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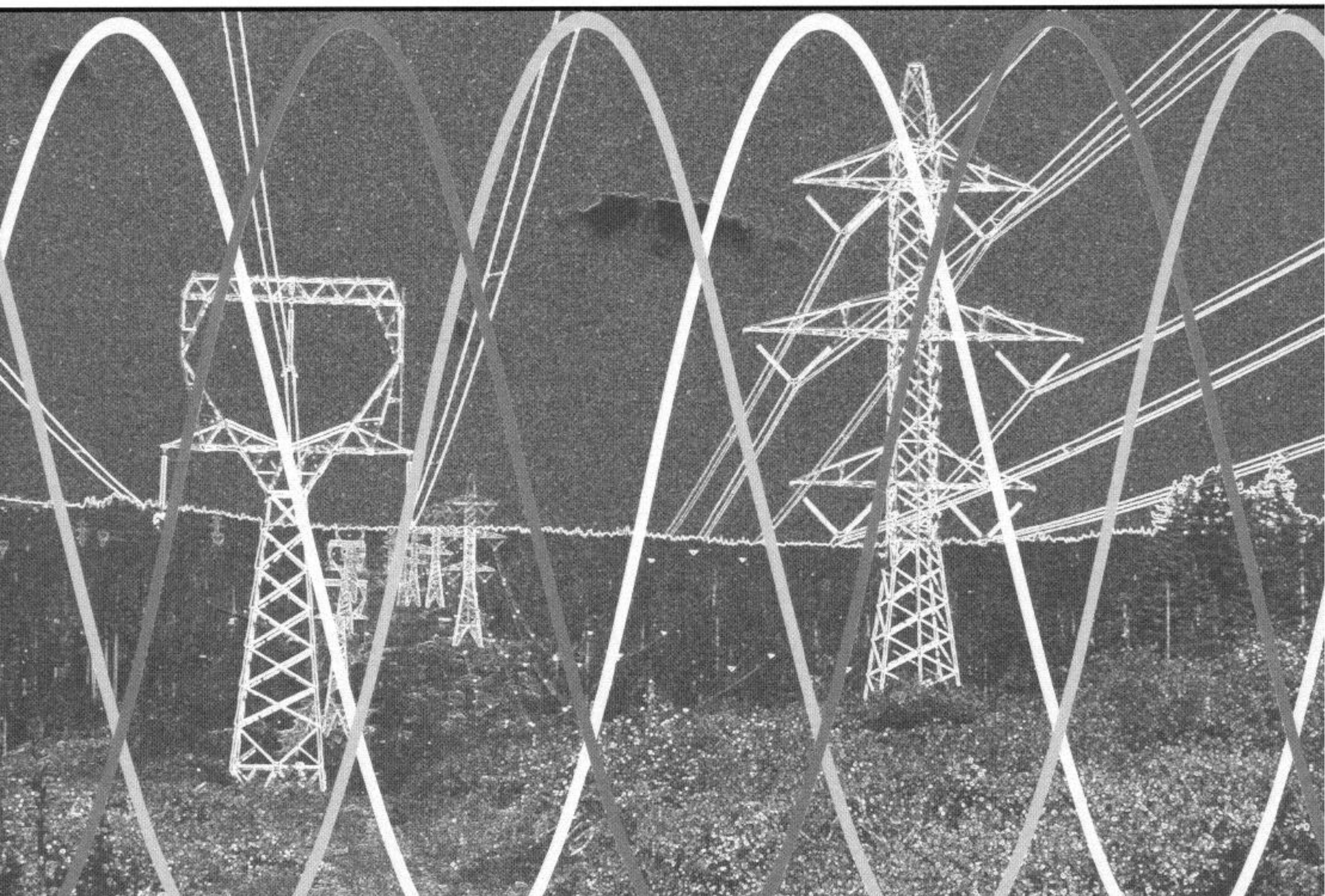
Electrical and Biological Effects of Transmission Lines: A Review



Electrical and Biological Effects of Transmission Lines: A Review

Jack M. Lee, Jr., Ph.D. (principal author)

Assisted by the BPA Biological Studies Task Team:

Katherine Semple Pierce
Colleen A. Spiering
Richard D. Stearns
George VanGinhoven

Bonneville Power Administration
Portland, Oregon
December 1996

This is BPA's most comprehensive and detailed publication on the electrical and biological effects of transmission lines. The other related BPA publications listed below are less technical. They can be obtained by calling BPA's document request line which is 800-622-452O.You will hear a recorded message. Please ask for the publication that you want by name. If you want to speak with someone, please call the BPA public involvement line which is 800-622-4519. From outside of the U.S. you can call 503-230-3478.

Living and Working Safe/y Around High-Voltage Power Lines (9 pages). This short booklet tells you about safety precautions you should take when you are around a high-voltage transmission line. It deals primarily with ways to prevent electric shocks.

What We Know (and don't know) About EMF (brochure). If you want a short summary of the health issues associated with electric and magnetic fields (EMF), you will find it in this publication.

Health, Safefy and New ***Electric Power Facilities*** (9 pages). This booklet describes how BPA considers health and safety issues when new electric power facilities are planned.

Electric Power Lines, Questions and Answers on Research info Health Effects (55 pages). This booklet describes with a moderate level of technical details, the electrical properties of transmission lines, and it reviews research on electric and magnetic fields.

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Foreword

This review was first issued in 1975 in response to public and scientific interest that developed in the early 1970s about the new extra-high-voltage (EHV) transmission lines (primarily 500 kV and 765 kV). (Abbreviations are defined on page I-4.) Interest centered on the possible effects of electric and magnetic fields, audible noise, radio noise, and ozone. This review serves as BPA's generic source of information on these subjects. A main purpose of this publication is to support BPA documents required by the *National Environmental Policy Act* that deal with environmental impacts of new electrical transmission facilities.

When the first version of this review was published in 1975, few biological studies directly related to transmission lines had been done. The review has since been revised several times to reflect a growing body of research results from throughout the world (the last major revision was in 1989).

The research expanded in the 1980s to include low-voltage distribution lines and a possible association between cancer and the magnetic fields in residences near these lines. During this same time, reports began to be published suggesting that electrical workers were also at increased risk of developing cancer. The use of electric blankets and electrically heated water beds and electrical appliances also began to be studied. Initial concerns about power lines focused on electric fields; when interest developed in magnetic fields, the acronym EMF (for electric and magnetic fields) began to be used.

Continued public interest in issues about EMF resulted in Congressional Oversight Hearings on health effects of transmission lines, in 1987 and in 1990. Section 2118 of the *Energy Policy Act* of1992 established a national EMF research and communication program that came to be known as "EMF RAPID." The program is funded by Federal and matching non-Federal funds. BPA first developed specific guidelines for addressing EMF issues in 1988, and revised the guidelines in 1992 and in 1995.

A large number of studies of EMF has been done since this book was last published. Many more studies are still underway and are planned in the U.S. and in several other countries. Currently in the U.S., the largest programs of research on EMF are managed by the Electric Power Research Institute, Federal agencies involved with EMF RAPID, and the state of California. This extensive research is intended to provide more definitive information needed for determining whether or not power lines and other electrical devices affect human health. A report to Congress on the results of the EMF RAPID program is expected at the end of 1997. In 1996 the World Health Organization began an extensive 5-year review of research on EMF.

This BPA review has, therefore, been revised again to include the findings of the most recent research, and related developments involving EMF. BPA is unique in the U.S. in having operating experience with commercial 500-kV AC and +500-kV DC transmission lines, a 1200-kV AC prototype, and a f600-kV DC test line. Also, for several years BPA conducted and managed extensive engineering and environmental research programs involving EMF. Experience and research with transmission facilities, information developed through an ongoing literature review, and continued communication with numerous researchers and the public provide the basis for the material presented in this review.

This review was prepared with the assistance of a team of BPA engineers and environmental specialists originally assembled in 1974 to gather information on the effects of transmission lines on people, animals, and plants. The current team would like to acknowledge the contributions of the following former team members who assisted in the preparation of previous editions of this publication: Dr. T. Dan Bracken, John H. Brunke, Allen Burns, A. Stan Capon, Vern L. Chartier, Ted R. Eyler, Dr. David P. Hartmann, Gary M. Ihle, Gerald E. Lee, Dean E. Perry, Gerald L. Reiner, Fay L. Shon, and Michael T. Zechmeister.

The assistance of several other people who assisted in this extensive effort is also greatly appreciated. Dr. Judith H. Montgomery provided extensive editorial services on a final draft of the book; Leroy P. Sanchez provided technical assistance with graphics; Jean M. Connors, Elizabeth A. Mulcahy, and John Fenker obtained copies of the hundreds of new references reviewed in this edition; and Ernest E. Estes and Patricia Tawney reviewed a final draft of the book.

This is BPA's most comprehensive and detailed publication on effects of transmission lines prepared for employees and the public. Other related less-technical publications are also available from BPA (see page ii).

Jack M. Lee, Jr., Ph.D.
Chair, BPA Biological Studies Task Team
December 1996

Introduction

Transmission lines are high-voltage power lines used to carry electric power efficiently over long distances. Usually, the lines extend from power generating plants to load centers such as cities or large industrial plants. Utilities then use lower-voltage distribution lines to deliver electric power to individual homes and businesses (Fig. 1.1).

The first AC transmission line in the U.S. was built in 1889 between Oregon City and Portland, Oregon; a distance of 21 km (13 mi) (Rustebakke 1983). The line was operated at 4 kV. Through the years, transmission lines have been built to operate at progressively higher voltages. The highest transmission voltage in the U.S. is now 765 kV. Lines of this voltage have been in operation in the Eastern U.S. since 1969. With each advance in voltage, larger amounts of energy have been moved more efficiently and at less cost over lines with greater individual capacity. With higher voltages, fewer lines are needed and some types of environmental impacts have been reduced. Table I. 1 shows when major BPA transmission voltages were introduced, and compares their power-carrying capability.

To market power from 29 Northwest Federal hydroelectric projects, BPA operates about 23,800 km (14,780 mi) of transmission lines (Fig. 1.2). Most of the transmission is at voltages of 230 kV, 345 kV, and 500 kV. BPA's 500-kV transmission system is one of the largest in the world. In addition, BPA operates the Oregon portion of the first commercial +500-kV DC transmission line in North America.

Before 345-kV lines were introduced, the most noticeable effects of transmission lines were conflicts with other land uses and changes in the visual appearance of the landscape. Additional effects became evident when the EHV (extra-high-voltage: 345 kV and above) lines were introduced in the 1950s. Operating 345-kV lines affected some radio reception in residences near the lines. More effects occurred with the introduction of

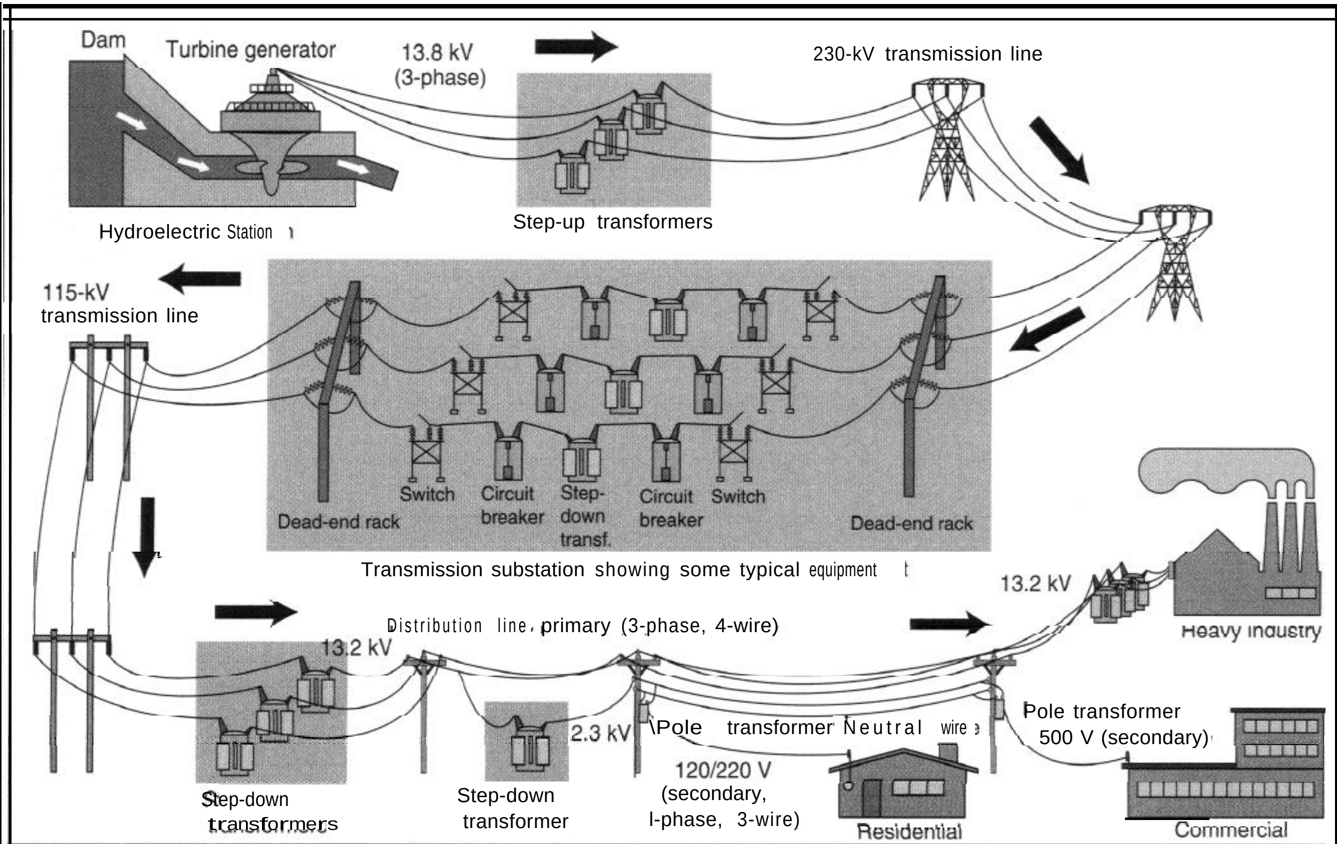


Figure I.1. A basic electric power system. BPA is responsible for transmission facilities only.

500-kV and 765-kV lines: television reception interference, audible noise. and nuisance shocks from induced voltages. These additional effects created some problems close to the lines. Through the years, BPA and utilities in general refined designs and procedures so that these short-term effects were reduced greatly.

In the 197Os, concerns began to be raised about the possibility of health effects from long-term exposure to electric and magnetic fields (Young 1974, Marino and Becker 1978). Interest in this controversial issue has continued to increase (Lee 1984, Cunningham 1991, Brodeur 1993, Taubes 1993, Pinsky 1995, Sagan 1996). Questions are frequently asked by persons planning to buy or sell property near transmission lines. Many questions are also raised when new transmission lines and substations are proposed. Many of these questions deal with the electrical and possible health effects of these facilities.

In the 19705, demand for electricity was growing rapidly, and it appeared that even more powerful transmission lines would be needed. The next class of transmission lines is referred to as UHV (ultra-high-voltage, 1000 kV and above). Research on UHV lines was conducted at several places throughout the world. BPA operated and studied a 1200-kV prototype line near Lyons, Oregon from 1977 to 1984 (Klinger et al. 1984, Lee et al. 1984). Although the technical feasibility of UHV lines was demonstrated, changing economic conditions, make it unlikely that they will be needed in the U.S. in the foreseeable future.

The purpose of this review is to provide factual information on the electrical characteristics of overhead transmission lines, and on the known and possible effects on people, animals, and plants. Methods used to reduce or eliminate the potential for undesirable effects are also described.

This review does not discuss other effects of transmission lines, such as those from construction and clearing of rights-of-way, or from the physical presence of the line (e.g., visual). Information on the overall effects of transmission lines can be found elsewhere (e.g., Crabtree 1984, Kroodsma and Van Dyke 1985, Doucet et al. 1995). Information on legal cases involving transmission lines can also be found in other publications (Creighton & Creighton 1996, Warnquest et al. 1996).

Electrical effects of overhead transmission lines addressed in this review fall into two broad categories: **electric and magnetic field effects,** and **corona effects.** Because there are some major differences in the effects of AC and DC transmission lines, they are discussed in two separate parts of this review. (Frequently used abbreviations are defined on page I-4.)

This book deals mainly with controversial issues involving the possible health effects of exposure to electric and magnetic fields. Our goal is to provide factual, objective information about these issues, and to present conclusions reached by individuals and groups other than BPA. BPA's own strategy for dealing with these issues is included in Chapter 5 in the section, "Policies, Standards, and Guidelines."

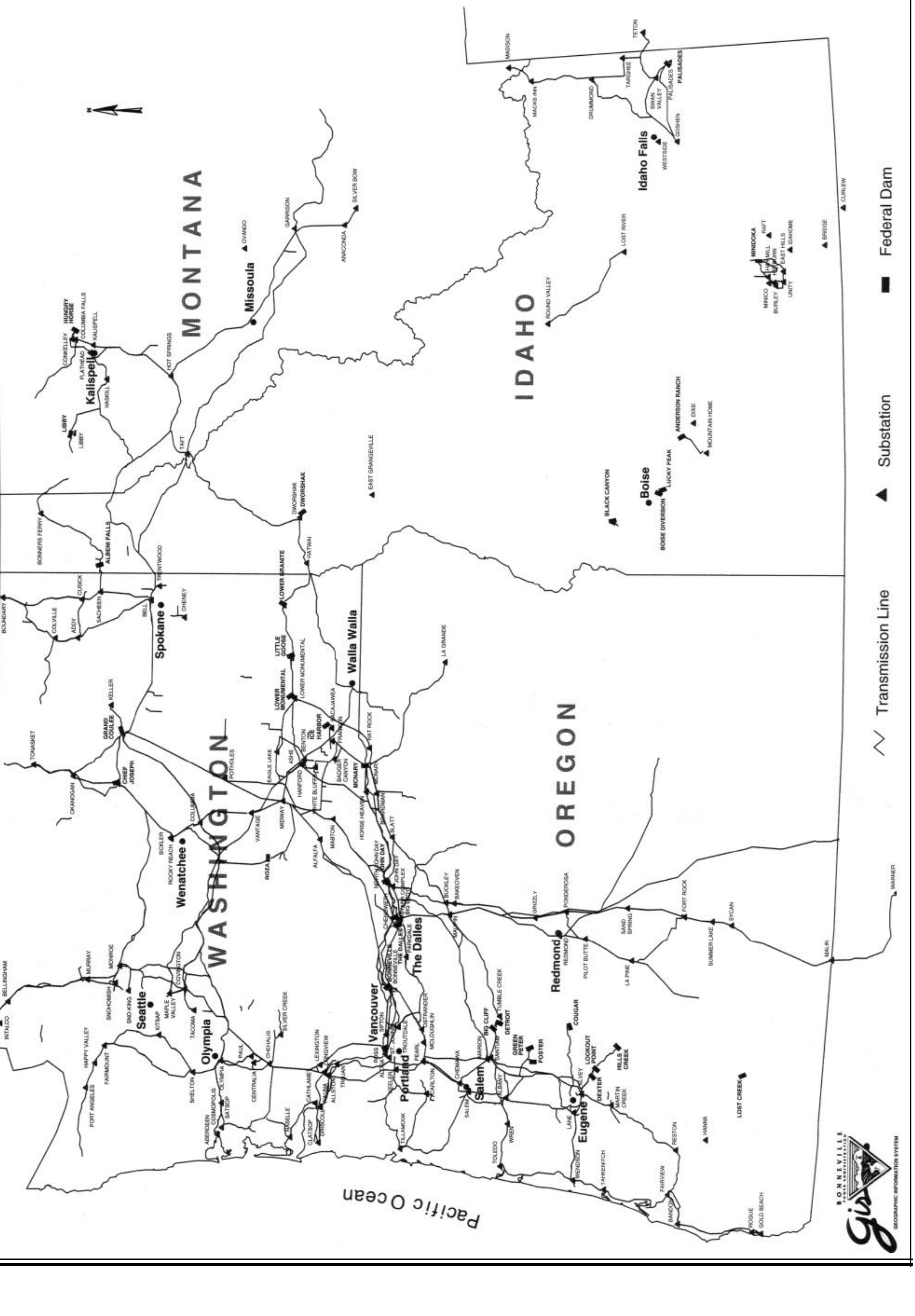
Table I.1. Dates of introduction and power capacity for major classes of BPA transmission lines.

Line Voltage	Year First Energized	Power Capability Per Circuit (MW)	Circuit Length km (mi) (Sept. 1994)	Typical Right-of-way Width m (ft)
115 kV	1939	100-350	6092 (3786)	18-38 (60-125)
230 kV	1939	200-700	8153 (5067)	27-38 (90-125)
345 kV	1955	300-1100	917 (570)	43 (140)
500 kV	1967	500-2500 [a]	7033 (4371)	32-50 (105-I 65)
±500 kV DC [b]	1985	3100	425 (264)	46 (150)

[a] Power transfer capability was calculated for a 240-km (149-mi) line with series compensation. One MW (megawatt) equals 1 million watts.

[b] From 1970 to 1985 the DC line was operated at ±400 kV The power capability of the line was increased from 2000 MW up to 3100 MW in 1989 by increasing current carrying capability of the line.

Figure I.2. The BPA transmission system.



Units of Measure and Abbreviations Used Frequently in this Book

Prefix (symbol)	Multification	factor
pico (p)	0.000000000001 =	1×10^{-12}
nano (n)	0.000000001=	1×10^{-9}
micro (μ)	0.000001=	1×10^{-6}
milli (m)	0.001=	1×10^{-3}
centi (c)	0.01=	1×10^{-2}
kilo (k)	1000=	1×10^{3}
mega (M)	1,000,000=	1×10^{6}
giga (G)	1,000,000,000=	1×10^{9}

Quantity	Abbreviation	Quantity	Abbreviation
ampere (amp)	A	milliampere	mA
foot	ft	milligauss	mG
gauss	G	millitesla	mT
gram	g	ounce	oz
hertz	Hz	pound	lb
inch	in	second	s
joule	J	square foot	ft^2
kilogram	kg	square meter	m^2
kilometer	km	tesla	T
kilovolts/meter	kV/m	volt	V
microtesla	μT	volts/meter	V/m
meter	m	watt	W
mile	mi	yard	yd

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Summary

This review describes the electrical properties of AC (alternating-current) and DC (direct-current) transmission lines and the known and possible effects on people, animals, and plants. Methods used to mitigate undesirable effects are also discussed. In addition to information on high-voltage transmission lines, the review covers related research on distribution lines and on electrical appliances. The transmission-line electrical properties discussed are electric and magnetic fields (EMF) and corona effects (high-frequency and audible noise, and ozone): first for AC lines, then for DC lines.

Information on EMF in this review is mainly about electric power frequencies (50/60 Hz). Some comparative information is also included on radio and microwave frequency fields (up to hundreds of millions of Hz). Abbreviations used in this summary and used frequently throughout this book are defined on page I-4.

AC Electric and Magnetic Fields (EMF)

Characteristics

In North America, AC electric power operates at a frequency of 60 Hz, i.e., 60 cycles per second. Voltage on any wire (conductor) produces an electric field in the area surrounding the wire. Power-line electric fields are measured by the difference in voltage between two points (usually 1 m apart). For example, the maximum vertical field in the air near the ground on a BPA 500-kV line right-of-way is usually less than 9 kV/m. The electric field from a power line gets weaker farther away from the line. Electric-field strength at the edge of a 500-kV line right-of-way is around 2-3 kV/m. Trees and building material also greatly reduce the strength of power-line electric fields.

Electric fields are also created by electrical wiring and appliances. Throughout a home the electric fields from these sources are usually less than about 0.01 kV/m (10 V/m). Close to appliances the fields are stronger. However, at 30 cm (1 ft) from appliances, electric fields are generally less than 0.100 kV/m (100 V/m).

A magnetic field is produced when electric current flows in a wire. The magnetic field (magnetic flux density) is described in units of tesla (T) or gauss (G). Under average loading conditions, average magnetic fields on the rights-of-way of BPA transmission lines are about 3-9 μT (30-90 mG). The fields average about 0.7-3 μT (7-30 mG) at the edge of the right-of-way. During peak loading conditions, the magnetic fields on and off of the right-of-way are about twice as strong as the levels during average loading conditions.

The magnetic field produced by electrical appliances decreases very rapidly away from the appliances. For example, the median of fields measured about 27 cm (10.5 in) away from electric ranges was about 0.9 μT (9 mG). For microwave ovens, the measured external 60-Hz magnetic fields had a median of about 3.7 μT (37 mG). However, at l-2 m (3-6.6 ft) from most appliances, the average magnetic field is usually less than 0.1 μT (1 mG).

Trees and most building material do not reduce the strength of magnetic fields. Therefore, power lines can be the dominant source of magnetic fields found throughout homes and other buildings near the lines. Currents on metallic plumbing systems that are connected to the neutral wire of the power distribution system can also be a significant source of magnetic fields in some buildings.

In addition to field intensity, EMF are also characterized by other parameters. These include polarization, harmonics, and transients. These characteristics are of increasing interest when considering the possible biological effects of EMF.

Instruments for measuring magnetic fields (gaussmeters) are available from several manufacturers. Some meters will also measure electric fields.

Electric and magnetic fields at radio and microwave frequencies are called *electromagnetic* fields because the two field components are tightly coupled into a propagating wave. The term radio frequency (RF) is often used to refer to the radio and microwave frequency range. RF electromagnetic fields are measured in units of power density (e.g., in units of mW/cm^2). If the intensity of one of the coupled fields is known (either the electric or the magnetic component), then the intensity of the other can be calculated. (At power frequencies electric and magnetic fields from a source vary independently and the fields must be measured or calculated separately.)

At sufficiently strong intensities, RF electromagnetic fields can heat biological material (e.g., a microwave oven). A variety of biologic effects has also been reported in studies of RF fields at intensities below where heating effects are expected. However, as with power-frequency EMF, these nonthermal effects of electromagnetic fields continue to be scientifically controversial.

Shocks and Perception Effects

AC electric fields induce voltages and currents into people and objects. If a person insulated from ground (e.g., wearing rubber boots) touches a grounded object such as a metal fence in a strong electric field, a perceptible current or an annoying spark discharge may occur. At most, the discharge may be similar to the shock received after walking across a carpet and touching a door knob. With the electric-field strengths normally found on BPA 500-kV rights-of-way, people seldom notice any sensation when contacting grounded objects.

Of more concern is the situation where a grounded person touches a large conducting object that is insulated from ground (e.g., a wire fence on dry wood posts). In this situation the person could receive a painful discharge shock. For this reason, fences and other large permanent metallic objects near the larger transmission lines are routinely grounded, as required by BPA policy and the *National Electrical Safety Code.*

Magnetic fields can also induce voltages on objects such as long fences parallel to a transmission line, resulting in nuisance shocks. However, techniques are available that can effectively mitigate shocks from magnetic field induction.

Electric fields also induce voltages on vehicles near transmission lines. BPA designs those lines that cross parking lots to have lower electric-field strengths to reduce the potential for nuisance shocks when people are getting in and out of their vehicles.

Potential Health Effects

Although shocks associated with EMF are well understood and largely controllable, questions have been raised as to whether there are health effects from exposure to these fields. Both electric and magnetic fields induce weak currents and electric fields into people and animals. These currents and fields are too small to be felt, other than by hair stimulation. Some scientists, however, suggest that long-term exposures to these fields may be harmful. Thousands of studies have been done throughout the world on the possible biological effects of power-frequency EMF.

Most of the early studies (1960s and 1970s) of people exposed to power-frequency EMF focused on general health, mental health, and reproduction. Most of the studies involved electrical workers and a variety of effects were reported. However, many of the early studies suffered from methodology problems. Together, these studies provide no consistent evidence for the existence of harmful effects of EMF on humans.

Beginning in the late 1970s and early 1980s epidemiologic studies began to focus on the risk of cancer in people who had lived or worked near electric power lines or equipment. Early studies in Denver, Colorado, found associations between distribution lines carrying high current and the occurrence of childhood cancer. Several more studies of cancer in children living near distribution and transmission lines have since been done in several countries. These studies provide some evidence for an increased risk of leukemia for children living near power lines. Scientists, however, have not determined whether EMF or some other factors are responsible for this finding. Studies of adults living near power lines generally found no increased risks of cancer.

Other studies have found that workers in various "electrical occupations" overall have increased risks of developing leukemia or brain tumors compared to those in other occupations. Some studies also found increased cancer risks associated with high occupational exposure to magnetic fields. The risk of breast cancer in women and men exposed to EMF is also being studied. As with the residential studies, it has not been determined whether EMF or other factors are the cause of these findings in the occupational studies. A main problem is a lack of knowledge about the most appropriate way to characterize and measure past human exposures to EMF.

The relative risks reported in the epidemiologic studies of EMF are generally small in magnitude. They are similar in size to other potential (unconfirmed) cancer risks reported in many studies of common environmental factors. In addition to the size of the potential risk, however, people consider other factors in deciding whether various risks are acceptable or not. People tend to be less likely to accept the potential for even small risks if they believe that the risks are imposed upon them. Risks involving children are also of particular concern to many people. It is not surprising that there are widely differing views about how to evaluate the evidence relating to possible health risks of EMF

Researchers have reported several effects of EMF on laboratory animals. However, few of the effects have been independently replicated by other researchers. Although the effects resulted in functional changes, e.g., a change in a hormone level, it has not been shown that the fields adversely affected animal health. Other studies have found that EMF can also cause functional changes in isolated cells and tissues. Some studies of laboratory animals found that magnetic field exposure increased the growth of tumors that had been purposely initiated by chemicals. Efforts are underway by other researchers to repeat these studies to see whether the same effects occur.

Some scientists believe that EMF cause biologic effects by interacting directly with cell membranes. Considerable laboratory research on biological interactions with EMF is ongoing. Scientists are trying to determine whether the effects are biologically significant, and to understand how the effects are caused.

Most of the epidemiologic studies, even those involving transmission lines, have focused on magnetic rather than electric fields. This is apparently because initial studies of childhood cancer involved high-current distribution lines which have relatively weak electric fields. Electric fields are also shielded to varying degrees by building material. Researchers assumed, therefore, that magnetic fields were more likely than electric fields to have a role in the observed associations with power lines. Shielding of electric fields is of less importance for people outdoors near transmission lines, and for electrical workers in some situations. Shielding also makes it harder to measure exposures to electric fields compared to magnetic fields.

Following the trend in the epidemiologic studies, laboratory studies also began to focus on magnetic fields. As a result, very few studies have looked at the potential carcinogenic effects of power-frequency electric fields on laboratory animals.

Some scientists believe that important biological effects from exposure to environmental EMF are not possible, because the internal fields that they induce are weaker than the electrical noise produced by natural biological processes. Other scientists, however, have proposed mechanisms to explain how biological effects of EMF reported in some studies are able to occur at relatively low field levels. Tests of these mechanisms have produced mixed results.

There have been several reviews of the epidemiologic and biologic research on EMF (see Appendix A). These reviews consistently concluded that no causal link has been established between EMF and adverse human health effects. However, they often acknowledged that there are still unanswered questions, and more research is needed. Many studies of EMF are still underway and more are planned.

Most of the recent reviews that commented on possible needs for field exposure reduction or prevention often recommend a variation of a concept called "prudent avoidance." This generally means taking low or no-cost steps to prevent or reduce exposures. Several studies have investigated ways to reduce levels of EMF produced by transmission lines (see Appendix B). Some reviews specifically recommended against a policy of prudent avoidance.

In addition to those cited in Appendix A, more national and international scientific reviews of research on EMF and possible human health effects are expected. These include reviews by the National Council on Radiation Protection and Measurements, agencies and committees involved with the national EMF program (EMF RAPID), and the World Health Organization.

Relatively few studies have been done of plants and animals exposed to EMF from transmission lines in natural environments. The studies that have been done provide no evidence for harmful effects of EMF on animal health. Followup studies are underway on a possible effect on one component of the immune system in sheep raised in EMF beneath a BPA 500-kV transmission line.

Studies have found that if wooden bee hives are placed near high-voltage lines, bees can receive shocks inside the hive. The adverse effects caused by these shocks can be prevented by proper hive placement, or by shielding and grounding techniques.

Tree branch tips that grow too close to transmission line conductors can be damaged by the strong electric fields. Such effects are generally of little practical importance, because tree growth near transmission lines is usually controlled to prevent electrical flashovers, which can cause power outages.

Standards and Guidelines

There are no national health standards in the U.S. for exposure to 60-Hz EMF. Only about six states have established field standards or guidelines for transmission lines, and of these only two (Florida and New York) included magnetic fields. Several local government organizations have addressed issues about EMF, and some have taken various actions to reduce or prevent human exposures to EMF.

A professional organization in the U.S. and two international organizations have established limit values for occupational exposures to EMF. The international organizations also included limits for public exposures. All three organizations based their limits on established biological effects of relatively strong EMF. The organizations believe that the epidemiologic studies of EMF that reported health-effect associations with much weaker fields, are not conclusive enough to be used as a basis for exposure limits. Organizations in Sweden established performance standards for EMF for computer monitors. The standards have been widely adopted by manufacturers of monitors.

Field Effects: Special Cases

Cardiac Pacemakers

Under some circumstances, cardiac pacemakers can be affected by extraneous voltages and currents from such things as automobile ignition systems and household appliances. Transmission lines have not caused any reported serious health effects for pacemaker patients. Research, however, has shown that the fields from transmission facilities can affect operation of some types of pacemakers.

The most likely effect would be for the demand-type pacer to revert to the asynchronous mode of operation, i.e., begin pulsing the heart at a regular rate. Reversion is basically a safety feature and is not necessarily harmful. Other studies indicate that the operation of certain pacemaker models can be inhibited by transmission line and substation fields. These represent a small percentage of models in use. As a precaution, pacemaker patients who may spend time outdoors close to a BPA transmission line or in a substation yard should consult with a physician to determine whether their pacemaker model is susceptible to 60-Hz interference.

Flammable Materials

It is possible that a spark discharge occurring from induced voltages could ignite a flammable mixture such as gasoline vapor and air. Circumstances leading to an ignition are unusual, and to date no such event is known to have occurred near a BPA transmission line. As a safety precaution, however, BPA recommends that vehicles be at least 21 m (70 ft) from transmission lines when they are refueled. Grounding techniques or electrical bonding of the vehicle and the fuel container should be used if refueling must occur nearer to the line.

Blasting

The electrical effects of a transmission line might cause premature detonation of explosives with electrical blasting caps if they are being used near the line. No such event is known to have occurred near a BPA line. As a precaution, persons planning to detonate explosives near a BPA transmission line should first obtain clearance from the nearest BPA office.

Irrigation Equipment

Metal irrigation systems near transmission lines pose a potential shock hazard because they are large and at times can be insulated from ground. However, with basic precautions, hazards can be eliminated. The precautions, described in this and other BPA publications, mainly involve grounding techniques and keeping pipe and other equipment away from conductors.

AC Corona Effects

Corona is the breakdown of air at the surface of transmission-line conductors. It mainly occurs when the electric field is greatly intensified at projections such as water droplets on the conductors. Corona is most noticeable on 500-kV and higher-voltage AC transmission lines during wet weather. Corona may result in audible noise, radio and television reception interference, light, and production of minute amounts of ozone.

Through the years, transmission-line designs were developed that greatly reduced audible noise levels and other corona effects. Few noise complaints are now received from persons living near BPA 500-kV transmission lines. Although radio and television interference problems sometimes occur, BPA policy requires that all such problems be investigated and corrected if a BPA facility is involved. Studies of 500-kV and 765-kV transmission lines and of the BPA 1200-kV prototype showed that the amount of ozone produced by corona is generally not detectable above average background levels.

DC Transmission

Characteristics

There are only seven high-voltage DC transmission lines operating in North America. BPA operates the Oregon portion of the 1361&m (846-mi) +500-kV Pacific Intertie, the first EHV (extra high voltage) DC transmission line constructed in North America. Over long distances, DC lines can be more economical than AC lines.

AC transmission lines have three sets (phases) of conductors. Bipolar DC lines, however, have only two sets (called negative and positive poles, like a battery). Unlike AC lines, some of the air ions (positive or negatively charged molecules) produced by corona move away from the DC conductors. This movement occurs because of forces exerted by electrical charges on the two conductors, and because of wind drift. The electric field from DC lines is produced by both the charge (voltage) on the conductors, and a "space charge" due to the air ions. Wind, therefore, has a great influence on the electric field near a DC line.

In contrast to AC, audible and radio-frequency noise produced by DC corona is generally greatest during fair weather. The positive conductor is the primary corona source. The DC audible noise is characterized by an impulsive popping sound at generally lower sound levels than AC lines. DC corona may result in radio reception interference. However, as with AC lines, BPA's policy is to mitigate such problems, should they occur. The amount of ozone produced by DC transmission-line corona is barely detectable above background levels.

DC Biological Effects

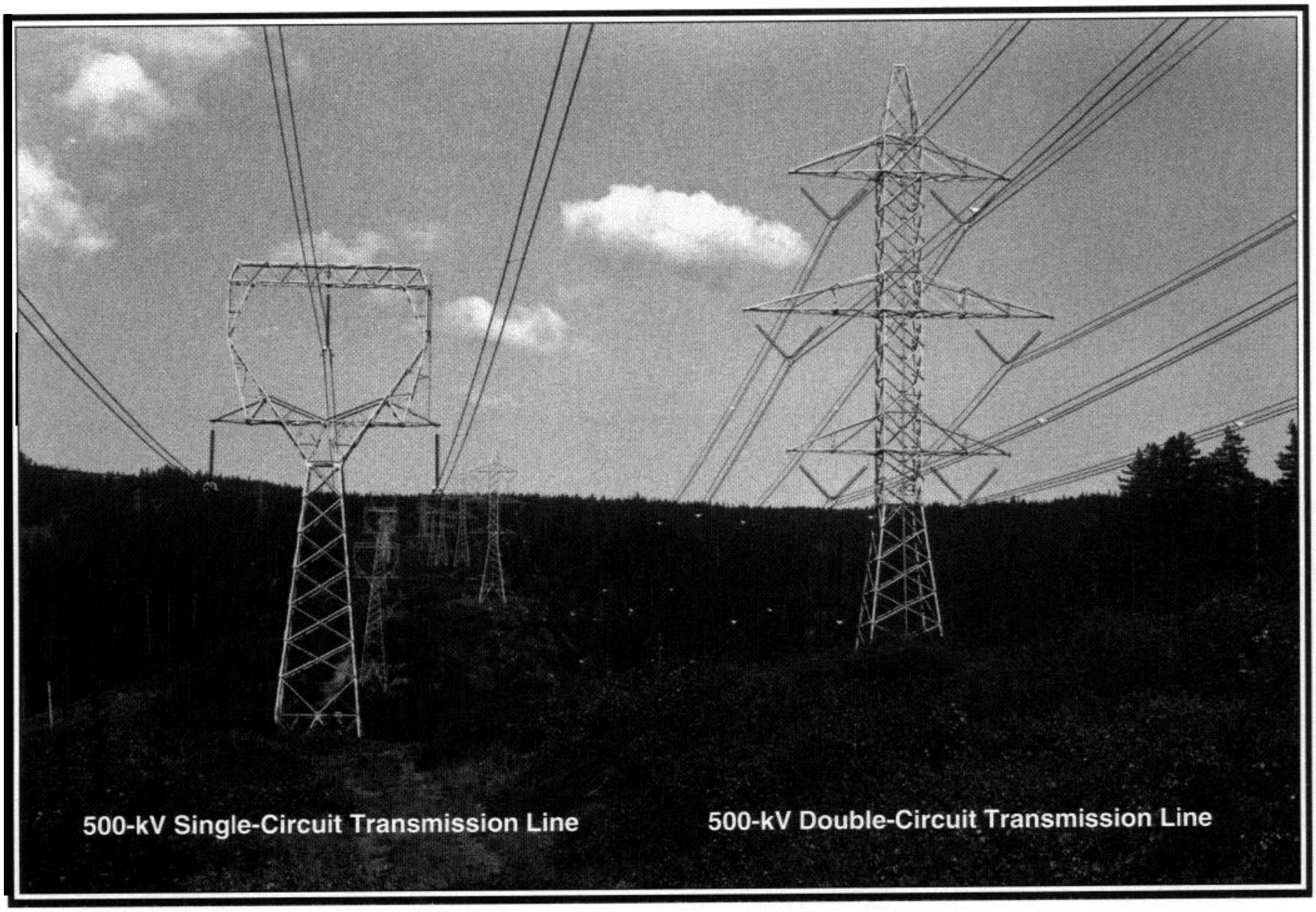
Charge will accumulate on insulated objects near DC lines. Typically, however, the DC current coupled by the flow of ions through air to people and objects is very much smaller than the currents induced by AC transmission lines. Nuisance shocks near a +500-kV DC line are less likely than for 500-kV AC lines. In both cases, grounding techniques are effective in minimizing shocks. Electromagnetic induction does not occur with DC because the current flow that causes the magnetic field is constant rather than alternating.

Operating experience and research has not produced any evidence for long-term biological effects of the Pacific DC Inter-tie on people, animals, or plants. Also, a large body of research on air ions and DC fields indicates that adverse effects are unlikely from DC lines. Some scientists have suggested that air ion concentrations differing from normal levels can have various beneficial or adverse effects on plants, animals, and people. However, most air ion research was not done specifically to assess possible effects of DC transmission lines.

BPA and several other organizations sponsored extensive long-term agricultural studies at a research site along the Pacific DC Intertie in Oregon. The 3-year-long studies found no adverse effects of the +500-kV DC line on growth and reproduction of beef cattle or crops.

PART 1

Alternating-Current (AC) Transmission


500-kV Single-Circuit Transmission Line
500-kV Double-Circuit Transmission Line

Chapter 1

Alternating-Current (AC) Fields

Summary

- Most electric power systems use AC (alternating-current) power, and operate at extremely low frequency (50 and 60 Hz).
- Power lines and all electrical devices produce EMF (electric and magnetic fields). Electric fields are produced by voltage, and are easily shielded by conducting material. Magnetic fields are produced by current, and are not shielded by most material. Field strength can be calculated, or measured.
- EMF decrease in strength with distance from the source. The decrease is faster for electrical appliances than for power lines. Electric fields in the center of rooms in most homes average less than 10 V/m, and the average magnetic field is less than 0.2 μT (2 mG). At the edge of BPA transmission line rights-of-way, average EMF range from about 0.5-3 kV/m, and 0.7-3.0 μT (7-30 mG).
- In addition to field strength, other factors used to characterize EMF include polarization, harmonics, and transients.
- EMF induce weak electric currents into conducting objects, including people and animals. The induced currents are usually much weaker than natural currents produced by the body. Scientists, therefore, do not agree on how EMF can cause biological effects.
- Currents and voltages induced on objects near transmission lines such as fences and vehicles can cause nuisance shocks, but measures are taken to minimize these effects.
- Electric fields from transmission lines can sometimes be felt by hair vibration, but magnetic fields cannot be felt by most people.
- In comparison to power frequencies, radio and microwave frequencies (RF/MW) are called electromagnetic fields, because the electric and magnetic fields are tightly coupled. RF/MW fields can have sufficient energy to cause heating of biological material.

Basic Electrical Concepts

Modern electric power systems are so reliable that most people don't think about electricity or how it works. As long as the light or the TV comes on when we flip the switch, how electric power is produced or transmitted is not of much concern. If. however, you are interested in whether electricity can affect us in ways other than by electric shock. then it is necessary to learn some basics about electric power. This chapter describes how electric power is produced and distributed, defines the properties of EMF. and outlines the basic biological interactions of EMF. This material involves several technical subjects which are presented here in only a general way. References are included for those who want to learn more about the technical details.

A primary reason for including this technical information is that it provides the background for discussing the biological research presented in later chapters. Issues about the possible health effect5 of EMF involve a complex mix of technical data involving biology. epidemiology, physics, and electrical engineering. Therefore, it is not surprising that definitive answers seem so hard to obtain, or that so many different views exist on this issue.

An AC electric power system begins where electric power is produced by generators at various kinds of electric power plants. Generators are turned by water or wind power, or by steam produced by burning fossil fuels or from nuclear reactions. A generator consists basically of loops of wire rotated through a magnetic field. This rotation produces electric current in the loops, and in the wires connected to the electric power system.

Figure 1. I shows how a simple generator produces AC current and voltage with a sine-wave form such as found in electric power systems. Actual generators consist of many turns of wire, and are often designed so that the wire loops are stationary. and the magnets rotate. The generator in Figure 1.1 produces single-phase power output.

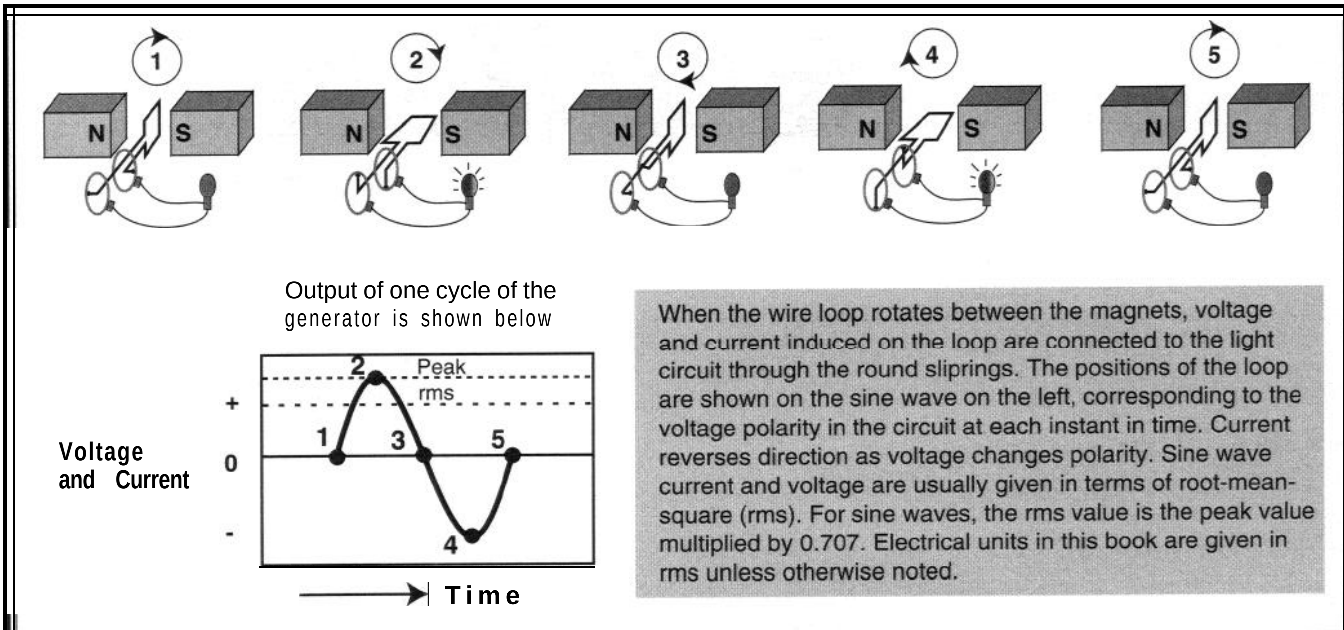


Figure 1.1. Basic operating principles of a simple single-phase AC generator.

Generators at electric power plants are designed to produce three-phase electricity. This is how power is carried on most transmission lines (Fig. 1.2). Many businesses and industries use three-phase power to operate large motors and other equipment. Most business and residential needs are met with single-phase electric power (see Fig. I. 1).

The three phases of an AC transmission line consist of three separate wires (conductors) each carrying electric power. For lines of 500 kV and above, each phase conductor usually consists of a bundle of two or more conductors. This makes the overall conductor diameter appear larger and reduces the electric field on the conductor. This reduces audible noise and other corona effects (corona is discussed in Chapter 5). The three phases make up one circuit. Figure 1.3 shows some typical BPA single- and double-circuit transmission line structures.

