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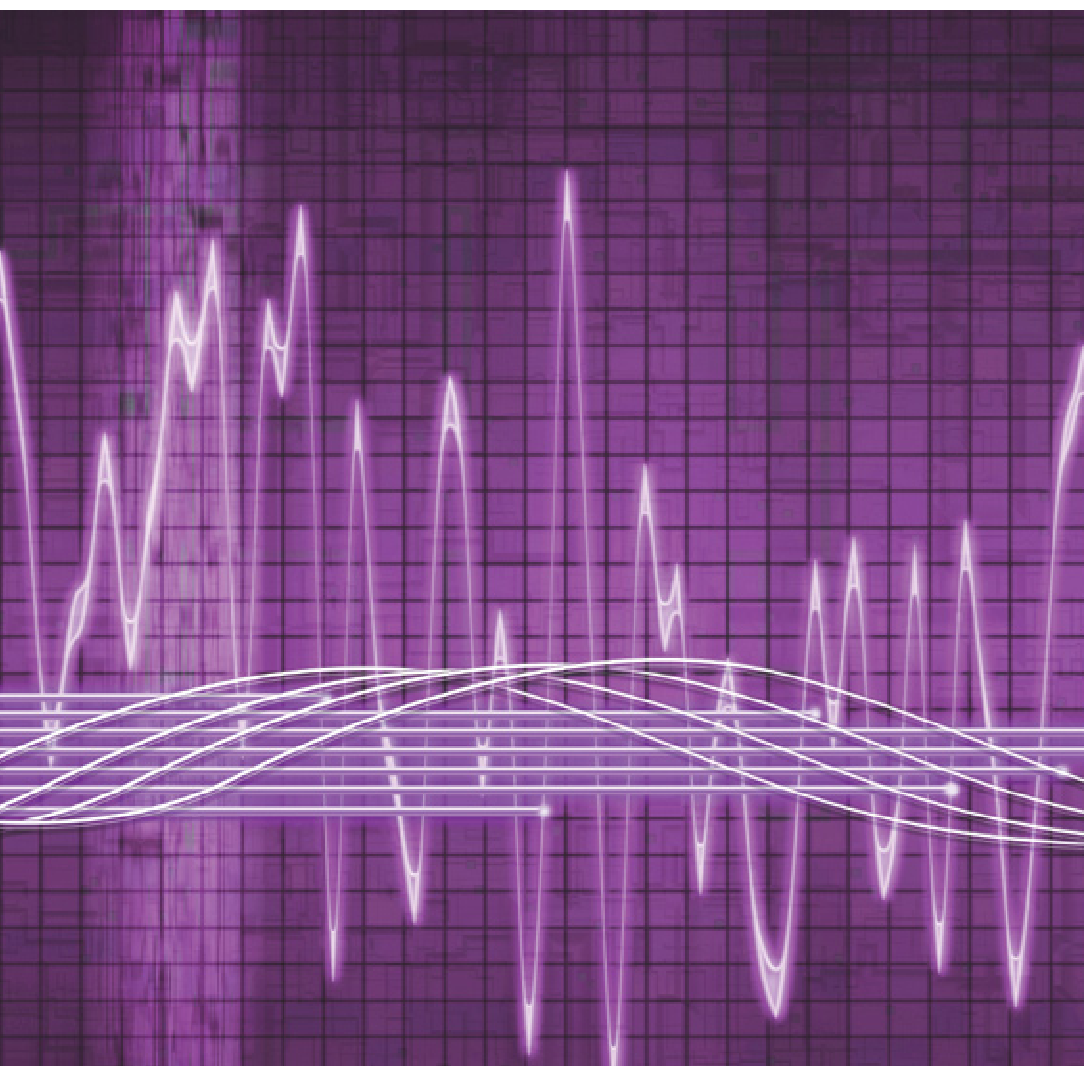
Technical Guide for Interpretation and Compliance Assessment of Health Canada's Radiofrequency Exposure Guidelines



Canada

Technical Guide for Interpretation and Compliance Assessment of Health Canada's Radiofrequency Exposure Guidelines

Consumer and Clinical Radiation Protection Bureau

Environmental and Radiation Health Sciences Directorate

Healthy Environments and Consumer Safety Branch

Health Canada

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1. Introduction

This document contains technical information for guiding individuals or groups in their understanding of Health Canada's radiofrequency (RF) exposure guidelines, commonly known as Safety Code 6[1], and provides recommended best practices for ensuring compliance with the maximum exposure levels for controlled and uncontrolled environments. Information regarding RF survey methods and examples of calculations for the basis of ascertaining compliance with the exposure limits are also provided.

2. Protection of Persons in Uncontrolled Environments

Uncontrolled environments are defined as areas where either insufficient assessment of RF exposure have been conducted or where persons who are allowed access to these areas have not received proper RF awareness training and have no means to assess or, if required, mitigate their exposure to RF energy.

2.1 Basic Considerations

(a) Members of the general public should not be allowed access to controlled environments, where RF exposure levels may exceed the basic restrictions for uncontrolled environments specified in Safety Code 6, Section 2.

(b) Where access to controlled environments is possible, demarcation signs should be posted to indicate the presence of RF emissions (See Section 4), where RF exposure levels may exceed the uncontrolled environment limits specified in Safety Code 6, Section 2. These signs should be clearly visible and identifiable at all viewing distances, where either significant exposures could occur or at the entrances to the controlled environment.

(c) Any device capable of producing leakage that would result in levels close to those specified for the uncontrolled environment in Safety Code 6, Section 2, and to which unrestricted public access is allowed, should be checked for conformity with existing applicable regulations after either installation, malfunction, modification or repair.

For the uncontrolled environment, it is recommended that the exposure limits specified in Safety Code 6, Section 2 should not be exceeded, even for short durations, since it is assumed that individuals in the uncontrolled environment lack sufficient knowledge of the RF field intensities they may be exposed to, the adverse health effects to be avoided, and the means by which they may be able to protect themselves from over exposure.

3. Protection of Persons in Controlled Environments

Controlled environments are defined as those where all of the following conditions are satisfied:

(a) the RF field intensities in the controlled area have been adequately characterized by means of measurements, calculations or modeling (such as with the use of FDTD [finite difference time domain] software),

(b) the exposure is incurred by persons who are aware of the potential for RF exposure and are cognizant of the intensity of the RF fields in their environment and,

(c) the exposure is incurred by persons who are aware of the potential health risks associated with RF exposures and whom can control their risk using mitigation strategies.

All situations that do not meet the specifications above are considered to be uncontrolled environments.

3.1 Basic Considerations

(a) RF exposure levels should be well characterized by RF surveys in controlled environments where restrictions on occupancy are in place.

(b) RF exposure levels, including induced and contact currents, should not exceed the limits for controlled environments specified in Section 2 of Safety Code 6, except under special circumstances (See Section 3.2).

(c) Demarcation signs (Figure 1, or suitable substitutes) indicating the presence of RF fields, should be posted according to the recommendations outlined in Section 4.

(d) The areas surrounding unmanned, high-power sources of RF energy should be fenced off to prevent unauthorized access to the controlled environment, where overexposures could occur. If a metallic fence is used, the contact current limits specified in Safety Code 6, Section 2 should be respected.

(e) The siting of RF devices should take into account the possibility that multiple source exposures from RF fields and leakage from other devices in the vicinity, may result in RF exposure levels that exceed the exposure limits outlined in Safety Code 6, Section 2.

