritative Dictionary of IEEE Standards Terms* are contained in a glossary (see Annex E).

3.1.1 action level: The values of the electric and magnetic field strength, the incident power density, contact and induced current, and contact voltages above which steps should be initiated to protect against exposures that exceed the upper tier, specifically, implementation of an RF safety program.

3.1.2 adverse health effect: A biological effect characterized by a harmful change in health. *See also:* **established adverse health effect.**

NOTE 1—Adverse effects do not include biological effects without a harmful health effect, changes in subjective feelings of well-being that are a result of anxiety about RF effects or impacts of RF infrastructure that are not physically related to RF emissions, or indirect effects caused by electromagnetic interference with electronic devices.

NOTE 2—Sensations (perceptions by human sense organs) per se are not considered adverse effects. Thus a sensation of warmth at millimeter and other wavelengths and the microwave auditory effect under the underlying special conditions are not recognized as effects to be protected against by this standard. Painful or aversive electrostimulation resulting from exposure at frequencies below 0.1 MHz is treated as an adverse effect.

3.1.3 adverse effects exposure level: The condition or set of conditions under which exposure to an electric, magnetic, or electromagnetic field can produce a harmful change in health. Conditions can be a property of the source (such as field strength, polarization, power density, frequency, modulation, pulse duration and repetition frequency), a dosimetric quantity (such as current, current density, specific absorption, or specific absorption rate), and an exposure characteristic (such as exposure duration and recurrence interval). This standard is based on the lowest known exposure levels for all established adverse effects. The maximum permissible exposure (MPE) values in this standard are derived from these exposure levels incorporating appropriate margins of safety.

⁵IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

⁶The IEEE standards or products referred to in this clause are trademarks of the Institute of Electrical and Electronics Engineers, Inc.

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

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

where

$P(t)$ is the instantaneous power.

The SI unit of average power is the watt (W).

NOTE—The time duration ($t_2 - t_1$) could be source related (e.g., the source repetition period, duty cycle) or use related (e.g., the averaging time specified in exposure guidelines).

3.1.5 average (temporal) power density: The instantaneous power density integrated (averaged) over a specific time duration. The time duration could be source related, e.g., the source repetition period, or use related, e.g., the averaging time specified in exposure guidelines. The SI unit of average power density is the watt per square meter (W/m^2).

3.1.6 averaging distance: The distance over which the *in situ* electric field is averaged when determining compliance with basic restrictions.

3.1.7 averaging time (T_{avg}): The appropriate time period over which exposure is averaged for purposes of determining compliance with a maximum permissible exposure (MPE) or reference level.

NOTE—Averaging time T_{avg} has an unambiguous meaning only at frequencies above 0.1 MHz, i.e., for the MPEs relating to heating effects. For an exposure time greater than T_{avg} , the MPE is an entity expressed in power units, e.g., SAR or power density, or in terms of field units, while for an exposure time smaller than T_{avg} , the MPE can be expressed as a power or field function of time or an equivalent integral quantity, e.g., specific absorption or energy density either on a volume or area basis.

3.1.8 averaging volume: The volume over which the peak spatial-average specific absorption rate is averaged when determining compliance with the basic restrictions.

3.1.9 basic restrictions: Exposure restrictions that are based on established adverse health effects that incorporate appropriate safety factors and are expressed in terms of the *in situ* electric field (3 kHz to 5 MHz), specific absorption rate (100 kHz to 3 GHz), or incident power density (3 GHz to 300 GHz).

3.1.10 biological effect: A biological effect is an established effect caused by, or in response to, exposure to a biological, chemical or physical agent, including electromagnetic energy. Biological effects are alterations of the structure, metabolism, or functions of a whole organism, its organs, tissues, and cells. Biological effects can occur without harming health and can be beneficial. Biological effects also can include sensation phenomena and adaptive responses.

3.1.11 chronic exposure: A sequence of many repeated or continuous exposures over a long period of time, e.g., months to years, depending on the biological system being considered and its lifespan.

3.1.12 confirmed adverse health effect: *See: established adverse health effect.*

3.1.13 confirmed effect: *See: established effect.*

3.1.14 contact current: Current induced in a biological medium via a contacting electrode or other source of current.

3.1.15 contact voltage: Voltage between a biological medium and an electrode or current source in the absence of direct contact with the body.

3.1.16 controlled environment: An area where the occupancy and activity of those within is subject to control and accountability as established by an RF safety program for the purpose of protection from RF exposure hazards. *See also:* **general public**.

NOTE—Implementation of an effective RF safety program such as IEEE Std C95.7-2005 is to ensure that persons are not exposed in excess of the “Controlled Environment” MPEs.

3.1.17 continuous exposure: For purposes of this standard, exposure for durations exceeding the corresponding averaging time.

NOTE—In this context, exposure for less than the averaging time is considered a *short-term exposure*. For cellular studies in the laboratory, continuous exposure refers to exposures for most of the cell-cycle of a proliferating cell system (or longer), while for non-proliferating cells *in vitro* or in tissues, “continuous exposure” is arbitrary. For cellular studies, *short term* refers to, at most, exposure over a small portion of the cell cycle time. With respect to non-proliferating cells *in vitro* or in tissues, the definition is arbitrary.

3.1.18 derived limits: *See:* **maximum permissible exposure**.

3.1.19 environmental limit: A limit on the electric and magnetic fields permitted in the general environment, whether or not people are present.

3.1.20 equivalent plane-wave power density (plane-wave equivalent power density) (S): 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. Specifically, the normalized value of the square of the electric or the magnetic field strength at a point in the near field of a radiating source. The SI unit of equivalent plane-wave power density is the watt per square meter (W/m²) and is computed as follows:

$$S = \frac{|E|^2}{\eta} = \eta |H|^2$$

where

E and *H* are the root mean square (rms) values of the electric and magnetic field strengths, respectively, and

η is the wave impedance ($\cong 377$ ohms in free space).

Synonym: **equivalent plane-wave power flux density**.

3.1.21 established adverse health effect: A biological effect characterized by a harmful change in health that is supported by consistent findings of that effect in studies published in the peer-reviewed scientific literature, with evidence of the effect being demonstrated by independent laboratories, and where there is consensus in the scientific community that the effect occurs for the specified exposure conditions. The development of this standard is based on the following established adverse health effects: 1) aversive or painful electrostimulation due to excessive RF internal electric fields, 2) RF shocks or burns due to contact with excessively high RF voltages, 3) heating pain or tissue burns due to excessive localized RF exposure, and 4) behavioral disruption, heat exhaustion or heat stroke due to excessive whole body RF exposures. *See:* **adverse health effect**.

3.1.22 established effect: An effect is considered *established* when consistent findings of that effect have been published in the peer-reviewed scientific literature, with evidence of the effect being demonstrated by independent laboratories, and where there is consensus in the scientific community that the effect occurs for the specified exposure conditions.

3.1.23 established mechanism: For purposes of this standard, a mechanism with the following characteristics: (1) It can be used to predict a biological effect in cells, animals, or humans; (2) An explicit model can be proposed using equations or parametric relationships; (3) It has been verified in humans, or animal data supporting the mechanism can be confidently extrapolated to humans; (4) It is supported by strong evidence; and (5) It is widely accepted among experts in the scientific community.

3.1.24 exposure: For purposes of this standard, exposure of a person to electric, magnetic, or electromagnetic fields or to induced and contact currents other than those originating from physiological processes in the body and other natural phenomena.

3.1.25 extremities: For purposes of this standard, the parts of the arms and legs distal from the elbows and knees, respectively.

3.1.26 general public: Individuals of all ages and varying health status, some of whom may be subject to requirements of the controlled environment. *See:* **controlled environment**.

NOTE 1—Generally, unless specifically provided for as part of an RF safety program, the general public includes, but is not limited to, children, pregnant women, individuals with impaired thermoregulatory systems, individuals equipped with electronic medical devices, and persons using medications that may result in poor thermoregulatory system performance.

NOTE 2—Unless specifically provided as part of an RF safety program, individual members of the public may not be aware of their exposure.

3.1.27 grasping contact: An electrical connection with a large energized conductor made by firmly holding the conductor in the hand. In this standard, a contact area of 15 cm² is assumed for such contact.

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

3.1.29 hazard threshold: The point above which some parameter related to exposure (e.g., SAR, *in situ* electric field strength) is associated with the existence of some hazardous effect.

3.1.30 *in vitro*: Refers to studies and/or effects that occur in an artificial environment outside a living organism.

3.1.31 *in vivo*: Refers to studies and/or effects that occur within the body of living organisms.

3.1.32 *in situ*: For purposes of this standard, *in situ* means within a biological tissue in its normal anatomical position.

3.1.33 localized exposure: For frequencies exceeding 100 kHz, an exposure of a portion of the body wherein the incident plane-wave equivalent power density, or the squares of the field strength exceed 20 times the spatially averaged value over the projected (cross-sectional) area of the body. *See:* **RF hot spot**.

3.1.34 long term exposure: Exposure for a duration much longer than the corresponding averaging time. *See:* **chronic exposure**.

3.1.35 lower tier: A set of limits that provide an additional margin of safety, i.e., a margin of safety greater than that for the upper tier. *See:* **action level**.

NOTE—The lower tier, which is recommended as an action level above which an RF safety program should be implemented, recognizes public concerns, uncertainties in exposure assessment, and supports the process of harmonization with other standards.

3.1.36 low-level effects: Biological effects ascribed to exposure to low-level fields, i.e., at or below the corresponding basic restrictions in the frequency range 3 kHz to 300 GHz.

3.1.37 low-level fields: Electromagnetic fields in the frequency range 3 kHz to 300 GHz that produce induced (*in situ*) electric fields, SAR, or power density at or below the corresponding basic restrictions.

3.1.38 margin of safety: The ratio of the minimum hazard threshold (HT) level to the maximum exposure level, with accounting for all uncertainties in HT and the exposure level, in a specific exposure situation.

NOTE—This is equivalent to the minimum possible safety factor when uncertainties are accounted for, while the nominal safety factor is interpreted as that derived from median measures of HT and basic restriction or MPE. The margin of safety can approach equality with the safety factor if the uncertainties are small or if there is a very large separation between HT and the MPE. The margin of safety is a value judgment based on informed opinion.

3.1.39 maximum permissible exposure (MPE): The highest rms or peak electric or magnetic field strengths, their squares, or the plane-wave equivalent power densities associated with these fields, or the induced and contact currents to which a person may be exposed without incurring an established adverse health effect and with an acceptable margin of safety. The MPEs are derived or estimated from the basic restrictions (induced electric field, SAR, or power density). If an exposure is proven to be below the basic restrictions, the MPE can be exceeded. MPEs are sometimes called *reference levels*, *derived limits*, or *investigation levels*.

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

3.1.41 near field exposure: Exposure that occurs in the near field region of a source. *See:* **near field region**.

3.1.42 near-field region: A region, generally in proximity to an antenna or other radiating structure, in which the electric and magnetic fields do not have a substantially plane-wave character, and vary considerably from point to point. The near-field region is further subdivided into the reactive near-field region, which is closest to the radiating structure and contains most or nearly all of the stored energy, and the radiating near-field region where the 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 $\lambda/2\pi$ from the antenna surface, where λ is the wavelength. The radiating near field region extends out to the far field region.

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

3.1.44 non-thermal effects: *See:* **low-level effects**, which is the preferred term.

3.1.45 non-thermal fields: *See:* **low-level fields**, which is the preferred term.

3.1.46 partial-body exposure: *See:* **localized exposure** and **RF hot spot**.

3.1.47 peak electric field: The instantaneous value of the electric field strength at the time of its maximum value.

3.1.48 peak power density: The maximum instantaneous power density occurring during the interval when power is transmitted. The SI unit of peak power density is the watt per square meter (W/m^2).

3.1.49 phase duration (t_p): The time between zero crossings of a waveform. For a sine wave of frequency f , $t_p = 1/(2f)$; for an exponential waveform, t_p is interpreted as the duration measured from the waveform peak to a point at which it decays to 36.8% (e^{-1}) of its peak value.

3.1.50 pinna (pl. pinnae): The largely cartilaginous projecting portion of the outer ear consisting of the helix, lobule, and anti-helix. The pinna is also called the *auricle*.