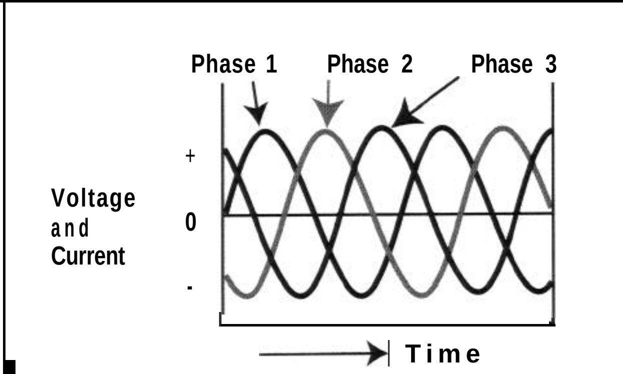


Figure 1.2. Waveform of the output of a three-phase generator. Each phase is separated 120 degrees from the other phases.

Various classes of transmission lines are referred to by a single voltage level called the "nominal voltage." The nominal voltage is usually less than the operating voltage which varies over some range. The operating voltage can be measured in two basic ways. For AC lines, the measurement refers usually to voltage between any two of the line phases. A BPA 500-kV line (nominal voltage) operates typically around 540 kV phase-to-phase (with a range of 525-550 kV). The voltage measured between a phase and ground is about 58 percent of the phase-to-phase value (e.g., 312 kV to ground when the line is operated at 540 kV between phases).

The (vector) product of voltage and current, expressed in watts, is a measure of electric power. Power is carried on transmission lines at very high voltage to reduce energy losses, which are largely related to current flow. In general, the higher the voltage, the lower the losses for equal amounts of energy transmitted. Transformers are used to increase voltage for transmission, and to reduce the voltage for distribution to homes, businesses, and factories.

The frequency of an AC voltage or current is given in units of hertz (Hz) (1 hertz= 1 cycle per second). For instance, in Figure 1.1, if the wire loop were rotated 10 complete turns in 1 second, the output would be 10 Hz. Notice that during each cycle the voltage and current changes between zero, and maximum positive and maxi-

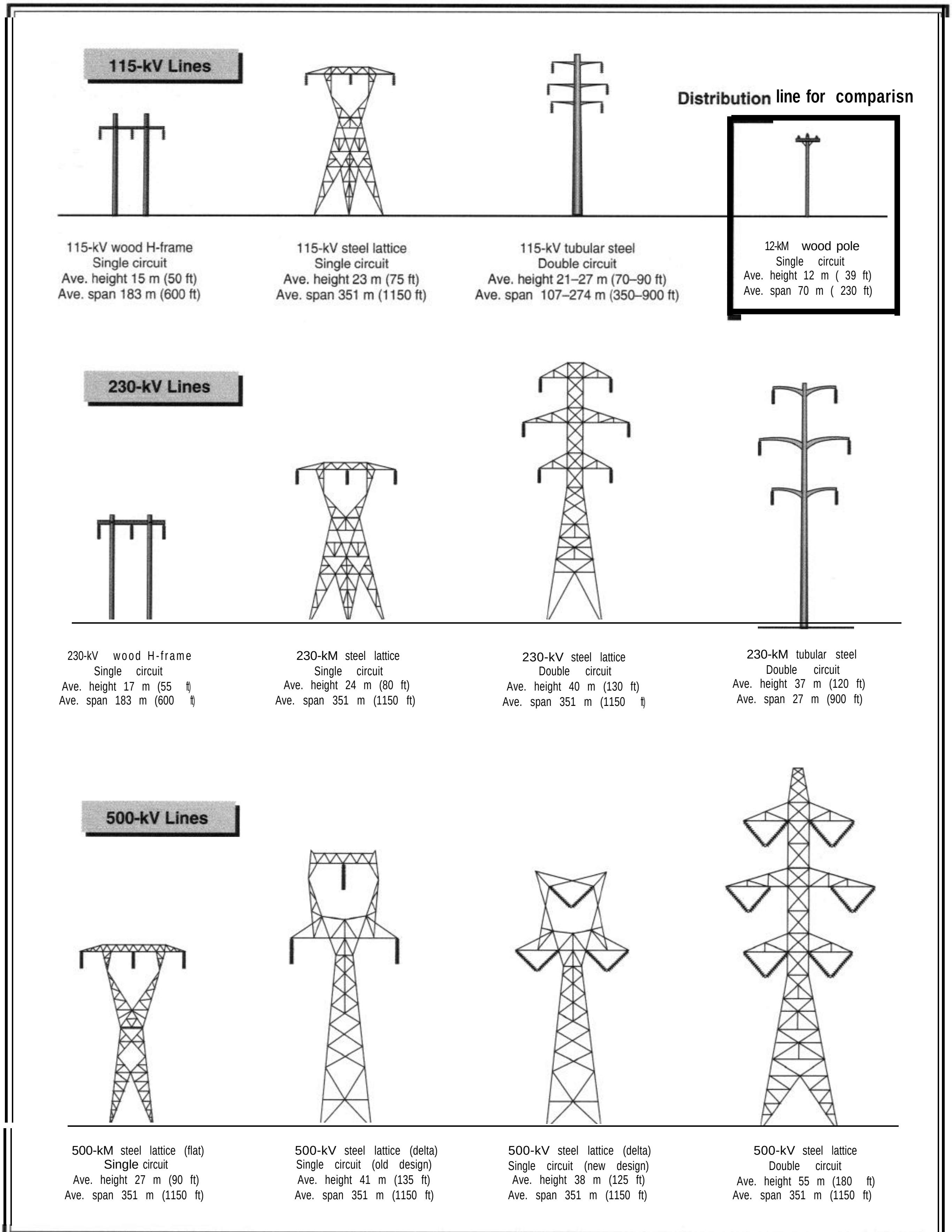


Figure 1.3. Examples of AC transmission-line structure designs used by BPA (conductors not shown).

mum negative values. A low frequency of 10 Hz would cause the lamp to flicker noticeably. If the loop rotated 60 times per second (60 Hz), the lamp would appear to our eyes to glow with a constant intensity. AC electric power in North America has a frequency of 60 Hz; in most other countries, 50-Hz AC is used. As a comparison, television transmitters operate at high frequencies in the 55-890 MHz (MHz = million hertz) range.

Frequencies throughout the electromagnetic spectrum, and some comparative wavelengths, are shown in Figure 1.4. Frequency is related inversely to wavelength, i.e., as frequency increases, the wavelength decreases. The wavelength of the microwave oven frequency (2450 MHz) is 12.2 cm (4.8 in). In contrast, the electric power frequency of 60 Hz has a wavelength of 5000 km (3100 mi). However, transmission lines are very poor 60-Hz transmitting "antennas." The low frequency power is not radiated away, as happens with high-frequency television or radio transmitting antennas.

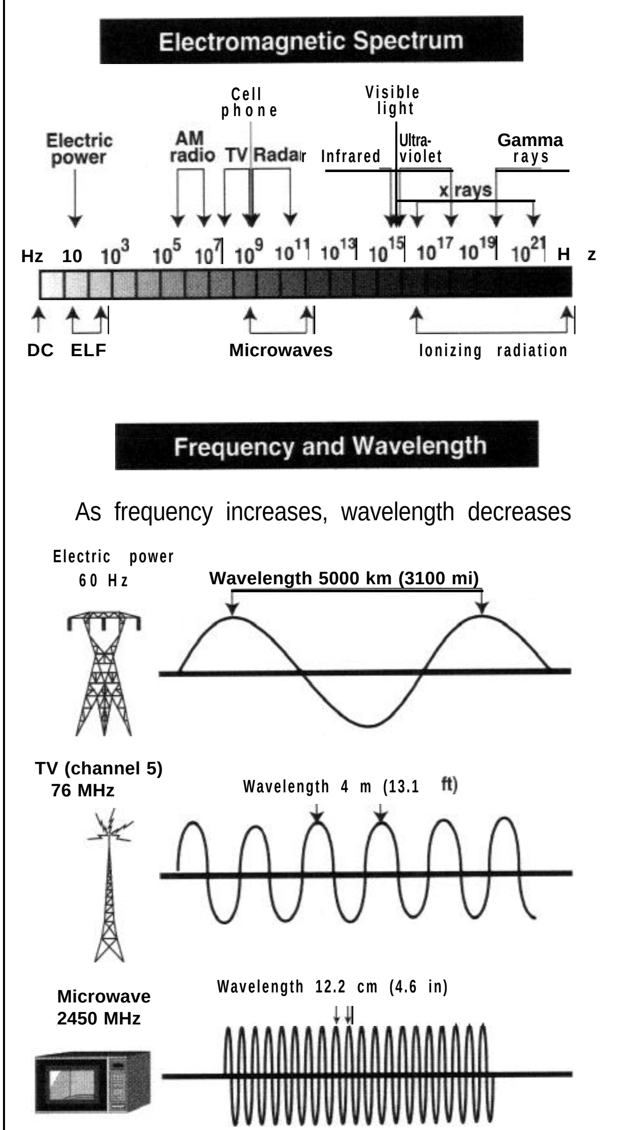


Figure 1.4. Comparison of frequency and wavelength for various sources of electric and magnetic fields.

The energy from higher-frequency fields (shorter wavelengths) is absorbed more readily by biological material, and it can produce heating such as with microwave ovens. The high energy associated with ionizing radiation, such as x rays, strips electrons from molecules. In contrast, the extremely long wavelength at 60 Hz allows the transfer of only a minute amount of energy to objects the size of a person.

It can be shown that a person-sized object absorbs about one trillion times less energy from a 60-Hz power-line field than from a 60-MHz television frequency field of equivalent power intensity (IITRI 1979). For ionizing radiation (above about 10^{12} Hz) the energy per photon is more than 1.4 *eV* (electron volts), whereas for 60-Hz, the energy per photon is only about 2.5 x 10^{-13} *eV* (Suess 1982, Bennett 1992).

Notice in Figure 1.4 that the waveforms for the examples all have uniform curved shapes. As noted above, AC electric power is generated in what is known as a sine waveform. There are a variety of other wave forms found in various electronic circuits. As an example, video displays produce both 60-Hz sine waves and pulsed wave forms (Fig. 1.5). The latter has the sharp appearance of saw teeth. There is some evidence that different types of wave forms also differ in their potential to cause biological effects (Bassett 1994).

Power-Frequency Electric and Magnetic Fields (EMF)

Power lines, electrical wiring, and electrical devices and appliances all produce AC electric and magnetic fields. We are almost continuously exposed to the fields from these sources when we are at home, work, or at school. The sections that follow describe the properties of electric and magnetic fields, tell how they are measured, and give examples of field intensities produced by various sources. Human exposures to electric and magnetic fields are described in Chapter 2. Chapters 2-4 describe the world-wide research aimed at assessing whether exposure to these fields can adversely affect people, animals, and plants. Information is also included on beneficial medical uses of fields.

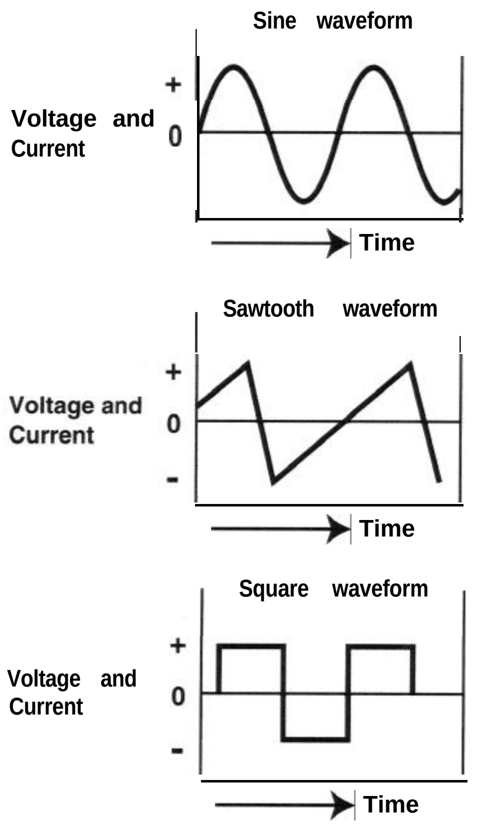


Figure 1.5. Examples of some different types of EMF waveforms.

In recent years, "EMF" has often been used informally to refer to power-frequency electric and magnetic fields. This can lead to some confusion because "emf' is the formal abbreviation for electromotive force (i.e., voltage). A further point of confusion arises because some authors use EMF to refer only to the power frequency magnetic field. The term "electromagnetic field" is also used by some authors to refer to power-frequency magnetic fields, but this term is more correctly applied to the tightly coupled electric and magnetic fields at radio and microwave frequencies. This book deals primarily with electric power, so we usually refer to the electric and magnetic fields separately. When we use EMF, we are referring to both the power-frequency electric and magnetic fields.

Electric Fields

Description and Comparative Levels

Description. Voltage on an object such as a wire produces an electric field, E, in the area surrounding the wire. An electric field is basically invisible lines of force that repel or attract electric charges. E is a "vector" quantity: This means that it has both direction and magnitude. An example of the electric-field pattern around a conductor above the ground is shown in Figure 1.6. Note that the field lines intercept the ground at right angles (as they do for any conducting object). In the figure, the conductor (in red) is shown from an end-on view. The electric-field pattern around the multiple conductors of a power line is more complicated than is shown for the single conductor in Figure 1.6.

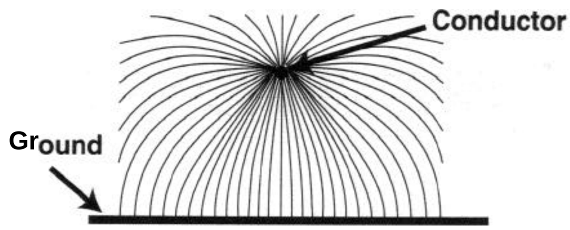


Figure 1.6. Example of the pattern of an electric field. For simplicity, the field is shown originating from a single conductor.

The presence of an electric field can sometimes be demonstrated with a hand-held fluorescent tube (Fig. 1.7). This phenomenon has been associated with transmission lines and distribution lines. Fluorescent tubes also glow in some other electric fields-near an automobile engine, or a CB radio antenna, or when simply scuffing your feet across a carpet. In all these instances, the illumination is much less than that produced by normal use.

Home fields. Examples of typical 60-Hz electric-field strengths found in the home are given in Figure 1.8. Electric field strength is described in terms of voltage-per-unit-distance at a specified position. For example, 100 V/m means that there is a difference of 100 volts between two points in air, 1 m (3.3 ft) apart vertically. Electric fields from appliances decrease rapidly with distance. In the center of the rooms in a typical home, 60-Hz electric-field strength is typically less than 10 V/m (Caola et al. 1983, Savitz 1987).

In addition to the appliances shown in Figure 1.8, the electric field measured 30 cm (1 ft) above conventional electric blankets was 250 V/m (Valentino 1972). Conventional electric blankets consist of a single insulated heating wire that is looped back and forth across the blanket. With positive temperature coefficient (PTC) electric blankets, the looped heating element consists

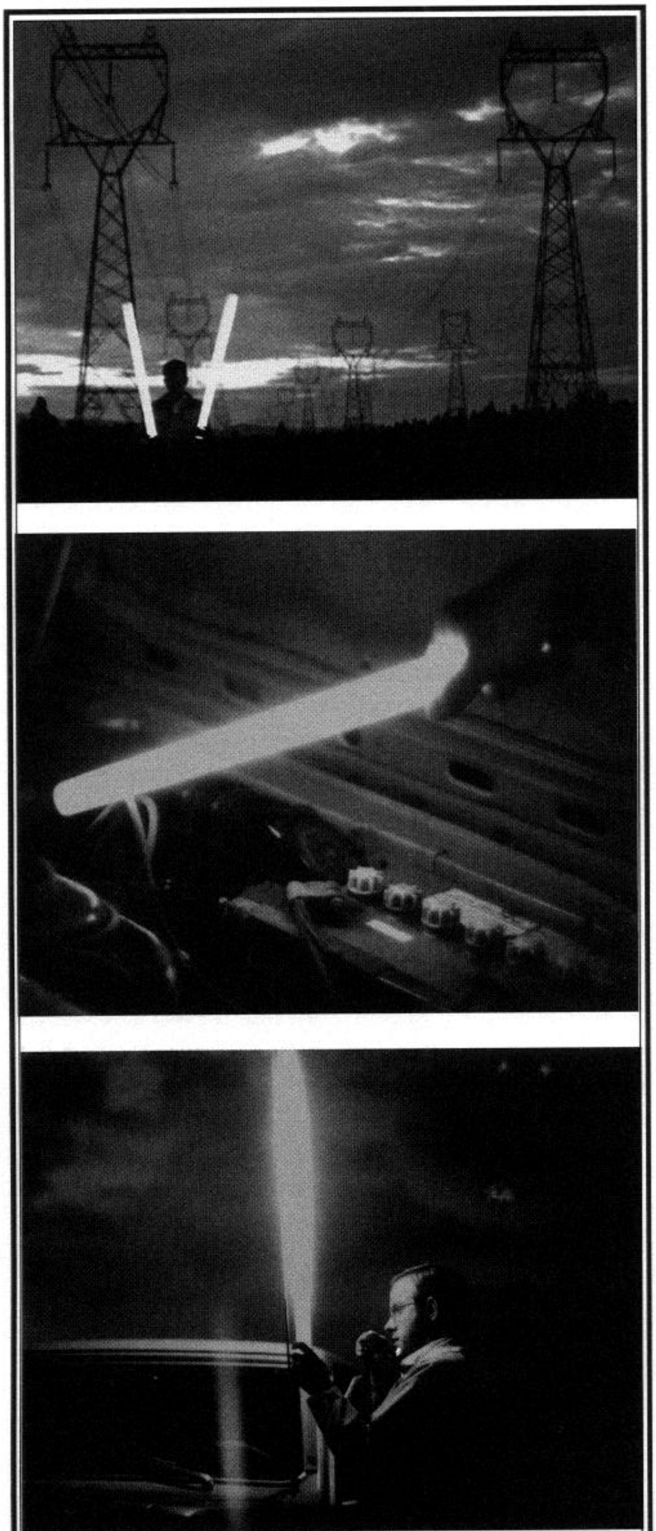


Figure 1.7. The presence of an electric field can sometimes be demonstrated with a hand-held fluorescent tube. These time-exposure photographs (several seconds) show tubes glowing beneath a 500-kV line (top), near an automobile ignition (middle), and next to a transmitting CB radio antenna (bottom).

of two closely spaced parallel insulated wires. Calculated electric fields 30 cm (1 ft) above PTC blankets were around 16 V/m; at 5 cm (2 in) the field ranged from 10 to 40 V/m (Florig and Hoburg 1991).

The electric field levels usually reported are called "unperturbed" because they are for the situation where a conducting object is not nearby. A person or any conducting object greatly perturbs (distorts) the electric field. This makes it difficult to measure exposure. In terms of human field exposures, electric-field levels produced by appliances cannot be directly compared to equivalent fields from power lines. This is because fields may be oriented differently with respect to the body.

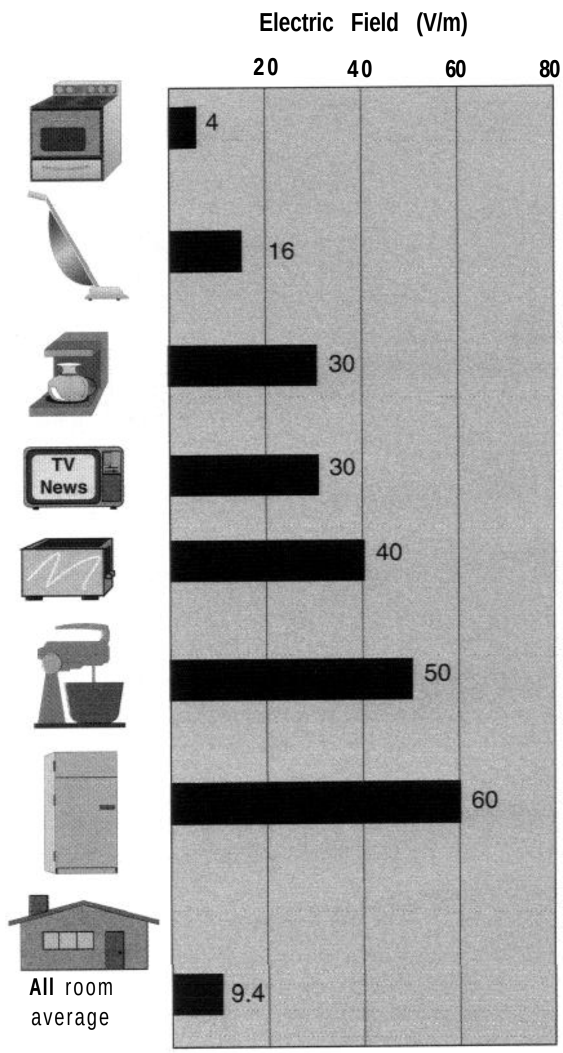


Figure 1.8. Typical 60-Hz electric field levels 30 cm (1 ft) from some electrical appliances, and the all-room average for 481 homes in Denver.

Sources: Appliance fields from Valentino (1972), home average from Savitz (1987).

For example, the current density induced in the chest of a person covered by an electric blanket is comparable to the current density induced in the chest of a person standing in a 90-140 V/m power-line field (Florig et al. 1987).

Power-line fields. Electric fields found near transmission lines are usually stronger than those near appliances, so they are typically measured in units of kV/m (kilovolts per meter) (1000 V/m= 1 kV/m). The electric field near an AC line can be measured with a hand-held meter (Figure 1.9). Computer programs are also available for calculating electric fields.

Figure 1.9. Electric-field strength is measured with a meter on the end of a long insulated handle. This keeps the meter away from the person's body which can distort the field.

Figure 1.10 shows the typical vertical electric-field strength at various lateral distances away from BPA transmission lines. The values were calculated for a point 1 m (3.3 ft) above ground (the standard reference height). For a fixed conductor-to-ground height, the electric-field strength does not vary more than 10 to 15 percent for heights up to 3 m (9.8 ft) above ground. There is also a small horizontal electric-field component.

The maximum electric field near the ground occurs usually just outside the outer conductors at mid-span (i.e., mid-way between two support structures). The field strength dips right under the center of the lines because the three phases partially cancel each other. The highest commercial AC transmission-line voltage in the U.S. is 765 kV. These lines, found in the Eastern U. S., produce maximum electric fields of about 10-12 kV/m. In the BPA system, the largest commercial line is 500 kV and the maximum electric field is about 9 kV/m. Other typical transmission line voltages include 115 kV, 230 kV, and 345 kV.

Figure 1 .11 shows the distribution of the electric field beneath a 500-kV transmission line. Notice that the maximum field occupies a small area near mid-span. This is where the conductors sag closest to the ground.

The electric-field strengths shown in Figures 1.10 and 1.11 are calculated for flat terrain and maximum conductor sag, i.e., when line current and air temperature conditions are highest. These maximum conditions seldom occur, and measured field levels near operating transmission lines are typically less than the calculated maximum design levels. Measurements made of 359 spans of 500-kV lines during late winter showed that the average maximum electric-field strength was only 3.7 kV/m (Bracken and Ray 1980). Fewer than 5 percent of the line spans measured had maximum fields greater than 6 kV/m.

Distribution-line primary voltages range from about 4 to 34 kV (Burke 1994). Measurements made of 60-Hz electric fields beneath 14.4-kV distribution lines in Quebec showed that the fields were less than 1 kV/m; typically, they were about 160 V/m (Heroux 1987).

The symmetry in field strength shown in Figures 1.10 and 1.11 would exist only when the line was located above a ground surface that was clear and level. Irregular ground or the presence of conducting objects such as vegetation or structures greatly perturbs electric fields. Beneath tall vegetation, or within buildings or automobiles, the electric field from a nearby transmission line is reduced considerably, because these objects act as a partial shield. In one study, the electric field inside a wood and brick home near a 500-kV line was eight times smaller than the field outside (Caola et al. 1983). The amount of shielding depends on the type of building material.

Another factor that determines field strength is the conductor configuration-the spacing and arrangement of the conductors (Fig. 1.3). The electric fields created by the three phases of high-voltage lines tend to cancel one another. In a delta (triangular configuration), the three phases are more compact than they are in a flat configuration. Thus, the electric-field strength near the ground for a delta configuration line is less than that of a comparable flat configuration line at the same height.

Depending on phase arrangements, similar cancellation effects can occur with two or more adjacent transmission lines and with double-circuit lines. The maximum ground-level electric-field strength beneath mul-

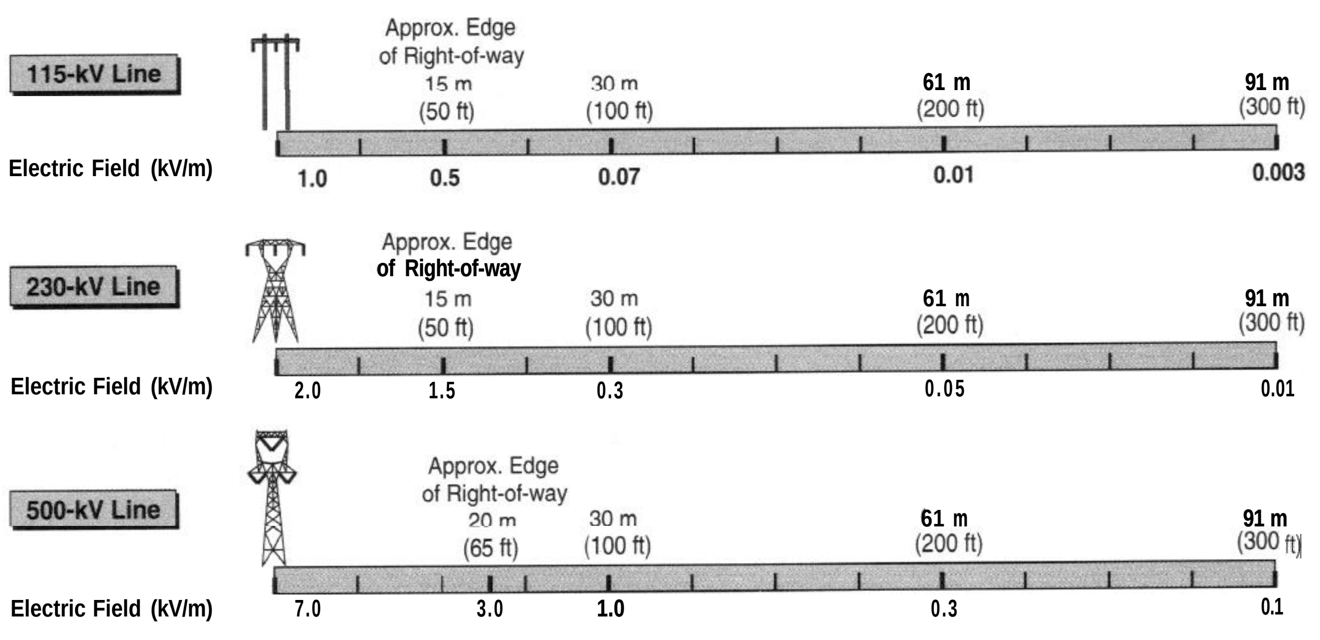


Figure 1.10. Typical 60-Hz electric field strengths for BPA transmission lines (see discussion in text).

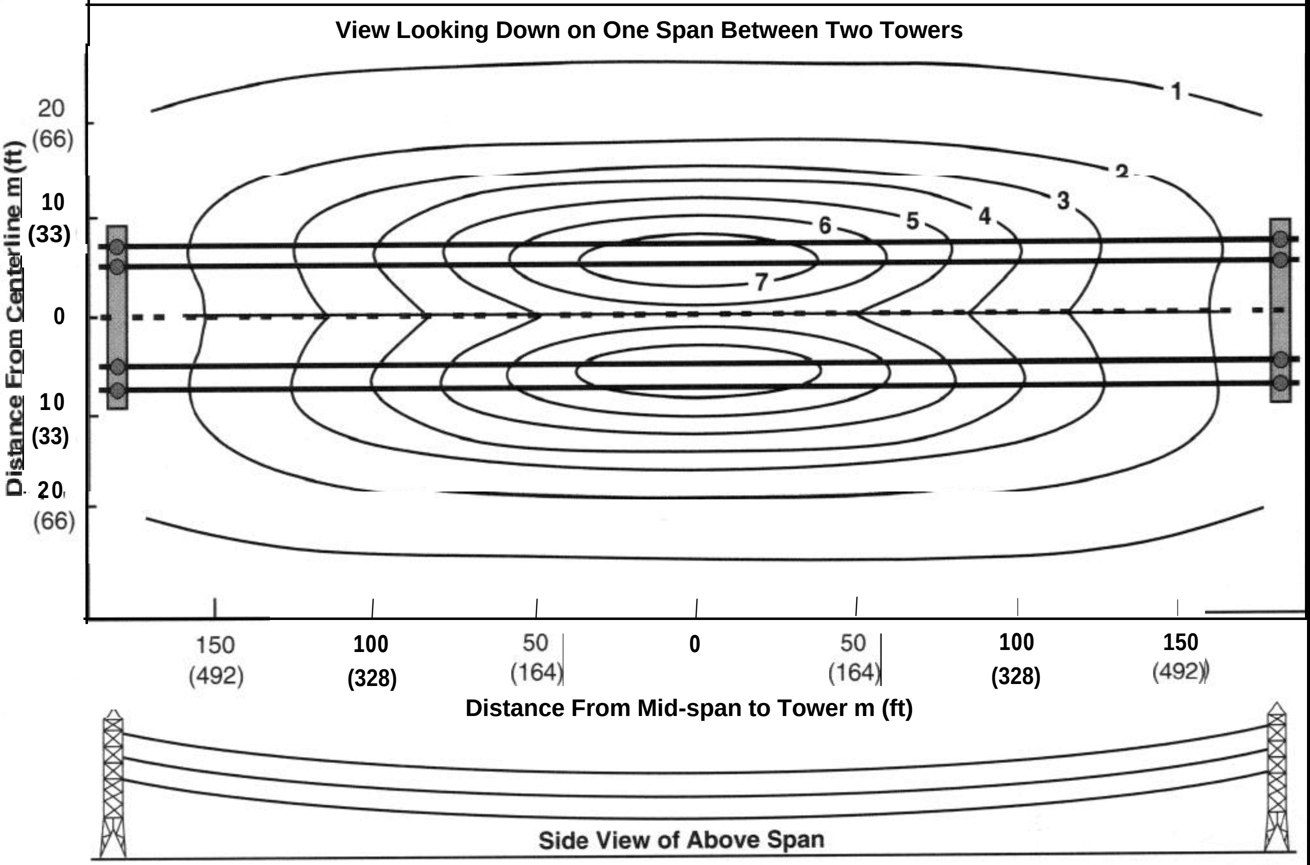


Figure 1.11. Maximum calculated 60-Hz electric-field strength (1-kV/m contours) at 1 m (3.3 ft) above level ground for a BPA 500-kV double-circuit transmission line. Measured levels are typically less than calculated levels. Note that the horizontal and vertical distances are at different scales.

tiple lines is about the same as would be found beneath the highest voltage line alone. In other words, the electric fields from multiple lines do not simply add together: two adjacent 500-kV lines do not represent a 1000-kV line.

Electric fields are vectors: they have both a direction (e.g., an angle in space) and a magnitude. The force on a charged particle in an AC electric field is, therefore, continuously changing. The situation is even more complicated with a three-phase power line because the electric fields produced by the line will also have different phases. At each point in the air around the line, the electric-field vector traces an ellipse in a plane as the line voltage and current alternate at 60 Hz (Deno 1976).

The shape of the ellipse is defined by a semi-major and a semi-minor axis. When the axes are equal in magnitude but are 90 degrees out of phase, the field is circularly polarized (also called a rotating field). At the other extreme, when the two axes overlap, linear polarization occurs. Electric fields within about 15 m (49.2 ft) of transmission lines tend to be polarized elliptically; beyond this distance they tend to be polarized linearly (Zaffanella and Deno 1978).

Induced Currents and Voltages

When conducting objects such as vehicles or people are in an AC electric field, currents and voltages are induced in them (Figure 1.12). The induced current varies with the electric field strength, the frequency of the field, the size and shape of the object, and the object-to-ground resistance. The charges in metallic conductors such as copper wire are mainly free electrons, whereas in body tissues and fluids, the charges are mostly ions (Adey 1981). With AC the charges don't actually move appreciable distances. The alternating current consists of minute oscillations (jiggling) of charges over a distance of about the diameter of an atom (Gary 1976).

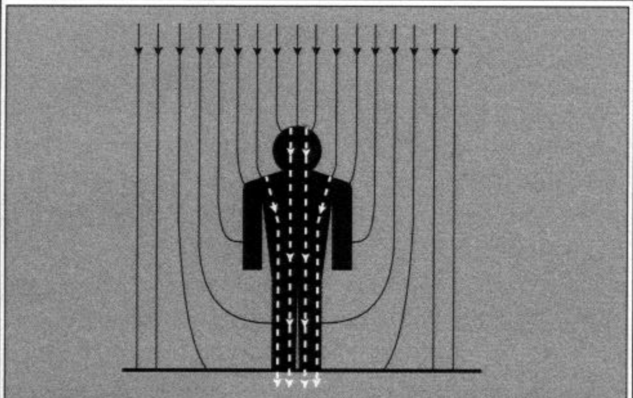


Figure 1.12. Basic pattern of the weak current induced (white dashed lines) in a person standing in the electric field (solid lines) beneath a transmission line.

Short-circuit currents. If an insulated object is grounded, the induced current to ground is called the short-circuit current. The short-circuit current induced in objects in a 60-Hz electric field can be estimated with formulas described by Deno and Zaffanella (1982). Short-circuit currents for a 1.7-m (5.6-ft) tall person, a cow, and some vehicles in a 1 kV/m electric field are shown in Figure 1.13.

Internal currents. As shown in Figure 1.12, the external electric field does not penetrate the body. The body or any other conducting object shields out most of the external field. This shielding is a result of the oscillations of electric charges within the body. As the external AC field on the surface of the body changes between positive and negative voltage, oppositely charged ions in the body oscillate toward the body surface. These charges create an internal electric field that opposes and almost entirely cancels the external electric field (Kaune and Anderson 1990). However, as the ions oscillate in the body, they create weak currents (Fig. 1.12). Also, the presence of currents in tissues and fluids is associated with weak internal electric fields.

Internal current densities and electric fields induced in a grounded person standing in a 1-kV/m 60-Hz electric field are shown in Figure 1.14. For any other field strength, multiply the field (in kV/m) by the values in the figure. Note that the internal electric fields are at least 100,000 times smaller than the external field. Internal currents and fields are even smaller when a person is not grounded (Kaune et al. 1987a).

The current densities in Figure 1.14 are averages for certain cross-sections of the body. The actual current densities within the sections depend on the types of tissue present. For instance, current densities are higher in muscle than in bone (Carstensen 1987). At the cellular level, most of the current occurs in the small spaces between the cells because the cell membrane is an effective insulator (Barnes 1992, Wachtel 1992).

The 60-Hz currents induced by transmission-line electric fields are comparable in only a general way to those produced in the body by the heart and nervous system (Fig. 1.15). Natural currents have a wide variety of frequencies and wave forms (Bemhardt 1979). The range of natural currents shown in Figure 1.15 is for frequencies of less than about 1000 Hz.

The maximum body current induced in a person (across the ankles) by a maximum transmission-line electric field (10 kV/m) falls within the range of natural current levels (Fig. 1.15). Shown for comparison are

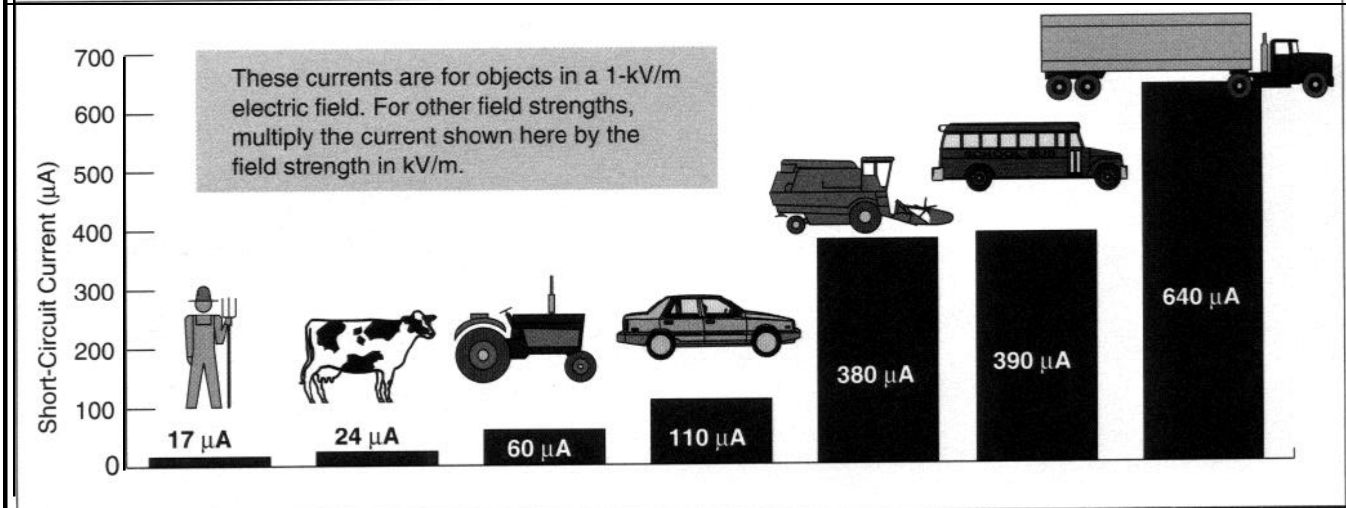


Figure 1.13. Short-circuit current in a person, a cow, and various vehicles in a transmission line 1-kV/m 60-Hz electric field. Source: Deno and Zaffanella (1982).

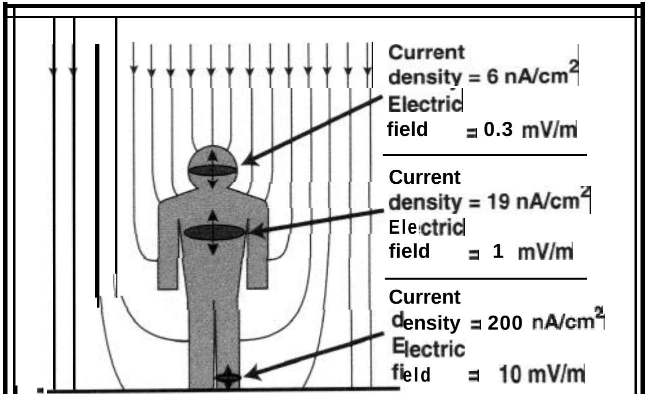


Figure 1.14. Current densities and electric fields induced in cross sections of a grounded person standing in a 1-kV/m electric field. Source: Derived from Kaune and Phillips (1980).

currents induced by a transmission-line magnetic field of 10 μT (100 mG), and a magnetic field of 0.2 μT (2 mG). The latter value is a threshold associated in some studies with increased cancer risks (see Chapter 3).

Some scientists contend that because currents induced by external fields are so small compared to natural levels, it is not possible for the external fields to cause biological effects (Adair 1991). Nevertheless, many published studies have reported biological effects associated with exposure to weak external fields (Bassett 1994, Goodman and S.-Henderson 1994). One extreme example from a frequently cited study of calcium efflux from chick brain tissue (Blackman et al. 1982) is shown in Figure 1.15. The effect observed from a 16-Hz, 3-V/m electric field was associated with current densities in the tissue that were 1 million times smaller than natural current levels (Kaune and Anderson 1990).

This example shows why the possible health effects of fields from transmission lines and other sources continues to be a controversial scientific issue. Many of the following sections of this book describe the biological research on EMF in detail, and discuss possible ways that effects could occur from exposure to weak fields.

Induced subperception body currents are not unique to a transmission-line environment. According to one study, currents induced in a person's neck and waist by an electric blanket were equivalent in magnitude to currents induced by a transmission-line field of 40-50 V/m (Silva 1985). The American National Standards Institute (ANSI) allows up to 0.5 mA leakage current from portable household appliances, and 0.75 mA from fixed appliances (ANSI 1973).

Perception Effects

When a person or animal contacts a conducting object that is insulated from ground within an electric field, a perceptible current (tingling sensation) or a shock may occur (Figure 1.16). This can also happen when the person or animal is insulated and the object is grounded. The amount of current is determined by the electric-field strength, the size of the object, and how well both the object and the person or animal are insulated from ground (see related papers by Reilly 1978, and Banks and Vinh 1984).

The short-circuit body current in Figure 1.13 is the maximum a person could receive from a 1-kV/m field. The values in Figure 1.13 are worst-case estimates, be-

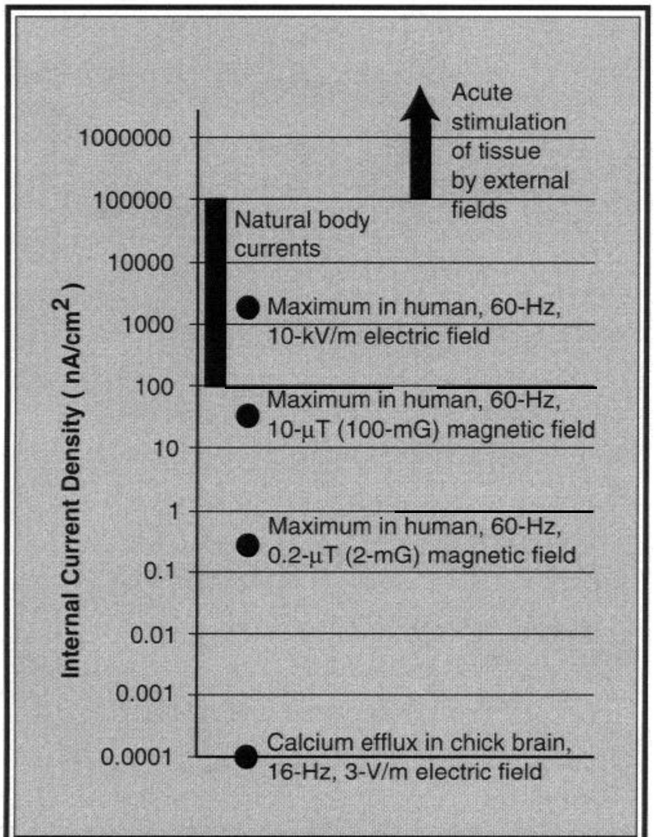


Figure 1.15. Comparison of natural internal body currents with currents induced by external electric and magnetic fields. (See text for discussion.)

Sources: Bernhardt (1979), Kaune and Anderson (1990).

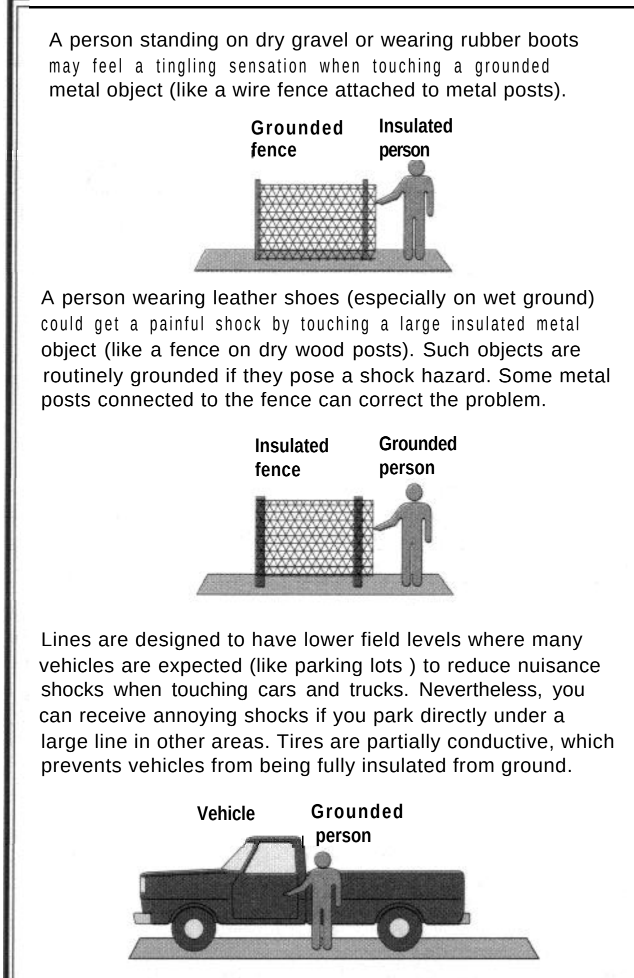


Figure 1.16. Typical situations where nuisance shocks can occur from induced voltages on objects near transmission lines.

cause they were made with people and objects placed on special rubber mats to insulate them completely from ground. Conditions conducive to maximum current in normal situations are rare. People and animals are usually grounded to some degree through their feet. Likewise, most vehicle tires are actually semi-conductive. In addition, soil and vegetation in contact with the tires or the vehicle provide additional paths for electrical charge to move to ground.

Shocks. Shocks can be classified as below perception, above perception, secondary, and primary. The mean perception level for an 82-kg (180-lb) man at 60-Hz is about 1.0 mA (Keesey and Letcher 1970). It is about two-thirds of that value for a 55-kg (120-lb) woman. Secondary shocks cause no direct physiological harm, but they may annoy a person, and cause muscles to react involuntarily. Though difficult to define precisely, the lower average secondary shock level at 60-Hz for an average-sized man is about 2 mA (Deno and Zaffanella 1975).

Primary shocks can be harmful. Their lower level is described as the current at which 99.5 percent of subjects can still voluntarily let go of the shocking electrode (conductor). Keesey and Letcher (1970) estimated the mean let-go level for an 82-kg (180-lb) man as 9 mA and 6 mA for a 55-kg (120-lb) woman. Their estimate for children was 5 mA. Dalziel(1943) earlier suggested 4.5 mA as a safe let-go current level for children. Ventricular fibrillation (the heart stops beating) is estimated to occur for 0.5 percent of adults with exposure for 3 seconds to a 60-Hz current through the heart of about 100 mA (35 mA for a small child) (Dalziel 1960).

The *National Electrical Safety Code* (NESC) (IEEE 1996) specifies 5 mA as the maximum allowable short-circuit current to ground from vehicles, trucks, and equipment near transmission lines. BPA lines are designed to meet requirements of the NESC. We are not aware of any instances where adults or children have been severely injured by induced currents from BPA lines. There have been reports of people receiving annoying shocks from vehicles and other objects near transmission lines.

Spark discharges. The discussion above dealt primarily with steady-state current that occurs while a person is in contact with the ground or an object. In the instant before contact, a spark discharge can occur. The effect is similar to the static discharge shock a person can feel after walking across a carpet and then touching a door knob. In the electric field of an AC transmission line, however, both charging and discharging are instantaneous and continuous, so long as there is a slight space between the objects involved. Spark discharges are a function of both voltage and energy. Energy is measured in joules (J) and is dependent on the size of the object which is discharged and the voltage on the object. For 50 percent of adult men, spark discharges reach the perception level (fingertip-touch) when they measure about 0.14 mJ (millijoule) (IEEE Working Groups 1985).

Fingertip-touch annoyance occurs around the 1.3 mJ level; hand-grab annoyance is estimated to occur at 4 mJ. The magnitude of spark discharges beneath transmission lines depends greatly on ground conditions, but, even under worst-case conditions for large vehicles, it would be less than 30 mJ. Although painful shocks are possible under certain conditions, shock levels are far below the 50 J level believed to represent a danger threshold in humans (IEEE Working Group 1972).

Utilities have for years mitigated problems associated with electric shocks from induced currents caused by transmission lines. Utilities have internal standards for grounding stationary objects such as fences, metal roofs, and antennas. Other examples of precautions to avoid electrical hazards are pointed out in subsequent sections of this report and elsewhere (Reiner 1972; IEEE Working Group 1972, 1973). BPA publishes safety information in a free nontechnical booklet titled, Living *and Working Safely Around High-Voltage Power lines.* An IEEE booklet also addresses the electrical effects of transmission lines (IEEE Working Group 1985).

Hair vibration. In addition to nuisance shocks, another short-term effect of 60-Hz electric fields is direct perception of the field. The alternating charges induced by an electric field on the body surface can cause a detectable sensation through hair vibration. With electric field strengths produced by most lines, people would normally not detect even the maximum field in this manner. By standing near mid-span of a 500-kV line on a still day, some people can feel a gentle vibration of hair on their head or on an upraised arm.

