RADIO-FREQUENCY AND MICROWAVE RADIATION

Third Edition

by R. Timothy Hitchcock, CIH, CLSO

AIHA NONIONIZING RADIATION COMMITTEE

American Industrial Hygiene Association
Fairfax, Virginia

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American Industrial Hygiene Association
2700 Prosperity Avenue, Suite 250
Fairfax, Virginia 22031
Tel: (703) 849-8888
Fax: (703) 207-3561
E-mail: infonet@aiha.org
http://www.aiha.org

CONTENTS

RADIO-FREQUENCY AND MICROWAVE RADIATION

I. PHYSICAL CHARACTERISTICS

Radio-frequency radiation (RFR) is nonionizing, electromagnetic energy. Compared with ionizing radiation, RFR is characterized by relatively long wavelength, low frequency, and low photon energy. RFR usually is described by its frequency. The unit of frequency is the hertz (Hz), defined as the number of cycles that pass a point in one second, where 1 hertz equals 1 cycle per second. For the purposes of this manuscript, the radio-frequency part of the electromagnetic spectrum extends from 300 gigahertz (GHz) to 3 kilohertz (kHz). Usually, microwave (MW) radiation is considered a subset of RFR; however, an alternate convention treats radiowave and MW as two spectral regions, as shown in Table I.

TABLE I. Physical Characteristics of Radio-Frequency Fields

Region[A]	*Frequency*	*Wavelength*	*Photon Energy*
Microwave	300 GHz[B]–300 MHz[C]	1 mm–1 m	1.24 meV[D]–1.24 µeV[E]
Radiowave	300 MHz–3 kHz[F]	1 m–100 km	1.24 µeV–0.01 neV[G]

A — Microwaves and radiowaves are subsets of the RF spectral region.
B — GHz = gigahertz
C — MHz = megahertz
D — meV = millielectron volt
E — µeV = microelectron volt
F — kHz = kilohertz
G — neV = nanoelectron volt

Various order-of-magnitude band designations (Table II) have been assigned to the RF and sub-RF portion of the spectrum. Frequencies in the specific bands are allocated for uses, including aeronautical radio, navigation, broadcasting, personal wireless communication services, and citizens' radio. In addition to band designations, specific frequencies are designated for industrial, scientific, and medical (ISM) uses. ISM frequencies are 13.56, 27.12, 40.68, 915, 2450, 5800, and 24,125 MHz. RFR is considered nonionizing radiation because the photon energies (Table I) are well below the 12–13 electron volts (eV) necessary to ionize water molecules. The energy is electromagnetic because it is characterized by two fields: an electric field and a magnetic field.

TABLE II. Nomenclature of Band Designations

Frequency	*Range*	*Designation*	*Abbreviation*
< 3	Hz	sub-extremely low frequency	sELF[A]
3–3000	Hz	extremely low frequency	ELF[B]
3–30	kHz	very low frequency	VLF
30–300	kHz	low frequency	LF
300–3000	kHz	medium frequency	MF
3–30	MHz	high frequency	HF
30–300	MHz	very high frequency	VHF
300–3000	MHz	ultra high frequency	UHF
3–30	GHz	super high frequency	SHF
30–300	GHz	extremely high frequency	EHF

A — Also called ultralow frequency, ULF

B — Current IEEE definition of ELF; may also be defined as 30 to 300 Hz.

A. Quantities and Units

Seven quantities may be used to characterize occupational exposure to RF fields. These are specific absorption rate (SAR), specific absorption (SA), electric-field strength (E), magnetic-field strength (H), power density (S), induced current (I_i), and contact currents (I_c).

The SAR is the fundamental dosimetric quantity of RF power deposition. It can be defined as the mass-normalized power deposition, or the RF dose rate, as

$$SAR = \sigma E^2_i / \rho \qquad (1)$$

where σ is the electrical conductivity (siemens/meter), E_i is the internal electric-field strength (volts/meter), and ρ is the density of tissue (kilogram/cubic meter). The SI unit for SAR is watts/kilogram (W/kg), which is compatible with those used for metabolic heating rate. The resting metabolic rate of an adult human being is about 1 W/kg.

SA is the time integral of SAR and, as such, represents the RF dose. The SI unit of SA is joules/kilogram (J/kg).

Determination of the magnitude and distribution of the SAR and SA is complex and is usually carried out experimentally in the laboratory by measuring the electric-field strength in phantoms containing tissue-equivalent material or analytically using computer simulations. Because of that, the incident field strength and power density typically are used in safety evaluations. Human exposure guidelines are expressed in terms of the field strength or power density that will ensure that the SAR remains below a level considered safe. Hence, field strength and power density may be regarded as surrogate measures of RF power deposition within the human body.

Field strength is used to describe both the electric and magnetic fields. The electric-field strength (E) and magnetic-field strength (H) are vector quantities but usually are treated as scalars in safety evaluations (i.e., only the magnitudes are reported). E can be described as electric potential (V) over some distance (d), V/d, and the SI unit is volts/meter (V/m).

H is more complicated but can be visualized by considering a long, thin wire. The movement of electric charge through this wire during a period of time produces a current (I). This current produces a magnetic field (Ampere's Law). If the current oscillates at a radio frequency, a RF magnetic field is generated. The magnetic-field strength at some distance (r) from the wire is

$$H = I/2\pi r \qquad (2)$$

The SI unit of H is ampere/meter (A/m). The magnetic permeability of free space or a material medium is represented by μ, where $\mu = B/H$. Therefore, the magnetic-field strength (H) is a function of the magnetic flux density (B) at a given distance from the source of current and the magnetic permeability. The SI unit of B is tesla (T).

As noted in the definition of SAR, power deposition, the rate of energy absorption, is important in RFR dosimetry. Since power and energy are related to the square of the voltage and the square of the current, hazard calculations are performed in terms of the square of the field strengths (i.e., $|E|^2$ and $|H|^2$).

The vector (cross) product of the E- and H-field vectors is called the Poynting vector, which describes a power density,

$$\bar{S} = \bar{E} \times \bar{H} \qquad (3)$$

Power density (S) represents the time-averaged energy flow across a given surface and is usually used when measuring microwave frequencies. The SI unit of power density is watts/meter squared (W/m^2), although the use of milliwatts/centimeter squared (mW/cm^2) in hazard evaluation is still common. Power density is related to E and H by the wave impedance (120π for plane waves in free space) and can be expressed as

$$S\ (W/m^2) = E^2/120\pi = 120\pi\ H^2 \qquad (4)$$

or

$$S\ (mW/cm^2) = E^2/1200\pi = 12\pi\ H^2 \qquad (5)$$

Another quantity of interest is the current induced within the body. The SI unit of current flow is the ampere (A); the milliampere (mA) is the magnitude usually addressed in safety evaluations of induced current and contact current.

B. Near/Far Fields and Plane Waves

An antenna is an element that is designed to transfer RF energy from a source to free space: in other words, to cause the energy to be radiated. The transition of RF energy from the current state on an antenna to a radiated field in free space is not immediate but passes through two regions. These are the near field, also called the Fresnel region, and the far field, or Fraunhofer region (Figure 1). The near field is composed of the reactive and radiating regions.

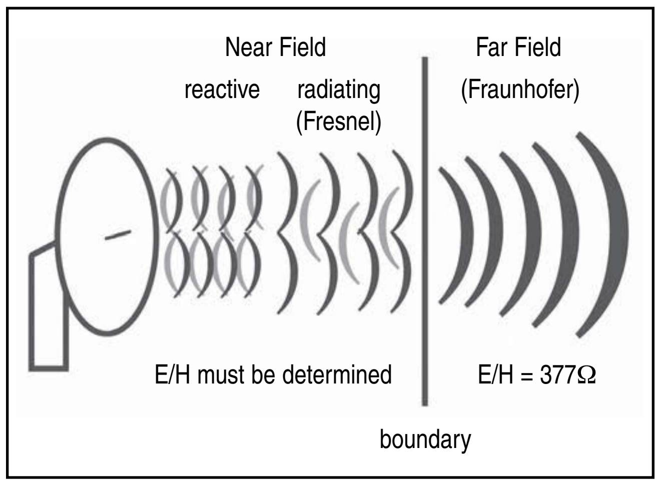

Figure 1*—Simplified view of near/-far-field concepts*

In the space immediately surrounding the antenna, the E- and H-field components exist in a complex temporal and spatial pattern. This region is called the reactive near-field region of the antenna. In the reactive field, energy is not radiated but is stored. A short distance from the antenna, the reactive field has decreased significantly, and the radiating near field predominates. The radiating near field is characterized by energy storage and radiation. Here, the spatial pattern of the fields is complex. It might increase or decrease with distance, or it might remain unchanged. The near field is followed by the far field of the source

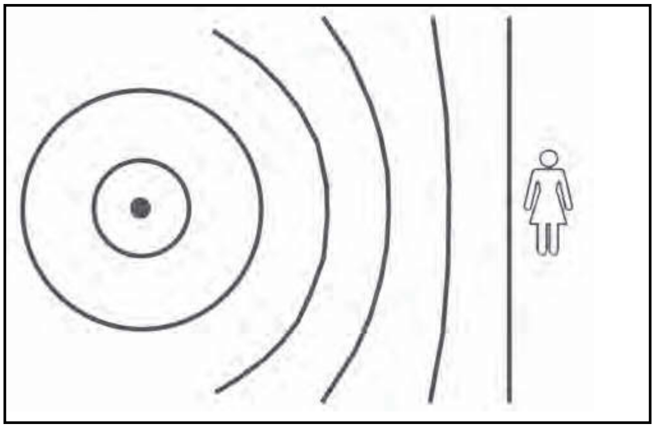

Figure 2*—Illustration of the plane-wave concept using a point-source antenna as the source and a person as the receiver.*

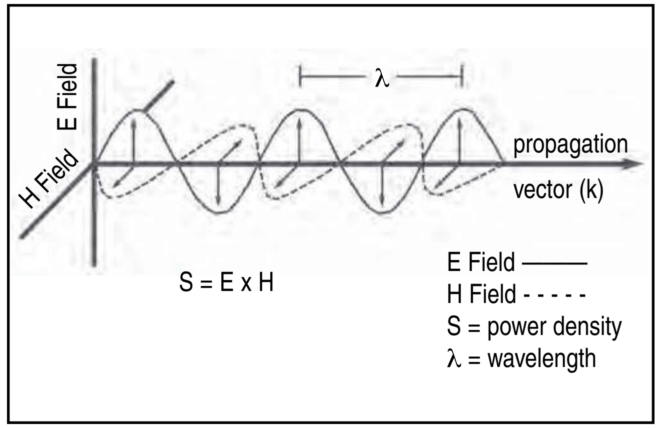

Figure 3*—Plane-wave conditions: space quadrature and time phase. Three vectors are shown: E, H (dashed sinusoid), and k. The direction of E is in the plane of the page; H is vibrating at right angles to the page; and the direction the radiation is propagating is shown by k.*

where there is radiation with the power density following the inverse square law with distance.(1,2)

Often the term "plane wave" is used to describe far-field radiation, but the two are not synonymous. Plane waves are illustrated in Figure 2. Near this theoretical point-source antenna, a receiver would detect curvature in the approaching field. However, if the receiver were removed sufficiently far from the source—some distance into the far field in this example—it would detect a planar front, or plane waves, approaching. Figure 3 is a representation of the plane-wave relationships of space quadrature and time phase. Space quadrature exists when the E- and H-field vectors are at right angles to one another and at right angles to the direction of propagation. Under plane-wave conditions, the time phase of the E and H fields is such that the vectors are simultaneously maximum and minimum. When a plane-wave condition exists, the free-space wave impedance is a constant value, 120π (~ 377) ohms (Ω)*, but this usually is not the case in the near field of the source or in other media (see Figure 1).

C. Impedance

The impedance of a medium is determined by the electric and magnetic properties of the medium and is usually frequency dependent. Wave impedance is equal to the quotient of the electric and magnetic fields (E/H) and thus depends on the distance from the source (e.g., near or far field). Higher values of impedance indicate a predominant E field, and low values mean the H field predominates. Note that the wave impedance near a RF source is not necessarily constant, as indicated in Figure 1. This is because the E and H fields near a source usually exhibit a great deal of temporal and spatial variability.

D. Polarization, Modulation, and Gain

Polarization is that property of an electromagnetic field describing the time-varying direction and amplitude of the electric-field vector. The field may be polarized linearly, circularly, or elliptically, or unpolarized. Specifically, the type of polarization is described as the figure traced as a function of time by the amplitude of the E-field vector at a fixed location in space. An observer would view this trace along the direction of propagation.

Modulation is the process by which some characteristic of a carrier wave is varied by a modulating signal. The modulating signal is by definition lower in frequency than the carrier. Modulation changes some characteristic of the carrier wave such as amplitude, frequency, or phase, designated AM, FM, and PM, respectively. AM and FM, which are illustrated in Figure 4, are used in broadcasting; FM and PM are used in communications. Other forms of modulation used in communications include frequency-division multiple access (FDMA), time-division multiple access (TDMA), and code-division multiple access (CDMA).

Some industrial and medical RF sources may be opportunistically amplitude modulated, with the modulating signal in the ELF spectral region. This occurs because the electric circuitry allows the imposition of the fundamental or a higher harmonic of the power frequency (50 or 60 Hz) on the RF carrier.(3,4)

If an emission is continuous for a long period, it is called continuous wave, designated CW. If the

*The characteristic free-space impedance is a fundamental physical constant that expresses the relationship between the intensities of the electric and magnetic fields.

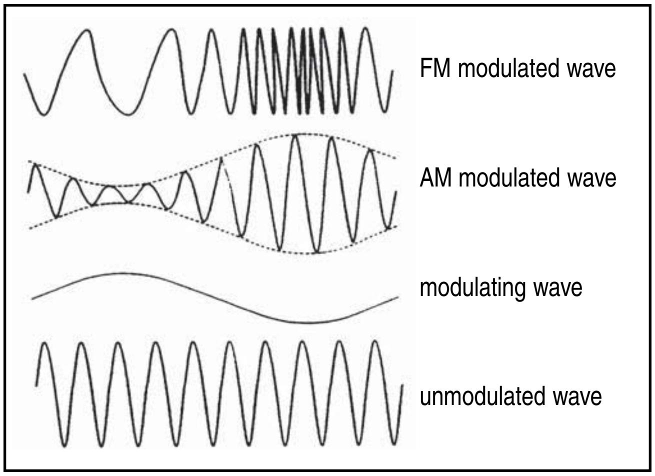

Figure 4*—Illustration of amplitude modulation (AM) and frequency modulation (FM). In AM, the amplitude of the carrier wave is bounded by the signal. In FM, the frequency of the carrier is varied by the signal.*

carrier signal is switched on and off (i.e., segmented by source interruption), pulse-modulated waves are generated.

Gain is a measure of the directional properties of an antenna. Antenna gain (G) represents the ratio of the RF intensity of an antenna in a specified direction to the intensity at the same distance from a reference antenna (e.g., an ideal isotropic emitter) as shown in Figure 5. For the case of an ideal point-source antenna, G = 1. If a reflector is placed near this antenna, it will change the radiation pattern, so that it no longer is isotropic (spherical) but directional because of collimation or focusing. The gain of the combination normally will be greater than 1 in the direction of maximum intensity but can be less than 1 in other directions.

Frequently, the gain of an antenna, particularly a linear antenna, is referenced to a resonant dipole antenna. In this case, the gain must be multiplied by 1.64 to determine the isotropic gain. If the isotropic gain of an antenna with area (A) operating at wavelength λ is unknown, a conservative estimate may be calculated from

$$G = 4\,\pi A / \lambda^2 \qquad (6)$$

Gain may also be defined in decibels, where

$$G = 10 \log_{10} G \text{ dB} \qquad (7)$$

When gain is used in calculations, the numeric value of the isotropic gain (not dB) is used. Gain, in dB, may be converted to the corresponding numeric value by

$$G = 10^{(g/10)} = \textit{antilog}\ (g/10) \qquad (8)$$

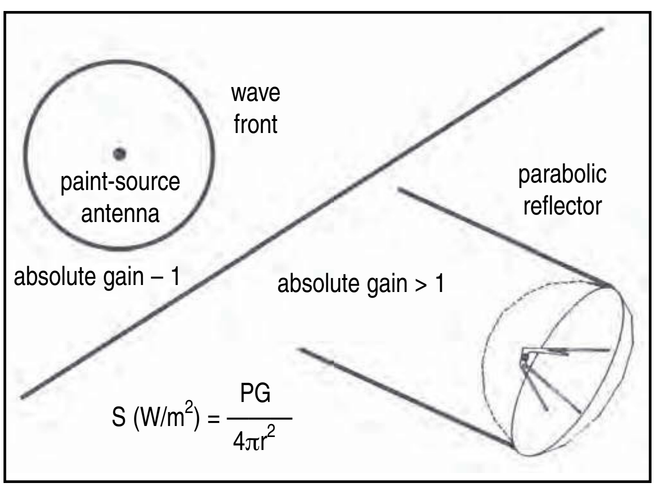

Figure 5*—Absolute gain for a point-source antenna and a parabolic reflector.*

E. Duty Factor

Some sources operate in an intermittent mode (i.e., they might generate the field necessary to accomplish some task, then terminate the field) or operate in a pulsed mode where the RF carrier is amplitude modulated with a lower frequency pulse. The frequency of the pulse train is called the pulse repetition frequency. Probably the most familiar source that exhibits this type of operation is radar, which is switched on to transmit a signal and then switched off to receive the returning signal.

For a periodic pulsed signal, the ratio of the on-time to the period of one cycle (on-time + off-time) is called the duty factor (DF) or duty cycle. Duty factor also is equal to the product of the pulse repetition frequency (prf) in pulses/sec or Hz and the pulse width (PW) in seconds. Duty factor is important because it allows determination of the average power (P_a), and, for the most part, exposure guidelines are expressed in terms of average values. Average power is determined by multiplying the peak power (P_p) of each pulse by the duty factor. These mathematical operations are summarized below.

$$P_a = P_p \text{ x DC} = P_p \text{ x } \frac{\text{on-time}}{\text{on-time + off-time}} = P_p \text{ x prf x PW} \qquad (9)$$

The duty factor is important when assessing exposure to RF sources such as radar, dielectric sealers, induction heaters, RF welding units, and medical diathermy units.