3.1.51 plane-wave equivalent power density: *See: equivalent plane-wave power density.*

3.1.52 probe length: The maximum physical dimension of the sensing element, e.g., dipole or loop of an electric or magnetic field probe, respectively, or the dimension of the largest sensing element in a multiple array.

3.1.53 projected area: For purposes of this standard, the geometric area equivalent to the vertical cross section of the human body in the configuration of interest, e.g., sitting or standing.

3.1.54 pulse-modulated field: An electromagnetic field characterized by a form of amplitude modulation in which a continuous wave is abruptly shifted in amplitude from zero to a level at or near the maximum and returning to zero; often characterized by a series of such shifts in a repeated pattern.

3.1.55 radio frequency (RF): A frequency that is useful for radio transmission. For purposes of this standard, the frequency range of interest is 3 kHz to 300 GHz.

3.1.56 reference level: The exposure field and contact current values derived or estimated from the basic restrictions, i.e., induced electric field, SAR or power density. For frequencies above 3 GHz the basic restriction and the reference levels are the same. *See: maximum permissible exposure.*

3.1.57 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.”

3.1.58 RF “hot spot”: A highly localized area of relatively more intense RF energy that manifests itself in two principal ways:

- 1) Near a conductive object that is the immediate source of intense electric or magnetic fields and is surrounded by ambient fields of lower intensity (often referred to as re-radiation), and
- 2) From reflections and/or narrow beams produced by high-gain radiating antennas or other highly directional sources. In both cases, there are very rapid changes in field strength over distances that are small with respect to the objects and wavelength. RF hot spots are normally associated with very non-uniform exposure of the body (localized exposure). This is not to be confused with an actual thermal hot spot within the absorbing body.

3.1.59 RF safety program (RFSP): An organized system of policies, procedures, practices and plans designed to protect against hazards associated with RF fields, contact voltage, and contact and induced currents. RFSPs shall be documented in writing.

NOTE 1—Implementation of an effective RF safety program is to ensure that persons are not exposed in excess of the MPEs of the upper tier.

NOTE 2—A program typically includes RF awareness training, implementation of protective measures such as signage and the use of personal protective equipment (PPE), incident response, periodic evaluation of program effectiveness, and assigned responsibilities for implementing the program (see IEEE Std C95.7-2005).

3.1.60 rheobase: The minimum threshold intensity in a strength-duration or strength-frequency relation for electrostimulation (applicable to a stimulus duration that is long in comparison with the strength-duration time constant). In a strength-duration curve, the rheobase forms a minimum asymptote to thresholds for pulsed stimulus durations greater than a strength-duration time constant, τ_c . In a strength-frequency curve,

the rheobase forms a minimum asymptote to thresholds for sinusoidal stimuli with frequencies less than a strength-frequency constant, f_c .

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

3.1.62 safety factor (F_s): A multiplier (≤ 1) or a divisor (≥ 1) used to derive maximum permissible exposure (MPE) values, which provides for the protection of individuals, and uncertainties concerning threshold effects due to pathological conditions or drug treatment, uncertainties in reaction thresholds, and uncertainties in induction models.

NOTE 1— F_s is usually taken as the ratio of the value of the threshold for an adverse effect, i.e., hazard threshold (HT), to the basic restriction (BR) or maximum permissible exposure value (MPE). Thus, $F_s = HT_{BR}/BR$ or HT_{MPE}/MPE , where HT_{BR} is expressed in the same units as BR and HT_{MPE} is expressed in the same units as MPE . This is usually considered the nominal safety factor derived from the median values of HT, BR, and the MPE.

NOTE 2—Upon consideration of statistical variation and uncertainties in the data on HT, extrapolation to humans, the models for calculation and measurement of BR or MPE and biological variability in humans, a safety factor may be increased to ensure a “margin of safety for all.”

NOTE 3—Allowance is also made to account for the fact that measurement error and other uncertainties attend any evaluation of the compliance of actual exposure to the BR or MPE.

NOTE 4—Since the entities in the ratio F_s could be current, voltage, field strength, power, or energy, when comparing safety factors, their expression in decibels (dB) ensures a meaningful and fair comparison. The actual (true) safety factor in any specific situation could be larger or smaller than the nominal safety factor.

3.1.63 scattered radiation: See: re-radiated field.

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

3.1.65 spark discharge: The transfer of current through an air gap requiring a voltage high enough to ionize the air, as opposed to direct contact with a source.

3.1.66 spatial average: For frequencies up to 0.1 MHz, the root-mean-square of the field over an area equivalent to a specified cross section of the adult human body, as applied to the measurement of electric or magnetic fields in the assessment of whole-body exposure.

NOTE—The spatial average is measured by scanning (with a suitable measurement probe) a planar area equivalent to the area occupied by a standing adult human (projected area). In most instances, a simple vertical, linear scan of the fields over a 2 meter height (approximately 6 feet), through the center of the projected area, will be sufficient for determining compliance with the MPEs. For frequencies from 0.1 MHz to 3 GHz, the plane wave equivalent power densities or squares of the electric or magnetic field strengths are to be averaged along a line representing the height of an individual.

3.1.67 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 SI unit of specific absorption is the joule per kilogram (J/kg).

3.1.68 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).

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

The SI unit of SAR is the watt per kilogram (W/kg).

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

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

where

- σ is conductivity of the tissue (S/m)
- ρ is mass density of the tissue (kg/m³)
- E is rms electric field strength in tissue (V/m)

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

$$SAR = \left. \frac{c \Delta T}{\Delta t} \right|_{t=0}$$

where

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

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

3.1.69 specific absorption rate—peak spatial-average: The maximum local SAR averaged over a specified volume or mass, e.g., any ten-grams of tissue in the shape of a cube. The SI unit of peak spatial-average SAR is the watt per kilogram (W/kg).

3.1.70 specific heat capacity: The amount of heat necessary to raise the temperature of a unit mass of a substance 1 °C. The SI unit of specific heat capacity is the joule per kg per kelvin (J/kg·K) or joule per kilogram degree Celsius (J/kg·°C).

3.1.71 strength-duration curve: The functional relationship between the threshold of excitation and the duration of an excitatory stimulus. In this standard, the strength-duration curve is approximated by two straight lines which are asymptotes to analytic or experimental representations of the curve displayed on a log/log scale: for pulsed stimulus durations greater than a critical time parameter, τ_c , the threshold asymptote is a horizontal straight line (see *rheobase*); for durations less than or equal to τ_c , the threshold asymptote rises in inverse proportion to the pulse duration. This approximation necessarily imposes a margin of conservatism in the representation of thresholds in the vicinity of τ_c .

3.1.72 strength-duration time constant (τ_c): The temporal point in the asymptotic representation of a strength-duration curve that describes the transition between the rheobase and the rising threshold segment of the curve. *See also:* **strength-duration curve.**

3.1.73 strength-frequency constant (f_c): The frequency in the asymptotic representation of a strength-frequency curve that describes the transition between the rheobase and the rising threshold segment of the curve. *See also: strength-frequency curve.*

3.1.74 strength-frequency curve: The functional relationship between the threshold of excitation and the frequency of an excitatory stimulus. In this standard, the strength-frequency curve is approximated by two straight lines which are asymptotes to analytic or experimental representations of the curve displayed on a log/log scale: for frequencies less than a critical time parameter, f_c , the threshold asymptote is a horizontal straight line (see rheobase); for durations greater than or equal to f_c , the threshold asymptote rises in proportion to the frequency. This approximation necessarily imposes a margin of conservatism in the representation of thresholds in the vicinity of f_c .

3.1.75 thermal effects: Changes in an organism associated with heating of the whole body or an affected region that are sufficient to increase temperature by a physiologically significant amount; thermoregulatory mechanisms of heat loss (sweating, blood flow) may delay, reduce, or prevent a measurable increase in temperature. Established adverse changes are associated with whole-body heating at levels that usually increase temperature by approximately 1 °C or more.

3.1.76 thermal level (RF fields): RF fields that are sufficiently strong to significantly increase the temperature of exposed bodies, tissues, and experimental samples.

NOTE—If strong enough, biological mechanisms of heat loss (sweating, blood flow) can reduce or effectively eliminate a temperature change or, alternatively, laboratory techniques (tissue cooling via water bath) can prevent a temperature rise in a biological sample.

3.1.77 touch contact: A contact of small area made between the human body and an energized conductor. In this standard, a contact area of 1 cm² is the assumed touch contact area.

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

3.1.79 upper tier: A set of RF exposure limits that are scientifically based and that provide a margin of safety for all, including those in a controlled environment.

3.1.80 weight of scientific evidence: For purposes of this standard, the outcome of assessing the published information about the biological and health effects from exposure to RF energy. This process includes evaluation of the quality of test methods, the size and power of the study designs, the consistency of results across studies, and the biological plausibility of dose-response relationships and statistical associations.

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

3.2 Abbreviations

BR	basic restriction
CW	continuous wave
dB	Decibel
FDTD	finite-difference time-domain
GSM	Global System for Mobile Communications
HF	high frequency (3–30 MHz)
HT	hazard threshold
ICES	International Committee on Electromagnetic Safety
ICNIRP	International Commission on Non-Ionizing Radiation Protection
LSWG	Literature Surveillance Working Group

MF	medium frequency (0.3–3 MHz)
MPE	maximum permissible exposure
NOAEL	no observable adverse effects level
PW	pulsed wave
RF	radio frequency
RAWG	Risk Assessment Working Group
rms	root mean square
SA	specific absorption
SAR	specific absorption rate
SASB	Standards Association Standards Board
SI	Système International d'Unités (international system of units)
UHF	ultra high frequency (300 MHz–3 GHz)
VHF	very high frequency (30–300 MHz)

3.3 Letter symbols for quantities

B	magnetic flux density
c	specific heat capacity
ϵ_r	relative permittivity
E	electric field strength
E_i	maximum allowed in situ electric field strength
E_o	rheobase in situ electric field strength
f	frequency
f_e	strength-frequency constant
F_s	safety factor
H	magnetic field strength
I	current
J	current density
MPE	maximum permissible exposure value
η	wave impedance
P	power
$P(t)$	instantaneous power
$\bar{P}$	average power (temporal)
q	charge
ρ	mass density
SA	specific absorption
SAR	specific absorption rate
S	power density
T_{avg}	averaging time
t_p	phase duration
W	energy
σ	conductivity
τ_e	strength-duration time constant
λ	wavelength
μ	permeability

3.4 Unit symbols

A	ampere
°C	degree Celsius
GHz	gigahertz (10^9 Hz)
h	hour
J	joule
K	kelvin
kHz	kilohertz (10^3 Hz)
MHz	megahertz (10^6 Hz)
min	minute
s	second
V	volt
W	watt

4. Recommendations

4.1 Basic restrictions (BRs) and maximum permissible exposures (MPEs) for frequencies between 3 kHz and 5 MHz

This standard provides recommendations to minimize aversive or painful electrostimulation in the frequency range of 3 kHz to 5 MHz and to protect against adverse heating in the frequency range of 100 kHz to 300 GHz. In the transition region of 100 kHz to 5 MHz, protection against both electrostimulation and thermal effects is provided through two separate sets of limits. Below 100 kHz only the electrostimulation limits apply, above 5 MHz only the thermal limits apply, and both sets of limits apply in the transition region. In the transition region, where both sets of limits apply, the limits based on electrostimulation will generally be more limiting for low duty cycle exposures, while the thermal-based limits will be more limiting for continuous wave fields.

4.1.1 BRs: *in situ* electric field

For human exposure to electromagnetic energy at frequencies from 3 kHz to 5 MHz, the basic restrictions refer to limits on the *in situ* electric fields that minimize adverse effects associated with electrostimulation. Such restrictions are derived with consideration of adverse electrical thresholds, their distribution among the population, and safety factors, as documented in IEEE Std C95.6-2002.