(f) Unnecessary metallic objects should not be located near any radiating RF device, as they may cause high intensity RF fields in some locations.

(g) Maintenance personnel and operators of RF devices should be aware of the potential hazards of RF fields.

(h) Particular care should be taken to ensure that all people are clear of any direct beam of an RF device before it is switched on for test or maintenance purposes.

(i) Instructions and procedures for repair, maintenance and operation of a device, as specified by the manufacturer or a competent person, should be readily available to, and be followed by, operators and maintenance personnel.

(j) Testing of a device either before or after completion of any repair work should be carried out after protective shields, waveguides and other components have been placed in their designated locations.

(k) The correct operation of electronic test equipment and power meters should be checked in advance, i.e., prior to using them at the repair station or test site.

(l) Adjustment of voltages, replacement of RF energy generating components, dismantling components or refitting transmission lines should be undertaken by persons specially trained for such assignments. The services of a qualified repair person should be sought when any malfunction is suspected.

(m) The correct operation of all safety interlocks should be tested and operators should not defeat any safety interlock.

(n) An RF generating component should be tested with an appropriate load connected to its output or with the radiated energy absorbed by anechoic material. The energy generated shall not be allowed to radiate freely into occupied areas.

3.2 Special Circumstances

In some instances, for operational purposes, it may be necessary for workers to enter areas where the RF exposure limits specified in Safety Code 6, Section 2, are exceeded for short durations. In such circumstances, in order to maintain protective measures, the amount of time spent in these conditions must be taken into account. For exposure durations less than 0.1 h (6 min), higher exposure levels for controlled environments than those specified in Section 2 of Safety Code 6 may be permitted under the following conditions:

(a) A single brief exposure above the limits specified in Safety Code 6, Section 2.2 (Table 6) is permitted provided the duration meets the time averaging conditions of Safety Code 6, Section 2.3. One minute is assumed to be the shortest duration which is of practical importance.

(b) Intermittent elevated exposures to electric and magnetic fields or power density are allowed on a continuous basis provided the time averaging conditions of Safety Code 6, Section 2.3 are met.

4. Demarcation Signs

Demarcation signs should be used to label RF emitting devices and controlled environments where RF exposure levels, including induced and contact currents, may exceed the exposure limits specified in Safety Code 6, Section 2. Figure 1 depicts examples of such demarcation signs.

4.1 Areas

(a) A ***WARNING*** sign should be placed at the entrance of any zone within which RF levels exceed those for uncontrolled environments, but are below those for controlled environments, specified in Safety Code 6, Section 2. The ***WARNING*** sign should designate the zone as ***RESTRICTED OCCUPANCY*** and indicate serious injury is possible.

(b) A ***DANGER*** sign should be placed at the entrance of any zone within which RF levels exceed those for controlled environments specified in Safety Code 6, Section 2. The ***DANGER*** sign should designate the zone as ***DENIED OCCUPANCY*** and indicate critical injury is possible.

CAUTION
RADIOFREQUENCY RADIATION
- Area of Unrestricted Occupancy
- Minor Injury Possible from Misuse

WARNING
RADIOFREQUENCY RADIATION
- Area of Restricted Occupancy
- Serious Injury Possible from Misuse

DANGER
RADIOFREQUENCY RADIATION
- Area of Denied Occupancy
- Critical Injury Possible from Misuse

Figure 1. Examples of demarcation signs for areas and RF emitting devices.

4.2 Devices

(a) A ***CAUTION*** sign may be used to identify RF energy emitting devices. Microwave ovens, for which regulations have been promulgated under the Radiation Emitting Devices Act[2], have the ***CAUTION*** sign as part of their labelling requirements.

(b) A ***WARNING*** sign should be applied to any device, under development or in use for any industrial, scientific or medical purposes, if the device produces exposure levels that exceed those specified for uncontrolled environments, but are below those specified for controlled environments, in Safety Code 6, Section 2. A ***WARNING*** sign should also be applied to a device if misuse or failure could cause RF exposure injury.

(c) A ***DANGER*** sign should be applied to any device, under development or in use for any industrial, scientific or medical purposes, if it produces exposure levels in excess of those for controlled environments specified in Safety Code 6, Section 2. A ***DANGER*** sign should also be applied if failure or misuse of the device could cause serious RF exposure injury.

5. RF Surveys and Compliance Evaluation

5.1 Surveys

The objective of a survey is to determine whether a device or installation complies with recommended performance requirements and to assess the RF exposure levels within controlled and uncontrolled areas in the surrounding environment. The following recommendations are made:

(a) RF surveys should only be conducted by qualified individuals, with specific training on RF survey instrumentation and techniques.

(b) RF surveys should be conducted for all new RF emitting installations/devices and following any repairs, malfunctions, increases in radiated power or changes in working conditions (such as protective shielding and/or barriers) to existing ones, that could potentially produce RF exposure-induced body currents and/or contact currents in excess of the limits set out in Safety Code 6, Section 2.

(c) RF surveys should be conducted as frequently as possible around RF emitting devices/installations that are capable of producing RF fields, induced body currents and/or contact currents in excess of the limits set out in Safety Code 6, Section 2, to ensure that human exposure limits are not exceeded.

(d) Survey instruments should be selected to match the RF source and exposure conditions, taking into account such parameters as frequency, level of field strength or power density and near or far field. Survey instruments should be fully calibrated periodically and their performance should be checked against another calibrated instrument before carrying out a survey.

(e) During the inspection of any RF device or installation, all safety interlocks and "ON-OFF" control switches should be examined and placed in working order. Warning signs, labels and tags should be affixed and be easily readable.

5.2 Measurements and Evaluation

The area surrounding any RF source is generally divided into two regions: the near-field zone and the far-field zone. In many RF safety surveys, the exposure levels need to be determined in the near-field region of the source. In some instances, the environment consists of RF fields from several sources and difficulties can be encountered in determining the total field strengths and power density of such fields. Special care should be devoted to the selection of appropriate survey instruments to ensure that they are designed for operation in the frequency ranges required.

5.2.1 Basic Characteristics of Survey Meters

When surveying fields in the near-field zone of an antenna or in close proximity to a device, both electric field and magnetic field strengths should be measured, when possible. However, instrumentation for the measurement of magnetic fields at certain frequencies may not be commercially available. In this case, the electric field strength should be measured. In the far-field zone, it is sufficient to measure any of the following parameters: electric field strength, magnetic field strength or power density. Many meters have indicators that are calibrated in power density units (e.g., mW/cm^2), but the quantity actually measured may be the square of the strength of the electric or magnetic field. It must be remembered that power density measurements in the near-field zone are not meaningful for the evaluation of exposure levels. The information about the measured field parameter is normally provided in the instruction manual.

If the frequency range covered by one survey instrument is narrower than the frequency range of the fields generated by the RF sources in the vicinity of the site surveyed, multiple instruments may be required to determine the fields in the whole range of frequencies.

Since, in the majority of RF surveys, the orientation(s) of the electromagnetic field vector is not known, a survey meter having an isotropic detecting element is preferred.