Before evaluating the potential hazard associated with a source, one should verify whether the duty factor applies to that source, since some of the sources might operate continuously (CW) where the duty factor is equal to 1.

II. GENERATION/SOURCES

A. Generation

RF energy is generated by the acceleration of charge in oscillatory circuits. An oscillator is a tuned or resonant electromagnetic circuit with amplification and positive feedback of part of the amplified energy. At frequencies less than about 100 MHz, these circuits usually involve "lumped" circuit elements such as capacitors, vacuum tubes, coils, transistors, and wiring.[2] At higher frequencies, these elements may be designed and built into the generating structure and are then referred to as "distributive" elements. Solid state (semiconductor) devices are important components for generating energy in the microwave bands at low-to-moderate power levels.[5] Many of the devices used for generating high power at MW frequencies use high-energy, relativistic electron streams in vacuum tubes to generate RF energy.[6]

Solid-state devices are semiconductor diodes and triodes that generate microwave radiation. Examples are Gunn-diode oscillators, tunnel diodes, GaAs- and Si-IMPATT diodes,[7–13] GaAs MESFETs (metal-semiconductor field-effect transistors), and GaAs MMICs (monolithic microwave integrated circuits).[12] These have a number of low-powered applications including automatic door-opening devices, police radar and radar detectors, handheld radios, and intrusion alarms.[12]

RF vacuum tubes include triode, tetrode, and pentode configurations.[14–17] These gridded tubes are used as oscillators and amplifiers in lower-frequency applications such as communications, broadcasting, radar, and industrial heating (e.g., dielectric or induction heating).

Microwave vacuum tubes include klystrons, magnetrons, travelling-wave tubes, and backward-wave oscillators that are used in microwave heating, high-frequency radar, and microwave communications applications. Other microwave tubes include the virtual-cathode oscillator (viractor), the gyrotron, the beam-plasma generator, the free-electron laser,[18] and other high-powered microwave generators such as the relativistic klystron and relativistic magnetron.[6] These generate microwaves by the modulation of the velocity of an electron stream in a vacuum tube. The electrons may progress in a straight line in linear-beam power tubes or in a curved path in crossed-field devices. The gyrotron produces microwave energy by a cyclotron resonance mechanism.[19]

When electronic devices accelerate electrons to greater than 5 kiloelectron volts (keV), there is the potential to generate X-rays[20] if the high-energy electron streams collide with a metal object (e.g., some mechanical circuit element inside a vacuum tube). Shields can be used to absorb these X-rays, or shielding can be provided by judicious use of normal parts of the same tubes (e.g., magnets or structural elements). Such shields, however, may be removed without replacement during repair or maintenance. Also, changes due to use can allow the production and emission of X-rays in older tubes. These changes might include pitting of the tube surfaces, depletion of the thoriated-tungsten cathode, or the development of "whiskers" from arcing.[2] Electron tubes that may be a source of X-rays include klystrons, magnetrons, hydrogen thyratrons, triodes, and other high-voltage vacuum tubes.[21]

B. Sources: Environmental RF Radiation

Naturally occurring background sources of RF include terrestrial, extraterrestrial and atmospheric electrical discharges (lightning), and even the human body.[22] In the late 1970s, the U.S. Environmental Protection Agency (EPA) conducted a study to estimate the exposure of the general population in the United States to RFR in the VHF and UHF region (30 MHz to 3 GHz). Measurement data were collected from 486 locations in 15 major cities. The EPA found that exposure of the general population is associated predominantly with FM radio and VHF television broadcast services. Other findings include the median value was approximately 0.00005 W/m^2, approximately 95 percent of the population is exposed to less than 0.001 W/m^2, and greater than 99 percent of the population is exposed to less than 0.01 W/m^2.[23]

Concerning exposure to RF radiation from cellular and personal communications service (PCS) base stations, the Federal Communications Commission (FCC) concludes that "in order to be exposed to levels near the FCC's limits for cellular frequencies, an individual would essentially have to remain in the main transmitting beam (at the height of the antenna) and within a few feet from the antenna."[24] The Institute of Electrical and Electronics Engineers' (IEEE) Committee on Man and Radiation (COMAR) states that the distance from the radiation surface of a fully loaded cellular antenna at which the general public exposure limits would be exceeded is 3 to 10 meters. To a large degree this depends upon the type of antenna and the radiated power.[25]

C. Sources: Occupational Exposure

Important sources of occupational exposure are listed in Table III. A brief review of some important sources follows. For the interested reader, more detailed reviews are available.[26–29]

TABLE III. Occupational Sources of RF Radiation

Sources	*Uses*	*Comments*
Dielectric heaters	Seal/emboss plastics; cure glues, resins, particle boards, and panels; bake sand cores; mold appliance covers and auto parts; heat paper products	1–100 MHz; mainly 27.12MHz; might produce high E and/or H fields and/or induced currents
Induction heaters	Deep hardening; forging; welding; soft soldering; brazing; annealing; tempering metals and semiconductors; heat and draw optical fibers; epitaxial growth; plasma torching	0.25–27 MHz and ELF; might produce high E and/or H fields
Microwave heaters	Drying wood, paper, film, inks; thawing, cooking, baking, dehydrating, pasteurizing, and sterilizing foodstuffs; curing plastics; solvent desorption; organic synthesis; protein hydrolysis	915 and 2450 MHz
Plasma processors	Chemical milling; nitriding steel; polymerization; modifying polymer surfaces; depositing and hardening coatings and films; etching, cleaning, or stripping photoresist	0.1–27.12 MHz; consider potential for exposure to plasma gases
Broadcasting	AM radio 535 currents 1605 kHz FM radio 88–108 MHz VHF TV 57–72, 76–88, 174–216 MHz UHF TV 470–890 MHz	May produce locally high field strengths and induced and contact currents
Communications	Fixed systems; tropospheric scatter; satellite communication; microwave point-to-point (relay); high-frequency radio; amateur radio; cell phone and personal communication service (PCS) base stations; military (e.g., Milstar)	3–30 MHz, 160's, 460's & 800–2000 MHz; 43–45 & 94 GHz; may produce locally high field strengths
	Mobile/portable systems: CB radios; two-way transceiver systems; walkie talkies; portable phones; cell phones and PCS	27 MHz for CB; others are UHF devices from 70 MHz (portable phones) up to 1990 MHz (PCS)
Radar	Acquisition and tracking; air and auto traffic control; marine and meteorological uses; surveillance	Mostly 1–35 GHz; usually pulsed; consider duty cycle
Welding	Production of pipe, tube, and beam; RF-stabilized arc (HF) welding	0.4–100 MHz with harmonics
Spectroscopic instruments	Excite emissions from lamps/phototubes used in quantitative analysis	2.45 GHz
Cathode-ray tubes	Information-processing systems such as CRT-based video display terminals and TVs	10–75 kHz with higher harmonics
Electronic security	Intrusion alarms; theft detection; speed sensors; distance monitors; motion detectors; tag systems	5–7.5 & 58–132 kHz; 8.8–10.2 MHz; 915 MHz
Diathermy	Shortwave (13.56 or 27.12 MHz) or microwave	Might be CW or pulsed; consider duty cycle and leakage field
Electrosurgical units (ESU)	Cauterize, coagulate or dessicate tissue	Might be CW or pulsed; solid state or sparkgap design; 0.25 to 3.3 MHz

1. Dielectric Heaters

Dielectric heaters may be used to weld, seal, and emboss plastics; cure glues and resins; dry synthetic fibers; cure particle boards and panels; bake sand cores; mold appliance covers and automotive components; and heat paper products. The components of a dielectric heater include the power supply, RF generator, tuning circuitry, press (hydraulic or pneumatic), and electrodes (die).

Dielectric heaters operate between 10 and 70 MHz but usually operate at ISM frequencies of 13.56, 27.12, and 40.68 MHz, with 27.12 MHz encountered most commonly. At these frequencies, workers are in the near field. There are some CW dielectric heaters, but most units operate for short periods of time (i.e., generally less than 10 s). Since the RF power follows an on/off cycle, measurement data must be corrected for the duty factor.

A number of workplace evaluations have demonstrated the potential for overexposure of individuals who work with dielectric heaters. These evaluations include the measurement of free fields[30–32] and induced currents[33,34] as well as numerical modeling of SAR.[35,36]

2. Induction Furnaces and Heaters

Induction heating is used to heat conducting materials, such as growing crystals, zone refining of semiconductors, and heat treating. Components of induction heaters include the generator, transmission line, and induction coil. The RF generator is usually a vacuum tube design. The materials to be heated are placed within a container (crucible) that is located inside the induction coil (which is connected to the generator). The induction coil can be considered the primary coil of a transformer; the material to be heated may be considered the secondary coil.[37]

Induction heaters and furnaces may operate at frequencies as low as 50–60 Hz up to 27 MHz. In reports of safety evaluations, most induction heaters operated between 3.8 kHz and 1.25 MHz.[38–40] Induction furnaces operate at frequencies less than 10 kHz.[40] At these low frequencies, workers are in the near field. The frequency at which a particular heater operates is determined by the depth of heating required.[39,41] The depth of heating increases for lower frequencies and more resistive materials.[37] Typically, units operate with an on-off cycle, and measurements will require duty-cycle correction.

Generally, lower frequencies produce higher magnetic-field strengths, and high values of the H field, in excess of exposure guidelines, might be found near these units.[38] The intensity of the fields, however, diminishes rapidly with distance from the source.[39,41]

3. Microwave Heating

Large units with conveyors are used in industrial applications, while smaller closed-cavity units are used in research and in consumer applications (e.g., microwave ovens). The leakage fields from industrial units should be evaluated and special attention paid to any commercially available ovens that have been modified for research and development use. Typically, leakage is minimal from intact commercially available units. Attention should also be paid to the potential for burns from superheating of liquids and possible explosion hazards of chemical reagents in closed cavity processing units.

4. Plasma Processing

Uses of plasma processing include chemical milling; nitriding of steel; synthesis of polymers; modifying polymeric surfaces; deposition (sputtering) and hardening of coatings and films; and etching, cleaning, or stripping photoresist[42–44] in the semiconductor industry. Plasma processing, as used in the electronics industry, may be classified as either dry etching or deposition operations. An etcher is used to etch the surface of a semiconductor wafer; a sputterer is used to metallize the surface of a wafer. The components of etching and deposition units include a RF generator, transmission line (coaxial cable), reactor vessel (typically cylindrical), RF tuning and control module, vacuum pump, gas cylinders, and gas delivery system.

RF operational frequencies can span 100 kHz up to 2450 MHz, with many units operating at 13.56 MHz. Some units might operate at more than one frequency. Workers usually will be in the near field of the units operating at lower frequencies.

Typically, evaluations have demonstrated that leakage from well-designed, well-installed, and well-maintained units is low. Viewing ports are a potential problem area if they are not shielded (metallized or contain a metallic screen). In one case, a RF generator powering two reaction vessels was installed. This created a potentially hazardous exposure because it made it possible for RF energy to be supplied to an open vessel that was not in use, while the second vessel was in use. Field strengths of more than 4200 V/m and 2.2 A/m were found during an inspection prior to initial use, and the condition was quickly remedied.[45] One evaluation found that peripherally attached equipment could act as an antenna because of conducted or coupled RF energy.[46]

5. Broadcasting

Broadcasting usually refers to standard amplitude modulated (AM) radio, frequency modulated (FM) radio, and educational and commercial television (which employs both AM and FM). The frequencies are allocated by the Federal Communications Commission (FCC). The basic components of interest in performing hazard evaluations are the transmitter, transmission lines, tower, and antennas (which, for AM radio, are usually the tower itself). A tower may contain multiple, stacked FM and TV transmitting antennas, and in metropolitan locations the antennas are frequently located on tall buildings.

Electric- and magnetic-field-strength measurements near a 50-kW standard AM antenna, at 2 and 5 m from the antenna, were 300 and 63 V/m and 5.5 and 1 A/m, respectively. Induced body currents were 260 to 290 µA/(V/m)*, and varied with body height of the subjects.[47] When work is performed on hot (energized) AM towers, it is possible that at some locations values of body current may exceed the recommended exposure criteria.[48]

Finding accessible areas on tower structures near energized FM and TV antennas—especially if there are multiple antennas—is a realm of concern. If maintenance personnel must service an antenna occupying a high position on the tower, it is possible they could be exposed to intense fields associated with energized antenna elements located lower on the tower.[49] The hands and feet of climbing personnel might receive high exposures, especially if the transmission line is located near the ladder. In addition to receiving exposures to high field strengths, workers might also be in areas susceptible to spark discharge and sustained contact currents.

6. Communications

Communication systems may be either mobile or fixed, or a combination of these two. Fixed systems are used in the telecommunications industry and include high-frequency (HF) radio, tropospheric scatter radio, satellite communications (SATCOM), and microwave radio (point-to-point radio relay) systems.[50–52] Mobile systems include vehicular units and portable transceivers such as walkie-talkies, cordless telephones, and cell phones, including those with personal communications service (PCS) and enhanced specialized mobile radio (ESMR). Combination systems may be used for paging or cellular radio. The components of these systems are similar to broadcast systems, and consist of a transmitter, transmission line, and transmitting and receiving antennas.

Evaluations of HF radio,[51] tropospheric scatter radio,[53] long-haul telephony, microwave radio, and SATCOM systems have not demonstrated potential overexposures[54,55] of ancillary and operational personnel. Evaluations of cellular telephone base stations indicate that exposure to members of the general public is well below exposure guidelines.[56–58] Maintenance personnel who work on the antennas of high-powered systems (such as SATCOM systems) have the greatest potential for overexposure if they do not follow proper lockout, tag-out procedures. In certain cases, personnel who maintain cell-site base stations[59] might be exposed to levels in excess of the standards and guidelines (e.g., while working very near an energized antenna on a tower or building).[60]

Locations where relatively high RF levels have been found with mobile communications sources include near the coupling box in a vehicle with UHF communications[61] and near energized antennas located on the exterior of vehicles.[62–64] Appropriate spatial averaging and time averaging of measured values is usually necessary in order to determine the actual exposure.

The power density immediately adjacent to many handheld, portable transceivers might exceed the corresponding exposure values found in RFR exposure guidelines[65] but the power deposition will not exceed the whole-body averaged SAR. Most FCC-licensed handheld devices are required to meet the peak spatial-average SAR limits for partial-body exposure.[66–69]

Studies have modeled the local SAR in the heads of users of cell phones.[70] The primary numerical method is the finite-difference time-domain (FDTD) method, which calculates electromagnetic fields for a 3-dimensional lattice of cubical "cells" representing the human

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*The unit µA/(V/m) for the normalized induced body current allows determination of the induced current from measurements of the electric-field strength.

head or some other anatomical feature.[71,72] The head model used in many of these studies is based on MRI data obtained for humans and includes the appropriate dielectric properties of the various tissues. Others have used physical models of the head and determined SAR from E-field measurements.[73,74] The technique used for certifying cell phones is based on the measurement of the electric-field strength in a shell phantom of the human head that is filled with a liquid with dielectric properties similar to brain tissue. A miniature isotropic E-field probe is scanned under robot control throughout the volume, and the peaks associated with transmissions from the cell phone placed in the normal use position next to the head are used to determine the peak-spatial average SAR.

7. *Radar*

Radar is an acronym for radio detection and ranging. Most radar units operate in the microwave part of the spectrum in the EHF, SHF, and UHF bands (see Table II). Lower frequencies, 5 to 300 MHz,[75,76] and submillimeter and millimeter microwaves may be used, however.[77,78] Radar frequencies are denoted by the order-of-magnitude band designations for the lower frequencies but have letter-band designations at microwave frequencies greater than 1 GHz.[79,80] (See Table IV.)

Radar system components include the transmitter, waveguide, antenna, receiver, and display. Typical transmitters may include magnetrons, klystrons, traveling-wave tubes, solid-state devices, or a combination of oscillators and amplifiers. Both reflector-type and phased-array antennas are commonly used for radar systems, but there also are phased-array antennas. Typically, radar antennas produce a narrow beam that is both pulsed and scanned.

TABLE IV. Radar Letter-Band Designations

Letter Designation	*Normal Frequency Range (GHz)*	*Specific Radar Bands (GHz)*
L	1–2	1.215–1.400
S	2–4	2.300–2.500
		2.700–3.700
C	4–8	5.250–5.925
X	8–12	8.500–10.680
Ku	12–18	13.4–14.0
		15.7–17.7
K	18–27	24.05–24.25
Ka	27–40	33.4–36.0
V	40–75	59–64
W	75–110	76–81
		92–100
mm	110–300	126–142
		144–149
		231–235
		238–248

Radar units normally operate in a pulse-modulated mode, at high peak transmitter powers, with typical duty factors on the order of 0.001. In addition to the duty factor associated with the pulsed transmitter output, antennas may rotate horizontally (azimuthal rotation), and move vertically (elevation). The combination of signal pulsing, as well as antenna rotation and elevation, further reduces the duty factor of an individual who is illuminated by the antenna.

