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EPRI Comments on the IEEE Standard for Safety Levels With Respect to Human Exposure to Electromagnetic Fields, 0 to 3 kHz (2002)

The Institute of Electrical and Electronics Engineers (IEEE) recently published a standard for human exposure to electric and magnetic fields in the frequency range of 0 to 3 kilohertz (kHz). [1] This standard was developed over several years by Subcommittee III of the IEEE Standards Coordinating Committee 28 (SCC-28), now known as the IEEE International Committee on Electromagnetic Safety (ICES).

The IEEE Standard is founded upon a careful examination of the current understanding of biological effects of electrostimulation. The Standard explains the extrapolation from internal dose to external exposure and characterizes the uncertainties associated with this process in detail. The resulting standard is a detailed and complex document with discussions of neurophysiological processes.

Other organizations that have developed guidelines for electric and magnetic field exposures in this frequency range are the American Conference of Governmental Industrial Hygienists (ACGIH), through its Threshold Limit Values (TLVs®); [2] the National Radiological Protection Board (NRPB) in the United Kingdom; [3] and the International Commission on Non-Ionizing Radiation Protection (ICNIRP), an affiliate of the World Health Organization (WHO). [4]

Description of the Standard

General Approach

Scope

The IEEE Standard recommends limits on exposures to magnetic fields, electric fields, and contact currents in the frequency range of 0 to 3000 hertz (Hz). Exposure limits are derived for both controlled (occupational) and uncontrolled (publicly accessible) environments; for uniform and nonuniform fields; for whole-body and extremity exposures; and for pulsed fields and multiple-frequency exposures. This commentary does not cover the last two factors.

The ICES states that the limits are intended to protect against the following adverse short-term effects:

- aversive or painful stimulation of sensory or motor neurons
- muscle excitation that may lead to injury while performing hazardous activities
- excitation of neurons or direct alteration of synaptic activity within the brain
- cardiac excitation
- adverse effects associated with induced potentials or forces on rapidly moving ions with the body, such as blood flow

Potential chronic effects associated with long-term exposure are not considered, the ICES states, for two reasons: (1) there is not sufficient reliable evidence that community or occupational exposures cause adverse chronic effects, such as cancer, and (2) there is no confirmed mechanism that would provide a basis for predicting long-term effects.

Basic Restrictions and Maximum Permissible Exposures

For effects involving a known internal mechanism of field interaction, limits for acceptable exposures are derived from a *basic restriction* for an internal body dose below which no adverse effects occur in humans. Given the basic restriction, physical and biological models are used to estimate exposure limits for external fields. Exposure limits, referred to in this standard as *maximum permissible exposures* (MPE) and in other guidelines as *reference levels*, represent the field level below which the basic restriction will not be exceeded.

However, exposures above the MPE may or may not cause the basic restriction to be exceeded. Thus, the basic restriction is the ultimate determinant as to whether the standard is exceeded.

When an internal mechanism is not known or quantified for an effect, exposure limits are derived from external field and current levels known to cause adverse reactions, as in the case of aversive spark discharges during electric field exposure. In such cases, the MPE level is derived directly from data on empirical effects and no basic restriction applies.

Adverse Effects and Mechanisms

In establishing basic restrictions for electric and magnetic field exposures, the IEEE Standard assumes that the *in situ* electric field is the fundamental electric parameter responsible for electrostimulation effects. This assumption is based on a contemporary understanding of neurophysiological effects. It allows for a more accurate derivation of MPE levels than does the previously relied-upon assumption that internal current density is the relevant parameter. [4]

Magnetic field exposure limits are extrapolated from permissible *in situ* electric field doses using simple elliptical induction models. Electric field and contact current limits are derived directly from data on sensory responses to external fields and currents.

Threshold Multipliers

For both occupational and general-public exposures, conservative assumptions are employed to ensure that limits are based on excitation thresholds below those of the vast majority (> 99 percent) of healthy adults. To derive limits, threshold multipliers (*safety factors*) are applied to empirical data. These multipliers account for overly sensitive individuals, including children, and for uncertainties in both the determination of adverse-effect thresholds and the extrapolation from internal dose quantities to external exposure levels. The response thresholds used in deriving limits for the general public are generally lower than those for controlled environments.

Magnetic Fields

Basic Restrictions

The IEEE Standard links the *in situ* electric field to effects in specific excitable tissues in the brain, heart, and peripheral nerves. The basic restriction on the electric field in the body varies by anatomical location and frequency, and is different for individuals in controlled environments than for the general public. The effect with the lowest exposure threshold for a given location in the body and a given frequency determines the MPE level for that exposure.

For example, 60-Hz head and torso MPE levels are determined by the basic restriction derived from the threshold for synaptic excitation in the brain; 60-Hz MPE levels for limbs are determined by the basic restriction for peripheral nerve (20-micrometer neuron) pain. Above 759 Hz, the MPE levels for the head and torso are determined by the basic restriction for peripheral nerve stimulation in the torso. At very low frequencies (< 0.153 Hz for head and torso; < 10.7 Hz for extremities), adverse effects associated with induced potentials and forces on rapidly moving charges in the body determine MPE levels.