If the only meter available is one having a single-axis detecting element, measurements of the total field can be performed by employing three mutually perpendicular orientations of the detecting element and calculating the resultant field from the following equations:

$$E = \left[E_1^2 + E_2^2 + E_3^2 \right]^{0.5} \qquad (5.1)$$

or

$$H = \left[H_1^2 + H_2^2 + H_3^2 \right]^{0.5} \qquad (5.2)$$

or

$$W = W_1 + W_2 + W_3 \qquad (5.3)$$

where the subscripts *1*, *2* and *3* refer to measurements in the three mutually orthogonal orientations.

When performing survey measurements in the near-field of an RF source, a meter suitable for operation in the near-field should be used. Special care is required to avoid perturbing the field by the instrument (e.g. the meter casing, but not the field probe), or by other objects or people in the vicinity.

When amplitude or frequency modulated fields and especially pulsed fields are surveyed, the meter response to such fields should be evaluated to determine if it is capable of measuring these types of fields.

Exposure levels in the vicinity of RF sources having scanning (rotating) antennas may have to be determined with the antenna stationary, because of limitations of the available measuring instruments. The exposure conditions, when the antenna is in motion, are then evaluated using methods described in Section 7.3.

5.2.2 Spatial Averaging

When conducting RF field surveys, locations accessible to people where maximum field strengths exist should be identified. Exposure in the near-field or in close proximity to reflecting objects typically results in spatially non-uniform fields. Even in the far-field zone of an RF radiator, the field strengths may vary considerably over the cross-sectional (projected) area of a human body (approximately 0.6 m^2) because of ground reflections and scattering from nearby objects. As a result, spatial averaging is required in most cases. A method for performing spatially averaged measurements is as follows:

(a) determine the location of the maximum field;

(b) establish a grid of points within approximately 0.35 m (width) x 1.25 m (height) surface area around the location of the maximum field, at a reasonable distance (e.g. 0.5 m) above the floor or ground and perpendicular to it. These points should be uniformly spaced within the grid with the point of the maximum field included;

(c) measure the field strength in all points within the grid; and

(d) calculate the average field.

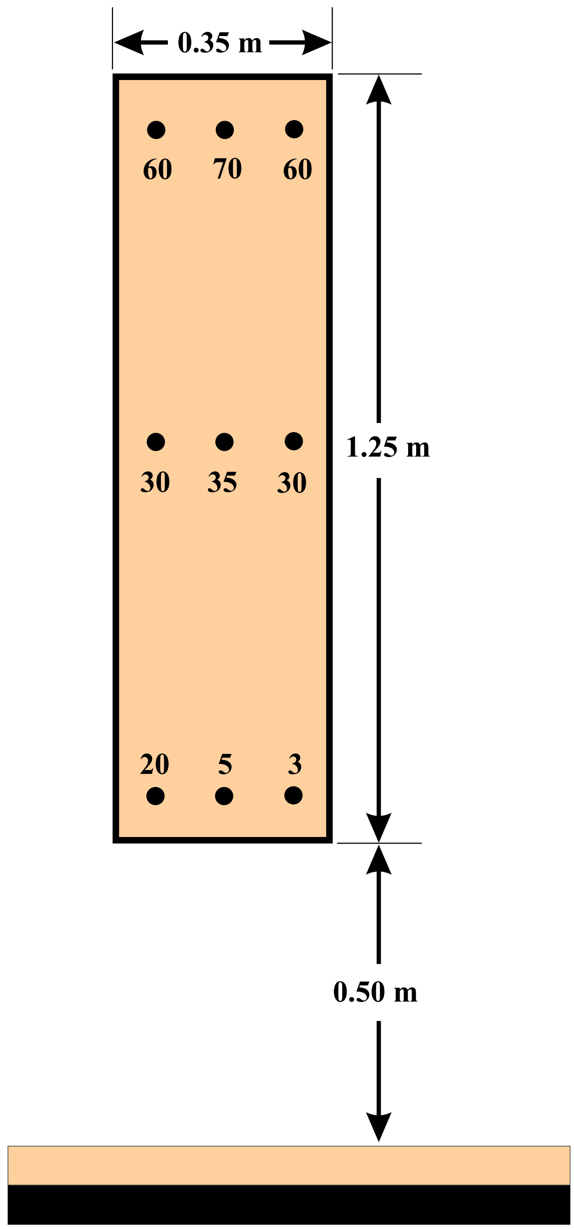
Note: A person performing survey measurements should approach the exposure source with caution to avoid potential overexposure. In questionable situations, measurements may be performed with the output power of the source reduced, or the surveyor may gradually approach the source from afar while monitoring the field as they approach.

The average field strength (for example, the electric field) along a grid of n points may be calculated from the equation:

$$E = \frac{1}{\sqrt{n}} \left[\sum_{i=1}^{n} E_i^{\,2} \right]^{0.5} \qquad (5.4)$$

where E_i is the rms field strength measured at the point i. An example of a measurement grid for the spatial averaging of a field is given in Figure 2.

Measurements at all Grid Points are in V/m



$$E = \frac{1}{\sqrt{9}}\left[20^2 + 5^2 + 3^2 + 30^2 + 35^2 + 30^2 + 60^2 + 70^2 + 60^2\right]^{0.5} = 41.6 \text{ V/m}$$

Figure 2. Example of a grid for measurements of a non-uniform electric field of 27 MHz and the calculation of the average field.

5.3 Specific Absorption Rate (SAR)

The SAR should be determined for cases where exposures take place at 0.2 m or less from the source. SAR assessments should be performed according to the requirements of Safety Code 6, Section 2.1.1 with respect to averaging volume as a function of the intended location on the body. It should be remembered that the internal field within a human body, and thus the SAR, is not related to the external field in a simple way.

Determination of SARs for near-field exposures of humans is difficult and can be done only on simulated models of the human body under laboratory conditions. Both computational methods and measurements are feasible.

There are two general approaches in computational methods(3). One involves the use of an analytical technique for calculating the distribution of absorbed energy in simplified tissue geometries such as plane slabs, cylinders and spheroids, while the other uses a numerical formulation for analysing the coupling of RF energy to the more complex shapes of human bodies. Examples of numerical methods for SAR calculations are the impedance method, the method of moments and the finite difference time domain (FDTD) technique. Detailed representations of the complex geometry and composition of the human body have been made available using data from magnetic resonance imaging scans(4).

Measurement methods have been developed for determination of SAR in human phantoms made of tissue-equivalent synthetic material(5,6). There are two basic methods for SAR measurements:

(1) The first method involves the use of a temperature probe to measure the temperature change induced by absorbed RF energy, and then calculating SAR from:

$$SAR = c\,\frac{\Delta T}{\Delta t} \tag{5.5}$$

where ΔT is the temperature rise (^{o}C) within the time interval Δt (seconds), and c is the tissue (or phantom material) specific heat capacity (J/kg^{o}C). This method is appropriate for local SAR measurements when the exposure levels are sufficiently intense that the temperature rise is not significantly influenced by heat transfer within or out of the body. To minimize the effect of heat transfer, only the initial, linear temperature rise after the application of RF power should be used in the calculation of SAR.

(2) The second method for SAR determination is to measure the electric field inside the body with implantable electric field probes and then calculate the SAR from:

$$SAR = \frac{\sigma E^2}{\rho} \tag{5.6}$$

where σ is the tissue conductivity (S/m), E is the rms electric field strength induced in the tissue (V/m) and ρ is the mass density (kg/m^3). This method is suitable only for measuring SAR at specific points in the body and for low values of SAR where the absorbed energy is insufficient to cause a detectable change in temperature. Instrumentation for this type of SAR measurement method usually includes an implantable electric field probe, a phantom and a computer controlled system for positioning the probe. The probes typically produce a DC voltage proportional to E^2 since they employ square-law detectors. In cases where the medium in which SAR is being determined is a homogeneous liquid, the probe can be calibrated directly in terms of SAR (σ and ρ are constant) and then used to scan spatially to produce SAR patterns.

