RESOURCE PAPER
An RF Safety Publication
October 2002

Radio Frequency Exposure Fundamentals

The purpose of this document is to introduce power system employees to the physical concepts used to describe electromagnetic fields and their interactions with the human body at radio frequencies. Such information will provide the background for understanding government and other standards on human exposure to radio frequency electromagnetic fields. This, in turn, can lead to an informed development of work practices appropriate near communications transmitters located on or near structures owned by electric power companies.

Although the extremely low frequency (ELF) electric and magnetic field environment near electric power transmission and distribution facilities is generally well understood by power company employees, the radio frequency (RF) electromagnetic field environment may not be. Here, the properties of 50/60 Hertz (Hz) electric and magnetic fields will be reviewed and then concepts and assumptions typically used to describe radio frequency electromagnetic fields will be introduced. Whenever possible, the low frequency concepts will be used as a bridge to explain high frequency concepts. Otherwise, appropriate contrasts between the two cases will be drawn.

The material will be presented as a set of questions and answers. This method facilitates identification of relevant portions by readers who have interests in specific issues covered in the document.

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Introduction

Why is electromagnetic field exposure an issue?

For many years, electric power companies have owned radio frequency communication systems that are used to support the company's internal communication needs. In recent years, however, the number of radio frequency transmitters on transmission and distribution facilities and other utility structures has increased dramatically as space for antennas has been leased to wireless communication companies. As a result, employees and contract workers in the electric power industry may sometimes be exposed to radio frequency electromagnetic fields that exceed the limits stated in applicable standards. Because of this, those that own and/or operate communication transmitters should be concerned if this exposure is safe. Some electric power companies have responded by developing training programs and work practices that ensure exposures that remain within guideline levels. To do this, they have been obliged to understand an exposure that is significantly different from the extremely low frequency (i.e. 50 or 60 Hertz (Hz)) electric and magnetic field environment.

What is frequency and why is it important?

One very important characteristic of electric and magnetic field sources (and hence the fields themselves) is their time variation. Perhaps the most important time variation is sinusoidal as characterized by a frequency measured in Hertz (Hz) that was formerly designated as cycles per second; a more descriptive term. Electromagnetic fields exist at all frequencies from 0 to well above 10^{15} Hz (visible light frequency). While all are electromagnetic fields, the interaction of fields with the human body at various frequencies can be very different, and the concepts that are used to understand these interactions can differ significantly. For example, the human body is essentially transparent to 50 or 60 Hz magnetic fields, but electromagnetic fields at 10^{10} Hz (equal to 10,000,000,000 Hz, 10,000,000 kilohertz (kHz), 10,000 megahertz (MHz) or 10 gigahertz (GHz)) only penetrate a short distance into the body.

What is the electromagnetic spectrum?

The electromagnetic spectrum is illustrated in Fig. 1. It is clear that the frequency difference between typical power system fields and most radio frequency (RF) fields is enormous. As mentioned earlier, this results in a significant difference in the way that fields interact with the human body and hence the way that exposure standards are developed.

Note that although the word "radiation" is used in Fig. 1 to describe RF electromagnetic fields, they are more specifically referred to as "non-ionizing radiation." This is because the energy in an elementary unit of RF electromagnetic radiation is not sufficient to break a chemical bond as is the case for higher frequency x-rays and gamma rays and, therefore, incapable of ionization of molecules within biological tissue such as DNA.

What is the difference between extremely low frequency and radio frequency exposures?

There is a significant difference between typical exposures found in the power industry and those in the communications industry. More specifically, power industry workers are usually exposed to fields that oscillate at the power frequency of 50 or 60 Hertz. The power frequency occupies the extremely low frequency (ELF) portion of the spectrum that extends from 3 Hz to 3 kHz. Communications workers are usually exposed to fields that oscillate at much

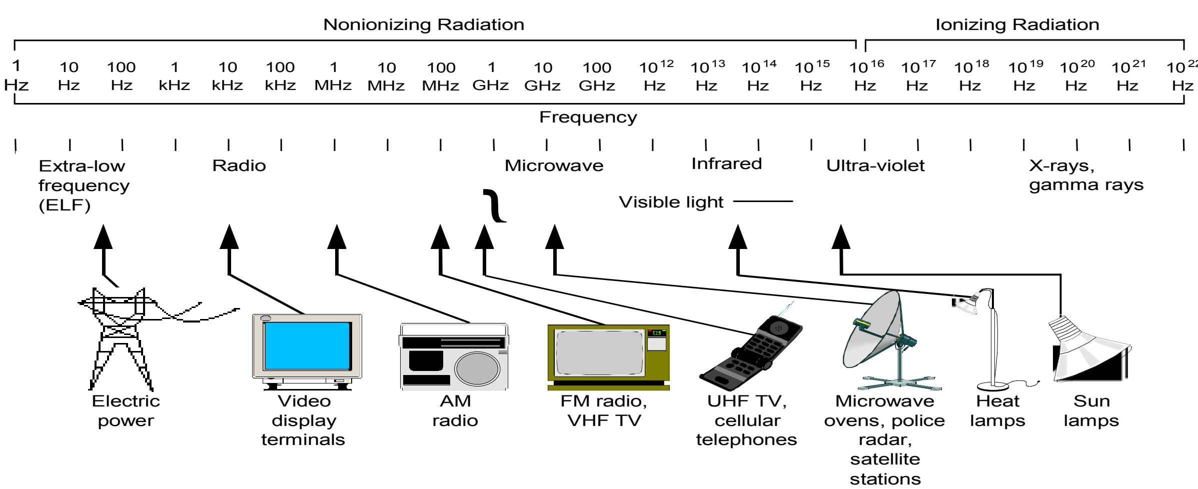


Figure 1. The electromagnetic spectrum.

higher frequencies (hundreds to millions of kHz) that are more useful for transmission of information. This difference is significant for two reasons. First, the interaction between electromagnetic fields and the human body is very different for very low and very high frequencies. Second, and because of this, the standards used to regulate exposure are different both qualitatively and quantitatively.

Regulatory Authority and Enforcement Procedures

What are the standards for power system frequencies?

There are no US Government standards for ELF electric and magnetic field exposure. However, there are international guidelines that have been written by, among others, the Institute of Electrical and Electronics Engineers (IEEE), the International Commission on Non-Ionizing Radiation Protection (ICNIRP), and the American Conference of Governmental Industrial Hygienists (ACGIH). These are well known in the electric power industry. The only purpose for introducing them here is to contrast them with the high frequency standards that apply to exposure from communications facilities. Specifically, the underlying basis for the IEEE, ICNIRP, and ACGIH guidelines is the limitation of induced current density or electric field in tissue. The limits, however, are written in terms of the electric and magnetic field exposures that cause these currents and fields in tissue. In contrast, the underlying basis for the high frequency standards is the limitation on power absorbed by tissue. The limits, however, are written in terms of the incident power density (related to the product of the electric and magnetic fields) that causes this absorbed power.

What are the Regulations for radio frequency exposure?

In the United States, essentially all communications facilities are licensed by the Federal Communications Commission (FCC). Given this, communication facilities must comply with the FCC regulations on human exposure to RF fields that are concurred with by the Environmental Protection Agency (EPA) and are found in Part 1, Section 1310 of Title 47 of the US Code of Federal Regulations. These regulations cover exposure to electromagnetic fields at frequencies greater than 300,000 Hz (alternatively 300 kilohertz (kHz)) and hence do not apply to 50/60 Hz fields typically encountered near the power system. International standards and guidelines prepared by the IEEE and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) also address RF exposure. These are quite similar to FCC regulation, but since they lack mandatory compliance, they will not be discussed further here.

How are radio frequency regulations enforced?

At the time a transmitter/antenna system is licensed by the FCC, the operator must certify that it complies with electromagnetic field exposure standards. Generally, the FCC does not inspect the system at this time. However, if a question is raised or a complaint is filed about electromagnetic field exposure, it is common for the FCC to require the owner of a transmitter to demonstrate that exposure limits are satisfied. If not, the FCC has the power to revoke the license to operate the system. It is more common, however, that the operator changes work rules or brings the system into compliance before this more drastic action is taken. Perhaps of more relevance to electric power companies is the fact that the Occupational Safety and Health Agency (OSHA) may also respond to questions and or complaints from workers about exposure to radio frequency electromagnetic fields. These questions and/or complaints may result in an inspection of a facility, measurements, and requests for documentation of work practices.

Differences Between Power and Radio Frequency Electromagnetic Fields

What are static electric and magnetic fields?

Static electric fields are used to describe the forces of interaction (F_e) between stationary electric charges (q). These charges may be either positive or negative and, if the charges have the same (different) signs, repel (attract) each other as shown in Fig. 2a. Since the basic building blocks of matter (i.e. atoms) contain electrical charge, these fields are ubiquitous. In many cases, however, the effects of the charge (i.e. electric forces) are not obvious because there are equal numbers of positive and negative charges and the forces cancel. They become obvious, however, whenever a material has an excess electrical charge of either sign. When this happens, a material is said to be charged and phenomena such as lightning discharges to earth caused by charged clouds or a spark experienced by a charged person when touching a doorknob can be observed. As shown in Fig. 2a, the electric field (E) of the first charge is equal to the force on the second charge divided by the second charge and is measured in volts per meter (V/m).

Electric charges in steady motion constitute a steady electric current (I). Separate currents that are in opposite (the same) directions repel (attract) each other with a force per unit length F_b for the two parallel conductors shown in Fig. 2b[1]. The magnetic field (B) of the first conductor is defined as the force per unit

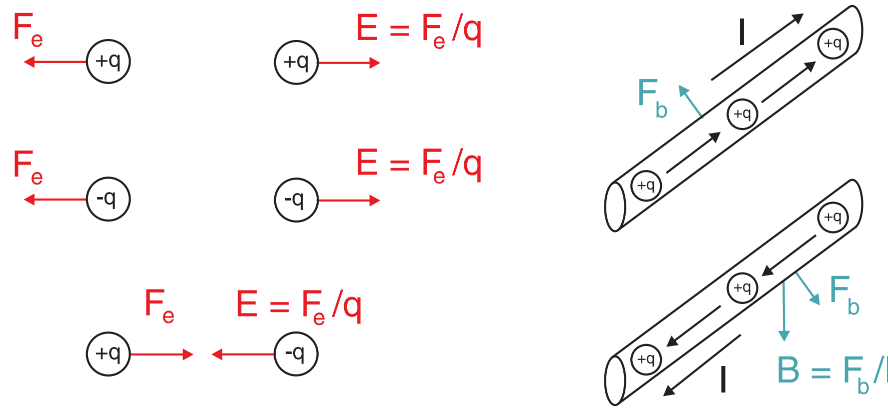
[1] Negatively charged electrons in a conductor that move in a direction opposite to that shown in Figure 2b cause a current in the same direction as shown.

length on the second conductor per unit current on the second conductor[2]. Its direction is perpendicular to both the current and the force as shown in Fig. 2b. B is measured in Tesla (T) but in the power engineering community typical units are either microTesla (μT) or milligauss (mG) where 1 mG = 0.1 μT. One common static magnetic field source is the earth's core. Currents in the core produce a magnetic field that causes the magnetized needle of a compass to point north.

