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INTEGRATED PERFORMANCE SOLUTIONS, INC.
BOULDER, COLORADO

NIOSH INVESTIGATOR:
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I. SUMMARY

On February 20, 1991, the National Institute for Occupational Safety and Health (NIOSH) received a request from Integrated Performance Solutions, Inc. in Boulder, Colorado for an evaluation of occupational exposure to 60 hertz (Hz) electric and magnetic fields produced by an electrical resistive heating system installed at the workplace. Visits were made to the worksite on March 20, 1991, and a follow-up visit was made to the manufacturer of the heating system on August 22, 1991.

Extra low frequency (ELF) measurements were made on the heating system at two different locations. The maximum levels of ELF were found to be 200 volts per meter (V/m) and 10 milligauss (mG) at one location and 4.9 V/m and 1.9 gauss (G) at the other location. These levels are to be compared to the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs) of 25,000 V/m and 10 G, respectively.

Based on the data collected in this survey and comparison with current exposure criteria, the NIOSH investigator concludes that no occupational hazard existed on the days of measurement from exposure to the electrical resistive heating systems installed at these locations. Recommendations are offered in Section VI to further reduce exposure levels.

Keywords: SIC 3634 (Electric Housewares and Fans), ELF radiation, electrical resistive heating, electromagnetic radiation.

II. INTRODUCTION

In February 1991, the National Institute for Occupational Safety and Health (NIOSH) received a request from management at the Integrated Performance Solutions, Inc. (IPSI) in Boulder, Colorado for an evaluation of occupational exposure to extremely low frequency (ELF) radiation emitted by an electrical resistive heating system at their facility. Radiation measurements were performed at IPSI on March 20, 1991. A follow-up visit was made with the manufacturer of the heating system on August 22, 1991. Measurements made during the second visit were performed at a different location than were the measurements for the first visit.

III. BACKGROUND

IPSI is a small two-person high-tech consulting company that provides software and computer support to companies in the training business.

The heating system installed at the facility, when operating at the necessary voltage and current, can produce both electrical and magnetic fields. These fields, if they exist at certain magnitude, could pose occupational radiation exposure consideration. An important feature of the resistive heating system is the heating element. Unlike other heating systems that use single or multiple wire/cables as the resistive element, this particular room-installed system uses a continuous 31 centimeter (cm) wide, 1 millimeter (mm) thick, bronze screen mesh positioned in the floor as the element. The mesh is folded and laid out in long runs parallel to the longest room dimension. Every room, on all floors (mainly up and downstairs) is normally designed in this manner. Zone heating is accomplished by electrically connecting special controllers to the mesh.

A step-down transformer is used with the heating element to produce 10-12 watts per lineal foot and screen temperatures up to 125^{o}F. The surface of the floor covering can reportedly reach about 85^{o}F. The system does not stay on continuously, but rather is designed to cycle around a pre-set level. In addition, the system has a safety feature that cuts off the heating elements for 10 minutes after being on for 55 minutes--if not switched off before.

These systems are very effective in areas of the country where electrical costs are comparable to costs associated with other energy delivery modalities. This unique heating system is presently manufactured by one company who reports over 1000 installations.

The NIOSH investigator was informed that the heating system had been installed about 10 years ago. However, IPSI had occupied the worksite for only 2 years. Moreover, since the time IPSI had been at its present worksite, the heating system was on for short periods of time due to concerns about its safety.

IV. **MATERIALS AND METHODS**

A Holaday Industries, Inc. Model HI-3602 ELF Sensor, connected to a HI-3600 survey meter, was used to document the electric and magnetic fields. The sensor also can measure the frequency as well as waveforms produced by the electromagnetic fields. The electric field (E-field) strength can be measured either in volts per meter (V/m) or kilovolts per meter (kV/m). The magnetic field strength (H-field) is expressed in units of milligauss (mG).

The NIOSH investigator made measurements of E- and H-field strengths at IPSI as well as at another Colorado site. The latter survey was arranged by the manufacturer of the heating system during the August visit. This second site (a private home) contained a heating system similar to that at IPSI and was installed by the same heating manufacturer. The visit to the second site was to learn more about the operating characteristics of the system and to obtain additional exposure data. Since both heating systems were not in routine use on the days of measurements, they were turned on by either IPSI personnel or the manufacturer. Measurements of the maximum E- and H-field were taken in several rooms on all floors at both sites. At least two readings were taken at each measurement site and the average of the two readings was recorded.

The limited number of measurements taken at both sites were not intended to represent an in-depth evaluation of the radiation fields at the site, but were, rather, intended to approximate occupational exposure levels found on the days of measurement. All measurements were made during daylight hours at floor, waist, and ceiling heights.

The heating system manufacturer invited a representative of the Public Service Company of Colorado (PSCC) to assist in the E- and H-field measurements at the second site. That individual used a calibrated Electric Field Measurement Model 116 magnetic field meter to document the magnetic field intensity levels. All measurements with this meter made on August 22, 1991, by the PSCC representative agreed to within 5% with those recorded by NIOSH using its meters on the same day.

V. **EVALUATION CRITERIA**

The American Conference of Governmental Industrial Hygienists (ACGIH) has published Threshold Limit Values (TLVs) for sub-radiofrequency electric and magnetic fields. At 60 hertz (Hz), which is classified as extremely low frequency (ELF), the E-field intensity TLV is 25,000 volts per meter (V/m) and the magnetic flux density TLV is 1 millitesla (mT) or 10 gauss (G). In general, the experience of the NIOSH investigator has been that both of these levels are far in excess of the reported typical exposure levels found in most environments and/or workplaces.

The basis of the ELF E-field TLV is to minimize occupational hazards arising from spark discharge and contact current situations. The H-field TLV addresses induction of magnetophosphenes in the visual system and production of induced currents in the body.

VI. RESULTS

Maximum measurements of the 60 Hz E- and H-field intensities at IPSI were 200 V/m and 10 mG, respectively. The H-fields levels were highest at the floor and ceiling (8 feet high) and were the lowest at waist level (4 feet from the floor). The H-field intensity levels also varied as a function of mesh direction as well as type of floor covering (i.e., carpeted areas less than tiled areas).

Maximum E- and H-field intensity levels measured at the site chosen by the manufacturer were different from those measured at IPSI. E- and H-field intensities of 4.9 V/m and 1.9 G were recorded. The same pattern of H-field intensities were observed both at the manufacturer's chosen location and at IPSI (i.e., high at floor and ceiling, and low at mid-level). Figure 1 shows this pattern. In addition, the same varying pattern of H-field intensities with mesh direction in the room was also observed and is shown in Figures 2 and 3.

Waveforms captured by the Holaday meter and displayed on a digital oscilloscope were found to be of the normal sinusoidal varying 60 Hz type at both sites.

VII. CONCLUSIONS AND RECOMMENDATIONS

While the pattern of exposures was similar at both sites, the NIOSH investigator believes the differences in the magnitude of the E- and H-field intensity levels between the two sites is a result of the heating systems being turned on to two different heating settings when measurements were made.

The results reported in this evaluation can be compared with the results shown in Figures 4 and 5.[1-7] Another source of comparison is the results reported by Wertheimer and Leeper for E- and H-fields in homes having ceiling cable electric heat systems. In that report it was stated that ceiling cable heat exposes room occupants to magnetic fields of about 10 mG and an electric field in the range of 10-50 V/m. Ambient fields in most homes, including those with the more common baseboard electric heat are otherwise less than 1 mG and about 10 V/m.[8]

The levels of electric fields measured at both locations in this study were at least on the same order of magnitude as the other reports indicate. The magnetic field levels measured at the second location were higher compared to either the worksite location, results from other types of sources (as shown in Figures 4 and 5), or the above cited reference.

Based on the results obtained on the days of measurement, the occupational exposure to 60 Hz electric and magnetic fields at both locations were below present ACGIH TLV levels.

The following recommendations are offered to further reduce potential exposures to the fields produced by these heating systems:

1. While it has not yet been shown that occupational exposure to either high or low levels of 60 Hz radiation, exclusive of electrical shock issues, is harmful, it may be prudent to limit access and exposure to these fields until more is known about the long-term effects on tissues. For example, one way to control access and exposure to E- and H-fields might be to limit the use of the heating system during certain times of the day. Another way would be to minimize the time one works in close proximity to either the floor or ceiling.

2. The manufacturer should label or mark their system with basic information about operating characteristics of the heating system, such as levels of E- and H-fields produced, frequency, etc. This may require them to purchase or acquire the use of such instrumentation to assist in documenting basic exposure parameters until further research, or exposure standards are developed, which specify other measurement parameters.

3. Attached with this evaluation are two enclosures. Appendix A is a resource paper published by the Electric Power Research Institute (EPRI) that discusses electric and magnetic field fundamentals. Appendix B is a copy of the background to the present ACGIH TLV.

VIII. **REFERENCES**

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IX. AUTHORSHIP AND ACKNOWLEDGEMENTS