Table 1 lists basic restrictions for particular areas of the body in terms of the electric field within the biological tissue (*in situ*). The listed parameters apply to frequencies above and below 3 kHz to show continuity with standards adopted below 3 kHz, i.e., IEEE Std C95.6-2002. Two parameters are listed in the table: the rheobase *in situ* field, E_0 , and a strength-frequency parameter, f_e . Limits are determined from Table 1 as:

$$E_i = E_0 \text{ for } f \leq f_e \quad (1)$$

$$E_i = E_0 (f/f_e) \text{ for } f \geq f_e$$

where

E_i is the maximum allowed induced *in situ* electric field.

The basic restrictions on the *in situ* electric field apply to an arithmetic average determined over a straight-line segment of 5 mm length oriented in any direction within the tissue identified in Table 1. The averaging

time for an rms measurement is 0.2 s. Basic restrictions expressed in Equation (1) apply to frequencies in the range of 0 to 5 MHz.

Table 1—BRs applying to various regions of the body

		Action level ^a	Persons in controlled environments
Exposed tissue	f_e (Hz)	E_0 (rms) (V/m)	E_0 (rms) (V/m)
Brain	20	5.89×10^{-3}	1.77×10^{-2}
Heart	167	0.943	0.943
Extremities	3350	2.10	2.10
Other tissues	3350	0.701	2.10
^a Within this frequency range the term “action level” is equivalent to the term “general public” in IEEE Std C95.6-2002.			

NOTE—Entries in Table 1 and elsewhere in this standard are sometimes given to three significant digits. This degree of precision is provided so that the reader can follow the various derivations and relationships presented in this standard, and does not imply that the numerical quantities are known to that precision.

4.1.2 MPE for the magnetic field

4.1.2.1 Exposure of head and torso to sinusoidal magnetic fields

Table 2 lists the MPEs for the magnetic field (flux density, B , and magnetic field strength, H) for exposure of the head and torso. The averaging time for an rms measurement is 0.2 second.

Table 2—MPE for exposure of head and torso: $f = 3$ kHz to 5 MHz

Frequency range (kHz)	Action level ^a		Persons in controlled environments	
	B_{rms} (mT)	H_{rms} (A/m)	B_{rms} (mT)	H_{rms} (A/m)
3.0–3.35	$0.687/f$	$547/f$	$2.06/f$	$1640/f$
3.35–5000	0.205	163	0.615	490
NOTE— f is expressed in kHz.				
^a Within this frequency range the term “action level” is equivalent to the term “general public” in IEEE Std C95.6-2002.				

NOTE—The MPEs in Table 2 minimize adverse effects associated with electrostimulation; Tables 8 and 9 apply to effects associated with tissue heating. All three tables must be considered and the corresponding values for the appropriate tier satisfied at all applicable frequencies.

Compliance with Table 2 ensures compliance with the basic restrictions of Table 1. However, lack of compliance with Table 2 does not necessarily indicate lack of compliance with the basic restrictions, but rather

that it may be necessary to evaluate whether the basic restrictions have been met. This would typically be done using analytical methods. If the basic restrictions in Table 1 are not exceeded, then the MPEs in Table 2 can be exceeded. Consequently, it is sufficient to demonstrate compliance with either Table 1 or Table 2.

4.1.2.2 Non-uniform exposure to sinusoidal magnetic fields

When the magnetic field is not constant in magnitude, direction, or relative phase over the head, torso, or limbs, the maximum field over the head, torso, or limbs shall be limited to the values in Table 2. Alternatively, demonstration of compliance with the basic restrictions is permitted.

4.1.2.3 Exposure of the limbs

The MPEs for the limbs (entire arms and legs) are listed in Table 3. The averaging time for an rms measurement is 0.2 s. Compliance with Table 3 ensures compliance with the basic restrictions of Table 1. However, lack of compliance with Table 3 does not necessarily indicate lack of compliance with the basic restrictions, but rather that it may be necessary to evaluate whether the basic restrictions are met.

Table 3—MPE for the limbs: $f = 3$ kHz to 5 MHz

Frequency range (kHz)	Action level ^a		Persons in controlled environments	
	B_{rms} (mT)	H_{rms} (A/m)	B_{rms} (mT)	H_{rms} (A/m)
3.0–3.35	$3.79/f$	$3016/f$	$3.79/f$	$3016/f$
3.35–5000	1.13	900	1.13	900
NOTE— f is expressed in kHz.				
^a Within this frequency range the term “action level” is equivalent to the term “general public” in IEEE Std C95.6-2002.				

4.1.2.4 Pulsed or non-sinusoidal magnetic fields

When the magnetic flux density waveform is non-sinusoidal, such as with pulsed or mixed frequency waveforms, the MPE shall conform to the rms values of Table 2 and Table 3. In addition, the maximum exposure shall conform to either 4.1.2.4.1 or 4.1.2.4.2. Since both criteria are conservative, adherence to either is sufficient to demonstrate compliance with the MPEs or BRs.

4.1.2.4.1 Restriction based on peak (temporal) field

Demonstration of compliance with either 4.1.2.4.1.1 or 4.1.2.4.1.2 is sufficient to demonstrate compliance with restrictions based on the temporal peak field. Subclause 4.1.2.4.1.1 applies to the *in situ* induced electric field; 4.1.2.4.1.2 applies to the external field.

4.1.2.4.1.1 Peak *in situ* electric field

The temporal peak of the *in situ* electric field shall be restricted to a value obtained by multiplying the rms values of Table 1 by $\sqrt{2}$. To interpret this table for non-sinusoidal waveforms, frequency, f , is defined as $f = 1/(2 t_p)$, where t_p is the phase duration of a peak excursion of the *in situ* electric field. Phase duration is defined as the time between zero crossings of a waveform. For an exponential waveform, t_p is interpreted as the duration measured from the waveform peak to a point at which it decays to e^{-1} (~36.8%) of its peak

value. Peak limits apply to instantaneous values measured through a bandwidth from zero to the highest frequency content of the waveform under consideration.

4.1.2.4.1.2 Peak external field

The temporal peak of the external magnetic field, B , shall be limited according to the following procedure, where B is a time-varying flux density waveform whose compliance is under evaluation. For conversion of magnetic field intensity, H , to magnetic flux density, B , note that $B = 4\pi \times 10^{-7}H$.

- Determine the time derivative of the external field, $\frac{dB}{dt} = \dot{B}$
- Identify the peak and phase duration of any excursion of $\dot{B}$. Phase duration shall be determined as in 4.1.2.4.1.1.
- Determine the allowable peak limit on B from Table 2 or Table 3 as $\dot{B}_p = \sqrt{2}MPE_B(2\pi f)$, where

$\dot{B}_p$ is the maximum permissible value of $\dot{B}$,

MPE_B is the peak flux density consistent with Table 2 or Table 3,

$f = 1/(2t_p)$, and

t_p is the phase duration of a peak excursion of $\dot{B}$.

4.1.2.4.2 Restriction based on Fourier components

The requirements of this subclause can be satisfied as an alternative to 4.1.2.4.1.

For an exposure waveform consisting of multiple frequencies, a test for compliance of the exposure waveform shall satisfy the following criterion:

$$\sum_{0}^{5 \text{ MHz}} \frac{A_i}{MPE_i} \leq 1 \quad (2)$$

where A_i is the magnitude of the i^{th} Fourier component of the exposure waveform, and MPE_i is the maximum permissible exposure (Table 2 or Table 3) or the basic *in situ* field restriction (Table 1) for a single sinusoidal waveform at a frequency f_i . The summation is carried out from the lowest frequency of the exposure waveform to a maximum frequency of 5 MHz. Note that A_i and MPE_i must measure the same quantity, as well as be in the same units. For instance, if A_i is the magnitude of a flux density, then MPE_i must also be a measure of flux density. Alternatively, both A_i and MPE_i could be measures of the time derivative of the field, the induced in situ electric field, or induced current density.

It may be necessary to evaluate Equation (2) at frequencies outside the limits of this standard. For purposes of such evaluations, the MPE_i values applying to frequencies less than 3 kHz shall be determined as follows:

- Basic restrictions* (Table 1). The BRs from 0 Hz to 3 kHz shall be determined as given in Table 1.
- Magnetic field MPEs* (Table 2 and Table 3). The MPE for B or H below 3 kHz shall be determined as given in IEEE Std C95.6-2002.
- Electric field MPEs* (Table 4). The MPE for the external electric field below 3 kHz shall be determined as given in IEEE Std C95.6-2002. The MPE applicable to 3 kHz shall be assumed up to a maximum frequency of 5 MHz.
- Induced and contact current MPEs* (Table 5). Values of induced and contact current below 3 kHz shall be determined as given in IEEE Std C95.6-2002.

4.1.3 MPE for the external electric field

4.1.3.1 Uniform whole-body exposure to sinusoidal electric fields

Table 4 lists MPEs in terms of the undisturbed (absent a person) external electric field, E . It is assumed that the undisturbed field is constant in magnitude, direction, and relative phase over a spatial extent that would encompass the human body. The averaging time for an rms measurement shall be 0.2 s. For a controlled environment in which an exposed individual is not within reach of a grounded object, it may be acceptable to exceed the MPEs in Table 4. This standard does not specify limits for situations involving contact with ungrounded objects, e.g., a person above ground on an elevated, insulated platform. (See Annex C.)

Table 4—Electric field MPE—whole body exposure: $f = 3$ kHz to 100 kHz

	Action level ^a	Persons in controlled environments
Frequency range (kHz)	E (rms) (V/m)	E (rms) (V/m)
3 kHz to 100 kHz	614	1842
^a Within this frequency range the term “action level” is equivalent to the term “general public” in IEEE Std C95.6-2002.		

4.1.3.2 Non-uniform or localized exposure to sinusoidal electric fields

When the external electric field is not constant in magnitude, direction, and relative phase over the dimensions of the human body, the spatially averaged external field (i.e., the fields are averaged as opposed to averaging the squares of fields as at higher frequencies) shall be restricted to the MPE in Table 4. For a controlled environment in which an exposed individual is not within reach of a grounded conducting object, it may be acceptable to exceed the MPE in Table 4. This standard does not specify limits for such cases. In no case shall the BRs of Table 1 or the contact current limits of Table 5 be exceeded.

4.1.3.3 Pulsed or non-sinusoidal electric fields

When the waveform of the external electric field is non-sinusoidal, such as with pulsed or mixed frequency waveforms, the rms value of the spatially averaged external field shall conform to the MPEs of Table 4, and also to either of the criteria stated in 4.1.2.4.1 and 4.1.2.4.2. For this application, the external magnetic field is replaced by the undisturbed electric field; A_i is understood to represent the magnitude of the i^{th} Fourier component of the external electric field waveform, and MPE_i is the maximum permissible electric field magnitude at frequency f_i .

4.1.4 Contact and induced current limits

4.1.4.1 Sinusoidal current

Contact and induced current shall be limited as specified in Table 5, subject to the following conditions:

- Table 5 limits for freestanding individuals without contact with conducting objects shall not exceed the induced current values listed in the rows labeled “Both feet” and “Each foot.”
- Contact limits in Table 5 assume a freestanding individual who is insulated from ground while touching a conductive path to ground. The criteria do not necessarily protect against aversive sensa-

tions from spark discharges just prior to, and just after the moment of direct contact with the ground path.

- c) The averaging time for rms current measurements shall be 0.2 s. The limits for peak exposure refer to instantaneous values measured through a bandwidth from zero to the maximum frequency determined by Fourier decomposition of the waveform of interest.
- d) In controlled environments, limits for grasping contacts apply where personnel are trained to make grasping contact and to avoid touch contacts with conductive objects that present the possibility of painful contact current. A grasp contact area is assumed to be 15 cm². The use of protective gloves, the prohibition of metallic objects, or the training of personnel may be sufficient to assure compliance with the contact current limit in controlled environments. For the general public, it is assumed that access, methods of contact, and protective measures are unconstrained.
- e) A touch contact is assumed to have a contact area of 1 cm².
- f) For long exposure duration ($t \gg 1$ s), the values of induced and contact currents in Table 7 for protecting against heating effects in the RF range, are more restrictive than the corresponding values of currents in Table 5 for frequencies greater than 100 kHz. Hence, for long exposure duration, compliance with this standard at frequencies greater than 100 kHz will be associated with meeting the limits of Table 7.
- g) The limits in Table 5 protect against adverse electrostimulation effects; the MPEs in Table 8 and Table 9 apply to effects associated with tissue heating.