In one study, 110 men were asked to describe their perceptions of various 60-Hz electric-field strengths (Reilly 1979). Approximately 20 percent of the men could perceive a 9-kV/m field through stimulation of head hair. At field strengths of 2-3 kV/m, less than 5 percent of the men reported that they could perceive the field. At the lower field strengths, a gentle breeze can cause enough hair movement to mask the feeling that is produced by the electric field.

Cabanes and Gary (1981) assessed men's and women's perception of a 50-Hz electric field in an indoor high-voltage laboratory. With both arms held by the sides, only 5 percent of the people could perceive a 5-kV/m field. With one arm raised above the head, 10 percent perceived a 2-kV/m field. Sensitivity to electric fields increases if the hair is wet (Deno and Zaffanella 1982).

Magnetic Fields

Description and Comparative Levels

Description. A magnetic field is produced by moving charges (current) in a conductor. Magnetic fields are described in terms of flux density, B, and field strength, H. The H field is given in units of A/m. In this book, magnetic fields are given in terms of the B field to be consistent with common usage in research involving power-frequency magnetic fields. Measurements of the magnetic B field are given typically in tesla's (T) or in gauss (G). We will usually be dealing with smaller subunits and a useful conversion is, 1 μT= 10 mG. In air and in biological material, a magnetic field strength (H) of 1 A/m corresponds to a magnetic-flux density (B) of about 1.25 μT (12.5 mG) (Deno and Carpenter 1994).

Figure 1.17 is an example of the pattern of a magnetic field from a single current-carrying conductor above the ground. Notice that the field is not affected by the ground (assuming no large amount of iron is present). The magnetic field pattern surrounding a three-phase transmission line is more complex than that for a single conductor.

Magnetic fields, like electric fields, are vectors and can be described in three dimensions designated as x, y, and z (Fig. 1.18). Notice in the figure that the three components of the vector are orthogonal, i.e., they are mutually perpendicular.

Polarization. Multi-phase or multi-source magnetic fields are also polarized as described above for electric fields. Three types of polarization are defined: elliptical, linear, and circular. Figure 1.19 shows the

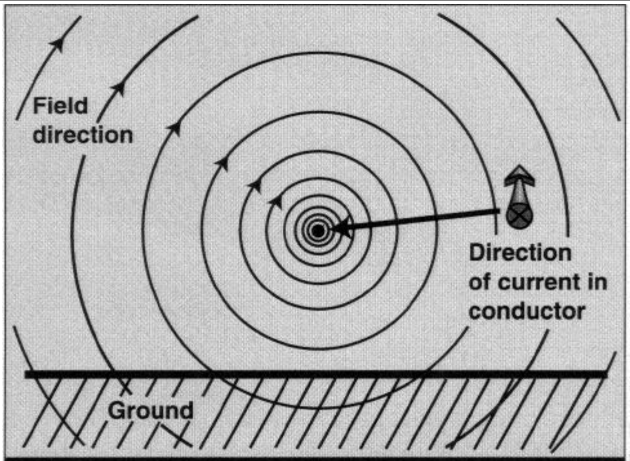


Figure 1.17. Example of the pattern of a magnetic field. For simplicity, the field is shown originating from a single conductor.

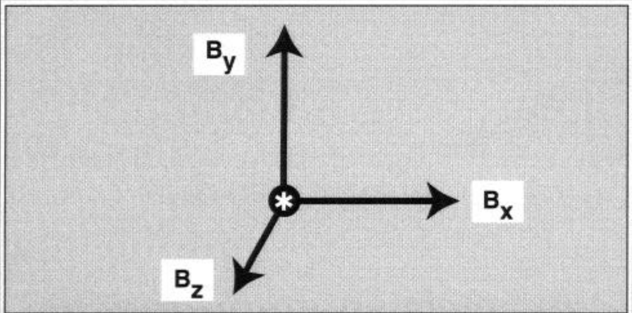


Figure 1.18. The magnetic field at any point (*) is a vector that can be described by three orthogonal axes, B_x, B_y, B_z.

pattern of polarization calculated for a 765kV transmission line. At each point surrounding the line, the direction and magnitude of the magnetic field changes throughout each cycle as the current in the conductors alternates at 60 Hz. The magnetic-field vector rotates around an ellipse in the x-y plane during each cycle (the z axis is parallel to the line). The direction and magnitude of the maximum magnetic field is shown by the semi-major axis. Similarly, the minimum field is shown by the semi-minor axis.

For three-phase transmission lines the magnetic field tends to be polarized elliptically near the ground within about 15 m (49.2 ft) of the conductors (Zaffanella and Deno 1978). Beyond this distance the fields tend to be polarized linearly, so they appear more like a single-phase field. With linear polarization, the semi-minor axis is a small fraction of the major axis. At some points near the conductors, circular polarization occurs: two axes are equal in magnitude but 90 degrees out of phase.

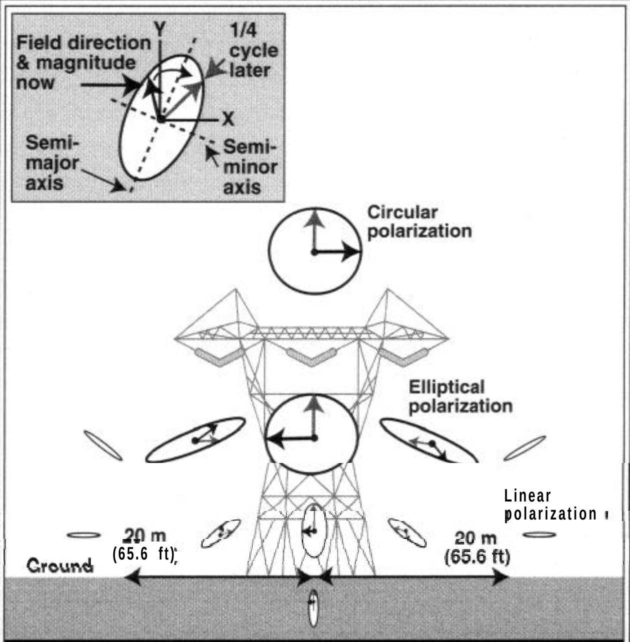


Figure 1.19. Magnetic-field polarization surrounding a transmission line. Only a few points are shown; however, the field is present everywhere around the line.
Source: Zaffanella and Deno (1978).

Harmonics. Harmonics are frequencies of magnetic or electric fields that are even multiples of the fundamental frequency. The harmonic content of the fields from transmission lines is small except where there is equipment serving large industrial loads (Zaffanella and Deno 1978). Harmonics are undesirable because they distort the voltage and current sine waveforms and, therefore, can adversely affect operation of some electrical appliances and equipment. Harmonics are also found in homes and businesses from the many electrical appliances which are present (Fig. 1.20).

A large study of homes across the U.S. found that residential harmonics consisted mainly of 180 Hz, the third harmonic of the 60-Hz power frequency (Zaffanella

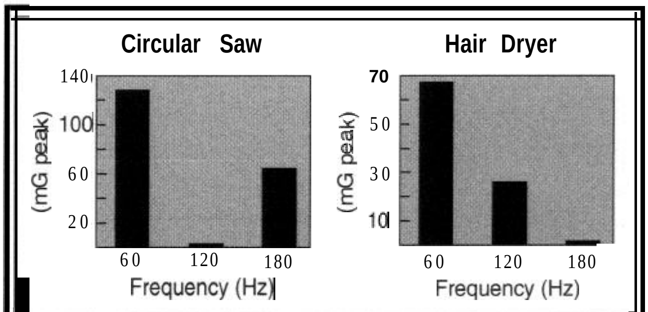


Figure 1.20. Magnetic-flux density for 60 Hz, and for the second (120 Hz) and third (180 Hz) harmonics for two electric appliances.
Source: Deno and Carpenter (1994).

1993). In that study, the total harmonic distortion was not large enough to affect significantly the rms measurements of the magnetic field. Harmonics can be important because induced current is directly proportional to frequency (e.g., a 120-Hz field induces twice as much current as a 60-Hz field of equal magnitude).

Transients. When power lines or appliances are switched on and off, high-frequency field bursts called transients are generated. Transients are more common with appliances because power lines usually remain energized for long periods. In contrast, appliances in homes and offices are continually being turned on and off, manually and automatically. Preliminary measurements of transients in homes made with special instruments have found that transients have frequency components ranging from below 60 Hz to at least 500 MHz (Guttman et al. 1994).

Transients have very short durations (e.g., approximately 100 to 200 nanoseconds for switching light circuits, Fig. 1.21). The duration of a transient can be characterized by the change (d) in magnetic flux density (B) as a function of change in time (t) (the time derivative is symbolized as dB/dt) The *dB/dt* waveform can be integrated to obtain magnetic-flux density; it is not clear which of the two parameters is most relevant in terms of biological exposures (Reilly and Kaune 1994).

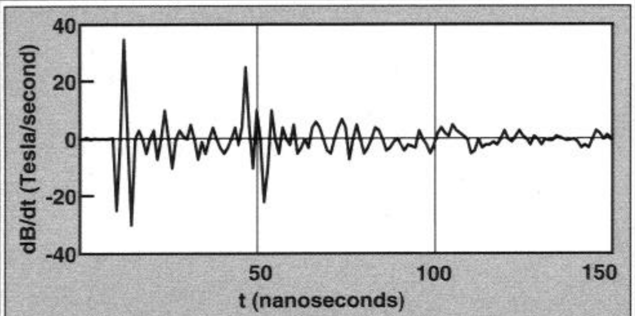


Figure 1.21. An example of a magnetic field transient when a 200-W lighting circuit is switched (as measured close to the switch). Source: Redrawn from Guttman et al. (1994).

Gaussmeters. Instruments used to measure magnetic flux density, commonly called gaussmeters (Fig. 1.22), differ in how they measure the three field axes shown in Figure 1.18. Three-axis gaussmeters measure what is called the resultant magnetic field. This is the square root of the sum of the squares of the three field components, $\mathbf{B}_x$, $\mathbf{B}_y$, and $\mathbf{B}_z$. With single-axis gaussmeters, the meter or the coil attached to the meter must be rotated carefully to measure each of the three axes.

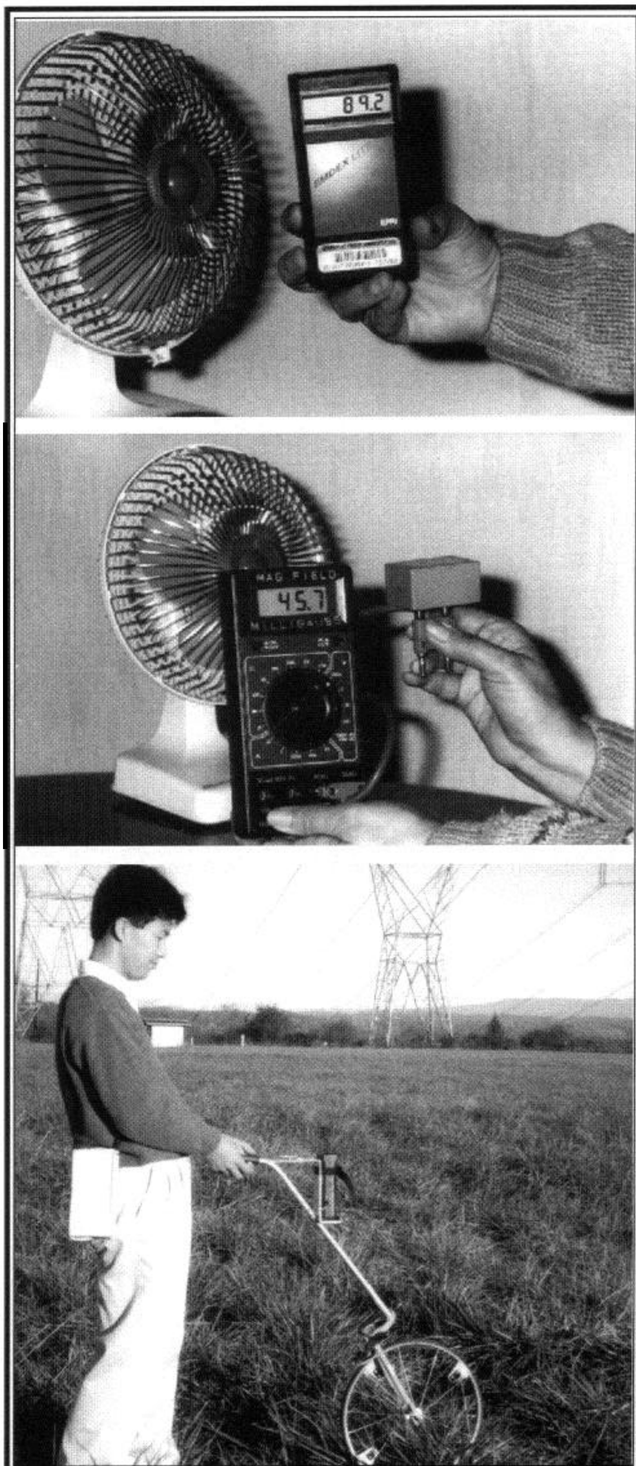


Figure 1.22. Magnetic flux density being measured with a three-axis EMDEX LITE gaussmeter (top). The reading is the resultant field in mG. With a Magnetics Sciences International single axis gaussmeter (middle) the coil attached to a digital multimeter is rotated to find the maximum field. The reading is also in units of mG. Three-axis meters can also be mounted on wheel devices to make magnetic field maps (bottom).

The resultant field must then be calculated by hand. A more direct approach, however, is just to record the maximum reading at a given point. This is usually sufficient for most purposes unless readings are to be compared with those from a three-axis meter. Some three-axis gaussmeters can store measurements for long periods, and can be used to record magnetic-field exposure automatically.

The maximum field value measured with a single-axis meter corresponds to the semi-major axis of the ellipse; the minimum value corresponds to the semi-minor axis (see Fig. 1.19) (NEMPG 1994). The resultant field, as measured with a three-axis meter, will be equal to or greater than the maximum field depending on the degree of polarization (IEEE MFTF 1992). The greatest difference occurs with circular polarization, where the resultant field is 41 percent greater than the maximum field.

The presence of harmonics can affect the reading from a gaussmeter, depending on the frequency response (bandwidth) of the meter. Most meters don't measure the field for a single frequency. Instead, they are sensitive to a range of frequencies. For instance, specifications for one single-axis gaussmeter used for 60-Hz fields give a bandwidth of from 10 Hz to 20 kHz. Specifications for a particular three-axis gaussmeter give a frequency response of from 40 Hz to 1 kHz. Depending on the harmonic content of the field being measured, the two meters could give different readings, in addition to differences between single and three-axis meters.

A publication that includes information and evaluations of available gaussmeters is for sale by the Electric Power Research Center in Ames, Iowa (telephone 5 15-294-8057). A list of gaussmeters is also available on the Microwave News home page on the "Internet" (http://www.microwavenews.com/).

Appliance fields. Magnetic fields from electric appliances are localized in the immediate vicinity of the device. Data in Figure 1.23 are from a study of 60-Hz magnetic fields from large numbers of electrical appliances. The magnetic flux densities in the figure are resultant fields measured with STAR (stand alone recorders) data-logging magnetic-field meters (Zaffanella 1993). For appliances in general, the field intensity decreases roughly with the inverse cube of the distance away from the device. In comparison, the magnetic fields from a transmission line typically decrease in intensity more slowly (approximately with the inverse square of the distance). The actual design of the line, however, influences the rate at which the field decreases.

Gauger (1985) used a single-axis gaussmeter to measure magnetic fields from 25 types of appliances. About 95 percent of his measurements of maximum magnetic flux density at a distance of 0.3 m (1 ft) from electrical appliances were below 10 µT (100 mG). At a distance of 1.5 m (5 ft), most appliance fields were less than 0.1 µT (1 mG). The background magnetic fields in the homes where the appliances were measured ranged from 0.05 to 0.1 µT (0.5-l .0 mG).

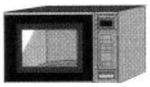
Florig and Hoburg (1991) studied the magnetic fields produced by electric blankets. They calculated that the 60-Hz magnetic flux density 5 cm (2 in) above conventional electric blankets ranged from about 1 .O to 3.5 µT (10-35 mG). For PTC electric blankets, the calculated magnetic flux density 5 cm (2 in) above the blanket ranged from about 2.0 to 4.5 µT (20-45 mG). For new low-magnetic-field-design PTC electric blankets made after 1990, average magnetic flux density measured 5 cm (2 in) above the blanket was only 0.09 µT (0.9 mG) (EPA 1992). Electric heaters used with water beds produce magnetic fields at the users' location of about 0.3-0.5 µT (3-5 mG) (Wertheimer and Leeper 1986, Bracken et al. 1995).

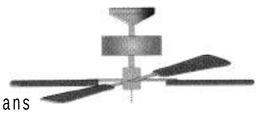
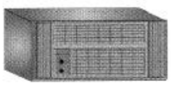
Magnetic flux densities at the surface of motor-driven personal appliances can exceed 0.4 mT (4 G) with time-rates-of-change exceeding 1000 T/s (Wilson et al. 1994). Such appliances (e.g., shavers, hairdryers, massagers) also produce high-frequency bursts in the low MHz range. Motor-driven appliances produce harmonic frequencies (see above section) that often induce higher currents in the user's body than those induced by the fundamental power frequency (Tofani et al. 1995).

Power-line fields. Magnetic flux densities for transmission lines are shown in Figure 1.24. The data in the figure are from a large study of BPA transmission lines; they show calculated average and peak field levels for average and peak load conditions. The actual field from a specific line depends on the design of the line and on the amount of current that it is carrying at a given time. The average magnetic flux densities beneath transmission lines are comparable in magnitude to those very close to appliances (see Fig. 1.23). The transmission-line fields, however, decrease in strength with distance much more slowly than appliance fields.

Magnetic fields are much more variable than electric fields because current varies greatly for a given line, and among lines. The current can vary by the hour, day, week, and by the season of the year, depending on the loads carried by a particular line. An example of the magnetic flux density measured over 1 week for a 500-kV transmission line is shown in Figure 1.25. Although the mean field during the week was 3.86 µT (38.6 mG), a "spot measurement" made during the week could have shown a level ranging from about 2.24-6.27 µT (22.4-62.7 mG) depending on when the measurement was made.

Magnetic Flux Densities At Two Distances From Appliances on the Left

Appliances	27 cm (10.5 in) Maximum	27 cm (10.5 in) Median	27 cm (10.5 in) Minimum	1.17 m (46 in) Maximum	1.17 m (46 in) Median	1.17 m (46 in) Minimum
95 Black & White TVs Measured	12.1 mG	2.9 mG	0.7 mG	1.3 mG	0.1 mG	0.0 mG
343 Color TVs Measured	18.6 mG	7.0 mG	0.4 mG	1.4 mG	0.4 mG	0.02 mG
383 Electric Ranges Measured	28.6 mG	9.0 mG	0.5 mG	6.2 mG	0.3 mG	0.0 mG
485 Microwave Ovens Measured (outside 60-Hz field, not inside the oven)	263.9 mG	36.9 mG	0.9 mG	17.2 mG	2.1 mG	0.2 mG
118 Analog Clock/ Clock-Radios Measured	41.2 mG	14.8 mG	1.8 mG	3.2 mG	0.3 mG	0.0 mG
95 Digital Clock/ Clock-Radios Measured	5.7 mG	1.3 mG	0.3 mG	1.3 mG	0.2 mG	0.0 mG
117 Ceiling Fans Measured	49.5	3.1 mG	0.2 mG	1.5 mG	0.3 mG	0.0 mG
86 Air Conditioners Measured (Window Units)	18.4	3.0 mG	0.1 mG	3.8 mG	0.2 mG	0.0 mG
397 Fluorescent Lights Measured	56.7 mG	5.9 mG	0.2 mG	3.5mG	0.4 mG	0.0 mG
367 Refrigerators Measured	15.7 mG	2.6 mG	0.1 mG	10.4 mG	0.4 mG	0.1 mG

Figure 1.23. Measurements of 60-Hz magnetic flux density at two distances from various electric appliances. To convert from mG to µT, divide by 10 (10 mG= 1 µT).
Source: Zaffanella (1993).

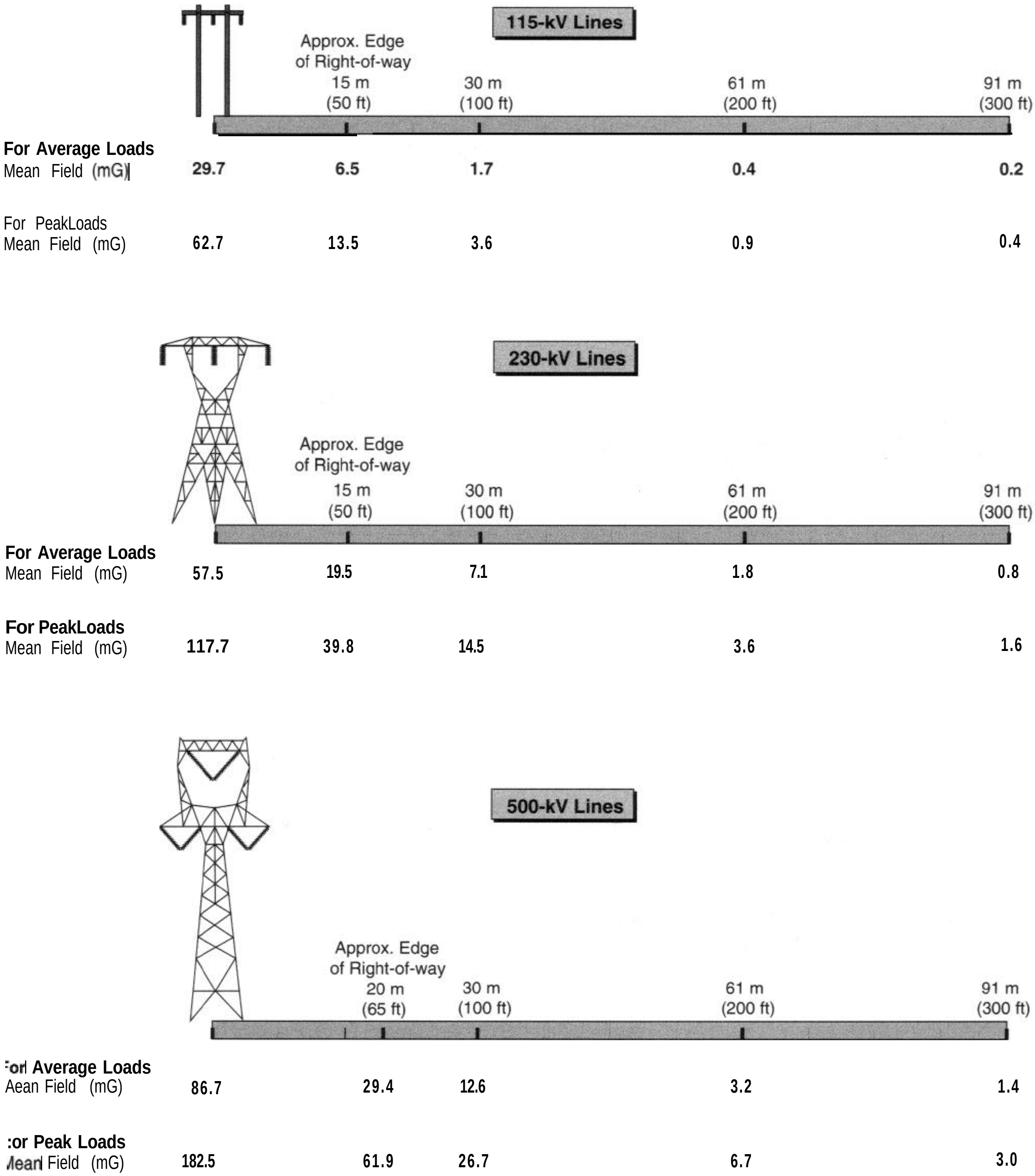


Figure 1.24. Magnetic flux densities (60-Hz) calculated for BPA transmission lines based on both average and peak loading conditions (peak conditions occur about 1 percent of the time each year). To convert from mG to μT, divide by 10 (10 mG = 1 μT). Source: Stearns et al. (1992).

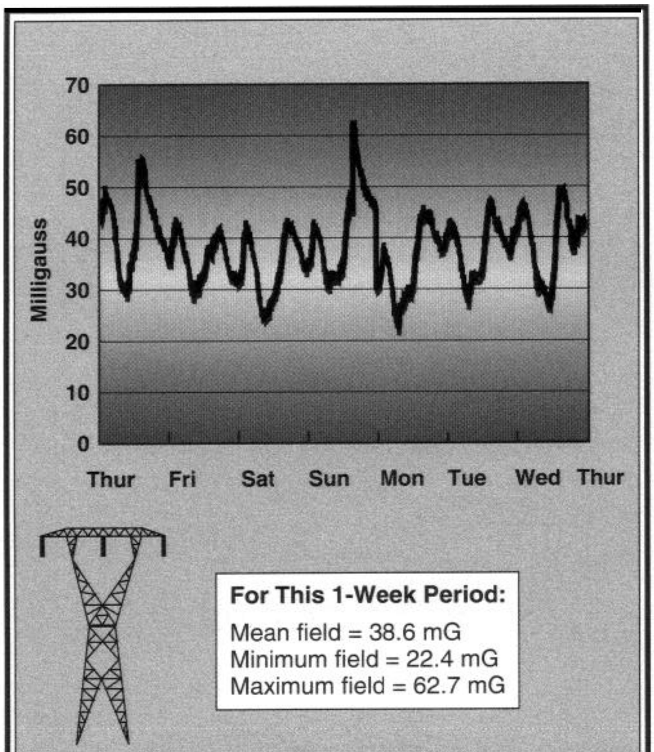


Figure 1.25. Magnetic flux density (60-Hz) measured every 5 minutes for 1 week on the right-of-way of a 500-kV transmission line. Measurements were recorded automatically with an EMDEX LITE meter.

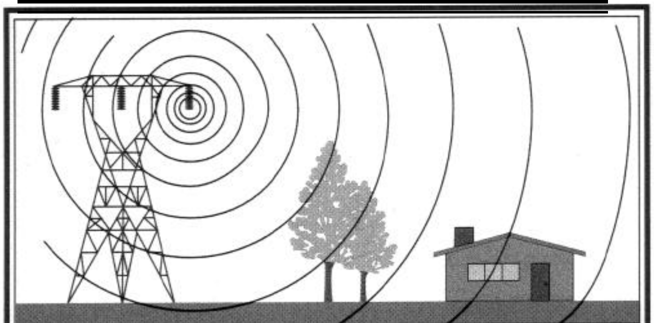


Figure 1.26. Magnetic fields are not shielded by most materials. They do decrease in strength with distance (see Fig. 1.24).

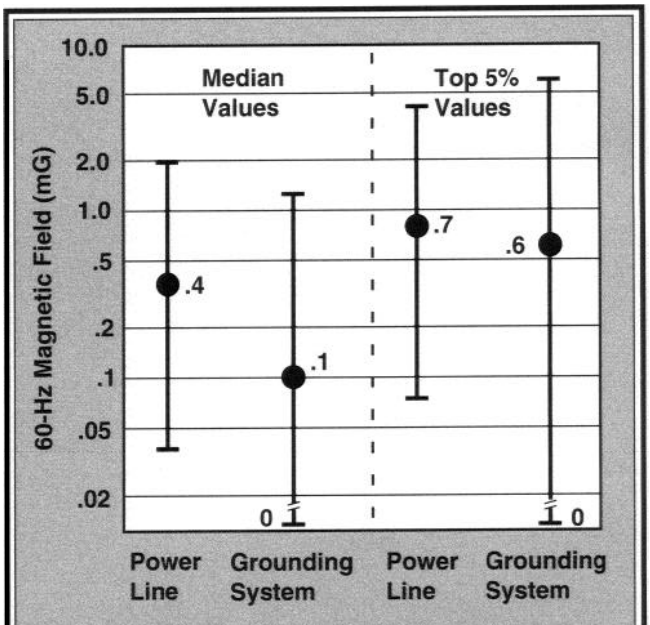


Figure 1.27. Median and top 5% of 60-Hz magnetic fields in 991 homes from power lines, and grounding systems (10 mG= 1 µT). Circles are the medians for each group. Upper bars show the field exceeded in 5% of the homes. Lower bars show the field exceeded in 95% of the homes. Source: Redrawn from Zaffanella (1993).

Unlike electric fields, 60-Hz magnetic fields pass easily through most objects, including buildings and people. Power lines can contribute significantly to the magnetic field found throughout homes near the lines (Figs. 1.26, 1.27). Savitz et al. (1988) reported that the average magnetic flux densities measured throughout homes near low-current power lines in Denver, Colorado, was around 0.0541 µT (0.5-l mG). In homes near high-current lines, the field averaged around 0.143 µT (l-3 mG). There was considerable variation in the measurements, however.

Measurements made in 138 homes in the Seattle area also indicated that household appliances made only a small contribution to the magnetic-field levels throughout homes. With most appliances off, the mean flux density in rooms was 0.09 µT (0.9 mG); with appliances on, the mean flux density increased only to 0.11 µT (1.1 mG) (Severson et al. 1988). The study also found no relationship between daily home electricity consumption and magnetic flux density measured in rooms in the home (Kaune et al. 1987b).

Silva et al. (1988) made magnetic-field measurements in 9 1 buildings in 6 states. The mean field levels in rooms were around 0.1 µT (1 mG). Average levels measured near appliances as they would normally be used ranged from 0.9 to 2 µT (9-20 mG). The way that homes are grounded and wired can have a big effect on the magnetic fields in the home. Silva et al. (1988) also found that the dominant magnetic field in homes located close to power lines appeared to be from the lines.

A large study was conducted of 60-Hz magnetic fields in nearly 1000 homes selected randomly across the U.S. (Zaffanella 1993). The study found that 60-Hz magnetic fields were strongest close to electric appliances (Fig. 1.23). However, power lines and grounding systems (Fig. 1.27) generally produced the largest magnetic fields throughout homes when fields were measured over 24 hours. Residential magnetic fields from power lines were highest for transmission lines, followed by three-phase primary distribution lines, single-phase primary or secondary distribution lines, and underground distribution lines. Only about 2 percent of the homes in the study had magnetic fields from transmission lines. No significant relation was found between home electric energy consumption, and residential magnetic fields. The overall mean of the mean 60-Hz magnetic flux densities measured in the center of rooms for all houses in the study was 0.09 µT (0.9 mG).

As described above, there are many factors that influence magnetic field levels in human environments: currents carried on nearby power lines, how well the currents are balanced, power line configurations, locations of return currents, and electric appliances and wiring (Figure 1.28). A report by an IEEE Task Force describes the numerous sources of magnetic fields and the problems involved in measuring and modeling these fields (IEEE MFTF 1988).

For power lines, an important factor that affects the magnetic field is how well the currents carried by the phase conductors are balanced. With three-phase transmission lines, the phase currents are generally well-balanced, and field strength decreases inversely with the square of the distance ($1/d^2$). The data on calculated transmission line fields in Figures 1.10 and 1.25 assume a balanced condition. Phase currents on distribution lines are usually not balanced because loads on the line are unbalanced (IEEE MFTF 1988). Unbalanced phase currents can increase fields greatly compared to the balanced condition.

The distribution primary branch line in Figure 1.28 is the common wye configuration: it has three phase conductors and a neutral (ground) conductor. Delta three-phase systems have three phase conductors but no neutral. Notice in Figure 1.28 that the electric service neutral wire is connected to a metal water pipe (sometimes it is connected to a metal ground rod), and the neutral is also grounded at the power pole.

Grounding is done for safety reasons (to protect against shocks and electrical fires). Ideally, current from the hot wires should all return over the neutral wire to the transformer. In reality, some of the current returns over water pipes and other buried objects or through the soil. This means that some magnetic fields around homes and other buildings come from currents on water pipes and other metallic objects that become connected to the electric power ground return system.

The magnetic field produced by the unbalanced (net) current on the power line decreases more slowly (inversely with distance, l/d) compared with the field from balanced current (Bracken 1994). Also, when current is balanced, magnetic field distributions are the same from wye and delta lines of the same configuration (Bennett 1992). However, with unbalanced conditions, the

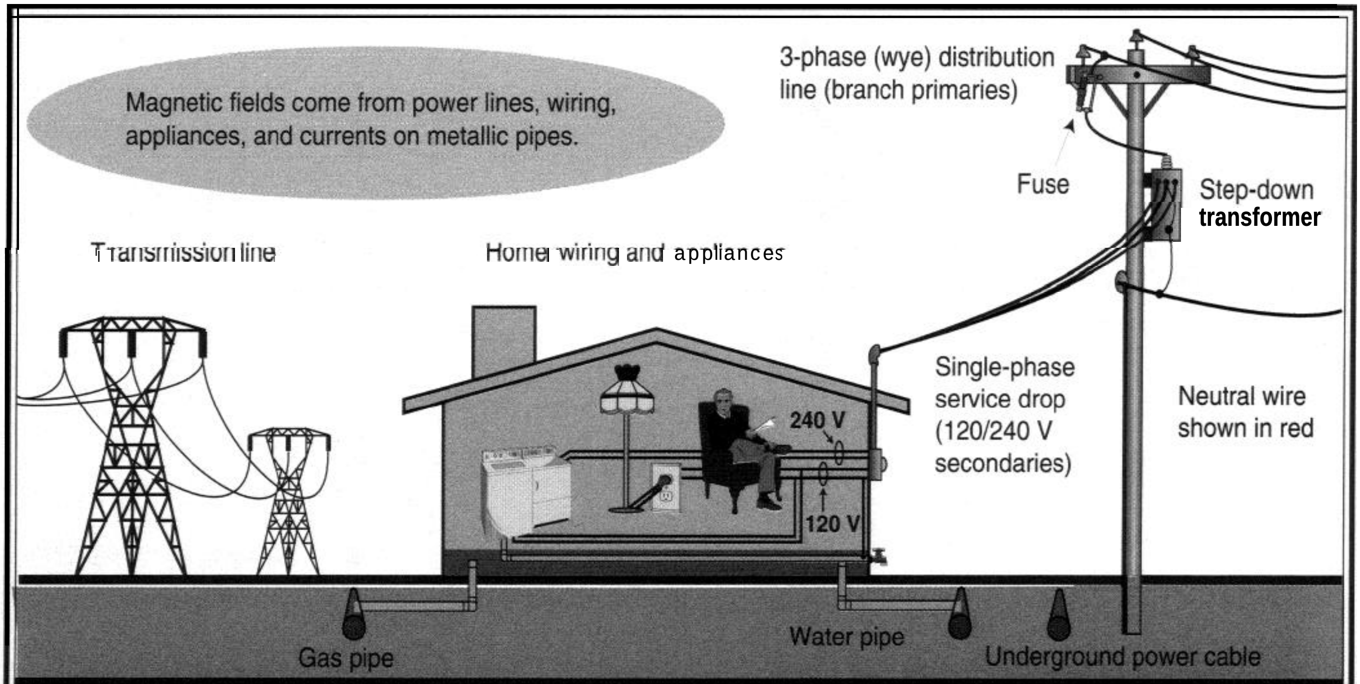


Figure 1.28. Sources of 60-Hz magnetic fields in and around homes

field distribution is different between the two systems, depending on the configuration (e.g., horizontal vs. vertical). Another factor that affects the magnetic-field distribution around buildings is how the electrical service drop wires are spaced. When the wires are twisted into a compact bundle (triplex), the field intensity is reduced considerably.

To summarize an important point made in the above sections, Figure 1.29 shows how fast field strength decreases with distance (d) at three different rates. Examples of sources where the field decreases as 1/d include a long straight conductor carrying current where the return-current conductor is very far away, and the net current on a power system. Fields decrease as $1/d^2$ from two conductors carrying equal currents in opposite directions, at distances that are greater than the distance between the conductors (e.g., balanced transmission lines). Examples of sources where fields decrease as $1/d^3$ include wire loops and coils (dipoles) represented by electrical appliances and transformers.

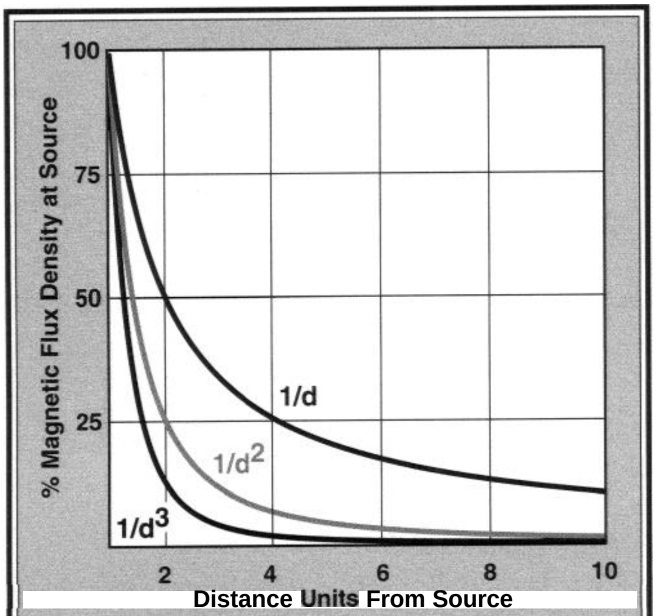


Figure 1.29. A comparison of how a magnetic field decreases inversely with distance (d) from the source at three different rates.

Induced Currents and Voltages

Body currents. AC magnetic fields induce electric fields and currents in conducting objects, including people and animals, through a process known as Faraday's law of induction. The internal current pathways induced by a magnetic field (called eddy currents) are different from those induced by an electric field. Current induced by the magnetic field occurs in loops perpendicular to the field. The largest loops and, therefore, the largest current densities, occur in loops around the periphery of the body. The current induced by the magnetic field can't be measured to ground (as opposed to the short-circuit current induced by the electric field). Nevertheless, magnetically induced current and induced electric fields can be calculated by assuming different sizes of current loops for various body parts (Bennett 1992, Carstensen 1987, Kaune and Anderson 1990, WHO/IRPA Task Group on Magnetic Fields 1987).

Figure 1.30 shows the patterns of the currents induced by the magnetic field from a transmission line. The magnetic field beneath the line is essentially horizontal, while away from the line the field is essentially vertical (see also Fig. 1.17). The maximum induced

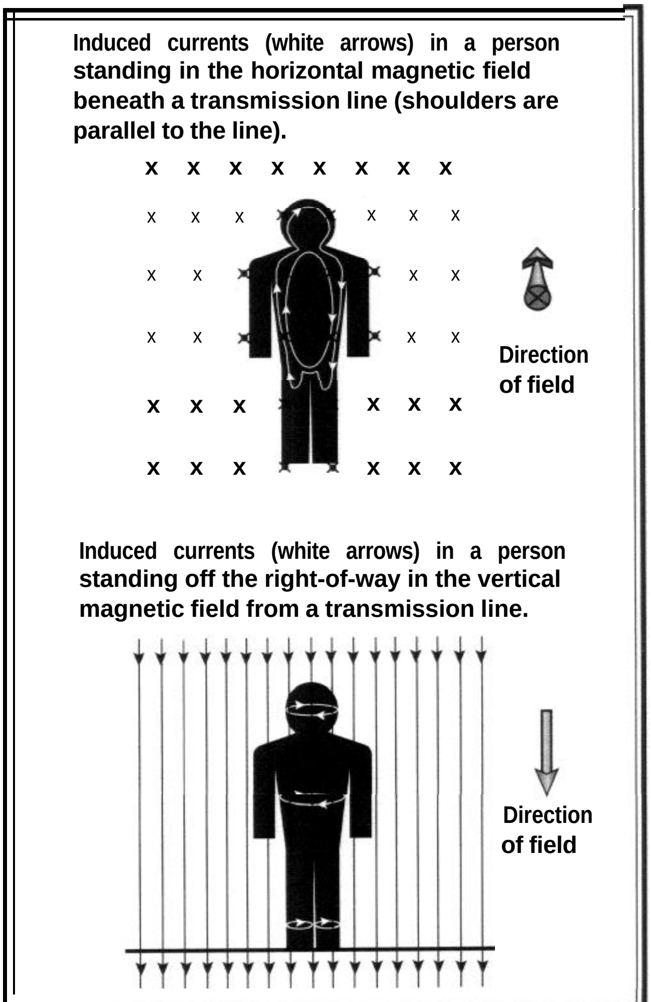


Figure 1.30. General distribution pattern of the current induced in a person standing in the horizontal and vertical magnetic fields from a transmission line.
Source: Carstensen (1987), Kaune and Anderson (1990).

current for a given magnetic flux density occurs when the field is horizontal and directed toward the front of the body, as in the top of Figure 1.30 (Carstensen 1987). In this case, around the trunk (radius= 0.2 m) of a person standing in a 5 µT (50 mG) magnetic field, the induced current would be about 4.7 nA/cm2, and the induced electric field would be about 235 µV/m. (For other magnetic field strengths the induced current and the induced electric field would be directly proportional to these levels).

For very small loops, such as the diameter of a single cell, the magnetically induced currents and electric fields are correspondingly very small. For a cell with a radius of 10 µm and in a 5-µT (50-mG) 60-Hz magnetic field, the electric field induced in the cytoplasm of the cell is only about 0.01 µV/m (based on Tenforde 1993).

Perception Effects

Most people cannot perceive 60-Hz magnetic fields of the magnitude produced by transmission lines. An extensive study involving 200 people found that they could not perceive 60-Hz magnetic fields of up to 1.5 mT (15 G) (a level more than 150 times stronger than the average magnetic field beneath a 500-kV transmission line) (Tucker and Schmitt 1978). Cook et al. (1992) also reported that none of the 30 men in their laboratory study could detect the presence of a 20-µT (200-mG) 60-Hz magnetic field.

Some studies have reported that certain people are "hypersensitive" to weak magnetic fields such as are produced by electrical appliances and power lines (Katajainen and Knave 1995). Such people may respond physiologically to such fields without being able to directly sense the field. However, there is considerable scientific uncertainty about this issue. (See "Electrical Hypersensitivity" in Chapter 2.)

Very strong AC magnetic fields, 10 mT (100 G) or more, can cause a flickering sensation in human vision (Tenforde 1985). However, the effect, called magnetophosphenes, disappears when the field is removed and there are apparently no reported harmful effects on the visual system.

Shocks. Magnetic fields can induce voltages at the open ends of long, partially grounded conducting loops such as fences, irrigation pipes, and distribution lines parallel to transmission lines. Normally, one end of the conductor is grounded and the earth serves as the remainder of the loop. A person or animal that closes the loop can experience steady state or spark discharge shocks.

Threshold and let-go levels are the same as for electric-field coupled currents. Magnetically induced voltages usually are lower and the current higher than in the electric field case. Here again, proper grounding of objects near transmission lines can prevent shocks. Grounding is very effective because objects long enough to create a hazard are usually permanent. For long parallel metal objects, such as fences, it may be necessary to break the electrical continuity. Further discussions of practical problems and safeguards appear in papers by IEEE Working Group (1973), Jaffa (1981), and by Jaffa and Stewart (1981).

Radio and Microwave Frequency Fields

Although this book deals mainly with power-frequency fields, questions are often raised about how effects of these fields compare to those at radio and microwave frequencies. The general term radio frequency (RF) has been used to describe frequencies from 3 kHz to 300 GHz (Hitchcock and Patterson 1995). This includes microwaves (frequencies from 300 MHz to 300 GHz). Some of the biological research described in this book was conducted with RF carrier frequencies modulated with power-frequency and other ELF (extremely low frequency, 3 Hz to 3kHz) fields. This section gives an overview of RF fields and compares basic properties with those of power-frequency fields. Some key references are included for readers who want more detailed information. The ongoing controversy about the possible health effects of RF fields has many similarities to the controversy associated with power-frequency fields (Hitchcock and Patterson 1995).

Description

Wavelengths for RF range from 100 km (62 mi) at 3 kHz, to 1 mm (0.04 in) at 300 GHz. The term "electromagnetic" field is usually applied to RF because in the "far field" region (more than about one wavelength from the source) the electric- and magnetic-field components are coupled tightly in propagating waves (Fig. 1.31). The two fields maintain the same relationship, so if the magnitude of one of the fields is known, the magnitude of the other field can be calculated.

Because power-frequency fields have extremely long wavelengths, their effects occur in what is called the "near field" region. This is a distance within about one wavelength from the source-about 5000 km (3 100 mi) for 60 Hz. In the near field, the electric and mag-

RF electromagnetic waves in the far field consist of tightly coupled electric and magnetic fields at right angles to each other. If the magnitude of one field is known, the other can be calculated.

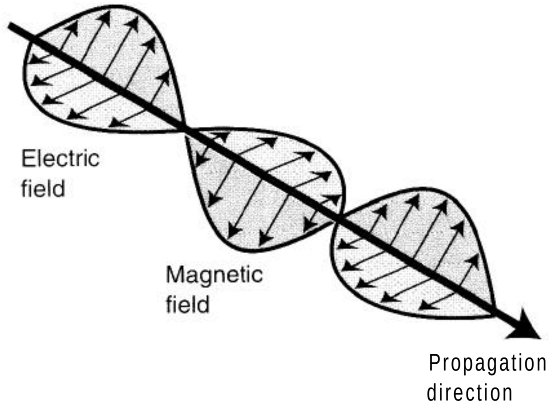


Figure 1.31. Pattern of an RF electromagnetic wave in the far field showing the relationship between the electric and magnetic fields.

netic fields are independent, and they can have widely differing values. Each of the two fields must, therefore, be measured or calculated separately.

The magnitude of RF electromagnetic fields in the far-field region is usually given in terms of power density: the measurement unit is Watts per square meter (W/m^2). For many environmental exposures, smaller subunits are used (i.e., mW/cm^2, or $\mu W/cm^2$). The size of the electric field, E, in V/m can be found by multiplying the power density in W/m^2 by 377 (the wave impedance in free space) and then taking the square root. The magnetic field strength, H, in A/m is found by dividing the power density by 377 and then taking the square root. The following is an example:

Power density	*Electric field*	*Magnetic field*
10 W/m^2	61.4 V/m	O.l6A/m

We are always exposed to RF fields from a wide variety of sources although field levels are usually very weak. Higher exposures occur when we are close to the RF sources, especially in occupational settings. Some examples of RF power densities in the environment are listed in Table 1.1.

Table 1.1 Some examples of radio and microwave frequency power densities in the environment.

Source, Location	Power Density ($\mu W/cm^2$)	Reference
Median in large cities [a]	0.005	Tell and Mantiply (1980)
1 % of U.S. population [a]	<1	Tell and Mantiply (1980)
In homes near broadcast antennas [b]	<100-200	EPA (1987)
Allowable leakage [c] from microwave oven:		
at 0.3 m (1 ft)	150	WHO/IRPA Task Group (1993)
at 1 .0 m (3.3 ft)	10	

a These are based on RF measurements made in 15 large cities in the U.S. FM radio broadcasts were a major contributor to the overall RF exposure.

b These were the highest levels in some homes located close to several AM/FM broadcast antennas in Portland, Oregon. Typical levels were well below 100 $\mu W/cm^2$,

c This assumes that RF leakage from the oven is at the maximum level allowed by the performance standard set by the Center for Devices and Radiological Health (5000 $\mu W/cm^2$, at 5 cm (2 in) from the oven surface (21 CFR 1030.10 (c).

Biological Interactions

For frequencies below about 1 MHz. effects of RF fields can be viewed as a function of induced currents in objects as described above for power-frequency fields (WHO/IRPA Task Group 1993). The amount of current is directly proportional to frequency. At higher frequencies, the currents can cause heating if power levels are sufficiently high. Maximum heating occurs when the object is similar in size to the wavelength of the field. For the human body, the maximum RF energy is absorbed when the body height is about 40 percent of the wavelength of the RF field (Gandhi 1980). For a 1.75-m (5.7-ft) tall human this corresponds to a frequency of about 70 MHz. Microwave ovens heat food efficiently because the frequency used (2450 MHz) has a wavelength of 12.2 cm (4.8 in), which is similar to the size of the food placed in the oven.