Maximum Permissible Exposures

MPE levels for magnetic field exposures are given in Table 1 as a function of frequency. The whole-body (head and torso) MPE level for uniform 60-Hz magnetic fields in a controlled environment is 2.71 millitesla (mT) or 27.1 gauss (G). For arms and legs, the occupational MPE level at 60 Hz increases to 63.2 mT (632 G). Whole-body MPE levels for the general public are lower by a factor of three than those for controlled environments. Exposures above these levels require evaluation to determine compliance with the basic restriction.

Table 1. IEEE uniform magnetic field maximum permissible exposure levels [1]

Frequency, Hz	Exposure Limit, mT			
	Controlled Environment[a]		General Public[a]	
	Head and torso	Limbs	Head and torso	Limbs
< 0.153	353		118	
0.153–20	54.3/f			
20–759	2.71		0.904	
759–3350	2061/f		687/f	
< 10.7		353		353
10.7–3350		3790/f		3790/f

[a] For nonuniform fields, limits apply to the maximum field on the body

IEEE, Institute of Electrical and Electronics Engineers; Hz, hertz; mT, millitesla; f, frequency in hertz

Nonuniform Fields

The IEEE Standard MPE levels are given in terms of uniform, single-phase fields over the body or a portion of the body. For nonuniform fields, the standard specifies that the maximum field on the body is to be compared with the MPE level. Most realistic magnetic field exposures at fields near guideline levels are not uniform. Comparing the highest measured field over the body with the MPE levels for uniform fields may be overly conservative; that is, exposure in measured fields that exceed MPE limits may not exceed the basic restriction. Evaluation of nonuniform magnetic field exposures can determine whether the basic restriction on the *in situ* electric field is in fact exceeded for such exposures. [5]

Electric Fields

Basic Restrictions

For electric field exposure, the thresholds for sensing contact currents and spark discharges and perceiving the field occur at much lower electric field levels than do the thresholds for direct electrostimulation. Thus, the MPE levels for electric field exposures are determined by sensory responses to external conditions rather than by an internal response to induced electric fields.

The short-term effects that electric field limits seek to avoid are annoying field perception, painful spark discharges, and aversive or painful contact currents. The currents and spark discharges can occur when an ungrounded person standing in an electric field touches a conductive path to ground. Field perception is enhanced when a person situated in an electric field is also well grounded.

Empirical data are available for the external conditions under which aversive shocks from spark discharges and contact currents and annoying field perception take place. [6, 7, 8] The MPE levels for electric field exposure at 60 Hz are derived directly from the external field levels below which spark discharges are not aversive. These conditions apply to a person standing upright in a uniform, vertical field. Above 282 Hz for controlled environments, and above 368 Hz for general-public environments, the contact current MPE levels are the basis for setting MPE levels for electric fields.

In controlled environments, spark discharges can be mitigated through the use of appropriate work clothing, grounding measures, and other work practices, allowing the MPE level to be increased to 20 kilovolts per meter (kV/m). At this level, however, field perception is also a consideration: 50 percent of standing adults perceive the field, and about 5 percent experience annoying sensations on the body caused by hair vibration. The 20-kV/m limit can be exceeded in controlled environments if no ground is within reach.

Maximum Permissible Exposures

MPE levels for whole-body electric field exposure are given in Table 2 as a function of frequency. The MPE level for 60-Hz uniform electric field exposure in a controlled environment is 20 kV/m. The MPE level for the general public is 5 kV/m, except on transmission line rights-of-way, where the limit is 10 kV/m.

Table 2. IEEE uniform electric field maximum permissible exposure levels [1]

Frequency, Hz	Exposure Limit, kV/m	
	Controlled Environment [a]	General Public [a]
< 1	≥ 20 [c]	≥ 5 [c]
1–272 [368][d]	20	5[b]
272 [368] [d]–3000	5440/f	1840/f
> 3000	1.813	0.614

[a] For nonuniform fields, limits apply to the average field over the body

[b] On power line rights-of-way, the recommended limit is 10 kV/m

[c] Limits below 1 Hz are not less than those at 1 Hz

[d] 272 Hz for controlled environment; 368 Hz for general public

IEEE, Institute of Electrical and Electronics Engineers; Hz, hertz; kV/m, kilovolts per meter; f, frequency in hertz

Nonuniform Fields

The IEEE Standard MPE levels would apply directly to electric field exposures under transmission lines, where the fields are uniform. However, in nonuniform fields on or near grounded structures, spatial averaging over the body is used to determine whether the MPE level is exceeded.

Contact Currents

The IEEE Standard also establishes MPE levels for contact currents that occur when an individual touches a grounded object when standing in an electric field. These limits are independent of frequency between 0 and 3000 Hz. The MPE levels for contact currents in controlled environments are 3 milliamperes (mA) and 1.5 mA for grasp and touch contacts, respectively. The MPE level for the general public is 0.5 mA for a touch contact. (Grasp contacts do not apply to the general public.)