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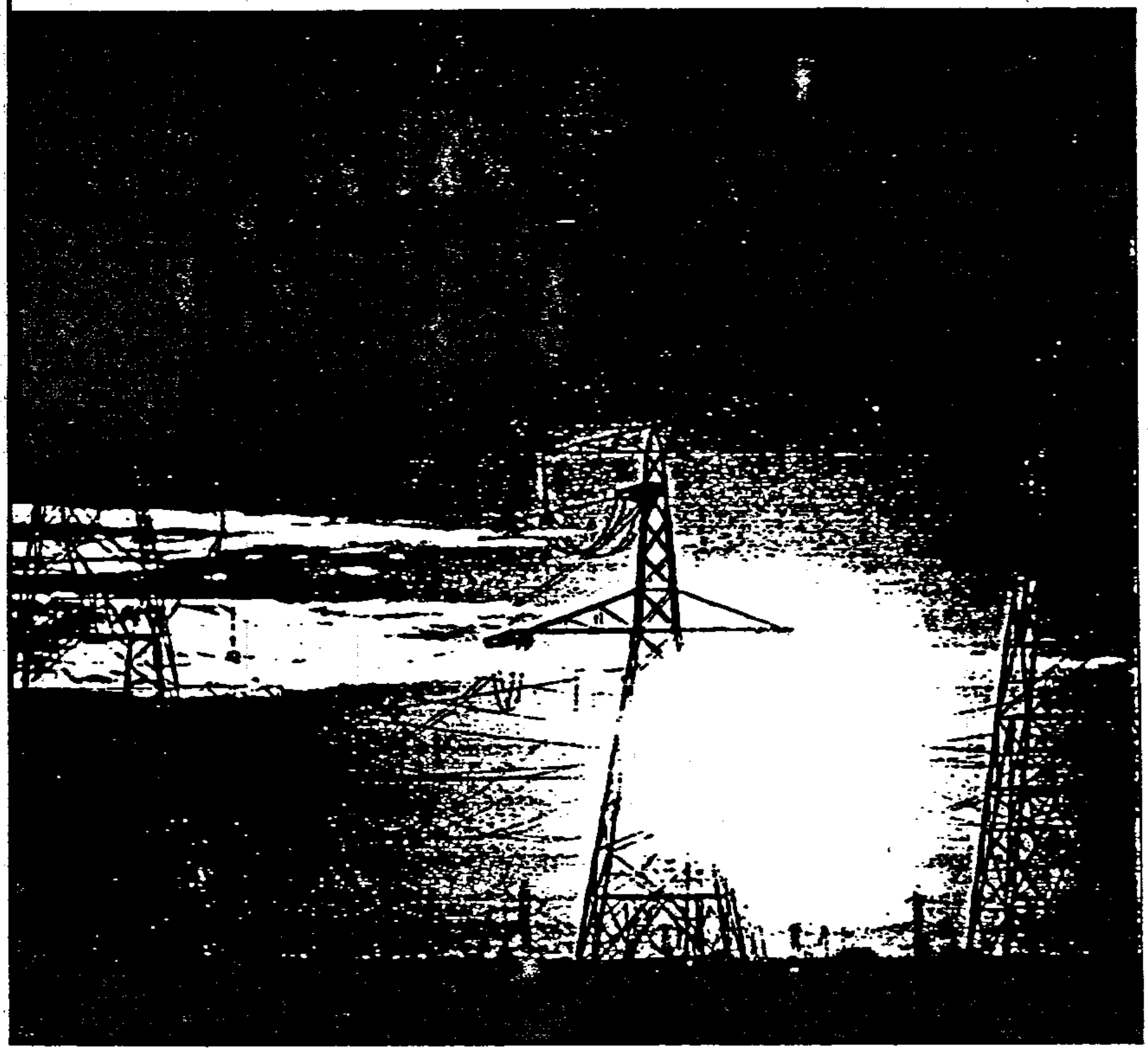
APPENDIX A

Electric and Magnetic Field Fundamentals

An EMF Health Effects Resource Paper

EPRI



ELECTRIC
POWER
RESEARCH
INSTITUTE

INTRODUCTION

This resource paper reviews the physical principles that are essential for understanding the potential relationship between power-frequency alternating-current electric and magnetic field **exposures** and health effects. It provides the general technical reader with a basic background in the principles of electricity, the physical characteristics of electric and magnetic fields, and the interactions between these fields and biological systems. The following topics are discussed:

- Basic electrical concepts
- Scalar and vector fields
- The non-ionizing electromagnetic energy spectrum
- The ambient electric and magnetic field environment
- Power-frequency field measurement
- Biological scaling and experimental design

This paper adopts two conventions that are not yet universally used in the power-frequency electric and magnetic field research literature. First, "EMF" is used to designate electric and/or magnetic fields. Although this acronym overlaps with the sometimes still-used engineering terminology, "electromotive force" (abbreviated, "emf"), the increasing acceptance of "EMF" as a generic label for power-frequency fields in their role as environmental agents dictates its use herein. Second, because the scientific community uses the International System of units (SI units) almost exclusively, this paper will follow SI conventions with only parenthetical listing of other units as necessary.

ELECTRICAL CONCEPTS

This section reviews the basic physical principles governing the transmission of electric power.

Electric Charge

Electric charge is carried by electrons and protons. Electrons are negatively charged; protons carry an equal positive charge. Like charges repel; opposite charges attract. For example, two protons will repel each other, while a proton and an electron will be drawn together. The force exerted by electric charges is very strong, approximately a billion-billion-billion-billion times stronger than the earth's gravity. In matter, the numbers of electrons and protons are usually equal and the forces due to electrical charges balance. When a substance has an excess of either protons or electrons, it carries a net electric charge.

Electric charge, whether positive or negative, is measured in units called **coulombs (C)**. One coulomb represents the combined charge of 6×10^{18} electrons or protons, and individual electrons and protons have charges of 1.6×10^{-19} C.

Conductors and Insulators

A **conductor** is any material in which electrons can move freely and thus redistribute charge. Conductivity is the property of a material that determines the amount of current that will flow through a unit area of the material. It is expressed in units of **siemens** per meter (S/m). Metals are usually good conductors. When the electrons in a material are not free to move readily, the material is said to be an **insulator**.

All substances are conductors and insulators to different degrees. The property which defines the insulating characteristics of a material is resistivity. (Resistivity and conductivity are reciprocal quantities.) If you compared the movement of electrons in two different materials and found that electrons move much less freely in the first material, then that material has greater resistivity. **Resistance**, a more familiar term, describes the insulating characteristic of a particular specimen of a material. Resistance is expressed in units called **ohms**, and one ohm is the reciprocal of one siemens (1/S). A perfect conductor has zero resistance, and a perfect insulator has infinite resistance.

A net charge on a conductor will be evenly distributed over the surface of the conductor. A conductor is **grounded** when it is connected to something that accepts excess charge, such as the earth.

Current

The movement of charge through a conductor is called **current** and is measured in **amperes (A)**. One ampere is the movement of one coulomb of charge per second past a given point. When there is a closed path for current to follow, a **circuit** is formed. With direct current, the current flows in one direction at a constant rate; with alternating current, however, both the rate and direction of current flow change periodically over time. The **frequency** of change for alternating current is expressed in cycles per second, or hertz (Hz). Electric power systems in the United States, Canada and Mexico operate at 60 Hz, while 50 Hz is the principal frequency in use elsewhere, including all of Europe. For 60-Hz alternating current, one complete cycle lasts 1/60 of a second, and current direction reverses twice during that time.

Electric potential

In order for current to flow from one point to another, there must be a difference in electric **potential** between the two points. Potential is the work required to move a unit charge to a given point from an infinite distance. A difference in potential is

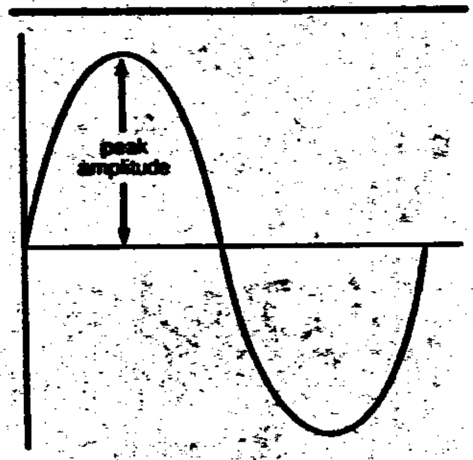


Figure 1. The changing magnitude (amplitude) and direction of a sinusoidally varying voltage or current. The root-mean-square (rms) is used to quantify the voltage or current. For a sinusoidally varying current or voltage, the rms value equals the peak amplitude divided by $\sqrt{2}$ (1.414) (Winch, 1963).

defined by the work necessary to carry a unit charge from one point to another. This work is measured in joules per coulomb, or volts. Therefore, a potential difference, or **voltage,** in a conductor creates moving charges, i.e., a current. With alternating current, both the voltage and current vary sinusoidally, as shown in Figure 1.

The property of a material that allows it to maintain a potential difference between two points is the **dielectric strength,** which has units of volts per meter (V/m). When the potential difference between two points exceeds a material's dielectric strength, electrical breakdown occurs, charged particles (ions) are formed, and current flows. The dielectric strength of air is about 2500 kV/m.

A non-conducting or insulating material can also be called a **dielectric.** Two conductors separated by a dielectric material form a **capacitor.** Charge may build up on the conductors and create a potential between them. When the potential exceeds the dielectric strength of the material between the conductors, current will flow.

Power

Power is the rate at which energy is used and may be expressed as joules per second, or watts (W). It is the product of voltage and current: volts x amperes = joules/coulomb x coulombs/second = joules/second = watts. A 100-W electric light bulb uses 100 joules per second, or 100 watts, of electrical power. Electric energy consumption is measured in kilowatt-hours (kWh), where one kWh is 100 W of power drawn for 10 hours, or any other product of power in kW and time in hours that equal one.

A potential of 120 V is supplied across most electrical outlets in the home. A 100-W bulb then draws about one ampere of current. A home that uses 720 kWh per month would average 1000 W and 8.3 A continuously. In contrast, a 765-kV transmission line may carry approximately 2 million kW and 2500 A. The voltage in transmission lines is reduced to the level used in the home by **transformers,** which convert power at high voltage and low current to power at lower voltage and higher current.

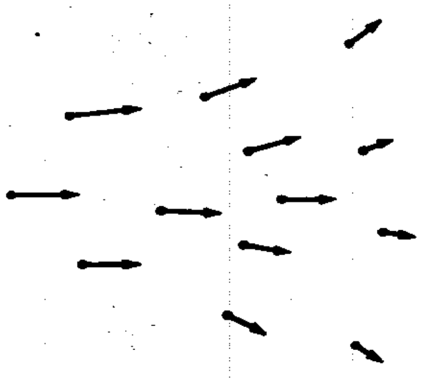


Figure 2. A vector field depicted by arrows whose magnitude and direction represent the values of the vector field at the points from which the arrows are drawn. The arrow lengths get shorter as the field weakens (Feynman, 1964).

FIELD CONCEPTS

A **field** is defined as any physical quantity that can take on different values at different points in space. Temperature, which varies over different locations on and above the earth's surface, is one example. The value of temperature at any point can be written mathematically as T(x,y,z). The coordinates (x,y,z) define the exact location in space, and T(x,y,z) is a number expressing the temperature measured at that location. If the coordinates (x,y,z) happen to be the location of a U. S. Weather Service thermometer, then T(x,y,z) will probably be the temperature reported on the local television station. Time, specified by the variable, t, can also be included, and the time-dependent temperature field would then be designated as T(x,y,z,t). The temperature field is an example of a *scalar field,* which defines a quantity (temperature) on a numeric scale (a thermometer).

A **vector field** differs from a scalar field in that there is a direction associated with the value at each point in the field. The velocity field of a flowing liquid is an example of a vector field. It describes both the speed and direction of the liquid's movement. Vectors are written with bold type, so the velocity field can be written as **v**(x,y,z,t).