For RF fields it is, therefore. not sufficient to know only the power density. the frequency of the field is also important in assessing biological effects. The depth that

RF fields penetrate tissue is related inversely to frequency. For instance, for the frequencies of 100 MHz and 2450 MHz, the penetration depth is 60.4 cm (23.7 in), and 11.2 cm (4.4 in), respectively (Johnson and Guy 1972).

Scientists have developed a method for comparing effects of different frequencies called the specific absorption rate (SAR). This is a measure of the rate that RF energy is absorbed by tissue. It is given in units of watts per kilogram of tissue (W/kg). SARs can be calculated, or determined experimentally.

SARs can be used to compare effects of RF on different species. The average SAR for humans, monkeys, rats, and mice peaks around 70 MHz, 310 MHz, 750 MHz, and 2450 MHz, respectively (Durney et al. 1979). Exposure to RF for 20-30 minutes with an SAR of up to 4 W/kg increased human body temperature by about 0.1-0.5 °C (WHO/IRPA Task Group 1993). In comparison, the largest tissue field that could be induced through air by a 60-Hz field would produce an SAR of only about 0.0001 W/kg (Tenforde 1993).

A variety of biological effects has been reported for RF fields at intensities below where heating effects would be expected (Hitchcock and Patterson 1995). These "nonthermal" effects include studies of animals exposed to RF fields modulated at ELF frequencies. To date, no hazardous nonthermal effects of low intensity RF fields have been confirmed; nevertheless, the issue remains controversial (Hitchcock and Patterson 1995).

RF Standards

There are several national and international standards and guidelines for RF (Hitchcock and Patterson 1995, Klauenberg et al. 1995). They tend to be complicated because different frequency ranges have different limits based on specific kinds of biological interactions. There are also different views among scientific groups about the best way to approach setting a standard. Nevertheless, there are some common features in the newer standards. For instance, there is a trend to identify an SAR of 4 W/kg as a threshold for adverse effects (based on heating). A safety factor of 10 is then applied resulting in an SAR limit of 0.4 W/kg (WHO\IRPA Task Group 1993). As a result, allowed power densities are reduced for frequencies around the resonance frequencies for human exposure (i.e., around 100 MHz).

As an example, the American National Standards Institute (ANSI) has a standard for frequencies between 3 kHz and 300 GHz that applies to workers and the general public (IEEE 1992). The ANSI standard for occupational exposure (controlled environments) limits whole body exposure to less than 0.4 W/kg, and to less than 8 W/kg for the peak energy absorption in any part of the body. The allowable power density associated with an SAR of 0.4 W/kg for the human resonance frequencies (30-300 MHz) is 1 mW/cm². For public exposure (uncontrolled environments), the corresponding limit is based on an SAR of 0.08 W/kg, resulting in a power density limit of 0.2 mW/cm².

General Safety

It is not practical to cover overhead transmission line conductors with insulating material. A specific amount of air space is the insulation. Electricity can, therefore, arc through air from a power-line conductor to any conductive object connected to ground that enters this space. This phenomenon, called "flashover," means that an object does not actually have to touch the conductor, but must simply come close enough for an arc to occur. To prevent flashover, transmission lines are designed and built to have specific clearances between the line and ground and nearby objects. These clearances are specified by the *National Electrical Safety Code* (IEEE 1996).

Later sections in this review describe specific safety practices to be followed when living or working around high-voltage lines. In general, BPA lines are designed so that vehicles and other objects up to 4.3 m (14 ft) high can safely pass under the lines. This height has a safety margin built in, but if you need to operate equipment somewhat taller than this, you should first check with a BPA office. General safety precautions are described in a BPA booklet, *Living and Working Safely Around High Voltage Power Lines (see* page ii).

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Chapter 2

Exposure Assessment and Non-Cancer Human Health Studies

Summary

- Most of the early health studies of people occupationally exposed to EMF used job titles to estimate potential field exposures. Early residential studies estimated exposure by describing characteristics of nearby electric power lines and substations.
- Small instruments were developed to measure personal exposures to EMF. Electric-field exposures are very difficult to measure because they are greatly perturbed by conducting objects including the body.
- Average occupational electric- and magnetic-field exposures measured for electrical workers ranged from about 10-700 V/m, and about 0.14-O-77 µT (1.4-7.7 mG), respectively. Average electric- and magnetic-field exposures measured in homes and offices ranged from about 1– 20 V/m, and O-07-0.7 µT (0.7-7 mG), respectively.
- There have been about 29 studies of the general health of electrical workers, and about 11 general health studies of residents near power lines. About six studies looked for damage to chromosomes in electrical workers.
- Reproductive factors were included in about 13 electrical worker studies, and in about six residential studies. About 22 other studies looked at spontaneous abortion or other reproductive outcomes among women who used computers. Seven additional studies involved reproduction and use of various sources of electric heat.
- About seven studies looked at mental health conditions among electrical workers; about nine mental health studies were done of residents near power lines.
- About 34 studies looked for effects of short-term field exposures on human volunteers under controlled conditions.
- Many effects have been reported, but reviews generally find that there is no strong, replicated evidence for adverse health effects from EMF.

Background

Most of the interest that first developed in the 1970s about possible human health effects of power-frequency fields can be traced to reports from the former Soviet Union. Beginning in the early 1960s Soviet researchers began to study the health of workers in new high-voltage substations (400 kV. 500 kV, and 750 kV). Researchers attributed a variety of physiological and subjective ailments to the workers' exposure to 50-Hz electric fields (Asanova and Rakov 1966). The Soviet reports were first widely reported to researchers in other countries at a scientific meeting in 1972 (Korobkova et al. 1972).

Although medical evaluations conducted on 10 linemen in the U.S. in the 1960s revealed no harmful effects of electric fields (Kouwenhoven et al. 1967) the Soviet reports prompted further studies in other countries. The health effects reported by the Soviets were generally not found in these studies of substation workers in other countries.

Research on electric fields and human health expanded in the 1970s and 1980s in part because of reports of adverse effects of these fields on laboratory animals (e.g., Marino et al. 1976). In the early 1980s interest also developed in power-frequency magnetic fields, prompted by reports about a possible association between these fields and human cancer. Wertheimer and Leeper (1979) reported that cancer mortality was increased for children who had lived near high-current distribution lines.

EMF and occupational cancer became an issue following the publication of a paper by Milham (1982). Milham reported that men in electrical occupations in Washington state died more frequently from leukemia compared to men in other occupations.

Since these early reports, hundreds of studies have been conducted throughout the world on the possible effects of power-frequency fields on human health. These studies have covered general health. mental health, reproduction, and cancer. Most of these studies used epidemiologic methods, and a brief tutorial on epidemiology is presented in this chapter. Several other studies were done with human volunteers in laboratory facilities.

This chapter summarizes the large body of research on the possible effects of EMF on human health, other than cancer. Research on EMF and cancer in occupational and residential environments is covered in Chapter 3. In this chapter we begin by describing research that has been done to characterize human exposure to power-frequency EMF.

EMF Exposure Assessment

General Considerations

The early epidemiologic health studies of EMF were often criticized because of problems in measuring exposures (Coleman and Berall988). Occupational studies often used job titles to estimate exposures; some included spot measurements of EMF in work environments. Residential studies often described exposures by estimating the distance of homes from electric power facilities. In more recent studies, sophisticated instruments have been used to quantify exposures to EMF (Bracken 1993, Bracken et al. 1993, Kavet 1995). The pioneering efforts to develop instrumentation to measure personal exposures to EMF are described in the sections below.

Electric Fields

Assessing human exposure to power-frequency electric fields is very difficult because the presence of the body (which is a conductor) greatly perturbs the field. The electric field at the surface of various body parts, and the amount and distribution of currents induced within the body, therefore, change with the position of the body, e.g., standing, sitting, bending over.

For instance, assume that a person stood perfectly still for 1 hour in a 1-kV/m electric field (as measured without the person present). In this case, a basic measure of exposure could be designated as 1-kV/m-hour. However, if the goal is to relate exposure to some potential biological effect, then it is necessary to specify what aspect of exposure is of interest. At least three basic possibilities exist; the electric field at the surface of a body part, the total short-circuit body current, or the induced current density across some body part. All of these parameters are affected by body position and the presence of nearby conducting objects. For example, for a person standing in a 1-kV/ml vertical 60-Hz electric field, the enhanced field at the top of the head would be about 18-kV/m (Kaune and Phillips 1980). If the person sat down or bent over, the field would be less than 18 kV/m. At this time, there is no agreement among scientists as to what, if any, measure of electric-field exposure is most appropriate.

As described below, various devices have been developed to assess human exposures to electric fields. These devices measure the electric field by detecting the current induced by the field between two conducting surfaces. Different approaches have been used in an attempt to correct the readings obtained to account for effects of placement of the devices on different parts of the body. In some cases measures were also developed to account for human activity in the field.

Magnetic Fields

The body does not perturb power-frequency magnetic fields, so measuring human exposure to these fields is not as difficult as for electric fields. Several small magnetic-field exposure meters have been developed that can be worn by people as they do their normal activities. These meters measure the magnetic field by detecting the voltages induced on coils by the magnetic field.

Three-axis personal magnetic field exposure meters record at specific time intervals, the resultant field at the point on the body where they are worn. As indicated above, the presence of the body does not affect this parameter. However, the size and position of the body in relation to the magnetic-field sources do affect the currents and electric fields induced in the body by magnetic fields.

Occupational Exposures

Electric Fields

Deno (1977, 1979) described one of the first uses of a device to measure occupational exposures to 60-Hz electric fields. In his studies, small meters were developed that could be attached to a worker's hard hat or to an arm band. The meters recorded the time integral of the unperturbed electric field in kV/m-hours, or integrated the field into three ranges: less than 5 kV/m, between 5 and 10 kV/m, and greater than 10 kV/m.

The work by Deno (1977) prompted researchers in Sweden to develop an instrument to measure personal exposures to 50-Hz electric fields in transmission substations (Lovstrand et al. 1979). The measuring electrode was attached to the worker's hard hat, and the electronics package was carried on a belt. In initial tests, electric field exposures varied greatly, depending on the particular work activity. The highest exposure recorded was for personnel working for 3 hours on top of a circuit breaker where 3 1 percent of their time was spent in fields above 10 kV/m.

BPA researchers also developed a small 118 g (4 oz) electric field exposure monitor (EFEM) to measure the electric field environment for high-voltage workers (Chartier et al. 1985, Chartier and Bracken 1987). The EFEM was worn on a hard hat, in a shirt pocket, or on a lanyard (Fig. 2.1). Tests were conducted to determine electric-field enhancement factors for each of these locations. Results of the BPA study (Fig. 2.2) indicated that, even for the most exposed personnel (230-kV and 500-kV workers), exposure to unperturbed fields above 4 kV/m occurred for only minutes per day (Bracken and Chartier 1987). However, accumulated exposure for high-voltage workers was nearly three orders of magnitude greater than exposures for office workers.

As shown in Figure 2.2, for indoor workers (the non-exposed group), the median daily cumulative electric field exposure above threshold was only about

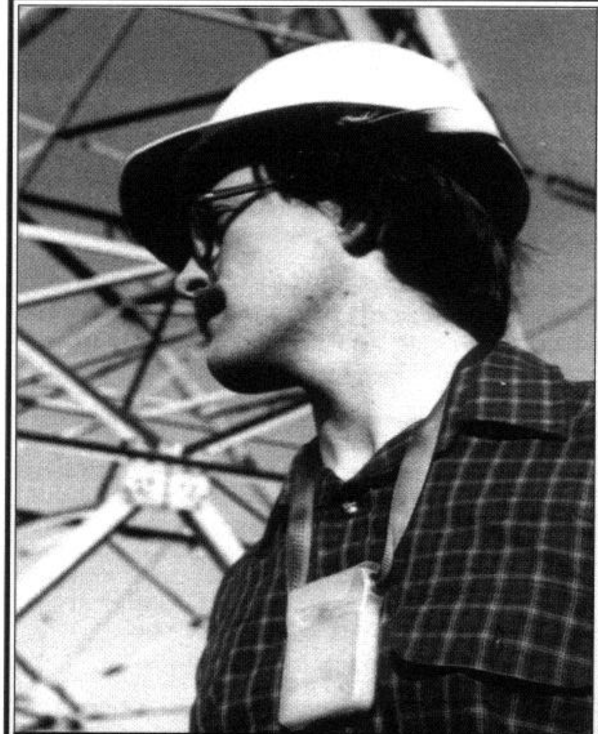

Figure 2.1. This man is wearing an electric-field exposure meter developed at BPA.

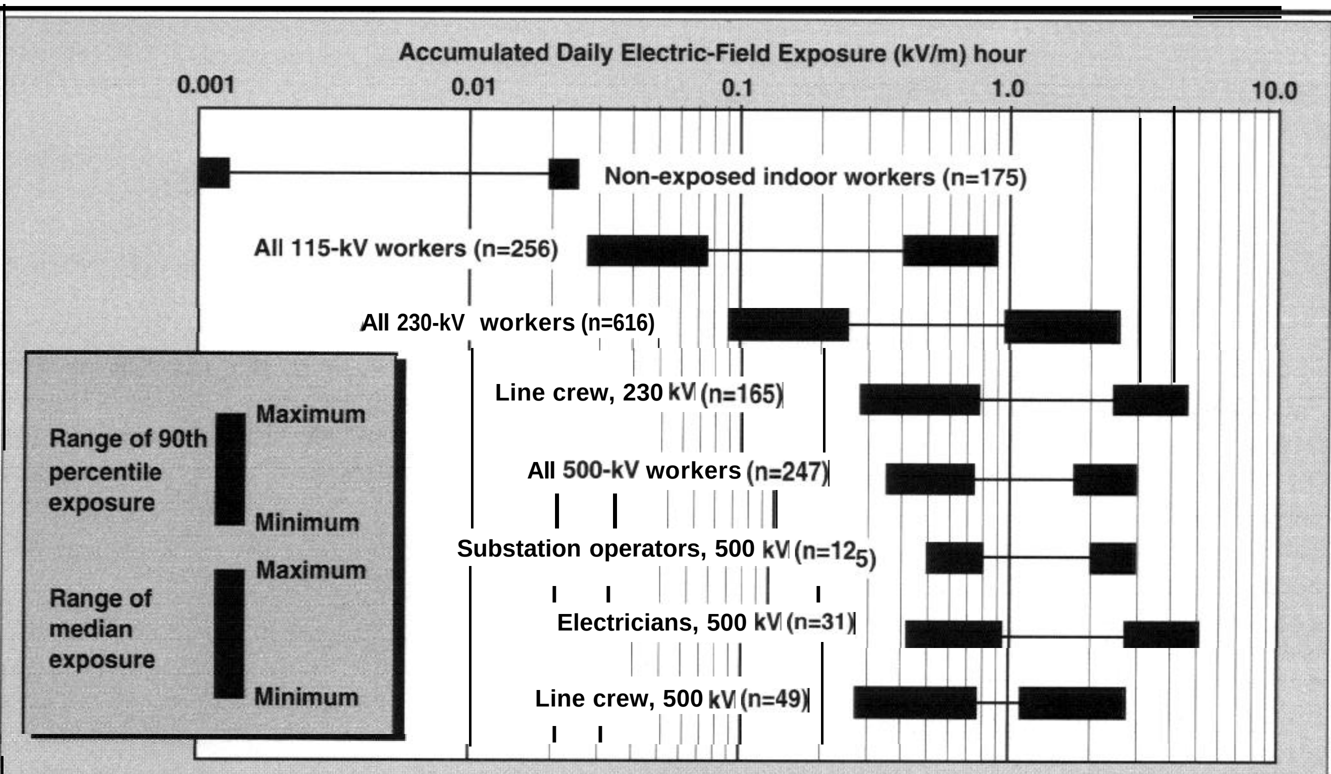

Figure 2.2. Daily accumulated 60-Hz electric-field exposure for BPA personnel. Data were obtained with an exposure monitor (EFEM) worn in a shirt pocket. The threshold of the meter was 0.4 kV/m. Source: Redrawn from Bracken and Chartier (1987).

0.001 kV/m-hours. In contrast, for all 500-kV workers combined, the median exposure was about 0.5 kV/m-hours per day. The highest (90th-percentile) exposure was about 5 kV/m-hours; it was recorded by electricians who worked around 500-kV facilities.

A study in the U.K. also employed a small meter to assess 50-Hz electric field exposures (Broadbent et al. 1985). The meter was worn on the worker's upper arm and it had a measurement threshold of about 150 V/m. During a 2-week period, only 28 of 287 electrical workers received exposures above 6.6 kV/m-hours. Estimates were made independently, for a 6-month period, of percentages of working time spent in fields of 1.5-5.5 kV/m, 5.5-9.5 kV/m, and greater than 9.5 kVl m. For the most highly exposed group, estimated percentages of working time in the three ranges were 5.6 percent, 15 percent, and 2.2 percent, respectively.

In another study, a specially designed vest was used to measure electric-field exposures received by people in various farming, recreational, and household situations (Silva 1985) (Fig. 2.3). The large surface area of the vest permitted detection of 60-Hz electric fields as low as about 50 V/m. For the 18 farms studied, the average time a farmer spent in fields above the threshold of perception (3 kV/m) was estimated as 1 hour per year for farms with 500-kV lines, and a few hours per year for farms with 765-kV lines. The total cumulative exposure (in kV/m-hours) for farmers working near transmission lines was comparable to the cumulative domestic exposures. About half of the latter exposure was related to the use of electric blankets. The recreational exposures studied (jogging, bicycling, horseback riding, skiing) were in general lower than those estimated for both agricultural and domestic exposures.

The performance of the electric-field monitoring vest was compared to the small BPA electric-field exposure meter (EFEM) during 2 days of controlled testing (Bracken 1985,1987). Seven men wore the meters during a variety of activities to simulate work tasks of substation electricians and operators. The vest and the EFEM produced similar results when the EFEM was worn on the arm or hard hat. When worn in a shirt pocket, the EFEM recorded field levels 30-40 percent lower than levels recorded by the vest. Both meters were judged to be adequate for measuring occupational exposures to electric fields. Only the vest was judged to be suitable for measuring public exposure to low-level electric fields.

Canadian researchers developed a small electronic instrument that could record EMF and transient fields for up to 2 weeks (Heroux 1991) (Fig. 2.4). In an initial test of the meter (later called the Positron), electrical workers' exposures to electric fields on the job and at home were studied (Deadman et al. 1988). Exposure meters were worn on a belt or in a shirt pocket at work and at home during a l-week period. The electric field threshold of detection for the meter was about 200 V/m; the sampling rate was 1 minute. Results of the study showed that, for 20 electrical workers, the geometric mean of the TWA (time-weighted average) electric-field exposure at work was 48.3 V/m, compared to only 4.9 V/m for 16 office workers. For the electrical workers the exposures ranged from 4.7 V/m for apparatus mechanics to 418.9 V/m for transmission linemen.

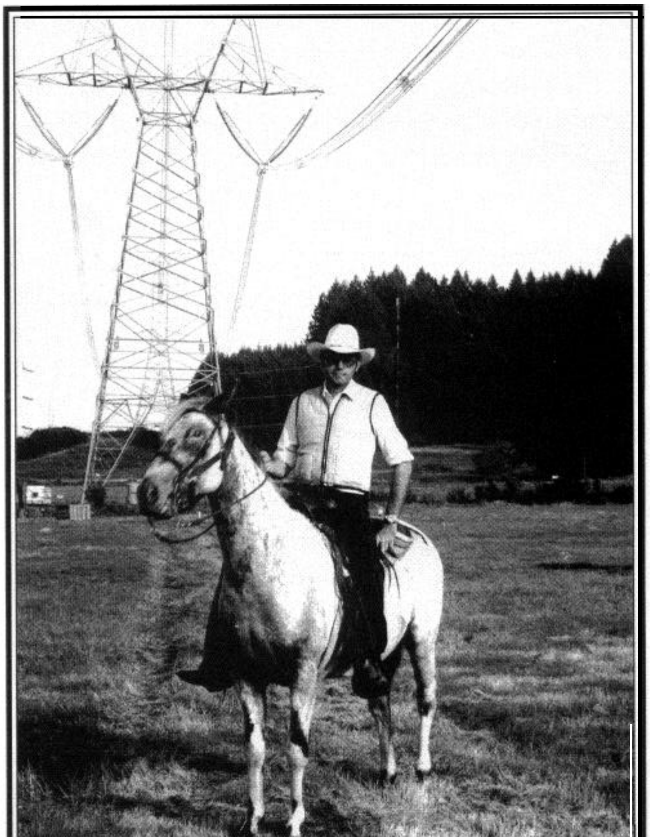

Figure 2.3. This horseback rider is wearing a special vest that measures exposure to 60-Hz electric fields. The vest was developed by ENERTECH Consultants for EPRI.

EPRI sponsored development of a digital exposure monitor called the EMDEX (Silva et al. 1988) (Fig. 2.5). This portable unit measured both electric and magnetic fields, and could operate for up to several days on one charging. A large multi-utility occupational exposure study was conducted to obtain information on performance of the EMDEX under actual operating conditions (Bracken 1990, Bracken et al. 1995b).

Electric-field exposure data were collected with the EMDEX for 2082 workdays and 657 nonwork periods (Bracken 1990). Because of problems in relating the EMDEX data to the unperturbed electric field, results were presented as relative comparisons among job categories. The highest electric-field exposures were received by line workers, substation workers, and utility electricians. Oflice workers received the lowest electric-field exposures.

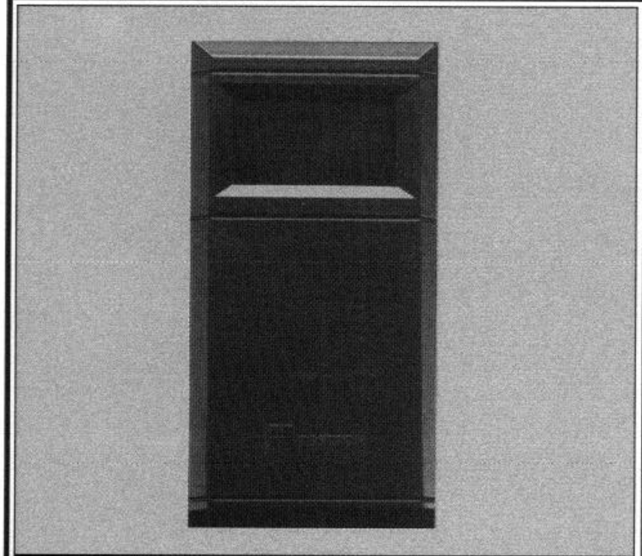

Figure 2.4. This electric and magnetic field exposure meter developed by IREQ, Montreal, Québec was licensed to Positron of Montreal. The meter measures 2.3 x 8 x 14.3 cm.
Photo courtesy of Dr. Sarma Maruvada.

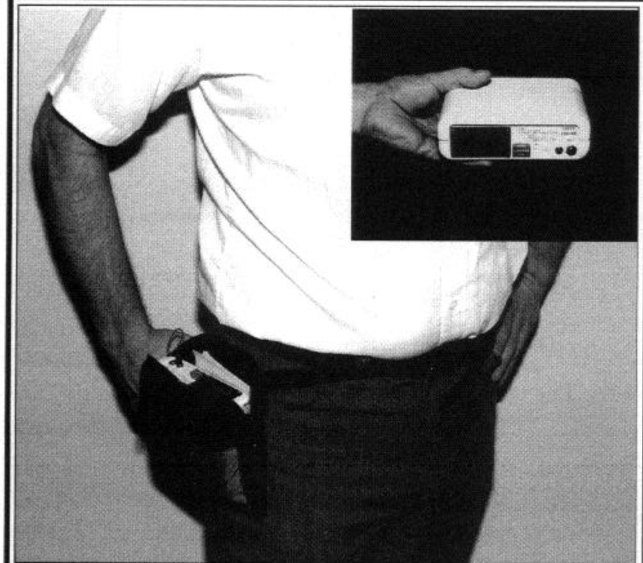

Figure 2.5. This man is wearing an early model EMDEX exposure monitor used in studies of occupational exposure to 60-Hz EMF described in the text. Development of the EMDEX was sponsored by EPRI.

Researchers in Denmark used a Positron meter to measure occupational exposures to 50-Hz EMF (Skotte 1994). In the study, subjects wore the meter during a 24-hour period. The medians of the mean electric-field exposures during work for utility employees in generation, transmission, distribution, and substations were, 9.7, 53.9, 6.2, and 17.5 V/m, respectively. The 95th-percentile exposures for these four occupational categories ranged from 24.2 to 592 V/m.

Magnetic Fields

Efforts to develop instruments to measure personal exposure to power-frequency magnetic fields followed the work with electric fields. The first instruments were developed in the early 1980s (Fujita andTenforde 1982, Lo et al. 1986, Male et al. 1987).

The BPA electric-field exposure meter (EFEM) was modified to measure 60-Hz magnetic-field exposures by adding a wire coil in the form of a bandolier worn across the chest. This version was based on the design of Male et al. (1987). The instrument measured the 4-second average of the magnetic field on the sensor. A small study was conducted to test the feasibility of using the single-axis instrument to collect data on occupational exposures (Bracken 1988). For eight substation operator days, the instrument recorded an average magnetic-field exposure of 0.41 ± 0.28 µT (4.1 ± 2.8 mG). In comparison, for nine office worker days the average exposure was only 0.074 ± 0.036 µT (0.74 ± 0.36 mG). Although occupational exposure measurements with the meter were feasible, the researchers suggested that a three-axis meter might produce more reliable data.

The personal-exposure meter used in the study by Deadman et al. (1988) (errors corrected in Deadman 1996) was a three-axis instrument that measured the 60-Hz magnetic field at l-minute intervals. The meter could also record high-frequency transient fields in the 5-20 MHz range. In a l-week test of the meter with 18 utility electrical workers, the geometric mean magnetic-field exposure during work was 0.77 µT (7.7 mG). The highest work exposure, recorded by apparatus electricians, had a geometric mean of 1.2 µT (12 mG). The comparison group of nonelectrical workers had a work-exposure geometric mean of 0.07 µT (0.7 mG).

The EMDEX personal-exposure meter was used to assess occupational and home exposures to power-frequency magnetic fields in a large study involving 58 utility organizations (Bracken 1990). The EMDEX is a three-axis magnetic field meter that can be programmed to take measurements at regular intervals, and to store data until they are downloaded to a personal computer. During the multi-utility study, magnetic fields were measured every lo-seconds by EMDEXs worn on the hip by about 2000 workers in the study (see Fig. 2.5).

Some of the general results of the EMDEX occupational exposure study are shown in Figure 2.6. Work in substations was associated with the highest median magnetic-field exposure; 1.056 μT (10.56 mG). The lowest occupational median magnetic-field exposure, 0.098 μT (0.98 mG), was recorded by workers in offices.

In the Danish study (Skotte 1994), a Positron meter was used to measure occupational exposures to 50-Hz magnetic fields. The medians of the mean magnetic field exposures during work for utility employees in transmission, distribution, and substations were 0.56 (5.6), 0.14 (1.4), and 0.89 (8.9) μT (mG), respectively. The 95th-percentile exposures for these three occupational categories ranged from 1.5 to 2.5 μT (15-25 mG).

Personal exposure meters were used to assess 60-Hz magnetic-field exposures of female employees in an office environment (Breysse et al. 1994). In the study, 15 women who worked with computers in a payroll office wore an EMDEX monitor in a hip pouch during most of one work day. The mean exposure for all 15 women was 0.32 +- 0.15 μT (3.2 +- 1.5 mG). The means for each woman ranged from 0.1 to 0.65 μT (l-6.5 mG). The high end of the exposure range was found to be caused by electrical wiring beneath the floor of one woman's workstation. Even with all office equipment turned off in the workstation, the background magnetic field was still 0.5 μT (5 mG).

Development of a very small magnetic-field exposure meter that can be worn on the wrist was sponsored by EPRI (Fig. 2.7). The first model of the meter, called AMEX (average magnetic-field exposure system), was a single axis meter that automatically recorded cumulative magnetic-field exposure over time. A later model called the AMEX-3D was a three-axis meter weighing 120 g (4.2 oz) that is worn in a hip pocket or pouch (Kaune et al. 1992).

The two AMEX models were compared in a test involving 50 employees, students, and spouses from a medical university (Dlugosz et al. 1994). The people wore both of the models at the same time for 2 days. The mean magnetic field recorded by the AMEX was 0.07 μT (0.7 mG) with a range of 0.02-0.27 μT (0.2-2.7 mG). The corresponding mean and range recorded by the AMEX-3D were 0.10 μT (1.0 mG), and 0.03-0.31 μT (0.3-3.1 mG), respectively. Differences be-

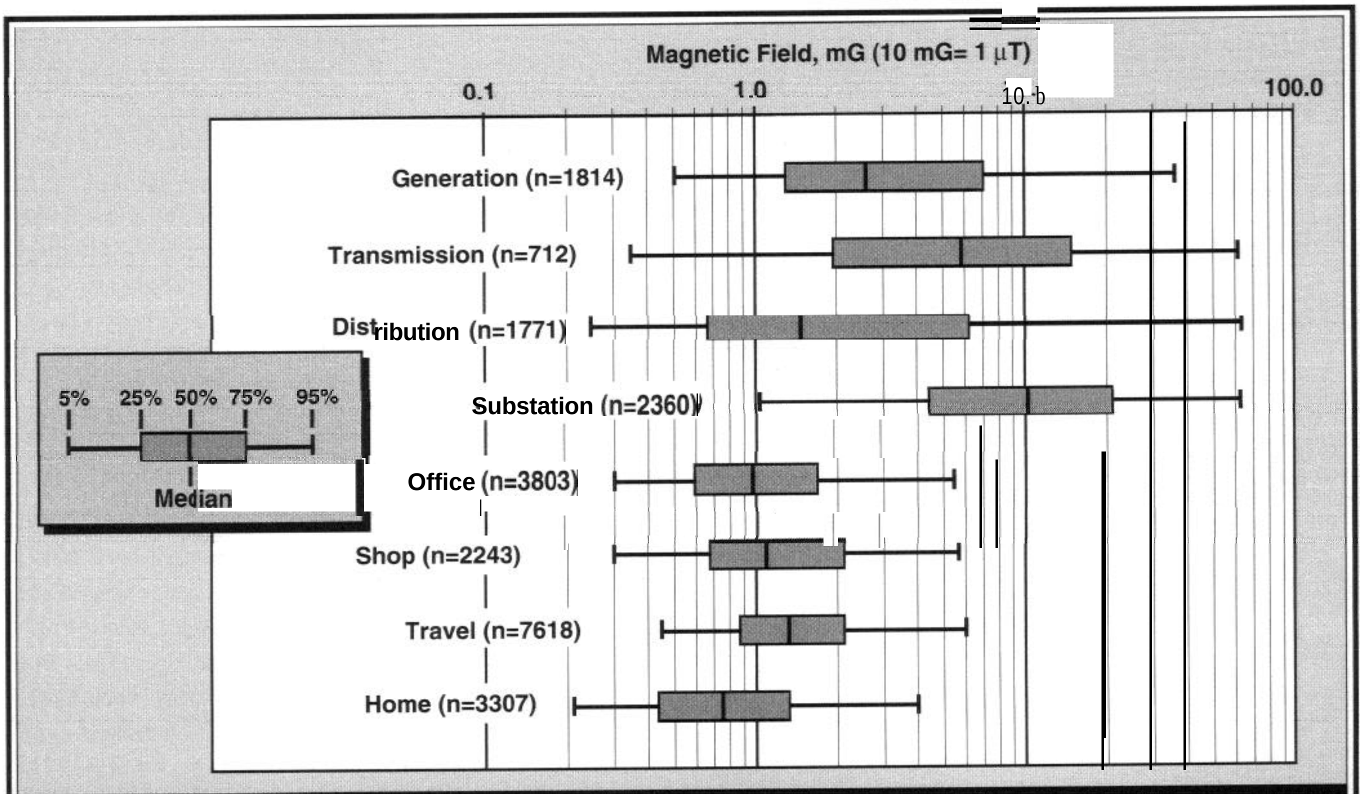

Figure 2.6. Distributions of magnetic fields measured by EMDEX monitors worn by workers in electric utility work environments and at home. The bars show the 5th, 25th, 50th (median), 75th, and 95th percentiles for the means of field measurements for continuous time spent in each environment.
Source: Redrawn from Bracken (1990).

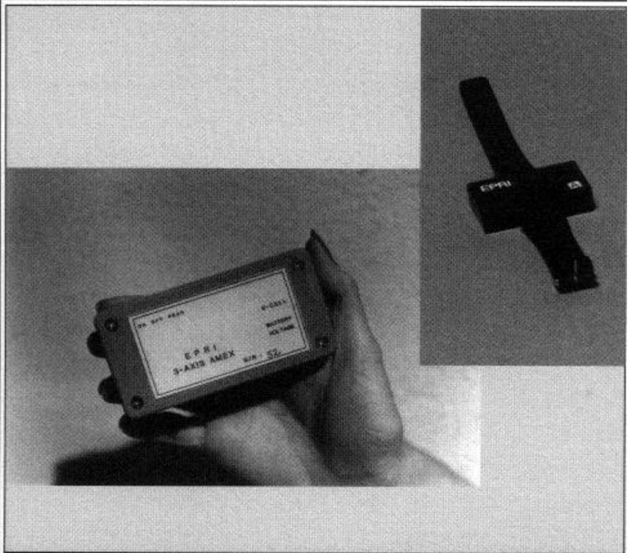

Figure 2.7. AMEX-3D (left) and wristwatch-size AMEX (right) magnetic-field exposure meters. Development of these meters was sponsored by EPRI. Photographs courtesy of Dr. Robert Kavet.

tween the readings for the two AMEX models were most likely due to electrical differences between the meters, and to differences in where they were worn on the body.

Residential Exposures

Electric Fields

Silva (1985) used a special vest to make extensive measurements of personal exposures to 60-Hz electric fields in residential environments (see Fig. 2.3). Exposures were reported in terms of equivalent fields. The equivalent electric field is the field that would induce the same body current as that induced in a grounded person standing in a uniform field of the same strength.

To estimate annual exposure, the equivalent field data were combined with estimates of the amount of time spent in various activities. For example, a person reading by a lamp experienced an equivalent electric field of about 9 V/m. If this activity occurred for 750 hours per year, the annual exposure from that activity would be 6.75 kV/m-hours. Based on this approach, the estimated annual electric-field exposure received by a person in a typical home was 69 kV/m-hours, almost half of which was from an electric blanket (Silva 1985).

In the occupational study by Deadman et al. (1988) workers were also asked to wear the Positron meter when they were not at work during the l-week test. At night they were to place the meter near the bed but not near an electrical appliance. The geometric mean of the time-weighted average electric-field exposure during the nonwork periods was essentially the same for both electrical workers and office workers (10.8 and 10.5 V/m, respectively).

The EMF personal-exposure study in Denmark (Skotte 1994) included home exposures of 38 people living near overhead power lines, 6 living near an underground cable, and 5 living near a substation. The power lines ranged in voltage from 50 to 400 kV. Home exposures were also measured for 267 people who did not live near power lines. The median of the mean exposures for people living near the electric power facilities was 21.9 V/m compared to 17.5 V/m for people who did not live near such facilities. The 95th-percentile exposure for the two groups was 91 V/m, and 47 V/m, respectively.

A Canadian study used Positron meters to compare 60-Hz EMF exposures for 18 people who lived within 60-73 m (190-240 ft) from a 735-kV transmission line, to 17 people who lived more than 366 m (1200 ft) from such lines (Levallois et al. 1995). Total electric field exposure at home (geometric mean) for those living near the lines was nearly twice as high as for those away from the lines (26.3 V/m, 14.OV/m, respectively). During sleeping time, exposure for those near the line was 2.8 times greater (27.3 V/m, 9.9V/m, respectively). For both home total and sleeping exposures, the differences between the two groups were statistically significant.

Magnetic Fields

Personal magnetic-field exposures were made during nonwork time in the occupational exposure study by Deadman et al. (1988) (errors corrected in Deadman 1996). The nonwork geometric mean of the TWA magnetic-field exposure for electrical workers was 0.20 µT (2 mG), compared to 0.11 µT (1.1 mG) for office workers. Authors of the study suggested that the higher exposure for the electrical workers may have been caused by misclassification of some work time as nonwork.

Data on residential 60-Hz magnetic-field exposures were obtained in a study of over 300 homes throughout the U.S. (Bracken 1994). A primary objective of the study was to collect measured data on magnetic fields associated with the power-line configuration types first developed in the childhood cancer study by Wertheimer and Leeper (1979). For part of the study, personal magnetic-field exposure data were collected with EMDEX meters using a lo-second sampling interval. Some of these data are shown in Figure 2.8. The study found that people in very-high-current-configuration homes had the highest magnetic field exposures. Overall, the power line classification types were poor predictors of residential magnetic fields because of high variability.

Personal 60-Hz magnetic-field exposures in homes were also obtained in the EMDEX occupational study (Bracken 1990) (Fig. 2.5). The median of the means for continuous exposures in the home was 0.073 µT (0.73 mG), and the 95th percentile was 0.401 µT (4.01 mG).

A study in Maine used EMDEX meters to measure magnetic field exposures of people living adjacent to and far away from transmission lines (Kavet et al. 1992). The mean magnetic-field exposure at home for five people who lived within 91 m (300 ft) of the center of a 345-kV transmission line right-of-way was 0.318 µT (3.18 mG). For 15 people who lived at least 213 m (700 ft) from any transmission line, the mean exposure at home was 0.159 µT (1.59 mG). The difference between these mean exposures for the two groups was statistically significant.

In the Danish study, the median of the TWA personal magnetic-field exposure of people living near electric facilities was 0.24 µT (2.4 mG) (Skotte 1994). For people who did not live near power facilities, the median exposure was 0.05 µT (0.5 mG). The 95th percentile exposure for the two groups was 1.54 µT (15.4 mG), and 0.17 mT (1.7 mG), respectively.

In a Canadian study, 18 people living near a 735-kV transmission line had magnetic-field exposures at home that were significantly greater than those of 17 people who did not live by such lines (Levallois et al. 1995). Total exposures at home (geometric mean) for the two groups were 0.71 µT (7.1 mG) and 0.16 µT (1.6 mG), respectively. During sleep the exposure ratio for the

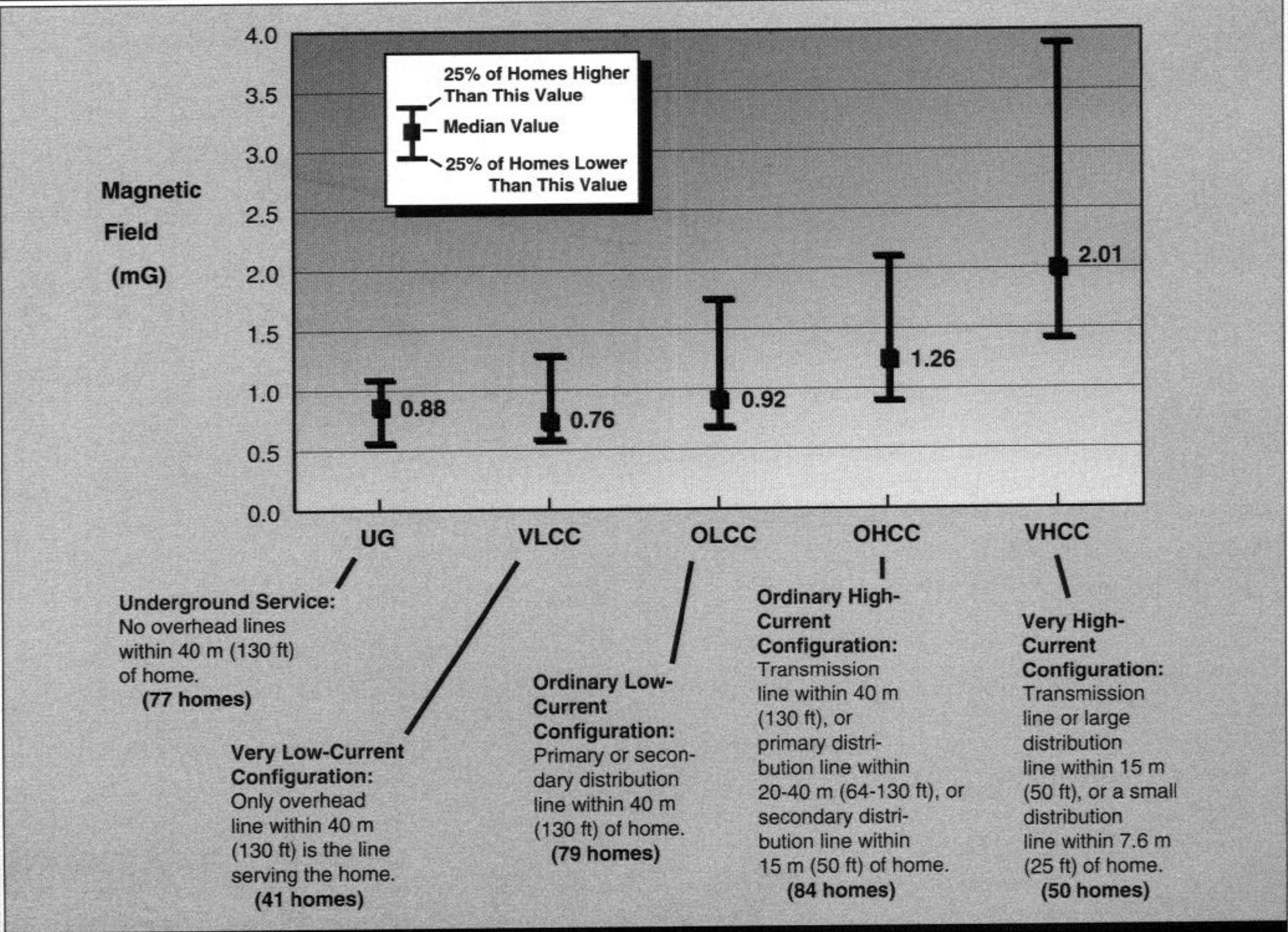

Figure 2.8. Exposures to 60-Hz magnetic fields measured by EMDEX meters worn by people living near electric power lines. The five power-line configuration types are those that have been used in some studies of cancer in residential areas. See text for more information. Source: Bracken (1994).

two groups was even greater; 0.68 µT (6.8 mG), and 0.11 µT (1.1 mG), respectively. All of these differences between the two groups were statistically significant.

24-Hour Magnetic Field Exposure

In the study by Deadman et al. (1988) (errors corrected in Deadman 1996) subjects wore the Positron meters at work and at home for about 1 week. The geometric mean of the weekly TWA magnetic field exposure for electrical workers was 0.34 µT (3.4 mG), compared to 0.10 µT (1 mG) for the office workers. The 3.4-fold difference in mean exposure between the two groups was statistically significant.

For the people living near a 345-kV transmission line in Maine, their 24-hour magnetic-field exposure was 1.6-fold greater than the mean for people living far away from transmission lines: 0.259 µT (2.59 mG), and 0.157 µT (1.57 mG), respectively. The difference was statistically significant. There was no statistically signiticant difference between the two groups for mean magnetic-field exposure while people were away from home. (These data exclude one person who had a very high exposure away from home and was considered by the authors of the study to be an outlier.)

The 24-hour magnetic field exposure (work plus home) for people living near a 735-kV line in the study by Levallois et al. (1995) was also significantly greater than for people living away from the line; 0.49 µT (4.9 mG), and 0.17 µT (1.7 mG), geometric means respectively.

Magnetic-field exposures over 24 hours were estimated from dosimeters worn by electrical workers and by people living near transmission lines in Denmark (Skotte 1994). The average exposure for the group of workers in generation, transmission, and substation, was roughly the same as for the people living near transmission lines-about 5 µT-hours (50 mG-hours).

AMEX-3D meters were used to assess magnetic field exposures of 29 children in the Washington, DC area (Kaune et al. 1994). Children wore the meters for 24-hours and exposure data were obtained for homes, schools, and daycare centers. Results showed that the mean of the TWA magnetic field exposures in homes was 0.141 µT (1.41 mG). For schools and daycare centers the mean exposure was 0.106 µT (1.06 mG). Exposures were highest for children living in high-current-configuration homes compared to low-current homes, but the variability in the measurements was high.

A study of 64 children from the mid-U.S. found that more than 40 percent of their time during a 24-hour week day was spent in their bedrooms (Friedman et al. 1996). Bedroom 24-hour magnetic field measurements correlated well with personal measurements made at home with AMEX-3D meters. The 24-hour median field in bedrooms was 0.086 µT (0.86 mG). The childrens' median total 24-hour exposure including time at home and away from home was 0.107 µT (1.07 mG).

Figure 2.9 shows data collected by two BPA employees to illustrate examples of patterns of 24-hour magnetic field exposure. One of the employees works in an office building with a computer. His highest exposure on the day of the measurements occurred when he used a microwave oven. The other employee works at a 500-kV substation. His highest exposure occurred when he made an inspection tour in the substation yard. For this particular 24-hour period, the substation operator's mean magnetic field exposure was about five-fold greater than that of the office worker.

Human Health Studies

The sections to follow summarize the research that has been conducted to assess the possible effects of EMF on human health. The information is presented in a rough chronology reflecting the order in which the major EMF health issues developed. Studies for each major type of health issue are described in tables that give the study design and primary results. Information in the tables is purposely brief, because over 200 individual studies are presented in this chapter. The text for each section compares and contrasts the studies, and provides more details on key studies. An introduction to epidemiology is presented on pages 2- 1 l-2- 12.

General Health

Occupational Studies

Occupational research on non-cancer health effects (summarized in Table 2.1) spans a period of nearly 30 years. The 29 studies from 12 countries listed in Table 2.1 mostly were concerned with the health of workers around high-voltage facilities. Studies began in the early 1960s when the first 400-700-kV transmission lines were introduced.

The first studies involved a small group of U.S. linemen (Kouwenhoven et al. 1967), and switchyard workers in Russia (Asanova and Rakov (1966). These studies were first compared and discussed by researchers in 1972 at the International Conference on Large High Voltage Electric Systems, held in Paris (Knickerbocker 1975). Overall, researchers from the U.S. and other countries attending the meeting were skeptical of the Russian reports of health effects attributed to electric

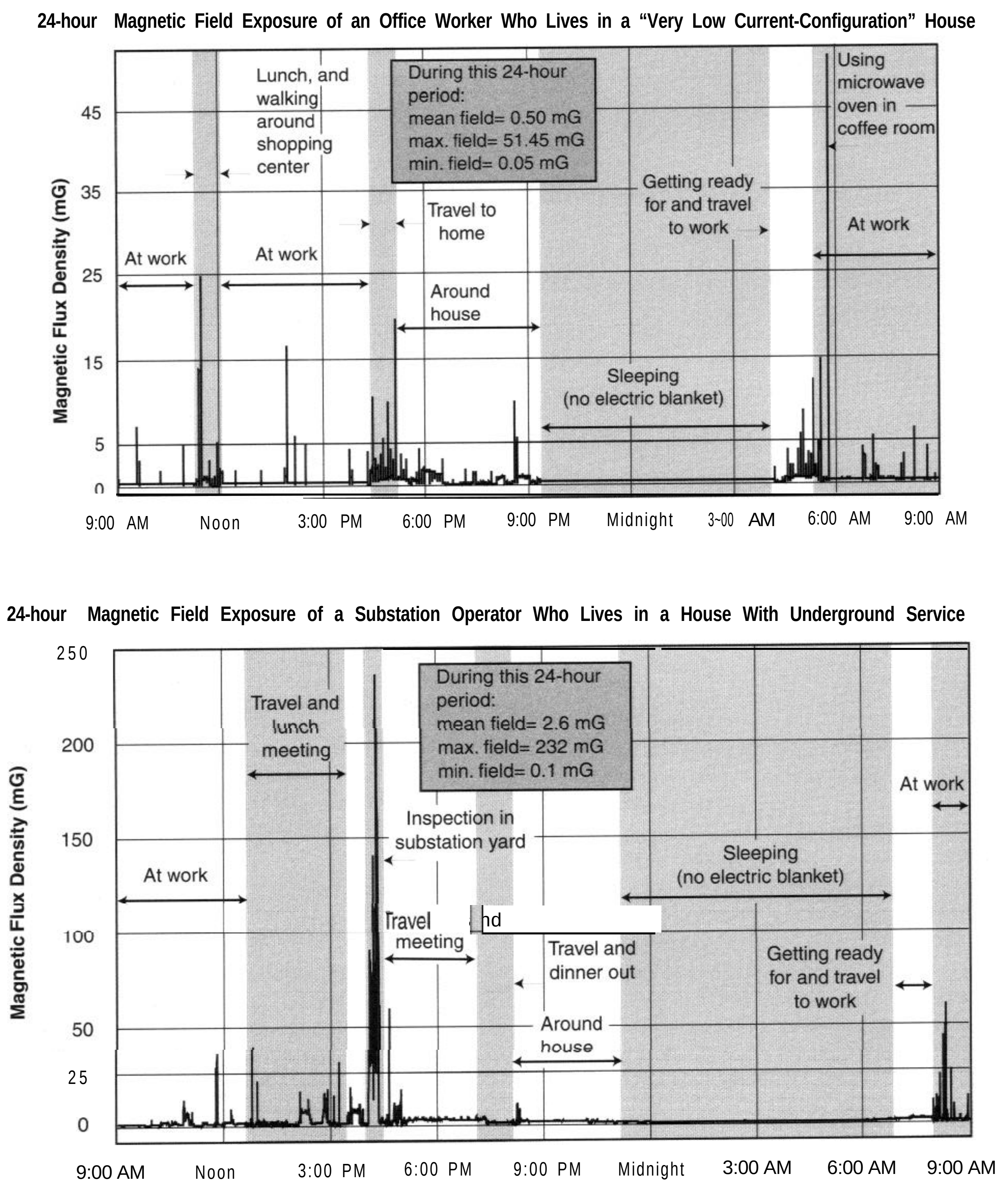

Figure 2.9. Examples of 24-hour 60-Hz magnetic-field exposures received by two BPA employees. One employee (upper) works in the main BPA office with a computer, and lives in a "very low current configuration" house (see Fig. 2.8). The other employee (lower) works at a 500-kV substation and lives in a house with underground electrical service. Exposure for the office worker was measured with an EMDEX Lite meter set to a sample rate of 4 seconds. Exposure for the substation worker was measured with an EMDEX II meter set to a sample rate of 5 seconds.