Evaluations of commercial radar (airport surveillance, airport approach traffic control, etc.) have not revealed potential overexposures during normal operation. Maintenance activities at some locations or on certain system components (such as a transmit-receive duplexer, magnetron cabinet, or trap door of the antenna pedestal) might produce relatively high local power densities.[81] Aircraft radar is usually located behind a microwave-transparent radome, situated in front of the cockpit at the "nose" of the aircraft. Evaluations by the EPA have indicated that overexposure of maintenance personnel is possible if an individual can access the beam near the aircraft. The EPA found that the typical beam location was 1.8 m above the ground.[82,83]

Exposures near marine radars have not been reported as a problem.[84,85] Evaluations of traffic control radar used by law enforcement have not demonstrated the potential for overexposure.[86–89]

Overexposure to RF energy from military radar units has been reported. For example, two servicemen apparently were overexposed while operating a high-powered, CW, X-band portable radar-tracking system[90]; another instance involved an F-4 aircraft with an AN/APQ-120 radar unit.[91]

Evaluations of a transportable AN/TPS-43E radar found a high value of 46 mW/cm^2 at the top of the transmitter cab with the beam stopped, which required an interlock to be disconnected. At the same location the average power density was 0.8 mW/cm^2 with the beam rotating.[92] There was no potential hazard for an AN/FPS-93 fixed unit located on a tower when the antenna was rotating.[92]

8. *Visual Display Terminals and Televisions*

There have been numerous reports involving emissions from cathode-ray-tube visual display terminals (VDTs) and TVs. RF energy is associated with the horizontal deflection system and the associated high-voltage circuit. A major source of RF energy is the high-voltage ("flyback") transformer. RF fields in CRT-VDTs and TVs typically have most of their energy in the VLF and LF band designations. VLF-LF energy is associated with the fundamental frequency of the high-voltage transformer. For color monitors and TVs, this normally is around 30 to 75 kHz. LF electromagnetic energy is associated with harmonic content of the emissions.

Evaluation of the emissions has shown that most of the energy resides in a relatively narrow range of frequencies from 10 kHz to 200 kHz, and that generally there were no detectable levels of MW radiation.[93–95] The intensity of the electric and magnetic fields decreases rapidly with distance. Hence, studies have not reported the potential for overexposure at conservative operator locations (i.e., normally 30 cm from the units).

Boivin [96] evaluated 52 TV sets. He found that at 30 cm in front of the screen the E-field strength was 21 V/m. At 30 cm from any other surface the highest value was 120 V/m. E- and H-field data at 30 cm in front of color and black-and-white sets that were 1 to 15 years old varied from 3-40 V/m and 0.006 to 0.290 A/m.[97]

9. *Medical Devices*

There are a number of medical sources,[98] although this review just includes occupational exposure to the operators of diathermy units, electrosurgical units, magnetic resonance imagers, and endometrial ablation units. Diathermy uses RF for therapeutic heating of tissue. The components of a diathermy unit include the generator, control console, transmission line, and applicator(s) (electrodes). For hazard evaluation during routine operations, the transmission line and applicator are most important.

Diathermy units operate at ultrasonic, microwave, or shortwave frequencies. Shortwave or microwave modes may be selected for treatments, depending on the required depth of penetration of the electromagnetic energy. Shortwave diathermy operates at 13.56 or 27.12 MHz, and microwave units operate at 915 MHz or 2.45 GHz. The output of a diathermy machine may be continuous wave or pulsed. It has been noted that fields from a CW shortwave unit might have an ELF ripple or be ELF modulated.[4]

The power density along the main beam of a microwave diathermy applicator usually is not part of the hazard evaluation because the beam is not projected into space, but is propagated into the subject. The leakage field around the applicator depends on the type of applicator used. Relatively high field strengths might be found in close proximity to the cables.[99,100] If the physician or physiotherapist adjusts the equipment during operation, the greatest exposure will be to the hands.[41,101] Service personnel might be exposed during maintenance of an energized system. Fields near the back of an energized unit with the access cover removed for servicing were found to be approximately 1000 V/m and 3 A/m.[41]

Electrosurgical units (ESUs) are used for cauterizing or coagulating tissues. Frequencies of operation typically span 500 kHz to 2.4 MHz, with some units operating up to 100 MHz.[22,41,102] ESUs may operate in a CW mode, or may be amplitude modulated. Modulation frequencies are in the tens of kilohertz. Components of the device are the generator, transmission line, surgical probe, and a current return cable that is grounded to the patient. The cable is insulated but might not be shielded.

Evaluations of solid-state and spark-gap units demonstrated that field strengths increased with increasing output power and levels were higher for solid-state units.[99] Levels near the probe and unshielded leads might exceed exposure criteria.[41,102,103] Relatively high levels have been reported near the eye/forehead region, about 20 cm from the active lead. E-field strength was higher in the coagulation mode than in the cutting mode.[103] Between 0.5 and 2 MHz, measurements of induced body currents were 20 to 40 mA.[104]

Measurements of occupational exposures at the bore of a 1.5-tesla magnetic resonance imaging device (64 MHz.)[105] and at the surgeon's position during RF endometrial ablation[106] were found to be within acceptable limits.

III. INTERACTIONS WITH MATTER

A. Basic Biophysics

Matter is classified into three groups on the basis of its electrical properties: conductors, dielectrics (insulators), and "lossy" dielectrics. Conductors typically are metals that have high electrical conductivities and are highly reflective. Dielectrics are

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B. Mechanisms of Interaction

RF energy interacts with tissues at the cellular, molecular, and atomic levels. These microscopic interactions may be averaged on a macroscopic level and expressed as electric- and magnetic-field responses.(107)

There are three modes of tissue interaction at the molecular level: polar molecule alignment, molecular rotation and vibration, and the transfer of kinetic energy to free electrons and ions.(108) Alignment of polar molecules with the field is an ubiquitous mechanism. For example, under the influence of an alternating electric field, a water molecule oscillates and rotates in an attempt to maintain a minimum energy configuration relative to the imposed field. As the molecule rotates, it meets with resistive forces associated with neighboring molecules, which results in frictional heating. Rotational and vibrational absorption modes are important in intramolecular interactions. The oscillation and translation of free electrons and ions associated with biological macromolecules might have functional consequences for those molecules.

C. Scattering and Absorption

Radiation is scattered from the body by reflection, absorption followed by re-radiation, and diffraction. The actual case is quite complex because of geometrical properties of the human body and its composition of layers of tissue with dielectric characteristics. These differences produce multiple interfacial reflections and standing-wave formation between the various tissues and at the air-tissue interface.

Specific factors important in absorption include the dimension of the wavelength and wave polarization relative to the geometrical length and girth of a body, dielectric properties of the body, and the presence of reflective (conductive) surfaces in the local environment.

In general, at microwave frequencies above several GHz, the interaction with the human body is largely topical. As the frequency is decreased toward the low-frequency MHz region, penetration deepens and absorption of electromagnetic energy within the body increases. Absorption may be enhanced because of resonance phenomena. In the subresonant MHz and kHz region, absorption decreases and the body becomes increasingly conductive.

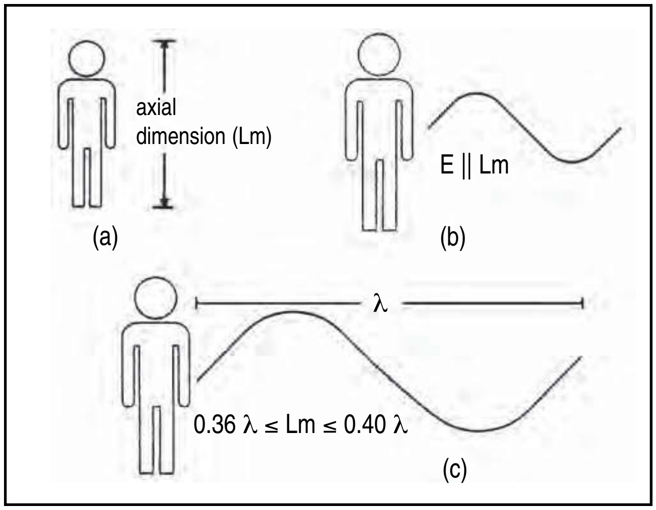

Figure 6*—Whole-body resonance is established when (a) the axial dimension of the body is (b) parallel with the direction of the E-field vector, and (c) the length of the body is 36% to 40% of the wavelength.*

D. Geometrical Resonance

For a far-field illuminated body in free space, human whole-body resonance is established when the body length is about 36% to 40% of a wavelength.(109) The resonant frequency varies from about 79 MHz to 54 MHz, respectively, for bodies of height 1.52 m (5 ft) to 1.98 m (6.5 ft). Power deposition in the body also depends on the polarization of the field vector relative to the long axis of the body. In the whole-body resonance part of the RF spectrum, the maximum energy absorption occurs when the E vector parallels the body's long axis, as shown in Figure 6. Energy absorption is minimized when the H vector parallels the body and energy absorption is intermediate for the case of propagation along the major axis of the body.

The whole-body resonant range is reduced in frequency, and the absorbed energy increased slightly when the body is in conductive contact with a ground plane.(109) In this case, the resonant range is shifted by a factor of approximately 2 to about 25 MHz to 40 MHz.

E. Specific Absorption Rate (SAR)

The SAR is the fundamental dosimetric quantity for exposure at frequencies between about 100 kHz and 6–10 GHz and has been shown to be the most reliable quantity for establishing thresholds for possible biological effects. Other important factors include exposure duration and modulation characteristics.(110) The SAR may be expressed in terms of a whole-body average (WBA) value or a spatial-peak SAR (averaged over a specific volume, e.g., 1 or 10 g) for partial body exposure. The IEEE exposure guideline, which is discussed below, allows a spatial peak SAR = 8 W/kg in 1 g of tissue in the shape of a cube. For the hands, wrists, feet, and ankles the allowable value is 20 W/kg in 10 g of tissue.

The concept of the SAR may be used across much of the RF spectrum, but it is most meaningful between approximately 1 MHz and 10 GHz. At higher frequencies, heating of superficial tissues is more important than the whole-body SAR; electrostimulation is more important at lower frequencies, especially between approximately 3 kHz and 5 MHz.

When the total delivered energy dose is the important quantity, as it might be for pulsed or short-term exposures, SA is used. SA is the RF "dose"; SAR is the RF "dose rate."

F. Induced and Contact Currents

A RF field can induce currents within the human body. This occurs when the wavelength of the incident wave is greater than about 2.5 times the body length.(111) These induced currents flow through the body to the ground, where they may be measured as the short-circuit current through the feet.(112,113)

The conduction path to earth can take the current through the ankle, where the current flows through high-conductivity muscle tissue.(114,115) The small cross-sectional area (9.5 cm^2) of the high-conductivity tissue in the ankle results in a high current density and higher localized SARs.(113)

These currents flowing to ground are associated with exposure to the E field, not the H field. When the magnetic field is parallel to the body, circulating eddy currents will be generated within the body. If the magnetic field is perpendicular with the body, the generated currents will cancel in the ground-plane* measurement because of a phase difference.(47)**

At low frequencies (less than about 100 MHz) the human body becomes increasingly conductive and contact currents could cause shock and burns, while internal RF-induced currents might reach locally high values. Modest values of RF current can be perceived as a tingling or pricking sensation at frequencies below about 100 kHz, and as a sensation of warmth at higher frequencies.(116–119) As the current increases, a sensation of pain might be elicited, with the possibility of RF-induced shock and burns becoming increasingly significant.

High currents might produce high local SARs, and these can be estimated from SAR = $J^2/\sigma\rho$, where J is the current density (A/m), σ is the conductivity, and ρ is the tissue density. From capacitance measurements made of a van parked at a 700-kHz AM broadcast station, estimates were for an 880-mA current and a local SAR of 1045 W/kg in the wrist of a person holding the door handle.(119)

IV. BIOLOGICAL EFFECTS

It is important to note that RF-induced biological effects do not equate necessarily to effects that are hazardous to health. RF-induced hormonal fluctuations, for example, might be within an animal's normal homeostatic limits maintained in the diurnal circadian cycle. Also, an effect can be well-established but its biological significance might not be understood, which greatly compromises its use in risk assessment.

Human exposure data are limited and present no clear trends. Scientists, therefore, have had to rely on animals as models to establish biological effects. Typically, animal studies have been conducted at 915 and 2450 MHz because of the availability of MW generators, although there is an expanding data base at other frequencies, including frequencies used for personal wireless communications. The effects established in test animals have been extrapolated to human beings and used in setting human exposure limits. Although extrapolation can be attractive and at times useful, it might also be a confounding influence because of interspecies differences and difficulties in interpretation. However, scientific studies over time have demonstrated that RF exposure influences both test animals and humans through thermal effects (i.e., the increase in tissue temperature).(120,121)

Animal studies have established biological effects in most major animal systems, including nervous, neuroendocrine, reproductive, immune, and sensory. This guide intends to offer a brief review of selected biological effects. For those who require more information, a number of useful general reviews of health/biological effects are available,(28,121–128) as are reviews of studies of potential health effects associated with the use of cellular telephones.(129,130)

A. Behavioral and Other Nervous System Effects

Human exposure criteria currently are based on a few well-established effects observed in studies with test animals. Reversible behavioral disruption in short-term studies is an effect often cited in these exposure guidelines. That is because this end point has been found to be a very sensitive measure of RF exposure and has been demonstrated in a number of different laboratories, at various frequencies, and with more than one animal species.(130,131) The

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threshold for behavioral responses occurs reliably at threshold SARs between 3 and 9 W/kg WBA and is associated with a significant increase in body temperature (1°C) caused by absorbed RF energy. Obviously, behavioral changes are important because behavior can be regarded as an indicator of the health of the nervous system. Additionally, it has been observed that the threshold for cognitive effects in test animals is often lower than the threshold for behavioral disruption.[132]

As noted, reports of human overexposure in the medical literature are sparse but do contain references to psychological effects. East European and Russian literature discusses the occurrence of certain nonspecific symptoms (e.g., headache, nervousness, fatigue, irritability, insomnia, loss of appetite) associated with the nervous system, with clinical signs extending to the cardiovascular system.[133–135] Although those effects typically are found in many workers not exposed to RF, there have been attempts to combine these symptoms and signs into three syndromes that have been considered stages in a progressive disease called "radiowave illness" or "microwave sickness or disease."[134–136] The early phase of microwave sickness is called the neurasthenic or asthenic syndrome, and the latter stages are neurocirculatory asthenia (also called autonomic cystonia) and the diencephalic syndrome.[133]

Similar symptoms have been described in Western medical literature[90,91] in two case reports of apparently high, acute overexposure to microwaves. A review of 27 patients whose heads were in an RF field during overexposure found that 12 reported postexposure headache and this finding demonstrated a weakly positive correlation with power density. However, psychological findings were not correlated with the head being in the field.[137]

Reviews of reported effects on the blood-brain barrier, electroencephalogram,[28,124,138,139] and interaction with drugs[140,141] are available.

B. Reproductive and Developmental Effects

RF overexposure can produce reproductive and developmental effects in test animals if the WBA-SARs are quite high. Researchers at the National Institute for Occupational Safety and Health (NIOSH) have reproducibly demonstrated teratogenic effects at 27.12 MHz with Sprague-Dawley rats, when the WBA-SARs are around 10–11 W/kg.[142–144] These effects seem to be thermal in nature, as a dose-response effect was found with high rectal temperatures.[144] EPA researchers observed developmental abnormalities in mice and hamsters exposed at 2450 MHz. Again, the effects appear at high values of WBA-SAR.[145,146] Hence, a general conclusion is that RF exposure can produce teratogenic effects that are associated with high temperature.[147]

Also, a few studies report synergistic effects of combined exposure to RF (10 MHz) and the solvent 2-methoxyethanol on fetal malformations in test animals.[148,149] These effects appear to be associated with colonic temperature and not SAR.[150]

Epidemiological studies of reproductive end points have not demonstrated any trends,[151–158] although studies of female physiotherapists who work with shortwave diathermy have found significant differences in sex ratio of their offspring[155] and low birth weight.[159] Two studies reported effects on semen,[160,161] but limitations of these studies—particularly the small number of subjects involved and lack of exposure data—make interpretation difficult. NIOSH researchers did not observe effects on semen but did report a moderate increase in follicle-stimulating hormone in RF heater operators. The results were viewed as inconclusive due to the small sample size.[162]

C. Ocular Effects

Cataracts have been demonstrated in laboratory animals. In these experiments, the most effective frequencies were 1 to 10 GHz, and acute thresholds were determined for rabbits receiving ocular exposure in the near field of a 2450-MHz applicator.[163,164] Threshold SARs were found to be more than 100 W/kg, which resulted in a significant temperature in the lens of the eye. Cataracts were not observed when the animals were not restrained and were exposed in the far field,[165,166] even if exposures were almost lethal. Cataracts have not been induced in nonhuman primates even at levels that produced burns around the orbit of the eye. One in vitro study suggested that pulsed MW might be more effective than CW microwaves.[167] A number of epidemiological investigations and clinical evaluations have been performed, but none has found an excess of cataracts in populations purported to have received RF and microwave exposure.[134,168–173]

D. Cancer

Because of focus on the public health issue of cell phone radiation and brain cancer, a large number of studies have been published in the past decade. These and earlier studies are summarized in Table V. A number of studies have evaluated cancer as an end point by treating animals with chemical agents or cancer cells and RF radiation. Limited *in vivo* data suggest that microwaves might be a tumor promoter or co-promotor in test ani-

TABLE V. *In Vivo* and Epidemiological Studies With Cancer as an End Point

End Point	*Methodology*	*Results*	*Reference*
<u>*In Vivo* Studies</u>			
Chronic effects	9.2 GHz (prf = 500 Hz, width = 2 μs), 50 W/kg (est), 4.5 min/d for 59 wks, 200 exposed mice, 100 controls	Leukosis or leukemia in 35% of exposed mice and 10% of controls	174
Promotional effects	2450 MHz, 2–3 or 6–8 W/kg, mice & three experimental protocols: Balb/c mice treated with benzo(a)pyrene to induce sikin cancer; L_1 sarcoma cells injected into lung tissue; C_3H/HeA species has high incidence of spontaneous breast cancer	Increase in neoplastic lung nodules & spontaneous breast cancer; accelerated skin cancer	175
Promotional effects skin cancer	2450 MHz, 2,4 or 6 W/kg for 6 months in mice treated with benzo(a)pyrene; 6 groups with 100 mice/group	Acc skin cancer development & shortened life span; dose-response effect observed	176
Skin cancer promotion or co-promotion	94 GHz, 1 W/cm^2 for 10 sec or 2 exposures per wk for 12 wks or infrared radiation at 1.5 W/cm^2 for 15 sec, mice treated topically with DMBA initiator, co-promotional experiments used DMBA + TPA	NSD in tumor incidence or mean number of tumors per mouse	177
Effect on mammary tumors	435 MHz (prf = 1 kHz, width = 1 μs), 0.32 W/kg, 200 exposed and 200 control mice for 22 hr/d, 7 d/wk for 21 months	NSD in latency to tumor onset & overall mammary tumor incidence; SSD in bilateral ovarian epithelial stromal tumors	178
Effect on mammary tumors	2450 MHz, 0.3 or 1.0 W/kg, 100 exposed and 100 control mice for 20 hr/d, 7 d/wk for 18 months	NSD in malignant, metastatic or benign tumors except for SSD in alveolar-bronchiolar adenoma in sham controls (Ref. 179)	179,180
Promotion of colon cancer	2450 MHz, 10–12 W/kg for 3 hr/d, 6 d/wk, for 5 months; mice treated with dimethylhydrazine to induce colon cancer and tumor promotor TPA	NSD in RF-induced tumor promotion; TPA accelerated tumor production	181
Promotion of liver cancer	929.2 MHz (TDMA), 0.58–0.8 W/kg (WBA), rats, 90 min/d, 5 d/wk for 6 wk; single dose of diethylnitrosamine	NSD in medium-term liver bioassay	182
Promotion of liver cancer	1.439 GHz (TDMA), 0.453–0.680 W/kg WBA), rats, 90 min/d, 5 d/wk for 6 wks; single dose of diethylnitrosamine	NSD in medium-term liver bioassay	183
Development of spon-taneous & induced transplacental tumors	836.55 MHz (TDMA); 0.72 W/kg (WBA) & 2.3 W/kg (brain) in rats for 2-yr single dose of ethylnitrosurea *in utero*	NSD in brain tumors	184
Effect on tumor development	900 MHz (prf = 217 Hz), 0.27 or 0.75 W/kg, (WBA), rats treated with benzo(a)pyrene; exposure 2 hr/d, 5 d/wk for 2 wk	NSD in sarcomas & survival times	185

TABLE V. *In Vivo* and Epidemiological Studies With Cancer as an End Point (cont.)