NOTE—All three tables must be considered and the corresponding values for the appropriate exposure group satisfied at all applicable frequencies.

**Table 5—RMS induced and contact current limits for continuous sinusoidal waveforms,
 $f = 3$ kHz to 100 kHz**

Condition	Action level ^a (mA)	Persons in controlled environments (mA)
Both feet	$0.90f$	$2.00f$
Each foot	$0.45f$	$1.00f$
Contact, grasp ^b	—	$1.00f$
Contact, touch	$0.167f$	$0.50f$
NOTE 1— f is expressed in kHz.		
NOTE 2—Limits apply to current flowing between the body and a grounded object that may be contacted by the person.		
NOTE 3—The averaging time for determination of compliance is 0.2 s.		
^a Within this frequency range the term “action level” is equivalent to the term “general public” in IEEE Std C95.6-2002.		
^b The grasping contact limit pertains to controlled environments where personnel are trained to make grasping contact and to avoid touch contacts with conductive objects that present the possibility of painful contact.		

4.1.4.2 Non-sinusoidal (pulsed or mixed frequency) current

When the current waveform is non-sinusoidal, such as with pulsed or mixed frequency waveforms, exposures shall conform to the rms MPEs of Table 5, and also to either of the criteria stated in 4.1.2.4.1 and 4.1.2.4.2. For this application, the external field is replaced by the applied current, A_i is understood to represent the magnitude of the i^{th} Fourier component of the current waveform, and MPE_i is the maximum permissible current magnitude at frequency f_i .

4.2 BRs and MPEs for frequencies between 100 kHz and 3 GHz

4.2.1 BRs for whole-body exposure for frequencies between 100 kHz and 3 GHz

The whole-body-average BRs shown in Table 6 are based on established adverse health effects associated with heating of the body during whole-body exposure (see Annex C.2 for explanation). Consistent with the approach used in the prior standard to derive exposure limits, a traditional safety factor of ten (10) has been applied to the established SAR threshold for such effects, yielding an SAR of 0.4 W/kg averaged over the whole body. In the absence of an RF safety program, the BRs of the lower tier (action level) may also be used for the general public. Applied to members of the general public, the lower tier provides more assurance that continuous, long-term exposure of all individuals in the population, will be without risk of adverse effects.

Table 6—BRs for frequencies between 100 kHz and 3 GHz

		Action level ^a SAR ^b (W/kg)	Persons in controlled environments SAR ^c (W/kg)
Whole-body exposure	Whole-Body Average (WBA)	0.08	0.4
Localized exposure	Localized (peak spatial-average)	2 ^c	10 ^c
Localized exposure	Extremities ^d and pinnae	4 ^c	20 ^c
^a BR for the general public when an RF safety program is unavailable.			
^b SAR is averaged over the appropriate averaging times as shown in Table 8 and Table 9.			
^c Averaged over any 10 g of tissue (defined as a tissue volume in the shape of a cube).*			
^d The extremities are the arms and legs distal from the elbows and knees, respectively.			

*The volume of the cube is approximately 10 cm³.

4.2.2 BRs for localized exposure for frequencies between 100 kHz and 3 GHz

In the transition region of 100 kHz to 5 MHz, two sets of BRs apply: c.f. Table 1 and Table 6. The localized exposure BRs shown in Table 6 are established to protect against excessive temperature rise in any part of the body that might result from localized or non-uniform exposure. When averaging SAR over a 10-g volume of tissue in the extremities and the pinnae, only SAR values for that tissue may be considered. If any cubic volume contains tissue from both the body and the extremities or pinna, each must be considered separately. Specifically, when determining the average SAR in a 10 g cube of tissue in the body, any lack of tissue contained in the cube from the extremities or pinna should be treated as air, i.e., mass = 0 and SAR = 0. In addition, the orientations of the cubes used for SAR averaging should align with the coordinate axes

used in the experimental measurement or numerical computational procedures. Detailed methodology for measurement and calculation using the appropriate averaging volume can be found in IEEE Std C95.3-2002.

4.2.3 Contact and induced current limits, 100 kHz to 110 MHz

In the transition region of 100 kHz to 5 MHz, two sets of contact and induced current limits apply. The limits in Table 5 protect against effects associated with electrostimulation and the limits in Table 7 protect against effects associated with tissue heating. Contact and induced current shall both be limited as specified in Table 7, subject to the conditions enumerated in 4.1.4.1, except for a greater averaging time. Figure 1 (upper tier) and Figure 2 (lower tier) provide E-field values below which induced current does not have to be measured. The electric field strength values plotted in Figures 1 and 2 are derived from estimated induced body currents from exposure to uniform electric fields (typically far field exposures) aligned with the axis of the body of a 1.75 m tall individual standing in good conductive contact with ground (Gandhi et al. [R346]⁷, Tofani et al. [R575]). These assumed exposure conditions will often not be applicable to realistic exposures with the result that substantially higher electric field strengths will be required to produce the induced body or touch current limits specified in this standard. For example, normal footwear can significantly reduce induced body current. In addition, the currents specified in this standard in the 100 kHz to 100 MHz frequency range are to be time-averaged over either 6 minutes or 30 minutes. Moreover, the values for induced current are based on the assumption that all current will flow through one foot to ground, resulting in a conservative indication of field strength below which induced current measurements are not required.

**Table 7—RMS induced and contact current limits for continuous sinusoidal waveforms,
 $f = 100 \text{ kHz to } 110 \text{ MHz}$**

Condition	Action level ^a (mA)	Persons in controlled environments (mA)
Both feet	90	200
Each foot	45	100
Contact, grasp ^b	—	100
Contact, touch	16.7	50
NOTE 1—Limits apply to current flowing between the body and a grounded object that may be contacted by the person.		
NOTE 2—The averaging time for determination of compliance is 6 minutes.		
^a MPE for the general public in absence of an RF safety program.		
^b The grasping contact limit pertains to controlled environments where personnel are trained to make grasping contact and to avoid touch contacts with conductive objects that present the possibility of painful contact.		

⁷The number in brackets preceded by “R,” e.g., [R342] corresponds to citations in the International EMF Project (IEEE/WHO) database and are listed in Annex F.

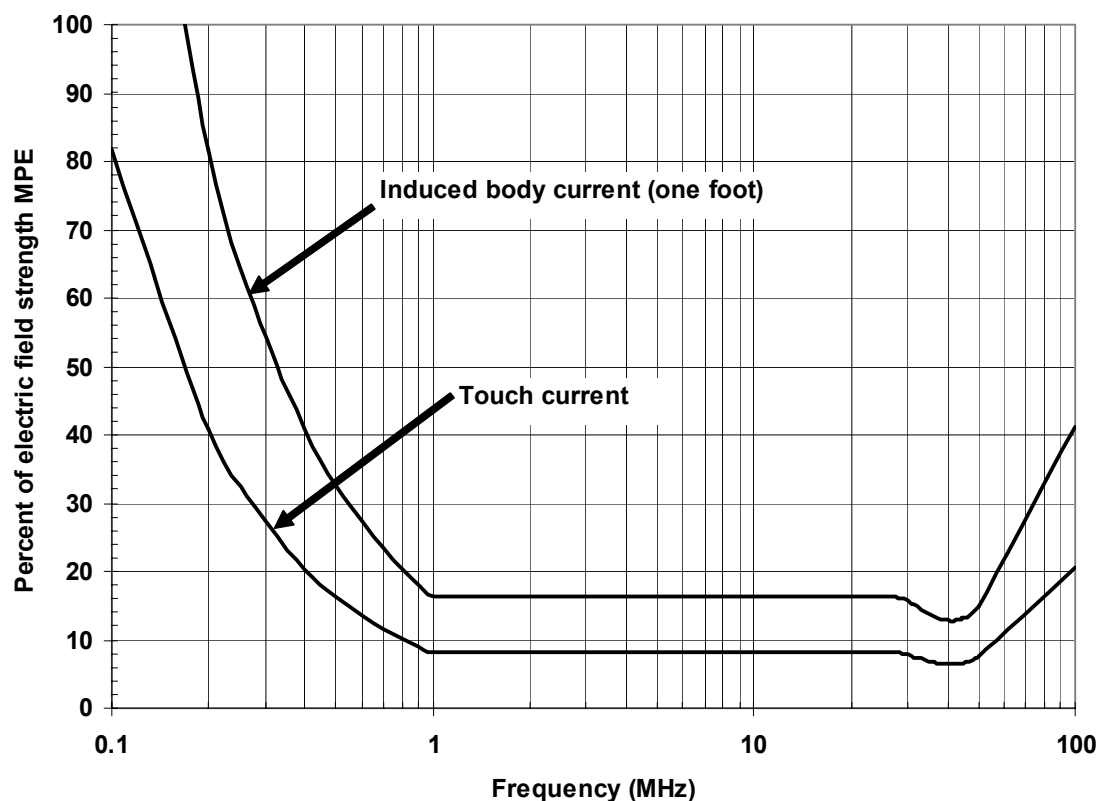


Figure 1—Percent of electric field strength MPE below which the induced current through one foot, or the touch current, will meet the MPEs of Table 7 for the upper tier (exposures in controlled environments); based on a body height of 1.75 m.

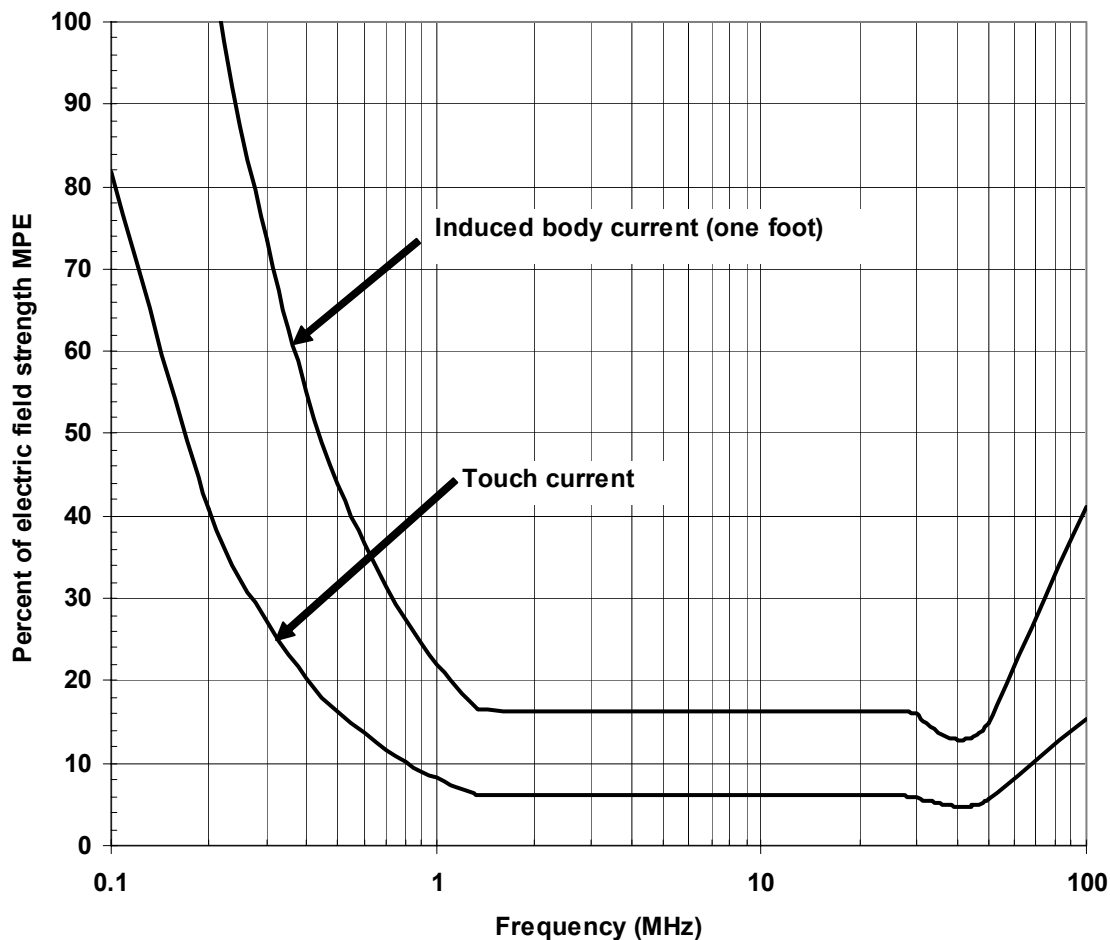


Figure 2—Percent of electric field strength MPE below which the induced current through one foot, or the touch current, will meet the MPEs of Table 7 for the lower tier; based on a body height of 1.75 m.