A Brief Introduction to Epidemiologic Terms and Concepts Used in Chapters 2 and 3

Epidemiology The study of the patterns of diseases or conditions in human populations, and of the factors that influence those patterns. The purpose of epidemiology is to obtain information to help prevent or control diseases and health problems. Although epidemiologists want to find the causes of disease, determining cause and effect often requires additional information from experimental studies.

Measures of Mortality and Morbidity

Mortality rate. The number of deaths among a specific population at risk during a specific time period. For example, the number of deaths per 1000 people from all causes in the U.S. during a given year. This is also a measure of the probability of dying during the specific time. Mortality rates are often adjusted to apply to specific age groups.

Proportional Mortality Ratio (PMR). The proportion of deaths from a specific cause among a specific population, compared to a reference population. For example, the number of deaths from brain cancer among electricians (e.g., within a company, industry, state) during a specific time period, divided by the expected number of deaths from brain cancer for all other occupations during the same time period, and multiplied by 100. The PMR is a relative comparison of the importance of deaths from a specific cause; it is not a mortality rate. A PMR of 100 means that, in the example, the electricians had the same proportion of deaths from brain cancer as in the reference population. A PMR of 200 means that the electricians died twice as often, and a PMR of 50 means that they died half as often from brain cancer as the reference occupations. The source of data for calculating PMRs is usually the death certificate, which includes cause of death and usual occupation. Data on age composition of the populations are not required to calculate a PMR.

Standardized Mortality Ratio (SMR). The number of deaths from a specific cause observed in a specific population (e.g., male welders in a large company), adjusted for age, divided by the number of deaths expected in an age-adjusted standard population (e.g., males in the state where the company is located), multiplied by 100. An SMR of 100 means that the mortality rate for the welders was the same as expected in the standard population (an SMR of 150 means that the welders had a 50% higher death rate).

Incidence rate. The number of new cases of a disease in a specific population at risk during a specific time period. An example is the number of new cases of leukemia among children during a given year. It can be expressed as the number of leukemia cases per 1000 children per year, or as the probability that a child will develop leukemia during the year.

Proportional Incidence Ratio (PIR). Similar to the PMR, except that incidence instead of mortality data are used.

Prevalence. The number of cases of a specific disease in a population at some specific time (it is not a rate).

Types of Epidemiologic Studies

Cross-sectional (prevalence) study. The presence of specific diseases or health conditions in a group or groups at a specific time. For example, questionnaires may be used to obtain data on the number of electricians in' a company who reported feeling depressed, as compared to the number of office workers in the company who reported depression. This type of study can be conducted relatively quickly, but it is usually difficult to determine the time sequence of how exposure may have preceded the effect.

PMWPIR study. Often used in occupational settings as a screening or hypothesis-generating study. A PMWPIR study yields only relative information on mortality or incidence among groups. An elevated PMR/PIR may suggest that the group of interest has a true elevated rate for some disease, or it may reflect that the rate from some other disease is lower in the group. Without further study, it is not known which possibility may be true.

Case-control study. A common epidemiologic study of relatively rare diseases. Cases are people who have a specific disease or health condition, and controls are people who are selected to be similar to the cases (based on age, sex, and other factors), but who do not have the disease or condition. One common approach for selecting controls is by random digit dialing of telephone numbers to contact people within the area near the locations of the cases. The basic approach in this type of study is to compare the exposure to some factor(s) received by the cases and controls prior to the development of the disease or condition. In most cases, exposures have occurred several or many years in the past. Estimating these historic exposures is a major problem in case-control studies. Exposures of cases and controls are compared by calculating an **odds ratio (OR).** The OR is the proportion of cases exposed to some factor (e.g., strong magnetic fields), divided by the proportion of controls exposed to the factor. It gives the odds that the cases were exposed compared to the controls. An OR of 1.00 means that there was no difference between the cases and controls in the proportions that were exposed to the factor (i.e., there was no **association** between exposure and the disease). An OR of 2.00 means that the cases were exposed to the factor twice as often as the controls, and this shows a **positive association** between exposure to the factor and the disease. This suggests that the factor may cause or influence development of the disease. An OR of 0.50 means that the cases were exposed to the factor half as often as the controls, and this is called a **negative association.** This suggests that exposure to the factor may help protect people from the disease. The OR may estimate the **relative risk** when relatively rare diseases are studied, exposure to the factor is common, and there are no important biases in the study.

A Brief Introduction to Epidemiologic Terms and Concepts Used in Chapters 2 and 3 (cont.)

Cohort study. In a **prospective cohort** study, a cohort can be a group of people exposed to some factor of interest (e.g., tobacco smoke) who initially do not have the disease of interest (e.g., lung cancer). The cohort is studied over a number of years to see how many individuals develop the disease. The incidence of disease in the exposed group can be compared with the incidence in another group that was not exposed (or exposed to varying degrees) to the factor (e.g., nonsmokers). The **relative risk** is the ratio of the incidences for the two groups, and the **attributable risk** is the difference between them. For example a relative risk of 5 means that the exposed group was five times more likely to develop the disease compared to the nonexposed group. SMRs can also be calculated from data collected in cohort studies. Prospective cohort studies can require very large numbers of people to be followed for long periods of time if relatively rare diseases such as certain cancers are studied. An alternative is the **retrospective cohort** study (such as are used in some studies of EMF). In this type of study, both the exposures and the disease or condition have already occurred. The cohort may be a group of workers in a company or group of companies beginning at some time in the past. Data on disease or deaths are obtained through company records or from state, regional, or national registries. As in case-control studies, a major problem is the estimation of exposures that may have occurred many years in the past. Risks can be calculated by comparing exposed and nonexposed groups internally within the company, or by comparing exposed groups to external populations such as state or national populations. Suppose, for example, that there were 50 deaths from a certain disease observed in a cohort of electrical workers. If the workers in each age group had the same death rate from the disease as in the state population, assume that 30 deaths would be expected. In this example the SMR= 50/30 xl 00= 167. As compared to the state population, the electrical workers in the company had a 67% increased risk of dying from the disease.

Confounders. A factor that is associated both with the exposure and disease of interest, and can be a cause of the association that may be attributed to the exposure of interest. As an example, suppose that electricians had high exposure to some chemical that causes cancer, and also happens to be present when exposures occur to magnetic fields. If the researcher was not aware of this, and only magnetic fields were measured, the association between magnetic fields and cancer could be due at least in part to the chemical. When information is available on potential confounders, they are often taken into account as epidemiologic studies are designed and analyzed.

Healthy worker effect. Generally, workers tend to be healthier and have lower death rates when external comparisons are made with the general population. This is because chronically ill and disabled people are generally less likely to be employed. This phenomenon can make it appear that employment or occupational exposures have a protective effect, or it may mask risks associated with occupational exposures.

Statistics

The various risk measures discussed above are usually point estimates from samples from larger populations. Therefore, they will have variability associated with them. The amount of variability depends on the size of the sample, and on the natural variability among people in the sample for the various factors under study. Statistical tests are used to give some idea about this variability and whether the results could have been due to chance.

Confidence intervals (Cl). A range calculated around a point risk estimate, such as an odds ratio, that includes the true risk with a certain level of probability (usually 95%). For example, an OR of 2.3 with a 95% Cl of 1.5-4.8 means than there is a 95% chance that the true risk is somewhere between 1.5 and 4.8 (and a 5% chance that it is outside of this range). In this book all confidence intervals included (usually following a comma after the point estimate) are for 95% unless noted otherwise. If (as in the example) the Cl does not include unity (1 or 100 depending on the risk estimate), the risk is considered to be **statistically significant,** i.e., it is very unlikely to be a chance finding.

p (probability) value. The probability that a difference observed between groups is due to chance. A statement that p= 0.15 means that the difference would be expected to occur by chance alone about 15% of the time. Usually, p values of less than 0.05 are considered to be statistically significant (shown as $p< 0.05$).

Cause and Effect

Although statistics can help epidemiologists decide whether their results may have been due to chance, a statistically significant association does not also mean that the finding proves that the association represents a cause-effect relationship. Determining whether some factor is a cause of a disease requires further analyses and study. Ultimately, the determination is a matter of judgement. Several criteria (e.g., Hill 1965) are often used to help in this judgement process. These attributes of the association to be considered include : 1) strength, 2) consistency, 3) specificity, 4) temporality, 5) biological gradient, 6) plausibility, 7) coherence, 8) experiment, and 9) analogy. Assessing cause and effect is difficult because diseases generally have multiple causes that may act through direct or indirect means. Epidemiologic evidence alone is generally considered insufficient to scientifically establish causality. However, there is also considerable judgement involved in assessing whether evidence for causality from epidemiologic and other studies is sufficient in practical terms to warrant preventative or public health action.

References: Ahlbom and Norell (1984) Hill (1965), Last (1995) Lilienfeld and Lilienfeld (1981), Rothman (1988)

Table 2.1. A summary of studies of general health of electrical workers exposed to EMF.

Study/Location	Subjects/Exposure	Selected Results
Asanova & Rakov (1966), Russia	Health exams of 41 men and 4 women working in 400-500-kV switchyards Electric fields measured in switchyard.	Variety of ailments attributed to 50-Hz electric fields: headache, fatigue, male sexual problems, chest pains, irritability, gastritis, and effects on blood composition. No quantitative data presented. Mean field = 14-1 8 kV/m
Sazonova (1967), Russia	Health exams of 29 switchyard operators (<2 hr exposure/day), and 25 maintenance people >5 hr exposure/day. Electric fields measured in switchyard.	Exams before and after work showed several statistically significant differences between groups. For maintenance group: pulse rate and blood pressure lower and sensitivity to current higher; slower reaction and higher test error rate. Overall, stronger electric fields increased fatigue.
Kouwenhoven et al. (1967), U.S.	Health exams given to 1 1 linemen over 42months. Exposure by hours of live line maintenance.	No significant health changes noted. Two men had low sperm counts. No quantitative data on results presented. Range of body currents during line work: 85-840 µA.
Singewald et al. (1973),	9-year follow-up of linemen in the above study-	Health of the linemen was not changed by exposure to high voltage lines. Few quantitative data from exams presented.
Krivova et al. (1973), Russia	Health exams were given to 319 men working around 220-500-kV facilities. ENM.	For 500-kV workers compared to workers at lower voltages, pulse rate and blood pressure deviated more from normal. Changes in blood composition were also reported.
Fole et al. (I 974) Spain	3 technicians and 3 medical people were examined while in a 400-kV station for 3-8 hr.	Some subjects complained of weakness and fatigue: heart rate was reduced and blood pressure increased. No quantitative data were provided. Field range: 2-21 kV/m.
Roberge (1976) Canada	56 male 735-kV substation workers given health and lab exams. Lab data were compared to a control group. ENM.	Subjective ailments reported by Russian substation workers were not found in this study. Differences between controls and substation workers in several lab tests were statistically significant, especially for the 30-39 yr group.
Malboysson (1976) Spain	Health of 84 men in 400-kV substations compared to 94 lower voltage workers for 4 yr. ENM.	Field exposure did not cause lasting pathological effects since no biochemical changes were found. Exposure to 400-kV facilities was of limited duration at time of study.
Knave et al. (I 979), Sweden	Health of 53 men in 400-kV substations was compared to 53 nonexposed workers. Electric field dosimeter used for base levels.	No health effects were attributed to electric fields and the 400-kV workers did better on psychological performance tests.
stopps & Janischewskyj (1979), Canada	Health of 30 high-voltage workers compared to 30 controls. Electric field exposure estimated by dosimeters and calculations.	No differences in health status were found between high voltage workers and matched controls selected from maintenance workers in the same utility.
Puntoni et al. (I 979), Italy	Mortality (I 960-75) for >2000 male shipyard workers by job title. ENM.	RRs. Total deaths: electricians I .35, electric welders 0.99; respiratory disease, electricians 2.48 electric welders 1 .09; heart disease electricians 0.41, electric welders 0.91.
Jingyi & Fanghua (1980), China	Health of 1138 men and women working around 44-220-kV lines compared to 290 controls.	No subjective complaints related to exposure, but some effects reported on cholesterol, blood pressure. ECG, and EEG. Few details of statistical tests reported.
Peceny et al. (I 983b), Czechoslovakia	Health of 19 men working in 200-kV switch rooms compared to 37 men in 400-kV switchrooms. Electric fields measured.	The 400-kV workers had higher frequency of leg pain, oversensitivity, fatigue, and respiratory infections, but lower frequency of disturbed concentration, and disturbed sleep. 400-kV electric fields: O-16 kV/m; 200-kV: O-12 kV/m.
McMillan & Pethybridge (I 983)U.K.	Causes of 52 deaths of welders at a shipyard (1 955-75) compared to 2 other groups of workers.	The only statistically significant cause of death for welders was for gastrointestinal diseases (PMR= 176, p<O.O5). Researchers did not attribute it to occupat!onal exposures.
Broadbent et al. (1985), U.K.	Health questionnaires of 390 power-line workers. Electric-field exposure meter worn for 2 weeks.	Some statistically significant health differences between groups were found, but there were no significant correlations with measured electric field exposures.

Abbreviations: **ECG=** electrocardiogram, **EEG=** electroencephalogram, **ENM=** EMF not measured, **PMR=** proportionate mortality ratio, **RR=** relative risk

Table 2.1. A summary of studies of general health of electrical workers exposed to EMF. (Continued)

Study/Location	Subjects/Exposure	Selected Results
Milham (I985), U.S.	Occupational PMR study of 486,000 male deaths. Exposure by job titles. ENM.	Statistically significant elevated PMRs: bronchitis, pneumonia, lung disease, stomach ulcer; deficits for diabetes, cerebral hemorrhage, heart disease, liver cirrhosis.
Olin et al. (1 985), Sweden	Mortality for 1254 electrical engineers during 30 years. ENM.	Compared to the general population, mortality was significantly lower for the engineers.
Deapen& Henderson (1986) U.S.	518 ALS patients and 518 controls by occupation. ENM.	Risk of ALS was significantly elevated for electrically related occupations-OR= 3.8*, 1 ,4-I 3.0 (I 9 cases).
Baroncelli et al. (1 986), Italy	Health exams of 627 male railway workers in three EMF exposure groups by hr/week and a control.	Workers exposed to EMF of moderate strength did not show the presence of clear health effects based on health exams and laboratory tests.
Gamberale et al. **(1 989),** Sweden	Health of 26 linemen was studied 1day working on an energized 400-kV line and 1day with line off. EMF dosimeter worn during study.	No statistically significant differences between the 2 days were found related to EMF exposures. Parameters studied included subjective complaints, reaction time, memory, EEG, and blood tests including hormone levels.
Gunnarsson et al. (1 992), Sweden	58 male, 34 female cases of motor neurone disease (MND), 372 controls. ENM.	Risks for MND were elevated significantly for welders (OR=3.7*, 1.1-13.0); risk for electricity work was on the borderline of statistical significance (OR=6.7, 1 .O-32.1).
Nakagawa & Koana (1993) Japan	Mortality for cohort of 32,545 railway workers in 6 groups by magnetic-field exposure.	The two groups with the highest exposure did not have elevated SMRs for total deaths, heart disease, or cerebrovascular disease.
Serdiuk & Tomachevskaya (I 994), Ukraine	Physiological data were collected on 3 groups of people working in a 750-kV substation.	No statistically significant differences among engineers, electricians, and serving staff were found in epinephrine, norepinephrine, or serotonin in urine.
Nikin et al. (1994), Yugoslavia	Blood samples from 27 women working near motors, 22 controls. Magnetic fields measured.	Levels of electrolytes (Na, K, Cl) in serum and in erythrocytes (Na, K) were significantly higher in the exposed group.
Savitz & Loomis **(1995),** U.S.	All causes of death in cohort of 138,905 men at five utilities. Magnetic field dosimeters used.	Mortality in utility workers was lower than in the general population. Total mortality for exposed jobs compared to other utility jobs was elevated (RR=I.I3*, 1.09-1 .18).
Davanipour et al. (1995) US	28 cases of ALS and 32 controls and estimated occupational magnetic field exposure. ENM.	Lifetime work exposure OR= 2.7, 0.9-8.3* At least 20 work years & 1 SD above average relative to minimum exposure OR= 4.7*, 1.3-1 6.4.
Reif et al. (I 995) U.S.	Preliminary results of measurements of the hormone melatonin in urine from 35 electric power workers,	A statistically significant negative association was found between nighttime melatonin secretion and magnetic field exposures during the workday, Mean cumulative work magnetic field exposures were higher than for nonwork.
Baris et al. (I 996b), Canada	1582 deaths (I 970-88) in a cohort of 21,744 men at an electric utility. EMF dosimeters were used.	For most causes of death, utility rates were lower than in the population. For utility workers with electric field exposure above background compared to below background, deaths from accidents and violence RR=I.82*, 1 .25-2.65.
Moen et al. (1996), Norway	Sick leave for musculoskeletal disorders for 342 aluminum plant potroom workers 222 controls.	No significant associations were found between sick leave over 5 yr for musculoskeletal disorders and work in potrooms with exposure to DC and AC magnetic fie!ds.

Abbreviations: **ALS=** amyotrophic lateral sclerosis, Cl= chlorine, **EEG=** electroencephalogram, **ENM=** EMF not measured, **K=** potassium, **MND=** motor neurone disease, **Na=** sodium, **OR=** odds ratio, **RR=** relative risk, **SD=** standard deviation

* statistically significant

fields. This was in large part because similar effects were not being reported by workers in those countries. However, at the time only the preliminary study of the 10 linemen had been completed. Also. the Russian per contained few details about the study design and results, so the study was difficult to evaluate. Several scientists called for additional research in response to the Russian study. Several of the studies in Table 2.1 were specifically conducted because of the Russian report.

Except for research in Spain (Fole et al. 1974) and in Czechoslovakia (Peceny et al. 1983b), the subjective ailments reported by the Russian workers were generally not found in later studies from other countries. One difficulty in comparing results among these studies is that the electrical work environments and work culture varied greatly among countries. For example, some work environments may cause workers to receive frequent shocks from objects due to induced voltages. Shocks, rather than field exposure could result in problems such as reported in some studies.

One of the largest studies to examine mortality patterns among electrical workers, and to include exposure assessment as well, was conducted by Savitz and Loomis (1995). Although the study focused primarily on cancer, deaths from other causes were also reported. For all causes of death, workers as a group at five U.S. electric utilities had a lower rate than in the general population (SMR= 77, 76-78). Deaths from specific non-cancer causes were also all less than in the population. Authors of the study pointed out that these findings were consistent with the healthy worker effect. When total mortality for magnetic-field-exposed occupations was compared with other utility occupations, there was a small but statistically significant elevation, especially for exposed workers with 20 or more years of employment (SMR= 113, 109-l 18). Information was not presented for specific non-cancer causes of death for occupations exposed to EMF.

Deaths from all causes were also reported for the Quebec utility (Baris et al. 1996b) that was part of the Canada-France study by Theriault et al. (1994). Almost all SMRs for individual causes of death were less than unity, and for the entire cohort the SMR for all causes combined was 75, 71-79. For deaths from accidents and violence (due in part to electrocutions), risks were elevated for EMF, and for pulsed magnetic fields (e.g., for above background exposure to electric fields, RR= 1.82, 1.25-2.65). Authors of the Quebec study said that the generally lower mortality for the utility workers compared to the population, was probably from the healthy worker effect, and possibility from underassessment of mortality.

Three studies suggested that occupational EMF exposure is associated with motor neurone disease, although in these studies exposure was estimated only by job title (Gunnarsson et al. 1992, Deapen and Henderson 1986, Davanipour et al. 1995). The latter two studies found statistically significant elevated risks for a type of motor neurone disease commonly called Lou Gel-trig's disease (amyotrophic lateral sclerosis).

Preliminary results of one study in Table 2.1 found that the pineal hormone melatonin was reduced in men by occupational exposure to 60-Hz magnetic fields (Reif et al. 1995). In another study, melatonin patterns measured at the beginning and end of shifts for switchyard workers were not significantly different (ReiBenweber and David 1996). When men were exposed to 60-Hz EMF in a laboratory setting, no effects on nighttime melatonin levels were found (Graham et al. 1995, 1996, see Table 2.10).

Six additional studies are covered in this section; they address possible effects of EMF on chromosomes in electrical workers (Table 2.2). These studies were prompted in part because of reports of reproductive effects in a study of Swedish substation workers (Nordstrom et al. 1983, see Table 2.4).

The six studies all looked at peripheral lymphocytes (which are somatic cells) in blood samples of various kinds of electrical workers and controls. If effects of some agent are found on somatic cells, this suggests the possibility of other effects in the whole organism, such as cancer or premature aging (Bloom 1981). Effects found on germ cells (spermatozoa and ova) theoretically suggests the possibility of sterility in the individual, or mutations that could be passed on to offspring. If only somatic cells are studied and chromosomal aberrations are found, this implies the possibility that germ cells may also be affected, assuming that exposure to the agent occurs for both types of cells (Bloom 198 1).

All but one of the chromosome studies in Table 2.2 reported one or more statistically significant effects, although there are some inconsistencies. Chromosome or chromatid breaks were reported in four of the studies. The studies by Bauchinger et al. (1981), and by Khalil et al. (1993) did not specifically mention chromosome breaks. None of the studies found a statistically significant effect on sister chromatid exchange (an indicator of potential genetic hazard). There is also evidence presented in some of these studies that an electrical worker's current or past smoking experience can increase the likelihood of chromosome damage.

The possible mechanisms associated with chromosomal effects in electrical workers was examined with in vitro tests in the study by Nordenson et al. (1984). The tests showed that a 50-Hz current density of 1 mA/cm² applied to blood samples did not cause chromosome breaks, while breaks were found after 3 μs long spark discharge pulses were applied (peak field

Table 2.2. A Summary of studies of somatic chromosomes from electrical workers exposed to EMF

Study/Location	Subjects/Exposure	Selected Results
Bauchinger et al. (1981), Germany	CA in lymphocytes from 32 men working in 380-kV switchyards and from 22 controls. Typical maximum electric-field level given.	No statistically significant differences between groups in chromosome gaps, breaks, acentrics, atypical, or SCE. Switchyard workers had occupational exposure to EMF for over 20 yr. Maximum electric field in switchyards: 12 kV/m.
Nordenson et al. (1984), Sweden	CA in lymphocytes from 20 men working in 400-kV switchyards and from 17 controls. Typical maximum electric-field given.	Statistically significant differences were found between groups for chromatid and chromosome breaks. The percent aberrant cells in exposed non-smokers was 5.1 compared to 2.6 in control non-smokers.
Nordenson et al. (1988), Sweden	CA in 19 men working in 400-kV substations and 19 controls. All subjects were nonsmokers. Electric fields were measured.	Compared to controls, substation workers had significantly more chromosome aberrations, and cells with micronuclei. The highest rate of aberrations was found in workers exposed to the highest electric fields. No effects on SCE.
Valjus et al. (1993), Finland	CA in 27 power-line workers and 27 telephone linemen controls. All subjects were current nonsmokers. Exposure was estimated.	The rate of lymphocytes with chromatid-type breaks was low in both groups but it was about twice as high in the power line workers, mainly for ex-smokers. No effects were found on SCE, replication, or micronuclei frequency.
Khalil et al. (1993), Jordan	CA in 15 men from 132-230-kV substations and in 8 controls. Smoking data separated. ENM.	The % aberrant cells was significantly higher in substation workers (12.8%) than in controls (7%). Proliferation, mitotic index were lower in substation workers. No effect on SCE.
Skyberg et al. (1993), Norway	CA in 13 high voltage laboratory workers and in 20 controls. Exposure was to AC and DC fields, pulsed and continuous.	Mean chromosome breaks for laboratory workers who were smokers (2.3) was significantly higher than in control smokers (0.7). No significant effects were found on SCE, % aberrant cells, or on chromatid breaks.

Abbreviations: **CA=** chromosome analyses, **SCE=** sister chromatid exchange, ENM= EMF not measured

strength of 3.5 kV/cm). These findings suggest that effects on somatic cells in electrical workers may be from discharge shocks received when workers contact objects in strong electric fields, instead of from exposure to EMF ***per*** se (see also "EMF and Genetics, Proliferation, and Cancer" in Chapter 4).

Residential Studies

Table 2.3 summarizes studies that looked at various health factors for people living near certain sources of EMF. The designs and methods varied greatly among the studies; only three of the studies reported any measurements of EMF. Perry and Pearl (1988) reported that mean 50-Hz magnetic fields in apartment groups near and distant from electric supply cables differed by only 0.154 μT (1.54 mG). For the 12 disease factors related to the cardiovascular system compared for the two groups, only one difference was close to statistical significance. A later study by this group found no association between myocardial infarction and residential magnetic fields (Perry et al. 1989).

Magnetic fields measured in the homes of people in The Netherlands who lived within 100 m (328 ft) of a 150-kV line or a substation ranged from 0. l-l. 1 μT (l-l 1 mG) (Schreiber et al. 1993). Mortality from culatory diseases was significantly elevated among these people, but authors of the study attributed this to social class distribution.

Four other studies of people living near transmission lines found no statistically significant effects on certain general heath factors related to proximity to the lines. The study by Strumza (1970). however. used a crude measure to identify such effects. i.e.. use of medical services. That study and the other two (Poole et al. 1993, McDowall 1986) all used distance from lines as a measure for EMF exposure. Poole et al. (1993) pointed out that residential proximity does not necessarily correlate with EMF exposure; they called for additional health studies with improved exposure assessment.

Three studies provide some evidence that living around transmission lines increases the risk of headaches. Poole et al. (1993) found an elevated risk of non-migraine headaches; however, it was not statistically significant. Those authors pointed out that they accepted self-reported migraine headaches without medical confirmation. The study by Havsom et al. (1990) did use a clinically tested headache questionnaire and found statistically significant elevated risks. However. risks were highest in that study for persons living at a mid-distance from transmission lines, and not for those closest to the lines. A similar result was found in an earlier study in the U.K. by Dowson et al. (1988). and Meyer

Table 2.3 A summary of studies of general health of residents exposed to power-line EMF.

Study/Location	Subjects/Exposure	Selected Results
Strumza (1970), France	Medical needs of 70 families within 25 m of 220-400-kV lines compared to 74 families > l25m from lines. ENM.	No statistically significant differences in medical needs between the two groups were found that were attributed to proximity to the transmission lines.
Eckert (1976), U.S., Germany	494 cases of sudden infant death syndrome were studied on the basis of possible EMF exposures. ENM.	Locations of cases showed regional concentrations close to uncommon magnetic fields or stray ground currents (power lines, railways, transmitters: airports, radar). Risk was higher in ground or first floors.
McDowall (1986), U.K.	510 deaths (1971-83) from circulatory and respiratory diseases among cohort living near power facilities. ENM.	Overall, mortality was lower than in the general population. Death rate for respiratory disease was elevated for residents closest to electrical facilities but it was not statistically significant (SMR= 127, 77-l 95).
Perry & Pearl (1988), U.K.	Survey of 576 hospital patients who lived in multistory buildings. Magnetic field exposure by distance to power supply cables.	Slightly more people (62%) with certain types of heart disease lived nearer to electric supply cables (on the borderline of statistical significance). Near field mean = 3.15 mG, distant mean field = 1.61 mG.
Perry et al. (1989), U.K.	Survey of 596 myocardial infarction cases and 596 controls by measured 50-Hz magnetic field outside the front door of residence.	There was no statistically significant difference in the magnetic fields measured for myocardial infarction cases, and the fields for control addresses.
Dowson et al. (1988), U.K.	Survey of headaches in 132 people close to 132-kV lines and 94 people away from lines. ENM.	Fifteen (11.4%) people living within 100 m of transmission lines reported recurrent or migraine headaches, compared to 1 (1 .1%) report from people away from lines.
Haysom et al.(1990), U.K.	Survey of headaches among 334 people within 100 m of transmission lines, and 358 people more than 100 m from lines. ENM.	There was a weak trend for headaches, especially migraine, to be more common among people living within 50 and 100 m from 132- and 400-kV transmission lines. Some results were statistically significant.
Poole et al. (1993), U.S.	Survey of headaches among 382 people including those living near 230- and 345-kV lines. ENM.	Prevalence of non-migraine headaches among people living near lines was elevated but it was not statistically significant (OR= 1.5, 0.76-2.8).
Schreiber et al. (1993), The Netherlands	Deaths among 1552 people living within 100 m of lines or substations.	For all causes of death, SMR= 1 II, 96-128; for circulatory disease, SMR= 126*, 101-l 55.
Coghill (1994), U.K.	Locations of 67 cases of sudden infant death syndrome and 64 controls were compared by proximity to EMF sources. ENM.	Cases lived closer to EMF sources (mean= 126 m) than controls (mean= 206 m); the closer to the source, the younger the age at death. EMF sources included power lines, railways, terminals. Statistical tests not described.
McMahan & Meyer (1995), U.S.	Survey of health problems for 152 women living near 66- and 220-kV lines, or 1 block away.	Women near lines were not more likely to report health problems (headaches, poor appetite, sleep disorders, poor concentration) than those away (OR= 0.85, 0.45-l .62).

Abbreviations: **ENM=** EMF not measured, **OR=** odds ratio, **SMR=** standardized mortality ratio,* statistically significant

(1 995) found no evidence that prevalence of headaches was increased in women living near transmission lines in California.

Two studies attempted to relate the proximity of SIDS (sudden infant death syndrome) to sources of EMF (Eckert 1976, Coghill et al. 1994). Both of these studies also used distance from sources to estimate exposure. Because of the wide variety in the sources identified in the studies, the weakness of this exposure measure is even more apparent. The study by Coghill (1994) was presented only in an abstract, with few details about how the study was conducted.

Reproduction

Occupational

The early study of Russian substation workers by Asanova and Rakov (1966) that initiated interest in possible health effects of EMF included a statement that one-third of the workers complained of "sexual weakness." This and 12 other studies of reproductive health of electrical workers are summarized in Table 2.4. Four of these specifically mentioned that they looked for the effects reported in the Russian study. but none reported

Table 2.4 A summary of studies of reproductive health of electrical workers exposed to EMF.

Study/Location	Subjects/Exposure	Selected Results
Asanova & Rakov (1966), Russia	Health exams of 41 men and 4 women working in 400-500-kV switchyards.	One-third of the men of ages 30-40 yr complained of sexual weakness after 8-10 months work in high-voltage electric fields.
Kouwenhoven et al. (1967) U.S.	Health exams given to 11 linemen over 42 months.	Two men had low sperm counts.
Singewaid et al. (1973) U.S.	9-year follow-up of linemen in above study.	Sperm counts were judged to be highly variable, and they were not affected by the electric field.
Roberge (1976) Canada	Health exams of 56 male 765kV substation workers.	Before 765kV work, the men had 27 boys and 25 girls. For 9 months after start of work; 17 boys, 3 girls. Four (7%) of high-voltage workers reported sexual weakness.
Stopps & Janischewskyj (1979) Canada	Health of 30 high-voltage workers compared to 30 controls.	Four (13%) high-voltage workers and four (13%) controls complained of sexual problems.
Knave et al. (1979) Sweden	Fertility was assessed in 53 men working in 400-kV substations and in 53 control workers.	Compared to controls, substation workers had fewer children, especially boys, but the difference in number of children was present before work began in substations.
Nordstrom et al. (1983), Sweden	Questionnaires on reproductive health were sent to 542 male power plant employees.	Mates of switchyard workers had statistically significant lower frequency of normal pregnancy outcomes, and higher frequency of births with congenital malformations. The 400-kV workers had more girls compared to controls.
Peceny et al. (1983b), Czechoslovakia	Health of 19 men working in 200-kV switch rooms compared to 37 men in 400-kV switch rooms.	No decrease in libido reported by workers (no data presented).
Buiatti et al. (1984) I taiy	112 male infertility cases were compared to 127 controls by occupation. ENM.	Risk for infertility was elevated for radioelectric workers but it was not statisticaify significant (RR= 5.89, 0.86-40.18). No other electrical occupations were named.
Sanjose et al. (1991) Scotland	Prematurity and parents' occupation was examined in a national study of 252,147 live births. ENM.	Female electrical workers had elevated risk for preterm delivery (RR=1.8*, 1.2-2.8) and male electrical workers had lower risks for low birthweight (RR=0.8, 0.7-0.9).
Juutiiainen et al. (1993), Finland	Early pregnancy loss studied in 89 cases and 102 controls. Exposure by job and some measurements.	No association found between early pregnancy loss and mothers' occupational magnetic-field exposure, based on 4 cases and 4 controls (OR=1 -15, 0.3-4.7).
Andrienko & Boyko (1994), Ukraine	Sexual function questionnaires, to 65 male and IO female substation workers (no voltage given).	For males only, there was a suggestion that work at substations is associated with decreasing sexual function for some parameters. No quantitative data presented.
Lundsburg et al. (1995), U.S.	Cases were men seeking care at an infertility clinic. Controls were men with normal semen. ENM.	No statistically significant associations found between high occupational magnetic-field exposure and three measures of semen quality. High exposure, >0.3μT (>3 mG).

Abbreviations: **ENM=** EMF not measured, **OR=** odds ratio, **RR=** relative risk, * statistically significant

finding the high percentage stated in that study. Of the four. the highest percentage of reports of sexual problems was given by Stopps and Janischewskyj (1979). However, in that study the percentage of complaints of sexual problems was the same (13%) for both the high-voltage workers, and the control men.

Three studies reported information on the sex ratio of children born to substation workers. Roberge (1976) found that the workers in his study had a larger percentage of' boys. On the other hand, Knave et al. (1979) found that substation workers had more girls. although the finding was largely dismissed because the difference existed before substation work began. In the study by Nordstrom et al. (1983) the male/female sex ratio for children born to men working in 400-kV substations was 0.92, compare to 1. I6 for the reference group.

Other results of pregnancy outcome associated with electrical workers were reported by three studies in Table 2.4. There was a statistically significant increase in the percentage of congenital malformations among children fathered by Swedish switchyard workers compared to the reference group, IO. 1 and 4.0 percent, respectively (Nordstrom et al. 1983). Authors of study said that the finding should be interpreted with caution because the total numbers were small (1 8 children with malformations for both groups).

The study from Scotland found both increased and decreased risks associated with electrical occupations of the mother and father, respectively (Sanjose et al. 199 1). However, no information was available about possible EMF exposures for these occupations. In Finland no association was found between mothers' occupational magnetic-field exposure and early pregnancy loss, although the finding was based on very small numbers (Juutilainen et al. 1993). Two studies looked at semen quality and they found no associations between poor quality and employment as an electrical worker (Singewald et al. 1973, Lundsburg et al. 1995).

Residential: Power Lines

At least six studies have investigated possible effects on reproductive health in women living near electric power lines (Table 2.5). Overall. the studies provide little evidence for such effects. The strongest evidence for a possible effect of magnetic fields comes from the study by Juutilainen et al. (1993). Results of the study. however, varied depending on the magnetic field cutoff level. Cutoff levels of 0.63 μT (6.3 mG), and 0.25 μT (2.5 mG) produced much different results depending on whether risk was calculated based on field levels at the front door, the room average. or the maximum level. Authors of the study said that results of the study should be vie-wed with caution because of the small number of exposed subjects in the study.

Savitz and Ananth (1994) found no evidence that miscarriage was associated with exposure of women to power line fields. In that studv. however. miscarriage was assessed at gestational ages later than those in the study by Juutilainen et al. (1993).

The lower risk for malformations reported bv Robert (1993) is very difficult to interpret in relation to possible exposures to EMF from power lines. Because of the way in which the study was designed. it is not known whether any of the women lived close to transmission lines. There is, therefore no real basis for comparing exposures between the cases and controls in the study.

Residential: Electric Heating Sources

Related to the studies described in the above section, is a group of studies that investigated reproductive effects associated with magnetic fields from electrically heated beds and ceiling cable heat (Table 2.6). Electric

Table 2.5 A summary of studies of reproductive health of residents exposed to power line EMF.

Study/Location	Subjects/Exposure	Selected Results
Perry & Pearl (1988) U.K.	Survey of 576 hospital patients from multistory buildings. Exposure by distance to cables.	The frequencies of complications related to pregnancy were essentially identical for women living near to and distant from electric supply cables.
Robert (1993) France	1688 cases of malformed infants were compared to controls by residence in areas with homes within 500 m of transmission lines.	A statistically significant lower risk of malformations was found between maternal residence in towns which had at least one home within 500 m of a transmission line. Distances of case/control homes to lines not determined.
Juutilainen et al. (1993), Finland	89 cases of early pregnancy loss and 102 controls. Magnetic fields measured in subjects' homes.	Risk was increased for women in homes with elevated magnetic fields. For homes with average of >2.5 mG, OR= 5.44*, 1 .1-28 (based on 7 cases and 2 controls).
Savitz & Ananth (1994), U.S.	Measured magnetic fields and power-line types were related to pregnancy outcome for cases and controls.	Pregnancies in homes above 2 mG were not more likely to end in miscarriage or preterm delivery. Risk for low birth weight was increased in the medium but not the high power line category (OR= 2.6*, 1.2-6.5) (7 cases and 12 controls).
Bracken et al. (1995a), U.S., Canada	Magnetic-field exposures during pregnancy were estimated by power line type near residence, and by dosimeters.	No associations found between residential power-line types and low birthweight or intrauterine growth retardation (2673 women). No associations found for 24-hour exposure (534 women) or for 7-day exposure (858 women).
Robert et al. (1996), France	151 cases of congenital anomalies and 302 controls compared by mothers' residential proximity to transmission lines. ENM.	No associations found between congenital anomalies and distance of mothers' home or apartment to transmission lines: within 100 m OR= 0.95, 0.45-2.03 (2 cases): within 50 m OR= 1.25, 0.49-3.22.

Abbreviations: **ENM=** EMF not measured, **OR=** odds ratio, * statistically significant

Table 2.6. A summary of studies of reproductive health and exposure to sources of electric heat.

Study/Location	Subjects/Exposure	Selected Results
Wertheimer & Leeper (1 986), U.S., co	Telephone survey of 1256 new parents about their use of electric biankets and heated water beds, and checks of birth records. ENM.	For heated bed users, conceptions during the heating season resulted in significantly more below-median birth-weights with above median gestations. Frequency of fetal loss was higher among heated bed users than nonusers.
Wertheimer & Leeper (1989) U.S., OR	Fetal loss for families with and without ceiling cable heat. Some magnetic field measurements.	Fetal loss ratio was the same for families with and without ceiling heat, but fetal loss occurred more often among the ceiling-heat group during months of increasing heating use.
Dlugosz et al. (1992) U.S., NY	542 cases of babies with congeni-tai defects and matched controls. Mothers' use of heated bed. ENM.	The use of electric blankets or heated water beds by mothers was not associated with neural tube or oral cleft defects in their children.
Yong et al. (1992) China	Womens' use of electric blanket for 986 cases of abnormal pregnancy and 975 controls.	Risk for spontaneous **abortion** and total abnormal preg-nancy were elevated for electric blanket use during early pregnancy (OR=l.95*, 1.31-2.90; OR=l.61*, 1 10-2.34).
Bracken et al. (1995a), U.S., Canada	Magnetic field exposure during pregnancy for about 2500 women; birthweight and fetal growth.	No statistically significant associations were found between measured exposures to magnetic fields and birth weight, or intrauterine growth retardation.
Li et al. (1995) U.S., WA	118 cases of babies with urinary tract defects and 369 controls. Mothers' use of heated beds.	For women with a history of subfertility association found between heated bed use during first trimester and urinary tract defects (OR=10.0* 1.2-85.5) (3 cases, 3 controls).
Lee et al. (1996), U.S., CA	Abortions among 5127 women and use of electrically heated beds.	Abortion risk for electric blanket use RR= 0.73, 0.52-l .08; for water bed use RR= 0.84, 0.65-l .07.

Abbreviations: **ENM=** EMF not measured, **OR=** odds ratio, **RR=** relative risk, * statistically significant

blankets and electrically heated water beds can produce relatively high magnetic-field exposures to users (Florig and Hoburg 1991). The first study to investigate whether the use of such devices during pregnancy affects fetal development was conducted by Wertheimer and Leeper (1986). In that study there was no difference between heated-bed users and non-users in the proportion of low birthweight babies (4.5 vs. 4. I percent, respectively. The users, however, had significantly more full-term gestations than non-users (46 vs. 21 percent, respectively). The proportion of above-median gestations was also higher for the September-June period for the users. Presumably, this is the period when heated beds were used most often. The study also looked at frequency of abortions in the year before the live birth. Abortions for electric-blanket users (7.8 percent) and for water bed users (6.3 percent) were significantly higher than those for non-users (4.2 percent).

Wertheimer and Leeper (I 989) conducted a second study in an attempt to distinguish effects due to heating from those due to magnetic fields. The study compared fetal loss at homes with ceiling-cable heat, to homes with mostly electric-baseboard heat. The estimated electric and magnetic fields in both types of homes were 10-50 V/m, 0.1µT (10mG) ; and 10 V/m, < 0.1 µT(< 1 mG), respectively. The study found that the overall rate of fetal losses/live births was the same in homes with and without ceiling heat (0.076 vs. 0.075. respectively). However, there was also a positive association for ceiling-heat homes compared to other homes in monthly fetal loss and monthly heating degree days.

Yong et al. (1992) reported a statistically significant association between electric-blanket use and spontaneous abortion. This result was found onlv for usage during early pregnancy and not during middle or late pregnancy. In a study 'with extensive measurements of magnetic-field exposures. Bracken et al. (1995a) did not find any statistically significant associations between fetal development and exposure. Some odds ratios were elevated, but they were less than 1.5, and there was no strong indication of a dose-response effect. Risk of spontaneous abortion was reduced for women in California who used electrically heated beds during pregnancy; it was on the borderline of statistical significance (Lee et al. 1996).

Two studies in Table 2.6 that examined birth defects found overall no statistically significant associations with use of heated beds (Dlugosz et al. 1992, Li et al. 1995). The significant association reported by Li et al. (1995) was only for a subpopulation of the women in their study. Further, statistical significance was found in this subgroup only for early pregnancy.

VDTs (Video Display Terminals)

Several studies investigated possible reproductive effects of occupational exposure to EMF from the video monitors that are used with computers (Table 2.7). These monitors are often called VDTs (video display terminals) or VDUs (video display units). VDTs are a source of complex EMF (Fig. 2.10) that extend from DC up to radio frequencies. Waveforms include sinusoidal from the power supply frequency, and sawtooth from pulsed fields from electrical circuits that direct the electron beam across the screen (see Fig. 1.5). As with TV sets, EMF from VDTs decrease in strength rapidly with distance, however, while using a VDT a person is much closer to the screen than when watching TV Because of the complex EMF environment around VDTs, field intensity alone may not be a sufficient measure of human exposure from these devices (Nair and Zhang 1995).

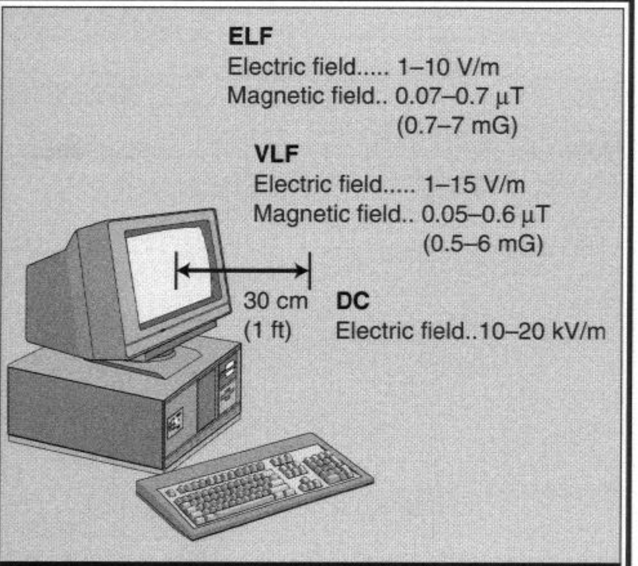

Figure 2.10. Typical ranges of EMF at 30 cm (1 ft) from computer monitor screens. As used here; ELF = below 3 kHz, VLF = 15–100 kHz. Note that EMF may be stronger at sides and back of some monitors.
Sources: Advisory Group on Non-ionizing Radiation (1994), Tofani and D'Amore (1991).

Interest in the possible health effects of VDTs arose because of reports of clusters of effects on pregnant women as computers began to be introduced into the work place. Table 2.7 summarizes results of several studies that have been conducted since the early 1980s of women who worked with VDTs . Only a few of the studies included measurements of EMF exposures; most researchers estimated exposure by asking women how many hours per week that they worked with VDTs. One study (Roman et al. 1992) also considered passive exposure to VDTs.

Spontaneous abortion was the factor most frequently investigated in studies of VDTs. Of the 12 studies in Table 2.7 that looked at this factor, five reported at least one statistically significant association with VDT exposure. Of these, the largest risk (OR= 3.4) was reported for the highest VDT exposure group in the study by Lindbohm et al. (1992). In that study, magnetic fields were measured for 17 VDT models as used by subjects in the study. One of the few other studies that included magnetic-field measurements found no association with spontaneous abortion (Schnorr et al. 1991). However, authors of that study (Schnorr et al. 1993) commented that fields from the VDTs in their study were much lower than those reported by Lindbohm et al. (1992). Lindbohm et al. (1993) in response pointed out that VDTs in their study included many older models made before manufacturers began to consider magnetic fields.

Birth defects were included in 11 of the studies in Table 2.7. Three of these reported statistically significant associations, but there is no consistency or pattern among results of the studies that suggests a causal association with VDT use.

Of the nine studies in Table 2.7 that included birthweight or low birthweight, only one (Ericson and Kallen (1986a) reported a statistically significant association with VDT use. That study assessed two categories of low birthweight for three VDT exposure levels, each of which included two time periods. Of the 12 risk calculations for these combinations, only one was statistically significant; it occurred in the medium exposure group. Two other studies in Table 2.7 assessed intrauterine growth retardation. Neither reported any statistically significant positive associations with VDT use (Windham et al. 1990, Bracken et al. 1995a).

Many of the studies in Table 2.7 were reviewed in a report on health effects of VDTs by the National Radiological Protection Board from the U.K. (Advisory Group on Non-ionizing Radiation 1994). The report concluded that the evidence does not indicate that womens' use of VDTs affects the fetus, and that there is no urgent need for further epidemiological studies of VDTs.