Because these mathematical concepts are somewhat abstract, several techniques are used to help visualize vector fields. Two methods are shown in Figures 2 and 3 which depict the same vector field. In Figure 2, the field is represented by a set of arrows whose lengths and directions indicate the values of the field vector at the points from which the arrows are drawn. The arrows get shorter as the field weakens. As Figure 3 shows, the same field can also be represented by drawing lines that are tangent to the direction of the field vector at each point. The density of the lines is proportional to the magnitude of the field vector; i.e., the number of lines per unit of perpendicular area is proportional to the field magnitude.

THE ELECTROMAGNETIC SPECTRUM

The electromagnetic spectrum encompasses the frequency range of non-ionizing electromagnetic energy. Visible light occupies only a small portion of the electromagnetic spectrum, and different frequencies of visible light produce different colors. Similarly, other frequencies produce television, radio and microwave transmissions. Figure 4 shows the entire electromagnetic spectrum by frequency and wavelength.

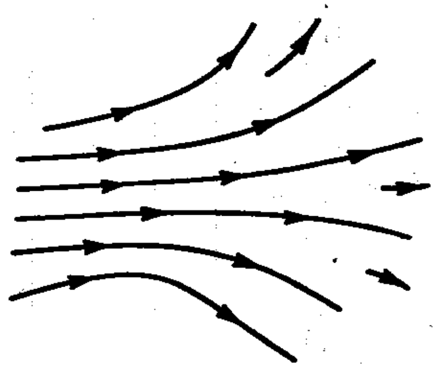


Figure 3. A vector field depicted by lines that are tangent to the direction of the field vector at every point. The density of the lines is proportional to the magnitude of the field (Feynman, 1964).

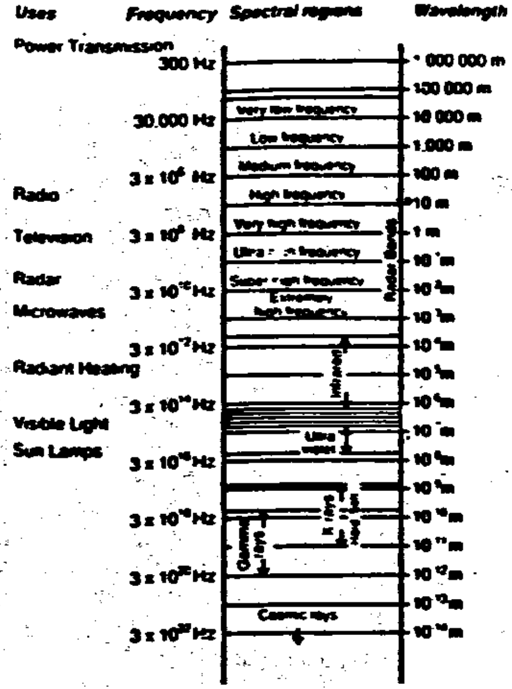


Figure 4. The electromagnetic spectrum shown by frequency and wavelength. At a frequency of 60 Hz and a wavelength of 5,000,000 m, power transmission is at the top of the figure. Frequencies less than 300 Hz are designated as the ELF (extremely-low-frequency) range.

The product of frequency and wavelength of electromagnetic energy equals the speed of light, 3×10^8 m/sec. The wavelength associated with the 60-Hz power frequency is very long—5000 km. In comparison, the wavelength of television transmission at 10^8 Hz is 3 m.

Electromagnetic Radiation
When the distance from a source of electromagnetic energy is large compared to the wavelength, the electric and magnetic fields are linked and are considered together as a radiating *electromagnetic* field. The area in which the linked fields can be observed is called the "far," or "radiation," zone. A television signal—with its relatively small 3-m wavelength—broadcasts, or radiates, as an electromagnetic quantity.

Electric and Magnetic Fields
When the distance from the source is small with respect to the wavelength, the electric and magnetic fields are not linked. The fields are independent and can be considered as separate entities. One is always in the so-called "near," or "static," zone of power-frequency fields because of their long wavelength. Hence, power-frequency fields behave as and may be treated as separate, independent, non-radiating *electric and magnetic* fields at any realistic observation point. In fact, any radiation of the fields would be contrary to the goal of transmitting energy along the conductors with minimum loss of energy. Thus, when studying power-frequency fields, we must consider separate electric and magnetic fields, not radiating electromagnetic fields.

Electric and magnetic fields are vector fields. They can have different magnitudes and directions at different points in space and time and can be described by the methods discussed above. These fields are defined by the forces they exert on electrical charges.

Electric Fields. Electric fields are created by electric charges. The electric field, **E**, is defined by the magnitude and direction of the force it exerts on a static unit charge, $\mathbf{E} = \mathbf{F}/q$, where **E** is the electric field (at the location of q), **F** is the force, and q is the charge. **E** has units of newtons/coulomb, or volts/meter. The magnitude of **E** describes the voltage gradient, or the difference in voltage between two points in the field. Electric field levels near high-voltage transmission lines are in the range of kilovolts per meter (kV/m).

Magnetic Fields. Magnetic fields are created by moving electric charges. Just as the electric field is defined by the force on a unit charge, the magnetic field is defined by the magnitude and direction of the force exerted on a moving charge or current, $\mathbf{F} = q(\mathbf{v} \times \mathbf{B})$, where **F** is the force, q is a unit charge, **v** is the vector describing the magnitude and direction of the relative motion of the field and the charge, and **B** is the magnetic flux density. Relative motion, **v**, occurs when a charge moves through the field or the field moves past the charge (see Figure 5). The force can also be written as a scalar quantity, $F = qvB(\sin \phi)$, where ϕ is the angle between the vectors **v** and **B**. The magnetic flux density, which may be represented by lines of induction per unit area, has units of newton-second/coulomb-meter, or weber/meter^2, or tesla, T. One tesla is 10,000 gauss (G), a frequently used engineering unit. For environmental levels, the

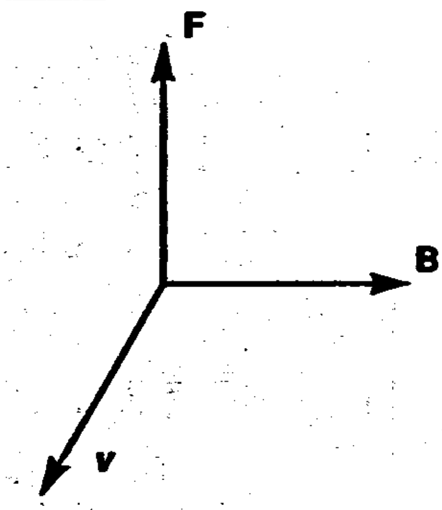


Figure 5. The spatial relationship of magnetic flux density, relative velocity, and force for a charge moving relative to a magnetic field. The vector cross product, $\mathbf{v} \times \mathbf{B}$, results in a force vector that is perpendicular to the plane defined by v and B.

microtesla (μT), which is one millionth of a tesla, is more convenient. One microtesla equals 10 milligauss.

The magnetic flux density, **B**, quantifies the magnetic field as **E** quantifies the electric field. It is related to the magnetic field, **H**, through the magnetic permeability, μ, by the relation $\mathbf{B} = \mu\mathbf{H}$. The magnetic permeability depends on the medium. The magnetic permeability of a vacuum is designated μ_0. The magnetic permeability of air and biological matter is essentially the same as μ_0. This means that the magnetic flux density is unchanged by the presence of these materials.

A system of units that preceded the present SI system was the CGS system, which has units of centimeters, grams, and seconds. In the cgs system, the permeability, μ_0, is dimensionless and equal to one. As a result, **B** numerically equals **H** in the CGS system, and the two came to be used interchangeably. The value of μ_0 in the SI system is

1.26×10^{-6} henry per meter (H/m). This factor can be used to convert true field magnitude, which has units of A/m, to flux density, in T, by the expression $\mathbf{B} = \mu_0\mathbf{H}$.

AMBIENT ELECTRIC AND MAGNETIC FIELDS

Naturally Occurring Fields

The earth has an essentially static, vertically-directed electric field of about 130 V/m near the surface that is caused by the separation of charges between the earth and the ionosphere. The earth is negative and the potential in the air is positive. Together, they form a spherical capacitor, with the two conducting surfaces being the earth and the upper atmosphere. The difference in electrical potential is maintained by lightning which carries negative charges to earth. There is a diurnal cycle to the field magnitude, as shown in Figure 6. On average, about 2000 thunderstorms are occurring at any time, and there are about 100 lightning flashes per second worldwide. Fields of 10 kV/m or higher can occur during thunderstorms.

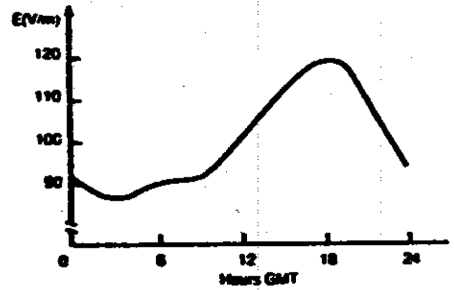


Figure 6. Average diurnal variation of the atmospheric potential gradient. The peak occurs near 7:00 pm Greenwich Mean Time (GMT) (2:00 pm Eastern Standard Time) and is associated with peak thunderstorm activity around the globe (Feynman, 1964).

The geomagnetic field is also essentially static, with a magnetic flux density that averages about 50 µT (0.5 G) at middle latitudes, but varies between the equator and the poles. Measured vertically, it is greatest at the magnetic poles—about 67 µT (0.67 G)—and has a value of zero at the magnetic equator. In the horizontal direction, it reaches a maximum of about 33 µT (0.33 G) at the equator and is zero at the magnetic poles.