End Point	*Methodology*	*Results*	*Reference*
***In Vivo* Studies**			
Effect on incidence of brain tumors	915 MHz (PM & CW), 0.0077 to 1.67 W/kg, 154 exposed & 154 control rats for 7 hr/d, 5 d/wk for 2–3 wks; rats injected with 5000 rat glioma cells (RG2)	All animals developed brain tumors; NSD in tumor size between RF-exposed and control animals	186
Tumor development	2450 MHz (CW & PM), 1.2 W/kg mice implanted with 3×10^6 B16 melanoma cells; exposed 2.5 hr/d, 6 times/wk until death	NSD in tumor development or survival times	187
Effect on progression of brain tumor	836.62 MHz (FMCW or CDMA) rats injected with 9L gliosarcoma cells; 0.75 W/kg in brain; 4 hr/d, 5 d/wk for 4 wk after injection for up to 150 d	NSD in survival times and brain tumors	188
Effects on life span	2450 MHz (60 Hz sinusoidal modulation), 35 W/kg for 4 in utero exposures then postpartum implantation with the avian, fast reticuloendotheliail T virus then exposed then 36 more daily RF exposures	Lower incidence of tumors in RF-exposed	189
Effect on incidence of lymphoma	900 MHz (prf = 217 Hz, width = 0.6 ms), transgenic mice, 101 exposed & 100 control 0.008–4.2 W/kg, adjusted avg. WBA-SAR 0.13–1.4 W/kg; 2 x 30-min/d for up to 18 months	SSD in RF-exposed mice for all types and non-lymphoblastic lymphoma; NSD for lymphoblastic lymphoma	190
Effect on incidence of lymphoma	Partial replication of reference 190; 898 MHz (GSM modulated); transgenic mice, 120 mice at each SAR, 0.25, 1.0, 2.0, & 4.0 W/kg & 120 controls; 1 hr/d for 24 months	NSD	191
Effect on brain tumors	860 MHz (pulsed & CW), 900 mice treated with ethylnitrosourea, 1 W/kg (brain); 6 hr/d, 5 d/wk from 2 to 24 months old	NSD in induced neoplasms or promotion for pulsed or CW for neural and non-neural neoplasms	192
Effects on mammary tumors	900 MHz (prf = 217 Hz, width = 0.6 ms), rats treated with DMBA, 0.018 to 0.07 W/kg for adults and 0.033 and 0.150 W/kg for young animals; animals exposed to RF until tumors reached a diameter of 1–2 cm	NSD on tumor latency and cumulative tumor incidence; SSD in median latency for 1st tumor for RF-exposed animals, but NSD in this endpoint in 2 other experiments	193
Effects on mammary tumors	Ultrawideband (prf = 1 kHz, width = 1.9 ns), peak E = 40 kV/m, 100 mice exposed 2 min/wk for 12 weeks, 100 controls, est. SAR = 0.0098 W/kg	NSD in tumor incidence, latency to onset, growth rate, or survival times	194
All tumors	2450 MHz (prf = 800 Hz, width = 10 ms), 100 rats exposed in lifetime study & 100 controls, 0.15 to 0.4 W/kg; evaluated 155 parameters but not designed with cancer as an end point	SSD of primary malignant tumors from collapsed data for all organs and tissues	195,196

TABLE V. *In Vivo* and Epidemiological Studies With Cancer as an End Point (cont.)

End Point	*Methodology*	*Results*	*Reference*
<u>*In Vivo* Studies</u>			
Effects on spontaneous tumors	835.62 MHz FDMA or 847.74 MHz CDMA, 160 rats divided into 2 exposure and sham-exposure groups, exposed 4 hr/d, 5 d/wk for > 2 yr, SAR in brain 1.3 ± 0.5 W/kg	NSD for any tumor	197
Effects on skin tumors	DAMPS (824-891 MHz) or GSM (~900 MHz), mice exposed 1.5 hr/d, 5 d/wk for 1 yr to UVR and pulsed RF radiation, SAR 0.5 W/kg	NSD on development of skin tumors, slight acceleration in development in nontransgenic group but not others	198
<u>*Epidemiological Studies*</u>			
Occupational			
All cancers	U.S. Navy personnel from Korean War categorized into high- or low-exposure groups for cohort study	Increase MR for neoplasms lymphatic/hematopoietic systems; SSD for respiratory cancer	200
All cancers	40-yr follow-up of Ref. 200	NSD in lung, brain, testicular; cancer; SSD for all leukemias (RR = 1.48, 95% CI = 1.01–2.17) and non-lymphocytic leukemia (RR = 1.82, 95% CI = 1.05–3.14); SSD in non-lymphocytic leukemia in aviation electronics technicians (SMR = 2.2 , 95% CI = 1.3–3.7)	201
All cancers with attention to testicular cancer	Retrospective cohort study of 22,197 police officers in Ontario, Canada; list of officers from 83 departments compared to cancer registry	SSD; SIR = 1.49 (95% CI = 1.15–1.98) for melanoma and 1.45 (95% CI = 0.96–2.1) for individuals in the 10 to 60 yr from hire group	202
Heart disease and neoplasms	Self-administered questionnaire to 3004 male physiotherapists	Possibly greater number of melanomas in 35–39 age group	203
Alimentary canal, nervous system, hematopoietic and lymphatic cancers	Polish military personnel exposed to pulsed emissions; most exposures were < 0.2 mW/cm^2	SSD; O/E = 1.19 (95% CI = 1.08–3.47) for brain cancer & 6.31 (95% CI = 3.12–14.32) for hematopoietic and lymphatic cancers	204
Brain tumor risk	US Air Force personnel with exposures > 10 mW/cm^2 analyzed by military rank	SSD; MR = 1.39 (95% CI = 1.01–1.90) for senior officers	205
Brain cancer, lymphomas, and leukemias	Communications products manufacturing employees between 1976 & 1996 assigned to exposure categories	NSD; RR for brain cancer in high vs low group = 1.13 (95% CI = 0.49–2.31) for usual exposure and 0.86 (95% CI = 0.38–1.73) for peak exposure; for leukemia, RR = 1.05 (95% CI = 0.49–2.02) for usual exposure and 0.74 (95% CI = 0.36–1.40) for peak exposure	206

TABLE V. *In Vivo* and Epidemiological Studies With Cancer as an End Point (cont.)

End Point	Methodology	Results	Reference
Epidemiological Studies			
Occupational			
All types of cancer	Members of the technical & scientific staff at the MIT Rad Lab between 1940 & 1946; est. exposures, job classification, and review of death certificates and social security information	>80% of the neoplasms were from digestive organs & peritoenum, respiratory system, genitourinary organs, & lymphatic and hemato-poietic sytems; SMRs were lower than for US males	207
Cancer mortality	Job title and period of assignment for operators of dielectric heaters with 30-yr follow-up; compared to regional population	NSD; SMR = 2.0 (95% CI = 0.7–4.3) for all malignant neoplasms (6 observed vs. 3 expected) in female workers	208
Testicular cancer	Subjects reported in Swedish Cancer Registry between 1989 & 1992; controls from Swedish Population Registry; assessed life-time work history & specific occupations	NSD for risk for work with radar equipment: OR = 2.0 (95% CI = 0.3–14.2)	209
Brain cancer	Case-control study in two regions of Sweden; 209 cases & 425 controls; questionnaires and telephone interviews	NSD for users of handheld cell phones; increased risk for tumor on same side of brain as phone use; right side: OR = 2.45 (95% CI = 0.78–7.76; 8 cases) & left side: OR = 2.45 (95% CI = 0.52–10.9; 5 cases) for analog phones	210
Brain cancer	Case-control study with 1429 cases and 1470 controls; mailed questionnaire & limited telephone interviews; histopathology from Cancer Registry	SSD for users of analog phones: OR = 1.3 (95% CI = 1.02–1.6); NSD for digital or cordless phones; use of phone on same side of brain as tumor had OR = 2.5 (95% CI = 1.3–4.9); OR = 3.5 (95% CI = 1.8–6.8) for acoustic neuroma for analog phones	211
Brain tumors	Case-control study of 209 patients and 425 controls; mailed questionnaire with supplemental telephone interviews	Increased nonsignificant risk of brain tumor on same side of the brain (OR = 2.42, 95% CI = 0.97–6.05)	212
Brain cancer	Case-control study of 5 medical centers; 469 cases & 422 matched controls; interviews with structured questionnaire	NSD for users of handheld cell phones	213
Brain cancer	Case-control study of 782 patients in hospitals in 3 US cities and 799 controls; personal or proxy interview	NSD for users of handheld cell phones	214
Brain and salivary gland tumors	Case-control study with 398 cases for brain cancer and 34 cases for salivary gland cancer, 5 controls per case; Finnish Cancer Registry for 1996; cell phone subscriptions vs. location & type of tumor	NSD for cell phone use; SSD (OR = 2.1, 95% CI = 1.3–3.4) for gliomas and analog phone use	215

TABLE V. *In Vivo* and Epidemiological Studies With Cancer as an End Point (cont.)

End Point	*Methodology*	*Results*	*Reference*
Epidemiological Studies			
Occupational			
Cancer morbidity and mortality	Cohort study of Moscow embassy workers and dependents; questionnaire and review of medical records and death certificates	NSD attributable to RF radiation	216
Cause of death	Population-based study of white males in the state of Washington between 1950 & 1979 in 200+ occupational classes	SSD in acute leukemia in TV and radio repairmen	217,218
Risk of uveal melanoma	Case-control study (hospital and population based); interview using questionnaire; pooled analysis used 118 cases & 475 controls	SSD; OR = 3.0 (95% CI = 1.4–6.3) for pooled data, OR = 3.2 (95% CI = (1.2–9.0) for population-based study, both for use of radio sets or mobile phones	219
Melanoma of the eye	Descriptive study of annual incidence of ocular malignant melanoma from registry compared with number of cell-phone subscribers in Denmark	NSD	220
Risk of acoustic neuroma	Case-control study of 90 patients and 86 controls in two New York hospitals; structured questionnaire and interview	NSD; no trend with increasing levels of exposure	221
General Population			
Cancer incidence	Evaluate a cluster of leukemias & lymphomas within 10 km of a specific transmitter	SSD for adult leukemia, O/E = 1.83 (95% CI = 1.22–2.74) & chronic lymphatic leukemia, O/E = 2.56 (95% CI = 1.11–5.05) for 0–2 km from transmitter	222
Cancer incidence	Follow-up and extension of Ref. 222; evaluate cancer incidence near 20 transmitters excluding the specific transmitter referenced above; used cancer registration data and determined cases within 10 km of transmitter	NSD for adult leukemia, O/E = 0.94 (95% CI = 0.67–1.31) & chronic lymphatic leukemia, O/E = 1.20 (95% CI = 0.83–1.74) for 0–2 km from transmitters	223
Cancer incidence and mortality	Ecological study of 3 TV towers; power density estimated; cancer registry used to identify cases	SSD; incidence of total leukemia RR = 1.24 (95% CI = 1.09–1.40) for adults, RR = 1.58 (95% CI = 1.07–2.34) for children, mortality for total childhood leukemia, RR = 2.32 (95% CI = 1.35–4.01)	224
Incidence of acute lymphoblastic leukemia in children	Partial replication of Ref. 224; power density estimated; cancer registry used to identify cases	NSD; incidence of acute lymphoblastic leukemia associated with one community, but exposure was similar in another community where incidence was much lower	225

TABLE V. *In Vivo* and Epidemiological Studies With Cancer as an End Point (cont.)

End Point	*Methodology*	*Results*	*Reference*
Epidemiological Studies			
General Population			
Incidence of childhood leukemia in a cluster	Case-control study with 14 cases and 56 controls; evaluated distance to low-frequency radio towers and childhood residence	NSD for living within 2.6 miles of tower	226
Leukemia mortality in adults and incidence in children	Geographic analysis of 49,656 inhabitants living within 10-km radius of Vatican Radio station; records for mortality system, hospital, and other records	NSD; reported excess for men and children within 2 km of station but not for women	227
Melanoma incidence	Evaluated the hypothesis that melanoma incidence is associated with exposure to FM broadcast radiation in 4 countries	Melanoma correlated with public FM broadcasting	228
Analysis of leukemia deaths	Population-based review of death to members of the American Radio Relay League in Washington and California; review of magazine death announcements and death certificates	SSD for all leukemias & acute and chronic myeloid leukemias	229
Testicular cancer	Subjects reported in Swedish Cancer Registry between 1989 & 1992; controls from Swedish Population Registry; assessed life-time work history & specific occupations	NSD for risk of amateur radio operators: OR = 2.2 (95% CI = 0.7–6.6)	209
Correlational study of cancer mortality	Evaluated cancer in counties with Air Force bases; 92 "case" counties and 91 population "control" counties	SSD	230
Correlational study of cancer mortality	An evaluation of cancer mortality in 91 case and 91 population control counties	NSD	231

acc = accelerated; CI = confidence interval; CW = continuous wave; d = day; DAMPS = digital analog mobile phone service; DMBA = 7,12-dimethylbenz[a]anthracene; est = estimated; FMCW = frequency-modulated continuous wave; GSM = global system for mobile; km = kilometer; MR = mortality ratio; ns = nanosecond; NSD = no significant differences; O/E = observed/expected; OR = odds ratio; PM = pulse modulated; prf = pulse repetition frequency; RR = relative risk; SMR = standardized mortality ratio; SSD = statistically significant difference; TDMA = time-division multiple-access modulation; TPA = 12-O-tetradecanoylphorbol 13-acetate; UVR = ultraviolet radiation; WBA = whole-body average mals,[175,176,190,193,195,196] while other studies do not demonstrate such effects.[177–189,191–194,197,198] Hence, the data from animal studies are not conclusive.[199] Moreover, there is no known mechanism that would result in tumor promotion or explain causation.

A number of epidemiology studies have been performed.[200–232] Some statistically significant associations have been reported for occupational epidemiological studies including an increased risk of respiratory cancer,[200] nonlymphocytic leukemia,[201] acute leukemia,[217,218] melanoma,[202] uveal melanoma,[219] brain cancer,[204,205,211,215] and hematopoietic and lymphatic cancers.[204] Some of these studies had mixed results,[201,202,211,215] such as an increase in risk of brain cancer for users of analogue cellular phones[211,215] but not for users of digital phones. Such findings require further study. A number of studies reported no significant differences between study groups for biologically plausible end points.[200,206–210,212–214,216,220,221]

Statistically significant findings for members of the general population include primarily reports of increased risk of leukemias. Follow-up, partial replication, or re-analysis of data of some studies have not corroborated earlier findings for transmitters and leukemia in the United Kingdom[222,223] and Australia[224,225] and for cancer mortality in U.S. counties with Air Force bases.[230,231]

The database of epidemiological studies is increasing but still is difficult to interpret due to a number of limitations.[232] For example, studies still lack actual information on exposure or dose. Hence, exposure information must be inferred from surrogate parameters such as job category or having a cell phone subscription. In general, where findings are statistically significant, the point estimates of risk are modestly elevated, typically less than a twofold increase, although the estimate of uveal melanoma was a threefold increase in risk. The results are also not highly specific, although brain cancer and leukemia have been reported most often. Risk assessment often includes the use of a questionnaire to gather information on retrospective events, so recall bias is possible.

A number of the studies looking at cell phone use and cancer are case-control studies where the potential for problems with latency period may occur. Also, as noted above, there is not a strong animal model to support the positive findings in epidemiological studies. A recent review of these studies concluded that, at this time, there is no convincing epidemiological evidence supporting an association between the use of cell phones and cancer,[233] although this review has been criticized.[234] In summary, epidemiological studies have provided no convincing evidence that RF energies are carcinogenic to human beings.

E. Thermal vs. Nonthermal Effects

Most effects seem to involve RF-induced thermal stress, although some bioeffects (such as calcium efflux from brain tissue) do not seem to be induced thermally. Nonthermal effects are responses caused by low levels of exposure that cause no significant thermal input and, hence, no significant change in local or core body temperature.[235] These nonthermal effects are not well-understood, although mechanisms have been hypothesized. A review of the literature shows that much of the information on nonthermal effects generally is inconclusive or incomplete, and sometimes contradictory. This can be attributed in part to differences in experimental methods, lack of replication of results, and lack of the establishment of mechanism(s) for measured end points.

