California Institute of Technology

NON-IONIZING RADIATION MANUAL

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Preamble

This document provides information and guidelines for working with non-ionizing radiation hazards. It is split into the following categories:

- Radio frequency (RF) and microwave radiation
  - Electromagnetic fields
    - Electric fields
    - Magnetic fields
  - Shielding
- Optical radiation
  - Infrared (IR)
  - Visible (VIS)
  - Ultraviolet (UV)

Introduction

Energy emitted from a source is generally referred to as “radiation”, or more fully “electromagnetic radiation” (EMR). When we can see this radiation, it is commonly referred to as “light”. Examples of electromagnetic radiation include heat or light from the Sun, microwaves from a microwave oven, radio waves from a mobile phone, X-rays from an X-ray tube, and nuclear radiation from radioactive elements such as uranium.

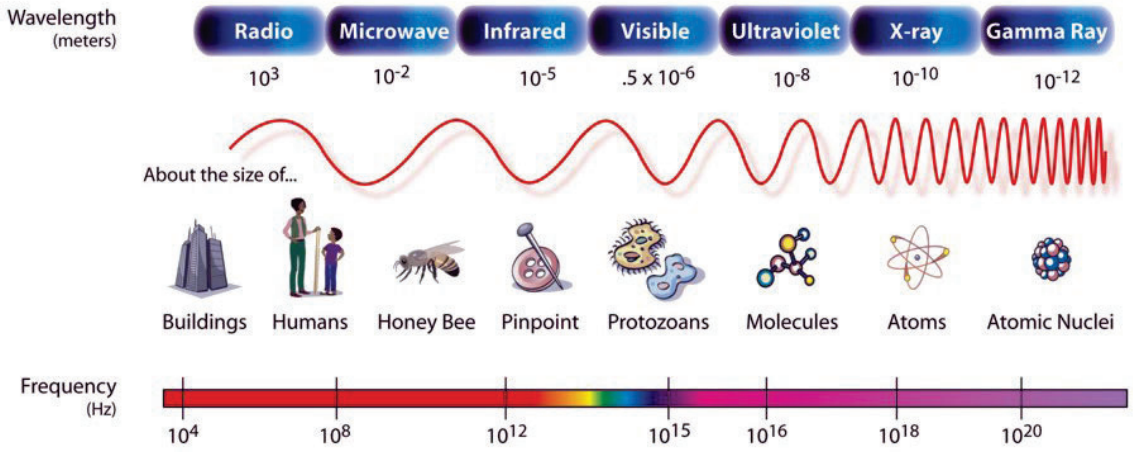

Figure 1. The electromagnetic spectrum ranges from long wavelength radio waves through to short wavelength gamma rays. (Image credit: NASA).

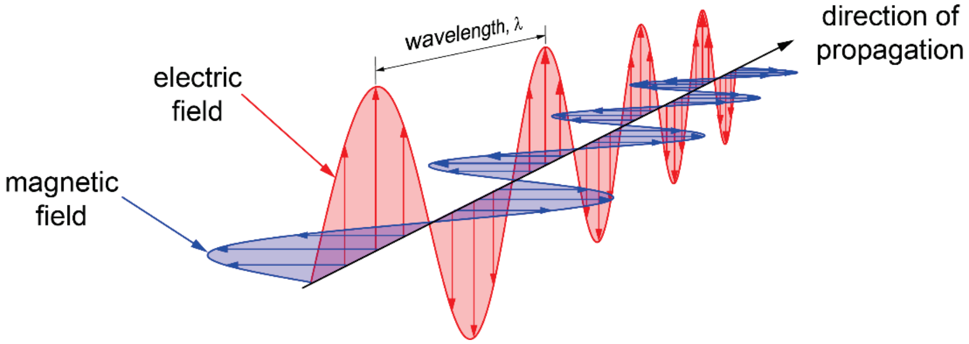

Figure 2. Pictorial representation of an electromagnetic wave of wavelength λ. The electric field is perpendicular to the magnetic field.

Radiation can be split into two categories: ionizing radiation and non-ionizing radiation. Matter consists of atoms and molecules, and these are electrically neutral. An ion is an atom or molecule that has acquired an electronic charge either by the gain or loss of one or more electrons. The process of acquiring an electronic charge is known as ionization. Thus "ionizing radiation" is radiation that is energetic enough to cause ionization of matter. The energy E of an electromagnetic wave is related to its frequency ν by

$$E = h\,\nu$$

Where h is Planck's constant. Or in terms of its wavelength λ,

$$E = h\,\frac{c}{\lambda}$$

Where c is the speed of light. The higher the frequency, the shorter the wavelength, and the higher the energy.

The human body is approximately 65% water. The energy required to ionize, or ionization energy, of water is 12.6 electron volts (eV). Using the conversion factor of 1 electron volt = 1.602×10^{-19} joules (J) to convert between electron volts and joules, the ionization energy of water is 2.0×10^{-18} J, which corresponds to a wavelength of approximately 100 nanometers (nm) which is in the UV region. Thus, ionizing radiation involves electromagnetic radiation whose wavelength is at the short end of the UV region and shorter.

Examples of ionizing radiation include X-rays, alpha and beta particles, and gamma rays. Examples of non-ionizing radiation are microwaves, radio waves, infrared radiation, and visible light. Sources of non-ionizing radiation include lasers, arc lamps, television and radio station transmitters, and Wi-Fi boosters. This document does not discuss lasers, which are addressed in the laser safety manual.[1]

A charged particle q moving with velocity $\boldsymbol{v}$ through an electromagnetic field with electric field $\boldsymbol{E}$ and magnetic field $\boldsymbol{B}$, experiences a force given by the Lorentz equation

$$F = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

The body contains a number of ions, or electrolytes, that perform a variety of functions. Some ions aid in the transmission of electrical signals in neurons and muscles. Other ions play important roles in the function of the human body. Some example important electrolytes are sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), hydrogen phosphate (HPO_4^{2-}), and hydrogen carbonate HCO^{3-}). Because of the electrolytes in the body, one has to exercise caution when working around or with electromagnetic fields.

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[1] https://safety.caltech.edu/documents/14130/Laser_Safety_Manual.pdf

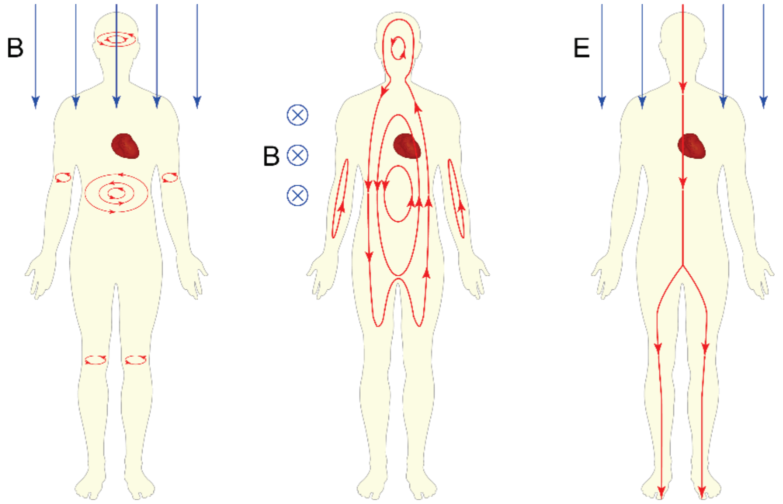

Figure 3. Induced electric currents in the body caused by exposure to electromagnetic fields. In the figure on the left, the magnetic field B direction is from top to bottom (in the plane of the paper). The magnetic field is pointed into the plane of the paper in the middle figure. The electric field is oriented from top to bottom in the rightmost figure.

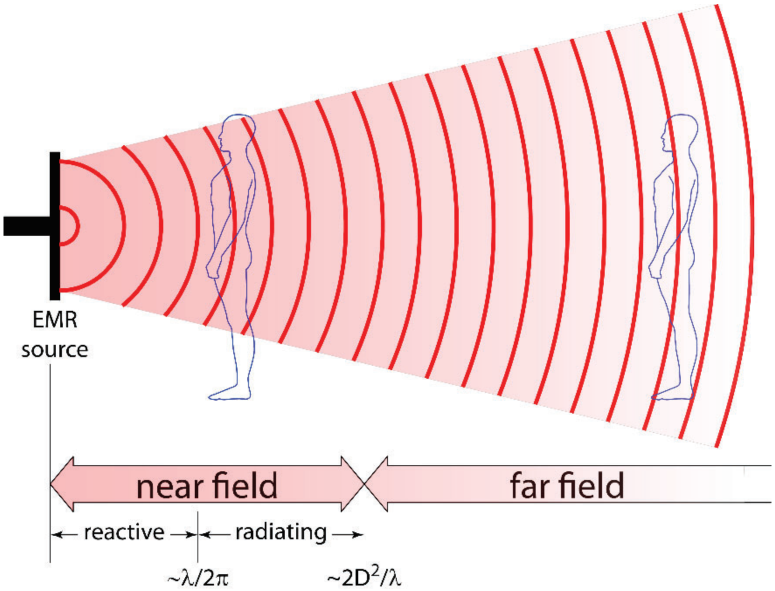

Figure 4. The near and far field from an electromagnetic radiation source. D is the largest dimension of the source antenna. Exposures in the near field are complicated by the effects of reflections, scattering, and the possibility of multiple sources.

The energy flux density delivered by an electromagnetic wave is given by the Poynting vector,

$$\boldsymbol{S} = \boldsymbol{E} \times \boldsymbol{H}$$

In the far field, where the plane wave approximation holds, the magnitudes of $\boldsymbol{S}$, $\boldsymbol{E}$, and $\boldsymbol{H}$ are related by

$$\begin{aligned} S &= \frac{E^2}{Z_0} \\ &= Z_0 H^2 \end{aligned}$$

Where Z_0 is a quantity known as the impedance of free space and has the value approximately equal to 377 ohms.

Biological effects

Non-ionizing radiation does not cause the ionization, free radical production, and chromosomal damage that may lead to cancer. Unlike ionizing radiation, the effects of non-ionizing radiation are not cumulative. That is, exposure to non-ionizing radiation at levels that individually do not cause any damage will not cause damage even with repeated exposure. Biological damage from non-ionizing radiation can be significant if its power density is sufficiently high and the exposure duration sufficiently long. Most of the biological effects of non-ionizing radiation are thermal in nature, and are caused by absorption which depends on the frequency of the incident non-ionizing radiation and the properties of the absorbing tissue.

The complex permittivity ε of biological tissue given by

$$\varepsilon = \varepsilon_\mathrm{r}\varepsilon_0 + j\,\frac{\sigma}{\omega}$$

Where ε_r is the relative permittivity and ε_0 is the permittivity of free space, σ is the conductivity, ω the angular frequency, and j is the imaginary number $\sqrt{-1}$. The penetration depth, or skin depth, is given by

$$\delta = \frac{1}{\omega}\left\{\left(\frac{\mu_0\,\varepsilon_\mathrm{r}\,\varepsilon_0}{2}\right)\left[\sqrt{1+\left(\frac{\sigma}{\omega\,\varepsilon_\mathrm{r}\varepsilon_0}\right)^2}-1\right]\right\}^{-1/2}$$

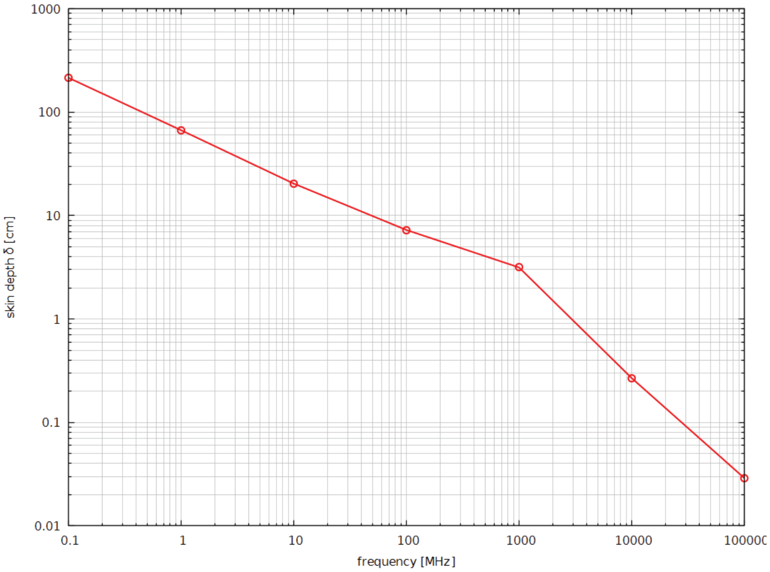

Figure 5. The skin depth of muscle tissue versus frequency. Clearly the absorption increases as the frequency increases.

The penetration depth at low frequencies is large and rapidly decreases beyond 1 GHz. Although the penetration depth is large, the energy deposited is small – the wavelength of 100 kHz is 3000 m, much larger than the size of the human body.

The amount and distribution of radiofrequency energy absorbed by the body is dependent on the body's own internal E and B fields. As the incident field enters the body, it interacts at various tissue interfaces. The result is a complex distribution of internal fields. These internal fields depend not only on the electrical properties of the body but also the geometry and orientation of the body with respect to the incident fields, and whether the body is in the near or far field of the source. The human body has a resonance frequency of approximately 70-80 MHz when standing and approximately 100 MHz when seated. The absorption of radiofrequency energy is greatest when the incident electric field is parallel to the major axis of the body.