4.3 BRs for frequencies between 3 GHz and 300 GHz

BRs to protect against adverse effects associated with heating are established for incident power density for frequencies between 3 GHz and 300 GHz. Such restrictions are derived with consideration of adverse effects thresholds (based on the literature review and evaluation), their distribution among the population, and safety factors. The BRs for frequencies between 3 GHz and 300 GHz are the same as the corresponding MPEs shown in Table 8 and Table 9, and are considered appropriate for all human exposure.

4.4 MPEs for frequencies between 100 kHz and 300 GHz

Because of the difficulty in determining whether an exposure complies with the BRs, derived limits (MPEs) to protect against adverse effects associated with heating are provided below for convenience in exposure assessment. For human exposure to electromagnetic energy at radio frequencies from 100 kHz to 300 GHz, the MPEs, in terms of rms electric (E) and magnetic (H) field strengths and the equivalent plane-wave free-space power densities (S) are presented as a function of frequency in Table 8 and Table 9. For multiple field exposure situations, e.g., different frequency field sources, compliance is determined by summing the per-

centages of the applicable MPEs that each frequency field represents and ensuring that this sum does not exceed 100 percent. When fields at multiple frequencies are present, the use of Figure 1 or Figure 2 to assess whether induced or contact currents need to be measured is not practical. If exposure levels are determined via theoretical analysis, consideration of possible reflections of fields must be included.

Compliance with Table 8 and Table 9 ensures compliance with the BRs on whole-body average SAR. However, lack of compliance with Table 8 and Table 9 does not necessarily imply lack of compliance with the BRs, but rather that it may be necessary to perform additional evaluations to determine whether the BRs have been met. If the BRs given above are not exceeded, the MPEs in Table 8 and Table 9 can be exceeded. Consequently, it is sufficient to demonstrate compliance with either the whole-body BRs or Table 8 and Table 9.

Table 8—MPE for the upper tier (people in controlled environments)
(see Figure 3 for graphical representation)

Frequency range (MHz)	RMS electric field strength (E) ^a (V/m)	RMS magnetic field strength (H) ^a (A/m)	RMS power density (S) E-field, H-field (W/m ²)	Averaging time E ² , H ² or S (min)
0.1–1.0	1842	16.3/ f_M	(9000, 100 000/ f_M^2) ^b	6
1.0–30	1842/ f_M	16.3/ f_M	(9000/ f_M^2 , 100 000/ f_M^2)	6
30–100	61.4	16.3/ f_M	(10, 100 000/ f_M^2)	6
100–300	61.4	0.163	10	6
300–3000	—	—	$f_M/30$	6
3000–30 000	—	—	100	19.63/ $f_G^{1.079}$
30 000–300 000	—	—	100	2.524/ $f_G^{0.476}$
NOTE— f_M is the frequency in MHz, f_G is the frequency in GHz.				
^a For exposures that are uniform over the dimensions of the body, such as certain far-field plane-wave exposures, the exposure field strengths and power densities are compared with the MPEs in the Table. For non-uniform exposures, the mean values of the exposure fields, as obtained by spatially averaging the squares of the field strengths or averaging the power densities over an area equivalent to the vertical cross section of the human body (projected area), or a smaller area depending on the frequency (see NOTES to Table 8 and Table 9 below), are compared with the MPEs in the Table.				
^b These plane-wave equivalent power density values are commonly used as a convenient comparison with MPEs at higher frequencies and are displayed on some instruments in use.				

**Table 9—Action level (MPE for the general public when an RF safety program is unavailable)
(see Figure 4 for graphical representation)**

Frequency range (MHz)	RMS electric field strength (E) ^a (V/m)	RMS magnetic field strength (H) ^a (A/m)	RMS power density (S) E-field, H-field (W/m ²)	Averaging time ^b $ E ^2$, $ H ^2$ or S (min)	
0.1–1.34	614	$16.3/f_M$	$(1000, 100\,000/f_M^2)^c$	6	6
1.34–3	$823.8/f_M$	$16.3/f_M$	$(1800/f_M^2, 100\,000/f_M^2)$	$f_M^2/0.3$	6
3–30	$823.8/f_M$	$16.3/f_M$	$(1800/f_M^2, 100\,000/f_M^2)$	30	6
30–100	27.5	$158.3/f_M^{1.668}$	$(2, 9\,400\,000/f_M^{3.336})$	30	$0.0636 f_M^{1.337}$
100–400	27.5	0.0729	2	30	30
400–2000	–	–	$f_M/200$	30	
2000–5000	–	–	10	30	
5000–30 000	–	–	10	$150/f_G$	
30 000–100 000	–	–	10	$25.24/f_G^{0.476}$	
100 000–300 000	–	–	$(90f_G-7000)/200$	$5048/[(9f_G-700)f_G^{0.476}]$	
NOTE— f_M is the frequency in MHz, f_G is the frequency in GHz.					
^a For exposures that are uniform over the dimensions of the body, such as certain far-field plane-wave exposures, the exposure field strengths and power densities are compared with the MPEs in the Table. For non-uniform exposures, the mean values of the exposure fields, as obtained by spatially averaging the squares of the field strengths or averaging the power densities over an area equivalent to the vertical cross section of the human body (projected area) or a smaller area depending on the frequency (see NOTES to Table 8 and Table 9 below), are compared with the MPEs in the Table.					
^b The left column is the averaging time for $ E ^2$, the right column is the averaging time for $ H ^2$. For frequencies greater than 400 MHz, the averaging time is for power density S					
^c These plane-wave equivalent power density values are commonly used as a convenient comparison with MPEs at higher frequencies and are displayed on some instruments in use.					

NOTES TO TABLE 8 AND TABLE 9

- a) The MPEs refer to exposure values obtained by spatially averaging the electric and magnetic field strengths, the squares of the electric and magnetic field strengths, or the plane wave equivalent power densities along a line corresponding to the axis of the human body as follows:

Frequencies between 100 kHz and 3 GHz: The MPE for fields between 100 kHz and 3 GHz are derived on the basis of limiting the whole body averaged (WBA) SAR, which is proportional to the spatial average of the incident plane wave equivalent power density (or squares of electric and magnetic field strengths), averaged over the projected area of the body. Therefore, the MPE corresponds to the spatially averaged plane wave equivalent power density or the spatially averaged values of the squares of electric and magnetic field strengths. In practice, a measurement over the length of the body is sufficient for assessing exposures for comparison with the MPE.

- Frequencies greater than 3 GHz:** For frequencies greater than 3 GHz, the MPE is expressed in terms of the incident power density. To provide a transition in the frequency range 3 GHz to 6 GHz, compliance with this standard may be demonstrated by evaluation of either incident power density or local SAR. From 3 GHz to 30 GHz, the power density is spatially averaged over any contiguous area corresponding to $100 \lambda^2$, where λ is the free space wavelength of the RF field in centimeters. For frequencies exceeding 30 GHz, the power density is spatially averaged over any contiguous area of 0.01 m^2 (100 cm^2), not to exceed a maximum power density of 1000 W/m^2 in any one square centimeter as determined by a calculation or a conventional field measurement.
- b) For near-field exposures at frequencies below 300 MHz, the applicable MPE is in terms of rms electric and magnetic field strength, as given in Table 8 and Table 9, columns 2 and 3. For convenience, the MPE may be expressed as equivalent plane-wave power density, given in Table 8 and Table 9, column 4. For frequencies below 30 MHz, both the rms electric and magnetic field strength must be determined; for frequencies between 30 and 300 MHz, either field component will be sufficient provided that the point in question is in the far-field of the source. For frequencies above 300 MHz, either field component may be used, when expressed as equivalent plane wave power density, for determining compliance with the MPEs in Table 8 and Table 9.
 - c) For mixed or broadband fields at a number of frequencies for which there are different values of the MPE, the fraction of the MPE [in terms of E^2 , H^2 , or power density (S)] incurred within each frequency interval should be determined and the sum of all such fractions should not exceed unity. See Annex D for an example of how this is accomplished.
 - d) In a similar manner, for mixed or broadband induced currents at a number of frequencies for which there are different values of the basic restriction, the fraction of the induced current limits (in terms of I^2) incurred within each frequency interval shall be determined, and the sum of all such fractions should not exceed unity.
 - e) For exposures to pulsed RF fields, in the range of 100 kHz to 300 GHz, the peak (temporal) value of the MPE for the instantaneous peak E field is 100 kV/m.
 - f) For exposures to pulsed RF fields in the range of 100 kHz to 300 GHz, the peak pulse power densities are limited by the use of time averaging and the limit on peak E field, with one exception: the total incident energy density during any one-tenth second period within the averaging time shall not exceed one-fifth of the total energy density permitted during the entire averaging time for a continuous field (1/5 of 144 J/kg), i.e.,

$$\sum_{0}^{0.1s} (S_{pk} \times \tau) \leq \frac{MPE_{avg} \times T_{avg}}{5} \leq 28.8 \text{ J/kg}$$

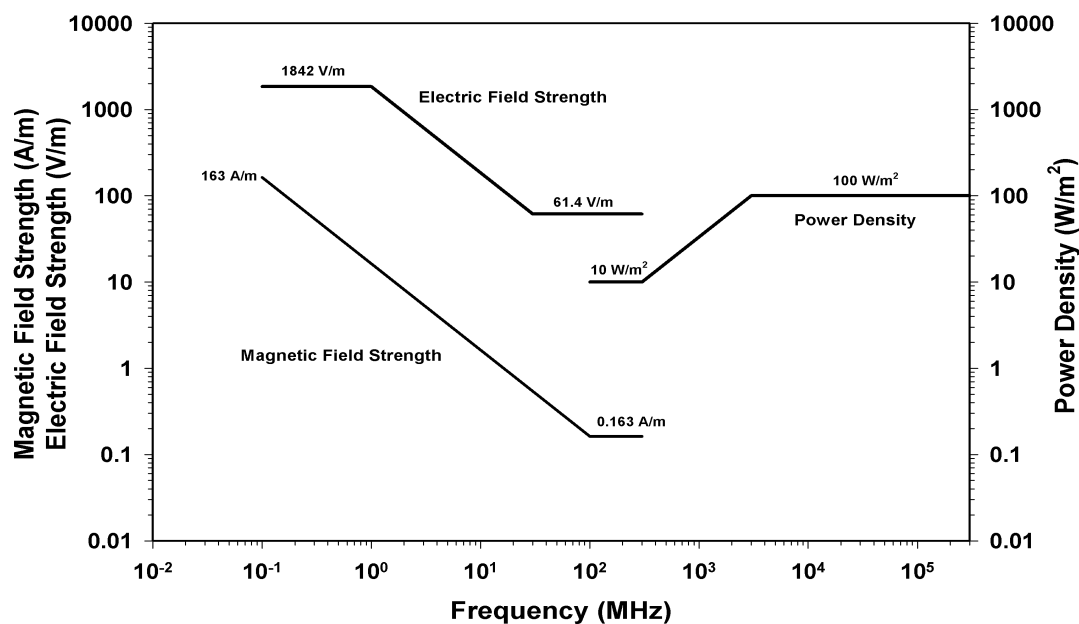


Figure 3—Graphic representation of the MPEs in Table 8 (exposures in controlled environments)