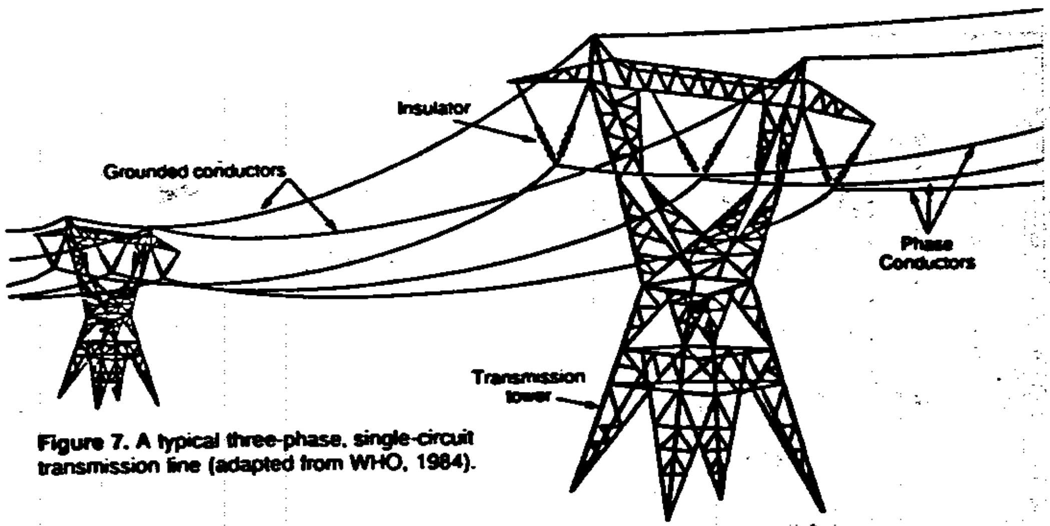


Figure 7. A typical three-phase, single-circuit transmission line (adapted from WHO, 1984).

Power-Frequency Fields

Fields near Overhead Transmission Lines. 60-Hz electric and magnetic fields near high-voltage transmission lines have been more extensively studied and better characterized than for any other environment. In the United States, bulk electric power is most commonly conveyed by overhead alternating-current transmission lines. Lines with voltage ratings of less than 345 kV are designated as *high voltage*, while 345 kV and above lines are *extra high voltage*. A typical transmission line consists of three phase conductors per circuit. Multiple, or "bundled," conductors for each phase are used at higher voltages to control corona-related effects (such as audible noise) or on heavily loaded lines. Each phase is sequentially separated from the other by 120 "electrical degrees," or one-third cycle, with respect to the 60-Hz power frequency. Figure 7 shows a typical transmission line.

Transmission lines are identified by their nominal phase-to-phase voltage. Typical nominal voltages in the United States are 69, 138, 230, 345, 500 and 765 kV. In practice, however, operating voltage, which is the difference between any two phases of the three-phase circuit, can vary from the nominal rating by a few percent, usually above the nominal rating. For example, a 500-kV line operates at around 540 kV, phase-to-phase, with a range from 525 to 550 kV. Phase-to-ground voltage is equal to the phase-to-phase voltage divided by $\sqrt{3}$ (1.732).

Electric fields near transmission lines are usually measured or calculated at a height of 1 m above the ground. The magnitude is largely determined by the line voltage and the height of the conductors above the ground. Figure 8 shows a plan view of electric field contours at 1 m above the ground calculated for a 500-kV double-circuit (six conductor bundles) line. The calculated values apply to a location above an open, flat surface. Conducting objects such as vegetation, buildings or people will "perturb," or distort, the field and can act as shields to reduce levels significantly.

Electric currents flowing through transmission line phase conductors also create a magnetic field. For a 500-kV double-circuit line, the maximum magnetic flux density at a height of 1 m above the ground is about 35 µT (350 mG). The flux density beneath a 765-kV line carrying 1000 A per phase is about 15 µT (150 mG). Figure 9 shows calculated magnetic flux density profiles for different transmission lines. Unlike the electric field, the magnetic field is not normally perturbed nor shielded by objects.

Fields near Underground Conductors. When the conductors are placed underground rather than strung overhead from towers or poles, the characteristics of the fields change. Because the conductors are closer together underground, the fields tend to be lower due to the canceling effect of the phase differences among the conductors. On the other hand, people can be in closer proximity to underground conductors, so the

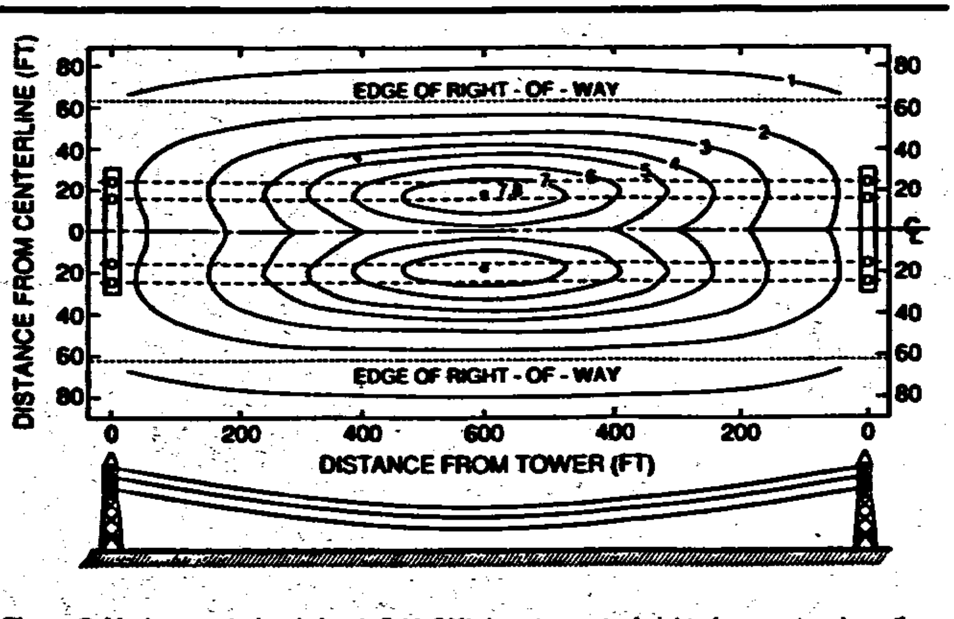


Figure 8. Maximum calculated electric field (kV/m) contours at a height of one meter above the ground for a 500-kV double-circuit line. Highest levels occur at midspan, where the conductors are closest to the ground (BPA, 1985).

exposure levels may be similar to those of overhead lines. Thus, putting the conductors underground does not necessarily eliminate EMF exposure.

Fields in the Home Environment. Electric and magnetic fields are produced by virtually every use of electricity. Electric field levels in the centers of different rooms in a typical United States home are shown in Table 1, while Table 2 lists levels measured 30 cm (about 1 foot) away from various home appliances. The difference in levels between the two tables shows how rapidly the electric field decreases with distance from a source.

These electric field levels are orders of magnitude below those that can exist under transmission lines. Because these data result from limited measurements, they should be considered anecdotal. They do indicate, however, the general range of levels that may be encountered in the home, although wide variability must be expected.

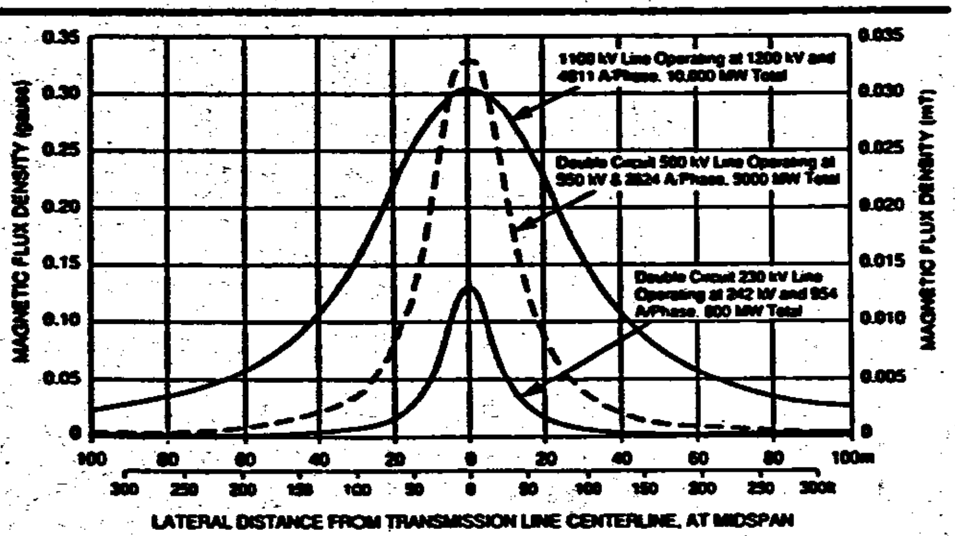


Figure 9. Profile of calculated magnetic flux density at a height of one meter above the ground at midspan for three different transmission lines (BPA, 1985).

Researchers have also measured magnetic flux densities in the vicinity of nearly 100 different household appliances. Table 3 shows the magnetic flux densities at distances of 3 cm, 30 cm and 1 m from different appliances. At 30 cm, levels range from 0.03 µT to 30 µT (0.3–300 mG). As Table 3 shows, magnetic flux densities decrease rapidly with distance. Unlike electric field levels in the home, magnetic flux densities close to some household appliances are higher than encountered under transmission lines.

Residential background magnetic fields, away from appliances, range from 0.05 to 1 µT (0.5–10 mG). Sources, some of which are shown in Figure 10, include distribution lines, residential grounding systems, unusual wiring configurations within the residence, and nearby high-voltage transmission lines.

Distribution lines that serve residences use a variety of primary voltages and transformer connections, generally having both **primary** and **secondary** conductors (wires). The primary conductors may include a **neutral** wire, which may or may not be connected to the secondary neutral wire. The secondary conductors generally consist of two energized wires at the nominal residential voltage of 120 V (240 V between the two wires) and the neutral which is at ground potential (0 V). The secondary conductors serve a number of residences, while service to each home is supplied via a **service drop**, which is generally a three-wire line connected to the secondary conductors.

The primary neutral wire is grounded at each distribution transformer and at regular intervals along the line. The secondary neutral wire is grounded at the distribution transformer and at each residence's service entrance. This multi-grounding practice is responsible for some of the sources of magnetic field found in residences.

Distribution lines can be subdivided into three separate magnetic field sources: balanced currents in primary wires, balanced currents in secondary wires, and net current which is the vector sum of all individual wire currents.

Table 1. 60-Hz electric field levels at the center of various rooms in a typical U.S. home, 1974.

Location	V/m
Laundry room	0.8
Dining room	0.9
Bathroom	1.2–1.5
Kitchen	2.6
Bedroom	2.4–7.8
Living room	3.3
Hallway	13.0

Source: WHO, 1984

Table 2. Typical 60-Hz electric field levels at 30 cm from 115-V home appliances.