In Figure 3a, a plot of the electric fields near a pair of oppositely charged electric charges (+/- q) separated by a distance d is shown. Here, the direction of the field line at any point in space is interpreted as the direction of the electric field[3]. As described above, the electric field of these two charges can be used to find the force on a third test charge at any location in the vicinity. In Fig. 3b, a plot of the magnetic fields that surround a line of current (I) are shown. Again, the direction of the field line at any point in space is interpreted as the direction of the magnetic field. As described above, the magnetic field can be used to determine the force on a parallel current carrying conductor.

What are quasi-static electric and magnetic fields?

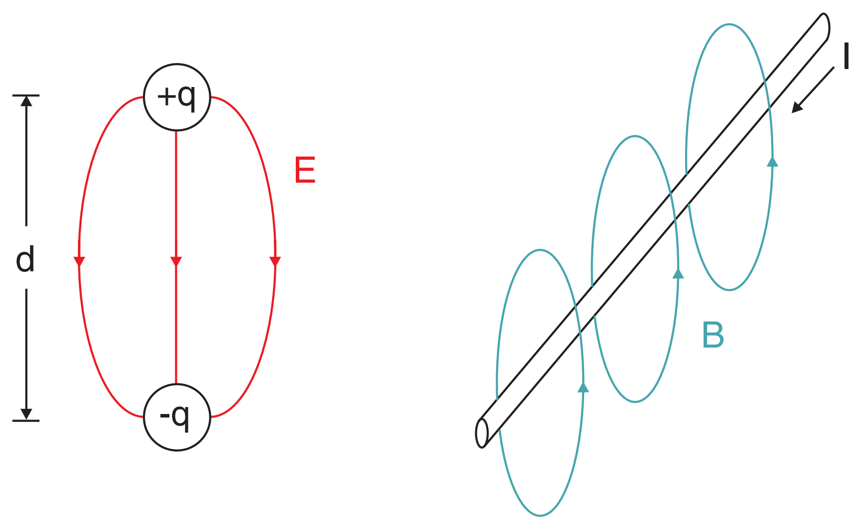
In many cases, electric and magnetic fields vary in time slowly enough that they can be described as "quasi-static." This means that they vary in space just like static (i.e., zero frequency) fields but have amplitudes that vary in time in the same way as the source[4]. 50/60 Hz power system fields are correctly treated as quasi-static.



(a) electric force and field

(b) magnetic force and field

Figure 2. Electric and magnetic forces and fields between static electric charges and parallel electric currents.



(a) electric field (E)

(b) magnetic field (B)

Figure 3. Electric (E) and magnetic (B) field lines near two static electric charges (+/- q) and surrounding an electric current (I).

[2] The magnetic field defined here (B) is officially the "magnetic flux density." In free space this field is related to the "magnetic field strength" (H) as $B = \mu_0 H$ where H is measured in amperes/m and $\mu_0 = 4\pi \times 10^{-7}$ Henries/m is the permeability of free space. Many people refer to B simply as the magnetic field. In this document B and H may both be referred to loosely as the magnetic field.

[3] In many field plots, the relative amplitude of the field can often be inferred from the density of field lines in the vicinity of the point of interest

[4] Even though quasi-static E and H fields can be properly treated as if they were independent, they actually are coupled in the same way as general time varying fields to be discussed in the next section.

What is the difference between time varying fields and static fields?

When electric charges do not move steadily (i.e. the currents are not steady), the situation becomes more complicated since both electric and magnetic fields are generated and they interact with each other. Because they are "coupled" to each other, they are often called an "electromagnetic" field. These fields can carry energy from one point to another at approximately the speed of light (approximately equal to 3 x 10^8 m/sec) and hence are useful for a variety of tasks. If the fields are guided by a physical structure (i.e. a waveguide or transmission line[5]) they can carry the energy from point to point. Examples are the transmission of electrical power over power lines and optical fiber communication. If the fields travel in space (i.e. they are not guided in a specific direction by a waveguide) they can be used for wireless communication to many different points simultaneously.

Electromagnetic Waves

What are electromagnetic "waves"?

As previously mentioned, time varying sources cause electric (E) and magnetic (H) fields that are coupled and usually referred to collectively as an electromagnetic field[6]. Consider an electromagnetic field that is generated by a sinusoidally time varying source and that does not decay as it propagates. Such a wave propagating along the z axis is plotted at the instant of time t = 0 in Fig. 4. For this wave, the electric field (red) is oriented ("polarized") along the x axis and the magnetic field (green) is oriented along the y axis. By convention, the wave polarization is defined as the orientation of the electric field and this wave is said to be "x" or "vertically" polarized. Since the source has a sinusoidal time variation, the amplitudes of the electric and magnetic fields also vary sinusoidally in time and along the z axis as shown. The portion of the wave between any two positive (or negative) crests of the wave is "one cycle" of the wave. The distance occupied by one cycle is defined as the wavelength (λ) and is indicated in the figure.

The amplitudes of the electric field for this wave at any point along the z axis for two different times ($t = 0$ and $t = \Delta t$) are shown in Fig. 5. Here, the vectors that correspond to the orientation of the field are not plotted in order to avoid clutter. It can be observed that the field at $t = \Delta t$ is displaced by a distance Δz but maintains its shape. In this case, the wave is said to "propagate" at a speed $v = \Delta z/\Delta t$ along the positive "z" direction.

A field with the behavior shown above is an example of an electromagnetic wave and can carry energy in the direction it propagates. Such electromagnetic waves can be found in many places. For example, the electromagnetic fields that emanate from an antenna can be treated as waves. Fields associated with power lines can also be treated as waves, however, it is usually more practical to treat them as quasi-static fields.

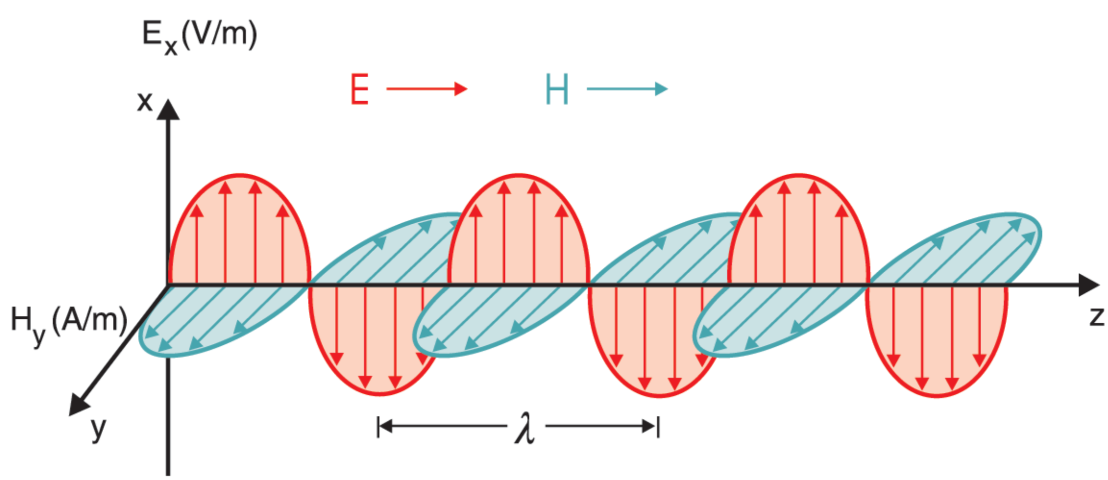


Figure 4. The electric (red) and magnetic (green) fields of a sinusoidally varying electromagnetic wave.

[5] The term "transmission line" as used by RF engineers is more general than the same term used by electric power engineers. It means any structure that supports a transverse electromagnetic (TEM) wave (to be discussed shortly). In this sense, a coaxial cable is a transmission line as well as any overhead power line.

[6] For RF safety standards, the magnetic field strength (H) is used rather than the magnetic flux density (B) that is commonly used at power system frequencies.

What is the relationship between frequency and wavelength?

A wave with frequency "f" Hz has the wavelength (λ) defined as

$$\text{wavelength} = \lambda = v/f \qquad (1)$$

where v is the velocity of the wave in the medium of interest ($3x10^8$ m/sec in free space). For example, the wavelength of a 60 Hertz power line field is 5000 km while that of a 1 gigahertz (i.e. 10^9 Hz) radio frequency wave is 30cm. As shown later, this difference will have an enormous impact on the way that these fields interact with the human body.

What is the most common type of wave that will be encountered?

One very important type of wave is a plane transverse electromagnetic (TEM) wave. This wave has the characteristic that its electric and magnetic fields are perpendicular to each other and to the direction of propagation. In addition, the "phase" (i.e. a point in time on the sinusoidal time variation of the wave) is constant within any plane perpendicular to the direction of propagation. This means that the field everywhere on the plane is maximum at the same time and minimum at the same time. Although the phase is constant on this plane, the amplitude may vary. Three examples of plane TEM waves that are propagating into the page are shown in Fig. 6.

The first (Fig. 6a) is a wave propagating in a coaxial cable[7]. Here the amplitude and direction of the wave's electric and magnetic fields vary over the plane of the paper but, as required for a plane TEM wave, the phase does not vary. In the figure, the length and direction of each arrow indicates the amplitude and direction of the electric or magnetic field at its center. Thus, it is clear that the field amplitudes are larger near the center conductor and the directions are opposite on opposite sides of the center conductor. Here, as in all other cases, conductors are assumed to be perfectly conducting (i.e. zero resistance, a good assumption for coaxial cable) and hence the fields do not penetrate into them. The second (Fig. 6b) is a wave that propagates on a wire over a ground plane. Aside from the fact that the ground plane is assumed to be a perfect conductor (not true for power lines over earth), this case is much like a single conductor power line and will be helpful for understanding propagation on power lines. One observation is that the electric and magnetic fields are much larger near the conductor than near the ground plane. The final example is a plane TEM wave propagating in free space (Fig. 6c). In this case, the electric and magnetic field amplitudes and directions are the same over the plane of the paper. For this reason, this special type of plane TEM wave is called a "uniform plane wave." This wave can be used to describe the electric and magnetic fields at a "large" distance from an antenna. It is often used to describe the incident electromagnetic field for the purposes of evaluating the potential for interacting with biological tissue.

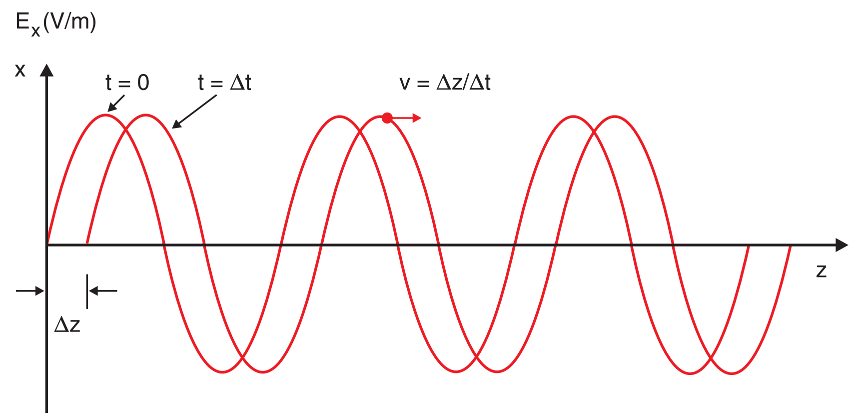
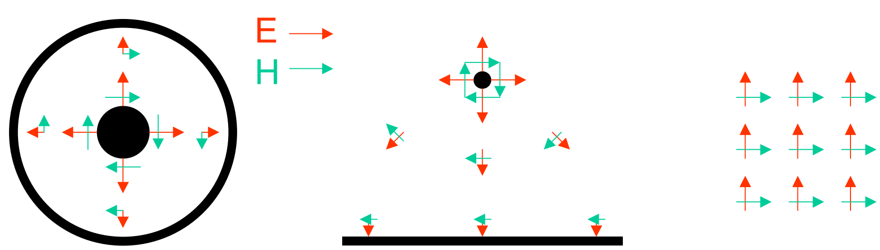


Figure 5. Electric fields of a sinusoidally varying propagating electromagnetic wave.