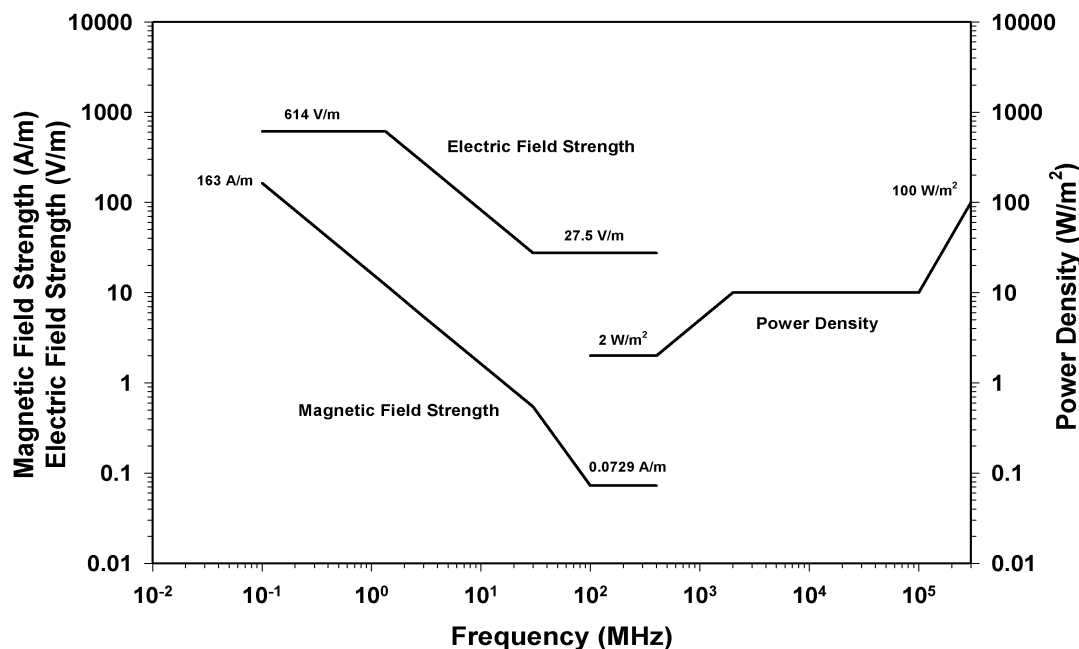


Figure 4—Graphic representation of the MPEs in Table 9 (lower tier—action level)

4.5 Suggested limit for contact voltage to protect against RF burns

In addition to the limits recommended for contact and induced currents, this standard also specifies an MPE for the open circuit voltage that exists on objects exposed to electric and magnetic fields in the frequency range of 0.1 to 100 MHz with which an individual may come into contact. The open circuit voltage is the factor most likely to lead to an electrical arc between the object and a person approaching contact, and hence a localized RF burn of the skin. The maximum suggested open circuit voltage is 140 volts (rms), as measured between any two points of contact with the body, unless it can be shown for specific situations via measurements that a higher open circuit voltage can be tolerated without surface arcing and an attendant RF burn. This suggested limit and rationale should be considered tentative until such time as a more thorough scientific and technical basis for the limit is developed (NAVSEA [B93]).

4.6 Relaxation of the power density MPEs for localized exposures

The following relaxation of the power density MPE is allowed for exposure of any part of the body. Compliance with the MPE of Table 8 (upper tier) 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 0.2 m from the field source. The spatial peak value of the power density or mean squared field strength shall not exceed 20 times the square of the allowed spatially averaged values (Table 8) at frequencies below 300 MHz, and shall not exceed the equivalent power density of 200 W/m^2 at frequencies between 300 MHz and 3 GHz, $200 (f/3)^{1/5} \text{ W/m}^2$ at frequencies between 3 and 96 GHz (f is in GHz), and 400 W/m^2 at frequencies above 96 GHz.

Compliance with Table 9 (lower tier) 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 0.2 m from the field source. The spatial peak value of the power density or mean squared field strength shall not exceed 20 times the square of the allowed spatially averaged values (Table 9) at frequencies below 400 MHz, and shall not exceed the equivalent power density of 40 W/m^2 at frequencies between 400 MHz and 3 GHz, $18.56 (f)^{0.699} \text{ W/m}^2$ at frequencies between 3 and 30 GHz (f is in GHz), and 200 W/m^2 at frequencies above 30 GHz.

4.7 Assessing compliance with this standard

Compliance with this standard would ideally include a determination that the basic restrictions are not exceeded. For the upper tier in the RF range, this means that the whole-body average and local SARs do not exceed 0.4 W/kg and 10 W/kg , respectively. In practice, however, assessing compliance with this standard will generally consist of determining whether potential exposure of an individual in terms of the various exposure parameters of electric and magnetic fields, plane wave equivalent power densities, contact and induced currents, and contact voltages, exceeds any of the corresponding MPEs. This is less complicated than an assessment of SAR. SAR evaluation may be necessary for some exposure conditions, however, especially for evaluating exposure when the body is extremely close to an RF field source (within the reactive near-field region) and for highly localized exposures. Evaluating whether exposure conditions exceed the upper or lower tier will normally not involve a direct assessment of SARs, but only that the exposure parameters, e.g., Table 8 and Table 9, are not exceeded.

Assessment of exposure to RF fields may be accomplished via either measurements or analysis, using appropriate instrumentation and measurement techniques or numerical/analytical methods. For measurements, reference should be made to IEEE Std C95.3-2002. The MPEs in terms of the RF field or power densities specified in this standard were derived to ensure compliance with the basic restriction on whole-body average (WBA) SARs, and are intended to be applied to field exposure over the entire body in terms of a spatial average. Two issues must be kept in mind when assessing compliance. While the MPEs of this standard are intended to protect against exposures that would result in the WBA SAR exceeding the basic

restrictions, assessment of exposure under conditions wherein the RF fields are strongly non-uniform over the body, typical of near-field exposures, may not in some cases ensure that local SARs will comply with the basic restriction on local SAR of this standard. Moreover, application of the MPEs for fields at locations extremely close to the RF field source (typically in the reactive near-field region wherein there can be substantial coupling between the individual and the source) may not ensure compliance with the basic restriction on local SAR. In both of these special cases, it may be necessary to directly evaluate local SAR through measurement or analysis. Further, care should be used in any RF field measurements conducted extremely close to an RF source to ensure conformance with the minimum measurement distance specified in IEEE Std C95.3-2002; this will prevent inaccurate readings due to probe-field coupling. Generally, however, most commercially available isotropic field probes, even when coupling to the source due to proximity, will read high compared with the actual value. Hence, while it is recommended that the minimum measurement distances prescribed in C95.3-2002 be used, measurements at closer distances will usually be conservative. An exception to this rule is when the measurement probe is large relative to the wavelength of the RF fields being measured.

In cases where the measured exposure parameters approach or exceed the MPE, the more complex evaluation of SAR may be used to make a further determination of compliance with the standard. In many cases, such evaluations may reveal that the SAR basic restrictions are not exceeded. A practical guideline for eliminating the need to assess whether the whole-body average SAR exceeds the basic restriction of 0.4 W/kg (or 0.08 W/kg when the lower tier is used as an exposure limit for the public) is to determine if the power of the source(s) exceeds 28 W (upper tier) or 5.6 W (lower tier) for an average man (70 kg). If the cumulative power of the relevant RF field sources is less than these values, the exposure will not exceed the basic restriction on whole-body average SAR. Such a determination, however, does not necessarily imply that the basic restriction on local SAR would not be exceeded.

4.8 RF safety programs

Throughout the RF spectrum applicable to this standard, the MPEs apply to exposure of people, i.e., compliance with this standard is determined by whether or not exposures of people to RF fields, currents and voltages exceed the applicable MPEs. Where there may be access to RF fields, currents, and/or voltages that exceed the lower tier (Action Level) of this standard, an RF safety program such as detailed in IEEE Std C95.7-2005 shall be implemented to ensure that exposures do not exceed the MPEs or BRs for persons in a controlled environment. Application of an RF safety program results in various mitigative measures that can be taken to reduce the probability of exceeding the MPE for the upper tier. This program typically includes RF awareness training, implementation of protective measures such as signage and the use of personal protective equipment (PPE), incident response, periodic evaluation of program effectiveness, and assigned responsibilities for implementing the program (IEEE Std C95.7-2005).

Annex A

(informative)

Approach to revision of IEEE Std C95.1, 1999 Edition

A.1 ICES revision process

The revision process established by the IEEE International Committee on Electromagnetic Safety (ICES) is a continuing rigorous and open scientific process that is transparent at all levels and includes the opportunity for input from all stakeholders.

A.1.1 Continuity of the IEEE standards revision process

IEEE Std C95.1, 1999 Edition [B70] was first approved by the IEEE Standards Board in 1991 and published as IEEE Std C95.1-1991. The 1991 standard was then reaffirmed in 1997, and then an updated version, containing minor revisions and clarifications, and incorporating IEEE Std C95.1-1991 with IEEE Std C95.1a-1998, was approved and published in 1999, and an amendment that addresses the peak spatial average SAR in the pinnae (IEEE Std C95.1bTM-2004 [B71]) was approved in 2004. This standard is a complete revision of IEEE Std C95.1-1991; the revision process implemented by ICES Subcommittee 4 is described below.

A.1.2 Open nature of the IEEE ICES standards development process

IEEE ICES and its Subcommittees are composed of volunteers representing all stakeholders. A balance of representatives from government, industry, academia, and the general public is maintained in accordance with the membership requirements of all standards committees sponsored by the IEEE Standards Association Standards Board (SASB). Subcommittee membership is open to all and consists of volunteers in engineering, physics, statistics, epidemiology, life sciences, medicine, and the public. This wide-ranging participation, including thorough discussions and open decision making, is the hallmark of the process that led to this standard.

A.1.3 Complete reassessment of the technical rationale

IEEE Std C95.1-1991 (and the 1999 Edition) was based on research published before 1986. Research has continued since 1986; a reevaluation of the RF biological effects database was therefore performed. A new risk assessment based on the results of this reevaluation was undertaken. Attempts were made to include and to evaluate all of the relevant literature in the database.

A.1.4 Process for interpretations, clarifications, and appeals

The evaluation of an IEEE standard is a process that is continually ongoing, i.e., IEEE standards are “living” documents. Requests for interpretation and clarification submitted to IEEE ICES by the Secretary of the IEEE-SASB are resolved by special working groups of the ICES subcommittees. The rules and procedures for responding to such requests are included in the ICES Policies and Procedures and are approved by the IEEE-SASB. Valid and applicable comments, received since the last revision, are incorporated in the current revision of the standard by consensus. Appeals of an approved standard are resolved in accordance with the IEEE-SASB Policies and Procedures.

A.1.5 The literature surveillance effort

A Literature Surveillance Working Group (LSWG) was established to compile a citation list of all relevant published literature. At the literature cutoff date of 31 December 2003, approximately 2200 papers had been identified. These were augmented by a few papers and documents appearing in 2004 and 2005. The committee agreed that only peer-reviewed papers and technical reports of original research would constitute the primary database on which any risk analysis would be based. Abstracts and presentations at scientific meetings or technical conferences were expressly excluded from the database. A list of all of the citations is provided in Annex E.

A.1.6 Literature evaluation process

Working groups (WGs) were established to review and evaluate the literature database. These WGs evaluated engineering, epidemiology, *in vivo*, and *in vitro* aspects of individual citations. Additionally, a WG on mechanisms assessed the role of mechanisms of interaction in standard setting and was available to evaluate the technical significance of particular interaction mechanisms. The Engineering WG was tasked with reviewing all papers. The *in vivo* and *in vitro* studies were evaluated in terms of the adequacy of engineering design. The engineering evaluation included assessment of the exposure systems, field characteristics and measurements, dosimetry, specific absorption rates, induced currents and fields, and temperature/humidity measurements. The sufficiency of the information provided in each publication, to allow a full understanding of how the experiment was performed, was paramount.

The Epidemiology WG was originally tasked with the evaluation of each paper for study design and population segments, quality of the methods and implementation, merit of data acquisition and analysis for specific endpoints, and presence or absence of positive statistical associations. Individual papers included possible effects both on specific segments of the general population and on subpopulations occupationally exposed to electromagnetic fields. Because the Chair of the Epidemiology WG changed hands several times; few papers were reviewed because of the lack of available volunteer epidemiologists and a review paper was used instead (see below).