The heating of tissue is the most important effect of exposure to radiofrequency energy. The resultant temperature increase depends on how well the body can dissipate the excess heat. For sufficiently high intensity exposures, the induced heating can exceed the body's ability to dissipate the heat, resulting in an increase in tissue temperature that may damage. Tissues with low blood circulation are particularly vulnerable. At prolonged temperatures above about 43 ºC, proteins begin to denature and coagulate, which may lead to damage to the cell membrane and cell death. Temperatures above about 60 ºC produce burns, the amount of damage of which depends on the magnitude and duration of the temperature increase. In an ordinary burn, the damage occurs at the surface of the skin. Absorption of radio frequency radiation may be deep inside the body and the internal heating caused by it may not be indicated by skin temperature.

Under typical conditions the skin temperature will be approximately 34 ºC. The sensation of pain arises when the skin temperature rises by 10 ºC or more. The higher the rise in temperature, the greater the pain, and if sufficiently high, tissue damage occurs. The amount of tissue damage depends on the magnitude and duration of the temperature increase. The threshold for first-degree burns is 55 – 60 ºC. First-degree burns result in pain, reddening of the outer layer of skin – the epidermis – and some swelling. The threshold for second-degree burns is 60 – 65 ºC. Second-degree burns affect all layers of the skin and cause pain, redness, swelling, and blistering. Temperatures of 70 ºC and higher lead to third-degree burns that goes through the skin and affects deeper tissues.

The eyes are vulnerable to radiofrequency energy, particularly the cornea and the lens. Within the eye, there is no blood flow around the lens, and thus no means for heat to be dissipated. Heat buildup in the lens may lead to cell damage and the formation of cataracts. Similarly, the cornea has no blood vessels and because of its exposed position, is vulnerable to heating by radiofrequency radiation. Damage to the cornea, or lens leads to visual impairment.

Long-term effects are those that last longer than 30 days. Scarring and the after effects of burns are considered long-term effects. At the time of writing, there is no conclusive evidence to indicate that exposure to radiofrequency radiation causes cancer or DNA damage.

The function of the nervous system can be affected by exposure to radiofrequency energy. So-called electrostimulation is the stimulation of excitable tissue such as nerves and muscle tissue when an excessive radiofrequency current passes through the tissue.

Exposure limits

Evaluating exposure to non-ionizing radiation is complicated, because a number of factors need to be considered. Environmental Health and Safety (EH&S) is available for advice and consultation.

The American Standard Association (ASA), which later became the American National Standards Institute (ANSI), set the first exposure limit of 10 $mW.cm^{-2}$ from 10 MHz to 100 GHz with its Radiation Hazards Standard Project C95. This established Committee C95, charged with developing RF/microwave safety standards, and evolved into the International Committee on Electromagnetic Safety (ICES) which is part of the Institute of Electrical and Electronics Engineers (IEEE).

There is also the International Commission on Non-Ionizing Radiation Protection (ICNIRP) that also develops exposure limits[2]. Both ICES and ICNIRP use the same whole body averaged specific absorption rate (SAR) but derive different exposure levels from them. The lowest threshold SAR for adverse biological effects is a whole-body SAR of 4 $W.kg^{-1}$ and a core body temperature increase of approximately 1 ºC. The maximum permissible exposure is set to one-tenth of this threshold for occupational workers and an additional factor of five lower for members of the general public.

The frequency ranges for the exposure limits are split into frequencies below 100 kHz, where electrostimulation limits apply, frequencies above 5 MHz where only thermal limits apply, and the range between 100 kHz and 5 MHz where both electrostimulation and thermal limits apply. In the 100 kHz to 5 MHz region, the electrostimulation limit is generally more limiting for low-duty-factor pulsed-EMR sources, and the thermal limits are more limiting for continuous-wave sources.

The exposure limits are split into three regions:

- 0 Hz to 5 MHz;
- 100 kHz to 5 MHz; and
- 100 kHz to 300 GHz.

Exposure to EMR in the 0 to 5 MHz range may result in painful electrostimulation of the body's nervous system. Heating of body tissues may result from exposure to EMR in the 100 kHz to 300 GHz range. In the 100 kHz to 5 MHz region, there may be both electrostimulation and heating.

Unfortunately, exposure limits for non-ionizing radiation are complicated and there is no single value based on frequency and exposure time to refer to, as is the case for lasers. The exposure limits are based on a threshold level at which harmful biological effects may occur. Different parts of the body have different exposure limits, which are given for the head and torso, and limbs. Long term effects to exposure to non-ionizing radiation are not well known, thus best practice should be followed and exposures be limited to the lowest values possible.

Two terms are encountered in exposure limits: the dosimetric reference limit (DRL), and the exposure reference level (ERL). The DRL is based on dosimetric thresholds for established adverse health effects. The ERL, or more commonly the maximum permissible exposure, is derived from the DRL.

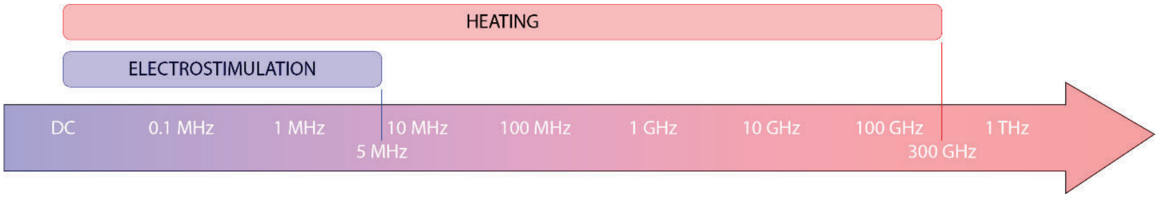

Figure 6. Biological effects and the frequency ranges over which they dominate. Dual limits apply in the frequency range 100 kHz to 5 MHz.

Note that the IEEE C95.1 limits do not specifically address the issue of active implanted medical devices (AIMDs) such as pacemakers and defibrillators.[3]

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[2] Plots of the exposure limits from other organizations are given in the Appendix.

[3] The American Conference of Governmental Industrial Hygienists (ACGIH) have exposure limits that take medical implants into consideration. The ACGIH recommends that the exposure of magnetic fields at 60 Hz for personnel with medical implants be limited to 0.1 mT or less, and a limit for electric fields of 1000 $V.m^{-1}$ or less.

0 – 5 MHz

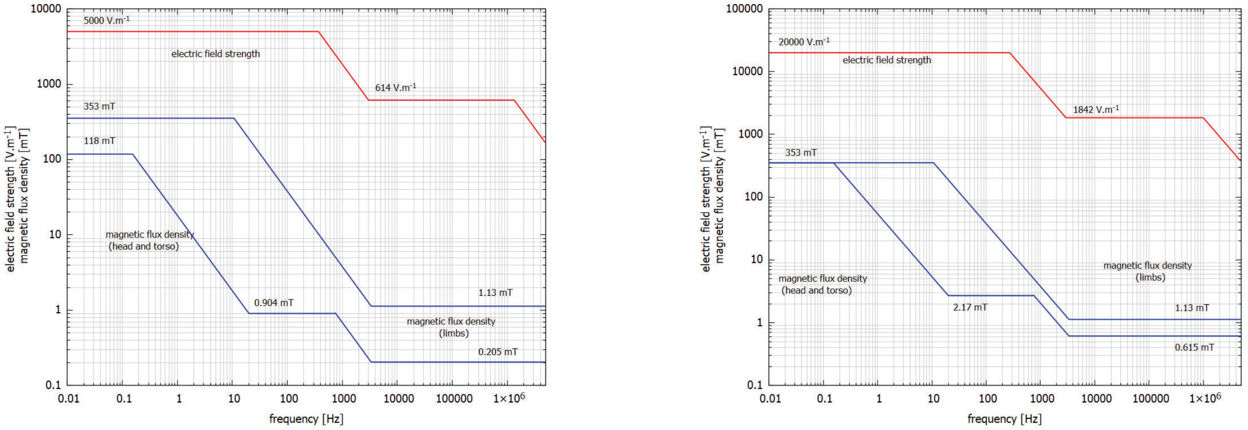

Figure 7. The unrestricted (left) and restricted (right) exposure reference levels for electric and magnetic fields. A larger version is in the Appendix.

100 kHz – 300 GHz

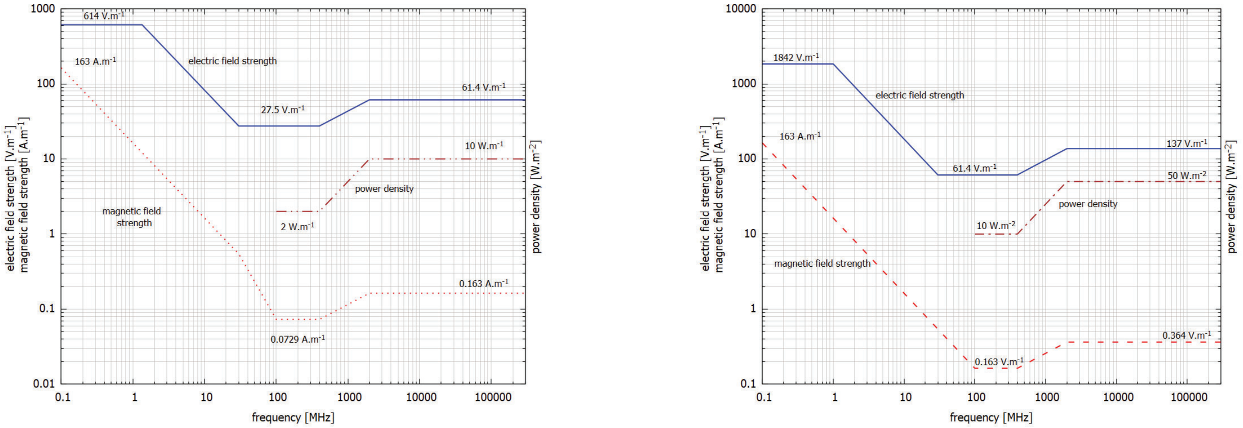

Figure 8. The exposure limits for unrestricted (left) and restricted (right) access areas for frequencies up to 300 GHz. A larger version is in the Appendix.

California exposure limit

The electromagnetic radiation exposure limit in California is given in Title 8, Section 5085.[4] Employees shall not be exposed to RF energy exceeding an average maximum of 10 mW.cm^{-2} over any six minute period, for frequencies between 3 MHz and 300 GHz. This is equivalent to an average electric field of 200 V.m^{-1} or a magnetic field strength of 0.5 A.m^{-1}.

Exposure environment

The exposure environment is an area defined by the maximum potential exposure that may occur within its boundaries. There are two types of exposure environments: restricted, and unrestricted. Within an unrestricted environment, exposure to non-ionizing radiation does not exceed the DRL. It can be thought of as an area that the general public can access. A restricted environment is one in which exposure to non-ionizing radiation may exceed the DRL. An additional safety factor of 5 is incorporated between restricted and unrestricted environments.

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[4] https://www.dir.ca.gov/title8/5085.html

Area classifications

There are five area categories for exposure to electromagnetic radiation:

- Class I areas: Areas where RF fields are too weak to cause exposure greater than the unrestricted limits. No signs are required.
- Class II areas: Areas where potential exposures are controlled to ensure compliance with the unrestricted limits. Notice signs are suggested.
- Class III areas: Areas where RF fields are too weak to cause exposure greater than the restricted limits. Caution signs are required.
- Class IV areas: Areas where potential exposures are controlled to ensure compliance with the restricted limits. Warning signs are required.
- Class V areas: Areas where exposure conditions cannot be controlled to comply with restricted limits. This includes surfaces which will cause RF burns if touched. Danger signs are required.

Radio frequency and microwave radiation signage

Figure 9. The OSHA RF energy advisory symbol and the California radio frequency radiation warning sign. The lettering for the California warning sign must be legible at a distance of 10 m (i.e. the letters must be at least 75 mm high).

Time-weighted average

The time-weighted average (TWA) is a method used to calculate the average workplace exposure to a hazard. It is used when the field strength f_i and the time of exposure $t_i$varies.

$$TWA = \frac{f_1 t_1 + f_2 t_2 + \cdots + f_n t_n}{t_1 + t_2 + \cdots + t_n}$$

Historically an averaging time of 6 minutes was used for restricted environments and 30 minutes for unrestricted environments.

Electromagnetic fields

Electric fields

Electric fields exert a force on the polarized molecules, such as water, in the body. The polarized molecules move in a manner so as to align with the applied electric field. Interactions with other molecules causes this kinetic energy to be converted to heat.

Biological hazards of electric fields

Some effects of exposure to electric fields include, but are not necessarily limited to:

- Electric fields below 10 MHz may stimulate the nerves, resulting in a tingling sensation.
- Heating and a sensation of warmth.
- Breakdown of cell membranes.

Magnetic fields

Materials are classified as either ferromagnetic, diamagnetic, or paramagnetic. In ferromagnetic materials individual atoms or groups of atoms, known as magnetic domains, are randomly aligned. When an external field is applied, the magnetic domains align and remain aligned when the externally applied field is removed, resulting in the material being magnetized. Examples of a ferromagnetic material are iron, nickel, and cobalt. Diamagnetic materials repel any externally applied magnetic field. Some examples of a diamagnetic material include copper, silver, lead, and water. Paramagnetic materials are slightly attracted by magnetic fields. Unlike ferromagnetic materials, the magnetic domains in a paramagnetic material do not retain their alignment when the externally applied field is removed. Paramagnetic materials are considered “non-magnetic”.