A special subcommittee of the National Research Council examined nonthermal effects and mechanisms, and stated that " . . . the connections among the various experimental findings and the theoretical constructs do not yet lead to a comprehensive conceptual structure for the reported phenomena sufficient to enable an evaluation of the significance of the theories."[236]

V. EXPOSURE STANDARDS AND GUIDELINES

Standards and guidelines for occupational exposure to RF radiation have been recommended by groups including the Institute of Electrical and Electronics Engineers (IEEE),[237] the American Conference of Governmental Industrial Hygienists (ACGIH),[231] and the International Commission on Nonionizing Radiation Protection (ICNIRP).[222]

The ACGIH guidelines apply to workers while ICNIRP recommends limits for workers and the general public. Currently, IEEE recommends limits based on the exposure environment, called controlled and uncontrolled environments. In general, individuals in the controlled environment are aware of the potential for exposure, which for the most part would be the occupational setting. Individuals in the uncontrolled environment have no knowledge or control over their exposure and are usually members of the general public.

There are a number of similarities among contemporary standards including fundamental and derived limits, whole-body absorption envelope, SAR-based limits, low-frequency criteria, brief (usually 6-min) averaging time, mixed frequency-exposure criteria, coverage of both pulsed and continuous-wave emissions, mals,[175,176,190,193,195,196] while other studies do not demonstrate such effects.[177–189,191–194,197,198] Hence, the data from animal studies are not conclusive.[199] Moreover, there is no known mechanism that would result in tumor promotion or explain causation.

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There are a number of similarities among contemporary standards including fundamental and derived limits, whole-body absorption envelope, SAR-based limits, low-frequency criteria, brief (usually 6-min) averaging time, mixed frequency-exposure criteria, coverage of both pulsed and continuous-wave emissions, near-field/equivalent plane-wave power density, measurement distance restriction, an order of magnitude safety factor for occupational exposures, and recognition of thermal and nonthermal effects.

A. Exposure Limits

The exposure limits include both a fundamental criterion, called the basic restriction, and a derived limit, also called the reference level or investigation level. For low frequencies, typically less than 100 kHz, biological effects are based on electrostimulation and the basic restriction is the current density or internal electric-field strength. Between 100 kHz and 6–10 GHz biological effects are based upon the rate at which RF energy is absorbed and the basic restriction is the SAR. At higher frequencies, approaching the infrared spectral region, the penetration depth into tissue decreases and the interaction is described as quasi-optical. Here, incident power density is the basic restriction.

The basic restrictions are not easily evaluated in the field so limits that are more practical to evaluate have been derived. Depending on the frequency, the derived limits are expressed in terms of field strength, power density, and induced and contact currents (see Table VI). In general, the derived limits can be exceeded if it can be shown that exposure is within the value of the applicable basic restriction.*

B. Absorption Envelope

Exposure limits (reference levels) for electric and magnetic fields and power density are frequency dependent. Five distinct exposure regions have been defined, as shown in the generic curve in Figure 7. Three of the regions plateau at invariant but different field-strength levels, and the other two are transition regions in which the field-strength values vary with frequency. For sources operating at frequencies in the transition regions, the exposure limits must be calculated. The five regions were established because of differences in the human body's ability to absorb RF energy at different frequencies. When depicted graphically, an exposure envelope is formed around the area of maximum RF-energy absorption rate, the human whole-body resonance region, where the exposure limits reach their lowest level.

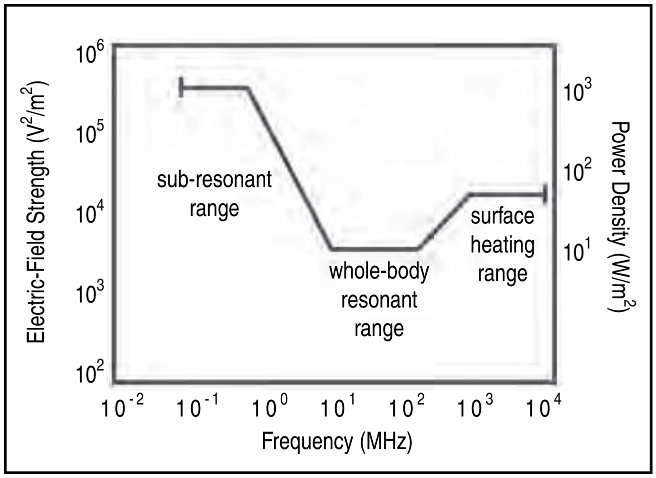

Figure 7—Generic human exposure guideline.

C. SAR-Based Exposure Limits

Typically, a whole-body average (WBA) value of 0.4 W/kg is the basic restriction for occupational exposure[237–239] and for individuals in the controlled environment.[237] The biological basis is reversible behavior disruption in nonhuman primates.[237,240] This occurred at WBA-SARs around 4 W/kg and this value was further reduced with a tenfold safety factor. A fivefold reduction of the 0.4-W/kg SAR yields a WBA-SAR of 0.08 W/kg, the value used for members of the general public[239]

TABLE VI. Types of Measurements

Source Type	*Frequency Band*	*Measurement*
All sources	300 GHz to 300 MHz	E or H or S; spatial average
Leakage sources	300 MHz to 3 kHz	E and H; spatial average
Intentional radiators		
Far field	300 MHz to 30 MHz	E or H or S; spatial average
Near field / unknown	300 MHz to 30 MHz	E and H; spatial average
All	30 MHz to 3 kHz	E and H; spatial average
All sources	100 MHz to 3 kHz	Induced currents if > threshold %E-field MPE Contact currents for reported/possible exposure

*This provision of the standards is often called the SAR exclusion rule. Exclusion rules state that if it can be shown that the basic restriction, in this case SAR, is not exceeded, an overexposure does not exist even if the measured values of field strength or power density exceed the applicable value of the reference level.

and individuals in the uncontrolled environment.[237] This additional fivefold reduction is achieved through the application of an additional safety factor and is not determined by findings from biological effects studies.

The value of the WBA-SAR basic restriction remains invariant across the applicable RF spectrum, while the values of the reference levels (i.e., field strength or power density) vary with frequency, as mentioned above. This reflects the fact that the body's ability to absorb RF electromagnetic energy from the imposed field varies with frequency, but the internal dose-rate criterion is invariant. Hence, if the measured value of field strength or power density does not exceed the applicable exposure limit, the WBA-SAR will not be exceeded.

Generally, the SAR is used across only a portion of the RF spectrum. It is most meaningful from about 1–3 MHz to 6–10 GHz, the extended resonance range.[237] However, IEEE applies the SAR between 100 kHz and 6 GHz.[237]

Spatial-peak (partial body) SARs also are included in the guidelines. A peak spatial-average value of 8.0–10 W/kg per gram of tissue is cited most frequently for workers and individuals in the controlled environment. IEEE recommends 1.6 W/kg per gram (of tissue in the shape of a cube) in the uncontrolled environment.[237] ICNIRP recommends 2 W/kg averaged over any 10 g* of contiguous tissue.[239]

D. Low-Frequency Criteria

Exposure to low-frequency RF might result in burns, shock, and high local SAR associated with contact currents and induced currents. Shock and burns are important because ungrounded, conductive objects illuminated by an RF source couple with the field and store the energy as an electrical charge. If a grounded person touches the object, excessive current could be discharged to the body.

In terms of the IEEE and ACGIH guidelines, low-frequency criteria apply between 3 kHz and 100 MHz. The ICNIRP criteria extends to 110 MHz, which includes the upper portion of the FM broadband, between 100 and 110 MHz currently not included in the IEEE and ACGIH documents, but this will change in all likelihood.

To control for potentially hazardous effects associated with high current density and high local SARs, ICNIRP and IEEE recommend limiting field strengths and induced and contact current at low frequencies. Generally, the E-field values reach an upper limit of 614 V/m at frequencies below 3 MHz to minimize the potential for electrostimulation including shock, burn, and spark discharge.

IEEE[237] recommends limits for contact and induced currents for both the controlled and uncontrolled environments. ACGIH recommends values for the workplace that are the same as those for the controlled environment, with the exception that the lower frequency boundary is 30 kHz versus 3 kHz for IEEE. The IEEE limits are frequency dependent between 3 and 100 kHz, but plateau between 100 kHz and 100 MHz for contact current and induced current (through one foot) for the controlled and uncontrolled environments (see Figure 8). For induced currents through both feet, the allowable level is doubled. The values for contact currents are for grasping contact with the hand.

E. Averaging Time

Generally, a 6-min averaging time is recommended for the SAR and corresponding derived exposure limits for workers. For the most part, the averaging time recommended for the general public is 5 times longer (i.e., 30 min). The 6-min averaging time is based on cooling time constants derived from the diathermy literature and from partial-body irradiation of test animals with 3-GHz microwaves.[241] The averaging time of 6 min is considered to be the juncture between exposures of short and long duration.

IEEE (controlled environment) and ACGIH reduce the averaging time when the frequency is 15 GHz or greater, where averaging time follows the function 616,000 $f^{1/2}$ (where f is in MHz)**. This reduces the averaging time from 6 min to 10 sec at 300 GHz—which corresponds to the averaging time found in the laser standards at the same wavelength (1 mm). The reason the averaging time is reduced is to protect against skin burns.[242]

The averaging time for induced and contact currents is 1 sec for frequencies between 3 and 100 kHz where effects are based on electrostimulation. For frequencies between 100 kHz and 100 MHz, which are based on thermal effects, the averaging time is 6 min.[237] Concerning the flow of current within the ankle, one study has noted that the sensation of warmth in the ankle can be sensed shortly (less than 5 sec) after exposure begins.[113]

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*Spatial peak SARs are applied to small, contiguous elements of tissue, often with homogeneous electrical properties. The mass of the tissue element is 1 or 10 grams which is called the averaging mass. The spatial peak SAR is averaged over the applicable averaging mass. One way this can be done is to measure the internal electric field strength in the small tissue element then use Equation (1) to determine the SAR in W/kg. This would result in a SAR in W/kg in a small (1 or 10 gram) tissue element.

** The IEEE has proposed changes to the averaging time in the both environments. If adopted, the averaging time in the controlled environment will be 19.63 / f1.079 from 3 to 30 GHz and 2.524 / f 0.476 between 30 and 300 GHz. Here, f will be in gigahertz.

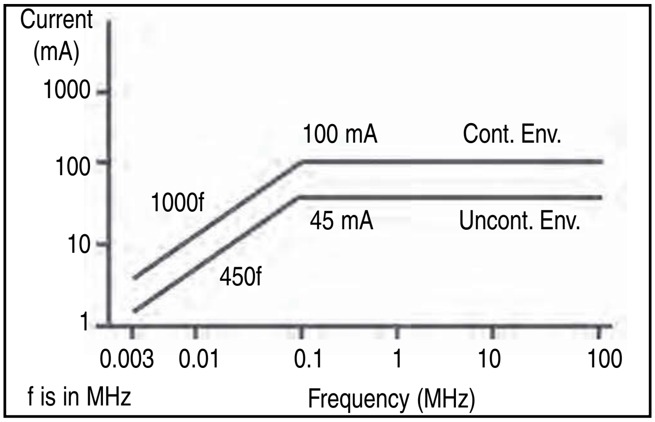

Figure 8*—Criteria for induced and contact currents for the controlled and uncontrolled environments.*

F. Mixed-Frequency Exposure

Exposure can occur to a single source operating at multiple frequencies, or from multiple sources operating at single but different frequencies. These frequencies may have different exposure limits because the limits are frequency dependent. To handle such exposures, the mixed-frequency exposure formula is used. The formula is used to weight each contribution according to the frequency-dependent limits so that the frequency invariant basic restriction (SAR) is not exceeded.

The mixed-frequency exposure formula sums the ratios of field-measured values (ML) to the recommended exposure limits (EL) for specific frequencies

$$ML_1 /EL_1 + ML_2 /EL_2 + ... + ML_n /EL_n \leq 1 \qquad (9)$$

for n values. The sum of these ratios should be less than or equal to unity, subject to professional interpretation. Note that ML and EL may apply to occupational or general public limits for E, H, S, I_c, or I_i. When using Equation (9), values of E, H, I_c, and I_i must be squared because the squares are related to power. However, it is not necessary to square power density because it is already in terms of power.

For frequencies less than 300 MHz, it is necessary to determine the mixed-frequency exposure for both electric and magnetic-field strengths, since the guidelines require measurement or determination of both fields, unless the exposure is clearly in the far field of the source. For each ratio, both the measured (or calculated) level and the exposure limit must have the same units and the same frequency. The units must be either power density or the square of the field strength.

G. Government Standards and Regulations

In the United States, there are three government RF standards or guidelines in use today. In 1997, the FCC published revised rules for the broadcast and communications industry. The exposure limits derived by the FCC are an integration of the guidelines recommended by IEEE and the National Council on Radiation Protection and Measurements (NCRP) recommendations.[243,244] These limits apply to fixed, mobile, and portable communications transmitters. The FCC's Office of Engineering & Technology (OET) published a document to assist in the application of this standard under the umbrella of OET Bulletin 65, *Evaluating Compliance With FCC Guidelines for Human Exposure to Radiofrequency Electromagnetic Fields*.[244] In addition to the base document there are three supplements. The supplements apply to the evaluation of radio and television broadcast stations, amateur radio stations, and mobile and portable devices. All four documents are available from the FCC's web page (http://www.fcc.gov/oet/info/documents/bulletins/#65).

The Department of Defense (DoD) publishes Instruction 6055.11, which applies to military and civilian personnel. The DoD exposure limits are adopted from the IEEE/ANSI C95.1 standard.[245] These requirements have been integrated into exposure criteria for the military including the Air Force Standard AFOSH Standard 48-9 and Marine Corps Order 5104.2.

A third government standard, promulgated by the Occupational Safety and Health Administration (OSHA), is the adoption of the 1966 ANSI C95.1 limits. These are included in 29 CFR 1910.97. These limits are outdated and the exposure limit is no longer enforceable because of the use of advisory (versus mandatory) language in defining the radiation protection guide.[28] OSHA does have a web page with links to useful information on RF radiation (http://www.osha-slc.gov/SLTC/radiofrequencyradiation/).

VI. INSTRUMENTATION

The measurement of RF field strength and power density is called densitometry.[121] Most instruments used by industrial hygienists to measure field strength and power density are broadband receivers that have a frequency-independent response over a large portion of the RF spectrum.[246] Broadband instruments with shaped-frequency response probes are also available. These probes have a response weighted to the frequency-dependent exposure limits of a particular guideline or standard.

Broadband E-field instruments are available to monitor approximately 3 kHz to 100 GHz, although no single instrument/probe will cover this entire range. Some instruments, typically used for microwave oven

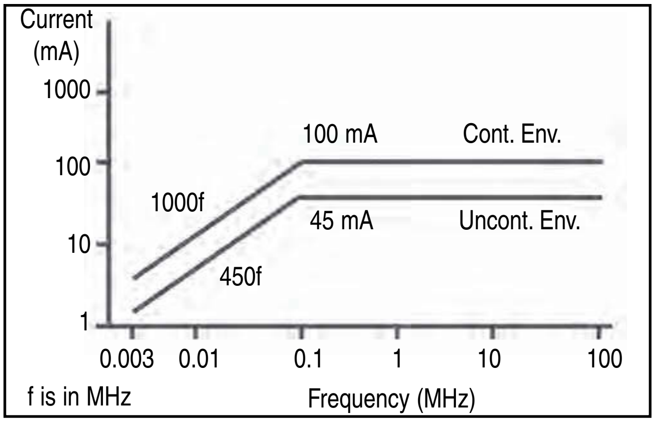

Figure 8—*Criteria for induced and contact currents for the controlled and uncontrolled environments.*

F. Mixed-Frequency Exposure

Exposure can occur to a single source operating at multiple frequencies, or from multiple sources operating at single but different frequencies. These frequencies may have different exposure limits because the limits are frequency dependent. To handle such exposures, the mixed-frequency exposure formula is used. The formula is used to weight each contribution according to the frequency-dependent limits so that the frequency invariant basic restriction (SAR) is not exceeded.

The mixed-frequency exposure formula sums the ratios of field-measured values (ML) to the recommended exposure limits (EL) for specific frequencies

$$ML_1 / EL_1 + ML_2 / EL_2 + \ldots + ML_n / EL_n \leq 1 \qquad (9)$$

for n values. The sum of these ratios should be less than or equal to unity, subject to professional interpretation. Note that ML and EL may apply to occupational or general public limits for E, H, S, I_c, or I_i. When using Equation (9), values of E, H, I_c, and I_i must be squared because the squares are related to power. However, it is not necessary to square power density because it is already in terms of power.

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Broadband E-field instruments are available to monitor approximately 3 kHz to 100 GHz, although no single instrument/probe will cover this entire range. Some instruments, typically used for microwave oven measurements, have been designed to respond accurately only to ISM-bandwidth fields around 915 and/or 2450 MHz and are not broadband instruments.

Broadband instruments do not require tuning by the operator and may measure individual or combined E and H fields. Most designs allow the user to select from multiple, interchangeable probes for different frequency ranges and field strengths or power densities. These instruments are small, portable, and battery operated. Data logging capabilities may be integrated into the metering instrumentation so that the fields can be monitored over several hours. The data can be downloaded into a computer and presented as a continuous plot of maximum, minimum or average value per sampling interval (usually a few seconds) or provide a sliding 6- or 30-min average. Those characteristics allow the user to collect measurement data in unusual places that might be frequented by maintenance personnel, such as on broadcast towers or in confining areas.