(a) coaxial cable (b) wire over ground plane (c) uniform plane wave

Figure 6. Electric (E - shown in red) and magnetic (H - shown in green) fields of several types of plane TEM waves that are propagating into the page.

[7] Any structure that causes an electromagnetic wave to be guided along its length is called a waveguide. As used by RF engineers, a transmission line is a special case of a waveguide that supports a TEM wave. In this sense, overhead power transmission and distribution lines and coaxial cables are examples of transmission lines.

All plane TEM waves have the property that the ratio E/H at any point in space and time is a constant and in free space is

$$E/H = \eta_0 = 120\pi \text{ ohms.} \qquad (2)$$

This ratio is called the "intrinsic wave impedance" and is a property of the material in which the wave propagates.

Finally, it is interesting to note that plane TEM waves such as those shown in Fig. 6a and 6b are "guided waves" because the electromagnetic fields 1) require that there be a long metallic structure (i.e. a waveguide or transmission line) that carries electric currents associated with the wave and 2) will tend to follow the structure if it changes directions. The difference between the two is that the coaxial cable is a "closed" waveguide for which the electromagnetic fields are completely enclosed within the structure while the wire/ground plane is an "open" waveguide for which the electromagnetic fields (while mostly confined to the region near the structure) may actually extend to infinity. The uniform plane TEM wave shown in Fig. 6c, however, does not require electric currents to support it and need not necessarily be attached to any structure. Hence it may propagate alone in space.

What difference does it make that a conducting material is not perfect?

The fact that a material (such as the ground plane in Fig. 6b) is not a perfect conductor means that electric and magnetic fields can penetrate into it. One example is the earth beneath a power line. In this case, the fields are not perfectly TEM but still (in most respects) behave similarly to TEM waves. One difference is that the conducting material absorbs some of the energy carried by the wave. As a result of this absorption, the amplitude of a wave will decrease (or attenuate) as it propagates.

What if there are waves propagating in more than one direction?

It has been assumed so far that the wave is propagating in one direction only (i.e., the +z direction). However, in general, waves may travel in any direction. If two or more plane TEM waves propagating in different directions exist, the E and H fields add vectorially. One example is two plane waves traveling in opposite (e.g. +/- z) directions. In this case the ratio E/H no longer is equal to 120π ohms and can vary considerably from this value.

What is the relationship between electric and magnetic fields and power density?

Since the FCC regulations on human exposure refer to the "plane wave equivalent incident power density" of an electromagnetic wave, it is important to describe how this relates to the electric and magnetic field strengths. For a uniform plane TEM wave that varies sinusoidally in time, the (time averaged) incident power density (S_{avg}) is

$$S_{avg} = (1/2)\, E \cdot H \text{ watts/meter}^2 \qquad (3)$$

where E and H represent the maximum positive amplitude of the sinusoidal wave. Since for a uniform plane TEM wave in free space $E/H = \eta_0 = 120\pi$ ohms,

$$S_{avg} = (120\pi)\, H^2 = E^2/(120\pi) \text{ watts/meter}^2 \qquad (4)$$

the word "equivalent" is used by the FCC because usually only E or H is measured[8] and the other calculated as if the field was a uniform plane TEM wave. If E/H ≠ 120π ohms, the two formulas given in (4) will not give the same result. Despite this deficiency, the method is acceptable to the FCC.

Antennas

What is an antenna and what is its purpose?

An antenna is any device designed to efficiently convert electromagnetic energy guided by a waveguide or transmission line (e.g. Fig. 6a or 6b) into propagating waves in space (e.g. Fig. 6c). A graphical depiction of this process is shown in Fig. 7. Here a transmitter that generates high frequency electric currents is connected to a transmission line that carries these currents and an associated guided plane TEM wave propagating on it to the antenna. The antenna, and a portion of space beyond the antenna, comprise

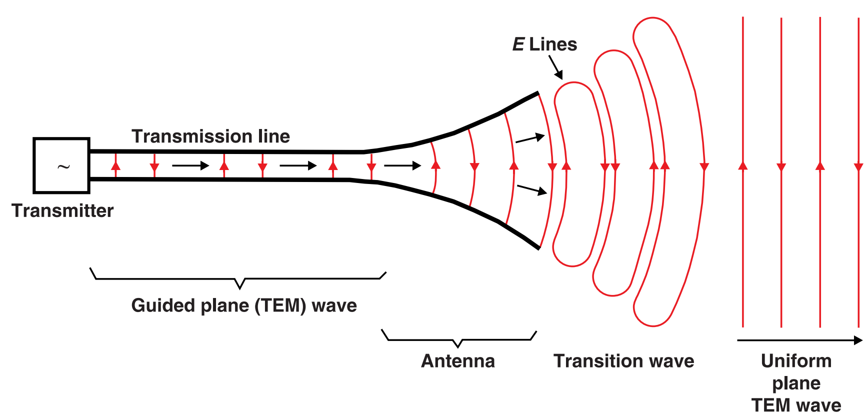


Figure 7. The process by which a guided plane TEM wave is transformed by an antenna into a uniform plane TEM wave in free space.

[8] As will be discussed later, measurement probes are designed to respond to either E or H, but not both.

the transition region between these guided plane TEM waves on the transmission line and radiating uniform plane TEM waves that propagate independently in space. By the same principle, an antenna can convert a wave propagating in space into energy guided by a waveguide or transmission line and send it to a receiver.

How Does an Antenna Generate Radiating Waves in Space?

Consider the very simple dipole antenna shown in Fig. 8. It consists of two wires connected to the two wires of a transmission line that is not shown in the figure. Because the wave propagating on the transmission line varies sinusoidally in time, the charge on the two wires and the current that transports charge between the wires also vary sinusoidally in time. When the antenna is first "turned on," the electric current is directed upward and a positive electric charge flows to the top wire and a negative charge to the bottom. At the time that the charge is maximum, the current is zero[9]. Consistent with the situation shown in Fig. 2, electric field lines form between these two wires as shown in Fig. 8a. As time passes, the current reverses direction and transports charges from the top to the bottom wire and the distribution of electric field changes as shown in Fig. 8b[10]. Simultaneously, magnetic fields (shown as x's and o's in the figure) form that surround the current flowing in the wires[11]. Eventually, the charge on the bottom wire exceeds that on the top wire and electric field lines must cross each other as shown in Fig. 8c. At this point, a circle of electric field is formed in space and "separates" from the source as shown in Fig. 8d. It and the magnetic field through it are coupled together. As one increases, the other decreases, and vice versa. This process continues indefinitely as the circles of field move away from the source at approximately the speed of light. The fields move away from the antenna in all directions (except directly up and down) as illustrated in Fig. 8e. As they move, the circles are distorted and become more "banana" like in shape. To the right edge of Fig. 8e, the lines almost become straight and can be thought of as uniform plane TEM waves such as the one shown in Fig. 6c. These fields will continue to propagate even if the antenna is "turned off" and are called "radiated waves." The process of conversion from guided to free space wave is then complete.

What are some properties of electromagnetic fields near an elementary antenna?

Any complex antenna can be constructed from a superposition of elementary antennas such as the short (compared to wavelength) dipole antenna shown in Fig. 8. Another diagram of the same antenna is shown in Fig. 9. Mathematical expressions for the specific electromagnetic fields of this antenna can be found in many textbooks, but are not reproduced here due to their complexity. However, it is important to note that the space surrounding the antenna can be divided into two parts; the "reactive near field" region where the electromagnetic field distribution is very complex, and the "radiation field" region 1) where the fields continue to exist even after the source is shut off and 2) for which there are some very simple expressions for the fields. The dividing line between these two regions is at approximately a distance of one wavelength (λ) from the antenna as shown in Fig. 9. The electric and magnetic fields (represented by vectors showing their respective directions) in the radiation field region each decay as the inverse of distance (1/r) away from the source. This is illustrated in Fig. 9 by making the lengths of the E and H vectors proportional to the electric and magnetic field amplitudes respectively. Also in this "radiation field" region, the waves can be represented locally (i.e. in

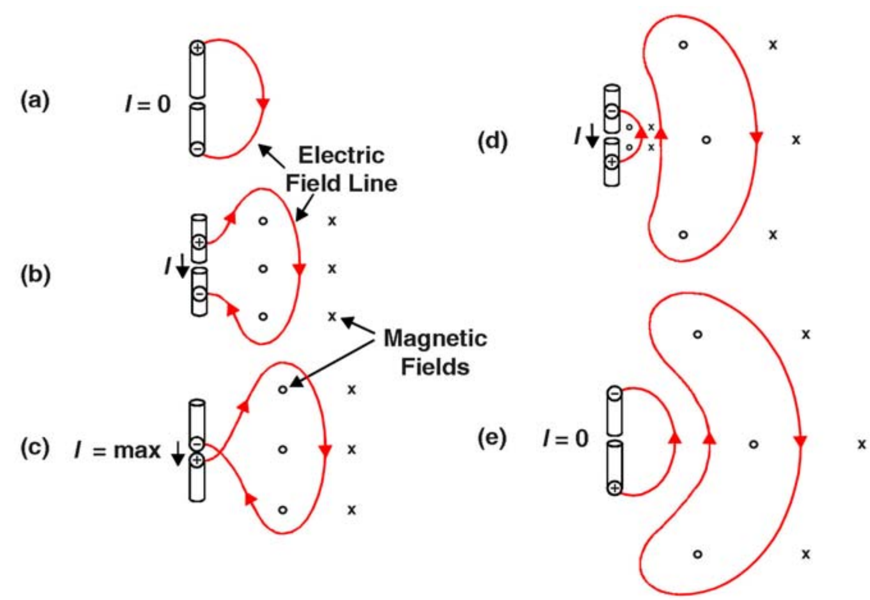


Figure 8. The process of creating radiation from an elementary dipole antenna. The x's and o's represent magnetic fields into and out of the paper respectively.

[9] Because i(t) = A· cos(2πft) and the charge is proportional to the integral of the current (i.e. sin(2πft)).

[10] Part of the reason that the lines distort as they do is that changes in the fields cannot occur faster than the speed of light.

[11] Even though it appears that there should be no current flowing on these wires because they are not connected, current can flow between them through the "stray capacitance" between the wires.