In referring to magnetic fields, two distinct but closely related terms are often used interchangeably:

- The magnetic field strength, H, measured in amperes per meter (A/m) or oersted (Oe)
- The magnetic flux density, B, measured in tesla (T) or gauss (G).

More commonly when one refers to a magnetic field, one means the magnetic flux density B because this can be measured. The two quantities B and H are related by[5]

$$B = \mu_0 \, \mu_r \, H$$

Where μ_0 is the permeability of free space and has the value $4\pi \times 10^{-7}$ henry per meter (H/m), and μ_r is the relative permeability. For practical purposes μ_r is often taken to be unity.

Magnetic field hazards

Magnetic fields are caused by the movement of electric charges. Thus anything that draws an electric current has an accompanying magnetic field. Static magnetic fields, those that do not vary over time, are generated by direct current (DC) sources. Time-varying magnetic fields are produced by alternating current (AC) sources. The magnetic field of some common equipment items is given in Table 1.

Equipment	Current [A]	Magnetic field at 1 m [T]
Laptop	< 0.5	1.1×10^{-7}
Printer	< 0.5	1.1×10^{-7}
Computer monitor	< 0.5	1.1×10^{-7}
Desktop computer	3	6.6×10^{-7}
Microwave oven	4.5	9.8×10^{-7}
Refrigerator magnet	N/A	10×10^{-3}

Table 1. The magnetic field due to the current draw of some common items.

When exposed to a magnetic field, the electrolytes in the blood stream are subjected to a force which may be harmful depending on the magnitude of the magnetic field. Workers may be exposed to high

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[5] More generally B and H are related by $B = \mu(H+M)$, where M is the magnetization.

magnetic fields if they work near electrical systems that use large amounts of electric power (ie draw large electric currents). Examples of such electrical systems include:

- Electric motors
- Electric generators
- Building power supplies
- Building power cables

Other examples of equipment that generate magnetic fields are:

- Magnetic resonance imaging (MRI) scanners
- Magnetrons
- Electromagnets
- Electric cars

Whilst it is possible to provide some shielding against magnetic fields, the best protective measure is physical separation. Shielding against magnetic fields does not block the magnetic field but merely redirects it.

The greatest physical hazard of a magnetic field is its ability to attract objects. Objects such as metallic implants and surgical clips within the body can be affected. Other objects such as tools, gas cylinders, jewelry, and watches may become projectile hazards if not removed or properly secured. Fingers may be caught and pinched between magnets, causing blood blisters or cuts. Impact resistant gloves should be worn when handling large magnets.

Information stored on magnetic media such as computer hard discs, credit cards, and other cards with magnetic strips can have the information stored on them wiped by exposure to magnetic fields.

Working with magnetic fields may involve cryogenic cooling of magnets and dewars. This gives rise to the possibility of the additional hazard of magnet quenching. Please consult the Chemical Hygiene Plan for extra precautions when dealing with cryogenics.

Biological hazards of magnetic fields

Exposure to magnetic fields is unavoidable; the Earth's magnetic field varies between 25 μT at the Equator and 65 μT at the poles.[6]

Some effects of exposure to magnetic fields include, but are not necessarily limited to:

- Time-varying magnetic fields in excess of 0.1 to 0.4 mT may induce voltages that can be mistaken for cardiac signals causing devices such as pacemakers and defibrillators to activate.
- Magnetophosphenes – the visual sensation of flickering white light in the eyes – if the frequency of the magnetic field is between 10 to 100 Hz and is of an amplitude between 10 to 100 mT. These flashes of light in the peripheral vision are perceptible without light actually entering the eye.
- High frequency magnetic fields can induce electrical currents in metallic implants in the body that may result in heating.
- The vitreous fluid of the eyes and synovial fluid of the skeletal joints can be affected if foreign bodies are present.
- For magnetic fields above 2 T, a person may experience vertigo and nausea, and sometimes a metallic taste in the mouth.
- Strong magnetic fields have been linked to slight increases in blood pressure.

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[6] Often magnetic flux density is expressed in gauss. One tesla (T) is equal to 10000 gauss (G)

- No conclusive evidence exists demonstrating a link between time-varying magnetic fields and cancer or leukemia.

Figure 10. Example warning signs for areas that contain magnetic fields.

Magnetic fields in excess of 5 mT may affect the performance of AIMDs. As such the 0.5 mT boundary should be clearly marked on the floor in addition to warning signs being posted at the area's access points.

Optical radiation

Optical radiation consists of the infrared, visible, and ultraviolet parts of the electromagnetic spectrum. Typically considered to be wavelengths between 100 nm and 1 mm. The biological effects of optical radiation depend on the energy of the photon, that is its wavelength, the absorption properties of the exposed tissue, and the ability of specific molecules to be chemically altered when the energy of the photon is absorbed. Optical radiation interacts with biological tissues to produce electron excitation that may result in:

- Disassociation of the molecule if the bonding electrons are involved.
- Dissipation of the absorbed energy in the form of luminescence.
- Dissipation of the absorbed energy into vibrational or rotational modes, which results in the production of heat.

Infrared

IR radiation lies between microwaves and visible light in the electromagnetic spectrum, and has wavelengths between 700 nm and 1 mm. IR radiation is divided into three regions:

- IR-A – wavelengths between 700 nm and 1400 nm.
- IR-B – wavelengths between 1400 nm and 3000 nm.
- IR-C – wavelengths between 3000 nm and 1 mm.

Biological hazards of IR radiation

Penetration of infrared radiation is strongly dependent on water absorption. For short wavelength IR-A radiation, absorption by the skin is fairly low, and it penetrates deep into body tissue. IR-B and IR-C is strongly absorbed by the skin, due to the peak in the absorption coefficient of water at 3000 nm. The skin's protection mechanism against thermal effects is the sensation of pain.

Prolonged exposure to IR radiation may result in erythema ab igne, also known as hot water bottle rash, which appears as a fishnet-like discoloration of the skin. These lesions that maybe painful, have the sensation of burning, and may be itchy.

The eyes cannot detect IR radiation, so blinking or closing the eyelids does not work to reduce or prevent damage to the eye. Exposure to IR radiation may result in retinal burns, or cataracts.

PPE for IR radiation

PPE for IR radiation includes:

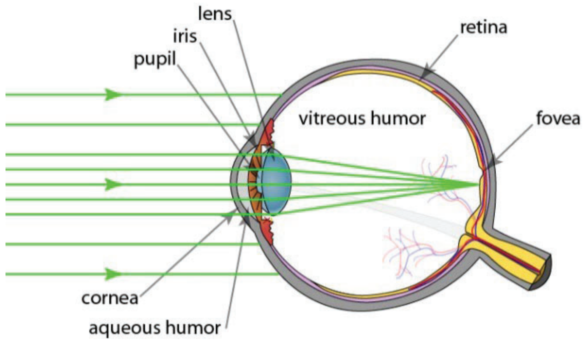
- A mask or protective eyewear (such as a full face shield) that has an infrared filter.
- Lab coats that are fastened securely at the wrists and up to the neck to minimize skin exposure.
- Thermal clothes.
- Tightly woven thermal gloves, footwear, and headwear. Gloves should overlap lab coat sleeves in order to minimize skin exposure.

Visible

Visible radiation lies between the infrared and ultraviolet parts of the electromagnetic spectrum, and has wavelengths between 400 nm and 700 nm. Human beings require exposure to visible light to function. Lack of sunlight can prevent the production of neurotransmitters in the brain that can lead to problems such as depression and other mood disorders. However, over exposure to blue light (400 – 500 nm) has some specific hazards.

Biological hazards of visible radiation

The primary hazard of visible light is the intensity. The pupils constrict or dilate to regulate the intensity of light that reaches the retina in normal circumstances. However, if the light is too bright the natural reflex to avert one's eyes away from the light source will take place. This reaction time is ~0.25 seconds and is known as the aversion response[7]. If the light is too intense in a time shorter than the aversion response, flash blindness or retinal burns may result. Viewing a flash lamp too close will result in this type of exposure.



Near infrared and visible radiation, those with wavelengths between 400 nm and 1400 nm – the so-called retinal hazard region, is absorbed by the cornea and lens of the eye. The optics of the eye focusses the light onto the retina.

Exposure to blue light

Blue light is close to the UV part of the electromagnetic spectrum. Display screens such as those found on laptops, mobile phones, and other digital devices can emit significant amounts of blue light. Too much exposure to blue light can damage the photoreceptors in the retina and resembles macular degeneration, which may lead to permanent vision loss. Blue light is more easily scattered than other visible light, owing to its shorter wavelength, and as such is not as easily focused. This reduces contrast and causes eye strain.

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[7] Previously referred to as the blink response.

Too much exposure to blue light at night may disrupt a person's circadian rhythm, affecting the sleep and wake cycle, leading to problems with daytime tiredness and problems sleeping. Limit exposure to blue light from display screens by minimizing the time spent in front of them, or by taking frequent breaks.

Blue light exposure that is too long or too intense will result in photochemical retinal injury and retinal aging. Arc welding and the sun are radiation source that will produce this effect.

Personal Protective Equipment (PPE) for visible radiation

Eyewear and face shields should comply with the ANSI Z87.1 recommendations.

Yellow-tinted glasses may increase the comfort level when working in front of a digital device for prolonged periods of time. Blue light filters are also available if wearing glasses is not comfortable.

Ultraviolet

UV radiation lies between visible light and X-rays in the electromagnetic spectrum, and has wavelengths between 10 nm and 400 nm. UV radiation is divided into four regions:

- Extreme – wavelengths less than 100 nm.
- Far – wavelengths between 100 nm and 200 nm.
- Middle – wavelengths between 200 nm and 300 nm.
- Near – wavelengths between 300 nm and 400 nm.

However, based on its interaction with biological matter UV light is more commonly thought of as being divided into the following three regions:

- UV-C, from 100 nm to 280 nm
- UV-B, from 280 nm to 315 nm
- UV-A, from 315 nm to 400 nm – which is also commonly known as "black light"

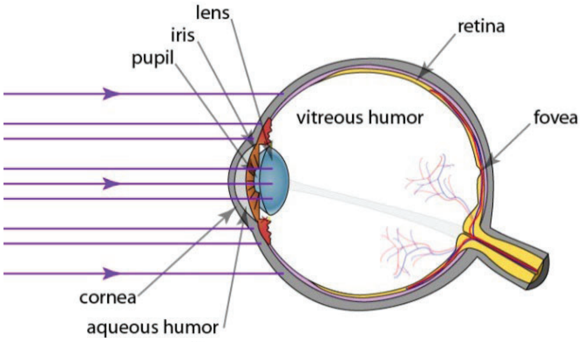
For most people the main source of UV radiation is the Sun. Most of the UV radiation that reaches the Earth's surface consists of UV-A and UV-B. UV-C is absorbed by atmospheric oxygen and does not reach Earth's surface. Sources of UV radiation that may be encountered in the workplace environment include:

- Lamps such as arc lamps, mercury vapor lamps, halogen lamps, fluorescent lamps, and light emitting diodes (LEDs)
- Germicidal lamps
- Excimer lasers
- Gas glow discharges
- Welding arcs and flames
- The Sun

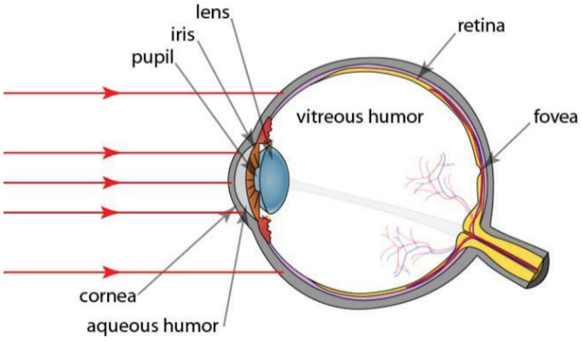
Biological hazards of UV radiation

UV radiation is a known cause of skin cancer, skin ageing, eye damage and affects the body's immune system. It is energetic enough to cause damage to a person's deoxyribonucleic acid (DNA). The effect on skin can be both acute and chronic. Acute effects on the skin appear within a few hours of exposure and give rise to redness and an inflammatory response known as erythema. In addition, reactive free radicals may be produced that may attack DNA and other skin cells, such as collagen. Collagen gives the skin its elasticity. Damaged collagen results in wrinkles and aged skin. The chronic effect of repeated exposure to UV results in a thickening of the upper layers of the skin and the production of the UV-absorbing melanin. Melanin is what gives sun tanned skin its color. The risk of thermal injury is also present with exposure to UV but this is limited due to the sensation of pain.

For the eyes, exposure to UV may result in photokeratitis which is commonly referred to as snow blindness. Photokeratitis is an inflammation of the conjunctiva – the thin membrane at the front of the eye – and cornea. Long term exposure to UV may increase the risk of cataracts.



UV-B radiation is mostly absorbed by the cornea and the lens. UV-A radiation is mostly absorbed by the lens.



UV-C radiation is strongly absorbed by the cornea.