5.4 Contact and Induced Currents

5.4.1 Contact Current

An RF field induces an alternating electric potential on ungrounded or poorly grounded conducting (metallic) objects such as cars, trucks, buses, cranes and fences. When a person touches such objects, RF current flows through the person to the ground (Figure 3). The amount of current depends on the object (its size, shape), the frequency and strength of the field and the person's impedance. The impedance in turn depends on the person's height, weight and body composition (ratio of the lean to fat body mass), type of contact (surface area of contact, i.e. finger or grasp, skin wet or dry), and the type of footwear. The impedance also varies with the frequency of the RF field.

Contact current flowing through the person is perceived at a certain level; at a higher level it becomes painful and at a still higher level may cause an injury (e.g. local burn, respiratory tetanus, heart effects). Below a frequency of about 100 kHz the perception is of a tingling, prickling feeling in the finger or hand touching the object. At higher frequencies heat is perceived. Thresholds for perception and pain under various conditions have been established[(7,8)].

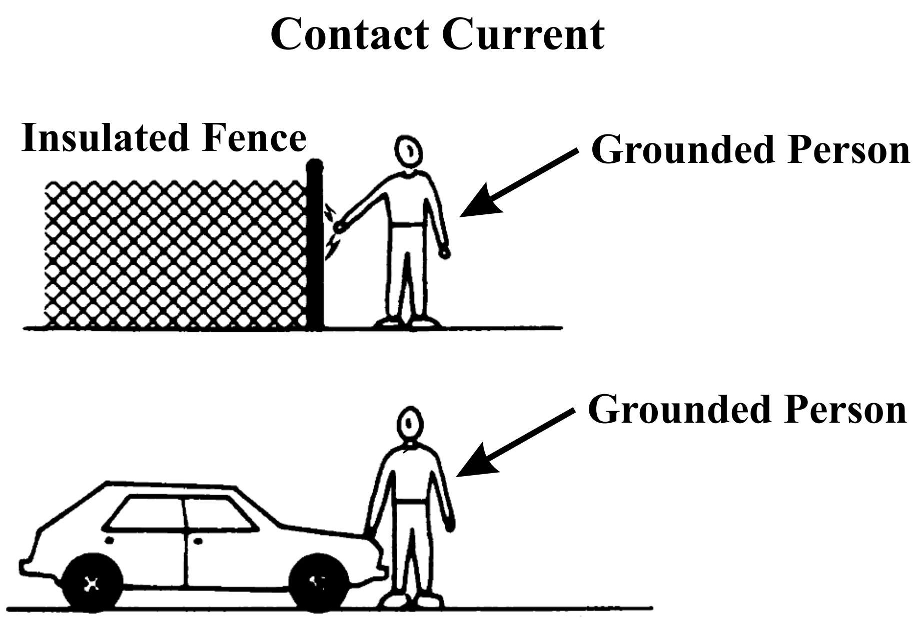


Figure 3. Typical situations where currents can be perceived by persons touching ungrounded or poorly grounded conducting objects.

Currents below the limits specified in Safety Code 6, Section 2.1.2 (Table 2) for controlled environments may be perceptible, but are not sufficient to cause any pain or damage such as burns. Currents below the limits specified in Safety Code 6, Section 2.1.2 (Table 3) for uncontrolled environments will not be perceived.

Contact currents are evaluated using an electronic circuit representing the impedance of the average human body in grasp contact with an insulated, conductive object, energized by an RF field. An evaluation for compliance with the limits for contact currents should be made with appropriate instruments, which are commercially available.

5.4.2 Induced Current

Even though a person may not be touching a metallic object, RF currents can be induced in the body by external RF fields and may flow through the body to the ground.

Induced current through both feet can be measured by using a clamp-on current probe or a stand-on (platform) type meter system. The latter consists of two isolated, parallel conductive plates located one above the other. The lower plate is placed in contact with the surface where the subject normally stands, and a person or a human equivalent antenna is placed on the upper plate of the platform. The voltage drop on a low-inductance resistor connected between the plates provides a measure of the induced current.

For compliance with the limits of induced currents, an evaluation should be made with either type of instrument. For stand-on type meters, the person or a human equivalent antenna should stand upright on the platform during measurement. Similarly, for clamp-on current probe type systems, the subject should be standing upright as well. Induced current meters and human equivalent antennas are commercially available.

Note: Under certain conditions, the induced current or contact current may exceed the limits specified in Safety Code 6, Section 2.1.2 (Tables 2 and 3), even though the electric field strengths are below the limits specified in Tables 5 and 6. These conditions may occur when the electric field strength is as low as 25% of the exposure limits.

5.5 Records and Recommendations

(a) Records should be kept for all RF survey measurements and their evaluation. The records should include the date the measurements were made, the number and type of devices in the area surveyed, the locations of measurements with respect to RF emitting devices, the names and organizations that conducted the survey(s), survey results, as well as the model, serial number and calibration date of the measuring instrument(s) used. Other information that may prove useful would be photographs, floor plans, etc.

(b) Recommendations on appropriate changes in shielding, location and operation of the device, based on the evaluation of the survey measurements, should be made to the person(s) responsible for the device. When a remedial action based upon these recommendations has been taken, another survey should be made to verify the effectiveness of the actions.

6. Examples for Assessing Compliance with Safety Code 6

This section provides examples of assessment of compliance with Safety Code 6 in the presence of RF fields at various frequencies. It is based on the following formula:

$$R_f = \left[\frac{\text{Measured Value of Field Strength at } f}{\text{Exposure Limit of Field Strength at } f}\right]^2 \qquad (6.1)$$

or

$$R_f = \frac{\text{Measured Value of Power Density at } f}{\text{Exposure Limit of Power Density at } f} \qquad (6.2)$$

as stated in Safety Code 6, Section 2.2.

Example 6.1: After time and spatially averaged measurements, the electric fields within a controlled environment where persons may be exposed are found to be 30 V/m, 40 V/m, 50 V/m and 60 V/m at 20 MHz, 90 MHz, 150 MHz and 1300 MHz, respectively. The relative values with respect to the exposure limits in the frequency bands of concern are given as follows:

$R_1 = (30/60)^2 = 0.25$	for 20 MHz (in the frequency band 10 - 30 MHz)
$R_2 = (40/60)^2 = 0.44$	for 90 MHz (in the frequency band 30 - 300 MHz)
$R_3 = (50/60)^2 = 0.69$	for 150 MHz (in the frequency band 30 - 300 MHz)
$R_4 = (60/127.6)^2 = 0.22$	for 1300 MHz (in the frequency band 300 - 1 500 MHz).

From which $R_1 + R_2 + R_3 + R_4 = 1.6$, which exceeds unity and therefore the combined electric field strength does not conform with the exposure limits in Safety Code 6, Section 2.2. Note that 127.6 V/m comes from substituting $f = 1300$ in the exposure limit term $3.54f^{0.5}$ which is found in Safety Code 6, Section 2.2 (Column 2 of Table 5).