Appliance	V/m
Electric blanket	250
Broiler	130
Stereo	90
Refrigerator	60
Electric Iron	60
Hand Mixer	50
Toaster	40
Hair Dryer	40
Color TV	30
Coffee pot	30
Vacuum cleaner	16
Incandescent bulb	2

Source: WHO, 1984

Table 3. 60-Hz magnetic flux densities near various appliances.

Appliance	Magnetic Flux Density, µT		
	3 cm	30 cm	1m
Can openers	1000–2000	3.5–30	0.07–1
Hair dryers	6–2000	0.01–7	<0.01–0.3
Electric shavers	15–1500	0.08–9	<0.01–0.3
Drills	400–800	2–3.5	0.08–0.2
Mixers	60–700	0.6–10	0.02–0.25
Portable heaters	10–180	0.15–5	0.01–0.25
Blenders	25–130	0.6–2	0.03–0.12
Television	2.5–50	0.04–2	0.01–0.15
Irons	8–30	0.12–0.3	0.01–0.025
Coffee makers	1.8–25	0.08–0.15	<0.01
Refrigerators	0.5–1.7	0.01–0.25	<0.01

Source: WHO, 1987

An important distinction exists between the magnetic field produced by balanced currents and that produced by net current. The field from net current is inversely proportional to the distance from the line, while balanced currents produce a field inversely proportional to the *square* of the distance. Magnetic field values predicted from only balanced distribution line currents are thus likely to underestimate measured levels. This is because the net current becomes the major contributor to the magnetic field far from the line. In the case of underground distribution lines, the field is usually negligible. It decreases rapidly with distance if the currents are balanced, or else the field decreases approximately in inverse proportion to the distance, indicating the presence of net current.

The spatial distribution of a magnetic field caused by a net current is more uniform throughout a residence than that caused by balanced currents (the magnetic field from balanced currents decreases more rapidly with distance), and much more uniform than the field caused by current in the grounding system.

A grounding system consists of all of the connections between the service drop neutral wire and the electrical ground at the residence. A common situation, one in which the neutral wire at the service entrance is grounded to a metallic water pipe, allows neutral current from a 120-V household appliance to return in part through the service drop neutral wire and in part through the ground connection to the water line. The current returning on the water pipe (the ground current) flows to the water main, and then to neighboring water pipes and service drop neutral wires. Grounding of the neutral wire at the service entrance, which is done for safety reasons, can have the effect of creating a current loop and thus be a source of magnetic field.

Usually, only a small percentage of a residence's neutral return current flows back to the transformer as ground current through water pipes or other ground return paths. However, in some homes a high proportion of the neutral return current may flow back to the transformer on ground paths other than the service drop neutral wire. Ground currents, when they occur, are most often found on water

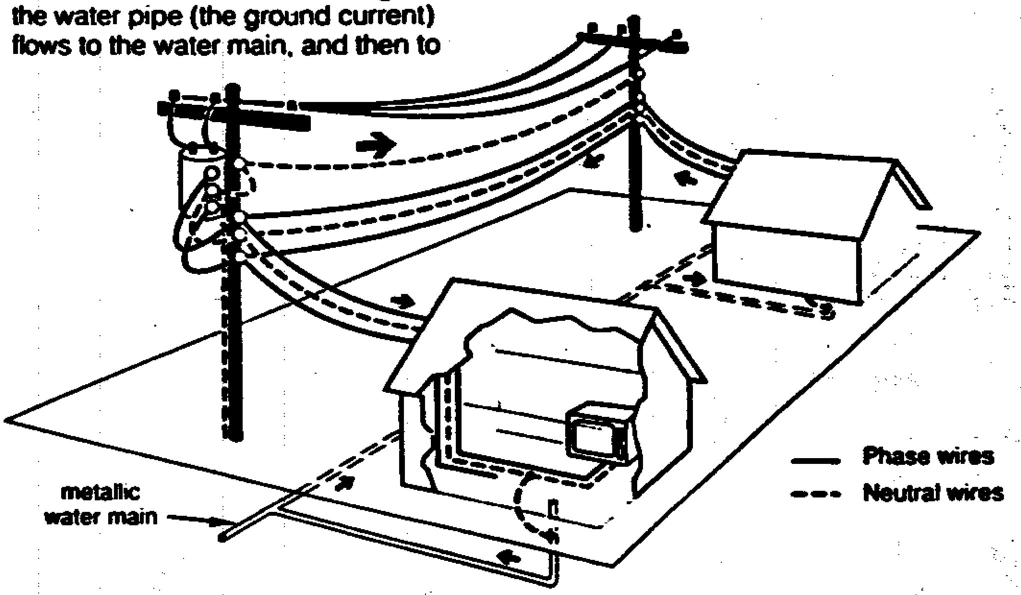


Figure 10. Some sources of residential magnetic fields: appliance (television), grounding system and overhead distribution line (primary current, secondary current and net current). The arrows indicate the direction of net current flow at a point in time. The net current may change with changing load, such as appliance usage. Other possible sources include unusual residential wiring, underground distribution lines and nearby high-voltage transmission lines.

pipes. In some cases, however, ground current may also flow on cable television lines, telephone lines, ground rods, connections to steel concrete reinforcing rods, and on other connections to ground.

Ground currents produce a very non-uniform magnetic field within the living space of a residence because of the widely differing distances from the grounding system current paths. The field also varies greatly in time since the ground current changes every time a 120-V appliance is switched on or off.

House wiring is generally not a source of magnetic field except in some unusual situations. For example, a source occurs when a neutral wire is grounded at another location inside the residence in addition to being grounded at the service entrance. This produces a current loop and a possible magnetic field source.

Finally, currents in a transmission line can be a dominant source of magnetic field in a home near the right of way, even though the distance may be greater than that from the distribution line supplying the residence.

A summary of residential magnetic field characteristics for different sources is provided in Table 4. The table includes appliances as a field source, as discussed previously, as well as observations on the harmonic content of the field.

Fields in the Workplace. Electric field levels in the work environment range from 1–100 V/m in offices to 10 kV/m or more in specialized settings. For persons in "electrical occupations," such as electricians, power station operators and electronics workers, values are typically on the order of 10 to 100 V/m. Typical magnetic flux densities in offices range from 0.1 to 10 µT (1–100 mG). Levels for electrical occupations also range to around 10 µT (100 mG), although magnetic flux densities of 8,000 µT (80 G) have been measured near furnaces in the electrosteel industry, and as high as 1,700 µT (17 G) near a spot welding machine.

FIELD MEASUREMENT

Many different techniques are available for measuring power-frequency electric and magnetic fields. Commonly used methods for measuring both types of fields are described here.

Electric Fields

Electric fields are usually measured with a free-body dipole probe, a device that measures the induced current between two halves of an isolated conducting body. Commercial meters often use a rectangular box for the conducting body. The current flowing between the two halves of the box in an electric field parallel to the axis of the box is proportional to the electric field magnitude and the frequency; i.e., $I = kf\mathbf{E}$, where I is the current, f is the frequency (60 Hz), **E** is the electric field vector (magnitude and direction), and k is a proportionality factor (see Figure 11).

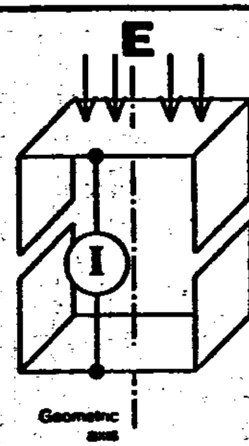


Figure 11. Diagram of a free-body electric field meter. The device measures the current induced between its two isolated, conducting halves. The current indicates the electric field magnitude according to the relation I = kfE (see text) (IERE, 1988).

Magnetic Fields

Instruments in common use for measuring power-frequency magnetic fields are based on Faraday's law of voltage induction in a conducting coil (see Figure 12). A conducting loop in a time-varying magnetic field will have a voltage induced in the loop. The device can be made more sensitive by increasing the number of loops, forming a coil. The induced voltage is calculated using the equation, $V = 2\pi fnAB$, where f is the frequency, n is the number of turns in the coil, A is the area of the coil, and **B** is the magnetic flux density perpendicular to the plane of the coil (see Figure 12). Simple coils must be oriented within the field to obtain a maximum reading. Other, more sophisticated instruments having three mutually perpendicular coils do not require manual orientation.

Table 4. Residential magnetic field source characteristics.

Source	Spatial Distribution in living space	Temporal distribution	Harmonic Content
Transmission Lines	Practically uniform	Relatively uniform	Practically zero
Distribution Primary	Non-uniform	Diurnal cycle	Low 3rd harmonic (1–5%)
Distribution Secondary	Non-uniform	Very non-uniform	High harmonic content
Net Current	Slightly non-uniform	Non-uniform	High 3rd harmonic (20–150%)
Grounding System	Very non-uniform	Very non-uniform	High up to 11–17th harmonics
Unusual Wiring	Very non-uniform	Very non-uniform	May be high
Appliances	Extremely non-uniform	Extremely non-uniform	Depends on appliance

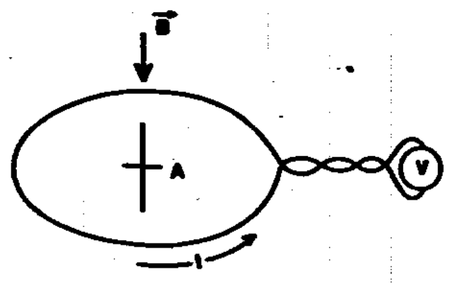


Figure 12. Diagram of a magnetic field coil. The magnetic flux density is proportional to the voltage induced in the coil, with proportionality constant $2\pi fnA$ (see text) (WHO, 1987).

BIOLOGICAL SCALING

EMF interactions vary between different animal species and between animals and humans. Interactions with biological organisms occur in two major ways. First, any conducting object (including animals or humans) will perturb and enhance an electric field. Second, both electric and magnetic fields will induce currents in biological material. In order for laboratory experiments using animals to be relevant to the EMF exposures humans might experience, the experimental design must take into account how these interactions differ from species to species. The following discussion briefly explains these interactions.

Field Perturbation

The electric field measurement method described above yields the value of the unperturbed electric field. This is the quantity that is reported when electric field levels are cited. When a conducting object is placed in the field, however, the field is perturbed and enhanced. The amount of enhancement depends on the shape and size of the object as well as on its orientation within the field. A thin disk perpendicular to the field will cause little perturbation. A sphere, on the other hand, will concentrate the electric field at its top up to several times the unperturbed value. The field level just above the head of a grounded, standing person is 15 to 20 times that of the unperturbed field. The enhanced electric field will have different values at different points about a human body and will vary with body posture.