Photochemical interactions generally follow the Bunson-Roscoe Law of Reciprocity, namely that a low-level, long-term exposure gives rise to the same amount of damage as a high-level, short-term exposure. Whilst it is possible to calculate the thresholds for acute effects and set exposure limits, the threshold for chronic effects is not known. Because of this, no exposure level is safe and exposure to UV should be reduced as much as possible.[8]

Other hazards of UV radiation

Other hazards that may be encountered when working with equipment that generates UV radiation are:

- Explosion
    - Arc lamps contain high-pressure gas and may explode if not handled properly. Do not stress the glass parts when tightening the electrical connections. Always wear gloves when handling the lamp. The oils from fingerprints absorb heat from the lamp, creating localized hot spots on the glass envelope that will cause the glass to break. Fingerprints should be removed with isopropyl alcohol and a clean lint-free tissue.
- Mercury
    - Mercury contamination may occur if a mercury vapor lamp breaks or explodes. Mercury requires specialist waste handling and disposal – see the hazardous waste guidelines.
- Ozone
    - Oxygen reacts with short-wavelength UV radiation to produce ozone. Ozone can be an irritant.
- Electric shock

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[8] There are no OSHA set limits on UV exposure (https://www.osha.gov/laws-regs/standardinterpretations/2003-02-26).

    - During normal operation of an arc lamp, the high voltage components of the arc lamp are not accessible. However electric shock may result if the power supply section is opened with the unit still plugged in. Only a trained electrical worker should work on the high voltage components.
- Heat
    - The case of an arc lamp reaches a very high temperature, which can be anywhere between 400 °C and 1000 °C depending on the type of arc lamp[9], during normal operation and may cause burns if touched.

PPE for UV radiation

- UV protective eyewear must be labelled and be impact resistant (ie should conform with the ANSI Z87.1 eye protection standard). Note that not all polycarbonate eyewear blocks UV radiation.
- Gloves with low UV transmission; nitrile or latex gloves are suitable.
- A tight weave long sleeve lab coat.
- Sunscreens such as zinc oxide or titanium oxide.
- Full-face shield or welding shield with appropriate shade factor.

Appendix

Useful constants and conversion factors

1 tesla = 10000 gauss

1 $W.m^{-2}$ = 0.1 $mW.cm^{-2}$

Speed of light, $c = 299792458$ meters / second

Permeability of free space, $\mu_0 = 1.257 \times 10^{-6}$ henries / meter

Permittivity of free space, $\varepsilon_0 = 8.854 \times 10^{-12}$ farads / meter

Frequency Bands

Frequency	Name
3 to 300 Hz	Extremely Low Frequency (ELF)
300 Hz to 3 kHz	Voice Frequency (VF)
3 kHz to 30 kHz	Very Low Frequency (VLF)
30 kHz to 300 kHz	Low Frequency (LF)
300 kHz to 3 MHz	Medium Frequency (MF)
3 MHz to 30 MHz	High Frequency (HF)
30 MHz to 300 MHz	Very High Frequency (VHF)
300 MHz to 3 GHz	Ultra High Frequency (UHF)
3 GHz to 30 GHz	Super High Frequency (SHF)
30 GHz to 300 GHz	Extremely High Frequency (EHF)

Table 2. Frequency ranges and categories.

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[9] Information from the Carl Zeiss Microscopy Online Campus.

Letter Designation	Frequency Range	Wavelength Range	Comments
L	1 to 2 GHz	15 cm to 30 cm	Satellite navigation (GPS), radar, cell phones
S	2 to 4 GHz	7.5 cm to 15 cm	Satellite radio, weather radar, Wi-Fi
C	4 to 8 GHz	3.75 cm to 7.5 cm	Satellite communications, satellite television
X	8 to 12 GHz	25 mm to 37.5 cm	Radar, air traffic control, vehicle speed detection
Ku	12 to 18 GHz	16.7 mm to 25 mm	Satellite television
K	18 to 26.5 GHz	11.3 mm to 16.7 mm	Satellite communication, radar, astronomical observations
Ka	26.5 to 40 GHz	5.0 mm to 11.3 mm	Satellite communication
Q	33 to 50 GHz	6.0 mm to 9.0 mm	Microwave communication, radio astronomy studies, automotive radar
U	40 to 60 GHz	5.0 mm to 7.5 mm	Radar, radio astronomy
V	50 to 75 GHz	4.0 mm to 6.0 mm	Point-to-point radio links
W	75 to 110 GHz	2.7 mm to 4.0 mm	Astronomy, automotive radar
F	90 to 110 GHz	2.1 mm to 3.3 mm	Defense
D	110 to 170 GHz	1.8 mm to 2.7 mm	Defense

Table 3. The letter designation of frequency bands of the microwave spectrum and some of their uses.

Area warning signs

The following are example notice and warning signs to indicate the presence of RF fields.

Notice sign for the general public required by the FCC. It should be posted at the boundary between a Category I and Category II area.

The same sign is optional for notification of a worker-based RF control program. It should be posted at the access points into a Category III area.

Caution sign for workers to use controls. It should be posted at access points into a Category IV area.

Warning sign posted to mark prohibited access into a Category V area without a power down or PPE.

Posted to mark prohibited access without a power down. PPE is not sufficient in these areas.

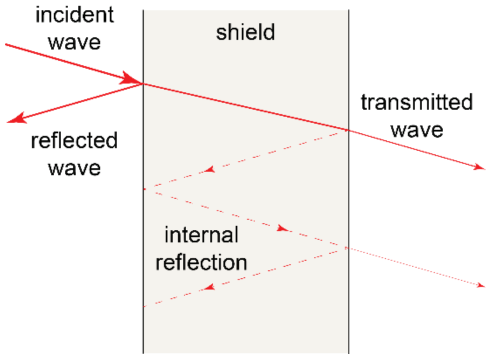
Electromagnetic shielding

Electromagnetic shielding is the process of lowering the electromagnetic field in an area by barricading it with conductive or magnetic material. This is accomplished by reflecting or absorbing/suppressing electromagnetic radiation.

When an electromagnetic wave encounters a material with different electrical properties, a fraction of the energy in the wave is reflected, and the remainder is transmitted into the new material. A medium with a conductivity of σ, has an intrinsic impedance η (or more commonly Z) given by

$$\eta = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}}$$

When the conductivity is non-zero, the intrinsic impedance is a complex number, indicating that the electric and magnetic fields are not in phase.



When AC current is applied to a conductor, the current concentrates near the surface of the conductor, and its strength decreases exponentially away from the surface. The depth until which current flows in a conductor is known as the skin depth. The skin depth is dependent on the frequency of the applied current, and the resistivity of the material.

The skin depth δ is approximated by

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

For any shielding material used, much thicker than the skin depth, the transmitted electric field is given by

$$E_{\mathrm{trans}} = \frac{4\,\eta_s\eta_0}{(\eta_s + \eta_0)^2}\; e^{-\frac{t}{\delta}}\, E_{\mathrm{inc}}$$

Where η_s and η_0 are the intrinsic impedance of the shielding material and of free space respectively, and t is the thickness of the shielding material. Typically, the best shield will be good conductors with a high conductivity. For these materials, $\eta_s \ll \eta_0$, and the transmitted field simplifies to

$$E_{\mathrm{trans}} = \frac{4\,\eta_s}{\eta_0}\; e^{-\frac{t}{\delta}}\, E_{\mathrm{inc}}$$

The shielding effectiveness SE is defined to be

$$\begin{aligned} SE &= 20\ \log_{10}\frac{E_{\mathrm{inc}}}{E_{\mathrm{trans}}} \\ &= 20\ \log_{10}\left(\frac{\eta_0}{4\eta_s}\ e^{\frac{t}{\delta}}\right) \end{aligned}$$

Which is often expressed in terms of the sum of a reflection loss R(dB) and an absorption loss A(dB). The reflection loss is the attenuation due to the incident radiation being reflected at the interfaces. The absorption loss is the attenuation due to the incident power being converted to heat as the wave propagates through the shielding material. The absorption loss is directly proportional to the thickness of the shielding material

$$A\ (\mathrm{dB}) = 20\ \log_{10} e^{\frac{t}{\delta}}$$

$$= 8.70\ \left(\frac{t}{\delta}\right)$$

The reflection loss is independent of the thickness of the shield and is given by

$$R\ (\mathrm{dB}) = 20\ \log_{10}\left(\frac{\eta_0}{4\eta_s}\right)$$

A conductive enclosure that blocks electrostatic fields is called a Faraday cage. The amount of EMF reduction depends on several factors such as the type of material used, its thickness, shape and orientation of openings in the shield and the frequency of incident electromagnetic field.

Shielding materials

Typical materials used for electromagnetic shielding include sheet metal and metal meshes. A metal's properties are an important consideration in material selection. For example, electrically dominant waves are reflected by highly conductive metals like copper, silver, and brass, while magnetically dominant waves are absorbed/suppressed by a less conductive metal such as steel or stainless steel.

Common sheet metals for shielding include copper, brass, nickel, steel, and tin. Shielding effectiveness is affected by the physical properties of the metal such as conductivity, permeability, thickness, and weight.

If a metal mesh is used for shielding, holes in the mesh must be significantly smaller than the wavelength of the radiation that is being kept out, or the enclosure will not act as an unbroken conducting surface.

Copper is often used for radio frequency (RF) shielding. Properly constructed enclosures satisfy most RF shielding needs for sensitive medical or laboratory equipment against interfering signals, including AM, FM, TV, pagers, cellular phones. For example, copper is used to shield MRI facilities or computer server rooms.

An example of a metal mesh screen is the microwave oven door. It has a metal mesh screen built into the window. This screen finishes a Faraday cage formed by the oven's metal housing. Visible light (~10^{-5} cm wavelength), passes easily through the screen holes, but the microwaves, with the wavelength of 12 cm are blocked. For microwaves, absorbing foams can also be used.[10]

Electromagnetic shielding for cables typically comes in the form of a wire braid surrounding an inner core conductor. The shielding impedes the escape of any signal from the core conductor, and also prevents signals from being added to the core conductor.

For static or slowly varying magnetic fields (below about 100 kHz) the Faraday shielding is not effective. In these cases shields made of high magnetic permeability metal alloys can be used, such as sheets of permalloy, a nickel–iron magnetic alloy, with about 80% nickel and 20% iron content. High permeability materials do not block the magnetic field, but rather draw the field into themselves, diverting the magnetic energy by providing a path for the magnetic field lines around the shielded volume. Some alloys used in magnetic shielding include mumetal, permalloy, and radiometal.

At high magnetic field, the material becomes saturated and the effectiveness of the shielding drops off. So to achieve desired protection, magnetic shields often consist of several enclosures one inside the other, each of which successively reduces the field inside it.

Metal screens

Thin screens made of periodic grids can be used for frequency selective shielding. Their transmission characteristics depend on the geometric properties of the grid [X].

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[10] See for example Eccosorb.

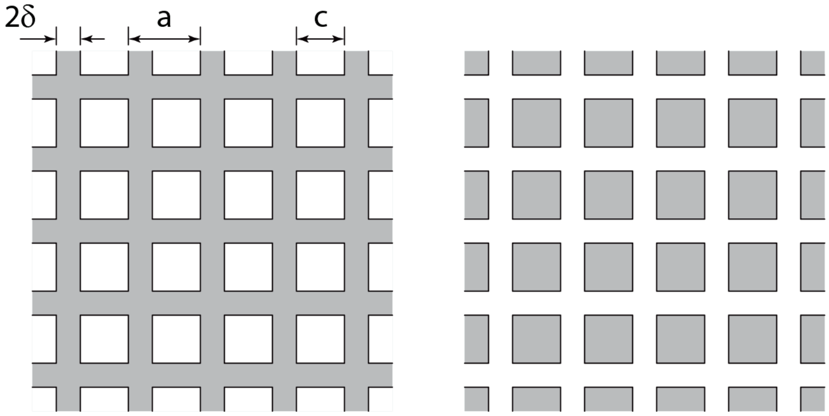

Figure 11. Two types of metal screens: inductive (left) and capacitive (right). The metallized areas are shaded.

Using a transmission line model, if the screen is sufficiently thin, so waveguide effects can be neglected, the transmission of the screen is given by

$$|T|^2 = \left|\frac{1}{1+Y}\right|^2$$

For a capacitive mesh, the admittance Y is given by

$$Y_{\text{inductive}} \approx -\mathrm{j}\left(\beta - \frac{1}{\beta}\right)\frac{\left[\left(\frac{a}{c}\right) + \frac{1}{2}\left(\frac{a}{\lambda}\right)^2\right]}{\log\left[\csc\left(\frac{\pi}{2}\,\frac{\delta}{a}\right)\right]}$$

Where

$$\beta = \left(1 - 0.41\,\frac{\delta}{a}\right) \Big/ \left(\lambda/a\right)$$

The admittance of the capacitive mesh can be calculated from Babinet's Principle.

$$Y_{\text{inductive}} = {Y_{\text{capacitive}}}^{-1}$$

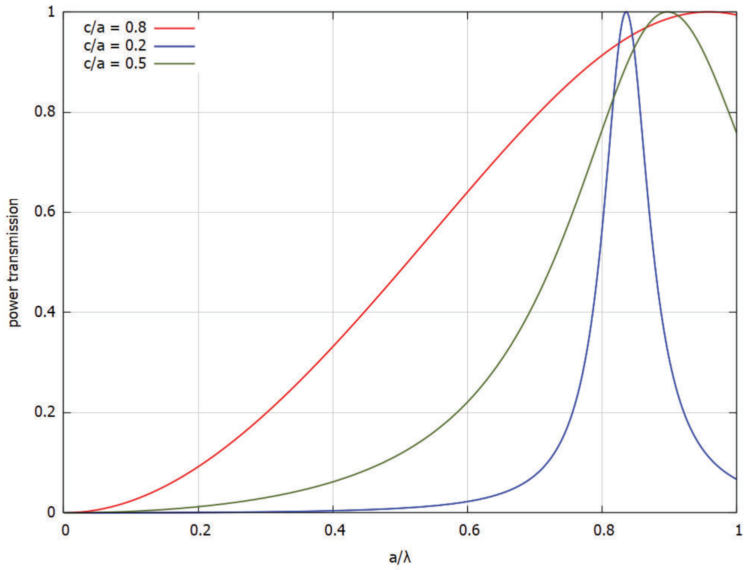

Figure 12. The transmission characteristics of a metal mesh as a function of the ratio between the grid spacing and the wavelength, for three values of grid spacing.