The output of the instruments can be in either field-strength units, field-strength units squared, percent of the IEEE standard, or power density. All instruments actually measure the E- or H-field strength. Power density is a vector that cannot be measured easily because of the complex temporal and spatial relationships between the E and H fields in most exposure situations of interest. It is possible, however, to measure independently both the E and H fields simultaneously, as some instruments do, and relate these values to a measure of the power density. Currently, most instruments that display power density do not measure both E and H fields but actually respond to the magnitude of E or H (or to $|E|^2$ or $|H|^2$) and use the plane-wave (far-field) impedance value of 377 Ω to convert to an equivalent plane-wave power density (S).[247] Here, $S = E^2/377\ \Omega$, where S is in W/m^2, or $S = E^2/3770$, where S is in mW/cm^2.

A. System Elements

The components of broadband instruments include probes, connective cable (lead), and metering instrumentation. The probes include antennas and detectors. Leads may be high-impedance connecting cable or fiber optics. The metering instrumentation* includes the electronics package, digital or analog readout display, connector and charging ports, and function selection capability (dial or keypad). Information on measurement equipment is available.[28,29,246–249]

1. *Antennas*

Antennas receive or couple the RF energies into the measurement system. They may be encased in plastic or foamed polystyrene, which are opaque to infrared and visible radiation. Polystyrene can act as an insulator against thermal shock of the sensing elements and can also serve as a spacer.

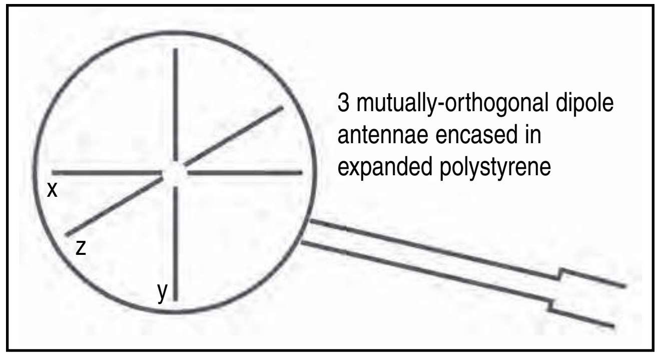

Figure 9—*Probe design: antenna array that responds isotropically.*

Antennas and detectors should be responsive only to the design parameter—that is, the response of an E-field probe to the H field should be minimal, and vice versa. E-field antennas are either monopoles or dipoles. H-field instruments usually have a loop antenna, which is more responsive to the magnetic field but still might require selective shielding to minimize the response to the E field.

Single or multiple antennas are used in instruments. Since a single-axis antenna element, such as a linear dipole, will respond appropriately when aligned with the direction of the E-field vector, it must be oriented properly with respect to the field to obtain a correct reading. The utility of such an instrument is that it can be used to determine the polarization of the field; however, it has limited utility in complex electromagnetic environments or environments with many sources.

Arrays with two mutually orthogonal antennas are available, most frequently with instruments designed to measure microwave oven leakage. The design using three mutually orthogonal antennas (so-called tri-axial designs) is used most frequently on modern broadband instruments (see Figure 9). Three antennas, here designated x, y, and z, provide spatial coverage (in three planes), which produces a response that is independent of direction and polarization of the field, (i.e., isotropic in nature). According to Ruggera and Nesmith,[250] "An isotropic probe is said to be circularly polarized and responds equally to all field polarizations."

*Some detectors used with RF measurement instruments may be sensitive to optical radiation and these must be encased in a material that is transparent to RF radiation but opaque to optical radiation.

Antennas may also respond to fields that have frequencies outside of the specified operational limits of the instruments, allowing an undesirable out-of-band response, which could generate misleading sample data. Historically, this problem has surfaced during evaluations of VDTs generating low-frequency fields (about 10 to 300 kHz) that were outside of the operational (calibrated) limits of most portable, broadband instruments. Today, instruments are available that have a calibrated response at these low RF frequencies. One such instrument is the displacement current sensor, a type of parallel-plate capacitor used for E-field measurement. This antenna has been combined with a loop antenna in an instrument that will measure both low-frequency E and H fields.

2. *Detectors*

Two main types of detectors are used in modern survey instruments: thermocouples and diodes. Other devices, including bolometers, thermistors, continuous films, thermally sensitive chemicals (e.g., liquid crystals), glow tubes, and electrooptic modulators, have also been used.

It is important to have some knowledge of the advantages and disadvantages of these detectors. Unless corrected, diode-based instruments could have a temperature-sensitive response. Also, diode-based instruments might not indicate accurately the field strength associated with pulse- and amplitude-modulated fields and can exhibit errors when irradiated with multiple source and multiple frequency fields[249,251] when the field components have equal amplitudes.

Thermocouples are true rms reading devices. The primary limitations of thermocouple-based instruments are the potential for probe burnout at approximately 10 times the full-scale reading as well as temperature sensitivity, which might cause drifting of the indicator.

B. Induced and Contact Current Instruments

Induced current instruments measure electric current or voltage that is proportional to the current of interest. Typically, the metric of interest is the foot current that flows to ground through an exposed worker. Foot currents may also be equated to SAR in the ankle. One early design was a parallel-plate capacitor with a noninductive resistor connected between the plates. A person stands on one of the plates, acting as a RF antenna, as illustrated in Figure 10. The induced RF currents flow through the body and through the instrument to ground. The current is determined from Ohm's Law from measurement of the voltage drop and the impedance. The output of the instrument is in mA.

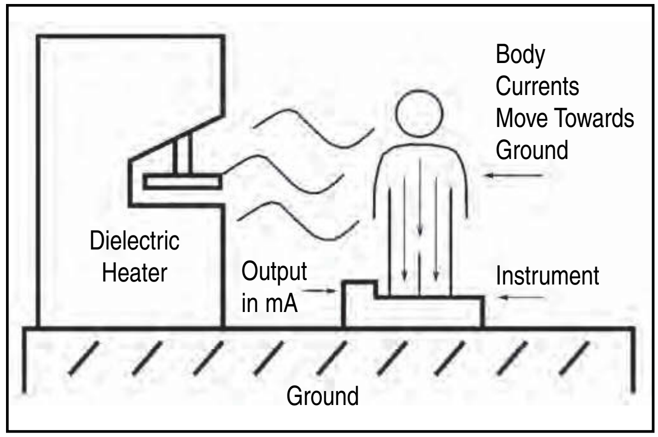

***Figure 10**—Illustration of measurement of induced currents. Worker stands on the intstrument, and when the source is energized, currents are induced to flow through the body to ground. The currents pass through the measurement instrument, and the output is in milliamperes (mA).*

Another type of induced current monitor is the current transformer. This is a coil that clamps around the ankle or wrist and connected via fiber optic cable to the readout device.

A contact current instrument includes a sample probe to contact the electrically "hot" surface. This is connected to a grounding lead and ground plate via an ammeter. The ground plate is the approximate area of two human feet. Current that would flow into the body is measured with the output expressed directly in mA.

C. Dosimeters and Personal Monitors

At present, RF dosimeters are not in general use because of a RF shadowing effect that develops when the body is facing away from the source.[252,253] This shields the dosimeter, resulting in the introduction of a bias into the measurement data. However, attempts at development are continuing to address this void in available instruments.[254]

Some manufacturers offer personal monitors with alarms that, although not dosimeters, respond to a selectable threshold intensity. These are available in models that respond to E or H fields and frequencies between 100 kHz and 100 GHz. Some models include data logging capability, computer interface, and processing software.

D. Spectrum Analyzers and Frequency Counters

These are tunable receivers that measure both frequency and amplitude. When connected to an antenna, they can provide narrowband monitoring (narrow bandwidth) of the RF spectrum. Handheld, battery-operated units are available. In general, most industrial hygienists will use broadband field strength meters and not spectrum analyzers.

Frequency counters are relatively inexpensive devices that determine the dominant frequency associated with a source. Handheld, battery-powered frequency counters are available for frequencies between 0 Hz and 10's of gigahertz and can measure both analog and digital signals. Frequency counters are sensitive devices, and care must be taken in their use around sources of intense RF.

E. Calibration

Calibration of survey meters and induced current meters is addressed in IEEE C95.3.[249] Calibrations should be accurate and meaningful to the anticipated field conditions. Broadband field instruments should be calibrated at a number of frequencies to ensure true broadband linearity, or to determine frequency-dependent calibration factors.[255] Single-frequency calibrations should be made only if the instruments will be used at that frequency. The frequency of calibration of an instrument depends on the conditions of use, but most instruments should be calibrated at least once a year. Instruments should be sent to the manufacturer for calibration. With that in mind, the material below is provided so the industrial hygienist has a basic understanding of RF calibrations.

Three basic methods of calibration may be used: the standard-field method, the guided-wave method, and the standard- (transfer-) probe (antenna) method.

The standard-field method involves determination of a known field intensity at a location in space. The probe to be calibrated is immersed in the field at this location, and the output value is noted. Typically, this method is used for microwave calibrations in the far field at frequencies of 500 MHz to 10 GHz.

Guided-wave methods involve the propagation of electromagnetic fields in a transmission line such as waveguides, parallel plate transmission lines, and transverse electromagnetic (TEM) cells. These devices generally are used for calibrations at frequencies less than 1 GHz.

The basis of the transfer-probe method is the operation of an arbitrary calibration field and a comparison of the readout of a probe calibrated using one of the methods discussed above (secondary standard) with that of the probe undergoing calibration.

VII. EVALUATION AND MEASUREMENT

Exposure may be evaluated numerically or by measurement, or both. Numerical models are used to predict RF field strength as a function of distance from the source, typically for intentional radiators such as antennas. Measurements are usually made for both leakage (unintentional) sources and intentional radiators. A number of useful references are available on measurement.[28,29,248,249,256,257]

A. Source Information

For leakage fields and intentional radiators, modulation characteristics, duty factor, and polarization should be determined. For radiated fields near antennas, radiated power, antenna type, diameter, and gain should be ascertained. Understand the temporal operation of the unit and the exposure patterns of the workers. This applies to both CW sources where exposure may or may not be continuous, and to pulsed sources. For pulsed sources, determine the pulse repetition frequency, pulse width, and duty factor. System components, such as the generator, transmission lines, applicator(s), and safety subsystems (interlocks and alarms), should be identified.

The location of the source and operator—relative to reflective objects (fences, vehicles, cranes, scaffolding, beams, metal buildings, metal roofs, etc.), conductive walls and floors, and other RF sources—should be identified. A workplace or site layout diagram will be a useful aid in specifying important features and measurement locations. The task to be monitored should be observed to determine interactions of the operator with the source (e.g., partial-body exposures, duration of exposure, and distance from the source).

B. Estimating Power Density—Numerical Models

For aperture antennas such as a parabolic dish or horn antenna, estimates of the on-beam power density may be made for near- and far-field regions and for the transition region.[244,248,258] In the near field it is assumed that the beam from a parabolic reflector antenna is confined to a cylindrical projection of the reflector along the beam axis (i.e., the output remains the size-diameter—of the antenna). Hence, the reflector would produce a cylindrical beam with a diameter equal to the antenna diameter. For this case, the maximum near-field power density (S) in the beam of an aperture antenna of area (A) and operating at a given power (P) and aperture efficiency (η) can be estimated by

$$S = 4P\eta/A \qquad (10)$$

If the value of η is not known, it can be numerically estimated.[244] Typically cited values are between 0.5 and 0.75 although many evaluators use unity to produce a high-side estimate (S_{max}). Note that Equation (10) predicts a value that is independent of distance within the near field, which extends from industrial hygienists will use broadband field strength meters and not spectrum analyzers.

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The power density in the far field can be calculated from

$$S = GP/4\pi r^2 \qquad (11)$$

where G is the isotropic (numeric) gain of the antenna [see Equation (7)] and P is the radiated power. Equation (11) may be rewritten in terms of the effective radiated power (ERP) effective isotropically radiated power (EIRP) as

$$S = EIRP/4\pi r^2 \qquad (12)$$

(Note: For linear antennas and linear arrays, such as a dipole antenna, the effective radiated power relative to a reference dipole is usually given and Equation (12) must be multiplied by 1.64 in order to convert between ERP and EIRP. ERP refers to the product of transmitter gain and RF power for a dipole antenna while EIRP refers to an isotropic emitter.[244])

For 100 percent ground reflection, the power density estimate in Equation (11) is increased by a factor of 4 to

$$S = GP/\pi r^2 \qquad (13)$$

Equation (13) can be rearranged and solved for the distance at which a given power density, usually the exposure limit (EL), will be reached. This sometimes is called the hazard distance (R).

$$R = (GP/\pi EL)^{1/2} \qquad (14)$$

For a scanning aperture antenna, it may be necessary to use time averaging to reduce the near-field value of S because the beam occupies a given region of space (representing potential exposure) for less time than a stationary beam [Equation (10)]. To determine if a reduction is necessary in the radiating near field, the scanned angle (θ) is compared to the ratio 360(a/2πd), where a is the antenna diameter and d is distance from the antenna. If $\theta \leq 360(a/2\pi d)$, no correction is used, but if $\theta > 360(a/2\pi d)$, the formula is

$$S = (4P/A)(a/2\pi d)(360/\theta) \qquad (15)$$

For vertical, collinear antennas, an estimate of the average value of power density in the near field may be determined from the cylindrical model,

$$S = P/2\pi rL \qquad (16)$$

where r is distance from the antenna and L is antenna length. One group of researchers recommends the use of Equation (11) for distances near D^2/λ for this type of antenna.[239] For directional collinear arrays, such as the “sector” antennas commonly used for cellular and PCS base-station applications, Equation (16) must be multiplied by the ratio (360/θ) where θ is the horizontal beamwidth of the antenna. Thus, for a 120-degree sector antenna, Equation (16) would be multiplied by 3; for a 90-degree sector antenna, by 4.

C. Measurement

Prior to performing the survey, it is important to establish a measurement protocol with respect to safety. This is because the spatial intensity of the fields and hot spots might be unknown and it is possible that there are potentially hazardous agents other than RF energy in the workplace, such as potential electrical hazards and moving antennas. Preferably, with the source switched off, a walk-through survey of the area to be evaluated should be conducted in conjunction with individuals who are knowledgeable of the system operation. During this time, the system components (e.g., waveguides, transmission lines, enclosures, ventilation openings, access doors, RFI-gasketed openings, interlocks, etc.) should be examined to see if they might be sources of leakage fields due to wear, damage, or improper maintenance. It is important to determine if there are any conductive objects in the area that may reradiate or perturb the field, such as corner configurations that could reflect and focus the energy. Locations for initial survey monitoring should then be identified.

1. *Instrument Selection*

A necessary step is the selection of the proper instrument.[248] This depends on a number of sources (frequency, temporal operation, modulation, expected intensity) and instrument (response parameter, frequency range, dynamic range) factors. One frequent source of measurement error is out-of-band response where the frequency of the source is outside the calibrated frequency response range of the instrument, or the instrument has an enhanced response to signals outside of the specified operational bandwidth. If the frequency of the source is unknown, it can be determined from an operations manual, a certification label on the equipment, or by discussion with the manufacturer. Alternately, a calibrated frequency counter or spectrum analyzer may be used to determine the dominant frequency, as long as the source frequency(s) resides within the bandwidth of the spectrum analyzer or the counter.[28]

2. Types of Measurements

The types of measurements that are recommended are shown in Table VI. At frequencies in excess of 300 MHz, the electric field or the magnetic field or the power density may be evaluated for purposes of comparison with the exposure limits. At frequencies between 300 and 30 MHz, both electric- and magnetic-field strengths must be evaluated unless the exposure is clearly in the far field of the source, in which case either E or H or S can be measured. Realistically, this can only be determined for intentional radiators (antennas) and not for leakage fields. Hence, for leakage fields and intentional radiators in the near field or where analysis to determine if the measurement location in the far field is not performed, it is necessary to measure both E and H fields at frequencies less than 300 MHz.

Free-field measurement data should be collected: 1) no closer than 5 cm from the source and its attachments and no closer than 20 cm (approximately 3 probe diameters) from passive or re-radiating objects[237]; 2) in the operator's workplace but with the operator absent; 3) as a spatial average; and 4) time averaged.

If practical, make measurements under actual operational conditions. Measurement data should be collected that are both representative of human exposure (e.g., location and temporal patterns of potentially exposed personnel) and indicative of source performance (emissions). Although source performance is important in determining where the leaks are and whether safety subsystems are operating properly, these data should not be used to determine the potential for overexposure unless they are representative of human exposure. In other words, if the detector is positioned in a narrow opening between a wall and the RF source but a person cannot occupy this position, the data do not represent human exposure though they might indicate a leak.

3. Measurement Distance

The 5-cm measurement distance and the operator's absence are recommended to minimize possible sources of measurement error associated with capacitive coupling of the source to the probe. Also, objects (e.g., human body or measurement instrument) immersed in the field may disturb the distribution of the field in space, otherwise known as perturbation. The E and H fields in close proximity to a body are composed of the original exposure fields and scattered fields produced by currents induced within the body. These secondary fields might result in decreased accuracy of the measurement data if collected near the human body because the probe might respond to both incident and reflected fields. This can result in measured field strengths higher or lower than incident levels. To minimize possible errors associated with perturbation, the evaluator, operator, and instrumental components should be located so they influence the field minimally. This may be accomplished by remote monitoring or shielding the instrument case with the body and extending the probe far from the body into the field.

For the probe, IEEE recommends maintaining a spacing distance of greater than 5 cm from the source and attachments and 20 cm from reradiators.[237] If measurements are made very close to relatively low-frequency sources (long wavelengths), the probe may capacitively couple with the field or there may be effects associated with high field gradients that can exist very near a source. Thus, recommendations for measurement distance should not be interpreted to mean that all measurement data must be collected at these recommended distances; measurements should be collected where human exposure is expected and in a manner that limits the possibility of measurement error.