Example 6.2: Assume that a person, qualified to work in a controlled environment, is exposed to RF fields at three different frequencies. Exposure measurements were performed, which were time and spatially averaged, producing the following conditions:

Magnetic field:	0.1 A/m at 27 MHz
Electric field:	35 V/m at 915 MHz
Power density:	25 W/m^2 at 10 000 MHz.

The relative values with respect to the exposure limits in the frequency bands of concern are given as follows:

$R_1 = (0.1/0.18)^2$	for 27 MHz (in the frequency band 10 - 30 MHz)
$R_2 = (35/107.1)^2$	for 915 MHz (in the frequency band 300 - 1 500 MHz)
$R_3 = 25/50$	for 10 000 MHz (in the frequency band 1 500 - 15 000 MHz).

From which $R_1 + R_2 + R_3 = 0.92$, which is less than unity and therefore the combined field strengths and power density conform with the exposure limits specified in Safety Code 6, Section 2.2.

Example 6.3: Assume that the time-averaged induced currents through both feet of a person in a controlled environment were found to be 5 mA, 80 mA and 120 mA at 0.005 MHz, 0.06 MHz and 1 MHz, respectively. The relative values with respect to the induced current limits in the frequency bands of concern are given as:

$R_1 = (5/10)^2 = 0.25$	for 0.005 MHz (in the frequency band 0.003 - 0.1 MHz)
$R_2 = (80/120)^2 = 0.44$	for 0.06 MHz (in the frequency band 0.003 - 0.1 MHz)
$R_3 = (120/200)^2 = 0.36$	for 1 MHz (in the frequency band 0.1 - 110 MHz).

From which $R_1 + R_2 + R_3 = 1.05$, which exceeds unity and therefore the total current through both feet does not conform with the exposure limits specified in Safety Code 6, Section 2.1 (Table 2). Note that 10 mA and 120 mA come from substituting $f = 0.005$ and 0.06, respectively, in the exposure limit term $2000f$ which is found in Safety Code 6, Section 2.1 (Column 2 of Table 2).

7. Theoretical Estimation of Exposure Fields

7.1 Near-field and Far-field Zones

Sources of RF fields may have widely different characteristics. RF sources can be divided as follows:

(a) small antennas; i.e. antennas whose dimensions are less than the wavelength (λ),

(b) large antennas; i.e. antennas whose dimensions are greater than the wavelength,

(c) sources producing leakage (stray) fields (e.g. RF dielectric heaters, RF induction heaters, radar components).

The space around a source antenna is often divided into two regions, the near-field zone and the far-field zone (Figure 4). The near-field zone can be further divided into two regions: the reactive near-field region and the radiating near-field region. The region of space immediately surrounding the antenna in which the induction (reactive) field exists is known as the reactive near-field region. Most RF energy in this region is not radiated but is stored. The near-fields vary rapidly with distance. At a short distance further away from the antenna, the reactive near-field is decreased significantly, and the radiating near-field predominates. In the radiating near-field region, the energy propagates away from the antenna, but the radiation still lacks a plane-wave character. Beyond the radiating near-field region is the far-field zone, in which the field strength varies inversely with distance from the antenna.

7.1.1 Small Antennas

An antenna whose largest dimension is no greater than the wavelength of its recommended operating frequency is referred to as a small antenna (e.g. resonant dipoles, Yagi and log-periodic antennas). The reactive near-field region of these antennas extends up to a distance given below:

$$R_s = \frac{\lambda}{2\pi} \tag{7.1}$$

where,
R_s = extent of the reactive near-field region, in metres (m)
λ = wavelength, in metres (m).

There is no general formula for theoretical estimation of the field strength in the near-field zone of small antennas. While reasonable calculations are possible for some small antennas (e.g. dipoles and monopoles), field measurements are required to evaluate field strength in the near-field zone in most situations.

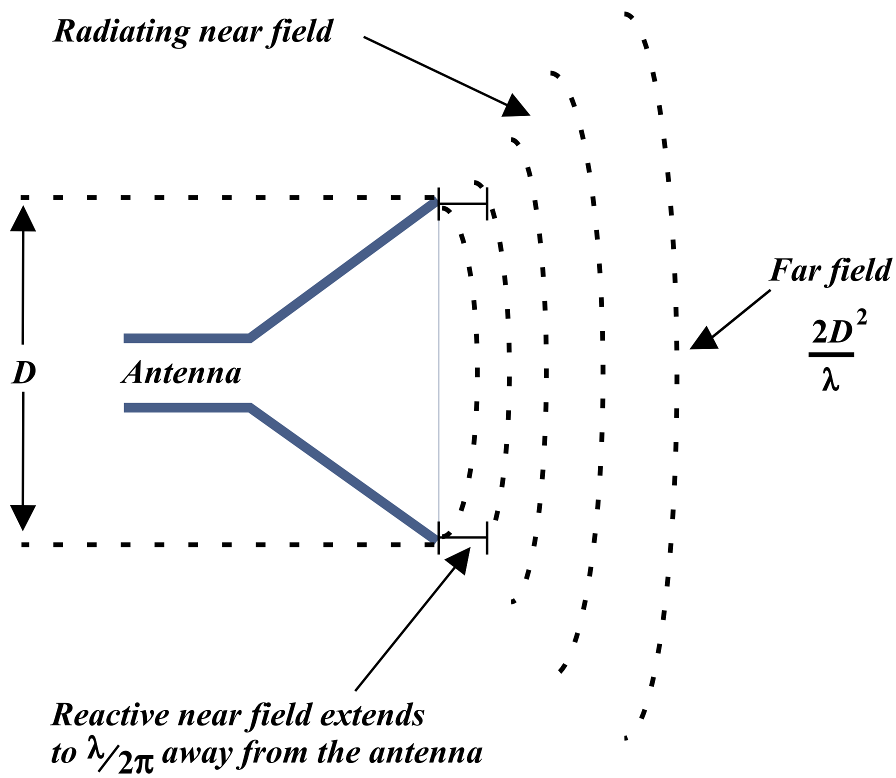


Figure 4. Antenna size versus separation of the reactive near-field region, the radiating near-field region and the far-field zone.

7.1.2 Large Antennas

An antenna whose largest dimension is greater than the wavelength of its recommended operating frequency is referred to as a large antenna. Examples of large antennas include parabolic reflectors, arrays and horn antennas. The near-field zone of these antennas consists of the reactive region extending to the distance given by Equation 7.1, followed by a radiating region. In the radiating near-field region, the field strength does not necessarily decrease with distance away from the antenna, but may exhibit an oscillatory character.

The distance from the antenna to the far-field zone is taken to be:

$$R_{FF} = \frac{2\,D^2}{\lambda} \tag{7.2}$$

where R_{FF} is the distance to the beginning of the far-field region, D is the greatest dimension of the antenna and λ is the wavelength.

At the onset of the far-field zone, the maximum phase difference of electromagnetic waves coming from different points on the antenna is 22.5 degrees[9]. For the purpose of estimating field strength compliance with Safety Code 6, a larger phase difference, and thus a shorter distance marking the beginning of the far-field zone is acceptable to estimate a worst-case scenario. A realistic practical distance from a large antenna (e.g. a parabolic reflector), where the far-field zone begins is[10]:

$$R_{FF} = \frac{0.5\,D^2}{\lambda} \tag{7.3}$$

where,

R_{FF} = distance from the beginning of the far-field region, in metres (m)
D = the greatest dimension of the antenna, in metres (m)
λ = wavelength, in metres (m).