Because enhancement depends on the object's size and shape, the electric field will be different around laboratory animals than around people. For example, pigs and rats, both of which have been used in electric field biological effects research, concentrate the field above their backs by factors of about 7 and 4, respectively, rather than the factor of 15 to 20 that applies to humans. Again, this value depends on posture. A rat rearing on its hind legs will create a higher level than when standing on all four legs—in fact, more like the levels an upright human will experience. In general, the field will be higher about surfaces with smaller radii of curvature.

Unlike electric fields, magnetic fields are virtually unperturbed by the presence of biological materials.

Induced Currents

Electric Field Exposure. When a conducting object is placed in a 60-Hz electric field, the force of the field causes charges within the object to move and electric fields and currents are induced in the object. If the object is grounded, the current all flows to earth, and this total current is referred to as the short-circuit-to-ground current. The amount of current flowing through various parts of a person standing in an electric field depends on the surface field, the conductivity of the body tissue through which the current passes, and the degree of grounding. Induced currents can be quantified as current density, which is the amount of current flowing through a unit area of the body. In a person, for example, the current density is less through the torso than through the neck and is greatest through the ankles.

Just as electric field levels are concentrated in different amounts at the surfaces of different animals, short-circuit currents and internal current densities also vary among different animals. Thus, the same unperturbed electric field will induce a total current in a person that is about two orders of magnitude greater than in a rat. The induced current density may be one order of magnitude greater.

Time-varying magnetic fields induce electric fields and currents in the bodies of humans and animals according to Faraday's law, $\mathbf{E} = \pi fr\mathbf{B}$, where $\mathbf{E}$ is the electric field, f is the frequency, r is the radius of a loop that is perpendicular to the magnetic field, and $\mathbf{B}$ is the magnetic flux density. The larger the radius, r, the larger the electric field and current. For a person, the radius is greatest at the perimeter of the body. The current density, $\mathbf{J}$, induced by the electric field, $\mathbf{E}$, is found from $\mathbf{J} = S\mathbf{E}$, where S is the electrical conductivity in siemens. As an example, a 10-μT (100-mG) field will induce an electric field of 0.19 mV/m if the radius is 0.1 m, which approximates the size of the human torso. The conductivity of the body is 0.2 S/m, so the resulting current density will be about 0.38 mA/m^2. An equivalent current density will be present in the ankles of a grounded person in an electric field of about 200 V/m.

Experimental Design

Because EMF interactions are so variable, levels of electric and magnetic fields used in laboratory research must be scaled to produce comparable **doses** in different species. For example, unperturbed electric fields of 30 kV/m for pigs and 65 kV/m for rats have been used to simulate the exposure of a person to a 12-kV/m field, considering maximum surface electric field as the dose of interest.

Experiments investigating the biological effects of EMF field exposure must identify the parameter to be studied and base the scaling on that variable. For example, if a study is designed using the assumption that the electric field is the important parameter, then scaling should be done based on the field. If a biological effect is associated with induced current, then current density would be the parameter of interest and scaling should be based on it. Faraday's law, $\mathbf{E} = \pi fr\mathbf{B}$, discussed in the section above, can be used to compare current densities due to different magnetic field levels in different species, for example, by considering differences in the radius of body dimensions.

SI System Units

Quantity	Unit
Current	ampere (A)
Current density	ampere/meter² (A/m²)
Electric field	volt/ meter(V/m)
Frequency	hertz (Hz)
Magnetic field strength	ampere/ meter (A/m)
Magnetic flux	weber (Wb)
Magnetic flux density	tesla (T)=Wb/m²
Permeability	henry/meter (H/m)
Voltage	volt (V)

Prefixes

micro	µ	10^{-6}	one millionth
milli	m	10^{-3}	one thousandth
kilo	k	10^{-3}	one thousand
mega	M	10^{-6}	one million

GLOSSARY

ampere - the unit of electrical current

capacitor - a device made of two conducting surfaces separated by a dielectric.

circuit - a closed conducting path for the flow of current.

conductor - a material that allows the flow of charge. The wires on transmission lines are conductors.

coulomb - the unit of electric charge (C). One electron (or proton) has a charge of about 1.6×10^{-19} C.

current - the flow of electrically charged particles. The unit is the ampere (A).

dielectric - an insulator or non-conductor.

dielectric strength - the maximum electric field strength that a material can withstand without breaking down and conducting.

dose - The amount of a physical or chemical agent interacting with a person.

electric field - a vector field describing the electrical force on a unit charge in space. Electrical charges are a source of electric fields. The electric field from a power line is an alternating, 60-Hz field due to charges on the conductors. The intensity of the electric field is expressed in volts per meter (V/m) or kilovolts per meter (kV/m).

ELF (extremely low frequency) - denotes the frequency range below 300 Hz.

exposure - the joint occurrence in space and time of of a person and the physical or chemical agent of concern, expressed in terms of the environmental level of the agent.

field - any physical quantity that takes on different values at different points in space.

frequency - the number of complete cycles of a periodic waveform per unit time. The units of frequency are Hertz (Hz), which is equivalent to cycles per second.

gauss - the historical, CGS unit of magnetic flux density. One gauss (G) is 10^{-4} T or 10^{-4} Wb/m².

grounding - connecting a charged conductor to something that will accept excess charge, for example the earth.

insulator - a non-conductor.

magnetic field - a vector field describing the force experienced by magnetic objects or moving electrical charges in space. The unit is the ampere per meter (A/m).

magnetic flux density - a vector field, which is related to the magnetic field by the magnetic permeability of the medium. The SI unit is the tesla (T). The historical unit is the gauss (G), which equals 10^{-4} T.

net current - the vector sum of the currents in all the wires (primaries, secondaries and neutrals) of a line.

neutral - the wire at ground potential carrying the return current of energized wires.

ohm - the unit of electrical resistance.

potential - electrical potential energy, defined at a point by the work necessary to bring a unit positive charge to the point from an infinite distance. The difference in potential between two points is defined by the work necessary to carry a unit positive charge from one to the other. The unit is the volt (V).

power - the time rate at which work is done. Electrical power is proportional to the product of current and voltage. The unit is the watt (W).

primary (of a distribution line) - the set of wires at voltages higher than the residential service voltage (120 V) that are connected to distribution transformers.

resistance - the property of conductors that determines the current produced by a given difference of potential. The unit is the ohm. A difference of potential of one volt will produce a current of one ampere in a circuit where the resistance is one ohm.

rms - root mean square, the square root of the average of the squares of individual values. For a sinusoidal variable, such as the amplitude of 60-Hz alternating current, the rms value equals the peak value divided by the square root of two. Measured and calculated E&M field levels are usually rms values.

secondary (of a distribution line) - the set of three wires, two of which are energized at the residential service voltage (120 V) and one of which is the neutral at ground potential, connected to one (or more) distribution transformer(s). The secondary supplies the service drops of individual residences.

service drop - the line composed of three wires (two energized wires at 120 V and a neutral) that goes from the secondary of a distribution line to a residence.

siemens - the SI term for the mho, the historical unit of conductance.

tesla - the unit of magnetic flux density (T), equivalent to 10^4 gauss (G) or 1 Wb/m^2.

transformer - a device for changing from one set of voltage and current levels to another while conserving their product, electrical power.

voltage - the electrical potential energy difference per unit charge between two points. The unit is the volt (V).

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APPENDIX B

*SUB-RADIOFREQUENCY (30 kHz and below) MAGNETIC FIELDS

These TLVs refer to the amplitude of the magnetic flux density (B) of sub-radiofrequency magnetic fields in the frequency range of 30 kHz and below to which it is believed that nearly all workers may be exposed repeatedly without adverse health effects. The magnetic field strengths in these TLVs are root-mean-square (rms) values. These values should be used as guides in the control of exposure to sub-radiofrequency magnetic fields and should not be regarded as a fine line between safe and dangerous levels.

Routine occupational exposure should not exceed:

$$B_{TLV} = \frac{60}{f} \text{ mT}$$

where f is the frequency in Hz.

At frequencies below 1 Hz, the TLV is 60 mT (i.e., 600 gauss).

The permissible magnetic flux density of 60 mT/f at 60 Hz corresponds to a maximum permissible flux density of 1 mT. At 30 kHz, the TLV is 2 μT which corresponds to a magnetic field strength of 1.6 A/m.

For workers with cardiac pacemakers, the TLV may not protect against electromagnetic interference with pacemaker function. Some models of cardiac pacemakers have been shown to be susceptible to interference by power-frequency (50/60 Hz) magnetic fields as low as 0.1 mT. It is recommended that, lacking specific information on electromagnetic interference from the manufacturer, pacemaker wearers should not be exposed to fields exceeding one-tenth of the TLV at frequencies above 6 Hz (e.g., the exposure limit would be 0.1 mT at 60 Hz and 1.0 mT at 6 Hz). Below 6 Hz, exposure of pacemaker wearers should be limited to 1.0 mT.

*SUB-RADIOFREQUENCY (30 kHz and below) AND STATIC ELECTRIC FIELDS

These TLVs refer to the maximum unprotected workplace field strengths of sub-radiofrequency electric fields (30 kHz and below) and static electric fields that represent conditions under which it is believed that nearly all workers may be exposed repeatedly without adverse health effects. The electric field intensities in these TLVs are root-mean-square (rms) values. The values should be used as guides in the control of exposure and, due to individual susceptibility, should not be regarded as a fine line between safe and dangerous levels. The electric field strengths stated in this TLV refer to the field levels present in air, away from the surfaces of conductors (where spark discharges and contact currents may pose significant hazards).

Occupational exposures should not exceed a field strength of 25 kV/m from 0 Hz (DC) to 100 Hz. For frequencies in the range of 100 Hz to 4 kHz, the TLV is given by:

$$E_{TLV} = \frac{2.5 \times 10^6}{f} \text{ V/m}$$

where f is the frequency in Hz.

A value of 625 V/m is the exposure limit for frequencies from 4 kHz to 30 kHz.