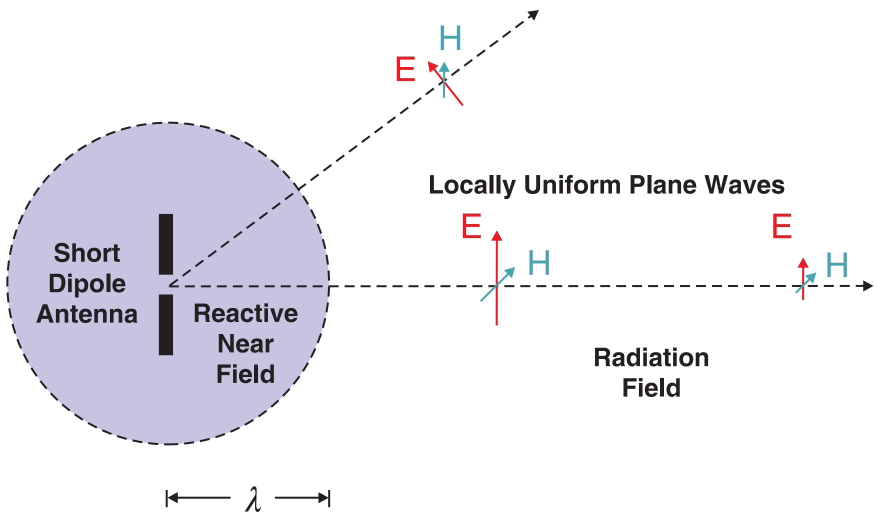


Figure 9. The reactive near field (blue) and radiation field (white) regions of an elementary antenna. Note that the fields decay with increasing distance and increasing angle as indicated by the length of the E and H vectors.

the near vicinity of any point) as uniform plane TEM waves that travel along a line between the antenna and the point at which the field is evaluated or measured. Because of this, the electric and magnetic fields are perpendicular to the direction of propagation and to each other as shown. Of course, electromagnetic waves also travel in directions other than horizontal away from the antenna as illustrated in the figure. In these cases, the electric and magnetic fields are (as before) always perpendicular to the direction between the antenna and the point at which the field is evaluated and to each other. They are uniform plane TEM waves but propagating in another direction. As also indicated in Fig. 9, the amplitude of these plane waves may not be the same as those on the horizontal axis, however, because antennas do not radiate equally in all directions. This issue will be discussed further in the answer to the question about radiation patterns.

Since the power density carried by the electromagnetic field is equal to the product of the electric and magnetic fields as in (3), the power density is proportional to $1/r^2$ where, again, r is the distance from the antenna. Clearly, the closer a person is to the antenna the greater the electromagnetic field to which he or she is exposed. This point will have significant implications for exposure calculations. The power density is also proportional to the total power radiated by the antenna (usually approximately equal to the power output of the transmitter).

What antennas can be found near power system facilities?

Typical antennas located on the power system are illustrated in Fig 10. These include rod, dish, yagi, and panel antennas as well as arrays of panel antennas. Typical characteristics of and applications for each antenna type will be discussed in the following paragraphs. Of particular importance is that the dimensions of these antennas are larger than a wavelength at radio frequencies. Because of this, the directions for which electromagnetic energy radiates from a particular antenna can be controlled by how it is designed.

What is the radiation pattern of an antenna?

As mentioned earlier, antennas generally do not radiate the same power density in all directions from the antenna. In fact, the "directionality" of antennas that are physically large compared to a wavelength can be quite complex and will generally vary with distance from the antenna. At very large distances from the antenna, however, the directionality becomes independent of distance from the antenna. The region where this occurs is called the "antenna far field" and begins at a distance

$$d = 2D^2/\lambda \text{ meters} \tag{5}$$

from the antenna where D is the largest physical dimension of the antenna[12]. The distance to the antenna far field can be very large for realistic antennas. For example, the far field of an antenna with maximum dimension (D) of 2 meters operating at 1 GHz (λ = 30 cm) is nearly 27 meters from the antenna.

A graphical display of the angular distribution of radiated power density is called the radiation pattern. To describe the information contained in this pattern, consider the two examples shown in Fig. 11[13]. Some antennas generate electromagnetic fields that propagate in all directions with almost equal amplitude as shown in Fig. 11a. Such "omnidirectional" antennas would be used in broadcast or mobile applications for which the location of the transmitter and/or receiver is not known. One example of such an antenna is the "rod" antenna shown in Fig. 10a. In applications for which the transmitter and receiver locations are known, such as point-to-point microwave communication, or for which signals should be sent in only one direction at a time such as radar, antennas are designed to generate fields

[12] The expression $2D^2/\lambda$ is an engineering derivation for a circular parabolic dish antenna and defines the distance at which the phase variation across the front of the wave will not exceed $\lambda/16$ degrees. It should be noted that a number of alternative definitions for far field distances have been developed over the years.

[13] As will be discussed shortly, these patterns represent the radiation in one plane only.

that propagate mostly in one direction. Antennas of this latter type, such as the yagi and dish antennas illustrated in Figs. 10b and 10c, have a narrow main beam as shown in Fig. 11b. In this figure, the "beamwidth" θ_{BW} is defined as the total angle between two points on the pattern that represent half the maximum radiated power. Antennas with a narrow beam generally have additional directions in which there is a local (and smaller) maximum in radiated power density. The portion of the radiation pattern in these directions is called a "sidelobe" and is illustrated in Fig. 11b. Panel antennas and arrays of panel antennas as shown in Figs. 10d and 10e are often used by wireless communication companies to communicate with mobile stations. These antennas generally have the property that they radiate energy only within the "sector" of the space (usually 120 degrees wide) that can be observed from the antenna location. When an array of three panel antennas is used as illustrated in Fig. 10e, usually one is used for transmission and two for reception[14].

Of course, the actual radiation pattern for any antenna is three dimensional as illustrated by the yellow/green surface in Fig. 12 because it is, in general, a function of both azimuth (horizontal) and elevation (vertical) angles. However, it is common to describe this pattern separately in the horizontal and vertical planes as illustrated in Fig. 11. For the example shown in Fig. 12, the main beam of the radiation pattern looks somewhat like a pancake that is thin near the antenna and fatter at the end furthest from the antenna. In the vertical plane, the radiation is (except for the small sidelobes) confined to angles almost directly in front of the antenna while in the horizontal plane, the radiation is more spread out. The reason for this is that the panel antenna is much taller than it is wide. The larger the dimension of an antenna in a given plane, the smaller the beamwidth in the same plane. The relation between these two can be approximated using the "5 and 10" rule. This rule states that an antenna with a dimension of 5 wavelengths has a beamwidth of approximately 10 degrees while an antenna with a dimension of 10 wavelengths has a beamwidth of approximately 5 degrees. Given this rule, the vertical radiation pattern of the panel antenna in Fig. 12 has a beamwidth of approximately 9 degrees since its height is 6 wavelengths. In the horizontal plane, however, the beamwidth is quite wide since the antenna dimension in this plane is only 1 wavelength.

Another result of the different height and width is that the minimum distance at which the radiation pattern is a useful concept is different in the vertical and horizontal planes. The vertical radiation pattern is not valid until a distance of $d_v = 2D^2/\lambda$ where D is the height of the antenna. In contrast, the horizontal radiation patterns is useful beyond $d_h = 2W^2/\lambda$ where W << D is the antenna width. One consequence is that the horizontal radiation pattern can be used to describe the horizontal

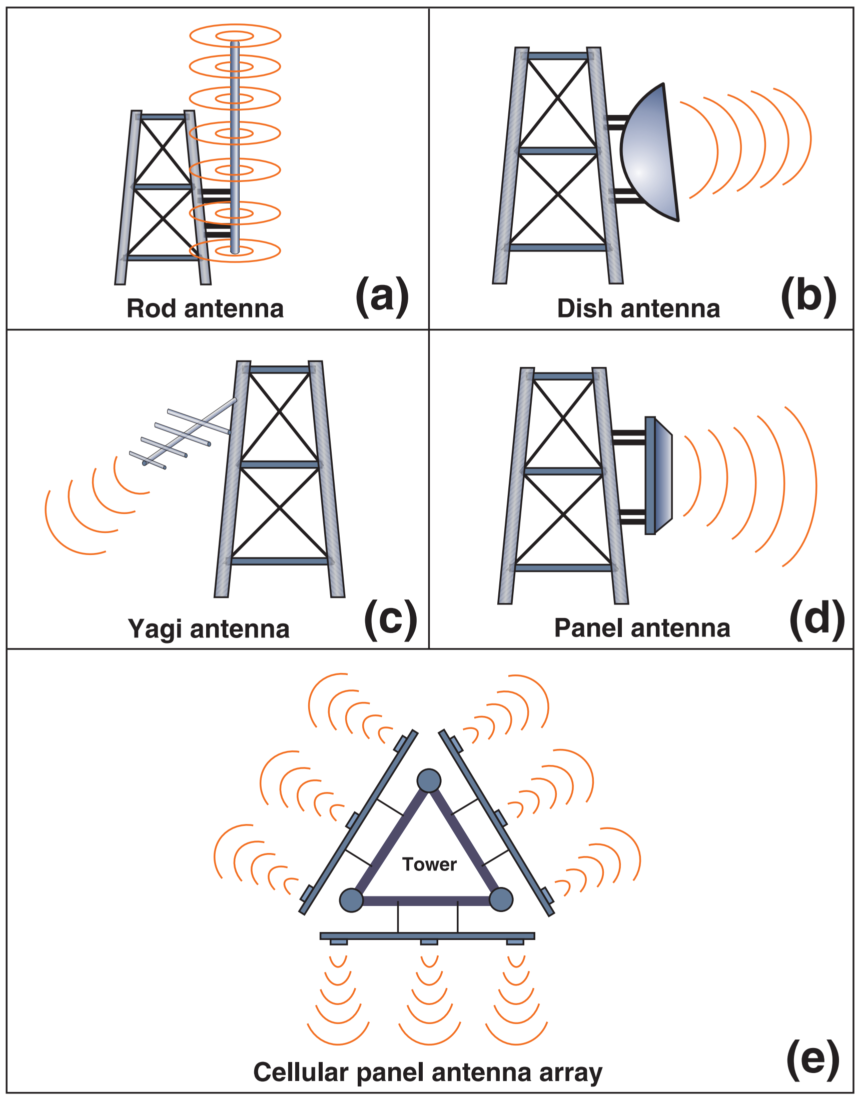


Figure 10. Typical antennas that may be found on electric utility facilities.

[14] Two antennas are used as receivers in order to improve reception using a "space diversity" technique. This is done because the signal arriving from the mobile may be significantly larger at one of the antennas than the other due to multipath propagation effects.

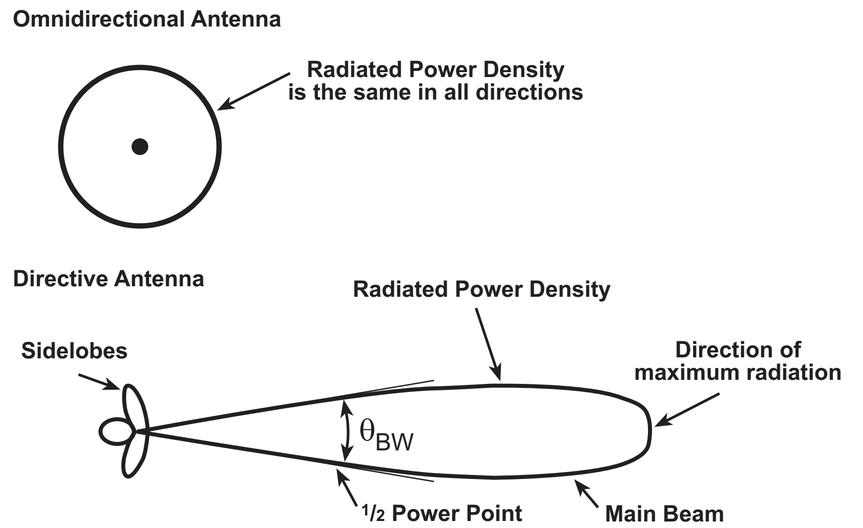


Figure 11. Radiation pattern examples that give a visual indication of the radiation intensity (and hence, potential exposure) in different directions from the antenna.