The contact current limits, and hence the electric field MPE levels, apply only to an ungrounded person touching a grounded conductor, and may not protect a grounded person touching large conductive objects that are insulated from ground. Limits on 60-Hz contact currents due to electric field induction on large objects located under transmission lines are established in the National Electrical Safety Code (NESC). [9]

EPRI Comments

Occupational Exposure

The 60-Hz magnetic fields in certain power company work environments can on rare occasions exceed the MPE levels and TLVs® cited in the IEEE, ACGIH, and ICNIRP guidelines. [10, 11,12] However, the generally nonuniform nature of these magnetic fields makes the likelihood of noncompliance much less probable. [5] In a nonuniform field, the *in situ* electric field may fall below the basic restriction after accounting for spatial variation of the field over the entire body. The nonuniform fields associated with realistic exposures in power company environments also make the exceedance of the more stringent basic restriction of 10 milliamperes per square meter (mA/m^2) found in the ICNIRP guidelines unlikely.

Exposures to electric fields in the electricity industry will generally be below the IEEE Standard MPE level of 20 kV/m. However, exposures for workers climbing towers near conductors at 500 kV or higher can result in whole-body average fields above this level. In these cases, body orientation with respect to the field may mitigate field perception and spark discharges relative to those experienced when standing in a vertical field. For performing bare-hand maintenance on high-voltage transmission lines, work practices generally require the wearing of hooded conducting suits and gloves as shielding.

Fields enhanced by corona-generated ions near high-voltage direct-current (HVDC) lines can sporadically exceed 20 kV/m. [13, 14] The IEEE Standard specifies a minimum MPE level (based on the occurrence of spark discharges) of 20 kV/m for electric fields below 1 Hz. Below 1 Hz the MPE level can be increased if the leakage resistance to ground of an individual standing in the field mitigates spark discharges. This provision would generally allow the high static electric fields found under HVDC transmission lines to comply with the IEEE Standard.

General-Public Exposure

The magnetic fields in spaces accessible to the general public are very unlikely to exceed the 60-Hz MPE level of 0.9 mT (9 G) cited in the IEEE Standard. Similarly, static magnetic fields near power facilities are very unlikely to exceed the static field limits established for the general public under this guideline.

The IEEE Standard explicitly increases the general-public MPE level for 60-Hz electric fields from 5 kV/m to 10 kV/m on transmission line rights-of-way. Exposure of the general public would not exceed the MPE of 10 kV/m, except in limited areas under some 765-kV lines.

Public use of HVDC transmission line rights-of-way could result in exposures to static electric fields above 20 kV/m. However, realistic leakage resistances make it unlikely that such exposures would exceed an MPE level based on potential spark discharges.

Summary

The IEEE Standard represents a clear advancement in the development and documentation of exposure guidelines in the designated frequency range. This advancement is accomplished by (1) assuming that the *in situ* electric field is the principal physical parameter defining the interaction of fields with the human body; (2) accounting for different interaction thresholds at specific locations in the body; (3) using the lowest demonstrated internal or external field threshold for interaction as the determinant of MPEs; (4) explicitly documenting the extrapolation from sensory responses such as field perception associated with external electric field and current exposures to the electric field MPE levels; and (5) introducing empirically based adjustments to thresholds to account for uncertainties.

Implementation of the IEEE Standard is expected to have minimal impact on current electric power company practices. One possible exception is that the design of 765-kV lines might need to be changed to meet the 10-kV/m limit for general-public exposure on rights-of-way. On the other hand, implementation of the ICNIRP guidelines, which specify lower MPE levels for both occupational and general-public exposure, could have an impact on transmission line design, work practices, and right-of-way management. [15]

For a comparison of IEEE guideline limits with those set by ICNIRP, [4] ACGIH, [2] the NRPB, [3] and the European Union, [16] which recently adopted ICNIRP limits for public exposure, see Table 3, below.

Table 3. Comparison of exposure guideline limits for 60-Hz fields and contact currents

	IEEE 2002	ICNIRP 1998	ACGIH 2000	NRPB 1993	EU 1999
Occupational					
Electric Field, kV/m	20	8.3	25	12	NA
Magnetic Field, mT	2.71	0.42	1.0[a]	1.3	NA
Contact Current, mA	1.5	1.0	NA	1.0	NA
General Public					
Electric Field, kV/m	5	4.2	NA	12	4.2
Magnetic Field, mT	0.904	0.083	NA	1.3	0.083
Contact Current, mA	0.5	0.5	NA	0.5[b]	0.5

[a] For persons with cardiac pacemakers or other medical electronic devices, the limit is 0.1mT.

[b]For children. The limit for adults is 1.0 mA.

IEEE, Institute of Electrical and Electronics Engineers; [1] ICNIRP, International Commission on Non-Ionizing Radiation Protection; [4] ACGIH, American Conference of Governmental Industrial Hygienists [2]; NRPB, National Radiological Protection Board; [3] EU, European Union; [16] kV/m, kilovolts per meter; mT, millitesla; mA, milliamperes

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