Notes:

1. This TLV is based on limiting currents on the body surface and induced internal currents to levels below those that are believed to produce adverse health effects. Certain biological effects have been demonstrated in laboratory studies at electric field strengths below those permitted in the TLV; however, there is no convincing evidence at the present time that occupational exposure to these field levels leads to adverse health effects.
2. Field strengths greater than approximately 5–7 kV/m can produce a wide range of safety hazards such as startle reactions associated with spark discharges and contact currents from ungrounded conductors within the field. In addition, safety hazards associated with combustion, ignition of flammable materials and electro-explosive devices may exist when a high-intensity electric field is present. Care should be taken to eliminate ungrounded objects, to ground such objects, or to use insulated gloves when ungrounded objects must be handled. Prudence dictates the use of protective devices (e.g., suits, gloves, and insulation) in all fields exceeding 15 kV/m.
3. For workers with cardiac pacemakers, the TLV may not protect against electromagnetic interference with pacemaker function. Some models of cardiac pacemakers have been shown to be susceptible to interference by power-frequency (50/60

Hz) electric fields as low as 2 Kv/m. It is recommended that, lacking specific information on electromagnetic interference from the manufacturer, the exposure of pacemaker wearers should be maintained at or below 1 kV/m.

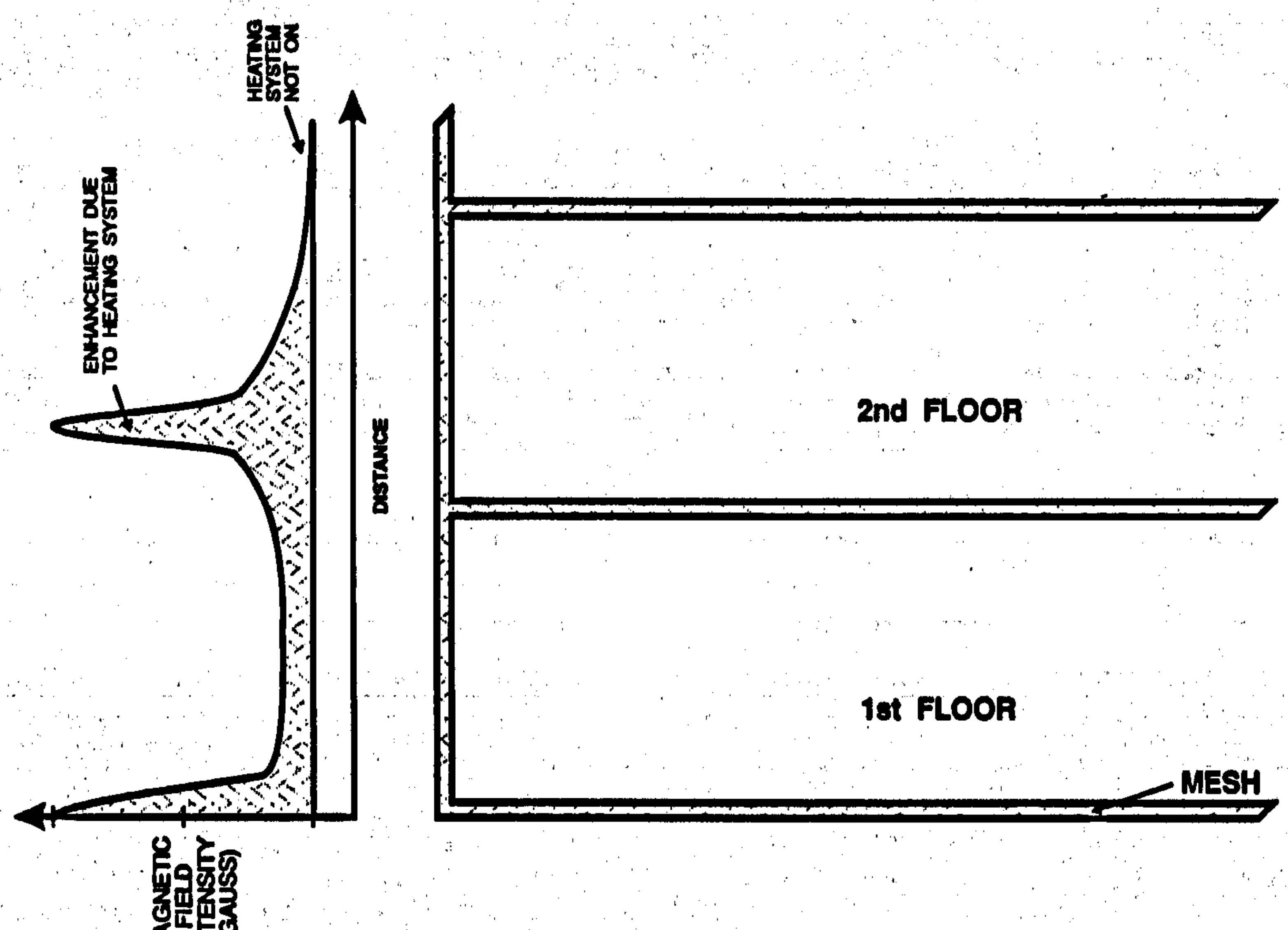


Figure 1. Spacial component of Magnetic Field at work sites

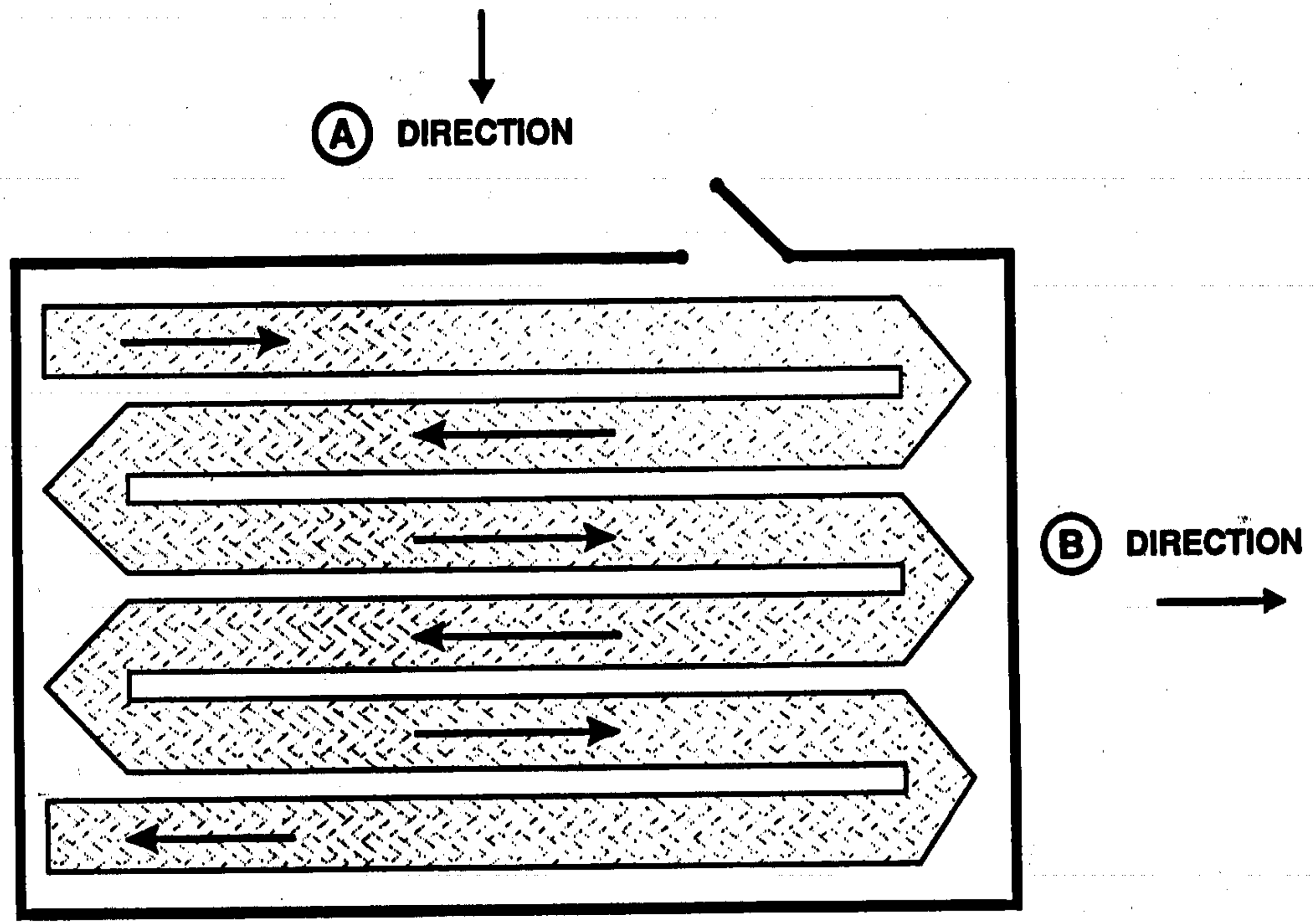


Figure 2. Typical bronze mesh layout in room

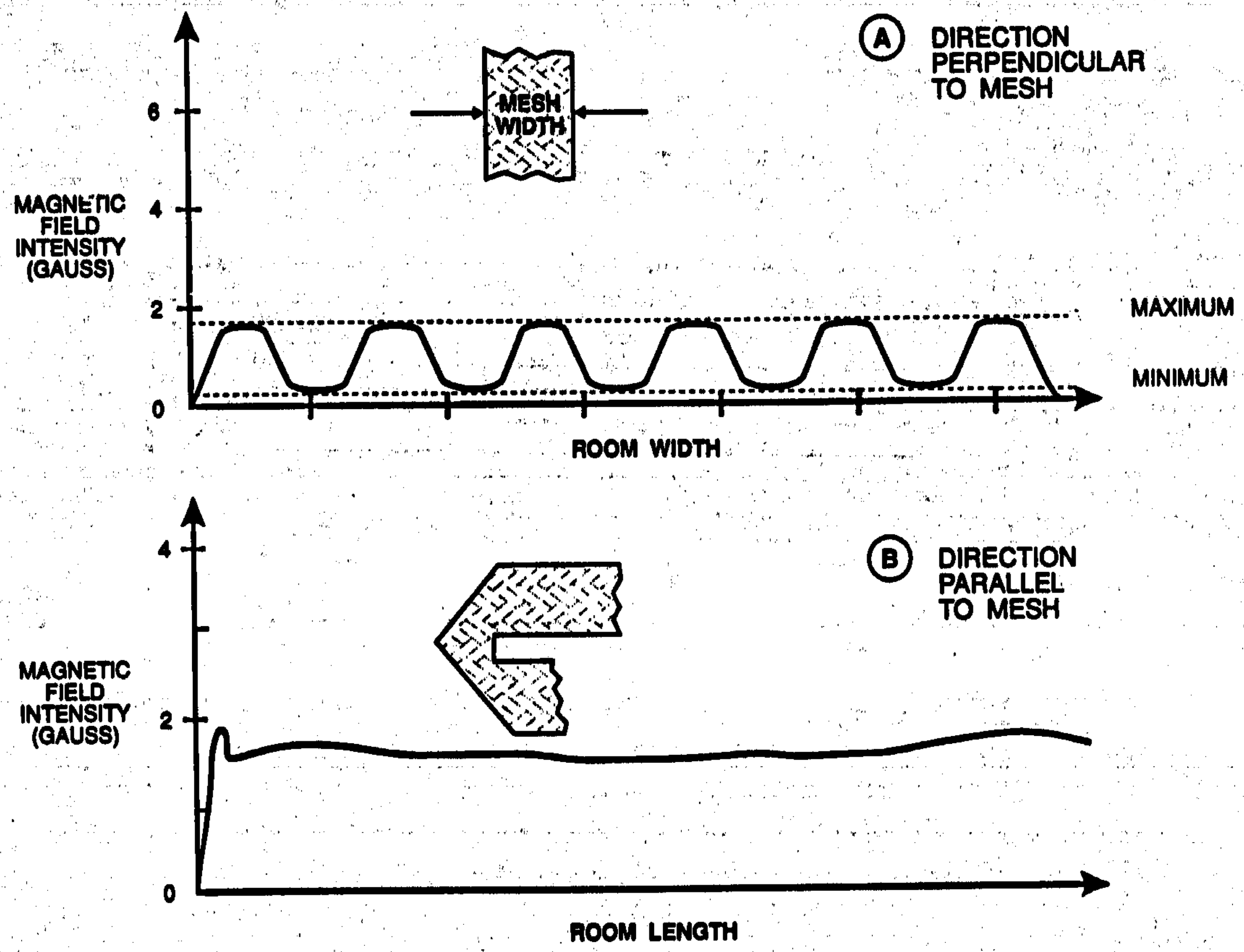
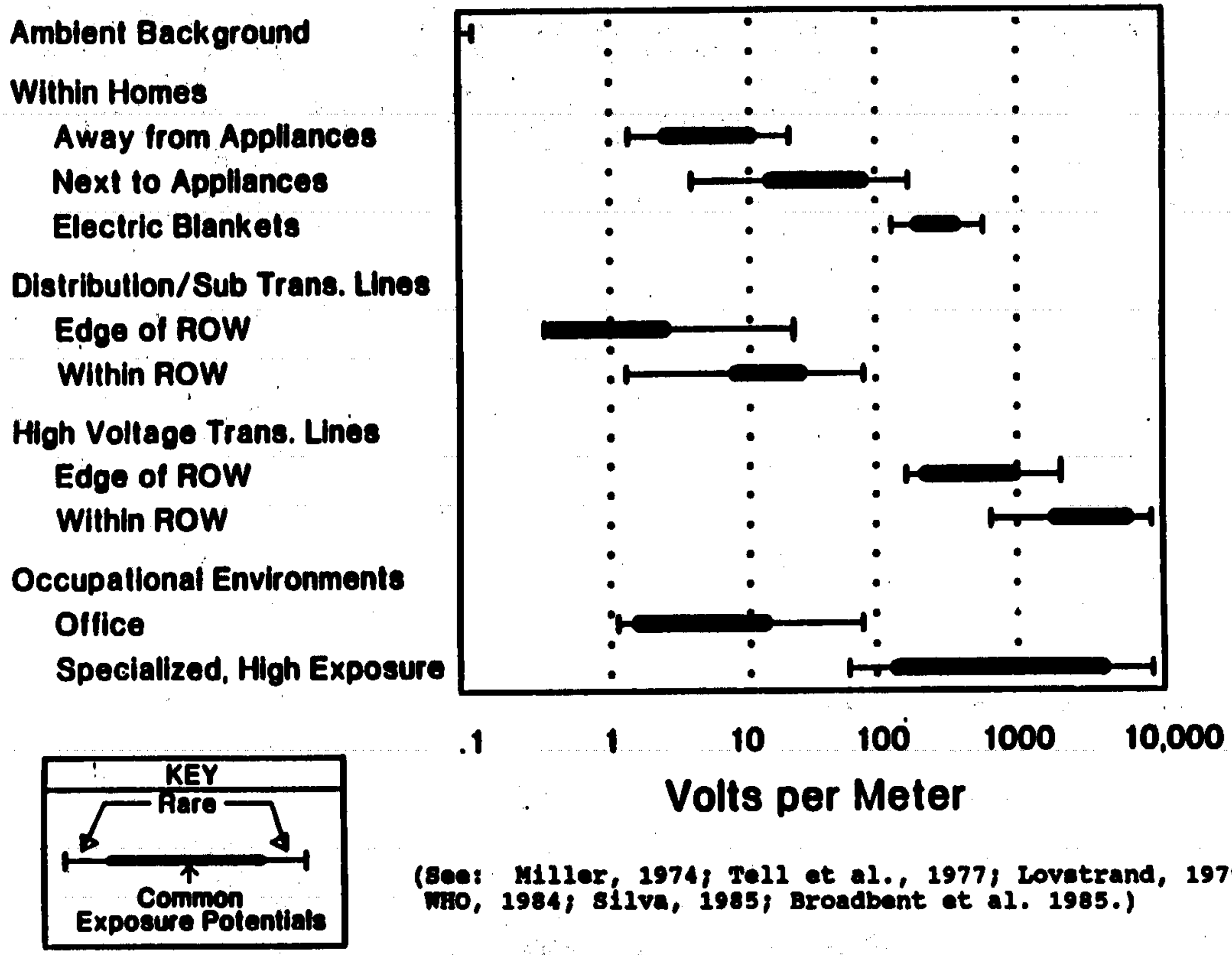


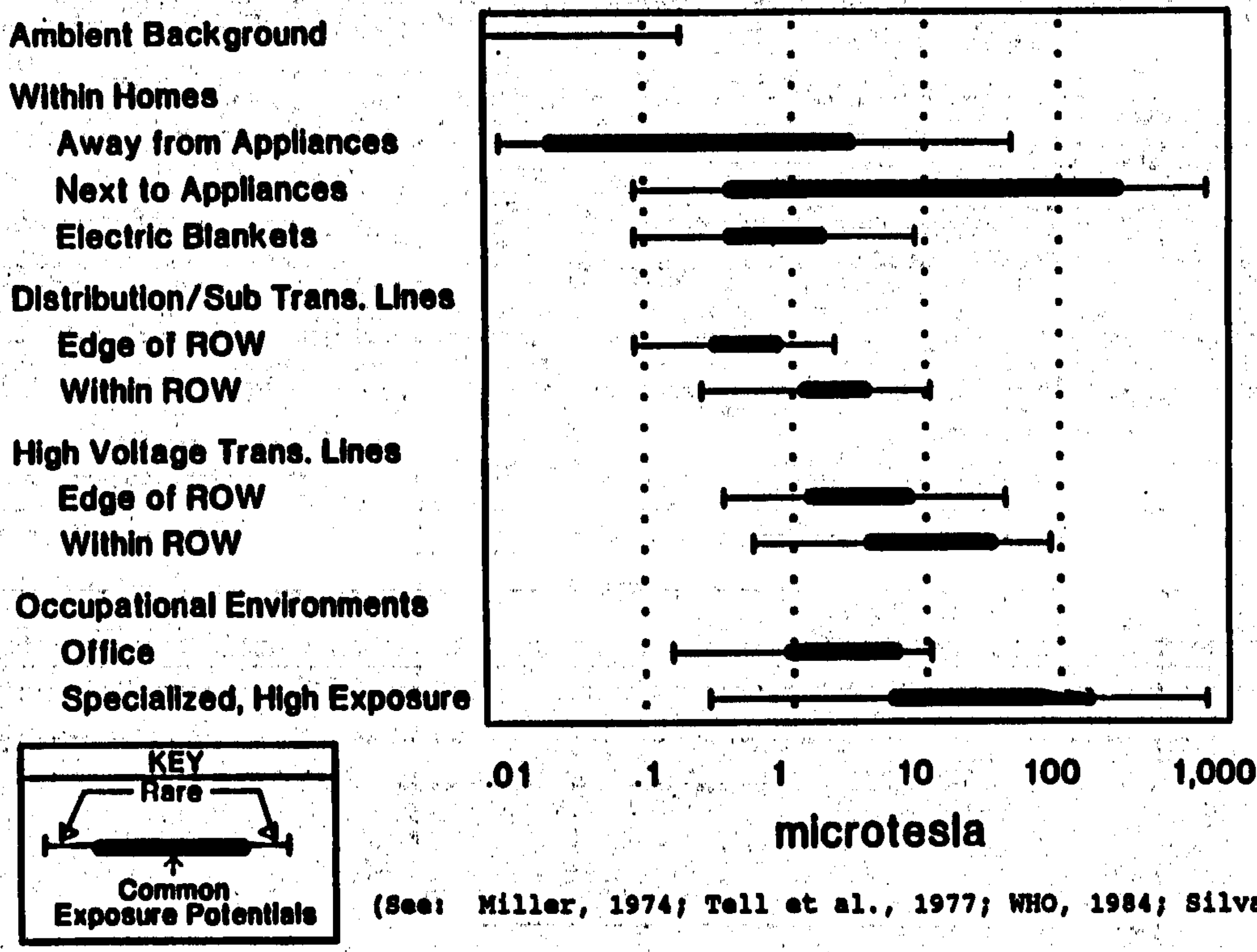
Figure 3. Variation in Magnetic Field Intensity as a function of movement direction across mesh

FIGURE 4. TYPICAL LEVELS OF 60 HERTZ ELECTRIC FIELD STRENGTHS FOR DIFFERENT EXPOSURE SITUATIONS FOUND IN THE LITERATURE.



(See: Miller, 1974; Tell et al., 1977; Lovstrand, 1979; WHO, 1984; Silva, 1985; Broadbent et al. 1985.)

FIGURE 5. TYPICAL LEVELS OF 60 HERTZ MAGNETIC FIELD STRENGTHS FOR DIFFERENT EXPOSURE SITUATIONS FOUND IN THE LITERATURE



(See: Miller, 1974; Tell et al., 1977; WHO, 1984; Silva, 1985.)