The *In Vivo* and *In Vitro* WGs were tasked similarly to examine the technological methodologies employed in each published paper. Both groups considered the biological entities studied in each paper and their special characteristics. The RF exposure conditions, specific organ systems and/or biological endpoints examined, the engineering and statistical methodologies employed, and provided assessments of the relevance of each study for setting human exposure standards, were evaluated. The *in vitro* papers typically emphasized possible effects at the cellular level, including those on cell viability and proliferation, genotoxicity, cell transformation, molecular synthesis, and cell function. The *in vivo* papers typically examined possible effects of exposure on the whole organism or on specific organ systems, including effects on the embryo/fetus, reproductive ability, immunological system, functional alterations of the metabolic or thermoregulatory system, various histological endpoints, and behavioral changes. As for the engineering evaluations, the adequacy of the information provided in each *in vitro* and *in vivo* publication, which would allow a reasonably knowledgeable research scientist to understand how the study was performed and to independently reproduce it, was essential. The *In Vivo* WG reviewed more than 90% of the *in vivo* papers, but the Epidemiology and *In Vitro* WGs reviewed only a small portion of the papers in their respective areas. This left gaps that, where critical, were filled by the hazard identification process and several review papers, as described in A.1.7, below. See also A.1.9.

The chair of each WG was responsible for providing copies of each paper to two independent reviewers, together with specially designed and approved review forms. These forms were in a computer format that required numerical scoring by individual reviewers for entry into a computerized database. When a review was completed, the reviewer gave the paper an overall technical merit rating on a 5-point scale. The rating scale was: Very High = 5; Moderately High = 4; Acceptable = 3; Low = 2; and Very Low = 1. For ratings of 1 or 2, a request was made for justification in writing by the reviewer. This was not requested for ratings of

3 and above, which were considered acceptable. Strong discordance between the two reviews of a given paper required a third independent review. Periodically, the chair of each WG submitted a summary of the reviews completed to the Chair of the Risk Assessment WG (RAWG). All of the reviews were performed by volunteers, who were randomly selected from within each working group. The identification of each reviewer in a specific paper will remain confidential; the list of reviewers who were active at any time in the review process will be publicly available.

A.1.7 Hazard identification and review papers

As the literature review process proceeded, it became clear that such a very large database would require many years of intense effort to accomplish the goal of identifying any potential hazard to human health or safety resulting from exposure to RF electromagnetic fields (3 kHz to 300 GHz). A special Revision WG was created to prepare a framework for the new standard and to discuss both the extent of the normative content and the informative annexes. As more reviews were being completed, certain individuals with considerable expertise in specific areas volunteered or were asked to prepare review papers to summarize the findings in specific topic areas. These included, for example, cancer induction or promotion, teratologic effects, ocular effects, epidemiology, thermoregulation, and animal behavior [cf. B.1 and B.5]. In each topic area, one of the goals was to search for definable hazards. Summaries and conclusions from each review paper appear in Annex B.

A.1.8 Role of the Risk Assessment Working Group

A literature cutoff date was established (December 31, 2003) as the literature evaluation process continued moving forward. The evaluations of the published papers continued to be submitted by the four WG Chairs to the Chair of the RAWG. The texts and conclusions of the various review papers were made available to the RAWG, whose charge was to evaluate the implied risk for human beings of exposure to RF electromagnetic fields. This activity was supported by a dialogue between RAWG members and a Revision Working Group (ongoing for several years) concerning the format, basis, and details of the new standard.

A.1.9 Current status of the literature evaluation and review process

As the current version of the revised C95.1 standard neared completion and was balloted by SC-4, it became clear that the literature evaluation process would not be completed on time. While the engineering WG evaluated nearly all of the papers in the database and the *In Vivo* WG evaluated more than 90% of their assigned papers, few epidemiology and *in vitro* papers were evaluated by members of their respective WGs. A lack of qualified reviewers was the principal reason for the latter. On the other hand, review summaries of the biological papers (~1300) in the principal database are presented in Annex B. These summaries are further enhanced by the 12 review papers published in Supplement 6, 2003 of *Bioelectromagnetics* [B15], including reviews of the epidemiology and *in vitro* literature (cf. B.1). The conclusions derived from this extensive review process are based on the weight of evidence approach throughout and form the basis of the current revision of the standard. Committee members believe that the literature review process should be a continuous, ongoing effort; if any new adverse effect is established which would require a change in the standard, the standard can be promptly revised by amendments.

A.2 Basic concepts for developing the MPEs

The process followed by the committee for establishing MPEs with respect to human exposure to RF electromagnetic fields, 3 kHz to 300 GHz, was dependent on the weight of the scientific evidence, a procedure used to develop guidance for assessment of risk from chemical and other physical agents known to be hazardous. These methods have been developed over the years and are widely reviewed (NRC [B99], [B100], [B101]). The process began with a detailed evaluation of the relevant literature in the scientific database,

took advantage of all completed evaluations in the computerized database, and proceeded to a determination of potential hazards to human beings exposed to RF energy (cf. A.1.6 to A.1.9 above), from which thresholds of individual responses and dose response functions were determined.

A.2.1 Publication of novel findings, supportive data, and general acceptance by the scientific community

Many novel experimental studies have been published in the peer reviewed scientific literature, and while of interest, cannot be applied to setting standards for allowable human exposure to RF energy. A number of these studies suffer from poor design, inappropriate or no controls, inadequate dosimetry, physical artifacts, defective measurements, or improper statistical analysis. Other studies suffer from erroneous conclusions and lack of scientific detail. Many published studies failed to replicate or support initially reported effects of RF exposure. The results of other published studies, of high-quality design or exceptional importance, although not independently replicated in the published literature, were seriously considered as part of the risk assessment because supporting evidence was available in that literature. While the body of potentially pertinent science is generally discussed and commented upon in scientific meetings or other forums, informal interchanges do not constitute contributions to a valid risk analysis, and were excluded as anecdotal. Painstaking review by experts of the papers in the scientific database was the only dependable means of sorting the meaningful data from the mediocre or unusable data. These reviews, performed as part of the process for establishing this standard, were careful to differentiate between evidence for a biological effect and that for an adverse human health effect. The procedures detailed above provide the basis for the evaluation of RF hazards and the associated risk assessment used in establishing this standard.

A.2.2 Assessing thresholds and dose-response relationships

For exposures to nonionizing electromagnetic energy, observed individual biological effects, whether adverse or beneficial, are characterized by thresholds and are a function of exposure level. For any given biological response, a threshold can be determined below which the specific response does not occur or is undetectable. Above the threshold level, a function that relates dose rate, e.g., SAR, to response magnitude is determined and the lowest level at which a potential hazard occurs is identified. Exposure limits can then be developed to protect against the occurrence of the effects to human beings.

A.2.3 Selection of safety factors and development of MPEs

Once a hazard threshold has been identified and enough supporting information is available, a safety factor can be applied to the threshold to derive an exposure limit that is based on the best available scientific information using the conservative approach common in standard setting. In practice, the better the hazards involved are understood, the better the numerical foundation for the safety factor, but the choice always relies on professional judgment.

The selection of a “safety factor” is generally an arbitrary process, which presupposes that a hazard has been identified and a threshold has been determined. The safety factor is influenced by the uncertainty in our knowledge of the degree of hazard associated with the hazard exposure threshold and is selected to prevent exceeding the threshold value in human exposure with a sufficiently wide margin. The magnitude of a safety factor may range from unity at low frequencies, where electrostimulatory effects may occur, to significantly greater values at frequencies above 100 kHz, where heating effects may occur. In all cases, however, the selection of the appropriate safety factor is based on informed expert opinion after considering the underlying biological and engineering uncertainties applicable to the exposed population for a broad range of exposure conditions. In this standard, for frequencies above 100 kHz, safety factors are equivalent to SAR or power density reduction factors relative to those exposure values representing the exposure thresholds for hazardous effects. These factors are not necessarily numerically equivalent to the degree of reduction in the resulting manifestation of RF energy absorption, such as an increase in localized tissue temperature.

Annex B

(informative)

Identification of levels of RF exposure responsible for adverse effects: summary of the literature

NOTE—References denoted in brackets with the letter “R” before the number (e.g., [R119]) are references from the IEEE/WHO Literature Database and are found in Annex F. References denoted with the letter “B” before the number (e.g., [B115]) are references that are not in the IEEE/WHO database and are found in the Bibliography (Annex G).

B.1 Introduction

The following summary of the literature is based on critical reviews of studies within the IEEE/WHO RF literature database⁸ (see Annex F). Although this standard considers the entire frequency range between 3 kHz through 300 GHz, a majority of the studies evaluated employ RF signals relevant to various communications, industrial, and radar technologies. In general, studies are not identified or separated according to specific frequencies or modulation characteristics, as the evidence does not support frequency or modulation-specific effects except for geometrical resonances for animal and human exposures that result in enhanced heat deposition and thermoregulation in mammalian models at certain frequencies.

Detailed review papers were drafted for twelve general subject areas by individual members of IEEE ICES TC-95/SC4 and were published together at the end of 2003 as Supplement 6 of the journal *Bioelectromagnetics* [B15]⁹. These include:

- 1) Historical Review of RF Exposure Standards and ICES (Osepchuk and Petersen [R1088]),
- 2) Thermoregulatory Responses to RF Energy Absorption (Adair and Black [R1091]),
- 3) Behavioral and Cognitive Effects of Microwave Exposure (D’Andrea et al. [R1093]),
- 4) Cancer, Mutagenesis, and Genotoxicity (Heynick et al. [R1095]),
- 5) Lifespan and Cancer in Laboratory Mammals Exposed to RF Energy (Elder [R1092]),
- 6) Microwave Effects on the Nervous System (D’Andrea et al. [R1089]),
- 7) Ocular Effects of RF Energy (Elder [R1099]),
- 8) Auditory Responses to Pulsed RF Energy (Elder and Chou [R1096]),
- 9) Epidemiological Studies of RF Exposures and Human Cancer (Elwood [R1097]),
- 10) RF Effects on Blood Cells, Cardiac, Endocrine, and Immunological Functions (Black and Heynick [R1111]),
- 11) RF Fields and Teratogenesis (Heynick and Merritt [R1098]), and
- 12) RF Exposure and Biological Effects: In vitro Studies with in vivo Correlation (Meltz [R1090]).

The review for this standard includes studies conducted under many different exposure conditions, some using levels of RF energy too low to produce significant heating in animal or *in vitro* test systems (herein referred to as “low-level” exposures rather than “non-thermal” exposures), others using levels of RF energy producing clear RF heating (“thermal”), and others employing conditions where RF currents can cause burns or nerve and muscle stimulation (“shocks”). In all categories particular attention was paid to variables that might occur prior to, or concurrent with RF exposure, and possibly result in effects at lower RF field levels. The IEEE/WHO database was used in developing this revision. References from this database

⁸The entire IEEE/WHO database can also be found at Internet site <http://www10.who.int/peh-emf/emfstudies/IEEEdatabase.cfm>.

⁹The individual papers can be found at Internet site <http://grouper.ieee.org/groups/sc28/sc4/contents.html>.

(shown in Annex F) are denoted [Rxx]; the number following each citation, e.g., [IEEE-xxx], is the IEEE Accession Number. References that are not in the IEEE/WHO database (usually because they are not studies specifically examining bioeffects of RF) are included in the Bibliography, Annex G, and denoted [Bxx].

B.2 Executive Summary

A review of the extensive literature on RF biological effects, consisting of well over 1300 primary peer reviewed publications published as early as 1950, reveals no adverse health effects that are not thermally related (except for electrostimulation discussed in B.2.4). This conclusion is consistent with those reached by other scientific expert groups and government agencies including the:

- Australian Government, Australian Radiation Protection and Nuclear Safety Agency, Committee on Electromagnetic Energy Public Health Issues (ARPANSA [B9], [B10]),
- European Commission Expert Group (McKinlay et al. [B88]),
- European Committee on Toxicology, Eco-toxicology and the Environment (CSTEE [B27], [B28], [B29]),
- France's Commission for Consumer Safety (the French Expert Report - 'Zmirou report' to the French Health General Directorate) (Zmirou et al. [R787]),
- French Environmental Health and Safety Agency (AFSSE [B2]), (Aran et al. [B8])
- Health Council of the Netherlands (HCN [B55], [B56]),
- Hong Kong-Office of the Telecommunications Authority [B59],
- International Commission on Non-Ionizing Radiation Protection (ICNIRP [B62], [B64]),
- Japanese Ministry of Post and Telecommunications [B76],
- New Zealand Ministry of Health and Ministry of Environment [B99],
- Royal Society of Canada Expert Panel (RSC [B109])
- Singapore Health Sciences Authority (SHSA [B122], [B123]),
- Swedish State Radiation Protection Authority (SSI [B126]),
- U.K. Independent Expert Group on Mobile Phones (IEGMP [B73]),
- U.K. National Radiological Protection Board (NRPB [B103]),
- U.S. Food and Drug Administration (FDA [B42]), and the
- World Health Organization (WHO [B135], [B136]).