A review by Lindbohm and Hietanen (1995) also concluded that the majority of the studies suggest that VDT use is not related to adverse pregnancy outcome. However, those authors suggested that some VDT studies did indicate increased risks, and they recommended further research on fetal development in high-field industrial environments. Nair and Zhang (1995) questioned whether the VDT health question should be con-

Table 2.7. A summary of studies of reproductive health of women who work with VDTs.

Study/Location	Subjects/Exposure	Selected Results
Lewis et al. (1982) Australia	30 cases of SAB and 60 controls from 13 companies were compared by estimated VOT use. ENM.	Risk of SAB associated with VOT use was elevated but it was not statistically significant (RR= 1.71, 0.1 O-29.04).
Kurppa et al. (1985), Finland	Birth defects for 235 case mothers and 255 referents were compared by potential exposure to VDTs ENM.	Mothers' use of VDTs during the first trimester of pregnancy was not associated with birth defects (OR= 0.9, 0.6-I .2).
Ericson & Kallen (1986a), Sweden	Pregnancy outcome among three cohorts of women with assumed different VOT exposures (total of 10,025 births). ENM	Significant elevated risks for LBW only in the medium VOT exposure group -observed/expected: 2.2*, 1. I-4.4, 1.5*, 1.2-I .8. No significant effects for SAB, perinatal death, or birth defects.
Ericson & Kallen (1986b), Sweden	429 cases, 926 controls from the three cohorts in the above study. Jobs were categorized into three VOT exposure groups. ENM.	Significant elevated risks for birth defects, especially for the highest exposure (for >20 hr VOT exposure/week, OR=2.3*, 1.4-3.9). No statistically significant risks for SAB (for >20 hr VOT exposure/week, OR=0.9, 1.4-I .7).
Westerholm & Ericson (1987) Sweden	Pregnancy outcomes (4117) for clerks. Estimated VOT job exposures classified into 5 levels. ENM.	Risk of birth defects was elevated for the two highest exposure groups combined but not significantly (observed/expected = 1.9, 0.9-3.8). No significant risks for SAB, birthweight, or perinatal mortality.
Mikolajczyk et al. (1987), Poland	SAB for 142 women at two airline booking offices. VOT users were compared to nonusers.	At one office SAB was significantly higher for VOT users (40% vs. 22% for 21-30 age group). VOT users at both offices suffered more from menstrual troubles. No statistical tests were reported.
Bjerkedal & Egenaes (1987), Norway	Pregnancy outcome (1820 births) for women at a postal office before and during introduction of VDTs into the work place. ENM.	Introduction of VDTs into the work place did not lead to increases in adverse pregnancy outcomes (sex ratio, stillbirths, birthweight, birth defects, mortality). No statistical tests were reported.
Nurminen & Kurppa (1988), Finland	Pregnancy outcomes for 60 VOT users and 179 nonusers who were referents in the birth defect study by Kurppa et al. (1985).	Work with VDTs was not associated with adverse pregnancy outcome including threatened abortion, gestation length, birthweight, placental weight, and mothers! blood pressure.
McDonald et al. (1988), Canada	Pregnancy outcomes (6876) for VOT users compared to other working women. Exposure by estimated VOT hr/week. ENM.	For current pregnancies elevated risks for VOT users were found (observed/expected) for SAB (1.19*, 1.09-I .30), and urinary birth defects (1.84*, 1.07-3.15). No effects were found on birthweight, stillbirth, or preterm birth.
Goldhaber et al. (1988), U.S.	452 cases of SAB or birth defects, and 723 controis among hospital workers. Exposure by estimated VOT hrlweek. ENM.	A significant elevated risk for SAB was found for women who worked with VDTs >20 hrlweek compared to nonusers (OR= 1.8*, 1.2-2.8). Risk of birth defects was also elevated but not significantly (OR= 1.4, 0.7-2.9).
Bryant & Love (1989), Canada	334 cases of SAB and two groups of controls. Home/work VOT exposure estimated. ENM.	There were no statistically significant elevated risks of SAB associated with VOT use (compared to postnatal controls, OR= 1.14, 0.83-I .56; compared to prenatal controls, OR= 0.81, 0.59-I .1 1).
Nielsen & Brandt (1990), Denmark	666 cases of SAB and 764 controls among office workers. Exposure by estimated VOT hr/week. ENM.	There were no statistically significant elevated risks of SAB associated with VOT use (for any VOT use, OR= 0.94, 0.77-I .14; for >30 hr VOT use/week, OR= 0.78, 0.48-I .25).
Tikkanen et al. (1990), Finland	Cardiovascular birth defects, fetal growth, birthweight for 500 case mothers and 1055 controls and estimated VOT exposure. ENM.	For mothers exposed to VDTs more than 4 hours/day the risk of birth defects was not statistically significant; OR= 1.4, 0.5-3.8. Risk was not significantly elevated for birthweight, placental weight, or length of pregnancy.

Abbreviations: **ENM=** EMF not measured, SAB= spontaneous abortion **LBW=** low birthweight, **IUGR=** intrauterine growth retardation, * statistically significant

Table 2.7. A summary of studies of reproductive health of women who work with VDTs. (Continued)

Study/Location	Subjects/Exposure	Selected Results
Brandt & Nielsen (1 990), Denmark	421 congenital maiformation cases and 1365 controls among office workers. Exposure by estimated VDT hr/week. ENM.	Only one of the 20 types of malformations studied, hydrocephalus, had a statistically significant elevated risk based on 7 cases (OR= 12.0*, 1.38-104). For all malformations and VDT exposure >31 hr/week; OR= 0.91, 0.43-l .92.
Windham et al. (1 990), U.S.	439 cases of SAB and 909 controls. Cases of LBW, IUGR from SAB controls. Exposure estimated by VDT hr/week. ENM.	For all SAB cases and VDT exposure >20 hr/week, OR= 1.2, 0.88-l .6; for Kaiser hospital members OR= 2.1*, 1.1-3.8. For LBW, OR= 1.4, 0.75-2.5; for IUGR, OR= 1.6, 0.92-2.9.
Schnorr et al. (1991), U.S.	SAB among cohort of 323 VDT using telephone operators and 407 nonusers. VDT EMF were measured for 2 models.	For SAB and VDT use in first trimester of pregnancy, OR= 0.93, 0.63-l .38; for >25 hr/week VDT exposure, OR= 1 .00, 0.61-l .64.
Lindbohm et al. (1992), Finland	191 cases of SAB and 394 controls from three companies. Magnetic fields were measured for 17 VDT types used by subjects.	There was no elevated risk for SAB for VDT use (OR= 1 .1, 0.7-l .6). Risk was increased significantly in the high field exposure (> 9 mG peak) groups for the two VDT models used by subjects (OR= 3.4*, 1.4-8.6; OR= 2.8*, 1 .l-6.8).
Roman et al. (1992), U.K.	150 cases of SAB and 297 controls. Occupational VDT use and passive exposure to VDTs were estimated. ENM.	Risk of SAB was not elevated by VDT use (OR= 0.9, 0.6-l .4) or by passive exposure to VDTs at work (OR= 0.9, 0.6 -1.6).
Bracken et al. (1995a), U.S.	LBW and IUGR for over 2500 pregnancies. Magnetic field exposures measured during pregnancy.	For VDT use .<20 hr/week during pregnancy for LBW. OR= 0.58, 0.31-l .09, based on 424 cases; for IUGR, OR= 1.17, 0.76-l .81, based on 424 cases.
Li et al. (1995), U.S.	Mothers of 37 cases of urinary tract birth defects and 116 controls and VDT use. ENM.	There was no statistically significant risk of urinary tract birth defects associated with mothers' use of VDTs. For > 225 hours of VDT use during pregnancy, OR= 1.4, 0.8-2.5.
Grajewski et al. (1995), U.S.	LBW and preterm births for a cohort of VDT using telephone operators and a cohort of nonusers. ENM.	VDT use was not associated with LBW (OR= 0.9, 0.5-1.7) or with preterm birth (OR= 0.7, 0.4-l .1).
Rodriquez-Pinilla & Martinez-Frias (1995), Spain	VDT use by mothers of 3040 babies with birth defects, and 20,151 control mothers.	There were no statistically significant associations between VDT use and: trisomy 13, 18, 21; Mendelian syndromes; or multiple congenital anomaly patterns.

Abbreviations: **ENM=** EMF not measured, **SAB=** spontaneous abortion, **LBW=** low birthweight, **IUGR=** intrauterine growth retardation, * statistically significant

sidered closed because new monitors are designed to have lower field strength. They believe that the complex EMF environment surrounding VDTs may not be best characterized by considering field strength alone.

Mental Health

Residential

Five of six studies from the U.K. reported statistically significant associations between suicide or depression and electric-power facilities (Table 2.8). A study by McDowall (1986) also reported an elevated SMR for suicide among people living closest to transmission facilities in the U.K.. but it was not statistically sienificant and it was based on only two cases. Bonnell et al. (1983) were critical of the study by Perry et al. (1991) based on how controls were selected. how magnetic fields were measured, and on the basic design of the study. Authors of the original study (Marino et al. 1983) responded that they did not conclude that magnetic-field exposure caused suicide, and that more data were needed to evaluate the association that they found.

The study by Perry and Pearl (1988) found statistically significant associations for depression and for various emotional disorders that were in opposite directions. Authors of the study did not address how living close to electric supply cables might cause both adverse and beneficial effects on mental health.

Table 2.8. A summary of studies of mental health and residents exposed to power line EMF.

Study/Location	Subjects/Exposure	Selected Results
Reichmanis et al. (1979), Perry et al. (1981), U.K.	In the 1981 study, magnetic fields were measured at the front door of residences of 590 suicides and 594 controls.	The mean 50-Hz magnetic field for suicide residences was significantly greater than for control residences, although both were small (0.867 mG vs. 0.709 mG, respectively). Also, more suicides than controls >1 mG (25 vs. 18%).
McDowall (1986) U.K.	Mortality for about 8000 people living in the vicinity of electric transmission facilities. ENM.	Based on 8 suicide cases? SMR= 75; it was not statistically significant. For people within 15 m of transmission facilities, SMR= 143 based on 2 suicide cases.
Dowson et al. (1988), U.K.	Survey of depression in 132 people living by 132 kV lines, and 94 controls away from lines. ENM.	7 people living within 40 m of transmission lines reported depression compared to 1 control person who lived away from lines. The finding was statistically significant.
Perry and Pearl (1988), U.K.	Survey of 576 hospital patients who lived in multistory buildings. Magnetic-field exposure by distance to power supply cables.	Significantly more cases (71%) of depression were from apartments near power cables compared to those away (29%) from cables. Significantly fewer cases (24%) of personality defects, anxiety, and confused young were near cables compared to those away (76%).
Perry et al. (1989), U.K.	Survey of 359 patients with depressive illness by magnetic fields measured at residence.	There was a small but statistically significant difference in the mean 50-Hz magnetic field measured for cases (2.26 mG) and controls (2.07 mG).
Poole et al. (1993), U.S.	Survey of depression among 382 people including those living near 230- and 345-kV lines. ENM.	Prevalence of depressive symptoms was higher for people living near transmission lines (OR= 2.8*, 1.6-5.1). Finding was not explained by peoples' attitudes about lines.
McMahan et al. (1994), U.S.	Depression test was given to 152 women who lived adjacent to or 1 block from 66-220-kV lines.	There were no significant differences in depressive symptoms between the two groups when demographic variables were controlled for (OR= 0.94, 0.48-l .85).
McMahan & Meyer (1995), U.S.	Survey of worry among 152 women who lived adjacent to or 1 block away from 66-220-kV lines.	Proximity to lines was not associated with level of worry about them. Those most worried about lines were more likely to report EMF-related illness (OR= 2.24*, 1.15-4.37).
Preece et al. (1996), U.K.	Survey of depression in 11,292 pregnant women and distance of their homes from power lines.	There was a significantly greater incidence of perinatal depression among women who lived within 100 m of transmission lines of 132 kV and above.

Abbreviations: **OR=** odds ratio, **ENM=** EMF not measured, * statistically significant

Although the study by Preece et al. (1996) found an association between depression during pregnancy and residential proximity to transmission lines, authors of the paper said that the finding was unlikely to be associated with 50-Hz magnetic field exposure (emf *Health & Safety Digest* July-August 1996: 13). They suggested that the-pattern of smoking among study subjects could have confounded the results.

Of the two U.S. studies Poole et al. (1993) found statistically significant associations between depression and adults living near transmission lines (for adults combined, and for women separately). The other study involved women only and no statistically significant associations were found (McMahan et al. 1994). In that study, magnetic fields were measured at subjects' homes, and a recognized test for measuring depression was used. Authors of the study stated, however? that the homogeneity of the population in the study may limit generalization of the results. Because the two studies differed in the way that subjects were selected and in the way that depression was defined, a direct comparison of the two studies is difficult.

Together, the studies summarized in Table 2.8 suggest that there may be some relation between living near power facilities and mental health effects. at least for certain populations.

Occupational

Studies that examined possible effects of EMF on mental health of electrical workers are summarized in Table 2.9. The two studies that looked at depression provide little evidence for any overall association with electric field (Broadbent et al. 1985) or with magnetic field (Savitz et al. 1994) exposures. In the latter study, however, there were suggestions that electricians may have elevated risk. For electricians, of the 20 RR calculations for depression reported in the study. 17 were

Table 2.9. A summary of studies of mental health of electrical workers exposed to EMF.

Study/Location	Subjects/Exposure	Selected Results
Broadbent et al. (1985), U.K.	Health questionnaires of 390 power-line workers. PEM (electric field).	Measures of depression, anxiety, and obsessional symptoms among male power-transmission and distribution workers were not associated with electric-field exposure.
Baris & Armstrong (1990), U.K.	495 suicides were examined among occupations with assumed exposure to EMF, for 2 time periods. ENM.	For 10 electrical occupational groups in one time period, two were significantly elevated: radio/radar mechanics PMR= 153*, telegraph radio operators PMR=256*, and one was significantly decreased, telephone installers PMR=57*.
Savitz et al. (1994), U.S.	Depressive factors were compared between 183 Viet Nam veteran electrical workers and 3861 nonelectrical workers.	For all electrical occupations combined, there was little evidence of increased risk of depression. For electricians, there were several indicators with increased risk but only one indicator of depression was statistically significant.
Savitz & Loomis (1995), U.S.	Mortality among 138,905 men from 5 electric utilities from 1950-86. PEM.	Compared to the general population, risk of death by suicide for utility workers was significantly less (SMR= 81*. 74-88). Suicide risk and magnetic-field exposure among the utility workers was not reported.
Sobel et al. (1995a), U.S., Finland	Cases of Alzheimer's disease and controls in 3 data sets were compared by estimated magnetic field exposure. ENM.	The main occupations in the medium- and high-exposure categories- seamstress, dressmaker, and tailor-had a combined significant elevated risk for Alzheimer's disease (OR=3.0*, 1.6-5.4; for women, OR=3.8*, 1.7-8.6).
Sobel et al. (1995b), U.S.	Followup to above study. 316 new cases of Alzheimer's disease and 135 controls. Magnetic field exposure by job title. ENM.	Statistically significant associations were found in a fourth data set. For high to medium occupational magnetic field exposure: for men and women, OR= 3.93*, 1.5-10.6; for men, OR= 4.90*,1.3-7.9; for women, OR= 3.40, 0.8-I 6.
Baris et al. (1996a), 1996b), Canada	49 suicides in 21,744 electric utility workers (1970-88). Risks compared inside utility and to the general population. PEM.	Out of IO EMF exposure indices studied, only the geometric mean electric field exposure showed a statistically significant increased risk for suicide; RR= 2.76*, 1 .1 5-6.62 (20 cases). Cohort compared to population, SMR= 56".

Abbreviations: **ENM** = EMF not measured, **OR=** odds ratio, **PEM=** personal exposures measured, * statistically significant

elevated (range = I. I-2.5) but only one was statistically significant. Authors of the study recommended that more comprehensive studies should be done.

Three studies found no elevated risk for suicide for electrical workers overall. Of these, Baris and Armstrong (1990) did find a few significant risks for certain occupational groups, but the risks were in different directions and were statistically significant in only one of the two time periods studied (1970-72). For that time period, for all 10 electrical occupations combined, the PMR was 89 with a 95 percent confidence interval of 75-104. The study by Savitz and Loomis (1995) was directed primarily at cancer mortality but they reported deaths from other causes, including suicide. Compared to the genera1 population most causes of death, including suicide, for the utility workers were reduced. Authors of the study said that the finding was consistent with the healthy worker effect. Suicide mortality was not analyzed on the basis of estimated magnetic-field exposure in the report as were data on cancer mortality.

Compared to the general population. the suicide rate for workers at a large utility in Quebec was significantly smaller (SMR= 56) (Baris et al. 1996b). That study also assessed suicide risk within the utility with a case-cohort study using 10 different indices of EMF exposure (Baris et al. 1996a). Only the electric-field geometric mean for the medium exposure group showed a statistically significant elevated risk (Table 2.9). However, there was no dose-response trend, and the geometric mean electric field was not determined to be the most relevant exposure at the start of the study.

The studies by Sobel et al. (1995a, 1995b) are. to date, apparently the only ones that have investigated a possible association between magnetic fields and Alzheimer's disease. The evidence for the association is strengthened because the finding is consistent among widely divergent data sets. Also. risks were elevated for people who work with sewing machines, and other studies have confirmed that exposures from sewing machines are among the highest recorded for occupational magnetic field exposures (Hansen et al. 1995).

Human Experimental Studies

Since the early 1970s several studies have been conducted of human volunteers exposed to power-frequency EMF under experimental conditions. Often these studies were conducted in specially constructed indoor facilities, but in some cases people were exposed outdoors to EMF from power lines. Table 2.10 summarizes these experimental studies of volunteers exposed to EMF.

Exposures in the human experimental studies typically lasted only a few hours or less, so such studies focus on possible acute effects. One result most often reported in these studies is an effect on the cardiac rhythm, especially a slight slowing of the heart rate. One of the first times this effect was mentioned was in the general health study of men who worked in Russian 400-500-kV substations (Sazonova 1967). In that study, men who had the highest exposure to 50-Hz EMF also had lower heart rates after work compared to men with lower exposures.

Nine of the experimental studies in Table 2.10 reported alterations in heart rate in people exposed to EMF. This finding was confirmed in the extensive laboratory studies conducted at the Midwest Research Institute and summarized by Graham et al. (1993) (Fig. 2.11). Those studies found that effects on the heart rate (both speeding and slowing) were not a linear function of field intensity or exposure duration. Effects were found with exposure to combined 60-Hz fields of 9 kV/m and 20 µT (200 mG), but not with 6 kV/m and 10 µT (100 mG), or with 12 kV/m and 30 µT (300 mG).

The studies also found that exposure to the 20-µT (200-mG) field without the electric field produced the effect on heart rate found in studies with combined fields. In contrast to effects found when the fields were rapidly switched on and off during exposure, exposure to a constant 60-Hz magnetic field did not affect heart rate (Sastre et al. 1995). Three other studies also found no effects of electric and/or magnetic fields on heart rate (Beischer et al. 1973, Hauf 1976, Eggert and Ruppe 1996).

The effects of EMF reported on human heart rate are generally small, transient, and to date have not been associated with any adverse health effects. As pointed out by Graham et al. (1993) the biological significance of the finding is that some mechanism(s) must exist for EMF at levels as found in the environment to cause a measurable physiological effect in exposed humans.

One known mechanism for a biological interaction of electric fields is surface stimulation of skin or hair. In the studies at the Midwest Research Institute in which subjects were sitting with their arms not raised, tests

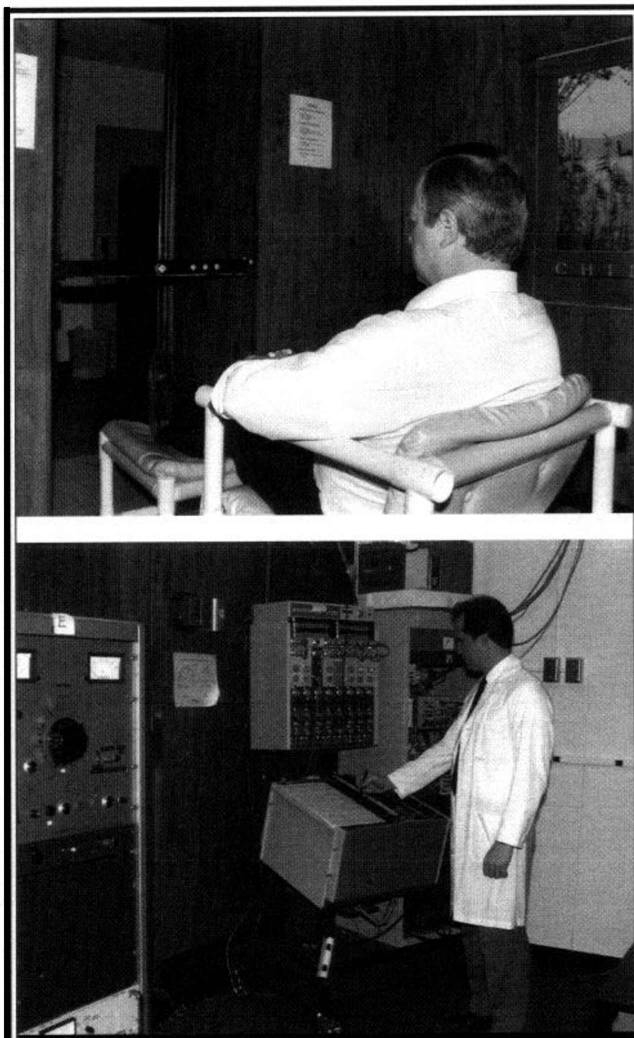

Figure 2.11. Facilities at the Midwest Research Institute used for short-term studies of people exposed to EMF. Volunteers are placed in an exposure room (upper) and they are monitored with instruments in a nearby room.
Photographs courtesy of Dr. Charles Graham.

showed that subjects could not reliably detect when the 60-Hz fields were on (Graham et al. 1987). This suggests that effects found in the studies conducted by that laboratory were due to other mechanisms, possibly subperception body currents induced by the fields.

Wachtel et al. (1996) used a model of pacemaker cells to see whether the cells would respond to the type of intermittent magnetic fields that affected human heart rate in the studies by Graham et al. (1993). The cells did respond at current densities similar to those estimated to be induced in the human body by exposures used by Graham et al. (1993).

Three of the studies in Table 2.10 were designed to measure thresholds for human perception of power-frequency electric fields. Two of these involved tests of people standing in electric fields; they produced similar

Table 2.10. A summary of experimental studies of human volunteers exposed to EMF.

Study/Location	Subjects/Exposure	Selected Results
Johansson et al. (1973), Sweden	2 groups of 20 men and women. One exposed, one not exposed in a laboratory. Average 50-Hz electric field was 21 kV/m.	There were no statistically significant differences in performance between the two groups.The study included psychological tests, reaction time, subjective complaints, performance tests, and memory.
Beischer et al. (1973) U.S.	10 men were exposed to a 45Hz 0.1 -mT (1 -G) magnetic field in a laboratory for up to 22.5 hr. 3 nonexposed controls.	A significant increase in serum triglycerides 1-2 days after exposure. No effects on blood, heart rate, blood pressure, temperature, urine, respiratory gas, reaction time, performance tests, memory, cholesterol, pupil diameter.
Krivova et al. (1973), Russia	23 men were examined during work activities in a IO-32 kV/m 50-Hz electric field.	Paper has few details but implies that biological effects were found which, along with results of other studies, led to establishment of occupational electric-field standards in Russia.
Hauf R. (1976) Germany	Groups of IO men and women were exposed in a laboratory for 3 hr to 50-Hz fields of 20 kV/m and 3 mT (30 G).	There were no significant effects on blood, WBC, RBC. ECG, EEG, heart rate, blood pressure, or triglycerides. When current was injected with electrodes! effects were seen on blood cell counts.
Cabanes & Gary (1981), France	Detection of 50-Hz electric fields by 75 men and women standing inside a high-voltage laboratory.	With both arms at sides, 4% of the people detected 5-kV/m field. With one arm raised above head 20% detected a 5- kV/m field and 40% detected a IO-kV/m field. 3 people detected a 0.35-kV/m field with any arm position.
Sander et al. (1982) Germany	50 people exposed for 1 wk to 50-Hz electric fields of IO or 20 kV/m, and 17 people exposed to a 5-mT (50-G) magnetic field.	Electric field: leukocytes increased 2.4% in 20 kV/m, blood sedimentation increased 12.5% in 10 kV/m less reduction in average EEG value end of day. Magnetic field: slight difference in hand temperature, small change in lactic acid.
Deno & Zaffanella (1982), U.S.	Detection of 60-Hz electric fields by 136 people standing outdoors by a test transmission line.	With both arms at sides, 7% of the people detected 5-kV/m field. With one arm raised, 30% of the people detected a 5-kV/m field and 65% detected a IO-kV/m field. With arms at sides 1% of the people could detect a I-kV/m field.
Peceny et al. (1983a) Tuhackova & Cenkova (1982) Czechoslovakia	Study 1: IO people exposed for 6 hr to 50-Hz 15-18 kV/m electric fields. Study 2: 13 people exposed over 3 days.	Statistically significant effects were found on heart rate. thyroxine, Achilles tendon reflex, epinephrine, cortisol, and testosterone. All results were not consistent for both studies.
Kalyada et al. (1985) U.S.S.R.	8 subjects exposed in a laboratory to 50-Hz electric fields of IO-15 kV/m for I-2 hr periods per week over 20 days.	Exposure resulted in some small effects: slowing of the heart rate by 8 beats/minute, tendency for reduced accuracy on performance tests, and changes in the EEG.
Silny (1985) Germany	>100 people exposed <1 hr (head or chest) to 5-1 00-Hz horizontal magnetic fields up to 100 mT (1000 G) while laying down.	Approximate thresholds for effects at 50 Hz: visual flicker at 7 mT (70 G), changes in visual evoked potential at 70 mT (700 G), headaches at 600 G. No effects on ECG. EEG, blood pressure! or body temperature.
Stollery (1986) U.K.	76 men were exposed to electric currents (up to 0.5 mA) such as induced by a strong electric field (36 kV/m) for 5.5 hr.	Significant differences between exposed and sham-exposed were found only on the second day with sham group more alert at end of the day, and improved response times to a complex syntax reasoning test.
Graham et al. (1987) U.S.	12 men exposed in a laboratory to 60-Hz EMF of 9 kV/m & 20 µT (200 mG), & sham exposed for 2, 6-hr periods over I-week.	Most factors studied were not affected by EMF (EEG. ECG, respiration rate, performance tests). Significant effects were found on heart rate, and on some components of auditory and visual evoked response.
Fotopoulos et al. (1987), U.S.	12 men exposed in a laboratory to 60-Hz EMF of 9 kV/m & 20 µT (200 mG), & sham exposed for 2, 6-hr periods over I-week.	Statistically significant effects found: lactic acid dehydrogenase lower in postexposure, lymphocytes increased on day 2 of exposure, T-helper cells lower in postexposure. No effects on cortisol, other hormones, other immune cells.

Abbreviations: **WBC=** white blood cells, **ECG=** electrocardiogram, **RBC=** red blood cells, **EEG=** electroencephalogram

Table 2.10. A summary of experimental studies of human volunteers exposed to EMF. (Continued)

Study/Location	Subjects/Exposure	Selected Results
Maresh et al. (1988), U.S.	11 men exposed in a laboratory to 60-Hz EMF of 9-kV/m & 20-µT (200-mG) for 2-hr in combination with 45 min of exercise.	Effects of exercise were not affected by EMF exposure. Heart rate was significantly slower at 30 and 120 minutes into EMF exposure periods. No effects of EMF on cortisol, growth hormone, testosterone, temperature, or lactic acid.
Teresiak & Szuba (1989), Poland	64 people (22-63 yr old) exposed to 50-Hz electric field of 0, 4.4, 10.9, or 13 kV/m; or to currents of 0, 50, 135, or 160 µA	Reaction times to both sound and light stimuli were increased significantly only at the highest electric field (13 kV/m), and the highest current level (160 PA). Currents were applied through the hand.
Kato et al. (1989), Japan	Detection thresholds for 7 men and 4 women for 50-Hz electric fields indoors from electrodes around the hand.	Detection thresholds in summer were 30-65 kV/m for the hairy back of the hand, and >1 15 kV/m for the palm. During fall, detection for back of the hand was 115 kV/m.
Wilson et al. (1990) U.S.	Melatonin excretion was measured in 32 women and IO men after sleeping with AC and DC electric blankets for up to IO wk.	No effects on urine melatonin metabolite with conventional electric blanket. With continuous polymer wire AC and DC blankets, 7 of 28 people showed a decrease in metabolite during exposure and an increase in post-exposure.
Cook et al. (1992), U.S.	30 men were exposed for 6 hr to 60-Hz EMF of 9 kV/m & 20 µT (200 mG) while sitting in exposure room in a double-blind study.	Statistically significant effects were found on slowing of heart rate, changes in event-related brain potentials, and decreased errors in a reaction test. No effects on subjective measures, sleepiness, time estimation, or field perception.
Bell et al. (1992), U.S.	EEG for 20 people exposed to 60 Hz 0.078 mT (0.78 G) and/or DC magnetic fields in a laboratory. Fields on 2 seconds, off 5.	Most subjects showed field-related increased EEG activity. The response during combined AC/DC exposure did not differ from the sum of individual responses.
Sadafi & Wood (1993), Wood et al. (1994), Australia	ECG for 12 men and 6 women exposed in a laboratory for 60-150 seconds to 15.3-20 µT (153-200 mG) 50-Hz magnetic fields.	A transient 5% slowing of the heart rate IO seconds after switching from field off to on and persisting for 60 seconds. An opposite effect occurred when switching from on to off. Because of high variability, results were not conclusive.
Korpinen et al. (1993) Korpinen & Partanen (1994), Finland	ECG for 27 male electric transmission workers and 26 volunteers were exposed outdoors to EMF from 50-Hz transmission lines.	Volunteers showed a slight slowing of the heart rate following exposure. Volunteers (mean age 25.7 yrs) were tested after walking beneath the line. Workers (mean age 40.8 yr) were tested after working in and out of EMF.
Korpinen & Partanen (1993), Finland	ECG for 26 men exposed for 1-hr periods to a 50-Hz 400-kV line in 3.5-4.3 kV/m, 1.4-6.6 µT (14-66 mG), 15 men sham exposed.	The slight slowing of heart rate in a previous study (above) was not found in this second study. A possible increase in systolic blood pressure was found in the men exposed to the line. Data presented were preliminary.
Lyskov et al. (1993), Russia	11 women & 9 men in a laboratory exposed to 45 Hz magnetic field (12.5 G) from coils around their head (continuous & intermittent).	Statistically significant effects found: increase in alpha brain wave activity, decrease in delta wave activity, beta waves and mean/peak EEG frequencies increased in frontal derivations. Also a possible decreased test learning rate.
Graham et al. (1994), U.S.	Three groups of 18 men each exposed sitting down in a laboratory for two 6-hr periods to 60-Hz EMF (6-12 kV/m & 100-300 mG).	For 9 kV/m & 200 mG: statistically significant slowing of heart, changes in event-related brain potentials. For 6 kV/m & 100 mG: significant decrease in reaction time and test performance accuracy. No effects for 12 kV/m & 300 mG.
Litovitz et al. (1994) U.S.	Diabetic subjects were exposed to a 60-Hz magnetic field (2-10 mG) and to noise while sleeping.	Blood glucose levels increased in magnetic fields >0.6 µT (6 mG) (no statistical tests were reported).
Sastre et al. (1994) U.S.	Heart rhythm in 2 studies of men exposed while sleeping to 60-Hz intermittent magnetic fields of 1 and 20 µT (10 and 200 mG).	There were statistically significant modifications to the heart rhythm in the 0.0-O. I, and 0.15-0.40 Hz spectral bands in men exposed to intermittent magnetic fields (on 1 hr, off I hr, on/off every 15 seconds during on period).

Abbreviations: **ECG=** electrocardiogram, **EEG=** electroencephalogram

Table 2.10. A summary of experimental studies of human volunteers exposed to EMF. (Continued)

Study/Location	Subjects/Exposure	Selected Results
Sastre et al. (1995) U.S.	Heart rhythm in 40 men exposed 9 hr to a continuous 60-Hz magnetic field of 20 µT (200 mG) while sleeping in a laboratory.	Unlike results of previous studies of intermittent exposures by this research group (see above study) no effects were seen on heart rate variability when men were exposed to continuous magnetic fields.
Graham et al. (1995, 1996b), U.S.	Three experiments of melatonin in men (113 total) exposed during sleep to 60-Hz magnetic fields, both intermittent and continuous.	in the first experiment, men with normally low night blood-meiatonin levels had statistically significant reduced levels after field exposure, but not in the second experiment. Authors concluded magnetic fields did not affect melatonin.
Graham et al. (1996a), U.S.	80 men in groups of 20 were exposed or sham-exposed overnight to intermittent 20-µT (200-mG) 60-Hz magetic fields.	No significant effects of exposure were found on blood meiatonin concentrations. Significant alterations associated with exposure were seen for testosterone, T-helper ceils (CD4), and natural killer ceil (CD56) activity.
Whittington et al. (1996), New Zealand	57 men and 44 women were exposed around the head to a 50-Hz 1 00-µT (1 -G) field for 9 minutes during performance tests.	Compared to nonexposure trials, during exposure subjects were 14 msec faster on the most difficult task in responding to compare the duration of 2 light flashes. No effects on 2 easier levels of difficulty, or on blood pressure or heart rate.
Eggert & Ruppe (1996), Germany	10 men and 10 women were exposed for 10 min to 50-Hz magnetic fields of 0.5, 1, and 2 mT (5,10, 20 G).	No effects of exposure were seen on body temperature or on heart rate. There was a tendency for a reduction in mental performance on psychological tests.
Kurokawa et al. (1996), Japan	Melatonin secretion was studied in 8 men who slept for 6 wk with special electric blankets that produced EMF but no heat.	Preliminary results indicated no significant effects of exposure on meiatonin concentrations measured in urine. The median magnetic field measured at the surface of the electric blankets was 3.4 µT (34 mG).
Lyskov et al. (1996), Russia	6 tests were given to 7 men and 8 women who were exposed for 30 min to different combinations of 50-Hz plus DC magnetic fields.	For 45 µT (450 mG) AC & 65 µT (650 mG) DC fields, significant changes in 3 of 10 memory and coordination variables; for the same AC field & 14-1 6 µT (140-l 70 mG) DC field, change in one variable; ambient fields no effects.
Selmaoui et al. (1996), France	Melatonin secretion in 16 men exposed at night, 50-Hz linear 1 0-µT (100 mG) field (continuous & intermittent). 16 controls.	Acute 9-hr exposure of young men at night to the 50-Hz magnetic field did not affect levels of serum melatonin, or a meiatonin metaboiite in urine as compared to control men.

Abbreviations: **ECG=** electrocardiogram, **EEG=** electroencephalogram

results (Cabanes and Gary 198 1, Deno and Zaffanella 1982). Most people in the studies could not detect electric fields of the strength found beneath transmission lines unless they stretched one or both arms above their head. In the tests by Cabanes and Gary (198 l), it was found that a small percentage of people are sensitive to relatively weak electric fields of less than 500 V/m. Not all of the studies in Table 2.10 that found biological effects of field exposures reported whether subjects in the studies could detect when the fields were on.

Six studies in Table 2.10 reported that field exposure resulted in a decrease in peoples' performance on various mental tests involving reaction time or accuracy (Kalyada et al. 1985, Lyskov et al. 1993, Graham et al. 1994, Eggert and Ruppe 1996, Lyskov et al. 1996). Three other studies reported improved performance on tests associated with exposure (Stollery 1986, Cook et al. 1992, Whittington et al. 1996). Comparisons among the studies are difficult to make because of the wide differences in exposure conditions and in the types of performance tests used in the studies. In a review of this research, Whittington and Podd (1996) suggested that the inconsistent results may have been caused by low statistical power of the studies. They found that on average, the 12 studies that they reviewed had only an 8 percent chance of detecting small effects-the size of effects on human performance or physiology most likely to be produced by EMF.

Four research groups examined the hormone melatonin in human volunteers exposed to 60-Hz magnetic fields. In one series of studies, melatonin was measured from blood samples taken from men while they slept in circularly polarized fields of 1 or 20 µT (10 or 200 mG) (Graham et al. 1995, 1996b). In one of the studies with intermittent field exposure of 20 µT (200 mG). nocturnal melatonin was significantly depressed only in men who had normally low melatonin levels, but the finding did not occur in a replicate study. A third study in the series found no effects on nocturnal melatonin from exposure to a 20-µT (200-mG) continuous magnetic field.

Other researchers measured a metabolite of melatonin in urine (6-hydroxymelatonin sulfate) of 35 women and 10 men who slept under electric blankets for several weeks (Wilson et al. 1990). When subjects used conventional electric blankets, there were no differences in nocturnal levels of the metabolite compared to pre- and post-use times. For 7 of 28 subjects who used continuous polymer wire blankets (CPW), the metabolite decreased with exposure, but it increased following exposure (the researchers called the latter a rebound effect). The CPW blankets switched on and off twice as often, and produced magnetic fields that were 50 percent stronger than conventional blankets.

Preliminary results of another study of electric blankets found no evidence that melatonin concentrations in urine were affected by the use of such blankets by eight men (Kurokawa et al. 1996). The blankets used in the study were modified so that they produced EMF but no heat. This was done so that heat would not be a confounder to possible effects of EMF.

The fourth experimental study of melatonin in humans found no indication that exposure to a linearly polarized 50-Hz 10-µT (lOO-mG) magnetic field affected levels of either serum melatonin, or the urine metabolite 6-sulfatoxymelatonin in men (Selmaoui et al. 1996). The men were exposed to the field while they were lying down for 9 hours at night, for two nights.

Some of the longest human experimental EMF exposures were included in the studies of 50-Hz fields by Sander et al. (1982). Up to three people at a time spent 1 week in a special room (including sleeping) exposed to electric fields for 6-22 hours per day, while three other people were in a nearby control room. Extensive data were collected on blood components, hormone levels, EEG, ECG, temperature, and blood pressure. Two psychological tests were administered, and eye flicker frequency was measured. For magnetic-field studies, one exposed and one control person were tested at a time during a several hour period. The same physiological data were collected as for electric fields. Most parameters in both the electric- and magnetic-field studies showed no differences between exposed and control subjects, with a few exceptions (Table 2.10).

Electrical Hypersensitivity

In addition to the possible reproductive effects of EMF from VDTs discussed in the section above, there are also reports of skin disorders and other symptoms among some users of these devices. These effects are often reported by persons who believe themselves to be hypersensitive to electricity (Knave 1994). Other people also believe that they are sensitive to the electric or magnetic fields produced by electrical appliances and equipment in general (Grant 1995, Knave 1994). Such people report a variety of health effects including headache, fatigue, nausea, insomnia, shortness of breath, heart palpitation, dizziness, and memory difficulties.

Grant (1995) considered electrical sensitivity to be a form of environmental illness such as chemical sensitivity, sick building syndrome, and probably Gulf War syndrome. The author acknowledged, however, that she was an electrically sensitive patient and not a medical doctor or a scientist.

Compared to many of the other health effects included in research on EMF (such as reproduction and cancer), there have been relatively few studies on human electrical sensitivity. One study in the U.S. investigated sensitivity of patients to square wave magnetic fields with frequencies of 0.1 Hz to 5 MHz (Rea et al. 1991). Of 100 patients who complained of being sensitive to EMF, 75 responded to field exposure (none of the controls responded). However, 50 of the patients also responded during field off conditions and they were removed from the study. Of the remaining 25 people, 16 were found to respond to the fields in subsequent phases of the study. Most reactions were neurological. Similar studies in Sweden could not confirm the ability of electrically sensitive patients to detect weak fields (studies cited in Knave 1994).

A review by the National Radiological Protection Board concluded that the skin diseases reported by some users of VDTs do not appear to be caused by exposure to AC magnetic fields (Advisory Group on Non-ionizing Radiation 1994). The Board did suggest that the DC electric fields from these devices may aggravate existing skin disorders, especially in conditions of low humidity. They added that strain associated with work may also give rise to skin problems. A study by Arnetz et al. (1993) found that people withVDT-associated skin complaints suffered more from occupational stress compared to healthy controls who also used VDTs.

Many of the reports of electrical hypersensitivity have come from Sweden. A report on EMF by several Swedish Government agencies pointed out that symptoms reported by electrically hypersensitive people are common in the Swedish population, and they can have many causes (Swedish Agencies 1996). The agencies said that such symptoms had not yet been produced in experiments where the sensitive individual was not aware that EMF had been activated. The agencies said that more research is needed to learn the causes of the symptoms reported by electrically hypersensitive people.

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Chapter 3

Human Studies of EMF and Cancer

Summary

- The question of whether EMF can affect development of cancer in people is now the main issue for EMF.
- Carcinogenesis is a complex multi-step process, and there are more than 100 cancer types. More than half of all cancers may be caused by diet and tobacco. There are many other potential risk factors, including EMF.
- The first studies of power-frequency EMF and human cancer were published in the late 1970s and early 1980s. These, and many of the studies that followed, did not measure exposures to EME Instead, exposures were estimated by describing power lines near homes, and by using "electrical" job titles.
- There have been about 19 studies of cancer in children living near power lines, and about 11 studies of adults. Twelve studies looked at cancer in children or adults and their use of electrical appliances, or heated beds. About 15 of these 42 studies reported at least one statistically significant increased risk.

There have been more than 100 studies of cancer in workers in various electrical occupations, and about 12 studies of cancer in children of electrical workers. More than half of these diverse studies reported at least one statistically significant increased risk.
- A few studies have attempted to compare trends in cancer rates with trends in electric energy consumption. There are many problems associated with this simple type of analysis.
- Research summarized in this chapter suggests that EMF may be a risk factor for leukemia, brain cancer, or possibly other cancers. Meta-analyses of this research find statistically significant increased risks of about 1.20-2.00. However, scientists generally agree that these studies do not prove that EMF cause or promote cancer. A major problem is the difficulty of assessing past exposures to EMF.

Background

As described in Chapter 2. early concerns about the possible health effects of EMF focused mainly on acute effects. mental health. and reproduction. Cancer became an additional issue in the early 1980s. and now most public and scientific interest in EMF involves some aspect of cancer. Hundreds of studies of EMF and cancer have been conducted. and many more are underway and planned. This strong interest in cancer in not unique to EMF: such interest is a common feature of many environmental health issues. For Americans. cancer is the number-one personal health concern (McAllister et al. 1993).

This chapter begins with a basic introduction to cancer processes and causes. and gives an overview of historical trends in cancer rates. It also describes how scientists go about assessing cancer risks. This information provides a context for discussing the lage body of' epidemiologic research that has been conducted to assess whether EMF affect the development of cancer in humans.

Cancer

Carcinogenesis

Carcinogenesis is a complex process that occurs when a cell become abnormal and multiplies uncontrollably The descendants then invade and destroy other cells (McAllister et al. 1993. Weinberg 1996). Cell growth is normally highlv regulated. but sometimes this regulation is altered. When this happens. the abnormal ceil multiplies rapidly into masses of abnormal cells called tumors. Benign tumors may cause problems because of their size. but it is malignant tumors (cancer) that are deadly because of their ability to destroy surrounding tissue. Cells from some malignant tumors also enter the blood vessels and spread the cancer to distant parts of the body (metastasize) (Ruoslahti 1996).

Most cancers are thought to originate from a single cell that has an alteration to the genetic material DNA (deoxyribonucleic acid) (Hart and Turturro 1988, McAllister et al. 1993). If not repaired, this alteration (mutation) can be passed on as the cell divides, resulting in many copies of the defective cell. Fortunately, most damage to DNA is normally repaired by biological processes. Over many years, however, the chances increase that the damage will not be repaired.

DNA carries all of the information needed for individual cells and the whole organism to function. This information is contained in individual parts of DNA called genes, which are located on chromosomes in the cell nucleus. Genes provide the basic information in the form of codes for amino acids that combine to form proteins. Mutations to certain genes appear to be especially important in carcinogenesis; they are often called cancer genes.

Two basic types of cancer genes are known: oncogenes, and tumor suppressor genes (McAllister et al. 1993). Oncogenes are slightly altered versions of proto-oncogenes, which have normal functions, including cell growth control. Tumor suppressor genes normally work to limit growth. Many cancers are thought to occur when mutations occur to both of these normal gene types, thus eliminating controls on cell growth.

Causes of mutations and, therefore, causes of cancer can originate from many factors. Some mutations are inherited from the parents; some are caused by environmental factors such as ionizing radiation or chemicals. Although most carcinogens such as x rays directly damage DNA (they are genotoxic), others may act through indirect (epigenetic) non-mutational mechanisms (Barrett and Shelby 1992). The latter includes some chemicals that affect gene expression or cell proliferation.

Carcinogenesis is considered to be a multi-step, multi-gene process (Barrett 1993). At least three steps are usually required: initiation, promotion, and progression (Fig. 3.1). During initiation, a mutation occurs in the DNA that may involve activating cancer genes. "Complete carcinogens" such as ionizing radiation at sufficiently high levels can encompass all three steps. In many cases, however, initiation alone will not lead to cancer unless a promoter is present.

The presence of a promoter alone typically does not cause cancer (Hart and Turturro 1988). During the promotion stage, the altered cell multiplies and forms a tumor. If EMF are involved in carcinogenesis, some scientists believe that they are most likely to function as promoters (Wertheimer 1989, Koifman 1993). During promotion, additional mutations may occur to tumor cells, causing a progression to a malignant tumor. Cancer cells dissolve the walls of blood vessels and enter the blood and lymph systems where they are carried to other sites. Common adult cancers may require 3-10 genetic events involving multiple cancer genes (Barrett 1993).

Scientific knowledge about the mechanisms of carcinogensis has increased tremendously in recent years. This trend will probably increase even more as new information is learned about molecular biology.

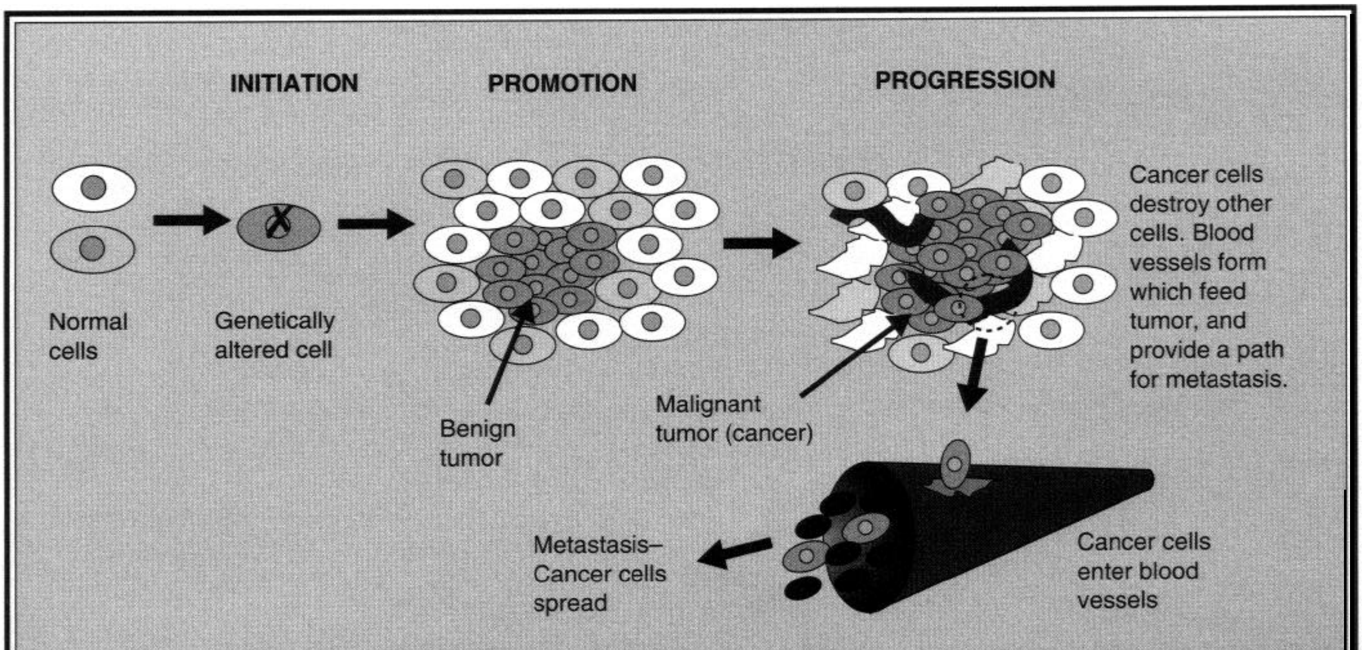


Figure 3.1. Highly simplified representation of the multi-step process of carcinogenesis (see text).