For large ratios of c/a, inductive meshes act as high pass filters and capacitive meshes act as low pass filters.

Instrumentation

Measurements of the EMF are obtained using an E-field sensor or H-field sensor. These sensors or probes can be generally considered as antennas although with different characteristics. A good probe should not perturb the electromagnetic field and must prevent coupling and reflection as much as possible in order to obtain precise results.

There are two main types of EMF measurements, broadband and frequency selective measurements:

- **Broadband measurements** are performed using a broadband probe, that is a device which senses any signal across a wide range of frequencies and is usually made with three independent diode detectors;
- **Frequency selective measurements** is a field antenna and a frequency selective receiver or spectrum analyzer allowing to monitor the frequency range of interest.

EMF probes may respond to fields only on one axis, or may be tri-axial, showing components of the field in three directions at once.

Single axis instruments have to be tilted and rotated on all three axes to obtain a full measurement. A tri-axis meter measures all three axes simultaneously, but these models tend to be more expensive.

Exposure limits

The California exposure limit for frequencies between 3 MHz and 300 GHz is 10 $mW.cm^{-2}$ averaged over any six-minute period, or equivalently:

- 200 $V.m^{-1}$
- 0.5 $A.m^{-1}$

Exposure from multiple sources

For exposures to multiple frequencies due to many uncorrelated sources, the sum of the relative power density at each frequency should total less than unity.

For example, work is to be carried out near a cell phone tower. This involves simultaneously exposure to 800 MHz, 850 MHz, and 1900 MHz. The whole body power density ERL for a restricted environment is given by $f_{\mathrm{M}}/40$, where f_{M} is the frequency in megahertz. The ERL for each frequency is 20 W.m^{-2}, 21.25 W.m^{-2}, and 47.5 W.m^{-2} respectively.

Then the exposure limit requirement equates to

$$\frac{S_{800}}{20} + \frac{S_{850}}{21.25} + \frac{S_{1900}}{47.5} \leq 1$$

Where S_{800}, S_{850}, and S_{1900} are the power densities at 800 MHz, 850 MHz, and 1900 MHz respectively. Should the power densities not be known, the exposure limit can be similarly expressed using the sum of the square of the field strengths.

American Conference of Governmental Industrial Hygienists (ACGIH)

For frequencies lower than 300 GHz, ACGIH splits the electromagnetic spectrum into two regions: sub-radiofrequency, and radiofrequency and microwave. Sub-radiofrequency is the region where the frequency is lower than 30 kHz. The radiofrequency and microwave region is between 30 kHz and 300 GHz. The listed ACGIH exposure limits below are from 2012.

Static magnetic fields

- Whole body (general workplace): 2 T
- Whole body (controlled workplace environment): 8 T
- Limbs: 20 T
- Medical device wearers: 0.5 mT

Power line frequency magnetic fields

- Whole body exposure: 1 mT
- Arms and legs: 5 mT
- Hands and feet: 10 mT

Electric fields

- 25 kV.m^{-1}

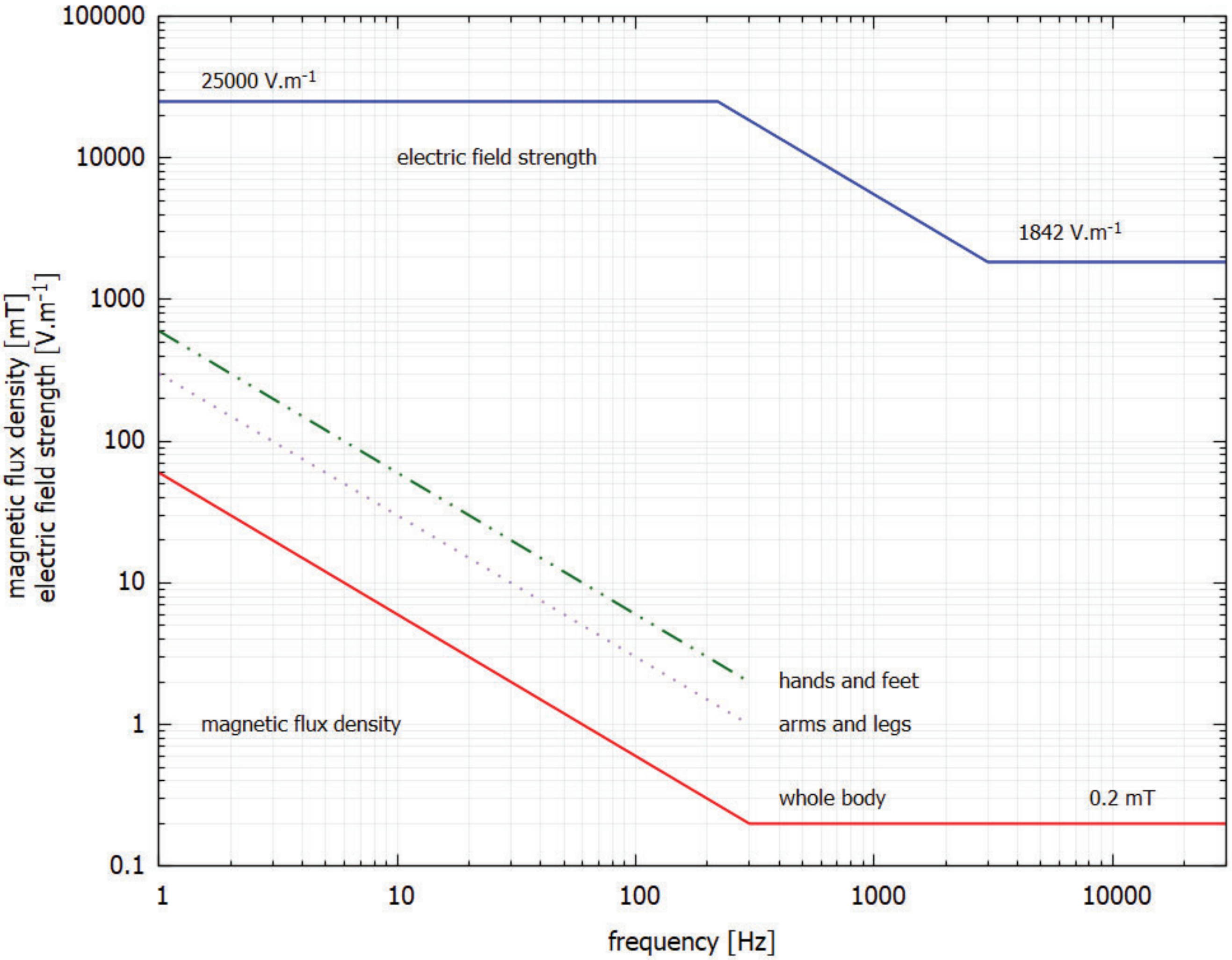

Figure 13. The low-frequency (DC to 30 kHz), occupational exposure limits for magnetic and electric fields.

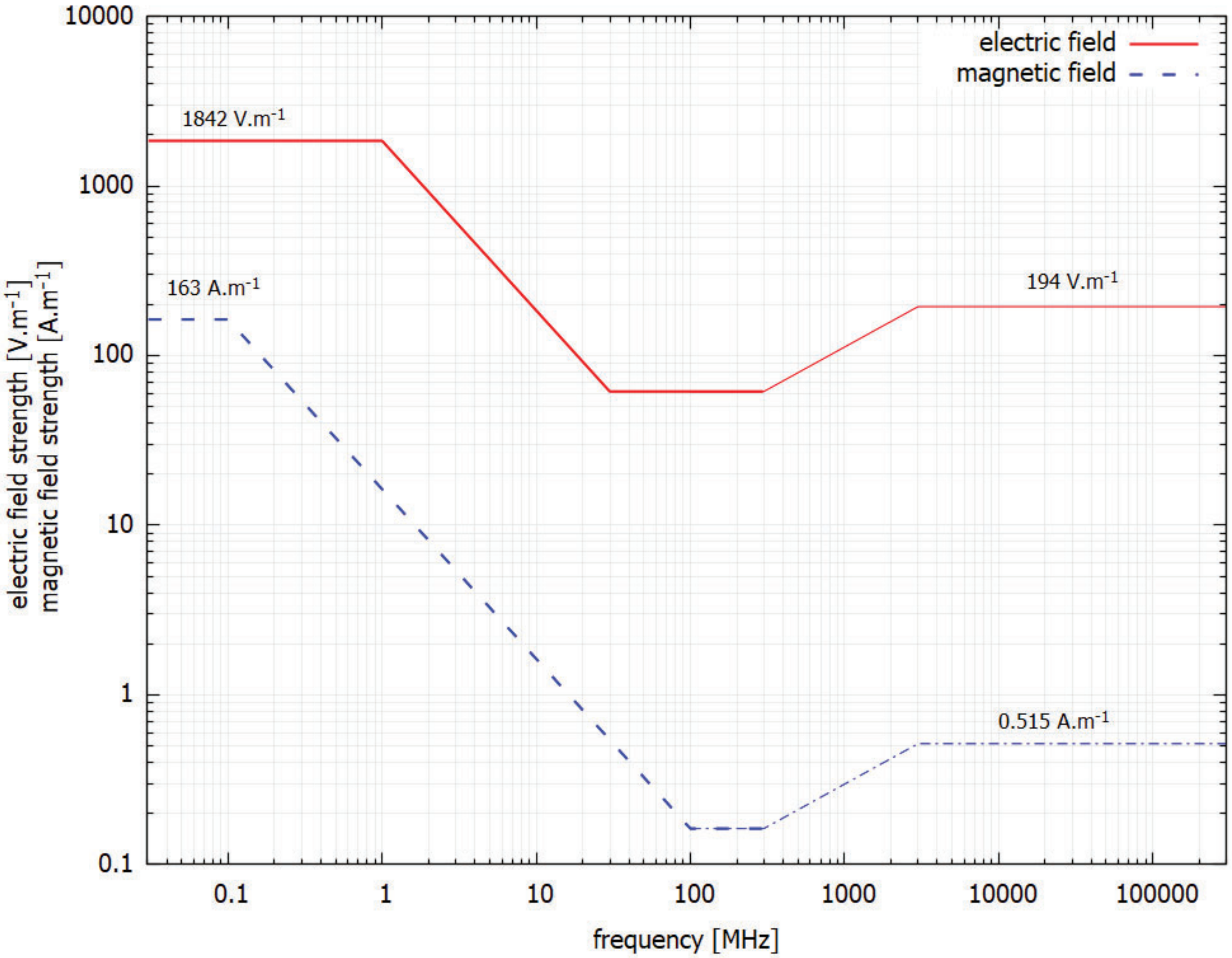

Figure 14. The high-frequency (30 kHz to 300 GHz) occupational exposure limits for electric and magnetic field. For frequencies beyond 300 MHz, the values plotted are the plane wave equivalents derived from the power density

FCC

The FCC limits are listed in Federal Register, volume 85, number 63, Rules and Regulations, dated April 1st, 2020.

The restricted environment maximum permissible exposure limits for electromagnetic energy are given in the table below.

frequency range [MHz]	electric field strength [V.m^{-1}]	magnetic field strength [A.m^{-1}]	power density [mW.cm^{-2}]
0.3 – 3.0	614	1.63	100
3.0 – 30	1842 / f	4.89 / f	900 / f^2
30 – 300	61.4	0.163	1.0
300 – 1500	-	-	f / 300
1500 - 100000	-	-	5

Table 4. The FCC restricted environment maximum exposure levels for frequencies from 300 kHz to 100 GHz.