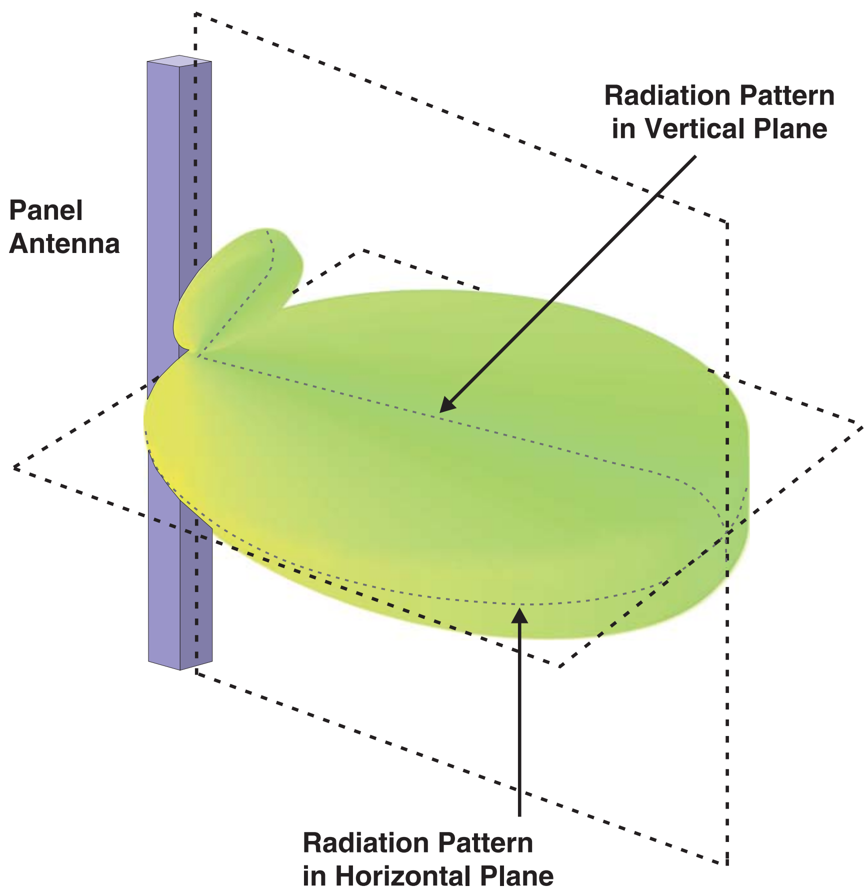


Figure 12. Vertical and horizontal plane radiation patterns of a panel antenna of horizontal dimension 1λ and vertical dimension 6λ.

distribution of RF exposure at points relatively close to the antenna.

Finally, as noted earlier, antennas of a large dimension, compared to a wavelength, will generally have sidelobes. Examples of sidelobes are shown in both Fig 11 (two dimensions) and Fig. 12 (three dimensions).

What are antenna gain and effective radiated power (ERP)?

Because antennas with narrow main beams radiate most of their energy in one direction, the power density in that direction is larger than in other directions and it is said that the antenna has "gain." "Gain" means that the intensity is larger than that of a reference omnidirectional antenna that radiates the same total power. Generally, the narrower the main beam, the higher the gain and vice versa. Note also that in directions other than the main beam direction, the radiated field power density is reduced. The gain of an antenna is another factor to be considered when evaluating the exposure of an individual to RF electromagnetic fields.

Another concept related to gain is the "effective radiated power" (ERP) of an antenna. This is defined as the total power radiated in all directions by the antenna multiplied by the gain of the antenna. It is the input power needed to produce the same far fields in the main beam direction if the antenna was omnidirectional.

What are some characteristics of electric and magnetic fields near large antennas?

Recall that radiation pattern, gain, and effective radiated power are useful concepts only beyond $d = 2D^2/\lambda$ and that d can be a very large distance away from the antenna (e.g. 27 meters for a 2 meter antenna operated at 1 GHz). Further, electromagnetic fields that may be of concern with respect to FCC limits are generally found closer to the antenna than this. Given this, radiation pattern, gain, and effective radiated power of an antenna are usually not useful for determining where the fields of a given antenna exceed the FCC limits. It is thus important to discuss the region closer to the antenna where the fields are stronger but distributed in a more complex way.

Consider the panel antenna shown in Fig. 13. As discussed above, the "antenna far field" is $d > 2D^2/\lambda$ from the antenna while the reactive near field is within 1 wavelength of the antenna surface[15].

The middle region is where most human exposure to field levels above the FCC limits can occur and hence is of most interest here[16]. This region may be divided into two parts; the "radiating near field" and the "single uniform plane wave" region as shown in Fig. 13. The radiating near field region begins at approximately one wavelength from the antenna. In this region, the field at any point is a set of plane waves that arrive from a variety of directions (i.e. from all points on the antenna) as shown in Fig. 13. Thus, the total field is not the same as that of a single uniform plane wave and, $E/H \neq 120\pi$ Ohms. As the field point moves further away from the antenna into the single uniform plane wave region, the individual plane wave incidence directions become more parallel and the total field is approximately that of a single plane wave for which $E/H \cong 120\pi$. The distance to the single uniform plane wave region can be approximately given as 2D[17]. In the single uniform plane wave region the power density decays as approximately $1/r^2$ and $E/H \cong 120\pi$. As a result of the latter, measurements made with electric and magnetic field probes should be identical. This is because magnetic (electric) fields measured with a loop (dipole) probe are converted to an equivalent electric (magnetic) field by multiplying (dividing) by 120π ohms. This subject will be discussed further later.

In some cases, the closest two regions are combined into a single region called the near field while the further two regions are combined into a single region called the far field. These are also identified in Fig. 13.

The power density as a function of distance away from a typical panel antenna is shown in Figure 14. It is clear that in the "antenna far field" the effect of distance reduces the field to levels well below the maximum levels permitted by the FCC. Since the concept of antenna gain is valid only in the antenna far field, it is usually irrelevant to calculation of exposure levels. Methods for approximating the fields in the radiating near field can be found in "Radio Frequency Safety for the Electric Power Industry," EPRI Technical Report 1005419.

Sources of Electromagnetic Field Exposure on the Power System

What are the waveguide sources of exposure?

The primary types of waveguides that will be encountered on the power system are 1) open wire transmission lines such as overhead power lines, 2) coaxial cables such as underground power lines and communications cables and, in some cases, 3) flexible elliptical waveguide. Devices in the latter two categories are used to carry radio frequency signals from the transmitter to the antenna.

Because 50/60 Hz overhead power lines are "open" waveguides, it is likely that workers near them will be close enough to be exposed to their electromagnetic fields. Given the way that regulations are written for ELF electric and magnetic field exposure, the parameters of interest are the electric

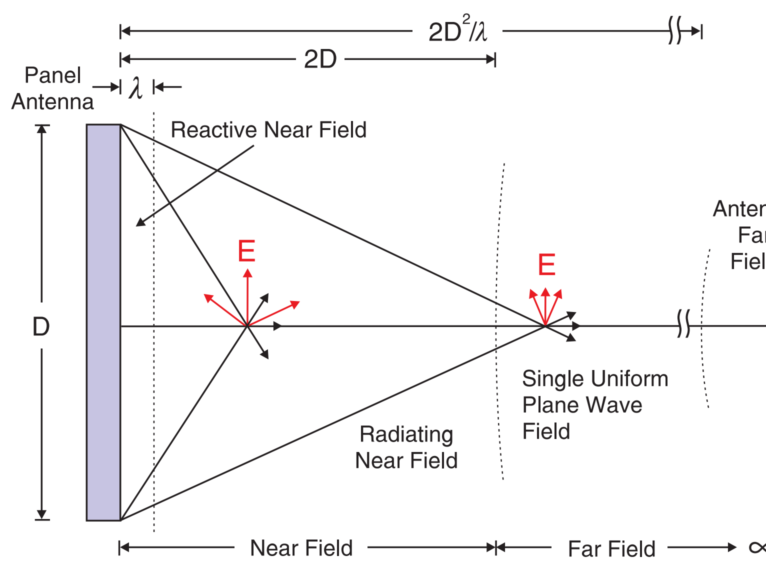


Figure 13. The different field regions near a large (compared to wavelength) panel antenna. The electric fields (E - shown in red) of the incoming waves in the radiating near field are not parallel, but in the single uniform plane wave field region they are approximately parallel.

[15] Near some points on large antennas, such as a parabolic dish reflector, the field may be described by plane waves.

[16] Most workers will not be close enough to the antenna to be in the reactive near field.

[17] At this distance, the angles of arrival for all incident plane waves at a point on the antenna main beam are within 15 degrees of horizontal.

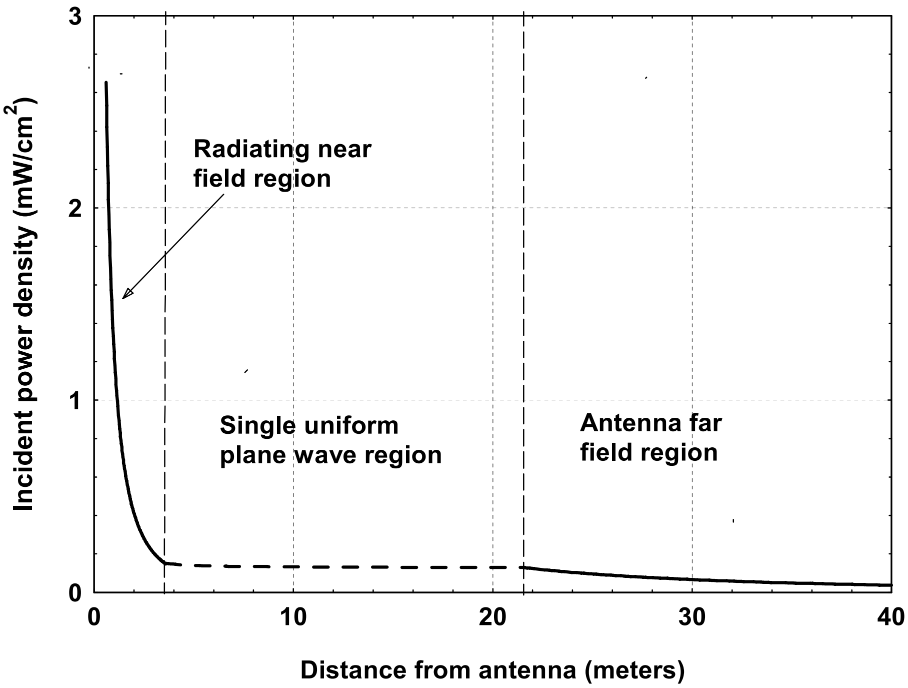


Figure 14. Radiated power density away from a 1.8 x 0.3 meter panel antenna that radiates a total of 100 watts at a wavelength of 0.3 meters (frequency of 10^9 Hertz).

and magnetic field amplitudes in the absence of the human body. Note that E cannot easily be calculated from H, since power lines generally have waves propagating in both directions so that, in general, $E/H \neq 120\pi$ ohms.