Cancer Types and Trends

There are more than 100 types of cancer, although most deaths are from a smaller number of the most common types (NC1 1983). Figure 3.2 shows the numbers of deaths in 1991 in the U.S. for the five leading cancer sites for two age groups. Cancer is the second leading cause of death in the U.S. after heart disease. In 1991 there were 514,636 deaths from cancer in the U.S., representing 24 percent of the total deaths from all causes (National Center for Health Statistics 1991).

From 1961 to 1991 in the U.S., the mortality (death) rate for some types of cancer increased, while others decreased (Fig. 3.3). The most striking feature of these data is the dramatic increase in the lung cancer mortality rate for women. Mortality rates for several cancer types have decreased; the cancer mortality rate for children has also decreased. Mortality rates reflect changes in cancer detection and treatment, and changes in lifestyle and in various environmental exposures.

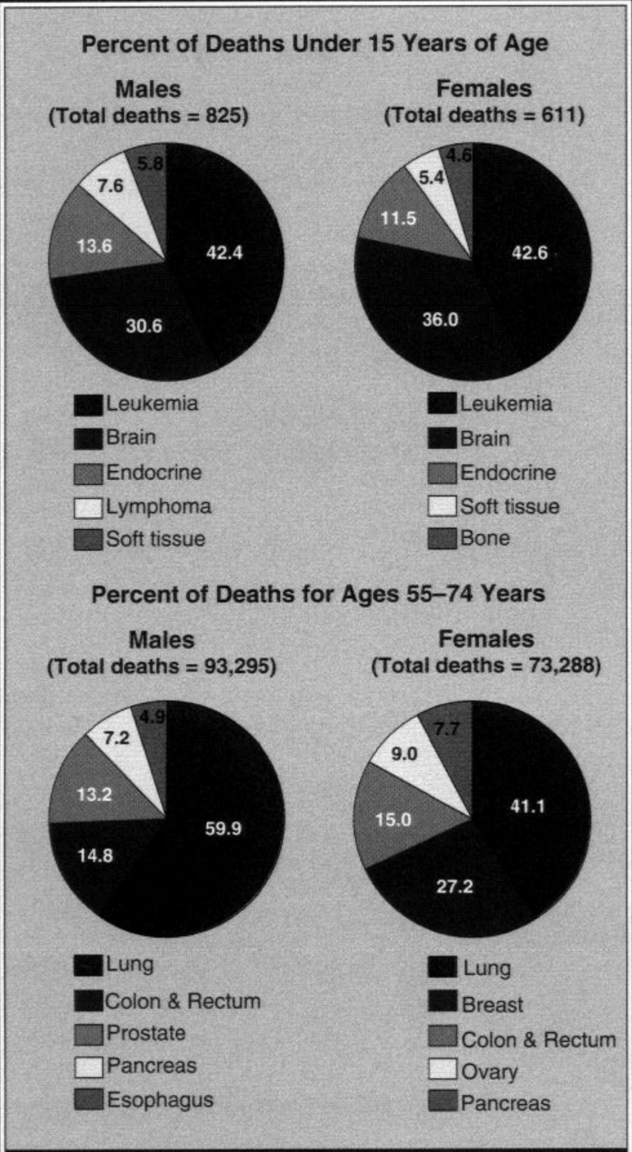


Figure 3.2. Deaths in 1991 in the U.S. for the leading five cancer sites for two age groups. Source: National Center for Health Statistics (1991).

Reliable information on U.S. cancer incidence rates (new cases per year per 100,000 population) have only been available since the early 1970s. As with mortality rates, incidence rates have shown both increases and decreases for various type of cancer (Fig. 3.4). Although leukemia incidence rates for all ages combined have decreased, for children under 14 years of age they have increased about 20 percent since 1973. Incidence rates for brain and nervous system cancer in children have increased about 38.4 percent. These data and those in Figure 3.4 are from the SEER (Surveillance, Epidemiology, and End Results) Program, which is administered by the National Cancer Institute. There are nine geographic areas in the SEER program (including Seattle-Puget Sound), representing about 9.5 percent of the U.S. population (Ries et al. 1994).

Incidence rates are influenced by changes in how cancers are diagnosed and reported, and in changes in cancers caused by various environmental factors. Scientists have differing opinions about how to interpret cancer mortality and incidence rates, and the historical trends in these data (Beardsley 1994).

Causes of Cancer

Many factors individually or in combination with other factors cause or contribute to the development of cancer. Some factors are from the internal environment (such as inherited mutations and hormones), but most factors are from the external environment. About 80 percent of all cancers may have an environmental component (Higginson 1993). Exposures to many of these external factors are controllable; therefore, many cancers are preventable (Doll and Peto 1981, American Cancer Society 1996).

For most cancers that are diagnosed, it is not possible to identify the exact factor(s) that caused the disease. Therefore, potential causes of cancer (or diseases in general) are usually called "risk factors." Many estimates have been published about the proportion of cancers that may be caused by various factors. Figure 3.5 shows some often-cited estimates of the relative contribution of various risk factors to total cancer cases. Tobacco and diet might be responsible for over half of all cancer cases. About 20-50 percent of cancers may be influenced by natural constituents of food and by chemicals from natural cell products (Higginson 1993).

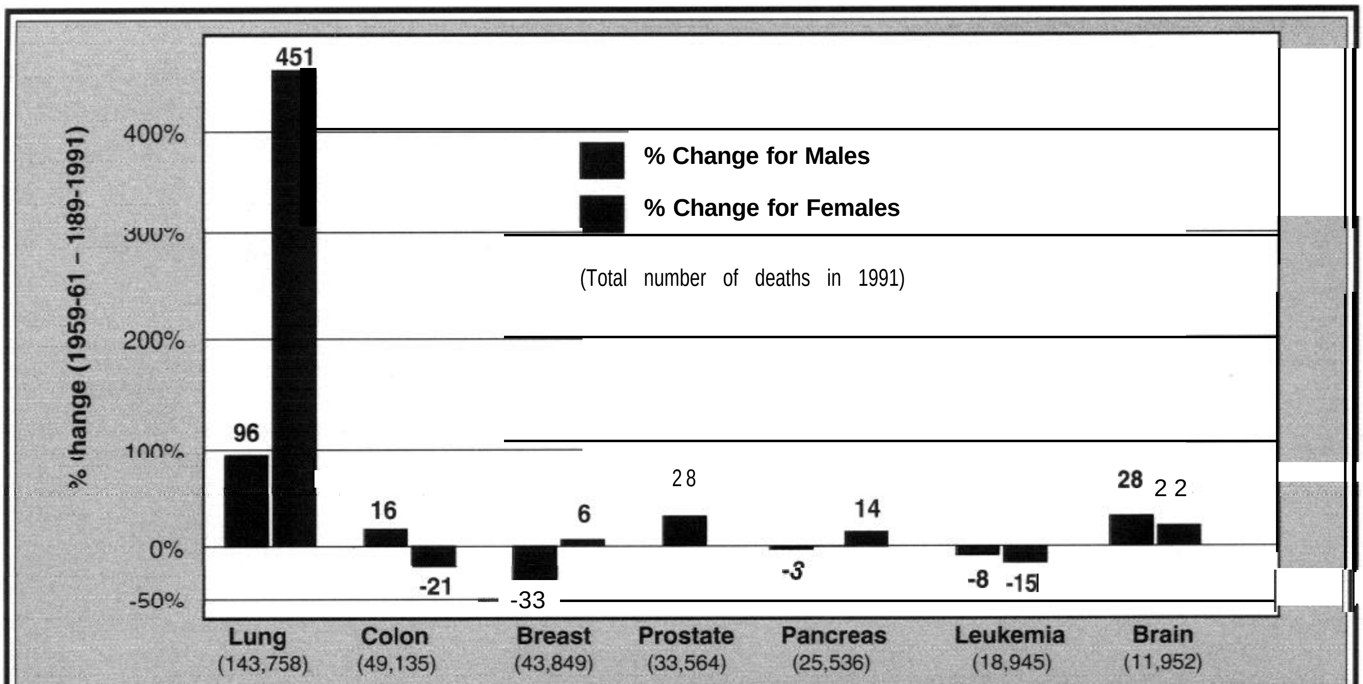


Figure 3.3. Thirty-year trends in death rates for selected cancers in the U.S. per 100,000 population, adjusted to the age distribution of the 1970 U.S. population. Data are for 1959-61 to 1989-1991. Source: American Cancer Society (1995).

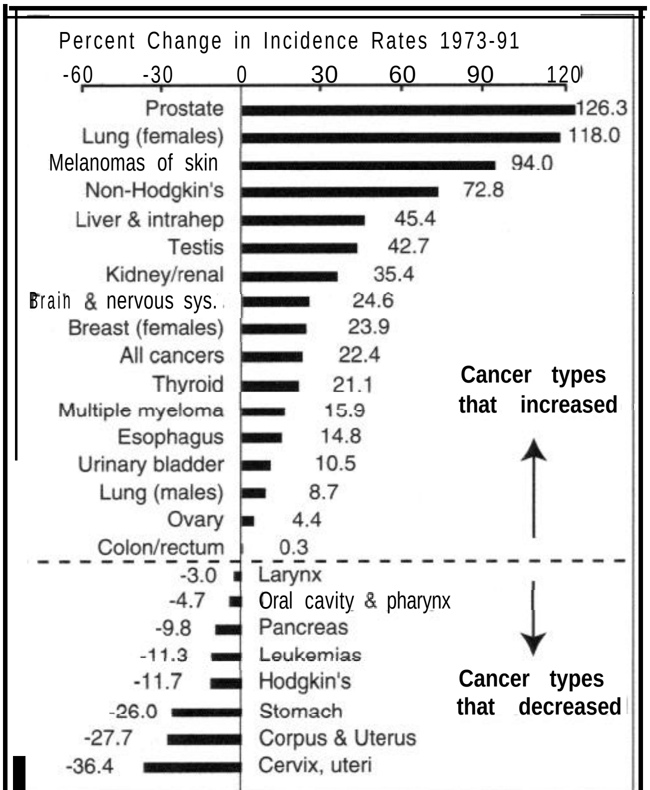


Figure 3.4. Percent change in U.S. cancer incidence rates for all ages from 1973 to 1991. Data are from nine geographic areas in the SEER program. Source: Ries et al. (1994).

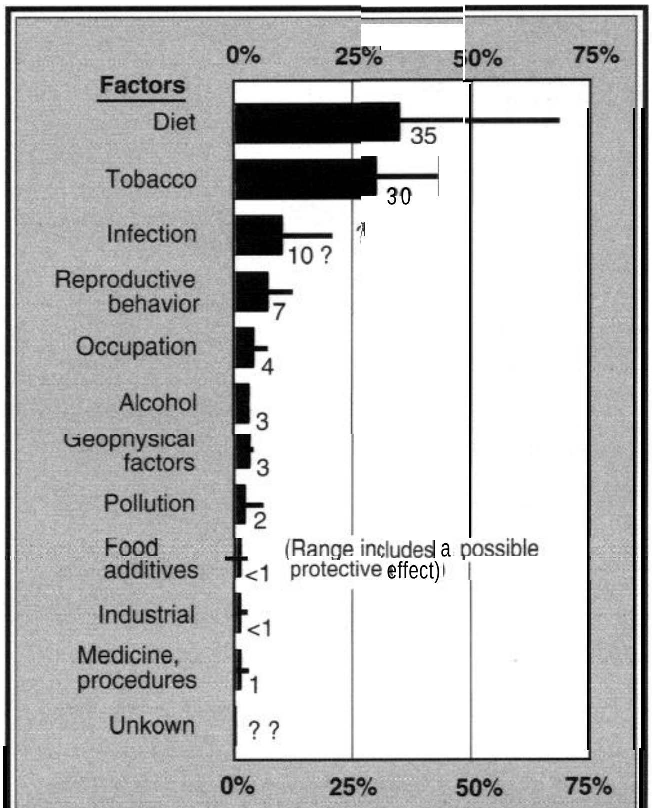


Figure 3.5. Possible proportions of cancer deaths attributed to various factors. The red bar is the best estimate, and the blue line is the range of estimates. Source: Doll and Peto (1981).

Cancer Risk Assessment

A risk can be defined as the probability of the occurrence of a hazardous event. Risk assessment consists of two basic steps; hazard assessment and exposure measurement (American Cancer Society 1996). In the first step, data are analyzed from epidemiological studies, animal studies, and studies of cells and tissues. This analysis provides the evidence to determine whether some agent is a hazard (is carcinogenic). In the second step, human exposure to a hazard is estimated. Exposures may come from the air, water, diet, or other sources. The exposure levels of the agent are assessed along with assessments of how the agent interacts with the body.

The results of the two steps may be expressed in terms of the chance that exposure to some level of the agent will increase the chance of cancer in a certain population by some amount. Risk management is the process by which risks are controlled; it includes the setting of safety standards by regulatory agencies. In practice, agents with individual lifetime cancer risks lower than 10^{-6} (one cancer in 1,000,000 people during their lifetime) are generally not regulated in the U.S. (Travis et al. 1987, Higginson 1993).

Epidemiologic Studies of EMF and Cancer

Beginning in the early 1980s interest in health research on EMF began to shift from general health issues to cancer. This was prompted by publication of epidemiologic studies by Wertheimer and Leeper (1979), and by Milham (1982). Since that time over 140 papers have been published on cancer studies involving residential and occupational exposures to EMF. Most of the studies have focused on magnetic fields. The sections below summarize this large body of epidemiologic research. An summary of epidemiologic methods and terms was presented in Chapter 2 (see pages 2-11 and 2-12).

Residential: Power Lines

The possible association between EMF and cancer was first investigated in studies of children and adults living in residences near power lines. To date a total of about two dozen residential cancer studies have been reported. An additional dozen studies have also looked for associations between cancer and EMF produced by household appliances.

Children

In the 1970s Wertheimer and Leeper (1979) conducted an exploratory study in Denver, Colorado, that was the first to identify 60-Hz magnetic fields as a possible risk factor for childhood cancer. Their study found statistically significant associations between child cancer mortality and proximity of children's homes to high-current electric power lines. The results seemed surprising because they pertained mainly to distribution lines, instead of transmission lines. The researchers said that their findings appeared to relate to current rather than voltage, therefore, they assumed magnetic instead of electric fields were of interest. Further, the study suggested that weak 60-Hz magnetic fields of only 0.2-0.3 µT (2-3 mG) and above may in some way affect cancer development. (Some measurements of magnetic fields were made but they were not used in the analyses of cancer data.) Wertheimer and Leeper (1979) pointed out that the main sources of magnetic fields include power lines and currents on water pipes.

The Denver study was criticized for a number of reasons (Michaelson 1987). The results seemed even more questionable after another study a year later in Rhode Island failed to find similar results (Fulton et al. 1980). However, apparent biases in the Rhode Island study were identified (Wertheimer and Leeper 1980), and the next two studies that were done (Tomenius 1986, Savitz et al. 1988) did find statistically significant associations between power line types and child cancer. The study by Savitz et al. (1988) was done in Denver, but researchers used newer child cancer cases. Savitz et al. (1988) concluded that results of their study were generally consistent with the earlier study in Denver. A reassessment of the second Denver study yielded statistically significant associations that were stronger than reported in the 1988 paper (Savitz and Kaune 1993a). Savitz and Kaune used a three-level code to classify homes near power lines, and they found statistically significant risks for total child cancer (OR= 1.9), leukemia (OR= 2.9), and for brain cancer (OR= 2.5).

Another reassessment of the study by Savitz et al. (1988) found a statistically significant threefold increase in child cancer risk for homes in Denver with metal water pipes, compared to homes with nonconductive pipes (Wertheimer et al. 1995). Nonconductive pipes do not conduct electric grounding current, so they are not a source of magnetic fields. More studies followed and to date there have been about 19 studies of power lines and child cancer conducted in 10 countries (Table 3.1). About a dozen other studies have looked at cancer in children of electrical workers (summarized in a later section of this chapter).

Table 3.1. A summary of studies of cancer and children living near power lines.

Study/Location	Subjects/Exposure	Selected Results
Wertheimer & Leeper (1979), U.S., CO	344 child cancer deaths compared to 2 groups of controls. Exposure by size and number of power lines and distance to home.	Excess of high-current configuration power lines was found near homes of child cancer cases.-/- Leukemia, OR= 3.00*, 1.78-5.00; lymphoma, OR= 2.08, 0.84-5.16; CNS, OR= 2.40*, 1.15-5.01; total cancer, OR= 2.23*, 1.58-3.13.
Fulton et al. (1980), U.S., RI	Power lines were classified and mapped within 46 m of addresses of 119 child leukemia cases and 240 controls. ENM.	No association was found between residential power-line configuration and leukemia in persons less than 21 years old. For leukemia and comparing high- vs. low-current configuration lines, OR=1.07, 0.73-l .57.
Tomenius (1986), Sweden	Lines within 150 m of homes of 716 child cancer cases and 716 controls were mapped. Magnetic fields measured at front door.	For total homes and fields >3 mG: leukemia OR= 0.3; CNS, OR= 3.7*, p<.05; lymphoma, OR= 1.8; total cancer, OR= 2.1*, p<.05. In this study analyses were based on case and control homes, not on persons.
Savitz et al. (1988), U.S., CO	Power lines were classified and mapped near homes of 356 child cancer cases and 278 controls. EMF were measured in homes.	For high vs. low current lines: leukemia, OR= 1.54, 0.90-2.63; brain cancer, OR= 2.04*, 1 .1 l-3.76; total cancer, OR= 1.53, 1.04-2.26. For >2 mG: leukemia, OR= 1.93, 0.67556; total cancer, OR= 1.35, 0.63-2.90.
Coleman et al. (1989), U.K.	Electrical substations were mapped within 100 m of residences of 190 child leukemia cases and 570 controls. ENM.	For persons less than 18 years old living within 50 m of a substation, the risk of leukemia was elevated but it was not statistically significant (OR= 1.5, 0.7-3.4) based on 14 exposed cases.
Lin & Lu (1989), Taiwan	Electric power facilities were mapped within 50 m of residences of 216 child cancer cases and 422 controls. ENM.	Some elevated risks were found, but none were statistically significant. Leukemia, OR= 1.31, 0.78-2.21; lymphoma, OR= 2.00, 0.62-6.5; brain, OR= 1.09, 0.50-2.37; total cancer, OR= 1.30, 0.92-l .84.
Myers et al. (1990), UK.	374 child cancer cases and 588 controls were compared by distance to power lines and by calculated magnetic fields.	No statistically significant associations were found between child cancer and proximity to power lines, or with calculated magnetic fields. For total cancer: within 100 m of lines, OR=1.04, 0.64-1.70; > 0.3 mG, OR= 1.73, 0.59-5.07.
London et al. (1991), U.S., Los Angeles	232 child leukemia cases and 232 controls were compared by power line types, and by spot and 24-hr magnetic fields in homes.	For very-high-current lines, OR= 2.15*, 1.08-4.26; adjusted OR= 1.73, 0.82-3.66. Adjusted trend of increasing risk with increasing power-line current type, p=0.017*. For bedroom mean 24-hr magnetic field >2.68 mG, OR= 1.48, 0.66-3.29.
Lowenthal et al. (1991), Australia	A pilot study of 76 child cancer cases and no controls. Exposure defined as residence within 50 m of a power line. ENM	Only 1 cancer case was found within 50 m of a power line. Authors stated that no conclusions could be made. For leukemia, observed cases (1) / expected cases (0.5) = 2.
Feychting & Ahlbom (1993), Sweden	142 child cancer cases within 300 m of 220-400-kV lines. Exposure by distance and by measured and calculated magnetic fields.	For all dwellings > 3 mG: total cancer OR= 1.3, 0-6-2.7 (10 cases); leukemia OR=3.8*, 1.4-9.3 (7 cases); CNS cancer OR=1 .O, 0.2-3.9 (2 cases). For all dwellings within 50 m: total cancer OR=l.0, O-5-2.2, leukemia OR= 2.9, 1.0-7.3.
Olsen et al. (1993), Denmark	1707 cases of child cancer and 4788 controls. Exposure by distance to power facilities and by calculated magnetic fields.	For dwellings > 4 mG: leukemia OR= 6.0, 0.8-44; CNS cancers OR= 6.0, 0.7-44; lymphoma OR= 5.0, 0.3-82; combined OR= 5.6*, 1.6-l 9 (6 cases). For dwellings > 2.5 mG, combined OR= 1.5, 0.6-4.1 (6 cases).
Petridou et al. (1993b), Greece	136 child leukemia cases and 187 controls were compared by home distance to electric power substations and lines. ENM.	For homes within 100 m of substations, leukemia OR= 0.35, 0.12-l .08. For homes within 5-49 m of power lines, leukemia OR= 1.06, 0.61-l .84; within 5 m, OR= 1 .1 9, 0.59-2.41.
Verkasalo et al. (1993), Finland	Cancer in all children living within 500 m of transmission lines (140 cases). Magnetic fields were calculated for all dwellings.	For fields > 2 mG: CNS cancer OR= 2.3, 0.75-5.4; leukemia OR= 1.6, 0.32-4.5; total cancer OR= 1.5, 0.74-2.7. A statistically significant increase in CNS cancers (5 cancers) was found for boys (but 3 cancers were in 1 boy).

Abbreviations: **OR=** odds ratio, CNS= central nervous system, **ENM=** EMF not measured

† Odds ratios were not included in Wertheimer & Leeper (1979) but they can be calculated from data in their paper.

* statistically significant

Table 3.1. A summary of studies of cancer and children living near power lines. (Continued)

Study/Location	Subjects/Exposure	Selected Results
Gutierriz et al. (1993), Mexico	81 child leukemia cases and 77 controls were compared by distance of homes to electric power facilities. ENM.	For living within 200 m of transmission lines leukemia OR= 1.57, 0.52-4.81; within 200 m of substations OR= 1.62, 0.32-8.94; within 20 m of distribution lines OR= 2.12, 0.79-5.85. For "near" distribution lines OR= 2.63*, 1.26-5.36.
Lin & Lee (1994), Taiwan	67 child leukemia cases were studied in relation to areas with elementary schools crossed by power lines. ENM.	Child leukemia risk elevated in districts with at least 1 elementary school crossed by a power line, SIR= 1.49*, 1 .1 6-l .91. Design of the study did not include determining whether schools attended by subjects had power lines.
Preston-Martin et al. (1996b), U.S., Los Angeles	298 child brain cancers, and 298 controls compared by power-line types near home and spot and 24 hr magnetic-field measurements.	No significant risks for high-current overhead power lines. Risk elevated significantly for underground lines, but this was considered an artifact. No significant risks for measured fields, but risks were elevated for the highest fields.
Gurney et al. (1996a), U.S., WA	133 child brain cancer cases and 270 controls compared by power line types near home. ENM.	No associations were found between child brain cancer and high-current power lines near the home. Comparing high- vs. low-current lines, OR= 0.9, 0.5-l .5.
Michaelis et al. (1996), Germany	244 child cancer cases and 328 controls compared by 24-hr magnetic-field measurements in rooms most used by child.	ORs for children with median 24-hr home exposure >2 mG: leukemia 3.24, 0.90-l 1.64 (4 cases); CNS tumors 2.09, 0.29-15.22; total cancer 1.99, 0.59-6.76.
Coghill et al,. (1996), U.K.	50-Hz electric and magnetic fields measured for 12 & 24 hr in bedrooms of 56 child leukemia cases and 56 controls.	Leukemia ORs for electric fields: >20 V/m= 4.69*, 1 .17-27.78; 1 O-l 9 V/m= 2.40, 0.79-8.09; 5-9 V/m= 1.49, 0.47-5.10; total cases >10 V/m cut off point= 2.86*, 1 .16-8.00. No statistically significant ORs for magnetic fields.

Abbreviations: **OR=** odds ratio, CNS= central nervous system, **ENM=** EMF not measured, **SIR=** standardized incidence ratio, * statistically significant

The study by Feychting and Ahlbom (1993) of all children in Sweden who lived on property within 300 m (984 ft) of transmission lines has received considerable attention. Among the findings was a fourfold increase in leukemia for children living in dwellings where the calculated magnetic field near the time of cancer diagnosis was > 0.3 µT (3 mG). There was also evidence of dose-response for magnetic fields and cancer.

The ORAU Panel (1993) concluded that the study by Feychting and Ahlbom (1993) was not compelling because of inconsistencies with an earlier Swedish study by Tomenius (1986). and because no significant associations with cancer were found when present-day magnetic field measurements were analyzed. Further analyses by Feychting et al. (1995a) of their Swedish study showed that the time interval between diagnosis and contemporary magnetic-field measurements could explain the different results when using historical and contemporary measurements .

To increase sample size, Feychting et al. (199Sb) pooled data from the transmission line study in Sweden (Feychting and Ahlbom 1993) with those in the study in Denmark (Olsen et al. 1993). The pooled results for child leukemia showed a more than twofold increase in risk associated with the highest cumulative lifetime magnetic field exposures (RR= 2.5, I. l-5.4, 9 cases>. For exposure to fields of 0.5 µT (5 mG) and above near the time of leukemia diagnosis, risk was elevated fivefold (OR= 5.1,2.1-12.6, 8 cases). Risks for lymphoma and for central nervous system tumors were not significantly elevated in the pooled analysis.

One frequent criticism of the early studies is that measurements of EMF in study homes were not made. Instead, exposures were estimated bv characterizing the types of power lines near subjects' homes. Wertheimer and Leeper (1979) devised a detailed scheme to classify homes in Denver based on distance from power lines, and on the size and number of conductors on power lines within about 40 m (130 ft) of homes. This scheme was based on assumed different levels of current carried by power lines, used as a surrogate for magnetic-field exposure. Later studies modified the scheme, but the fundamental approach remained the same (see Fig. 2.8). Other studies have since shown that people living in high-current homes do tend to have higher magnetic fields than people in low-current homes. However, there is considerable overlap among categories (see Fig. 2.8).

Child cancer studies that included magnetic-field measurements generally found smaller risks associated with the fields, compared to risks associated with power line classifications (Miller et al. 1995). However. in reanalyses of three studies. stronger and statistically significant odds ratios were found when higher magnetic-field cutoff points of about 0.3-0.5 μT (3-5 mG) were used (Wartenberg and Savitz 1993, Feychting et al. 1995). Some researchers conclude that factors other than magnetic fields are more likely causes of the observed associations between power lines and child cancer (discussed below). Others suggest that power-line classifications or calculated magnetic fields near the time of cancer diagnosis, may be more meaningful estimates of past exposure than present day magnetic field measurements (Feychting and Ahlbom 1995a, Savitz 1995).

Differences in residential mobility and in the age of residences between cases and controls have been suggested as reasons to believe that the cancer-magnetic field association in the Denver study, by Savitz et al. (1988) is false (Jones et al. 1993, Jones 1993, Jones et al. 1994). In the Denver study cases and controls differed on the basis of residential mobility (controls were more residentially stable). Jones et al. (1993) found that in Columbus, Ohio, residents near high-current-carrying power lines moved more often than those near low-current lines.

This type of selection bias could produce an elevated OR associated with high current lines. Savitz and Kaune (1993b) and Wertheimer and Leeper (1994a) acknowledged that studies should consider these factors, but they believed that the factors were unlikely to have substantially biased the Denver study. In a child brain cancer study in Los Angeles, no associations were found between residential mobility and case-control status, or with power-line types (Preston-Martin et al. 1996b).

Poole and Trichopoulos (1991) suggested that the Denver study by Savitz et al. (1988) may have been biased in a way that resulted in fewer subjects of low socioeconomic status participating as controls. This could be a problem if such subjects were more likely to live near high-current lines, and if there was an association between socioeconomic status and child cancer. Gurney et al. (1995) investigated this issue in a hypothetical case-control study in Western Washington state. They found that, at least for the area studied, low participation of subjects of low socioeconomic status as controls is not likely to account for elevated risks of the size reported in the Denver study.

Sahl (1994) hypothesized that residential proximity to power facilities is a surrogate for viral contacts that may be a risk factor for child leukemia. This could be important if possible risk factors for viral contact were also associated with proximity to power facilities. Possibilities include residential mobility, being first born, or use of child care facilities. Savitz and Ahlbom (1994) suggested that it is extremely unlikely that viral associations, if present, are strong enough to explain the reported associations between power lines and cancer.

From the data collected in the Denver power line study by Savitz et al. (1988), statistically significant associations were also found between child leukemia and hamburger consumption (Sarasua and Savitz 1994), insect pest strips (Leiss and Savitz 1995), and traffic density (Savitz and Feingold 1989). Other studies in Denver identified several factors that are associated with power-line types based on current-carrying contigurations (Wachtel et al. 1995). Of these, only renter status was also significantly associated with child cancer (Wachtel et al. 1996). Although these studies have not eliminated magnetic fields as possible factors, they do point out the difficulty in determining the true causal factors that may be involved.

Publication of the child brain cancer studies by Preston-Martin et al. (1996b), and by Gurney et al. (1996a) was accompanied by invited commentary and responses from the authors. Preston-Martin et al. (1996b) found no statistically significant elevated risks for either power-line types or measured magnetic fields. However, for the highest in-home magnetic fields, > 0.3 μT (3 mG), the authors said that their results were consistent with the hypothesis of elevated risk. Gurney et al. (1996a) found no associations between brain cancer and power-line types, and they did not measure magnetic fields. Neither study found significant risks associated with appliance use; both studies had low statistical power to detect risks smaller than 2.0.

In his commentary about these two studies, Poole (1996) suggested that magnetic-field exposures from power lines and appliances should somehow be combined. Preston-Martin et al. (1996~) agreed in principle with the need for consolidating exposures from multiple magnetic-field sources. They questioned whether the existing knowledge about magnetic-field dosimetry, allows for a meaningful consolidation at this time.

Poole also raised concerns about how control subjects were selected including the use of random-digit dialing. Gurney et al. (1996b) questioned whether control selection introduced significant biases in their study, but they acknowledged the need for careful consideration of this issue in case-control studies of EMF. Poole added that the lack of magnetic-field measurements in the study by Gurney et al. (1996a) makes it difficult to interpret the null results of that study.

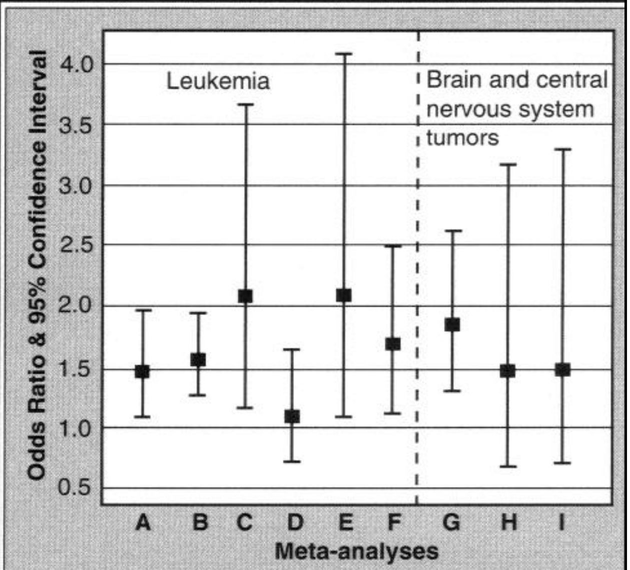
Only two of the studies in Table 3.1 included measurements of electric fields. Savitz et al. (1988) found no significant associations between child cancer and spot measurements of electric fields (> 12 V/m) in the center of rooms. The researchers suggested that possible effects of long-term electric field exposure could not be addressed by their study. Coghill et al. (1996) found a more than fourfold increase in risk of acute lymphoid leukemia with electric fields (I 20 V/m) measured for 12 hours at night near the pillow on the child's bed. This, and the risk for field exposures of 10 V/m and above (OR= 2.86), were statistically significant. The mean electric field measured in homes of leukemia cases was also significantly greater than in homes of controls (13.9 vs. 7.3 V/m, respectively). None of the Nordic child-cancer studies that looked at high voltage transmission lines included measurements of electric fields.

Henshaw et al. (1996) presented data suggesting that 50-Hz electric fields in homes can concentrate radon progeny in such a way that human exposure to ionizing radiation could be increased. Radon, instead of EMF, could presumably be an explanation for increased cancer risks reported in some residential power line studies. In one of their tests an electric field of 5 kV/m was used. Structures typically shield much of the electric field from outside power lines, and electric fields of this strength would seldom, if ever, be found inside homes.

The research on childhood cancer and power lines has prompted considerable interest and there have been a number of attempts to synthesize this body of research. One basic way of summarizing the studies is to identify those studies that reported statistically significant results. As shown in Table 3.1, 16 power-line studies examined child leukemia; six of these found at least one statistically significant association (OR range about 1.5 4.69). Of the 10 studies that included brain or CNS cancer, five found significant associations (OR range about 2.0-4.2). Half of the eight studies of total cancer reported significant associations (OR range about 1 .5-5.6). Most of the studies in Table 3.1 did report positive associations that were not statistically significant, in some cases possibly because of small sample sizes.

Another way to summarize data from separate studies is to combine the results (whether statistically significant or not) by means of a meta-analysis (Blair et al. 1995). This type of analysis has gained widespread use by epidemiologists in recent years; however, there is ongoing controversy over the use of this type of analysis (Greenland 1994, Olkin 1994).

Figure 3.6 shows results of some meta-analyses that have been conducted to combine results of studies of child cancer and power lines. For leukemia, statistically significant positive associations were found when studies estimated magnetic field exposure by methods other than by spot measurements. Three meta-analyses found positive associations between child brain or central nervous system tumors, but only one was statistically significant. An analysis by Poole and Ozonoff (1996) of the power line childhood cancer studies found evidence of an increasing dose-response (i.e., increasing risk with increasing magnetic field exposure). The trend was stronger for leukemia than for brain cancer.



A = Washburn et al. (1994). Distance from power lines or power-line types (13 studies).
B = Miller et al. (1995). Power-line types (4 studies).
C = Miller et al. (1995). Distance to power lines (2 studies).
D = Miller et al. (1995). Spot magnetic-field measurements (4 studies).
E = Ahlbom et al. (1993). Calculated magnetic field (3 studies).
F = Meinert & Michaelis (1996). Power-line types (4 studies).
G = Washburn et al. (1994). Distance from power lines or power-line types (7 studies).
H = Ahlbom et al. (1993). Calculated magnetic field (3 studies).
I = Meinert & Michaelis (1996). Power-line types (3 studies).

Figure 3.6. Results of meta-analyses of studies of power lines and child cancer. Data are for the most common types of child cancer; leukemia, and brain and central nervous system tumors

The meta-analysis conducted by Washburn et al. (1994) summarized in Figure 3.6 was criticized in a review by Feychting and Ahlbom (1995b). The review focused on problems of attempting to combine results of diverse studies which were not originally designed to be combined. In response, Washburn et al. (1995) acknowledged the limitations of the meta-analysis approach, but they see no acceptable alternative to understanding a body of studies on the same topic.

None of the authors of the analyses summarized in Figure 3.6 concluded that the combined studies have established that EMF cause cancer in children. Wilson (1996) applied "Hill's criteria" (see page 2-12) for assessing causation to the child leukemia studies and concluded that all the criteria would have to be modified to find that magnetic fields are a hazard. He added that this is not proof that a hazard does not exist. Levallois

(1995) used these same criteria and concluded that magnetic fields cannot be dismissed as a possible causal factor for childhood leukemia. He suggested that considering interim preventative measures while further research is conducted might be prudent.

Adults

As with child cancer, Wertheimer and Leeper (1982. 1987) were the first to publish a study on cancer in adults living near power lines (Table 3.2). Their study of adults was also done in Denver, and they used a five-level version of their previous two-level method to estimate magnetic-field exposure bv classifying homes based on prox-

Table 3.2. A summary of studies of cancer and adults living near power lines.

Study/Location	Subjects/Exposure	Selected Results
Wertheimer and Leeper (1982, 1987), U.S., co	1179 cancer cases and 1179 controls. Exposure by power-line types near homes. Magnetic fields measured, but not for exposure.	Statistically significant elevated "C-ratios" were found for high-current lines and for cancer of the nervous system, uterus, breast, and for lymphoma, and total cancer For total cancer: OR= 1.28*, I .08-1 .52.
Wrensch (1983), U.S. CA	102 brain cancer deaths (1977-80) in white men and proximity of residence to electric power facilities or power plants. ENM.	ORs for brain cancer calculated from data in paper: within 1 block of substation 2.55, 0.72-8.99 (7 cases); high-tension lines within 1 block 1.33, 0.61-2.91 (14 cases); power plant within 1.6 km 5.70, 0.63-51.96 (4 cases).
McDowall (1986), U.K.	213 cancer deaths for people within 50 m of a substation, or within 30 m of a power line were compared to regional rates. ENM.	Statistically significant excess mortality found only for lung cancer. For men and women within 14 m of a power facility, lung cancer SMR= 215*, 1 18-361. For women within 50 m of a substation, or 30 m of a line, SMR= 175*, 107-271.
Severson et al. (1988), U.S., WA	114 leukemia cases and 133 controls. Exposure was by power-line types, and by spot and 24-hr magnetic-field measurements.	There were no statistically significant associations between acute nonlymphocytic leukemia and any exposure type. For very high-current lines, OR= 0.79, 0.22-2.89. For > 2 mG, OR= 1.50, 0.48-4.69.
Coleman et al. (1989), U.K.	190 leukemia cases and 570 controls. Exposure was by distance of residences from substations. ENM.	For residences within 50 m of an electric power substation, leukemia OR= 0.9, 0.5-l .7.
Youngson et al. (1991), U.K.	3146 cases of leukemia and lymphoma and 3146 controls. Exposure by distance to lines and calculated magnetic fields. ENM.	Elevated ORs were found but not statistically significant. For residences within 75 m of an overhead power line, OR= 1.29, 0.99-l .68 (99 cases). For residences in magnetic fields > 3 mG, OR= 3.00, 0.61-l 4.86 (6 cases).
Eriksson & Karlsson (1992), Sweden	275 multiple myeloma patients and 275 controls. Exposure by distance of residences from power lines. ENM.	For subjects who lived within 1 km of a power line, RR= 0.94, 0.64-l .40 (40 cases). Information was not collected on risks for persons living at various distances from lines within 1 km.
Schreiber et al. (1993),, The Netherlands	Mortality among 1552 people who lived within 100 m of a 150-kV line or a substation was compared to the general population.	No statistically significant risks were found. For all cancer, SMR= 85, 63-l 14 (46 cases); female breast cancer, SMR= 115, 63-l 93 (14 cases); Hodgkin's disease, SMR= 496, 53-1679 (2 cases); trachea & lung SMR= 114, 65-185.
Shore et al. (1993), Canada and U.S.	610 leukemia patients and 618 controls were asked whether they lived near high-voltage lines in the previous 2-yr. ENM.	No elevated leukemia risk was found for people who lived within sight of transmission lines; OR= 1 .O, 0.7-l .5 (66 cases). For people who lived near electric light and power plants, OR= 7.9, 0.9-375.
Feychting & Ahlbom (1994), Sweden	548 cancer cases and matched controls. Exposure by line distance, and by measured and calculated magnetic fields.	For cumulative exposure to > 2 mG 15 yr before diagnosis: leukemia, RR= 1.5, 1 .O-2.4 (29 cases); acute myeloid leukemia, RR= 2.3. 1 .O-4.6 (9 cases); CNS tumors RR= 0.7, 0.3-l .3.
Verkasalo et al. (1996), Finland	8145 cancer cases in 383,700 adults living within 500 m of 1 10-400 kV iines in 50-Hz magnetic fields 20.01 µT (0.1 mG).	For total cancer SIR= 0.98, 0.96-l .OO. Melanoma risk increased significantly at a cutoff point of 0.40 µT-yr, but not at higher points. Risks for female breast cancer, CNS cancer, and leukemia did not differ by exposure level.

Abbreviations: **OR=** odds ratio, CNS= central nervous system, **ENM=** EMF not measured, **SMR=** standardized mortality ratio, **SIR=** standardized incidence ratio, * statistically significant imity to various types of power lines. Some magnetic-field measurements were made in and around some homes, but the data were not used in the cancer analyses.

The results of the case-control study by Wertheimer and Leeper (1982,1987) were presented as "C-ratios" instead of the more commonly used odds ratios. With some assumptions, the latter can be calculated from data in their paper. As in their child cancer study (Wertheimer and Leeper 1979) cancer risk was also elevated in adults living near high-current power lines (Table 3.2). Leukemia risk was not elevated except for the subgroup of persons over age 70. Wertheimer and Leeper (1982) cited several features of their data that they believed suggested that the associations that they observed may represent a causal link.

There have now been about 11 studies of cancer in adults living near power lines (Table 3.2). All but two of these (Wrensch 1983, Ericksson and Karlsson 1992) included leukemia. None of the leukemia findings was statistically significant. However, two studies found elevated risks for leukemia in adults near power lines that were on the borderline of statistical significance (Youngson et al. 1991, Feychting and Ahlbom 1994). In addition, Shore et al. (1993) reported about an eightfold increased risk of leukemia for adults living near electric light and power plants that was of borderline significance. Authors of that study pointed out that they could not distinguish between exposure to EMF and to pollutants produced by power plants-neither was measured in their study.

One study found statistically significant associations between lung cancer and proximity of residences to power lines and substations (McDowall 1986). The author of the study said interpretation of results is diffrcult because data were not available on smoking in the study population. Two other studies found no significant associations between lung cancer and power lines (Wertheimer and Leeper 1982, Schreiber et al. 1993).

Wertheimer and Leeper (1982,1987) found about a twofold elevated risk for nervous system cancer in people who lived near power lines that was statistically significant. Wrensch (1983) also reported that higher percentages of men who died from brain cancer had lived close to electric power facilities, compared to control men. Because of small numbers of exposed subjects, no statistical tests were done on these data (odds ratios and 95 percent confidence intervals calculated from data in the paper are shown in Table 3.2). Elevated risks for nervous system tumors in adults were not found in three other residential studies (Schreiber at al. 1993, Feychting and Ahlbom 1994, Verkasalo et al. 1996).

Of the four studies in Table 3.2 that looked at breast cancer, only Wertheimer and Leeper (1987) reported a statistically significant elevated risk (for women, C-ratio= 1.64, which is roughly similar to an odds ratio). Risks were higher for premenopausal breast cancer (C-ratio= 2.53). McDowall (1986) found no statistically significant elevated risk of breast cancer in women living in the vicinity of electrical transmission facilities (SMR= 106). No cases of male breast cancer were found in that study. Schreiber et al. (1993) also found no cases of male breast cancer in men living near transmission facilities. The elevated risk for women was not statistically significant (SMR= 115). (Several other studies have investigated breast cancer risk among electrical workers-see Table 3.6.)

Residential: Cancer Clusters

The above studies of cancer among people living near power lines were conducted mainly by using case-control or cohort studies. The cancer cases used in such studies usually come from some source of centralized records such as cancer registries. The studies attempt to determine whether cases and controls lived in locations that exposed them to some factor(s) that might have increased their risk of cancer. Sometimes, even before a formal study is done, the public or health agencies notice what appears to be unusually high numbers of cancers that occur as a "cluster" in some geographic area. These areas might be a city or a part of a city, a county, a state, or a region.

A cluster can be generally defined as an "Aggregation of relatively uncommon events or diseases in space and/or time in amounts that are believed or perceived to be greater than could be expected by chance" (Last 1995:30). Some studies of clusters have provided the initial data that led eventually to identification of rare or new diseases. Examples include toxic shock syndrome in women, angiosarcoma of the liver in workers exposed to vinyl chloride, Legionnaire's disease, and acquired immunodeficiency syndrome (Rothenberg et al. 1990, Rothman 1990). However, these same authors pointed out that most investigations of clusters are not helpful in identifying causes of disease. Bender et al. (1990) observed that cancer clusters occur continually in populations, often from chance, and so ". . . cancer clusters most often represent expectedly unexpected events."

Several situations have been reported that some persons believe are cancer clusters associated with exposure to EMF. Journalist Paul Brodeur (1993) believed that cancer clusters existed near a substation in Guilford, Connecticut (Meadow Street), in part of a County near a power plant near Dukeville, North Carolina, and in some schools near transmission lines in California.

Investigations of the Guilford case by the Connecticut Department of Health and the Connecticut Academy of Science and Engineering found no evidence for a recognizable cancer cluster related to the substation (Connecticut Academy of Science and Engineering 1992). The North Carolina Department of Health and Natural Resources found that brain cancer rates in the county and in the townships near the power plant were not elevated compared to national rates (Transmission/*Distribution Health & Safety Report* August 31, 1990). The California Department of Health Services found that the 13 cancers identified among staff at the Slater School were twice the expected rate (Neutra and Glazer 1993). However, the Department concluded that the cancers could have occurred by chance.

Public concerns in Omaha, Nebraska about a possible cancer cluster associated with exposure to EMF prompted an investigation by the Nebraska Department of Health (Larm 1995, *EMF Health & Safety Digest* Supplement November/December 1995). The Omaha Parents for the Prevention of Cancer believed that the findings of the Department's report confirmed their belief that the cancers were related to children's exposure to EMF. The report, however, concluded that because of the diversity of the cancer types, and their largely representative distribution, no cancer cluster existed.

Community concerns about EMF also developed on Long Island in New York in relation to high rates of breast cancer among women in that area (Schoenfeld et al. 1996). An epidemiologic study began in 1996 that will investigate the possible association between EMF and breast cancer on Long Island.

Residential: Appliances and Electrically Heated Beds

Several studies have investigated cancer in adults and children and use of electrically heated beds and electrical appliances (Table 3.3). None of these studies measured personal exposures to EMF from these devices; instead, use was assessed from questionnaires. Other studies have shown that magnetic fields close to electrical appliances can be strong although they decrease rapidly with distance (Gauger 1985). Motor-driven appliances also produce high frequency bursts in the low MHz range with high time-rates-of-change (dB/dt) (Wilson et al. 1994). Appliances such as shavers, hair dryers, massagers are used close to the head.

Older electric blankets can produce high magnetic fields close to the heating wire, which is also close to the user's body (Florig and Hoberg 199 1). Electric blankets made after 1990 were redesigned to produce much lower fields (EPA 1992a). Electrically heated water beds produce magnetic fields at the user's location that are less than half the strength of fields from electric blankets (Wertheimer and Leeper 1986, Bracken et al. 1995).

As shown in Table 3.3, there are 13 studies of electric blanket users and cancer, of which only two reported statistically significant associations. Of these, Savitz et al. (1990) found positive associations for child brain cancer, and Vena et al. (1994) found a negative association with premenopausal breast cancer. The latter finding, however, occurred only in the lowest electric-blanket-use exposure category. Six studies included users of electrically heated water beds; none found any statistically significant cancer risks (Wrensch 1983, Savitz et al. 1990, Ryan et al. 1992, McCredie et al. 1994, Preston-Martin et al. 1996a, 1996b).

Preston-Martin et al. (1996b) reported that, in Los Angeles, the risk of child brain cancer was increased twofold for mothers' use of electrically heated water beds; the risk was on the borderline of statistical significance. Children's use of water beds was also associated with an elevated brain cancer risk, but not significantly so (OR= 2.0,0.6-6.8). Combining data from California and Western Washington, no significant brain tumor risks for use of electric blankets or heated water beds were found (Preston-Martin et al. 1996a).

The two studies of breast cancer and electric blanket use by Vena et al. (1991, 1994) prompted Stevens (1995) to comment that the two analyses should be combined because they are for the same study population. Combining the data would increase the statistical power of the study. In response, Vena et al. (1995a) reported on combined results which did produce statistically significant associations. However, the strength of the associations was not consistent with increasing exposure estimates. Vena et al. (1995a) emphasized that they believe that it is not appropriate to combine data on pre- and postmenopausal breast cancer, because they are different diseases.