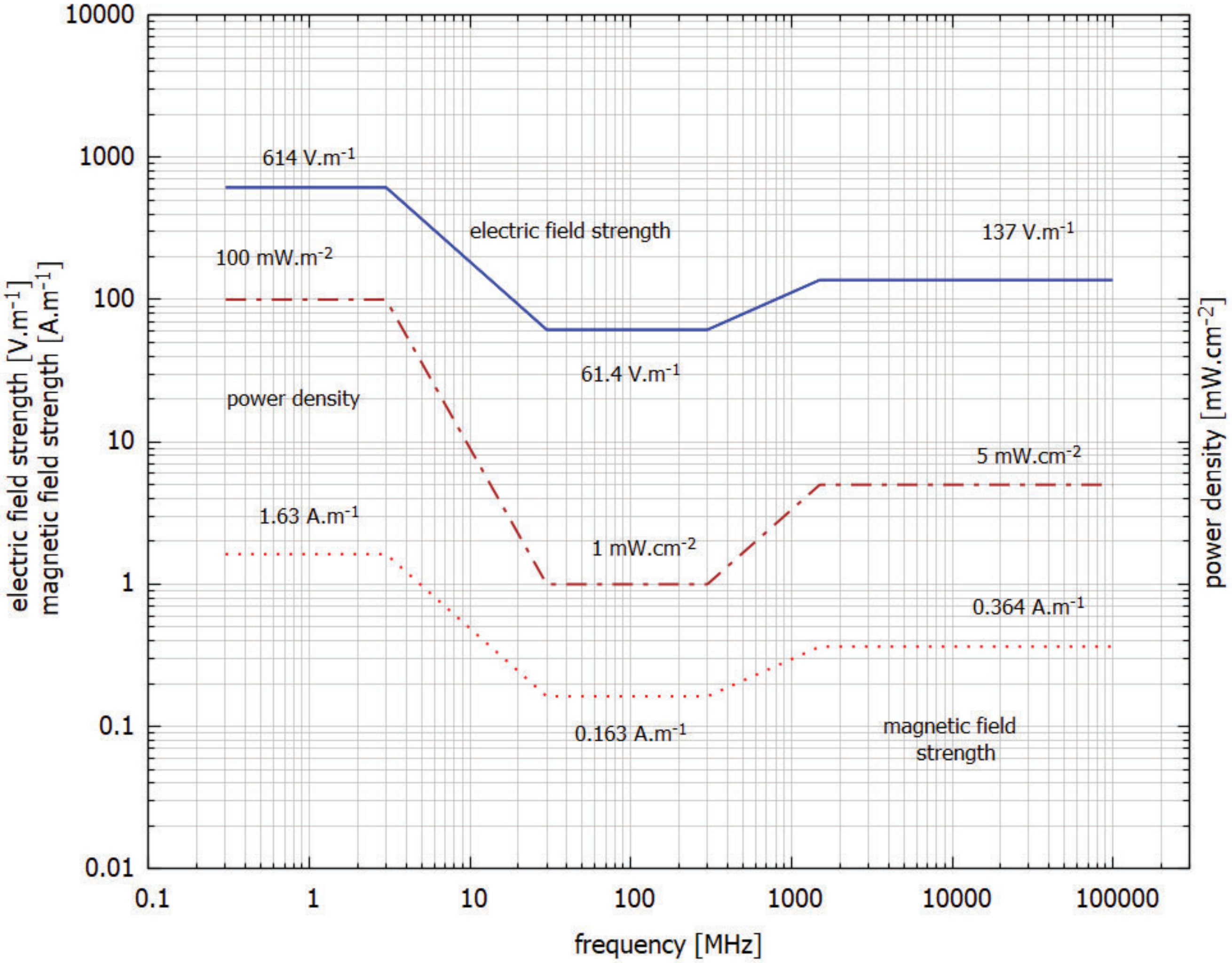

Figure 15. The restricted environment maximum permissible exposure limits for electric and magnetic fields for frequencies between 300 kHz and 100 GHz. For frequencies greater than 300 MHz, the values plotted are derived from the power density plane wave equivalents.

The unrestricted environment maximum permissible exposure limits for electromagnetic energy are given in the table below.

frequency range [MHz]	electric field strength [V.m^{-1}]	magnetic field strength [A.m^{-1}]	power density [mW.cm^{-2}]
0.3 – 1.34	614	1.63	100
1.34 – 30	842 / f	2.19 / f	180 / f^2
30 – 300	27.5	0.073	0.2
300 – 1500	-	-	f / 1500
1500 - 100000	-	-	1.0

Table 5. The FCC unrestricted environment maximum exposure levels for frequencies between 30 kHz and 100 GHz.

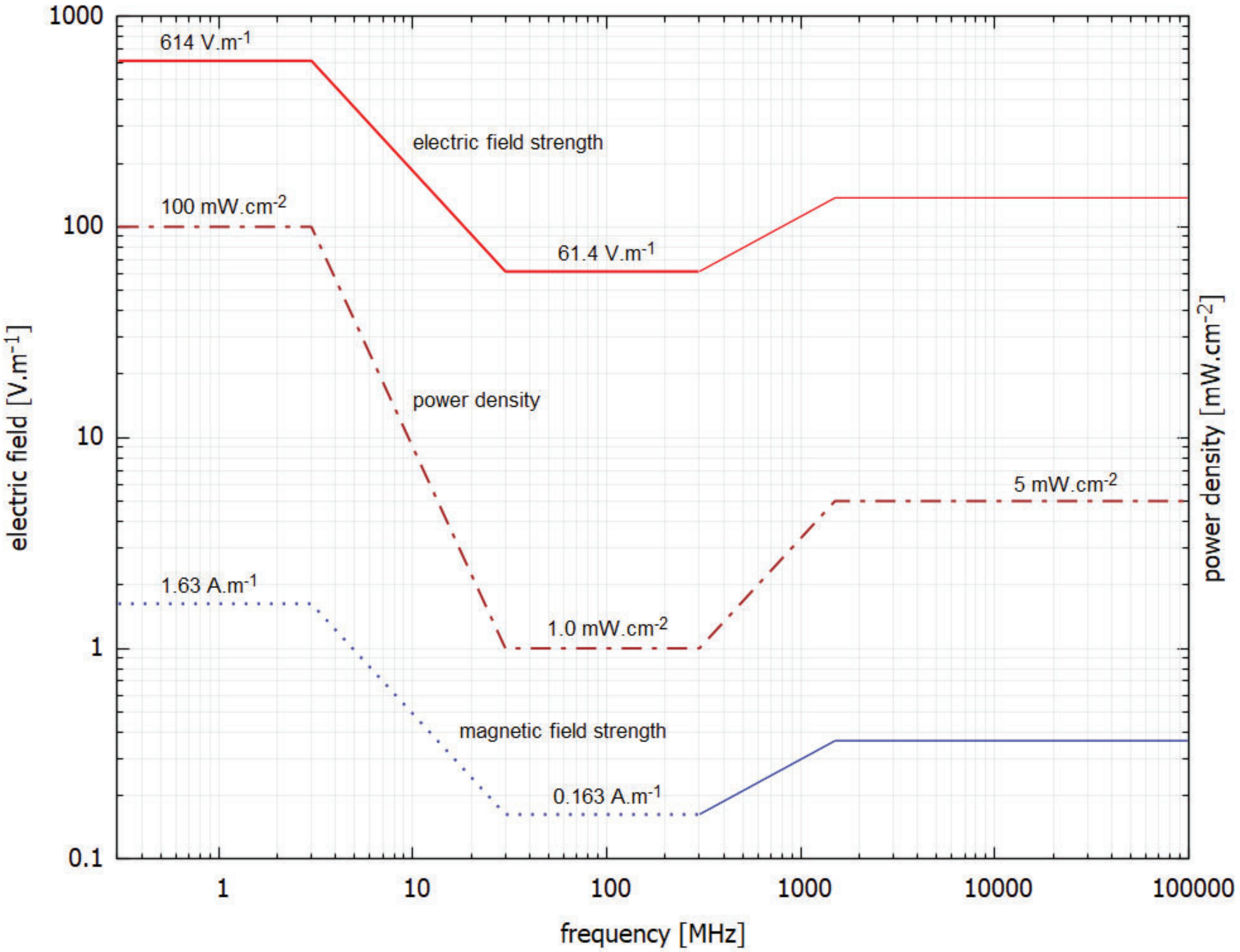

Figure 16. The unrestricted environment maximum permissible exposure limits for electric and magnetic fields for frequencies between 300 kHz and 100 GHz. For frequencies greater than 300 MHz, the values plotted are derived from the power density plane wave equivalents.

International Commission on Non-Ionizing Radiation Protection (ICNIRP)

Only ICNIRP has exposure limits listed for frequencies as low as 1 Hz.

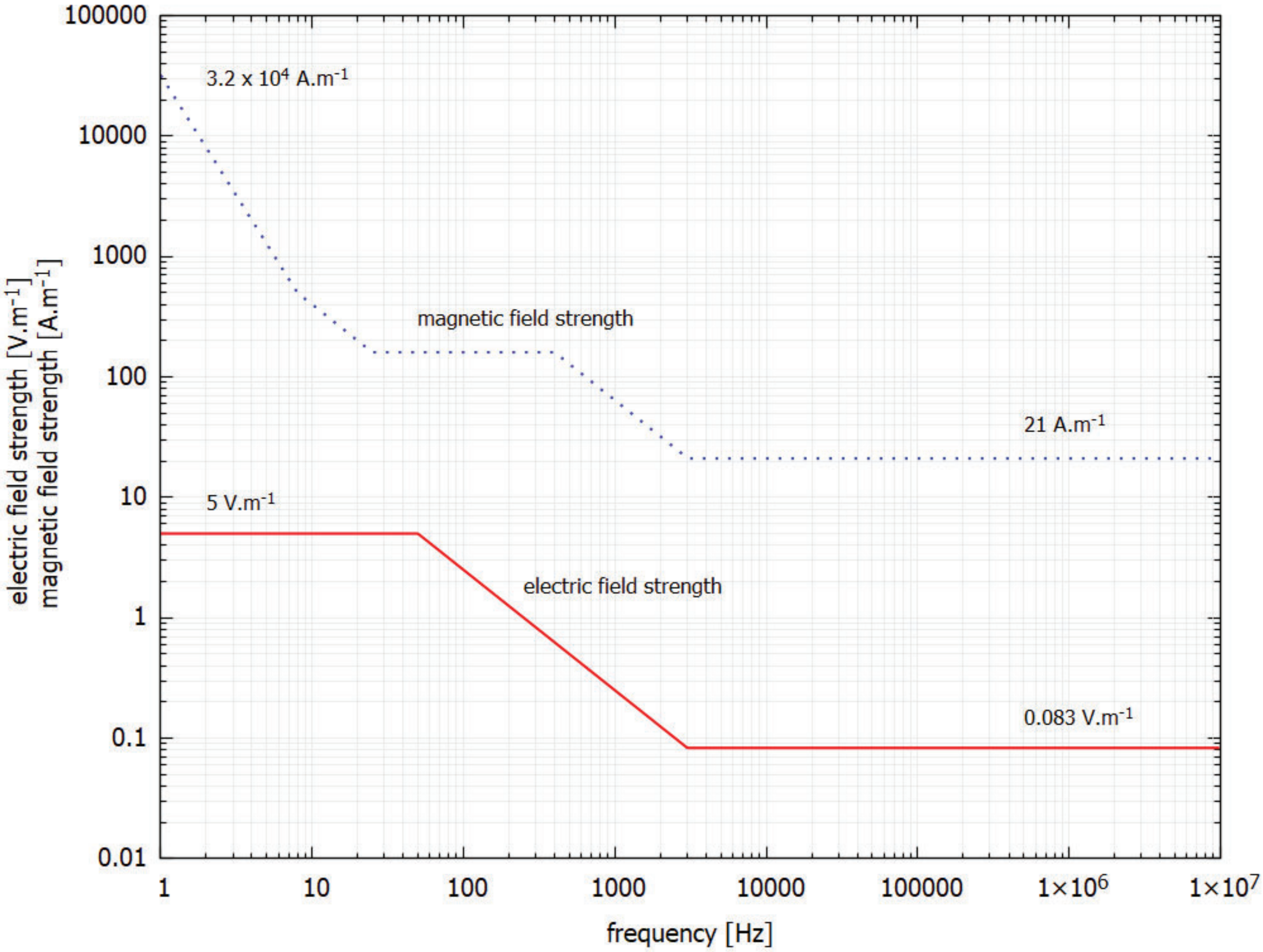

Figure 17. The 2010 reference levels for general public exposure to time-varying electric and magnetic fields.