50/60 Hertz electric field exposure in the vicinity of structures, such as transmission line towers, are generally much more complicated than those near midspan. As a result, these are usually measured rather than modeled. Magnetic fields, on the other hand, are relatively insensitive to the tower structure and are not too different from those calculated by ignoring the towers. Knowledge of these fields is important, however, because 1) workers may be exposed to these fields and 2) the fields may influence instrumentation used to monitor high frequency electromagnetic fields.

Underground cables and most communication cables are "closed" waveguides that (if operated with balanced currents) have fields that are confined within them. Thus, these are not generally treated as sources of radiation. It is interesting to note, however, that some occupational exposure might come from working near radio frequency waveguides mounted on transmission line structures. For example, a damaged or improperly maintained waveguide may radiate electromagnetic fields. A nearby worker could be exposed to these fields. Since these fields are at high frequency and are regulated by the FCC, the parameter of interest will be the incident power density of a wave emanating from the defect.

What are the antenna sources of exposure?

Antennas that can be found near the electric power system include 1) antennas mounted on transmission or distribution line structures, 2) antennas on personal communication devices, and 3) antennas on other facilities or vehicles owned by the utility (e.g. microwave towers, cars, and trucks). As indicated earlier, the closer one comes to one of these, the greater the potential exposure to RF electromagnetic fields.

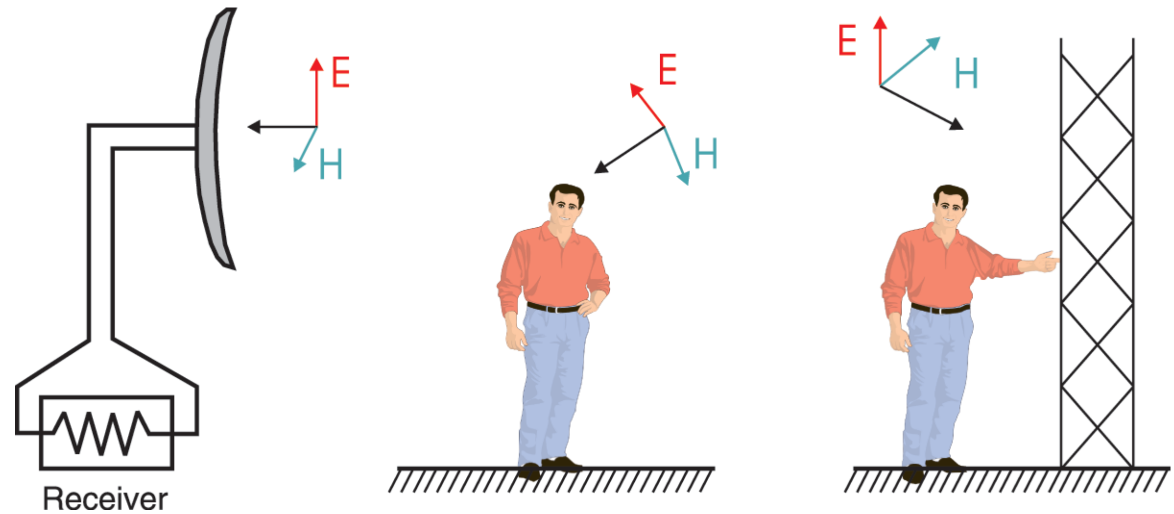
The environment in which the antenna is located can complicate the exposure. For example, plane waves can be reflected from metallic structures, hence creating a very complicated environment that can be described by several plane waves propagating in different directions. In such a "multipath" environment the electromagnetic field may vary rapidly in space and there may be regions for which the field is greatly enhanced. Generally, only measurements are useful for estimating exposure levels in these cases.

Interaction of Electromagnetic Fields and The Human Body

What is a receptor?

A receptor is any system that can absorb energy from an electromagnetic field. Several examples are shown in Fig. 15. In some cases, it is desirable to absorb as much energy as possible. Examples are a receiving antenna connected to a radio receiver such as shown in Fig. 15a or food in a microwave oven. In other cases, an object (e.g., an RF field meter in a 60 Hertz electric field or a human body in a high frequency field such as shown in Fig. 15b) incidentally absorbs some power from the field and hence might be adversely affected by the presence of the fields.

It is important to note that the fields absorbed by a receptor may be increased if an additional structure is attached to the receptor either by design or by momentary contact. One good example is the receiving antenna connected to the receiver shown in Fig. 15a. The purpose of the antenna is to increase the power absorbed by the receiver. Another example of this is the case for which a human body is in contact with a larger metallic system as shown in Fig. 15c. At low frequencies this might represent an unsafe exposure when a fault current is grounded through the tower. At radio frequencies however, a human touching the tower may be exposed to currents or discharges that can cause RF burns. Such currents might include those induced on



(a) antenna/receiver (b) human above earth (c) human in contact with tower

Figure 15. Different types of receptors with incident fields.

a transmission line tower by a nearby broadcast station.

Although there are regulatory limits on exposures that might cause RF burns, the emphasis here will be on the direct interaction of an electromagnetic wave with the human body as shown in Fig. 15b rather than the body augmented by a metallic system.

What are incident, scattered and total fields?

The electromagnetic fields inside an exposed human are not the same as those that would exist if the body was not there. More precisely, the "total" electromagnetic field inside and near the receptor can be divided into "incident," and "scattered" fields (sometimes called the reradiation field). The former are the fields in the absence of the receptor[18] while the latter are the additional fields generated by interaction with the receptor and are very dependent upon the shape and electrical characteristics of the object. The total electric field (incident plus scattered) inside the body has been designated as E_b while the incident field is designated as E.

What characteristics of the field inside the body are related to biological effects?

The fundamental assumption behind the FCC limits is that biological effects of electromagnetic fields (above 300 kHz) are related to observation of behavioral disruption in trained laboratory animals. This behavioral disruption is assumed to be caused by RF energy absorption and hence heating in the body due to electromagnetic field exposure.

The body heating is related to the Specific Absorption Rate (SAR) (i.e. the rate of electromagnetic energy absorption per unit mass within the body that is proportional E_b^2/ρ where E_b is the electric field in the body and ρ is the resistivity of body tissue). It is the SAR that forms the basis for exposure estimates. Specifically, the SAR (averaged over the entire body) allowed by the FCC is limited as will be explained later in this document.

Unfortunately, the electric field in the body (E_b) is not the same as the much more easily calculated or measured electric field at the same location when the body is absent (E). In fact, a direct determination of SAR in any given body from calculations or measurements of E is very difficult. In order, then, that the guidelines be more easily applied, they are written in terms of electromagnetic field exposure (i.e. the electromagnetic field in the absence of the body) that will cause a given SAR over a typical range of human body sizes. To understand how this has been done, it is necessary to introduce some basic information about how electromagnetic fields interact with the human body.

What are the factors that govern the mode of interaction between electromagnetic fields and the body?

A body's interaction with an electromagnetic field is determined by the direction of wave propagation relative to the body, the orientation, and amplitude of the electric and magnetic fields, the body's shape and distribution of resistivity, and its physical dimensions with respect to the wavelength in the body. Note that the wavelength inside the body may be significantly smaller than the free space wavelength given in (2). For example, at 10 MHz, the free space wavelength is 30 meters while the wavelength inside a typical human body is 2 meters. This difference is important because it is this wavelength that

[18] These are designated E and H in this document.

determines 1) whether quasi-static theory can be used, 2) the frequencies at which resonances occur, and 3) the attenuation rate of very high frequency fields that enter the body.

How do extremely low frequency fields interact with receptors?

As long as the relevant distances (e.g., the size of a human body) are a small fraction of a wavelength in the body, it is reasonable to treat the dominant electric and magnetic fields as separate (i.e., the currents induced in the body by the electric and magnetic fields can be calculated separately and the results added) and to use quasi-static theory to calculate them. For calculation of the dominant electric fields, the body is assumed to be a perfect conductor. However, (as long as the body is not magnetic), it is assumed to be transparent for calculating the dominant magnetic fields.

Although the dominant electric and magnetic fields are relatively easy to calculate, the secondary fields are also of interest for estimating induced electric fields and current density at power frequency. In a human body, for example, the dominant electric field (calculated using electrostatic theory) is zero. Because the frequency is not exactly zero, however, there is a small (secondary) electric field in the body. The magnetic field also can contribute to the (secondary) electric field in the body through eddy currents induced according to Faraday's law.

How do radio frequency electromagnetic waves interact with receptors?

At radio frequencies, the interactions with a person are very different than at ELF. Electric and magnetic effects must be calculated simultaneously rather than separately. Generally, this is done by assuming a uniform plane TEM wave incident on an assumed model of the body and calculating the electric field and then the SAR distribution within the body. Of course, as mentioned earlier, this distribution varies with the direction, amplitude, and orientation of the incident wave as well as the size, shape, and electrical characteristics of the assumed body model. As a result, a range of SAR's may be calculated for different incident waves and body sizes exposed to a given incident field. Finally, it should be noted that it is not generally possible at these higher frequencies to characterize the body by its resistivity only. It is usually necessary to include the distribution of relative dielectric constant (ε_r) within the body in the formulation[19].

What is the body resonance phenomenon and how does it affect exposure standards?

Another difference between high and low frequency field interactions with the body is the resonance phenomenon. It can be shown that when the size of the body is approximately equal to a half-wavelength in the body (i.e. the resonant frequency), the field inside the body caused by an incident electromagnetic field can be significantly enhanced. This means the incident field amplitude necessary to produce a given SAR in the body is smaller at frequencies near to than away from the resonant frequency. Note that for a typical adult man, the frequency at which "resonance" occurs is close to 65 MHz. For a typical head dimension of 20 cm, resonance can occur at 375 MHz. This observation is the fundamental reason why the exposure limits are reduced in the 30-300 MHz frequency range. Outside of this range, the limits are tapered to meet the low and high frequency limits.