Further examination of the RF literature reveals no reproducible low level (non-thermal) effect that would occur even under extreme environmental exposures. The scientific consensus is that there are no accepted theoretical mechanisms that would suggest the existence of such effects. This consensus further supports the analysis presented in this section, i.e., that harmful effects are and will be due to excessive absorption of energy, resulting in heating that can result in a detrimentally elevated temperature. The accepted mechanism is RF energy absorbed by the biological system through interaction with polar molecules (dielectric relaxation) or interactions with ions (ohmic loss) is rapidly dispersed to all modes of the system leading to an average energy rise or temperature elevation. Since publication of ANSI C95.1-1982 [B6], significant advances have been made in our knowledge of the biological effects of exposure to RF energy. This increased knowledge strengthens the basis for and confidence in the statement that the MPEs and BRs in this standard are protective against established adverse health effects with a large margin of safety.

B.2.1 Thermal physiology and associated behavioral responses form the basis of the RF standard

Behavioral studies indicate that a threshold of ~4 W/kg causes disruption of complex behavioral performance in several animal species, including non-human primates, and under diverse exposure conditions. The

disruption of behavior is often (but not always) accompanied by an increase in core body temperature of $\sim 1.0^{\circ}\text{C}$. These accommodating responses to a thermal challenge, while not considered detrimental, can be compared to the response when humans take off or put on a light sweater to adjust to mild temperature changes. It is this level of impact that is significant in establishing the basis for this standard. However, the extrapolation of these behavioral results from animals to humans is considered conservative. This is because comparable increases in core body temperature are not easily produced in humans due to their more efficient thermoregulatory system. Even at exposure levels considerably higher than current standards allow, human body temperature is efficiently regulated by the mobilization of appropriate heat loss mechanisms, such as sweating and skin blood flow.

Exposure to RF energy produces a sensation of warmth. The sensitivity to exposures has been shown to increase monotonically from microwave to millimeter wave frequencies. Thus much less energy is needed at the higher frequencies to produce a thermal sensation because the depth of penetration at the higher frequencies deposits energy closer to the skin where most thermal sensors are located. The threshold of cutaneous thermal pain is $44\text{--}45^{\circ}\text{C}$ and, if generated by RF energy, will result in a prompt effort to escape from the field, thereby preserving normothermia.

B.2.2 Non-cancer related studies supportive of the standard

Studies on teratogenic effects of RF exposure, and other conditions that cause heat stress in animal models, have demonstrated that significant increases in the incidence of heat-induced abnormalities are seen at maternal temperature increases of approximately $2\text{--}2.5^{\circ}\text{C}$. This mostly occurs following exposures of tens of minutes up to one hour or so. The results of a few studies reporting teratogenic, reproductive and developmental effects at low levels of RF exposure are generally weak in design, and have not been confirmed independently. The weight of evidence from animal studies supports the conclusion that teratogenic, reproductive, or developmental effects do not occur unless the RF exposure is $>4\text{ W/kg}$ and causes a significant temperature increase above the normal body temperature. The weight of evidence from studies of human populations exposed to RF fields from video display units, magnetic imaging devices, medical diathermy units, heat sealers and radar does not suggest that teratogenic, reproductive or developmental effects occur at exposures lower than the upper tier MPEs in this standard.

While studies have reported effects on hematological and immunological endpoints in animals and *in vitro* models, the majority was performed at thermal levels of RF exposure and is most likely the result of heating and elevated temperature. In the few studies that have reported effects at low-level (non-thermal) exposure levels (i.e., below the MPEs), the findings are generally inconsistent with each other, as well as with the larger body of evidence reporting no effects at these exposure levels.

The results of many investigations have confirmed that the permeability of the blood brain barrier (BBB) can be affected by a significant increase in temperature caused by absorption of RF energy, but fail to support a repeatable low-level effect. Based on modeling studies, the localized exposure limit for the lower tier will produce an increase in brain temperature of about 0.2°C (Van Leeuwen et al. [R711]), (Bernardi et al. [R725], [R1109]), (Gandhi et al. [R1105]), (Van de Kamer and Lagendijk [R1114]) (see B.6.3.2). This increase is very small in comparison with the increase in temperature that is associated with reported changes in BBB permeability. Published reports of permeability changes in the BBB at SARs $<4\text{ W/kg}$ have not been confirmed and no exposure- or dose-response relationship is evident.

Adverse effects of RF exposure of the eye (e.g., cataracts) are associated only with significant temperature increases due to the absorption of RF energy. There is no evidence of other significant ocular effects (including cancer) that would support a change in the adverse effect level of 4 W/kg .

The phenomenon of RF hearing in humans is a well-established biological effect with no known adverse health consequence. The RF-induced sounds are similar to other common sounds. A quiet environment is needed for the sounds to be heard.

A few studies have reported effects of RF exposure on *in vitro* membrane function and protein leakage through artificial and cellular membranes. However, significant variability and a lack of a consistent correlation with SAR were common in these responses. It is possible that the RF exposure resulted in local temperature increases, which may have contributed to the observed effects. Numerous studies have documented effects of higher (thermal) levels of RF exposure on membrane fluidity and ion transport.

Several reports that have reviewed the calcium efflux effects literature support the conclusion that, notwithstanding unresolved research questions, calcium efflux effects from exposure to low-level amplitude modulated RF fields cannot be used in setting RF exposure standards. WHO EHC 137 [B137] concluded that insufficient information is available to define these reported weak field interactions, and this observation could not be characterized as a potential adverse health effect. An NRPB report [B103] observed that if the phenomenon of calcium efflux were biologically significant, concomitant changes would be expected in the functions of nervous tissues that depend on the movement of calcium ions. No such functional alterations have been demonstrated unambiguously; the report included the statement that there was no reason to believe that 16-Hz modulation has special effects.

Increases and decreases in both evoked and spontaneous population spikes in hippocampal slices exposed *in vitro* to CW RF energy have been reported, but not supported by similar studies. Reports that modulated RF exposure decreased electrical activity in isolated snail neurons seem to contradict reports that RF exposure either increased firing rate or had no effect on isolated neurons. A number of studies have reported that clearly thermal levels of exposure can result in decreased firing amplitude and a prolonged refractory phase in isolated neurons. However, no effects of even very high levels of RF exposure were observed if cooling techniques were used to prevent temperature elevation.

Various other non-cancer endpoints affected by acute thermal RF exposures to animals have included altered digestive function, increased serum triglyceride and beta-lipoprotein levels, increased rate of liver regeneration, increased tissue water content, and conductivity. These un-replicated studies present no consistent evidence of effects due to RF exposure and are in general inconsistent with long term animal study results that indicate no detrimental effects of exposure at SARs up to 4 W/kg.

A review of human provocation studies, including cognitive function and memory, EEG, sleep disturbances, event related potentials, headache and fatigue, hypersensitivity, and effects on blood pressure/heart rate, showed no consistent evidence of an adverse effect of low-level RF exposure on the nervous system. However, because of the variety of different effects reported by some investigators and many contradictory reports, research in this area continues.

B.2.3 Cancer-related studies

The scientific weight of evidence for 35 animal bioassay studies completed to date provide no evidence of physiological, pathological or disease-specific effects of long-term RF exposure, including lifetime exposures, at levels up to 4 W/kg. Those few studies that have reported effects are either not corroborated in similar studies, or the results could not be verified in specific replication attempts. These long term studies clearly indicate a lack of evidence that RF exposure causes or promotes tumor induction or any other life shortening disease. No adverse effect was found on longevity or body mass as a result of chronic RF exposures at SARs in the range of 0.5–4 W/kg. Even though these studies do not give clear thresholds for thermal effects, they are helpful in defining no observable adverse effect levels (NOAEL) in the long-term studies.

A review of numerous supportive studies addressing cancer and basic cellular interactions show no consistent evidence for a reproducible biological effect of low level (non thermal) RF exposure. These studies include examination of DNA breaks, mutation, specific DNA absorption, chromosome aberration induction, micronucleus formation, sister chromatid exchange induction, DNA repair synthesis, inhibition of DNA repair synthesis, phenotypic mutagenesis, transformation, cell cycle elongation, cell toxicity, proliferation, growth rate, cell cycle analysis, gene and protein expression and activity, and oxidative stress. The majority

of studies report no effect. The magnitude of the reported effects are generally very small, often in the range of variability that normally occurs in clinical laboratory tests ordered by physicians, and thus the direct health implication of such reports would still remain unclear even if they were independently verified.

The epidemiological studies to date do not show clear or consistent evidence to indicate a causal role of RF exposures in connection with human cancer or other disease endpoints. Many of the relevant studies, however, are weak in terms of their design, their lack of detailed exposure assessment, and have potential biases in the data. While the available results do not indicate a strong causal association, they cannot establish the absence of a hazard. They do indicate that for commonly encountered RF exposures, any health effects, if they exist, must be small. Even though epidemiological evidence cannot rule out a causal relationship, the overall weight-of-evidence is consistent with the results of the long term animal studies.

B.2.4 Electrostimulation and effects below 100 kHz

At frequencies below 100 kHz, electrostimulation reaction thresholds will typically be lower than thermal reaction thresholds. Above 100 kHz, however, thermal effects typically exhibit lower thresholds of reaction than do electrostimulation effects when the stimulus waveform is of a continuous oscillatory nature. However, with pulsed waveforms of low duty factor, the frequencies at which electrostimulation thresholds are lower than thermal thresholds can extend into the megahertz region. This occurs because the heating capacity of electric current (i.e., its rms value) is proportional to the square root of the duty factor.

B.3 Role of mechanisms in determination of levels for adverse effects

A sound working knowledge of mechanisms of interaction is desirable for unification and simplification of health and safety standards in face of the variety and complexity of biological systems, the multitude of technological applications that constitute the electromagnetic environment, and the resulting potential for compounded complexity upon their interaction. Ideally, a thorough understanding of interaction mechanisms can be used to develop quantitative models for exposure that would allow calculation of dose in a biologically significant manner. The analysis of biological and biophysical mechanisms also permits evaluation of the plausibility of various theories proposed to explain laboratory results and others offered as speculations. Of even more importance, well-established quantitative mechanisms reduce uncertainty for the physical and biological measures used to assess health and safety effects for exposed people. Consequently, there could be reduced uncertainty about the sufficiency of the health and safety guidelines.

Mechanisms of interaction play a critical role in application of results from studies with laboratory animals to human beings. In the case of exposure to fields over the range 3 kHz to 300 GHz, physical mechanisms of interaction greatly influence which tissues and organs are affected and to what degree. Biological mechanisms for thermoregulation, sensory responses to skin temperature and auditory responses to pulsed fields (“microwave hearing”) are critical factors for utilization of results from studies with laboratory animals and human subjects. Likewise, meaningful investigations of speculative mechanisms for biological effects require that the mechanism be specified in a way that allows conduct of experiments at comparable levels. The foregoing remarks also apply to *in vitro* research, where the experimenter needs to establish plausibility for the hypothesis in terms of both dosimetry and biological mechanisms.

Standards development requires differentiation between proven and speculative mechanisms. Proven mechanisms have been established for RF interactions in human beings, with these exhibiting thresholds of reaction that are understood in terms of established biophysical and biological principles. An established mechanism that does not produce adverse effects, even at high doses, is not useful for setting the quantitative limits required in standard setting. On the other hand, speculative mechanisms are those that are not sufficiently well understood to define the threshold of interaction in human beings, and may not have confident support from the experimental literature. However, a speculative mechanism can be useful for designing experiments that will allow for an experimental determination of biological activity. A well established