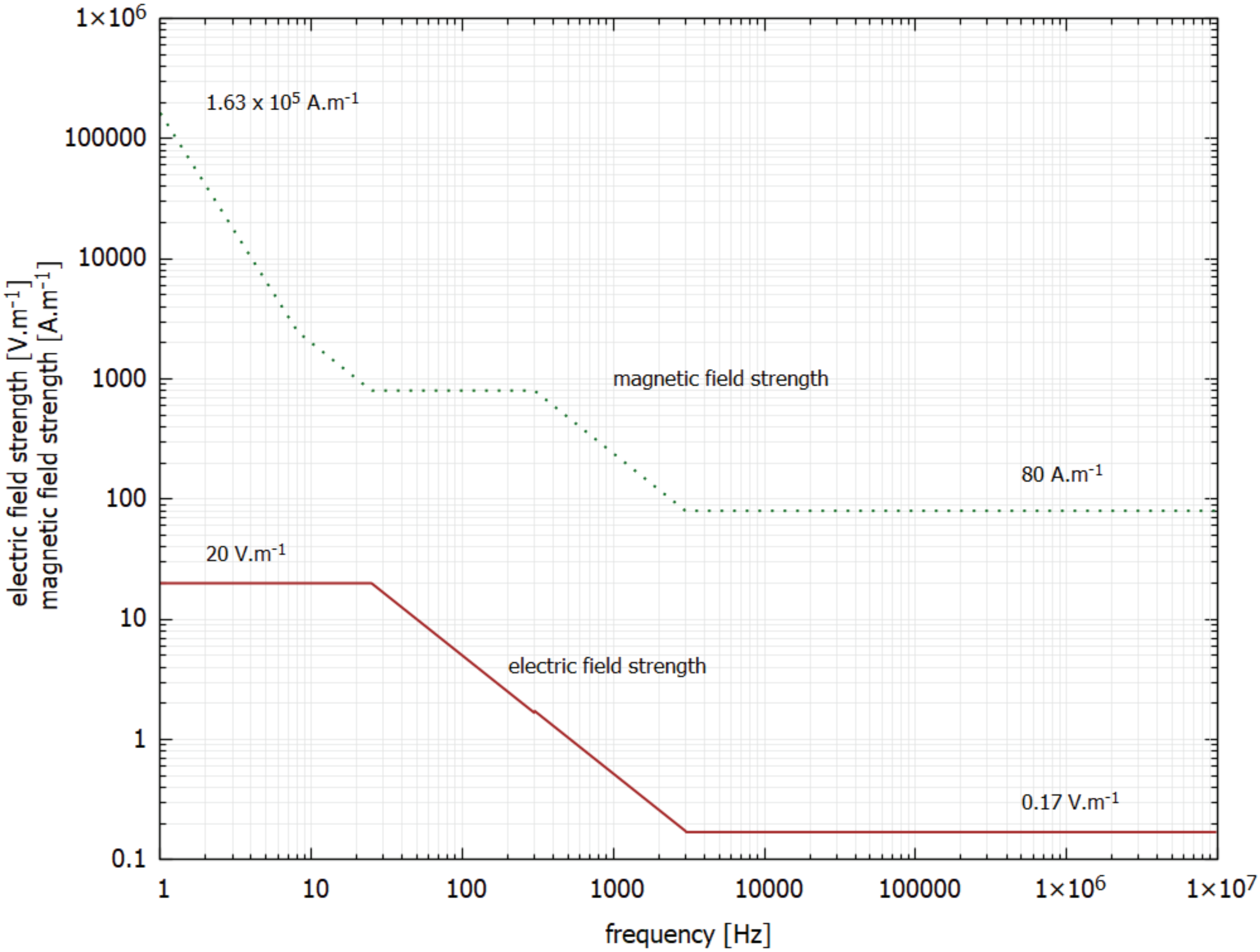

Figure 18. The 2010 occupational reference levels for exposure to time-varying electric and magnetic fields.

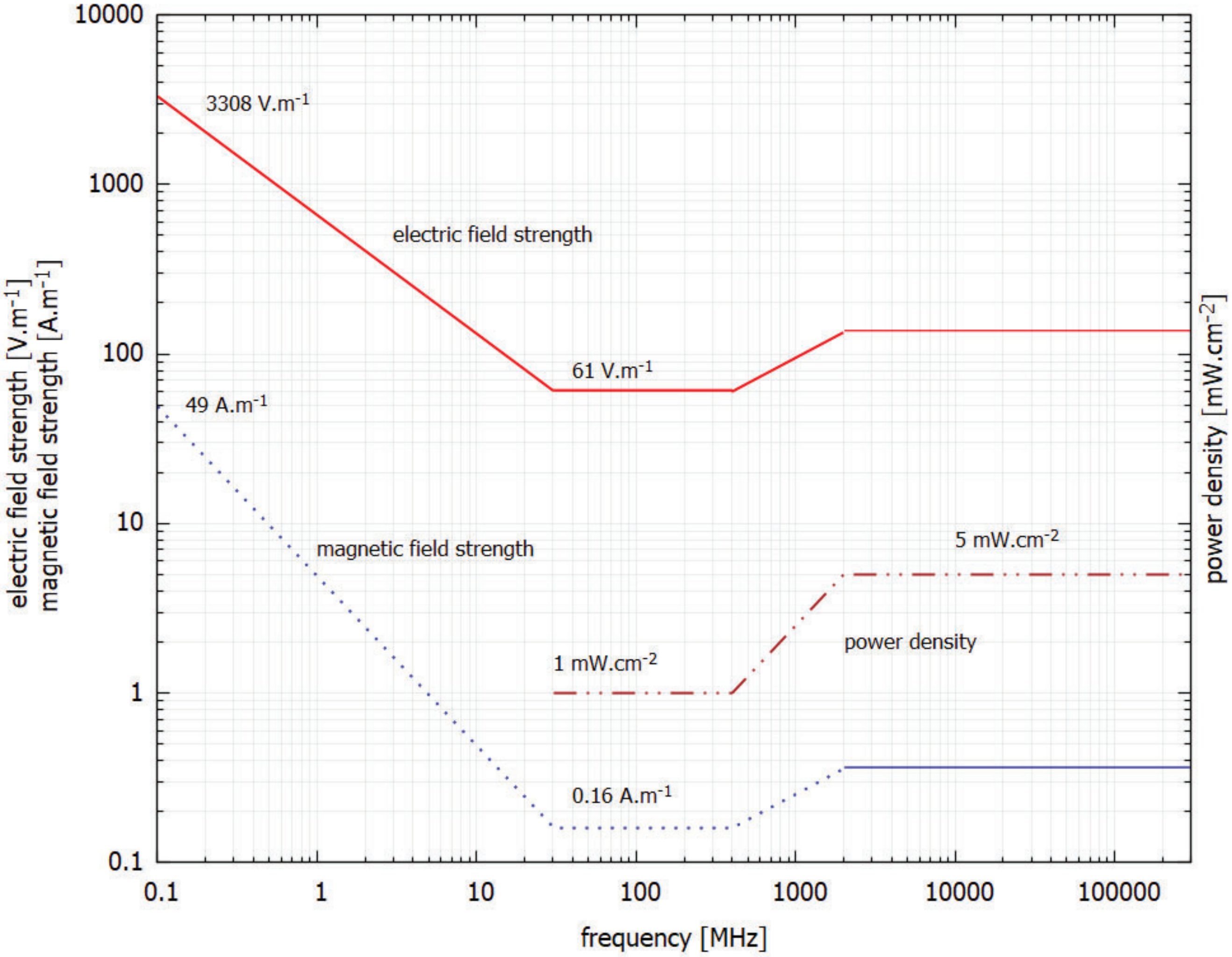

Figure 19. The 2020 exposure limits for occupational whole body exposure to time-varying electric and magnetic fields for frequencies between 100 kHz and 300 GHz.

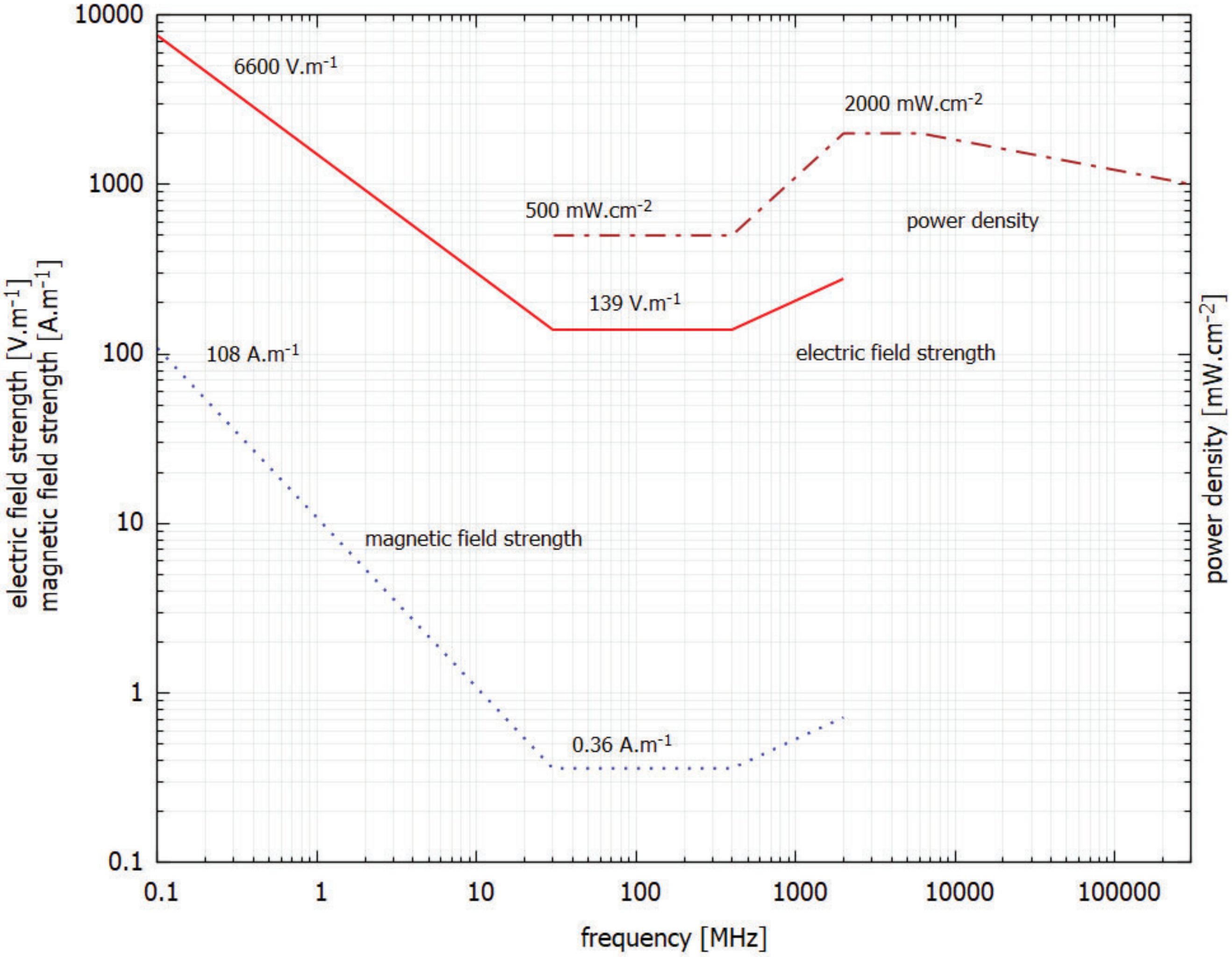

Figure 20. The 2020 exposure limits for occupational local exposure (head and limbs) to time-varying electric and magnetic fields for frequencies between 100 kHz and 300 GHz.

Institute of Electrical and Electronics Engineers (IEEE) C95.1-2019

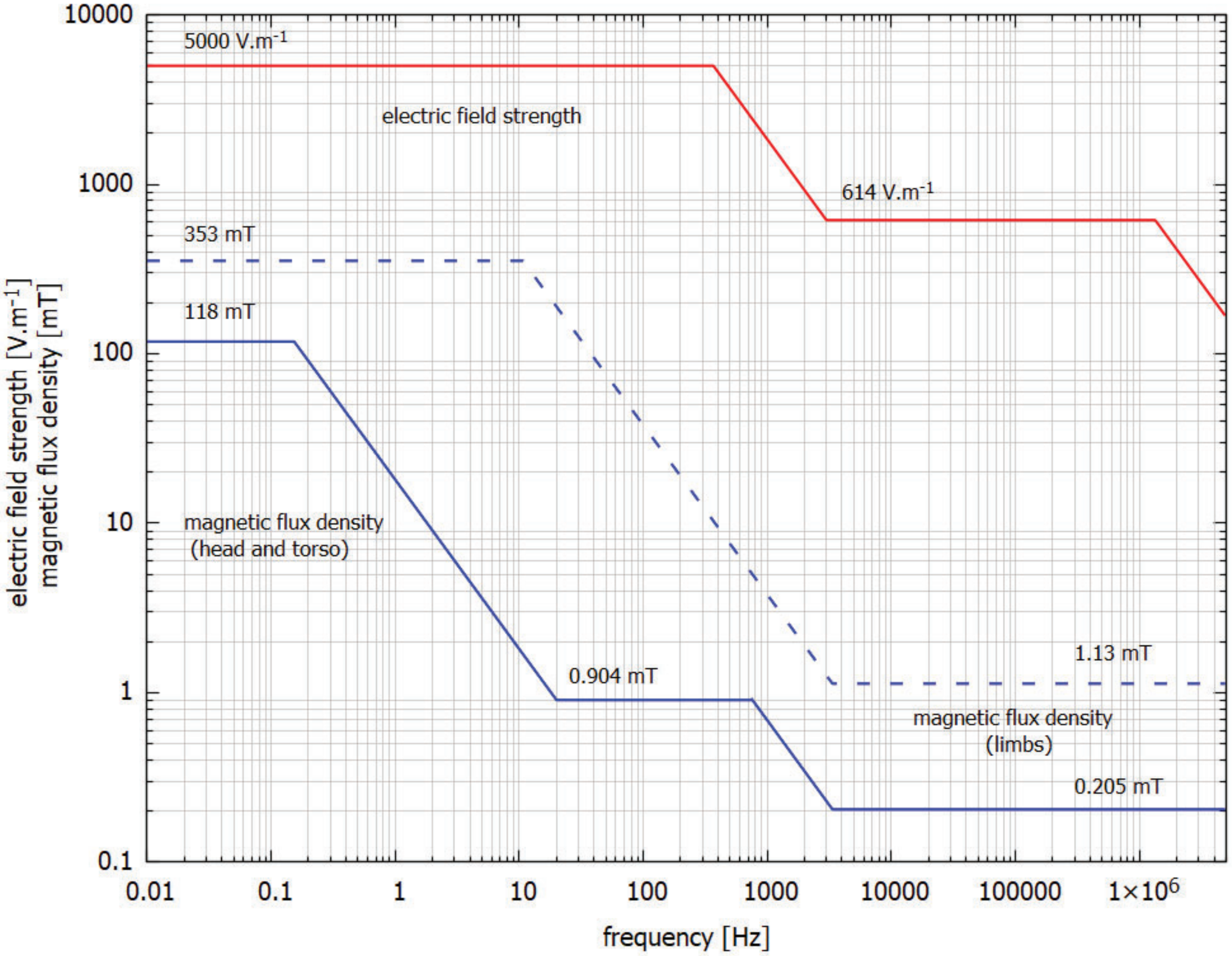

Figure 21. The exposure limits for unrestricted environments for frequencies from DC to 5 MHz.