The resonance phenomena can be illustrated by reference to Fig. 16. Here, the specific absorption rate (averaged over the whole body) for a man, rat, and mouse are plotted as a function of frequency. At lower frequencies, the SAR

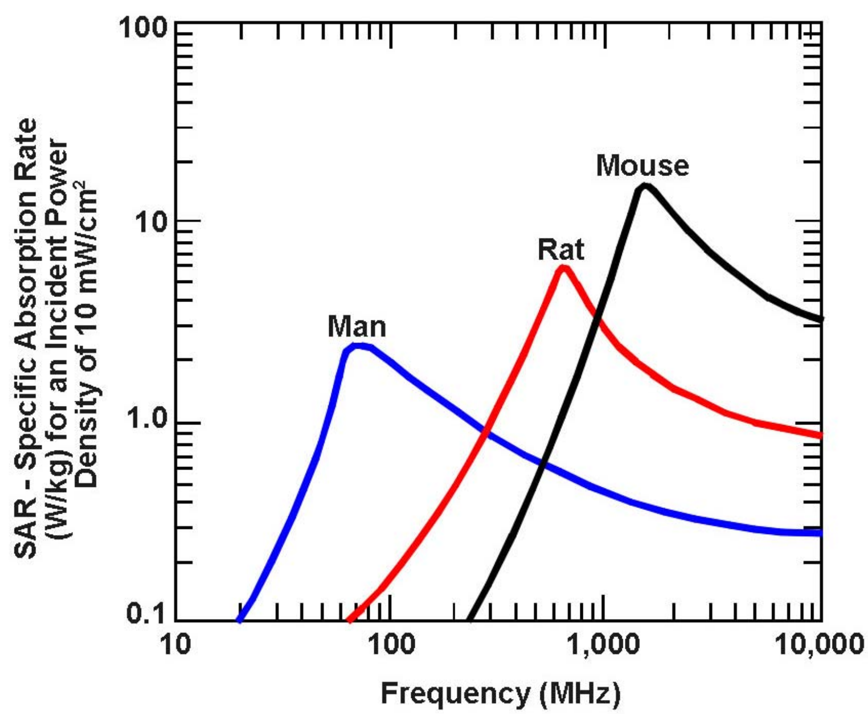


Figure 16. Specific Absorption Rate (SAR) (averaged over the whole body) in W/kg for a 10 mW/cm^2 incident field as a function of frequency for man, rat and mouse.

[19] ε_r is an electrical constant that characterizes the polarizability of material. The relative dielectric constant of free space is 1.

for each curve in Fig. 16 increases with frequency. This occurs because the electric field in the body is proportional to the ratio of the relative dielectric constants of air ($\varepsilon_r = 1$) and body tissue[20]. Since the effective relative dielectric constant of tissue decreases with frequency, the electric field in the body—and hence the SAR—increases. At higher frequencies, the SAR is limited by the skin effect in the body (to be discussed further in the answer to the next question) that causes the electric field to be concentrated near the periphery of the body. Since the skin depth decreases with frequency, the electric field and the SAR decrease as well, as shown in Fig. 16. Between these low and high frequency regimes, the SAR peaks due to the resonance phenomenon.

How are very high frequency electromagnetic fields attenuated by the human body?

At frequencies above body resonances, the penetration of fields into the body is limited by the skin effect. This effect is related to the decay of plane waves that propagate through conducting material. It is characterized by a skin depth (δ) that represents the distance for a plane wave to be attenuated to 37% of its initial amplitude. The skin depth is found to become smaller as the frequency is increased. One result of this is that currents induced in the body at these very high frequencies will often exist only near the body surface. Several skin depth calculations for typical human tissue are illustrated in Table 1.

Table 1
Typical Skin Depths in Human Tissue

Frequency	Skin depth (δ) in meters human tissue - $\rho = 4\ \Omega$-m
60 Hz	130
10 MHz	0.32
1000 MHz	0.14

Safety Standards for Exposure to Radio Frequency Electromagnetic Fields

What is the rationale for the FCC limits on field exposure?

As mentioned above, the fundamental assumption behind the FCC limits is that biological effects of electromagnetic fields (above 300 kHz) are related to the observation of behavioral disruption in trained laboratory animals subjected to electromagnetic fields. It is further assumed that the behavior change is the result of RF energy absorption in the body that, in turn, causes tissue heating. Specific Absorption Rate (SAR) is the rate of electromagnetic energy absorption per unit mass within the body and is used to identify the maximum allowable electromagnetic field levels. The maximum values of SAR allowed by the FCC standard are 0.4 Watts/kg, or 0.08 Watts/kg, depending on whether the exposure is for cognizant workers (workers with certified RF safety training) or the general public. These levels include safety factors of 10 and 50 for cognizant worker and general public exposures respectively. In both cases, the SAR values represent the average over the entire body. Local or peak SAR levels of 8 Watts/kg are allowed at body extremities.

How are high frequency exposure limits written?

The exposure limits set by the FCC are described as "maximum permissible exposures" (MPE's) in terms of incident plane wave equivalent power density per unit area that produce the levels of SAR mentioned above in a range of human body models. Although not always correct, it is assumed that the incident electromagnetic field is a single uniform plane wave. When this is true, the exposure is related to the electric field as $E^2/(120\pi)$ and to the magnetic field as $120\pi H^2$. Since $E/H = 120\pi$ for a uniform plane wave, these two quantities are equal. When the incident wave is not a single uniform plane wave, the exposure is again related to either $E^2/(120\pi)$ for electric field measurements /calculations or to $120\pi\ H^2$ for magnetic field calculations/measurements even though these two quantities are not equivalent. These limits are called "plane wave equivalent" exposures[21]. Note that the orientation of the field with respect to the human body is not specified by the standard.

As an example, the limits on electric field strength (E), magnetic field strength (H), and power density for occupational/ controlled exposure in the 30 - 300 MHz frequency range are 61.4 V/m, 0.163 A/m[22], and 1.0 mW/cm^2 respectively. Multiplication of the first two (and converting the units to mW/cm^2) yields

[20] For body tissue it is appropriate to define an "effective" relative dielectric constant (ε_b) that is a complex number equal to $\varepsilon_r - j/(2\pi f \rho \varepsilon_o)$. Here f is the frequency in Hertz, ρ is the body tissue resistivity in ohm-meters, and $\varepsilon_o = 10^{-9}/(36\pi)$ Farads/meter is the permittivity of free space. At low frequencies, it is typical that the second term dominates the first so that ε_b is inversely proportional to frequency.

[21] Note that the exposure is actually a spatially averaged exposure over the entire body and over a specified amount of time (i.e. 6 minutes for occupational exposure and 30 minutes for general population exposure).

[22] It is interesting to note that H = 0.163 A/m is equivalent to B = 0.2 µT or 2 mG.

the third so the three are equivalent. The same is true for the 3.0 - 30 MHz range with the caveat that the power density limit is in terms of the "plane wave equivalent power density." This means that the power density is a "computed" quantity. It is computed either as $E^2/(120\pi)$ or $120\pi\ H^2$ depending upon whether the probe measures electric or magnetic fields. It is interesting to note that the same field may produce two results if the measurement is not made in the single plane wave or antenna far field regions. Above 300 MHz, there are no separate limits on E and H. Rather, only power density is specified. Of course, this could be converted into equivalent values of E and H.

What are the MPE limits adopted by the FCC?

The limits adopted by the FCC are summarized graphically in Fig. 17. This graph shows the limits for occupational and general population exposure in terms of equivalent plane wave power density only. A full description of the limits in terms of electric and magnetic fields along with averaging times and associated application notes can be found in "Radio frequency safety for the electric power industry," EPRI technical report 1005419. Of specific interest here is the fact that the limits are reduced in roughly the 10 to 1000 MHz range. This is due to the resonance phenomena discussed earlier.

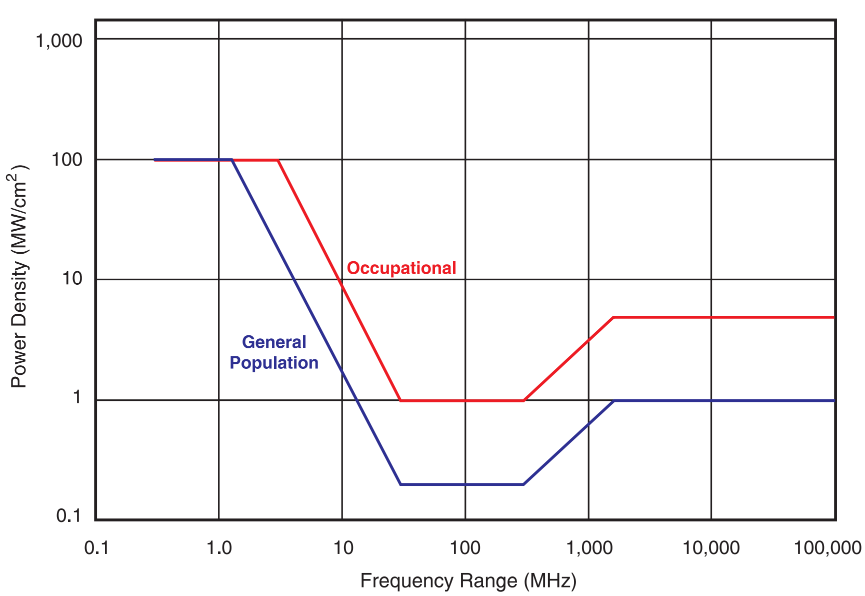


Figure 17. FCC incident power density exposure limits for occupational and general population as a function of frequency.

Issues in the Measurement of Radio Frequency Electromagnetic Fields

How do field probes respond to fields with unknown orientations?

Electromagnetic fields are measured using a special receptor (i.e., a probe) that is calibrated to have a given response (generally a voltage) to a known electric or magnetic field. Typical receptors used to evaluate the exposure to electromagnetic fields respond to either electric or magnetic fields, but not both. Since the orientation of the electromagnetic field is usually unknown, it is also generally true that probes consist of three separate sensors; one that responds to each orthogonal component of the field. The outputs of the three sensors are detected to give "amplitudes" for each component that are usually given as root mean square (RMS) values. These three amplitudes are combined by squaring each, adding the squares, and taking the square root of the sum to form what is known as a "resultant" field. Because of the way the components are measured, this result is independent of the orientation of the probe, and the probe is said to be isotropic. It is useful to note that this type of probe can overestimate the maximum amplitude of elliptically polarized fields by as much as 41%.

What is the consequence of the fact that probes respond to E or H but not both?

At 50/60 Hz, it is common to measure magnetic fields using three orthogonal coils. At higher frequencies, probes may respond to either the electric or magnetic field but generally not both. A probe that uses orthogonal coil elements to measure the magnetic field is shown in Fig. 18. High frequency field exposure meters used for RF safety assessment often do not report the result as electric or magnetic field. Rather, it is assumed that the incident wave is a uniform plane TEM wave and the equivalent plane wave power density is calculated as $E^2/(120\pi)$ or $120\pi\ H^2$ depending upon whether the probe is a measurement of electric or magnetic field. One important consequence of this is that two meters that use different types of probes may not agree if the field is not a single uniform plane wave for which $E/H = 120\pi$ ohms.

How is filtering used to alter the characteristics of a probe?

The probes have other characteristics that will only be summarized briefly here. First, the output of all probes is filtered so that they respond only to frequency components within a certain range. Some of the filters are tailored to account for the frequency dependence of the FCC standards, while others have a uniform response over a given bandwidth. Another issue is the dynamic range of these probes. Generally, they are designed to perform well in fields that are somewhat below and above the MPE limits.

What care must be taken when measuring fields?

Since the standards for exposure are for fields in the absence of the receptor, it is important that they be used in such a way that the "incident" fields are not perturbed by the person making the measurement. This is generally not a problem for 60 Hz magnetic fields (except near large ground planes) but can be quite serious for either 60 Hz electric, or high frequency electric, or magnetic field measurements. In these cases, the probes should be held away from the body.

It is also possible that broadband RF field probes may not operate properly in high 60 Hz electric fields due to cable pickup of 60 Hz electric fields, leading, typically, to an over-response indication of the actual field. Prior to using the probes in this environment, the characteristics of the probe should be investigated.