It should be noted that towards the end of the radiating near-field region and in the far-field zone, the electric and the magnetic fields are interrelated with each other and with the power density as follows:

$$\frac{E}{H} = \eta \tag{7.4}$$

and,

$$W = \frac{E^2}{\eta} = H^2\eta \tag{7.5}$$

where,

E = electric field strength, in volts per metre (V/m)
H = magnetic field strength, in amperes per metre (A/m)
W = power density, in watts per square metre (W/m^2)
η = characteristic impedance (for free space η = 377 ohms).

In the far-field region, the power density on the main beam axis can be calculated from the expression:

$$W = \frac{EIRP}{4\pi r^2} = \frac{P_T\,G}{4\pi r^2} \tag{7.6}$$

where,

$EIRP$ = effective isotropically radiated power, in watts (W)
r = distance from the antenna, in metres (m)
P_T = net power delivered to the antenna, in watts (W)
G = antenna gain (power ratio) with respect to an isotropic antenna.

Equation 7.6 can be used to estimate power density at distances greater than R_{FF} (Equation 7.3). For distances slightly greater than R_{FF}, equation 7.6 overestimates power density no greater than 0.8 dB (or 20 %)[11].

The antenna gain is related to the antenna dimensions by the following equation[9]:

$$G = \frac{4\pi A_e}{\lambda^2} \tag{7.7}$$

where,

A_e = effective area of the antenna, $A_e = \varepsilon A$
A = physical aperture area of the antenna, in square metres (m^2)
ε = antenna efficiency (typically $0.5 \le \varepsilon \le 0.75$)
λ = wavelength, in metres (m).

An electromagnetic wave can also be characterized by the electric field strength and magnetic field strength. The rms electric field strength at a distance *r* from a source with the *EIRP* on the main beam axis, as derived from Equations 7.5 and 7.6, is equal to:

$$E = \frac{\left[30\ EIRP\right]^{0.5}}{r} \tag{7.8}$$

and is expressed in volts per meter (V/m).

Graphs relating power density and electric and magnetic field strengths in free space are shown in Figure 5.

Equations 7.6 and 7.8 are used to determine the power density and field strength in the far-field region in a worst case condition where maximum power gain (Equation 7.7) is applied. It should be noted that it is not always possible to predict the levels of maximum fields in and around sites of concern. This is due to the fact that RF fields may be absorbed, reflected and refracted by objects in a random and unpredictable manner. As such, the only way to determine actual levels of RF fields is by measurement.

7.1.3 Sources Producing Leakage Fields

For leakage RF sources such as poor contacts between waveguide flanges, there is no reliable method for estimating the extent of the near-field zone, its type (whether reactive or radiating region) or the field strengths.

Example 7.1: Calculation of minimum distance where exposures fall within the limits. A parabolic antenna (0.5 m diameter), operating at 1.2 GHz (1200 MHz) with an *EIRP* of 50 W is to be installed in an area accessible to the general public (uncontrolled environment). What is the minimum distance from the antenna where the exposure does not exceed the limits specified in Safety Code 6, Section 2 for uncontrolled environments?

Step 1. Calculate the maximum power density exposure limit for uncontrolled environments from Safety Code 6, Section 2.2 (Table 6):

$$W_{limit} = f/150 = 1200 / 150 = 8 \text{ W/m}^2$$

Step 2. Calculate the minimum distance by rearranging Equation 7.6 to solve for the distance from the antenna r :

$$\begin{aligned} r_{min} &= [EIRP/(4\pi W_{limit})]^{0.5} \\ &= [50.0/(4.0 \times 3.14159 \times 8.0)]^{0.5} \\ &= 0.705 \text{ m} \end{aligned}$$

Step 3. Check to make sure that the minimum distance calculated above is in the far field zone (where Equation 7.6 is valid):

First calculate the wavelength (λ):

$\lambda = 300 / f$ (f in MHz) $= 300 / 1200 = 0.25$ m

Since the antenna diameter (0.5 m) is larger than the wavelength (0.25 m), it should be considered as a large antenna. Thus, the beginning of the far field region should be calculated using Equation 7.3, where the parameter D is taken to be the diameter of the dish:

$$R_{FF} = 0.5\, D^2 / \lambda = 0.5 \times (0.5)^2 / 0.25 = 0.5 \text{ m}$$

Since the minimum distance (0.705 m, as calculated above) is in the far-field zone of the antenna (as calculated above), the basis for the calculation is valid. Therefore, members of the general public should not stand closer than 0.705 m directly in front of the antenna.

7.2 Average Power of Pulsed Waves

A pulse-modulated wave (pulsed wave) is shown in Figure 6. This type of radiation is characteristic of radar emissions.

The duty factor (F) can be calculated as:

$$F = \frac{T}{T_r} \tag{7.9}$$

where,
T = pulse duration, in seconds (s)
T_r = time lapse between the start of consecutive pulses, in seconds (s).

The pulse repetition frequency is equal to:

$$f_p = \frac{1}{T_r} \tag{7.10}$$

where,
f_p = pulse repetition frequency, in hertz (Hz)
T_r = time lapse between the start of consecutive pulses, in seconds (s).

The average power P_a for a pulsed wave can be calculated as:

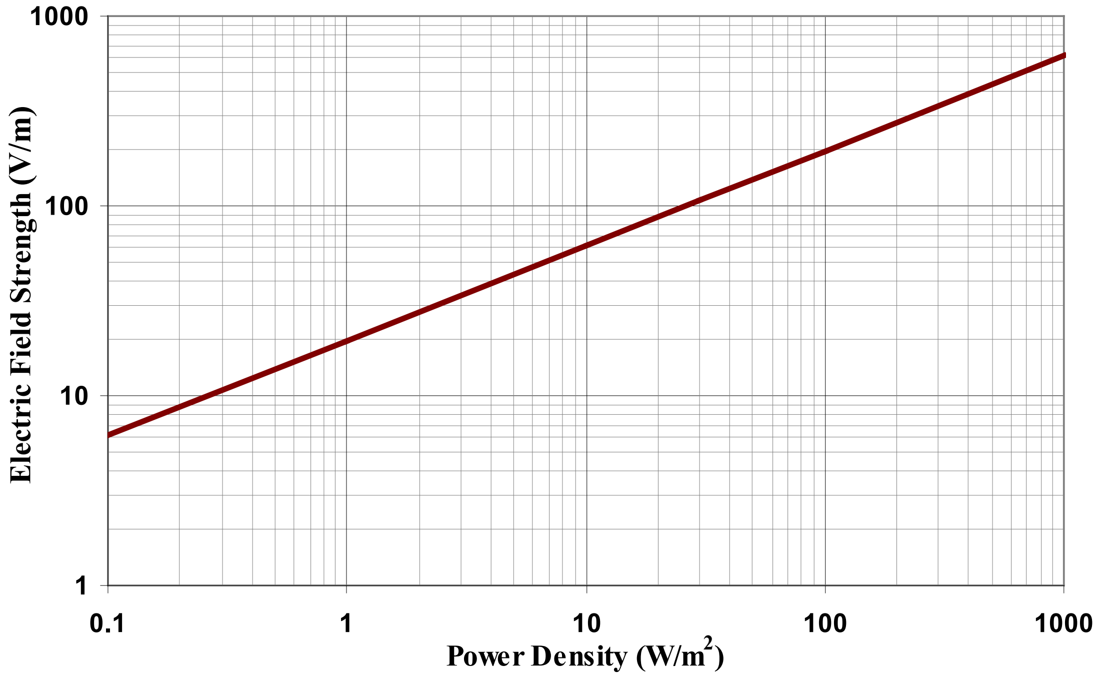
$$P_a = P_p F \tag{7.11}$$

where,
P_p = peak power, in watts (W)
F = duty factor.