4. Spatial Averaging

Spatial averaging is a technique that allows measurement data to be compared with the derived limits.[237] Fundamental to this recommendation is the fact that the derived limits are based on the WBA-SAR. In the past, evaluators often selected sample locations representative of exposure to different anatomical locations (e.g., ankle, knee, waist, chest, head), but the data were not averaged. Commonly, the highest measured datum at any one of the anatomical locations was used to determine the safety of the exposure, relative to the guidelines. Since the guidelines were developed on the basis of whole-body exposure, this was not a fair comparison. Therefore, the present guidelines require spatial averaging where anatomical data are collected along the vertical extent of the worker, then arithmetically averaged. Because RF biological effects are power dependent, spatial averaging must be performed with power density or the squares of the electric-field and/or magnetic-field strength, as shown in Equations (17) and (18). In Equation (17), X = electric or magnetic field strength and n is the number of measurements.

$$\text{spatial avg.} = \sqrt{\frac{\sum_{i=1}^{n} X_i^2}{n}} \tag{17}$$

When the measured quantity is power density (S),

$$\text{spatial avg.} = \frac{\sum_{i=1}^{n} S_i}{n} \tag{18}$$

Spatial averaging may be done manually, with a data logger, or with a spatial-averaging module. Today, many instruments are provided with a spatial averaging function. If done manually, a minimum of 10 anatomical measurements, with 20-cm spacing, should be made between 20 and 200 cm from the floor. Typically, this is done with a guide, called a “stickman,” which is made from a RF-transparent material (low relative permittivity) such as polyvinyl chloride tubing.

In addition to spatial averaging, the IEEE standard requires comparison of the individual datum points to the frequency-specific relaxations (basically, excursion factors). Also, special attention must be given to the locations of the eyes and testes,(237) although it is possible that this requirement may change in future revisions of the standard. Measurement data, therefore, should be collected at appropriate locations.

5. *Measuring Contact and Induced Currents*

The present requirements for measurement of induced and contact currents are for sources with frequencies of 100 MHz or less. The IEEE standard also has a frequency-dependent provision based upon the intensity of the measured E field. In general, current measurements are required if the spatially averaged E-field strength exceeds a certain threshold value. For example, measurement would be required if the measured E-field spatial average exceeds 16 percent of the MPE between 3 and 50 MHz for the controlled environment.(237)

If the above requirements are satisfied and there are conductive surfaces that might store electrical energy, the surface should be evaluated for contact currents. To do this, the ground plate is located on the floor, and the instrument switched on. If the control panel allows selection of the type of contact (grasping, grasping with an insulated glove, touching, touching with an insulated glove, etc.), select grasping contact. Touch the sample port to the surface and note the measured value of current.

When determining induced currents, worker-source interactions must be observed to determine the appropriate locations at which to place the monitor. Locate the monitor, and zero out or note (for later subtraction from the measured value) any background level of current associated with picking up the electric field by the monitor. For the stand-on instrument, have the worker stand at the appropriate locations, and determine the induced current. Note whether this requires one or both feet since the exposure limits are written for one foot, but the exposure values are doubled for both feet. If using a current transformer to measure ankle or wrist current, clamp the instrument on the extremity and have the worker proceed with the task.

6. *Time Averaging*

Time averaging requirements are frequency dependent for field strength, power density, and current measurements. For induced and contact currents, the averaging time is 1 sec for frequencies less than 100 kHz because of the potential for shock and burns. For frequencies between 100 kHz and 100 MHz, the averaging time is 6 min on the basis of thermal effects.

In the controlled environment, the averaging time for free fields is 6 min from 3 kHz to 15 GHz. In the uncontrolled environment, it is 6 min for frequencies up to 1.34 MHz for E fields and 30 MHz for H fields. Following transition regions, the averaging time is 30 min for E fields up to 3 GHz and H fields up to 300 MHz. Between 3 and 15 GHz, it is 90,000/f for E fields in the uncontrolled environment. Above 15 GHz, for both controlled and uncontrolled environments, the averaging time decreases to 10 sec at 300 GHz and is expressed by the function $616{,}000/f^{1.2}$.(237,238)

If the exposure duration is less than the averaging time, the value of the MPE is adjusted by the ratio of the averaging time (T_{avg}) to the exposure duration (T_{exp}) as

$$MPE' = MPE\ (T_{avg} / T_{exp}) \qquad (19)$$

Because the averaging time for current measurements between 3 and 100 kHz is so brief, this might be a more sensitive or conservative measure of exposure than measurement of free fields, especially for pulsed sources or sources that operate intermittently. This is because longer averaging times can moderate the effect of momentarily high exposure levels with momentarily low exposure levels. With a 1-sec averaging time, it is likely the instrument will capture the momentarily high value during a brief operational cycle, unless the source's cycle time is less than 1 sec. This might result in values of current that exceed the applicable limit, where measurements of free fields that are averaged for 6 min might not indicate overexposure.

D. Data Reduction

After sample collection, the data should be corrected for the duty cycle, if necessary, then averaged over the applicable averaging time, typically a 6-min period of exposure for free-field exposures. The spatial average should be used to determine the potential for overexposure, by comparison with the applicable exposure limit. If time-averaging is performed manually, remember that all calculations must be performed with the square of the measured quantity (field strength or currents), except for power density. Time-averaging may be performed by the instrument or with a data logger.[259]

In interpreting field measurements, three quantities should be considered: spatial-average exposure, relaxations, and eye/testes levels, as noted earlier. In interpreting the spatial average, the time-averaged magnitude should not exceed the WBA-exposure limit. Next, the magnitude of the individual data points used in determining the spatial average should not exceed the magnitude of the allowable relaxation for partial-body exposure. (IEEE recommends frequency-dependent relaxations of the exposure limits for exposures to part of the body.[237]) The relaxation may be viewed as an excursion limit that must not be exceeded at the individual measurement points. Last, the magnitude of individual values at the location of the eyes and testes are compared to the WBA-exposure limits. Note that the partial-body relaxations do not apply to the eyes and testes, so the time-averaged magnitude of these measurements should not exceed the applicable WBA-limit. Hence, it is possible that measurement data collected at the locations of eyes and testes may be the most restrictive.

For current measurements, compare the value of induced and contact current with the applicable exposure value. If more than one frequency was sampled, use the mixed-frequency exposure formula to combine the data. Remember to square the values of current when performing these calculations.

E. Probe Burnout and Field Zeroing

If measurement probes are illuminated by intense fields, probe burnout is possible. Most manufacturers report potential burnout levels, which can be compared with levels estimated by calculation, at least for sources of radiation such as antennas. (Note that burnout can occur with high peak pulse power when the average emitted power is within the instrument's operational limits.)

Since numerical estimates are not reliably predictive for leakage fields, one method of averting potential burnout is to approach an unknown field with a probe rated for high field strengths (least sensitive). The lowest output range (most sensitive) of the instrument should be selected and a rapid time constant should be selected if possible. The rationale for this combination is that if intense fields are encountered, the most sensitive scale of the least sensitive probe will decrease the likelihood of burnout, and will alert the evaluator to the potential for overexposure. The evaluator always should approach the field with the probe first to avert overexposure. Alternately, the evaluator could wear an appropriate personal monitor with the alarm set to alert the user that the measured levels are approaching the exposure limit. The detector should be immersed slowly into the field, and the deflection of the indicator or the audible output (if available) of the instrument should be monitored closely.

Instruments that do not have an automatic zero function should be zeroed before field measurement. If it is necessary to zero the instrument in the field, this can be accomplished by 1) taking the instrument to an area of known "zero" field; 2) switching off the source; or 3) shielding the probe with a grounded (not always feasible) metal can or foil or with other suitable shielding material.

F. Conversion of Units

In some cases, the evaluator might need to convert a measured value of power density to field strength. This can be accomplished by use of the free-space wave impedance value, Z = 377 Ω, and the measured power density, S. To convert to the electric-field strength use

$$E^2 = S \times Z \quad (20)$$

For the magnetic-field strength the formula is

$$H^2 = S / Z \quad (21)$$

Here, the units of E, H, and S are, respectively, V/m, A/m, and W/m^2. If S is in mW/cm^2 and Z = 377 Ω, then the formulas are:

$$E^2 = 3770 \times S \quad (22)$$

and

$$H^2 = S / 37.7 \quad (23)$$

VIII. CONTROLS

A. Engineering Controls

Engineering controls include but are not limited to interlocking, shielding, filtering, bonding, grounding, and waveguides below cutoff. Good design practices should include redundant, fail-safe interlocks, built-in leakage detectors, and visual and audible alarms. Limit switches should be used on antennas to prohibit switching on or off the beam at angles that might be hazardous to personnel. A maintenance program should be established to evaluate safety system performance periodically.

1. Shielding

Shielding mechanisms include reflection, absorption (attenuation), and internal reflection.[260,261]

- Reflection results from an impedance mismatch at the boundary of two media and generally is independent of reflector thickness. Reflection is the primary shielding technique for electric fields and plane waves where the characteristic impedance is in excess or equal to 377 Ω.
- Absorption losses result from the exponential decrease of the field amplitude as an electromagnetic wave is transmitted into the shield. Absorption increases with increasing shield thickness and is of primary importance in shielding low-frequency, low-impedance magnetic fields.
- Losses resulting from internal reflection are attributed to multiple reflections within a material. These may be ignored if the absorption is in excess of 10 to 15 decibels (dB).

A quantity called the shielding effectiveness (SE) is used to determine the effectiveness of a material to shield as a function of losses resulting from reflection (R), absorption (A), and internal reflection (B). SE is expressed in decibels

$$SE = A + R + B \text{ dB} = \log_{10} (P_i / P_t) \text{ dB} \quad (24)$$

where P_i and P_t are, respectively, the incident and transmitted power. Good-to-excellent SE is represented by a reduction of between 60 dB and 100 dB.

2. E-Field and H-Field Shielding Materials

E-field shielding materials include silver, copper, gold, aluminum, brass, bronze, tin, lead, and conductive polymers. These materials may be combined or machined to produce electroless-plated (copper or nickel) plastics, composite plastics, laminates and film coatings, clad metals, conductive paints, and arc-sprayed metals. Meshes, other woven textiles, and perforated materials may be used.

H-field shielding materials are iron, some stainless steels (430), steel (SAE 1045), and nickel-iron and cobalt-iron alloys.

3. Shielded Enclosures

Shielded enclosures are used to reduce leakage and penetration of RF fields. In designing an enclosure, pay special attention to the selection of the base shielding material and to seams, panels, flanges, cover plates, doors, ventilation openings, cable penetrations, and grounding.

4. Waveguide Below Cutoff

A waveguide is a hollow metal tube (circular, rectangular, or square) that is used to confine and guide electromagnetic waves (Figure 11). Although waveguides usually are designed to minimize transmission losses, a waveguide below cutoff is designed to increase attenuation. It often is necessary to include holes, apertures, and other openings in shielded enclosures or cabinets for ventilation, controls and

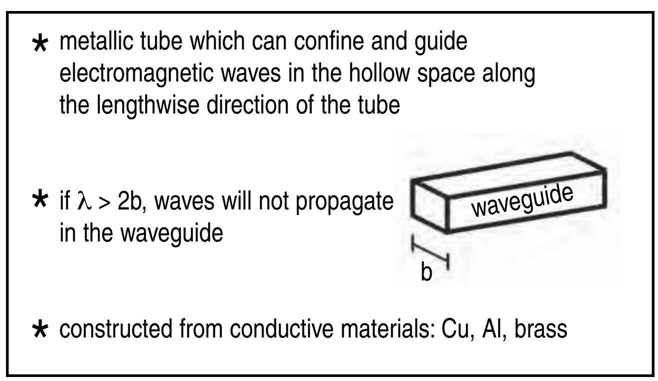

***Figure 11**—Waveguide as an attenuator.*

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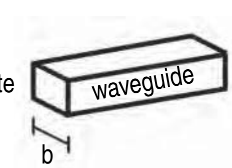
* metallic tube which can confine and guide electromagnetic waves in the hollow space along the lengthwise direction of the tube
* if λ > 2b, waves will not propagate in the waveguide



* constructed from conductive materials: Cu, Al, brass

Figure 11—*Waveguide as an attenuator.*

switches, indicator lamps, and meters, or to have conveyor openings in processing equipment that uses RF energy. Leakage of RF energy through these openings will degrade the shielding effectiveness of the enclosure. The use of waveguide-below-cutoff sleeves in the openings will help maintain the shielding effectiveness of the enclosure. An example is honeycomb air vents that allow the passage of air but attenuate electromagnetic waves. Waveguides below cutoff also have been used to successfully control leakage around conveyors in industrial microwave dryers and RF sealers.[262]

When the wavelength is greater than the width of the waveguide, the attenuation is proportional to the ratio of the length to the width. Thus, lengthening the waveguide or reducing the width will increase the attenuation, thereby reducing leakage from the aperture and improving the shielding effectiveness of the enclosure. If the wavelength is greater than twice the width of a rectangular waveguide below cutoff, waves will attenuate exponentially in the waveguide. With this rapid attenuation, the waveguide does not have to be very long to achieve significant improvements in shielding effectiveness, compared to a plain hole.

B. Clothing

It has been shown that everyday footwear and socks can modify the absorption of electromagnetic energy by human volunteers exposed on a ground plane at frequencies between 10 and 40 MHz. This is accomplished by reducing the grounding effect. The use of shoes and socks reduced the SAR in comparison with barefoot volunteers: between 15 and 45 percent for nylon socks and thin leather-soled shoes, and between 35 and 75 percent for wool socks and rubber soles.[263]

As noted, this simple control might be useful at frequencies less than 100 MHz. The degree of effectiveness can be demonstrated with an induced current meter. For example, an evaluation could include the induced currents with a worker's normal work shoes, and then the values with running shoes (large rubber soles) and wool socks (bulky with lots of air space).

C. RF-Protective Suits

Typically, the base material for these suits is wool or polyamides, like nylon. The material is impregnated with a highly conductive metal, such as silver, or is woven with metallic stainless-steel thread. If the metallic fibers are oriented in the vertical direction, they might demonstrate polarization sensitivity (i.e.,

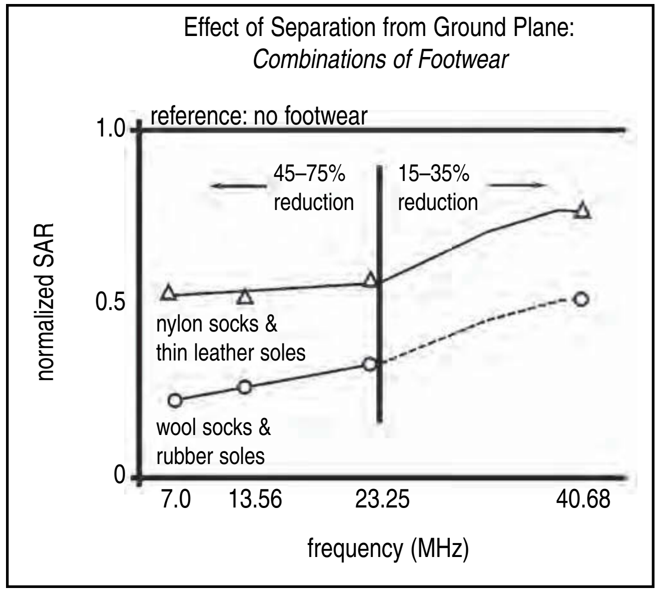


***Figure 12**—Frequency-dependent reduction of the SAR normalized to the barefoot condition for two combinations of shoes and socks. [From reference 182.]*

the shielding effectiveness is greatest when the E field is parallel with the fibers). A mesh design, in which the fibers occupy vertical and horizontal positions, is optimum.

Suits should be used with caution because of the potential for arcing and standing-wave formation and their low flame resistance. RF leakage is expected to be greater at access points and openings in suits such as the zipper and cuffs.

Some experts and organizations recommend against the use of suits. Nevertheless, if protective clothing is the method of choice, one should be sure there are adequate test data for both the suit material and the intact suit indicating that the necessary attenuation will be achieved at the specified frequency. Information on protective clothing is available.[28,264]

D. Resonance-Frequency Shift

For frequencies near the whole-body grounded-resonance frequencies (around 10 to 40 MHz) it has been shown that the SAR can be reduced by separating the body from the ground plane by a small distance. This effect was established by simulating an air gap between the subject and the ground with expanded polystyrene and hydrocarbon resin foam, as shown in Figure 12.[263] Hence, electrically insulating materials that have low values of relative permittivity can be used to simulate an air gap. The degree of effectiveness of this control can be demonstrated at frequencies less than 100 MHz with pre- and postmeasurement data using an induced current meter with the worker located atop the platform.

E. Administrative Controls

Administrative controls include prepurchase review of sources, controlling the duration of exposure, increasing the distance between the source and workers (although this can be achieved by engineering modifications), restricting access, and placing warning signs.

1. *Distance*

Increasing the distance between the source and operator probably is one of the more frequently used control measures but also the most easily circumvented. Employees should be aware of the extent of the zone of exclusion and the supportive rationale. Zone limits should be delineated by clearly visible methods or should be limited physically.

Access in the horizontal or vertical extent might be limited. Control of vertical distance can be used to control exposure of maintenance personnel on radio and microwave towers.

2. *Duration of Exposure*

The duration of exposure may be controlled so the SA remains constant for the applicable averaging time. For most frequencies, the exposure guides recommend limiting the energy dose in a 6-min period to 144 J/kg (SA = 0.4 W/kg x 360 seconds). Therefore, exposure to higher field strengths might be acceptable for shorter periods. The allowable exposure duration can be calculated from the following formula:

$$T = \frac{EL\ (W/m^2) \times T^a}{ML\ (W/m^2)} \qquad (25)$$

where T is the acceptable duration of exposure, EL is the exposure limit, T_a is the applicable averaging time, and ML is the measured level. This control measure should be used only when ML exceeds EL and T is less than T_a.

3. *Warning Signs*

The IEEE C95.2 subcommittee[265] recommended the design and color scheme of a warning symbol to be used for RF energies between 3 kHz and 300 GHz. This includes symbols for RF electric current hazards, RF radiated energy, and touch hazard. The RF radiated energy symbol is a point-source antenna with emanating wavefronts as shown in Figure 13. Recommendations for inclusion of this symbol onto a sign are made by IEEE.