Summary

Communication facilities must comply with the Federal Communications Commission (FCC) regulations on human exposure to radio frequency electromagnetic fields. Questions or complaints about electromagnetic field exposure may result in investigations by either the FCC or the Occupational Safety and Health Agency (OSHA).

The number of radio frequency communication transmitters on transmission and distribution facilities and other electric power utility structures has increased dramatically. As a result, employees and contractors may be exposed to radio frequency electromagnetic fields that exceed the limits given in applicable guidelines or standards.

The extremely low frequency (ELF) electric and magnetic field environment near electric power transmission and distribution facilities is generally well understood by power company employees, but the radio frequency (RF) electromagnetic field environment may not be. These environments are significantly different.

The interaction between electromagnetic fields and the human body is significantly different for ELF and RF frequencies. Because of this, standards for exposure to RF fields are also different qualitatively and quantitatively from standards for exposure to ELF fields. For example, the basis for the RF limits is absorbed power density, and hence temperature rise in tissue, while the basis for ELF limits is the electric field or current density induced in tissue. The limits for RF are written in terms of equivalent plane wave incident power density while those at ELF are written in terms of the electric or magnetic field in the absence of the body. The RF limits also account for the resonance phenomenon observed at RF frequencies.

The most significant exposure to RF electromagnetic fields occurs close to antennas in what is called the near field. Here, the use of concepts such as radiation pattern, gain, and effective radiated power are not useful. Care must be taken to ensure that near field calculations and measurements are correctly carried out.

Care must be taken to properly interpret the reading of instruments used to survey the RF electromagnetic field environment. Care must also be taken to ensure that the large 50/60 Hertz electric and magnetic fields do not interfere with the operation of these instruments.

Additional Reading

"Radio frequency safety for the electric power industry", EPRI technical report 1005419, prepared by Richard Tell Associates, March 2002.

"An overview of common sources of environmental levels of radio frequency fields", EPRI technical report 1005496, prepared by Richard Tell Associates, September 2002.

"Health and safety issues of radio frequency fields from wireless communications devices", EPRI technical report 106938, prepared by C.N. Rafferty, September 1996.

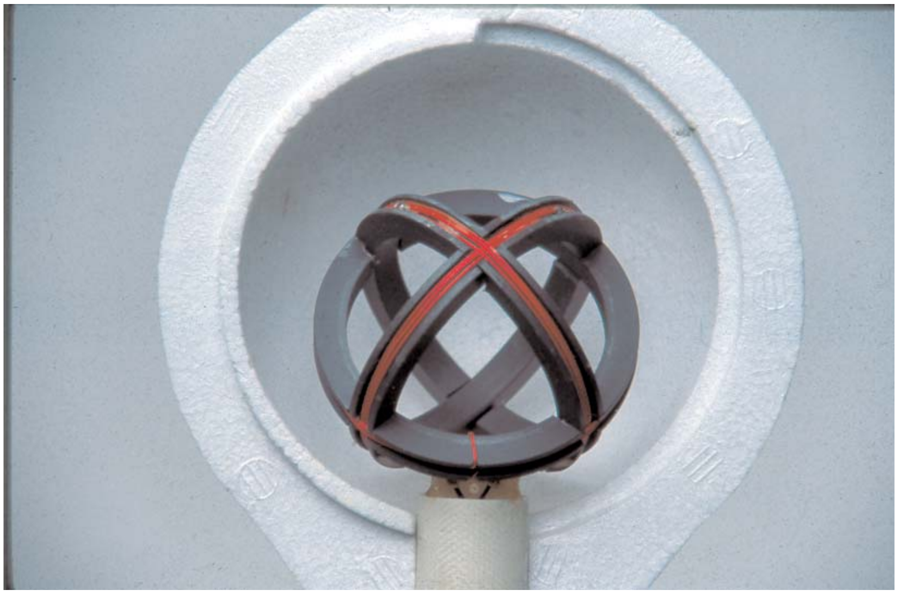


Figure 18. Photograph of the sensors inside an RF magnetic field probe consisting of orthogonally arranged loop sensors. (courtesy ETS - Lindgren)

"Evaluating compliance with FCC guidelines for human exposure to radiofrequency electromagnetic fields", OET Bulletin 65, Edition 97-01, Federal Communications Commission, Office of Engineering & Technology, Washington, DC, August 1997.

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Glossary

antenna – A device designed to efficiently convert guided electrical energy into radiating electromagnetic waves in free space (or vice versa).

antenna far field – A term used to denote the region further than $2D^2/\lambda$ from a large antenna where D is the maximum dimension of the antenna and λ is the wavelength corresponding to the frequency of operation. In this region, transmitted power densities decrease inversely with the square of the distance and the electromagnetic field has the characteristics of a plane-wave: it propagates at the speed of light in a direction perpendicular to its electric (E) and magnetic (H) fields and $E/H = 120\pi$ ohms. Only in this region are the concepts of radiation pattern, gain, and effective radiated power valid.

beamwidth – The range of angles for which the transmitted signal power density or reception sensitivity is within 1/2 of that in the main beam direction.

effective radiated power (ERP) – the product of the power radiated by an antenna and the antenna gain (in the direction of maximum radiation) relative to an isotropic antenna-expressed in watts.

electric field strength – a field vector quantity (E) representing the force that electrical charges have on other electrical charges, often related to voltage differences, measured in volts per meter (V/m).

electromagnetic field – a composition of both an electric field and a magnetic field that are related in a fixed way that can convey electromagnetic energy. Antennas produce electromagnetic fields in their vicinity when they are used to transmit signals.

extremely low frequency (ELF) – frequencies between 3 Hz to 3000 Hz.

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

free space – an ideal, homogenous medium having a relative permittivity and permeability of unity and in which there is no reflection, scattering, or absorption of electromagnetic energy. The intrinsic wave impedance for a uniform TEM plane wave propagating in free space (i.e. the ratio of the electric field to the magnetic field) is equal to 120π (377) ohms.

gain – the gain of an antenna is usually expressed as a ratio of the power required at the input of a loss-free reference antenna to the power supplied to the input of a given antenna to produce, in a given direction, the same field strength or power density at the same distance. Gain is often referenced to an isotropic antenna.

gigahertz (GHz) – one billion hertz; one gigahertz.

hertz (Hz) – the unit for expressing frequency, one Hertz (Hz) equals one cycle per second.

kilohertz (kHz) – one thousand hertz; one kilohertz.

intrinsic wave impedance – The ratio of the electric and magnetic fields of a plane TEM wave propagating in a material. It is a property of the material and is measured in ohms.

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

magnetic flux density – a field vector (B) that results in a force that acts on a moving charge or charges. The vector product of the velocity at which an infinitesimal unit test charge is moving and B is the force which acts on the test charge divided by the charge. Magnetic flux density is expressed in units of Tesla (T). One T is equal to 10^4 Gauss (G).

main beam – A term used in describing the directional characteristics of an antenna. The main beam direction is defined as an angle (referenced to the center of the antenna) that defines the direction of the strongest transmitted signal or the most sensitive reception.

megahertz (MHz) – one million hertz; FM radio broadcast stations operate in the range of 88-108 MHz.

omnidirectional antenna – an antenna that emits a signal of essentially constant strength in all directions, in contrast to a directional antenna.

plane transverse electromagnetic (TEM) wave – electromagnetic propagation mode where the electric and magnetic field vectors are both perpendicular to the direction of propagation and the surfaces of constant phase are plane parallel (flat). $E/H = 120\pi$ ohms. There is no field component in the direction of propagation.

polarization – the orientation of the electric field component of an electromagnetic field. Vertical polarization refers to the condition in which the electric field component is vertical, or perpendicular, with respect to the ground; horizontal polarization refers to the condition in which the electric field component is parallel to the ground.

power density – the quantity used for expressing the intensity of an electromagnetic field, expressed in units of power per unit area such as microwatts per square centimeter, milliwatts per square centimeter, or watts per square centimeter.

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

radiating near field – a region near a large antenna where the total field consists of a set of plane waves arriving from different points on the antenna. Since the arrival directions are not parallel, $E/H \neq 120\ \pi$ ohms.

radiation – a term to describe emissions outwards from a source. For electromagnetic waves, it refers to those waves with independence from the originating source that continue to transfer energy, although the source is no longer energized.

radiation pattern – a description of the spatial distribution of RF energy emitted from an antenna. Two radiation patterns are required to completely describe the transmitting performance of an antenna, one for the azimuth plane and another for the elevation plane.

radio frequency (RF) – although the RF spectrum is formally defined in terms of frequency as extending from 0 to 3000 GHz, the frequency range of interest is 3 kHz to 300 GHz.

reactive near field – a region very near antennas in which the relationship between the electric and magnetic fields is complex and not simple as in the far field, and in which the power density does not necessarily decrease inversely with the square of the distance. The near field predominately contains reactive energy that enters space but returns to the antenna.

resistivity – The resistivity (ρ) of a material reflects the relative difficulty with which electric current moves through it. Resistivity is the reciprocal of Conductivity (σ) and both are characteristics of a material rather than a particular specimen; it is defined for isotropic materials in units of ohms per meter (Ω/m); like resistance, resistivity is a function of temperature.

resonance – human body- an enhancement in the electromagnetic field inside the human body caused by the fact that scattered waves inside the body propagating in similar directions add in phase. The human body is electrically resonant in the frequency range of about 40-90 MHz, where the body acts like an antenna and there is maximum absorption of induced radio frequency energy. Because of this, exposure guidelines are more stringent in this frequency range. Partial body resonant frequencies are 175 MHz (for the arm) and 375 MHz (for the head) but are not considered in the exposure guidelines.

sidelobe – a portion of an antenna radiation pattern (other than the antenna main beam) between two adjacent points of minimum radiation.

single uniform plane wave region – used to denote the region farther than 2D from a large antenna where D is the maximum dimension of the antenna. In this region, transmitted power densities decrease inversely with the square of the distance and the electromagnetic field generally has the characteristics of a plane-wave: it propagates at the speed of light in a direction perpendicular to its electric and magnetic fields and $E/H = 120\pi$ ohms. The concepts of radiation pattern, gain, and effective radiation pattern are not valid in this region.

skin depth – the depth in a material at which the current density (induced by an electromagnetic wave) is attenuated to about 36.8% (1/e) of its value at the surface of the material.

specific absorption rate (SAR) – the time derivative of the incremental energy absorbed by (dissipated in) an incremental mass contained in a volume of a given density. SAR is expressed in units of watts per kilogram (or milliwatts per gram, mW/g). Guidelines for human exposure to radio frequency fields are based on SAR thresholds where adverse biological effects may occur. When the human body is exposed to a radio frequency field, the SAR experienced is proportional to the squared value of the electric field strength induced in the body.

speed of light – the velocity of propagation of electromagnetic waves in free space is 299,792.46 kilometers per second (about 186,283 miles/second).

transmission line – A special case of a waveguide that supports plane TEM waves. It requires that the waveguide be constructed of at least two separate conductors.

waveguide – a system capable of guiding electromagnetic waves from one place to another. A waveguide is often a hollow metallic tube or a solid dielectric material.

wavelength – the length of one complete cycle of an electromagnetic wave (the speed of light/frequency). The distance is measured in the direction of propagation between a reference point on one wave and the next point that has exactly the same relative phase.

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