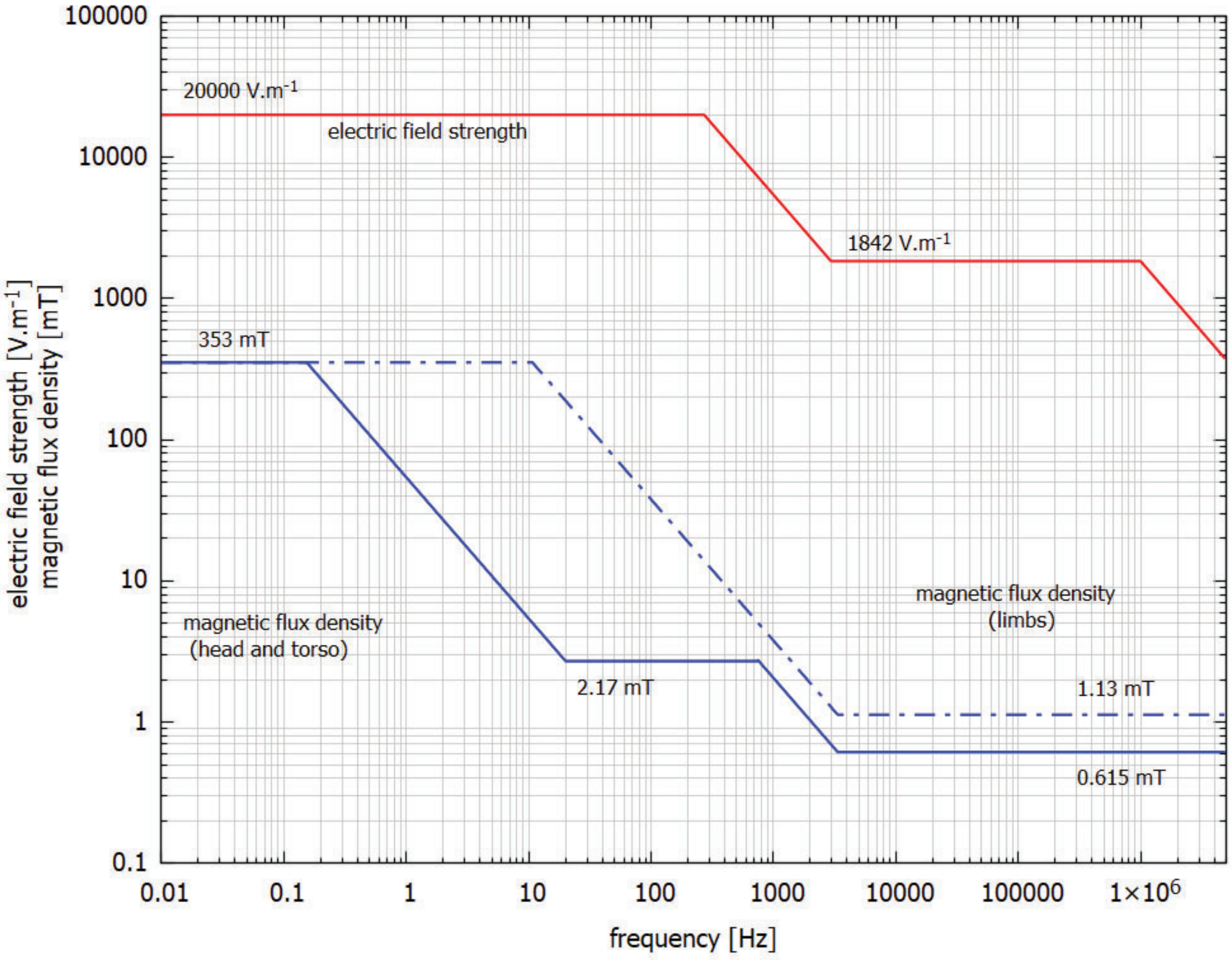

Figure 22. The exposure limits for restricted environments for frequencies from DC to 5 MHz.

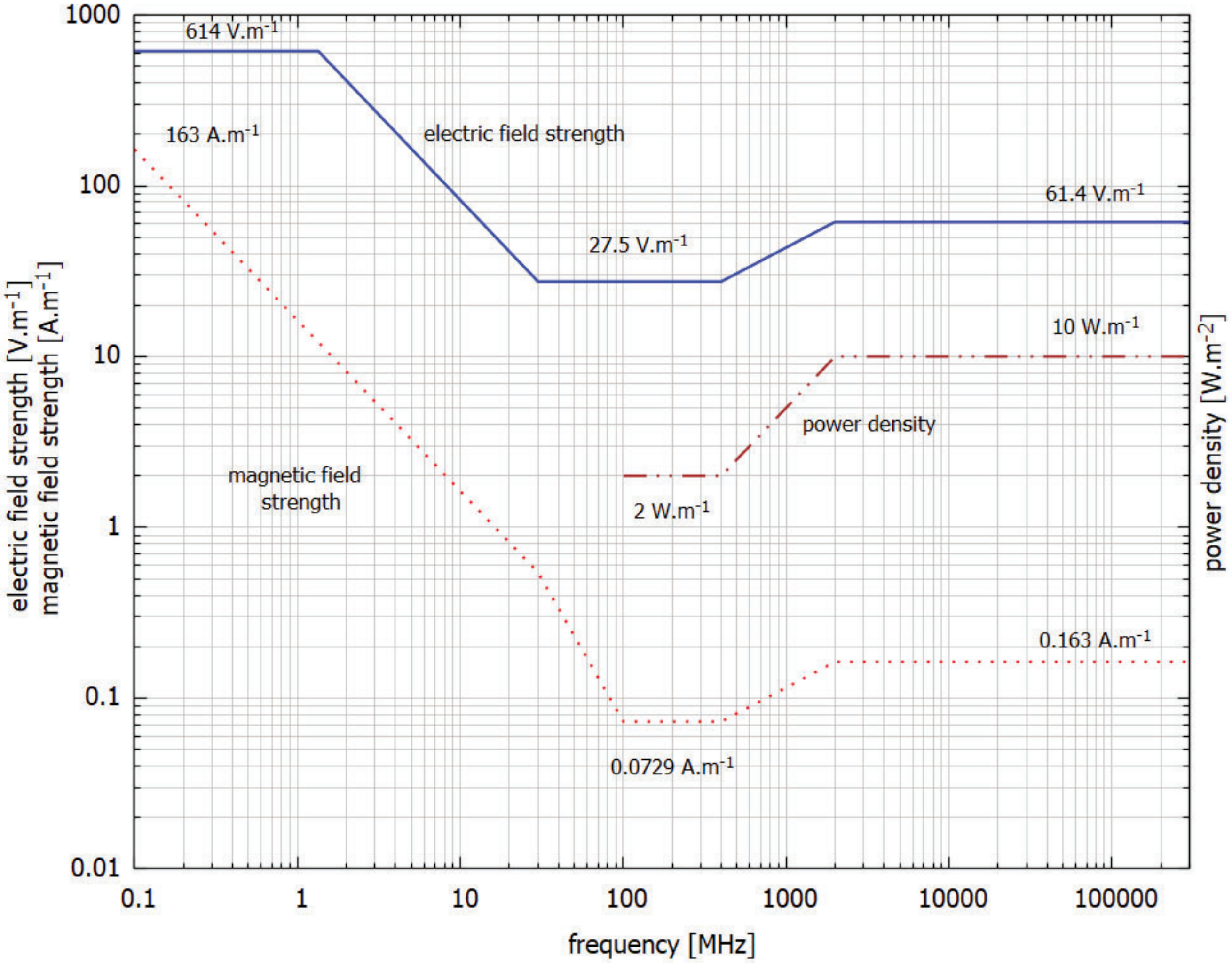

Figure 23. The exposure reference level for persons in unrestricted environments for frequencies between 100 kHz and 300 GHz.

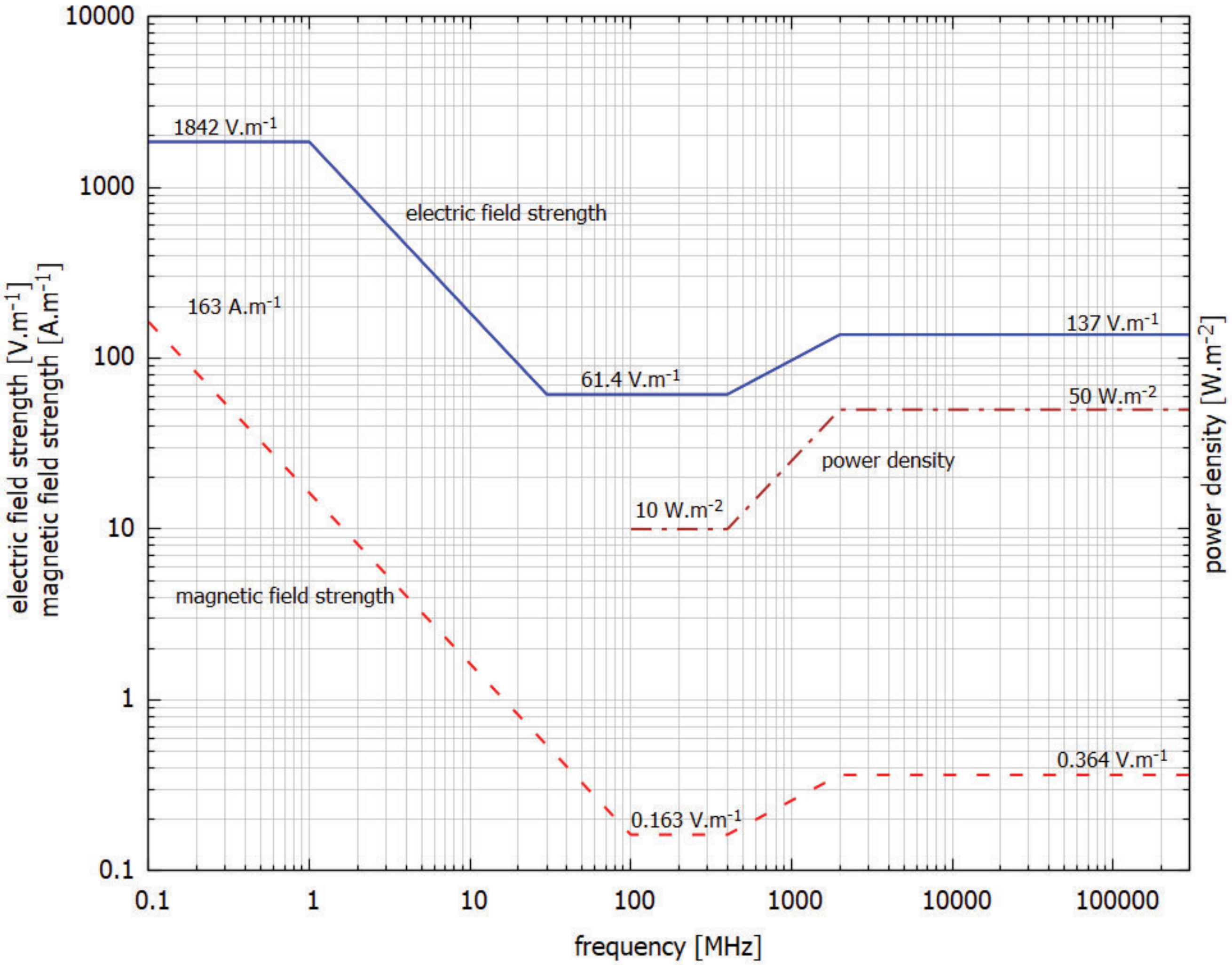

Figure 24. The exposure reference levels for persons in restricted environments for frequencies between 100 kHz and 300 GHz.

Equipment vendors

The following is a short list of vendors that manufacture or sell equipment that measure exposure to non-ionizing radiation. No endorsement or recommendation is given, nor implied.

- AlphaLab Inc.
- Keysight Technologies
- L3 - Narda
- PCE Instruments
- Reed Instruments
- Trifield
- Wavecontrol

References

[1] IEEE Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 Hz to 300 GHz
IEEE Standards Coordinating Committee 39
IEEE Std C95.1-2019

[2] Biological Effects And Exposure Criteria For Radiofrequency Electromagnetic Fields
NCRP Report No. 86

[3] Simple Formulas for Transmission Through Periodic Metal Grids or Plates
Lee, Zarrillo, and Law
IEEE Transactions on Antennas and Propagation, vol. AP-30, No. 5, pp 904 – 909, September 1982.