Figure 13*—ANSI-recommended symbol.*

IX. OTHER CONSIDERATIONS

Special consideration should be given to personnel who have metallic implants. Conductive objects within the body tend to localize the RF field,[266] which might enhance the absorption rate. Interference may occur with cardiac pacemakers,[267] cochlear implants,[268,269] and other medical devices.[270] For industrial and medical sources, the potential for RF interference with the operation of implanted cardiac pacemakers should be evaluated on a case-by-case basis. This is because of the great variety of sources, differences in their operational characteristics, and the complexity of modern cardiac pacemakers. Sources of information include manufacturers of pacemakers and equipment.

The use of metallic frames with spectacles can concentrate the field in the vicinity of the frames,[271] thereby enhancing the local SAR.[73] Therefore, it seems prudent to use nonconductive frames with processes that leak or emit RF.

RF fields might activate electro-explosive devices or ignite flammable materials and mixtures. The manufacturers of explosive devices that are activated electrically should be consulted to determine field/device compatibility.

When collecting samples around RF emitters for chemical substances or other physical agents with electronic sampling equipment, keep in mind that there is potential for radio-frequency susceptibility with the electronic circuitry of the samplers. Some instruments, such as sound-level meters, audio dosimeters,[272] and combustible gas monitors, might be more sensitive to RF fields at specific frequencies. Output indications can be positive or negative, which will generate spurious measurement data.

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X. PROGRAM CONSIDERATIONS

Recommendations for a RF safety program are available.[28,273,274] At this writing, IEEE has prepared a draft recommended practice on RF safety programs. Elements of such a program include responsibility, inventory of sources, hazard assessment, accident investigation, control measures, information and training, hazard communication, medical surveillance, instrument calibration, audits, documentation, and record keeping.[28] Recommendations for medical evaluation have been made.[275]

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GLOSSARY

antenna: A transmitter or receiver of electromagnetic radiation. Most detection systems used by health professionals have an array of monopole or dipole antennas.

array: A system of antennas coupled together to enhance the response of a measurement probe. Typically, modern instruments have three antennas in an isotropic array.

averaging time: The applicable time for averaging measurement (exposure) data. For occupational exposure to free fields, it varies between 10 sec and 6 min, depending on the frequency. For induced currents it is 1 sec or 6 min.

collinear array: The antenna elements lie in a straight line (e.g., back-to-back dipole antennas). This has the effect of increasing the gain in the direction of propagation.

contact current: The current flowing into the hand when grasping an energized conductor.

continuous wave: Source that operates continuously, as opposed to sources that are pulsed. *Abbreviated CW.*

controlled environment: Nomenclature used in the IEEE C95.1 standard. Locations where there is exposure that may be incurred by persons who are aware of the potential for exposure as a concomitant of employment, by other cognizant persons, or as the incidental result of transient passage through areas where analysis shows the exposure levels and induced currents may be above those for the uncontrolled environment, but do exceed those for the controlled environment.(237)

current density: The level of current, in amperes, that flows across a unit cross-sectional area.

duty factor (cycle): The ratio of the time that a RF source is on ("on time") to the total time of operation ("on time + off time"). For a continuous-wave source, the duty cycle would be 1.

electric-field strength: The force on a positive test charge divided by the magnitude of the charge. It usually is considered the magnitude of the electric field.
ELF: The extremely low-frequency band designation for the sub-RF spectral region often defined as 0 to 3000 Hz. Includes the frequencies associated with power generation, transmission, and distribution (50 and 60 Hz).

equivalent plane-wave power density: The power density that would occur if the energy of the field was contained in plane waves. This concept is applied to long-wavelength radio waves in the near field of the source. If the radio-wave exposure criteria are written in terms of equivalent plane-wave power density, they are adjusted for the impedance of free space, in parallel with measurement instruments that have their output in power density.

far field: A region some distance from the source where the electric and magnetic fields have the properties of radiation. Also called free space or the Fraunhofer region.

flux: The density of lines of force in an electric or magnetic field.

impedance: A measure of the opposition to the propagation of electromagnetic energy. Wave impedance (Z) equals the quotient of the electric- and magnetic-field strength ($Z = E/H$).

***in vitro*:** Literally "in glass"; applied more generally to experiments that do not involve an intact animal.

***in vivo*:** Experiments involving an intact animal.

induced current: The current induced within the body that flows to ground and associated with exposure to the electric field.

isotropic: As applied to the response pattern of a measurement system, this means the response is independent of orientation of the detector or the polarization of the incident field. An ideal isotropic receiving antenna would have a spherical reception pattern.

magnetic-field strength: The magnitude of the magnetic field. A magnetic field exerts a force on moving charges. This force is due to a quantity associated with H, called the magnetic-flux density, B. H and B are related by the permeability of the medium (μ), a fundamental measure of interaction, where $H = B/\mu$. is equal to 4p x 10^{-7} henry/meter in free space, air, and biological tissues.

modulation: The superimposition of signal onto a carrier wave. Typically, the signal is lower in frequency.

near field: A region of space near the source. Very near the source is the reactive near field where energy is stored and there is no radiation. Further from the source is the radiative near field, called the Fresnel region, where energy storage and radiation coexist.

nonionizing radiation: Radiation or fields that have insufficient energy to ionize water molecules. Typically, a photon energy less than 12.4 eV.

plane wave: A property of radiation where the electric- and magnetic-field vectors are at right angles to each other and the amplitude is reached simultaneously. Typically, plane waves exist at some distance into the far field of the source.

power density: The power of the radiation arriving at a surface divided by the cross-sectional area of the surface, or time average-energy flow. Typically applied to microwaves, the equivalent plane-wave power density may be used at frequencies above 30 MHz for antennas (far field) and above 300 MHz for leakage sources.

poynting vector: The vector cross product of the electric- and magnetic-field vectors.

pulsed wave: Electromagnetic waves that are emitted from sources that operate intermittently or switch the RF signal on and off. Radar is the best known source of pulsed waves.

re-radiator: Conductive objects in which the exposure field induces currents that, in turn, produce secondary RF fields. Object may include support beams, poles, fences, metal walls, and roofs. Also called passive, secondary, or parasitic re-radiators.

resonance: The response of a system when stimulated at its natural frequency. The response normally is maximized in terms of the energy input into the system. In terms of RF biophysics, geometrical resonance deals with the response of the human body to an incident RF wave. At a constant energy input, the absorption of energy is maximized at the resonant frequency.

scan angle: For scanning antennas, the scan may include a plane angle of 360 degrees or less. The scan angle is used with beamwidth to estimate the power density for such an antenna.

scattering: A physical process that changes the direction, frequency, phase, or polarization of an incident electromagnetic wave.

spatial average: A measurement technique that allows data collected in the vertical extent to be averaged arithmetically and compared with the whole-body average specific absorption rate (SAR).

specific absorption: As the time integral of the SAR the SA represents the RF dose. The units are those of mass-normalized energy absorption, J/kg. Generally used for exposures to pulsed sources or to illustrate the total allowable energy absorption during the applicable averaging time.

specific absorption rate: The mass-normalized rate of energy absorption or RF dose rate. This is the fundamental quantity of the exposure criteria for the spectral region from about 3 MHz to 6 GHz. *Abbreviated SAR*.

uncontrolled environment: Nomenclature used in the IEEE C95.1 standard. Locations where there is the exposure of individuals who have no knowledge or control of their exposure. The exposures can occur in living quarters or workplaces where there are no expectations that the exposure levels or induced currents might exceed those for the uncontrolled environment.[237]

X. PROGRAM CONSIDERATIONS

Recommendations for a RF safety program are available.[28,273,274] At this writing, IEEE has prepared a draft recommended practice on RF safety programs. Elements of such a program include responsibility, inventory of sources, hazard assessment, accident investigation, control measures, information and training, hazard communication, medical surveillance, instrument calibration, audits, documentation, and record keeping.[28] Recommendations for medical evaluation have been made.[275]

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APPENDIX A: PROBLEMS

1. Determine the average power density for a source that is switched on for 1 second, then switched off for 13 seconds. The peak power density is 55 mW/cm^2.

$P_a = P_p$ % DF

P_a = 55 mW/cm^2 % (1 sec / 14 sec) = 3.9 mW/cm^2

2. Workers are exposed to three different RF frequencies in an environment with multiple sources. Does the following measurement information represent an overexposure?

Frequency (MHz)	Measurement Data Electric Field (V/m)	Magnetic Field (A/m)
27	66.3	0.1449
40	44.7	0.0707
200	55.0	0.0316

(a) First, determine the exposure limits. (For this problem, the controlled environment limits in IEEE Std C95.1 are used.) Both E- and H-field exposure limits at 27 MHz are in transition (sloping) regions as is the H-field limit at 40 MHz. Exposure limits in transition regions must be calculated. The E-field limit at 40 MHz and both limits at 200 MHz are in plateau regions where the exposure limits are invariant.

Once the limits are determined we will square the field strength levels and use the squares in the calculations. This is because biological effects are based on power (rate of energy) absorption, and power is related to the square of voltage (V) and the square of current (A). [Note: It is not necessary to square power density because it is already in terms of power.]

27 MHz: E field = 1842/f (MHz) = 68.2 V/m = 4654 V^2/m^2
H field = 16.3/f (MHz) = 0.60 A/m = 0.36 A^2/m^2

40 MHz: E field = 61.4 V/m = 3770 V^2/m^2
H field = 16.3/f (MHz) = 0.41 A/m = 0.17 A^2/m^2

200 MHz: E field = 61.4 V/m = 3770 V^2/m^2
H field = 0.163 A/m = 0.027 A^2/m^2

(b) Now, use the mixed-frequency exposure formula, Equation (9), to determine whether this represents an overexposure or not. ML is the measured level (field strength or power density) and EL is the exposure limit (field strength or power density).

$$ML_1 / EL_1 + ML_2 / EL_2 + \ldots + M_n / EL_n \leq 1$$

Electric field

$$\frac{4396\ V^2/m^2}{4654\ V^2/m^2} + \frac{1998\ V^2/m^2}{3770\ V^2/m^2} + \frac{3025\ V^2/m^2}{3770\ V^2/m^2} = 2.28$$

Magnetic field

$$\frac{0.021\ A^2/m^2}{0.36\ A^2/m^2} + \frac{0.005\ A^2/m^2}{0.17\ A^2/m^2} + \frac{0.001\ A^2/m^2}{0.027\ A^2/m^2} = 0.12$$

(c) The combined E-field values represent an overexposure, while the combined H field does not.

3. Determine the power density for a fixed position, 22-inch dish antenna that has a peak power of 75 kW. The pulse repetition frequency (prf) is 400 Hz; the pulse width (PW) is 2 µs; and the gain is 33 dB. This is a microwave device that operates at 5 GHz. The exposure limit is 10 mW/cm^2.

(a) Determine the duty factor, then the average power.

DF = prf % PW = 400 s^{-1} x 2%10^{-6} s = 8%10^{-4}

$P_a = P_p$ % DF = 75,000 W x 8%10^{-4} = 60 W = 60,000 mW

(b) Now, calculate the power density in the near field. The area, in cm, for a 22-inch dish is 2453 cm. Assume that the aperture efficiency = 1.

S = 4P/A = (4 % 60,000 mW) / 2453 cm^2 = 99 mW/cm^2

(c) Compare the near-field power density to the exposure limit.

99 mW/cm^2 *vs* 10 mW/cm^2

Since the calculated power density exceeds the exposure limit, calculate the distance to 10 mW/cm2 (i.e., the hazard distance). Express the answer in meters and feet.

(d) First, convert gain to absolute gain.

G = 10g/10 = 1033/10 = 1996

(e) Now, calculate the distance, R, using Equation (14).

$R = [(1996 \% 60\,000 \text{ mW}) / (\pi \% 10 \text{ mW/cm}^2)]$ ½

R = 1953 cm = 19.5 m = 64 ft

(f) This is an estimate of the distance at which the power density has decreased to the value of the exposure limit. Time-averaged exposure to the main beam at distances closer than R may result in an overexposure.

4. At 70 MHz the exposure limit is an equivalent far-field power density of 1 mW/cm^2 for 6 min. You determine that a maintenance activity will expose workers to a 3-mW/cm^2 level, but a trained worker can perform the task quickly. What is the acceptable exposure duration at the measured power density?

$$T_{exp} = \frac{\text{EL (mW/cm}^2\text{)} \% T_{avg}}{\text{ML (mW/cm}^2\text{)}} + \frac{1 \text{ mW/cm}^2 \% 360 \text{ s}}{3 \text{ mW/cm}^2} = 120 \text{ s} = 2 \text{ min}$$

Therefore, if the job can be performed in 2 min or less, the exposure would be acceptable. Hence, the exposure limit for this 2-minute exposure is 3-mW/cm^2.

APPENDIX B1: MEASUREMENT PROTOCOL

The following is one example of a measurement protocol. It is most applicable to a continuous-wave, leakage source with requirements to measure currents and free fields with spatial and time averaging. For the specific measurements required, see Table VI. The IEEE Std C95.1 exposure limits are used.

1. Source frequency

a. < 100 kHz, measure induced and contact currents first, then E and H fields.
b. 100 kHz–300 MHz, measure E field first.
c. 300 MHz–300 GHz, measure E or H or S

2. Broadband instrument selection (field measurement)

a. Ensure that the frequency of the source is within the calibrated frequency band of the instrument.
b. Select instrument with E and H measurement capability for leakage sources with frequencies < 300 MHz.
c. Select an E-field probe rated for high power set on the least sensitive scale.
d. Consider the use of an instrument with a shaped probe for multiple frequencies.

3. Perform a walk-through survey of the source and surroundings.

a. Observe worker-source interactions (source may be switched off for rest of survey).
b. Discuss the operation with worker(s).
c. Determine the location of any other sources of RFR.
d. Determine the location of possible re-radiators.
e. Examine enclosures/transmission lines (intact?), shield-panel fasteners (in place), etc.

4. Field measurement

a. If the instrument came from a much different temperature (e.g., trunk of car), allow it to equilibrate thermally.
b. Away from the source, switch the instrument on and allow ample warm-up time, as applicable.
c. Set the scale alarm to 50%, if applicable.
d. To minimize possible perturbations, shield the electronics case with your leg or body.
e. Coil connective (resistive) cable in a loop or use fiber optic cable.
f. Moving toward the source, scan the surrounding area.
g. Extend your arm, positioning the probe before you as you approach the source.
h. Be aware of the potential for hot spots in space and/or re-radiation.
  i. Scan a small area of space in the horizontal then vertical direction, probing for significant changes in intensity (i.e., hot spots).
  ii. Conductive objects in the field are possible re-radiators; measure no closer than 20 cm.

5. Determine locations for spatial averaging and place the stickman at the first location.

a. Perform spatial averaging with spatial averaging module or data logger.
b. If performing manually, collect data as described in Section VII, C, 4.
c. Collect measurements at the location of the eyes and testes.
d. Calculate spatial average using either Equation (17) or (18), as applicable.

6. Time averaging

a. If worker is at fixed location for 6 min, make no adjustments.
b. If the exposure duration is less than 6 min but the measured level exceeds the exposure limit, then adjust the MPE using Equation (19).

7. Perform three comparisons to the exposure limits:

a. Compare spatial average values to the whole-body average (WBA) exposure limits.
b. Compare values at the locations of the eyes and testes to the WBA exposure limits.
c. Compare each individual measurement point to the relaxation for partial body exposures.

8. If any of the measured values exceed the applicable limits, it represents an overexposure.

9. Induced current measurements are required if:

a. Measured E field > MPE at f = 450 kHz (controlled environment) or f = 200 kHz (uncontrolled environment).
b. Measured E field > allowable % of the E-field limits at frequencies up to 100 MHz.

10. Induced current measurement

a. For foot current, locate the stand-on instrument at the location (s) of the worker and record value(s) with worker standing on instrument.
b. For ankle current, place current transformer around ankle and record value(s).
c. Compare to exposure limits for one or both feet, as applicable.

11. Contact current measurements

a. Locate ground plate on floor where worker stands.
b. Select appropriate scale.
c. Touch measurement probe to surface to be sampled.
d. Compare measured values to frequency-dependent limits for currents.

APPENDIX B2: MEASUREMENT PROTOCOL PROBLEM

This problem utilizes the protocol above and illustrates the steps applicable to measurement of field strength. The operational frequency of the source is 27 MHz. The location of the testes and eyes are approximate for a 5 ft 10 in (~178 cm) male. The value for the eyes is not used in calculating the spatial average. Only the E field is considered for brevity.

Vertical Distance (cm)	Measured E-Field Value (V/m)	Square of Measured E-Field Value (V^2/m^2)
20	30	900
40	30	900
60	120	14 400
80 (testes)	250	62 500
100	310	96 100
120	300	90,000
140	110	12 100
160	100	10,000
170 (eyes)	70	[4900]
180	30	900
200	10	100

1. The MPE (controlled environment) and TLV® at 27 MHz are:

   E field = 1842 /f = 1842/27 = 68.2 V/m
   H field = 16.3 /f = 16.3/27 = 0.6 A/m

2. Determine the spatial average using Equation (17). For this calculation, it is necessary to square the values of field strength, as displayed in the third column of the table above.

   $\Sigma X^2 = 287{,}900\ V^2/m^2$
   $\Sigma X^2 /n = 287{,}900\ V^2/m^2/10 = 28{,}790\ V^2/m^2$
   $\sqrt{(\Sigma X^2 /n)} = 170$ V/m

   [Note: For comparison, if the values of E field had not been squared, the average would be 130 V/m.]

3. Determine the frequency-dependent relaxation for partial body exposures, which is < $20E^2$ or $20H^2$.

   $20E^2 = 20 \times (68.2\ V/m)^2 = 93{,}025\ V^2/m^2 = 305$ V/m
   $20H^2 = 20 \times (0.6\ A/m)^2 = 7.2\ A^2/m^2 = 2.7$ A/m

4. Compare measured values to the MPEs.

MPE @ 27 MHz (V/m)	Spatial Average (V/m)	Eye Value (V/m)	Testes Value (V/m)	Relaxation Value (V/m)
68.2	170	70	250	305

5. Conclusion: The spatial average and values at the location of the eyes and testes exceed the exposure limit. The measurement at 100 cm from the floor exceeded the relaxation value. Hence, this represents an overexposure by all three methods of comparison.