Similarly for the average power density (W_a):

$$W_a = W_p F \tag{7.12}$$

where,
W_p = peak power density, in watts per square metre (W/m^2)
F = duty factor.



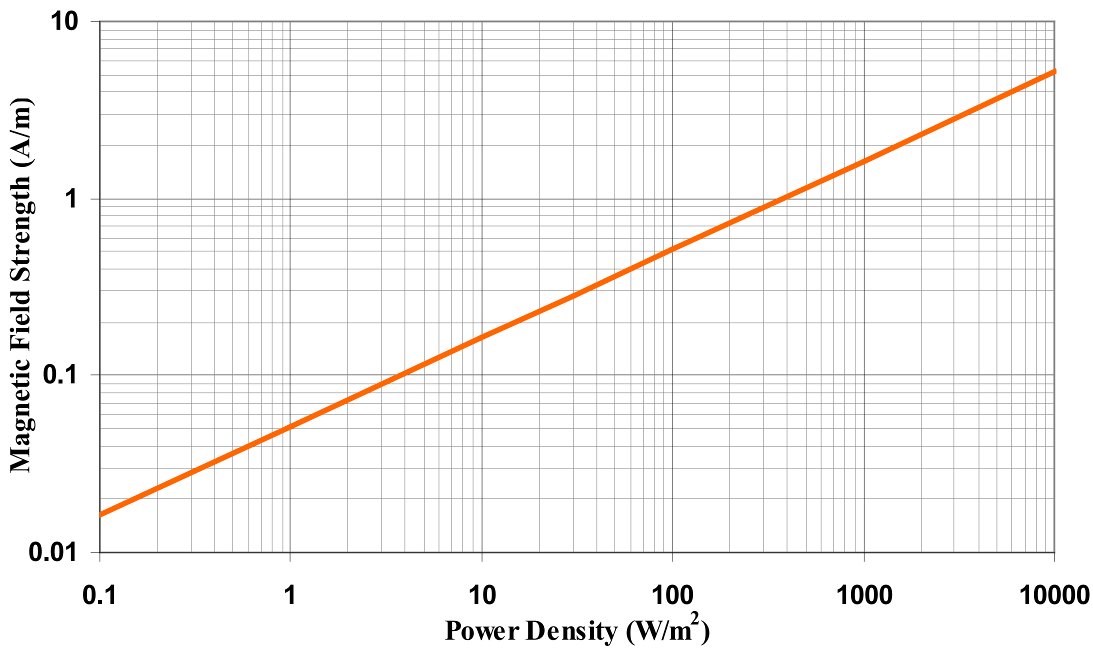


Figure 5. Conversion charts for plane wave (10 W/m^2 = 1 mW/cm^2).

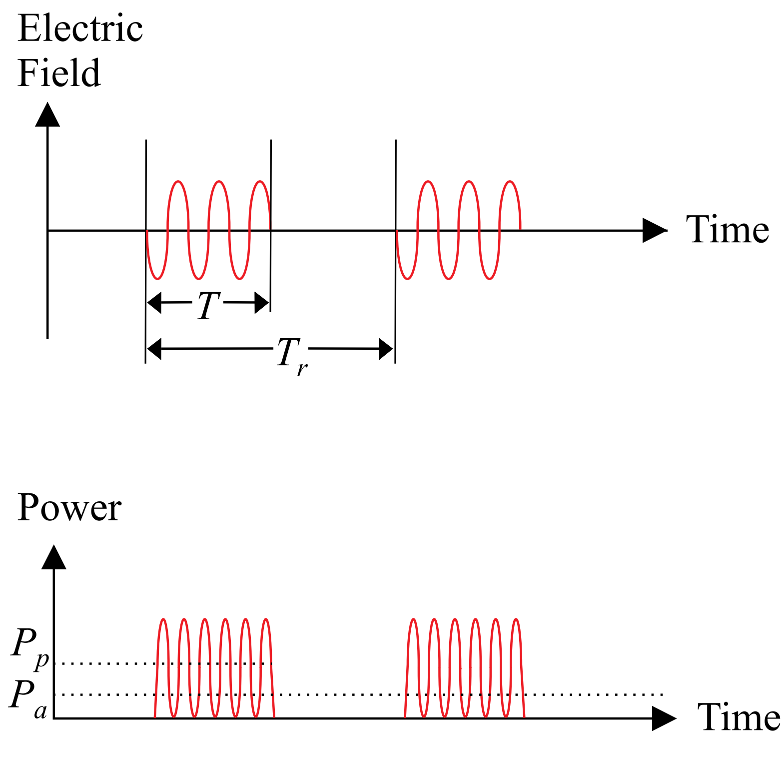


Figure 6. Pulse-modulated field.

7.3 Scanning Antennas

The effective power density as seen from a stationary point for a scanning antenna in motion can be estimated from the power density measured with the antenna stationary using the expression:

$$W_m = K\,W_s \tag{7.13}$$

where,
W_m = effective power density for the antenna in motion, in watts per square metre (W/m^2)
K = antenna rotational reduction factor
W_s = power density measured on the main beam axis of the stationary antenna at a given distance, in watts per square metre (W/m^2).

The rotational reduction factor for the near-field region is equal to:

$$K = \frac{a}{R_\text{ø}} \tag{7.14}$$

and,

$$R_\text{ø} = r\,\text{Ø} \tag{7.15}$$

where,

a = the dimension of the antenna in the scan (rotation) plane, in metres (m)

$R_ø$ = the circumference of the antenna scan sector at the given distance (r), in metres (m), at which the measurements have been done (Figure 7)

ø = scan angle, in radians.

The rotational reduction factor for the far-field region is:

$$K = \frac{3\ dB\ beamwidth}{Scan\ angle} \tag{7.16}$$

Example 7.2: Estimate the average power density at a distance of 450 m in front of the antenna of a radar system with the following characteristics:

Operating frequency (f): 10 GHz (gigahertz)
Transmitter peak power (P_p): 1 MW (megawatts)
Pulse duration (T): 3µs (microseconds)
Pulse repetition frequency (f_p): 400 Hz
Antenna dimension (D): 5 m in diameter (parabolic dish)
Antenna efficiency (ε): 70%

Steps of calculation:

Step 1. The wavelength, $\lambda = 300/f$ (f in MHz) = 0.03 m

Step 2. The distance where the far-field region begins,

$R_{FF} = 0.5\ D^2/\lambda = 417$ m.

The 450 m location is in the far-field region.

Step 3. The antenna physical aperture area, $A = \pi D^2/4 = 19.63\ m^2$

Step 4. The antenna gain, $G = 4\pi\varepsilon A/\lambda^2 = 191{,}860.56$

Step 5. The duty factor, $F = Tf_p = 1.2 \times 10^{-3}$

Step 6. The average power, $P_a = P_p F = 1.2$ kW.

This is the net power delivered to the antenna, P_T.

Step 7. At the distance of 450 m, the average power density,

$W_m = P_T G/(4\pi r^2) = 90.48\ W/m^2$

Exposure of a person at this distance should be avoided or limited to a short duration since the power density exceeds the limits (50 W/m^2 for controlled environments, 10 W/m^2 for uncontrolled environments).

Example 7.3: Determine the effective power density at 10 m and 30 m from a scanning antenna in motion, given the following parameters:

Power density at 10 m with the antenna stationary: 100 W/m^2
Power density at 30 m with the antenna stationary: 20 W/m^2
The distance where the far-field region begins: 20 m
Antenna rotation (ø): full (360° or 2π radians)
Antenna aperture dimensions (a, b): 2 m wide, 10.16 cm high
Antenna beam widths: 1.23° horizontal, 25° vertical

Steps of calculation:

Step 1. The 10 m location is in the near-field region. At this location,
the circumference of the antenna scan, $R_ø = 2\pi \ x$ 10 m
the rotational reduction factor, $K = a/R_ø = 2/(2\pi \ x \ 10) = 0.1/\pi$
the effective power density when the antenna is in scanning mode,
$W_m = KW_s = (0.1/\pi)(100) = 3.2$ W/m^2.

Step 2. The rotational reduction factor is different, since the 30 m location is in the far-field,
K = 3 dB beamwidth / scan angle = 1.23°/360°.
The effective power density when the antenna is in scanning mode is:
$W_m = KW_s = (1.23/360)(20) = 0.07$ W/m^2.

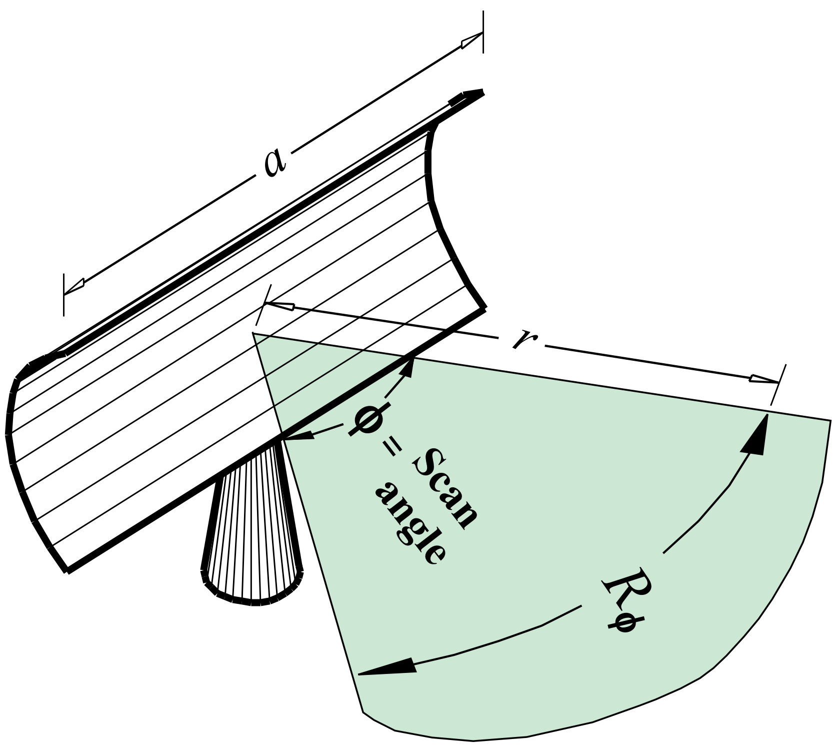


Figure 7. Rotational reduction factor in the near-field.

Definitions

anechoic – Neither having nor producing radiofrequency (RF) reflections.

antenna – A device for radiating or receiving RF energy.

basic restriction – Dosimetric limit directly related to established health effects that incorporate safety factors and are expressed in terms of internal body currents or specific absorption rate (100 kHz to 6 GHz).

contact current – Current flowing between an energized, isolated, conductive (metal) object and ground, through the human body.

continuous wave (CW) – Successive oscillations which are identical under steady-state conditions (an unmodulated electromagnetic wave).

controlled environment – A condition or area where exposure is incurred by persons who are aware of the potential for RF exposure and are cognizant of the intensity of the RF fields in their environment, where exposures are incurred by persons who are aware of the potential health risks associated with RF exposure and whom can control their risk using mitigation strategies.

electric field – The region surrounding an electric charge, in which the magnitude and direction of the force on a hypothetical test charge is defined at any point.

far-field zone – The space beyond an imaginary boundary around an antenna. The boundary marks the beginning where the angular field distribution is essentially independent of the distance from the antenna. In this zone, the field has a predominantly plane-wave character.

field strength – The magnitude of the electric or magnetic field, normally a root-mean-square value.

frequency – The number of sinusoidal cycles made by electromagnetic waves in one second; usually expressed in units of hertz (Hz).

general public – Individuals of all ages, body sizes and varying health status, some of whom may qualify for the conditions defined for the controlled environment in certain situations.

impedance – A measure of opposition to a sinusoidal alternating current (AC).

induced current – Current induced in a human body exposed to RF fields.

isotropic – Exhibiting properties with the same values when measured in all directions.

magnetic field – A region of space surrounding a moving charge (e.g. in a conductor) being defined at any point by the force that would be experienced by another hypothetical moving charge. A magnetic field exerts a force on charged particles only if they are in motion, and charged particles produce magnetic fields only when they are in motion.

microwave – A portion of the radiofrequency spectrum that has a frequency between 1 GHz and 300 GHz or a wavelength between 1 mm and 30 cm.

near-field zone – A volume of space generally close to an antenna or other radiating structure, in which the electric and magnetic fields do not have a substantially plane-wave character, but vary considerably from point to point.

power density – The rate of flow of electromagnetic energy per unit surface area usually expressed in W/m^2 or mW/cm^2 or $\mu W/cm^2$.

radiofrequency (RF) – A frequency or rate of oscillation within the range of about 3 kHz to 300 GHz.

radiation (electromagnetic) – The emission or transfer of energy through space in the form of electromagnetic waves.

radiating near field region – The region between the reactive near field and the far field wherein the radiation field dominates the reactive field, but lacks substantial plane-wave character.

reactive near field region – The region that is closest to an antenna or other radiating structure and contains most or nearly all of the stored energy.

RF device – A device which generates and/or utilizes RF energy.

rms – root mean square. Mathematically, it is the square root of the average of the square of the instantaneous field or current taken throughout one period.

safety – The absence of detrimental health effects from RF exposures.

safety interlock – Switch which ensures that the doors, gates, or guards are closed before a process which could be harmful to individuals can start up.

specific absorption rate (SAR) – The rate of RF energy absorbed in tissue per unit mass. Quantitatively, it is the time derivative (rate) of the incremental energy (dW) absorbed by an incremental mass (dm) contained in a volume element (dV) of given mass density (ρ).

$$SAR = \frac{d}{dt}\left[\frac{dW}{dm}\right] = \frac{d}{dt}\left[\frac{dW}{\rho dV}\right]$$

SAR is expressed in units of watts per kilogram (W/kg). Also,

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

where σ is the tissue conductivity (S/m), E is the rms electric field strength induced in the tissue (V/m) and ρ is the mass density (kg/m^3).

uncontrolled environment – A condition or area where exposures are incurred by persons that do not meet the criteria defined for the controlled environment.

wavelength – The distance travelled by a propagating wave in one cycle of oscillation.

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