Wertheimer and Leeper (1995) reanalyzed results of the two studies by Vena et al. (1991, 1994) using as the referent group, persons who used electric blankets only to warm the bed. Their reanalysis found statistically significant two- to threefold increases in breast cancer risks for women who used electric blankets during the night. They also combined results of the two studies and found statistically significant results. Vena et al. (1995b) responded that they believed neither reanalysis was appropriate.

Table 3.3. A summary of studies of cancer and the use of electrically heated beds and appliances.

Study/Location	Subjects/Exposure	Selected Results
Wrensch (1983), U.S. CA	102 brain cancer deaths (1977-80) in white men and use of electrically heated beds. ENM.	ORs for brain cancer calculated from data in paper: electric blanket OR= 0.86, 0.49-I .51(44 cases); water bed OR=1 .10, 0.44-2.78 (9 cases); radiant heat OR= 0.64, 0.23-I .75.
Preston-Martin et al. (1988), U.S., Los Angeles	224 adult leukemias (2 types) and matched controls, and use of electric blankets. ENM.	Adult leukemia was not associated with use of electric blankets. For acute myeloid leukemia, OR= 0.9, 0.5-I .6; for chronic myeloid leukemia OR= 0.8, 0.4-I .6.
Severson et al. (1988), U.S., WA	114 adult leukemias (1 type) and 113 controls, and use of electric blankets. ENM.	Borderline risk of adult acute nonlymphocytic leukemia for 1 income group. For family income < $15,000, OR= 2.40, 0.99-5.84; for family income > $15,000, OR= 1 .01, 0.53-I .94.
Verreault et al. (1990) U.S., WA	214 men with testicular cancer and 658 controls, and use of electric blankets. ENM.	Testicular cancer was not associated with electric blanket use. For electric blanket use in previous 10 yr, RR= 1 .0, 0.7-1.4; for cumulative use I-24 months, OR= 0.9, 0.5-I .3: for cumulative use 25-125 months, OR=I.2, 0.7-I .9.
Savitz et al. (1990), U.S., Denver	252 cases of child cancer, 222 controls, and use of electrical appliances and heated beds by mothers and children. ENM.	Statistically significant associations for brain cancer and electric blanket use: for prenatal use, OR=2.5*, 1 .1 -5.5; for use in first trimester, OR= 4.0*, 1.6-9.9. No significant associations for use of clocks, hair dryers, or water beds.
London et al. (1991) U.S., Los Angeles	232 cases of child leukemia and 232 controls, and use of electrical appliances and electric blankets. ENM.	Statistically significant associations for leukemia were found for use of: black-and-white TV, OR= 1.49*, 1 .01-2.33; and hair dryer, OR= 2.82*, 1.42-6.32. For child's use of electric blanket, OR= 7.00, 0.86-I 21.8.
Vena et al. (1991), U.S., New York	382 cases of postmenopausal breast cancer, and 439 controls and use of electric blankets. ENM.	For use of electric blanket any time in the previous 10 yr, breast cancer OR=1 .OO. For use continuously through the night, OR=I.46, 0.96-2.20. For highest use group and for daily use through the night for 10 yr, OR=I.36, 0.77-2.40.
Ryan et al. (1992) Australia	170 cases of brain cancer, 417 controls, use of electric blankets, and heated water beds. ENM.	Electric blankets: glioma, OR= 1.48, 0.83-2.63; meningioma, OR=0.86, 0.39-I .88. Heated water beds: glioma, OR= 0.67, 0.18-2.45; meningoma, OR= 1.27, 0.25-6.42.
McCredie et al. (1994) Australia	82 cases of child brain tumor and 164 controls, and mother's use of electric blankets and heated waterbeds. ENM.	No associations were found between child brain cancer and mother's use of electric blankets, or heated water beds. For regular electric blanket use, OR= 0.4, 0.2-I .2. For regular water bed use, OR= 0.2, O-I .5.
Vena et al. (1994), U.S., New York	290 cases of premenopausal breast cancer, and 289 controls, and use of electric blankets. ENM.	One association was statistically significant, and it was negative. Blanket use: to warm bed only, OR=0.43*, 0.21-0.90; sometimes to warm, sometimes all night, OR= 1.39, 0.72-2.69; continuously all night, OR=I.43,0.94-2.17.
Lovely et al. (1994), U.S., WA	114 cases of adult leukemia, and 133 controls, and use of personal electrical appliances. Magnetic fields measured for a sample.	Massage units were positively associated with leukemia, and use of hair dryers was negatively associated. Use: any appliance, OR=0.71, 0.41-I .24; massage units, OR=3.00*, 1.43-6.32; hair dryers, OR= 0.38*, 0.22-0.66.
Preston-Martin et al. (1996b), U.S., Los Angeles	298 child brain cancers and 298 controls, and mother's and child's use of electrical appliances and electrically heated beds. ENM.	Only one child brain cancer risk was of borderline statistical significance; mother's use of electrically heated water bed OR= 2.1. Child's use of: water bed OR= 2.0; electric blanket OR= 1.2; ham radio OR= 2.1; hair dryer OR= 1.2.
Gurney et al. (1996a), U.S., WA	133 child cancer cases and 270 controls, and use of electric appliances and heated beds, and home electric heat.	No statistically significant brain cancer risks were found. ORs for child/mother use: electric blanket 0.5/0.9, water bed 0.8/0.7; computer 0.9/0.8; bedside digital clock 1.8/1 .0. Child: portable B/W TV 1.6; color TV 1.3; electric heat 0.6.
Preston-Martin et al. (1996a), U.S.	538 child brain tumors, 795 controls, use of electric blankets and heated water beds. ENM.	No statistically significant brain cancer risks were found. Electric blanket use; in utero OR= 0.9, child OR= 1 .0. Water bed use; in *utero* OR= 0.9, child OR=I.2.

Abbreviations: **OR=** odds ratio, **RR=** rate ratio, **ENM=** EMF not measured,
* statistically significant (confidence interval is not always shown because of space limitations)

Of the three studies that looked at the use of electrical appliances, London et al. (1991) found statistically significant positive associations for child leukemia and use of black and white TV and hair dryers. In the adult leukemia study by Lovely et al. (1994) there was a statistically significant negative association for use of hair dryers, and a significant positive association for use of massage units. There was also a marginally significant 2.4-fold increase in leukemia risk for the highest category of daily use of electric shavers. Sussman and Kheifets (1996) suggested that this finding was probably not true because it was most likely influenced by bias from using proxies to obtain appliance use data for cases but not for controls. Savitz et al. (1990) found no statistically significant associations between child cancer and the use of hair dryers or bedside clocks.

Taken together, the studies summarized in Table 3.3 provide little consistent evidence for any links between cancer in adults or children, and the use of appliances or heated beds.

Occupational Cancer: Background

In their paper on cancer in children living near power lines, Wertheimer and Leeper (1979) briefly reviewed an earlier report on mortality and occupation by Guralnick (1963). From data in the latter report, Wertheimer and Leeper (1979) found that as a group, men in six occupations with assumed frequent exposure to AC magnetic fields had a small (15 percent), but statistically significant, excess mortality from cancer. This may have been the first published report to point out a possible link between work in electrical occupations and cancer.

The report by Guralnick (1963) was later reviewed in more detail by Roth (1985) who found that, among six electrical occupations, three had statistically significant increased cancer rates (stationary engineers, motormen, and electricians), while power-station operators had a significant deficit in cancer mortality. Wertheimer and Leeper's (1979) brief mention of occupational magnetic-field exposure and cancer did not generate much interest in this issue. Interest that eventually developed can largely be traced to publication of a paper 3 years later by Milham (1982): it reported associations between electrical work and leukemia.

Occupational: Leukemia

Milham (1982, 1983) conducted an analysis of a large data set consisting of 438,000 deaths of men in Washington state from 1950-79. From death certificates, information was obtained on causes of death and occupation, and Proportional Mortality Ratios (PMRs) were calculated. For 11 occupations with presumed exposure to electric and magnetic fields, the combined PMR for all leukemias was 137; for acute leukemia it was 163. Both PMRs were statistically significant. Four of the occupations also had statistically significant elevated PMRs (electricians, TV/radio repair, power station operators, and aluminum workers). When the analysis was updated to include 3 more years of data, the results were essentially unchanged (Milham 1985).

Milham's work prompted several other researchers to conduct similar studies (Table 3.4). PMR studies can be conducted relatively quickly, and several more studies were published. Like Milham (1982) many of these were published as brief letters to the editor in scientific journals. Savitz and Calle (1987) combined the results of 11 studies of leukemia among electrical occupations such as those identified by Milham (1982). For electrical occupations combined, their summary relative risks for 11 studies were: 1.2 (1.1-1.3) for total leukemias, 1.4 (1.2-1.6) for acute leukemias, and 1.5 (1.2-1.8) for acute myelogenous (myeloid) leukemia.

Figure 3.7 shows the summary relative risks from 11 studies for acute leukemias for each of 10 electrical occupations as calculated by Savitz and Calle (1987).

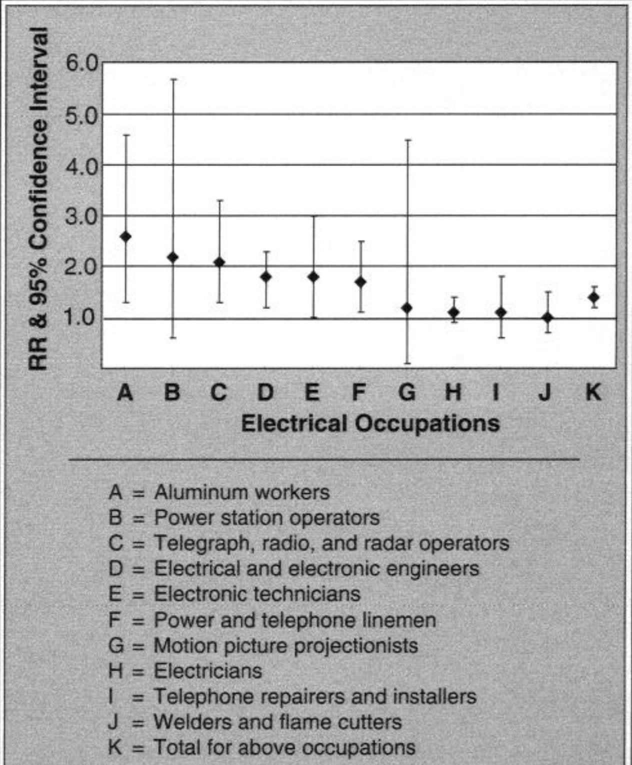


Figure 3.7. Combined relative risks for 11 studies of acute leukemia and electrical occupations with assumed exposure to EMF.
Source: Savitz and Calle (1987).

Table 3.4. A summary of studies of leukemia in workers exposed to EMF.

Study/Location	Subjects/Exposure (men unless noted otherwise)	Selected Leukemia Results (for all leukemias unless noted otherwise)
Guralnick (1963), Wertheimer & Leeper (1979),U.S.	Mortality for US. men who died in 1950. Job titles from death certificates.	SMRs for: electrical workers 113, electricians 107, linemen/service men 143.
Houten et al. (1977), U.S.	6434 male cancer cases, non-cancer patient controls. Lifetime job histories.	RRs for: electricians 0.58, linemen/service men 0.69, welders 0.41.
Puntoni et al. (1979), Italy	Mortality in >2000 shipyard workers compared to 2 types of controls.	RR for lymphoma/leukemia in electrical welders 5.56 (1 case); no cases for electricians.
Peterson & Milham (1980), U.S., CA	Mortality patterns of 200,000 men by occupation.	For electrical occupations RR= 0.9. (Cited in Savitz and Calle 1987.)
Wiklund et al. (1981), Sweden	Leukemia cases among telephone operators compared to population.	Observed cases (12) / expected (11.7) = 1.03.
Milham (1982, 1985), U.S., WA	146 leukemia deaths among electrical workers (1950-l 982).	PMRs for electrical workers: 136*, AL 162*. LL 126, ML 126.
Wright et al. (1982), U.S., CA	35 leukemia deaths in electrical workers compared to other jobs.	PIRs for electrical workers: 128.6, AL 172.6*, AML 207.1*; for power linemen, AML 816.6*.
Howe & Lindsay (1983), Canada	10% sample of mortality among Canadian labor force (1965-73).	No significant leukemia risks for electrical workers. Data not included.
Coleman et al. (1983), U.K.	113 ieukemias for electrical workers compared to other occupations.	PRRs for electrical workers: I 17*; ALL 146; CLL, 129; AML 123; CML 91.
McDowall (1983), U.K.	Mortality study (98) and a case (36)-control study for electrical workers.	PMRs for electrical workers: 98, LL= 100, ALL= 104, ML=107, AML= 104; RR for AML= 2.3*.
Dubrow & Wegman (1984), U.S., MA	Cancer mortality patterns for white men by occupation (1971-73).	No significant leukemia risks for electrical workers. Data not included.
Morton & Marjanovic (1984), U.S., OR	Leukemia mortality (1678) by occupation in a metropolitan area.	Electricians and welders did not have statistically significant elevated leukemia rates.
Calle & Savitz (1985), U.S., WI	81 leukemia deaths (1963-78) for electrical workers.	PMRs for electrical workers: 103, AL 113.
Gilman et al. (1985), U.S.	40 leukemia deaths among coal miners.	ORs for >25 yr underground mining: 2.53*, AL 2.85, CL 8.22*, AML 3.8.
Olin et al. (1985), Sweden	2 leukemia deaths for 1254 electrical engineers from 1930-79.	Compared to the general population, no significant leukemia risks, SMR= 90.
Blair et al. (1985), U.S.	14 leukemia deaths for electricians and electrical engineers (1954-l 970).	SMRs for: electricians 75, for electrical engineers 101.
Stern et al. (1986), U.S., NH	53 leukemia deaths and 212 controls among shipyard workers (1952-l 977).	ORs for electricians: 3.00*, ML 2.33, LL 6.00"; welders 2.25, ML 3.83"; electrical shop 2.57".
Flodin et al. (1986), Sweden	59 AML cases (1977-82) from 5 hospitals and 354 referents.	For 8 AML cases for electrical workers, LRR= 3.8*.
Tornquvist et al. (1986), Sweden	26 leukemias (1961-79) in 10,061 linemen and power-station operators.	Leukemias: linemen SMR=130 (10 cases), power-station operators SMR=l00 (16 cases).
Lin (1987), Taiwan	17 leukemia/lymphoma deaths (1971-85) in electric power utility employees.	Observed (17) / expected in the general population (8.48) = 2.00*.

Abbreviations: **AL=** acute leukemia, **ALL=** acute lymphoid leukemia, **AML=** acute myeloid leukemia, **ANLL=** acute nonlymphoid leukemia, **CLL=** chronic lymphoid leukemia, **CML=** chronic myeloid leukemia, CNS= central nervous system, **LL=** lymphoid leukemia, **LRR=** logistic rate ratio, **ML=** myeloid leukemia, **OR=** odds ratio, **PIR=** proportional incidence ratio, **PMR=** proportional mortality ratio, **PRR=** proportional registration ratio, **RR=** relative risk, **SIR=** standardized incidence ratio, **SMR=** standardized mortality ratio

* statistically significant (confidence intervals are not given because of space limitations)

Table 3.4. A summary of studies of leukemia in workers exposed to EMF. (Continued)

Study/Location	Subjects/Exposure (men unless noted otherwise)	Selected Leukemia Results (for all leukemias unless noted otherwise)
Pearce (1988), New Zealand	18 leukemia cases for electrical workers (1979-83).	ORs for: electrical workers 1.70, radio/TV repair 8.17*, electricians 4.75*.
Cartwright et al. (1988) U.K.	13 cases of AML among electrical workers (1976-86).	AML for electrical workers RR= 2.5*.
Linet et al. (1988), Sweden	125 leukemia cases for electrical workers (1961-79).	SIRS for electrical workers: ALL 100, CLL 120, ANLL 110, CML 110; linemen CLL 190".
Tola et al. (1988), Finland	3 leukemia cases (1953-81) welders at shipyards and machine shops.	SIRS for welders: at shipyards, 91; at machine shops, 125.
Preston-Martin & Peters (1988), U.S., CA	130 CML cases (22 welders) (1979-85) and 130 controls.	For CML among welders: crude OR= 19*, adjusted OR= 25.4*
Brownson & Reif (1988), U.S., MO	475 cancer cases and 1425 controls compared by occupation.	No evidence of elevated leukemia risk for electrical workers (no data shown).
Pearce et al. (1989), New Zealand	21 leukemias (1980-84) in electrical jobs, controls other cancers.	ORs for: electrical workers 1.62*, electrical engineers 4.74*; CLL for 20-64 yr old 3.36*.
Guberan et al. (1989), Switzerland	Leukemia deaths and cases (1970-84) for electricians and painters.	For 1948 electricians: SMR= 143 (2 deaths), SIR= 125 (2 cases).
Matanoski et al. (1989), U.S., New York.	Cancer among 50,582 telephone linemen (1976-80).	SIRS for: cable splicers 700* (3 cases), central office technicians 107 (2 cases).
Koifman et al. (1989), Brazil	4 leukemia cases for electric power workers compared to Rio's population.	Workers with occasional EMF exposure SMR= 59. No leukemias for higher exposure jobs.
Forastiere et al.(I989), Italy	Cancer mortality among 406 workers at 2 power plants.	For all workers for lymphatic/hematopoietic cancers: observed (1) / expected (1.05) = 0.95.
Gallagher et al. (1990), Canada	59 leukemia deaths (1950-84) among 8 electrical worker groups.	No statistically significant PMRs were found; welders 103, electricians 96.
Loomis & Savitz (1990), U.S.	3400 leukemia deaths (1985-86) from 16 states by occupation.	ORs for electrical workers: 1 .O (76 cases), less than 65-yr-old 1.3 (38 cases).
Garland et al. (1990), U.S.	102 leukemia cases (1974-84) among active duty Navy personnel.	Only electrician's mate showed a borderline statistically significant risk, SIR= 250.
Juutilainen et al. (1990), Finland	Leukemia cases among all industrial workers (1971-80).	RRs for workers with possible EMF exposure: 1.42* (94 cases), AML 1.37 (34 cases).
Robinson et al. (1991), U.S.	183 leukemia deaths for 11 electrical occupations from 14 states.	All electrical workers PMRs: 119*, AML 114. Telegraph/telephone operators AML 499*.
Crane et al. (1991), U.S.	Occupational and environmental exposures for 60 cases and controls.	No associations found between electrical work and AML. No data presented in abstract.
Tornqvist et al. (1991), Sweden	534 leukemia cases for 35 electrical occupations (1961-79).	SMRs for: telegraph/telephone 2.1*, linemen CLL 2.8*, electrical engineers CLL 1.7*.
Spinelli et al. (1991), Canada	Leukemia mortality and incidence for 4213 aluminum plant workers.	For all workers: SMR 175 (7 cases), SIR 76 (3 cases).
Richardson et al. (1992), France	185 acute leukemia cases (1984-88) and 513 controls by occupation.	ORs for: all EMF exposure except arc welding AL 3.9*, EMF exposure AML 4.83*.
Tynes et al. (1992), Norway	107 leukemia cases among 37,945 electrical workers.	SIRS for: from 1960 census 1.08, workers active in 1970 14*, AL 1.50*, CL 1.49*, AML 1.50*.

Abbreviations: **AL=** acute leukemia, **ALL=** acute lymphoid leukemia, **ANLL=** acute nonlymphoid leukemia, **AML=** acute myeloid leukemia, **CL=** chronic leukemia, **CLL=** chronic lymphoid leukemia, **CML=** chronic myeloid leukemia, **MDS=** myelodysplastic syndromes, **O/E=** observed/expected, **OR=** odds ratio, **PMR=** proportional mortality ratio, **RR=** relative risk, **SIR=** standardized incidence ratio, **SMR=** standardized mortality ratio

* statistically significant (confidence intervals are not always given because of space limitations)

Table 3.4. A summary of studies of leukemia in workers exposed to EMF. (Continued)

Study/Location	Subjects/Exposure (for men unless noted otherwise)	Selected Leukemia Results (for all leukemias unless noted otherwise)
Sahl et al. (1993), U.S., CA	44 leukemia cases (1960-88) for male and female utility workers. PEM.	For electrical workers: internal cohort study RR= 1.09, case control study OR= 0.91.
Matanoski et al. (1993), U.S.	124 leukemia cases (197580) for telephone linemen. PEM.	For peak magnetic-field exposure above median IO-yr latent OR= 2.4 , 15yr latent OR= 6.6.
Floderus et al. (1993), Sweden	250 leukemia cases (1983-87) from half of Swedish population. PEM.	ORs for mean daily exposure > 2.9 mG, longest job 10 yr before diagnosis : 1.6*, CLL 3.0*.
Guenel et al. (1993), Denmark	Leukemia incidence among a cohort of 2.8 million people by occupation.	O/Es for continuous magnetic-field exposure: men 1.64* (39 cases), women 0.56 (2 cases).
Ciccone et al. (1993), Italy	86 cases of AML, CML, MDS (1989-90) and 246 controls by occupation.	ORs for magnetic-field exposure and AML CML MDS: men 1.6 (17 cases), women 0.8 (4 cases).
Theriault et al. (1994), Canada, France	140 leukemias (1970-89) at 2 utilities in Canada, and 1 in France. PEM.	ORs for > median magnetic field exposure: ANLL 2.41*(33 cases), AML 3.15* (26 cases).
Floderus et al. (1994), Sweden	Leukemia cases (1961-79) among electric railway (16.6 Hz) workers.	RRs for engine drivers and conductors: 1961-69, 1.3 (13 cases); 1970-79, 0.9 (18 cases).
Mele et al. (1994), Italy	Leukemia in electrical workers among 619 leukemia cases (1986-l 990).	ORs for electrical worker: AML 1.6, ALL 1 .1, CML 2.2.
Tynes et al. (1994a), Norway	52 cases of leukemia (1958-90) for railway workers & magnetic fields.	For magnetic-field exposure 19-36 G-yrs, OR= 1.07. Electric vs. nonelectric railways, OR=0.74.
London et al. (1994), U.S., CA	121 leukemia cases among electrical workers (1972-90). PEM.	ORs per 10 mG increase for ave. exposures: 1.2, CML 1.6* (for % time >25 mG, CML 2.2”).
Armstrong et al. (1994), Canada, France	95 leukemia cases among electric utility workers (1970-l 989). PEM.	ORs for above median exposure to pulsed magnetic fields: 0.69, CML 0.72, ALL 1.21.
Tynes et al. (1994b), Norway	Leukemias (1953-91) at 8 hydroelectric companies. PEM.	Cumulative magnetic-field exposure: 50-350 mG-yrs SIR= 74, >350 mG-yrs SIR= 104.
Linet et al. (1994), Sweden	1260 leukemia cases for Swedish women (1961-79) by occupation.	Electrical workers too few to analyze. Machine/ electronic SIRs: CLL 90, CML 50, ANLL 50.
Dosemeci & Blair (1994), U.S.	68 leukemia deaths (1984-89) for women in the telephone industry.	Telephone operators MOR= 0.6, no deaths for engineers & technicians, or mechanics/repair.
Savitz & Loomis (1995), U.S.	164 leukemias (1950-86) at 5 electric power utilities. PEM.	Exposed occupations > 20 yr employment, RR= 1 .OO, for electricians RR= 2.50* (6 cases).
Baris et al. (1996b), Canada	20 leukemias (1970-88) at an electric utility in Quebec. PEM.	Total cohort SMR= 105, above background magnetic-field exposure SMR=121, RR= 141.
Fear et al. (1996) U.K.	214 leukemias (1981-87) for male & female electrical workers.	Male electrical workers PRR= 123*, AML= 129*. Female electrical workers PRR= 143.
Miller et al. (1996), Canada	50 leukemia cases (1970-88) at an electric utility in Ontario. PEM.	Male electrical workers >345 V/m-yr, OR=4.45*, 1.01-19.7; >71 mG-yr, OR= 1.56, 0.47-5.14.
Tynes et al. (1996), Norway	2 leukemia cases among 2619 female radio & telegraph operators,	Female radio/telegraph operators SIR= 1 .1, 0.1-4.1.
Alfredsson et al. (1996), Sweden	20 leukemia cases among electric railway workers.	Lymphoid leukemia for male locomotive engineers and conductors SIR= 2.3”: 1.3-3.2.

Abbreviations: **AL=** acute leukemia, **ANLL=** acute nonlymphoid leukemia, **AML=** acute myeloid leukemia, **CL=** chronic leukemia, **CLL=** chronic lymphoid leukemia, **CML=** chronic myeloid leukemia, **MDS=** myelodysplastic syndromes, **MOR=** mortality odds ratio, **O/E=** observed/expected, **OR=** odds ratio, **PEM=** personal exposure measurements, **PMR=** proportional mortality ratio, **PRR=** proportional registration ratio, **RR=** relative risk, **SIR=** standardized incidence ratio, **SMR=** standardized mortality ratio

* statistically significant (confidence intervals are not always given because of space limitations)

As shown by the 9.5 percent confidence intervals, individual risks for four of the occupations were statistically significant. Savitz and Calle (1987) concluded that while the early studies of leukemia and electrical occupations showed modest elevated risks, the results were not sufficient to establish that EMF caused cancer. They added that there was a need for better characterization of exposures beyond simply using job titles.

The early electrical worker studies were also reviewed by Coleman and Beral(1988) and they reached conclusions similar to those of Savitz and Calle (1987). Both papers called for more studies with better measures of exposure to determine whether occupational exposure to EMF is causally linked to cancer.

Dozens of studies have now been done of leukemia and other cancers for electrical workers; the leukemia studies are briefly summarized in Table 3.4 and in Figure 3.8. At least 62 studies have looked at leukemia for one or more electrical occupations, and about 28 have reported at least one statistically significant elevated risk. Savitz and Loomis (1995) reported a significant decreased leukemia risk for electric utility workers as compared to the general population (SMR= 76,64-88).

Beginning in 1993, studies began to be published that included some measures of personal exposures of electrical workers to magnetic fields. About a half-dozen such studies are identified in Table 3.4 by the abbreviation, PEM (personal exposure measurements). Floderus et al. (1993) were among the first cancer studies to measure personal magnetic field exposures. A sample of workers from many occupations wore an EMDEX meter for one work day. The results were then applied to the jobs held longest during the 10 years before cancer diagnosis for subjects in the study, to provide at least a rank order of relative magnetic-field exposure. The study found that the risk of chronic lymphoid leukemia increased significantly with increasing magnetic field exposure in a dose-response pattern, For the highest magnetic-field exposure categories, risks were elevated three- to over fivefold depending on which other factors were controlled for. No significant associations were found for acute myeloid leukemia.

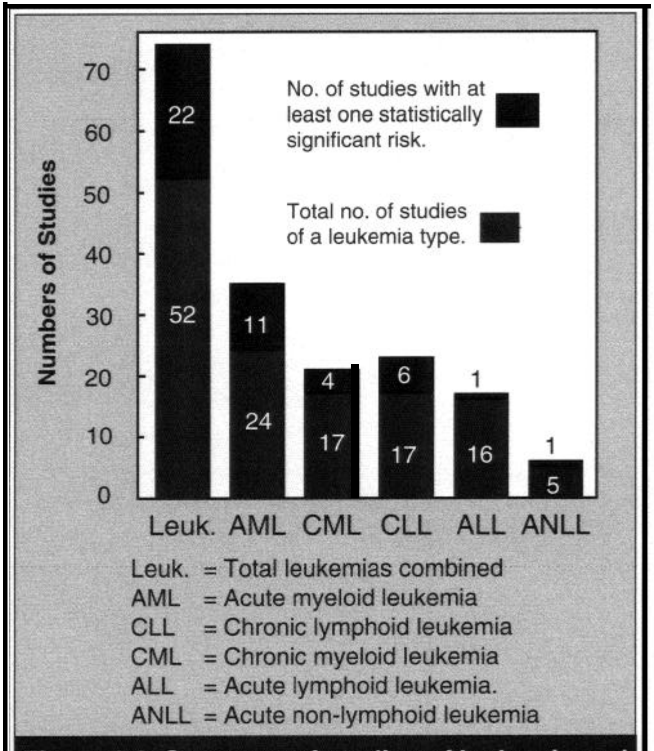


Figure 3.8. Summary of studies of leukemia and electrical workers in Table 3.4 by leukemia type. Graph shows numbers of studies that reported at least one statistically significant risk.

Sahl et al. (1993) also used EMDEX meters to measure magnetic field occupational exposures for workers at the Southern California Edison Company. No association was found between total leukemias and exposure for all occupations. Electricians had the highest measured magnetic field exposure-a mean of 3 .O 1 µT (30.1 mG)-and they also had the highest leukemia risk in the internal cohort analysis. However, the relative risk of 1.95 (0.64-6.00) was not statistically significant. Authors of the study pointed out that because of small numbers of deaths, their study provided little information on possible risks of less than 2.0. Also, because of small numbers, leukemia subtypes were not analyzed.

The large study by Theriault et al. (1994) included measurements of EMF exposures of a sample of 2066 workers using Positron meters. For magnetic-field exposures above the median, statistically significant elevated risks were found for acute leukemias (Table 3.4). Risks were also elevated for total leukemias (RR= 1.54) and for chronic lymphoid leukemia (RR= 1.48), but they were not statistically significant. There were no clear dose-response trends, and there was no consistency among results for the three utilities in the study. Further analysis of data from the utility in Quebec showed no significant leukemia risk compared to the general population (SMR= 105) (Baris et al. 1996b). Leukemia risk was significantly elevated more than fourfold for the Quebec workers with cumulative electric field exposure of > 345 V/m-years (Miller et al. 1996). This is one the few epidemiologic studies of electrical workers that included electric field exposures.

In the study involving five large utilities in the U.S., AMEX meters were used to obtain a sample of 2842 measurements of occupational magnetic-field exposures (Savitz and Loomis 1995). For all exposed occupations, there were no statistically significant associations between magnetic field exposure and total leukemias, or for two subtypes (acute myeloid, chronic lymphoid). When job titles were used in the analyses, risk for total leukemias was elevated significantly, only for men who had worked for 20 or more years as an electrician-RR= 2.50 (1.08-5.76).

Occupational: Brain Cancer

Studies that have looked at brain or central nervous system cancers are summarized in Table 3.5. Many of these are the same studies as those summarized in Table 3.4 for leukemia. As noted above, most of the studies used job categories as a surrogate for exposure to EMF.

Milham (1985) added to his 1982 leukemia study of electrical workers in Washington by including mortality from brain cancer. Based on data from death certificates, statistically significant elevated brain cancer risks were found for electrical workers as a group, and for electricians (Table 3.5). Demers et al. (1991) conducted a death-certificate-based case-control study of occupational brain cancer mortality in Washington for 1969-78. For communication and utilities industry occupations as a group, brain cancer risk was not elevated. For stationary engineers in Washington, risk was significantly elevated more than twofold for all brain cancers, for gliomas, and for astrocytic tumors. This occupational group includes workers who maintain power generating plants.

Lin et al. (1985) also used death certificates to conduct a case-control study of occupational mortality from brain cancer. They grouped electrical occupations by estimated magnetic-field exposure. Brain cancer risk was found to increase with increasing level of estimated exposure, with a significant twofold increase for the highest exposure group.

Speers et al. (1988) also studied brain cancer mortality by grouping electrical occupations by estimated EMF exposure. Their analyses showed a statistically significant linear trend for brain cancer risk with increasing magnetic field exposure. The highest category, probable exposure, was associated with a nearly fourfold elevated brain cancer risk.

For occupations in Los Angeles with assumed high exposure to EMF, brain cancer risk increased up to nearly twofold with increasing years of work (Preston-Martin et al. (1989). The dose-response trend was on the borderline of statistical significance. For astrocytomas, the risk increased more than fourfold; the trend for increasing risk with increasing years worked was statistically significant.

Koifman et al. (1989) attempted to assess brain cancer mortality by differing degrees of exposure to EMF. However, of the only five brain cancers in the study, none occurred in the top two exposure categories. Using two EMF exposure groups (possible and probable), Juutilianen et al. (1990) found a statistically significant linear trend in central nervous system cancer, but with only a 3 1 percent increase in the highest exposure group. Lewis and Buffler (199 1) found no dose-response trend for brain cancer risk when a three-level estimate of EMF exposure was used. The highest level, however, had a nonsignificant odds ratio of 1.78 (0.70-4.5 1).

Mack et al. (1991) used job titles to estimate exposure, but they also looked at increasing years worked in the occupations. For all brain cancers, there was no linear trend for years worked and risk. For astrocytoma, there was a statistically significant trend with a lo-fold elevated risk for more than lo-years work.

Sahl et al. (1993) measured personal magnetic-field exposures for utility workers; no associations were found between brain cancer and exposure. Two occupations among the highest exposed (electricians, plant operators) had elevated brain cancer risks in an internal cohort analysis, but they were not statistically significant.

No evidence was found of a dose-response for brain cancer risk and personal magnetic-field exposures in the study by Floderus et al. (1993). Risks were elevated significantly in the very highest exposure category. For exposure in which > 39 percent of the work time was over 0.20 μT (2 mG), and average daily exposure was > 0.41 μT (4.1 mG): brain tumors OR= 1.9 (1.2-3.1), astrocytoma OR= 2.1 (1.2-3.8).

In the large Canada-France study by Theriault et al. (1994), brain cancer risk was elevated 54 percent in workers with magnetic-field exposures above the median, and elevated twofold for workers in the highest exposure category (190th percentile). Neither risk was statistically significant, however. There was a statistically significant 12-fold elevated risk for astrocytoma, based on 5 cases. Authors of the study called the latter finding suspicious given similar results in the literature, but they said that it could have been an artifact.

Further analyses of data from the utility in Quebec showed that brain cancer risk was not elevated significantly compared to the general population; however some significant risks were found for certain exposures (Baris et al. 1996b, Table 3.5). There were no brain cancer deaths for the highest magnetic-field exposure category, and when the medium and low categories were combined the risk was elevated but not significantly (RR= 3.43, 0.82-14.38). Brain cancer risks were not significantly elevated for workers at the Ontario utility in the Canada-France study (Miller et al. 1996).

Table 3.5. A summary of studies of brain cancer in workers exposed to EMF.

Study/Location	Subjects/Exposure (men unless noted otherwise)	Selected Brain Cancer Results (for all types unless noted otherwise)
Guralnick (1963), Wertheimer & Leeper (1979) U.S.	US. mortality in 1950 by job titles from death certificates.	For electrical workers, SMR= 152*, for electricians, SMR= 217*.
Houten et al. (1977), U.S.	6434 cancer cases, non-cancer patient controls. Lifetime job histories.	No brain cancer cases for electrical workers.
Howe & Lindsay (1983), Canada	10% sample of mortality among Canadian labor force (1965-73).	No significant brain cancer risks for electrical workers. Data not included.
McMillian et al. (1983), U.K.	2 CNS cancer deaths (1955-75) among welders at shipyards.	CNS cancer deaths for welders: PMR= 100.
Wrensch (1983), U.S., CA	102 brain cancer deaths (1977-80) by occupation.	For assumed EMF exposure OR= 0.80, 0.38-1.71 (13 cases) (calculation from data in paper).
McMillan & Pethybridge (1983), U.K.	Mortality among 131 welders in a shipyard (1955-75).	2 deaths from CNS diseases (PMR= 100) but there were no deaths from brain tumors.
Dubrow & Wegman (1984), U.S., MA	Cancer mortality patterns for white men by occupation (1971-73).	No significant brain cancer risks for electrical workers. Data not included.
Vagero et al. (1985), Sweden	5 CNS cancers (1958-79) in telecommunications industry workers.	CNS cancers SMR= 100.
Milham (1985), US., WA	101 brain cancer deaths among electrical workers (I 950-I 982).	PMRs for: electrical workers 123*, electricians 155*, power operators 130, linemen 77.
Olin et al. (1985), Sweden	2 brain cancer deaths for 1254 electrical engineers from 1930-79.	For electrical engineers, SMR= 100.
Lin et al. (1985), U.S., MD	951 brain tumor deaths (1969-82) by estimated job EMF exposure.	Primary brain tumor ORs by EMF exposure: definite 2.15*, probable 1.95, possible 1.44".
Coggon et al. (1986), U.K.	97 brain cancer cases (1975-80) by occupation.	RRs for: electrical engineers 1.9 (3 cases), workers in gas/electricity/water 1.7 (3 cases).
Tornqvist et al. (1986), Sweden	30 CNS cancers (1961-79) in 10,061 linemen and power station operators.	CNS cancers: linemen SMR= 150 (13 cases), power station operators SMR= 100 (17 cases).
Thomas et al. (1987), U.S., NJ, PA	138 brain cancer deaths (1979-81) for MW/RF exposed occupations.	RRs for: exposed electrical jobs 2.3*, > 20 yr exposure 3.1*, electronics manuf./repair 4.6*.
Magnani et al. (1987), U.K.	432 brain cancer deaths (1959-63,1965-79) by occupation.	RRs for: electrical/electronics workers 1.3, electrical engineers 0.9, EMF exposed 0.9.
McLaughlin et al. (1987), Sweden	Gliomas for electrical workers from 3394 for all occupations (1961-79).	SIRs: welders/cutters 1.4* (46 cases), linemen 1 .O (13 cases), electricians 0.8 (42 cases).
Lin (1987), Taiwan	8 brain cancer deaths (1971-85) for electric power utility employees.	For all employees: O/E= 4.21" (8 observed cases).
Speers et al. (1988), U.S., TX	202 brain cancer deaths (1969-78) by occupation & possible EMF exposure.	ORs for: EMF-exposed workers 3.94*, probable EMF exposure 2.86* (11 cases).
Lin (1988), Taiwan	374 deaths (1976-86) among employees of a telephone/telegram company.	For all employees O/E= 2.4 (5 observed cases).
Guberan et al. (1989), Switzerland	Brain cancer deaths and cases (1970-84)among electricians and painters.	For 1948 electricians: SMR= 154 (2 deaths), SIR=1 18 (2 cases).
Matanoski et al. (1989), US., New York	Cancer among 50,582 telephone linemen by occupation (1976-80).	SIRs for: cable splicers 179 (2 cases), central office technicians 90 (4 cases).

Abbreviations: CNS= central nervous system, **MW/RF=** microwave/radio frequency, **O/E=** observed/expected, **OR=** odds ratio, **PMR=** proportional mortality ratio, **RR=** relative risk, **SIR=** standardized incidence ratio, **SMR=** standardized mortality ratio

* statistically significant (confidence intervals are not always given because of space limitations)

Table 3.5. A summary of studies of brain cancer in workers exposed to EMF. (Continued)

Study/Location	Subjects/Exposure (men unless noted otherwise)	Selected Brain Cancer Results (for all types unless noted otherwise)
Reif et al. (1989), New Zealand	452 brain cancer deaths (1980-84) by occupation.	ORs for: electrical workers 0.78 (8 cases), electrical engineers 4.74*, electricians 1.91.
Preston-Martin (1989), U.S., CA	8612 brain cancers (1972-l985) by occupation.	Electricians: all brain cancers, PIR= 124.9 (22 cases); for gliomas PIR= 175.6* (20 cases).
Preston-Martin et al. (1989), U.S., Los Angeles	202 glioma cases and 70 meningioma cases (1980-84) by work years.	For >5 yr work in high EMF exposure: glioma, OR= 1.8 (14 cases); astrocytoma, OR= 4.3”.
Koifman et al. (1989), Brazil	5 brain cancers in electric power workers compared to Rio’s population.	Workers with occasional EMF exposure SMR= 95. No brain cancers for higher-exposure jobs.
Loomis & Savitz (1990), U.S.	2173 brain cancer deaths (1985-86) from 16 states by occupation.	ORs for electrical workers: 1.4” (75 cases), electrical/electronics technicians 2.7*.
Schlehofer et al. (1990), Germany	226 brain cancer cases (1987-88) for men and women by occupation.	RRs for >5 yr as an electrician: all 1.87, women 5.2*, men 0.9. Female electrical jobs RR=1 1.8*.
Juutilainen et al. (1990), Finland	162 brain cancer cases (1971-80) in occupations with EMF exposures.	CNS cancer RRs for: possible exposure, 1.29; probable exposure, 1.31, for linear trend*.
Tornqvist et al. (1991), Sweden	398 brain cancer cases for 35 electrical occupations (1961-79).	SMRs: radio/TV repair 290*, glioblastoma 340*, welders/cutters glioblastoma 150*, linemen 1 lO.
Mack et al.(l991),Preston-Martin et al.(1989)U.S.,CA	272 brain cancer cases (1980-84) by electrical occupations.	ORs for >1 0-yr electrical work: 1.3 (15 cases), meningioma 0.3, glioma 1.7, astrocytoma 10.3*.
Lewis & Buffler (1991) U.S., TX, LA	375 CNS cancer cases (1980-84) by electrical occupations.	ORs for: all electrical occupations 0.65, definite probability of magnetic-field exposure 1.78.
Gallagher et al. (1991), Canada	120 brain cancer deaths (l 950-84) among 9 electrical worker groups.	PMRs for all EMF-exposed occupations: 125 for ages 20-65 yr, 121 for ages >20 yr old.
Spinelli et al. (1991), Canada	Brain cancer mortality and incidence for 4213 aluminum plant workers.	Brain and CNS cancers for all workers: SMR= 217* (10 cases), SIR= 194 (8 cases).
Demers et al. (1991), U.S., WA	904 brain cancer deaths (1969-l 978) by occupation.	Communications/utility workers OR= 0.9; plant & system operators OR= 4.5*.
Ryan et al. (1992), Australia	170 brain cancer cases (1987-90) for men and women by occupation.	RRs for all & high currents: meningioma 1.70, glioma 0.93; women glioma & CRTs 4.99*.
Tynes et al. (1992), Norway	119 brain cancer cases among 37,945 electrical workers.	For electrical workers: SIR= 109.
Sahl et al. (1993), U.S., California	32 brain cancer cases (1960-88) for male and female utility workers. PEM.	For electrical workers: internal cohort study RR= 1.09, case-control study OR= 0.95.
Floderus et al. (1993), Sweden	261 brain cancer cases (1983-87) from half of Swedish population. PEM.	ORs, mean daily exposure >4.1 mG, longest job IO yr before: 1.2; > 39% work time > 2 mG 1.9*.
Guenel et al. (1993), Denmark	Brain cancer incidence for a cohort of 2.8 million people by occupation.	O/Es for continuous magnetic-field exposure: men 0.69 (23 cases), women 1.23 (9 cases).
Theriault et al. (1994), Canada, France	108 brain cancers (1970-89) at 2 utilities in Canada, 1 in France. PEM.	ORs: >median magnetic-field exposure 1.54 (48 cases), >90th % exposure, astrocytoma 12.29*.
Floderus et al. (1994), Sweden	Brain cancer cases (1961-79) among electric railway (16.6 Hz) workers.	RRs for engine drivers and conductors: 1961-69, 1.2 (24 cases); 1970-79, 0.8 (25 cases).
Tynes et al. (1994a), Norway	39 brain cancers (1958-90) for railway workers & magnetic-wfield exposures.	For magnetic-field exposure 19-36 G-yrs, OR= 97. Electric vs. nonelectric railways, OR=0.82.

Abbreviations: CNS= central nervous system, **O/E=** observed/expected, **OR=** odds ratio, **PEM=** personal exposure measurements, **PIR=** proportional incidence ratio, **PMR=** proportional mortality ratio, **RR=** relative risk, **SIR=** standardized incidence ratio, **SMR=** standardized mortality ratio

* statistically significant (confidence intervals are not always given because of space limitations)

Table 3.5. A summary of studies of brain cancer in workers exposed to EMF. (Continued)

Study/Location	Subjects/Exposure (men unless noted otherwise)	Selected Brain Cancer Results (for all types unless noted otherwise)
Tynes et al. (1994b), Norway	Brain cancers (1953-91) at 8 hydro-electric companies & magnetic fields.	Cumulative magnetic field exposure: 50-350 mG-yrs SIR= 71, >350 mG-yrs SiR= 44
Armstrong et al. (1994), Canada, France	84 brain cancer cases among electric utility workers (1970-l 989). PEM.	For above-median exposure to pulsed-magnetic fields OR= 0.84, for 90th percentile OR=l.9.
Rodvall et al. (1994), Sweden	343 brain cancer cases (1987-90) for men and women by occupation.	For people probably exposed to magnetic fields, RR= 1,5, for longest exposure RR=1.9.
Dosemeci & Blair (1994), U.S.	54 brain cancer deaths (1984-89) for women in the telephone industry.	MORs: Telephone operators 1.3, mechanics & repair 3.0, no deaths for engineers/technicians.
Savitz & Loomis (1995), U.S.	151 brain cancers (1950-86) in men at 5 electric power utilities. PEM.	For magnetic-field exposure of >7 mG-yr for past 2-10 yr, RR= 2.56*.
Heineman et al. (1995), China	276 brain cancers (1980-84) in women, by occupation.	For exposure to electromagnetic fields, SIR= 120.
Baris et al. (1996b), Canada	20 brain cancers (1970-88) at an electric utility in Quebec. PEM.	For total cohort SMR= 113, power plant workers SMR= 3.90*, high magnetic fields RR= 4.88*.
Grayson (1996), U.S.	230 brain cancers (1970-l 989) in male U.S. Air Force personnel by job title.	For ever EMF exposure, OR= 1.28; for highest cumulative months of exposure OR= 1.44.
Beall et al. (1996), U.S.	149 brain cancer deaths (1975-89) in men & women at an electronics plant.	For >10 yr in programming jobs OR=2*, Glioma 5-yr programming IO yr before death OR=3.9*.
Fear et al. (1996), U.K.	281 brain/meninges cancers in male & female electrical workers (1981-87).	For male electrical workers PRR= 114*, for female electrical workers PRR= 140.
Mitler et al. (1996), Canada	35 brain cancer cases (1970-88) at an electric utility in Ontario. PEM.	Male electrical workers >345 V/m-yr, OR=0.99, 0.16-6.24; >71 mG-yr, OR= 2.36, 0.52-10.8.
Tynes et al. (1996), Norway	5 brain cancer cases among 2619 female radio & telegraph operators.	Female radio/telegraph operators SIR= 1 .0, 0.3-2.3.
Alfredsson et al. (1996), Sweden	12 astrocytoma cases among railway engine drivers and conductors.	For "active" drivers and conductors combined astrocytoma RR= 1 .1, 0.5-2.0.

Abbreviations: CNS= central nervous system, **O/E=** observed/expected, **OR=** odds ratio, **MOR=** mortality odds ratio, **PEM=** personal exposure measurements, **PIR=** proportional incidence ratio, **PMR=** proportional mortality ratio, **PRR=** proportional registration ratio, **RR=** relative risk, **SIR=** standardized incidence ratio, **SMR=** standardized mortality ratio, * statistically significant (confidence intervals are not always given because of space limitations)

A primary finding of the large study of cancer among U.S. electric utility workers by Savitz and Loomis (1995) was an elevated risk of brain cancer associated with magnetic-field exposures. For total exposure and for the highest exposure category, > 4.3 µT (43 mG)-year, the relative risk for brain cancer was 2.29, and it was statistically significant. For exposures over the last 2-10 years, the risk was also elevated significantly (RR= 2.56) in the highest exposure category, > 0.7 µT (7 mG)-yr. In this same exposure category, brain cancer risk per unit of magnetic field exposure per year was also increased significantly: RR= 1.94 per µT-yr Figure 3.9 shows the pattern of brain cancer risk with increasing magnetic-field exposure for the past 2-10 years for workers at five U.S. electric utilities in the study by Savitz and Loomis (1995).

Results of 29 studies of brain cancer and occupational magnetic-field exposure were combined in a meta-analysis by Kheifets et al. (1995). The review found that the combined results of these studies showed a small but statistically significant increase in brain cancer risk for electrical workers (Fig. 3.10). The analysis, however, did not establish whether magnetic fields or other factors were the cause of the increased risk. The results of the analysis were not sensitive to effects of unpublished data, influence of individual studies, or to weighting or modeling.

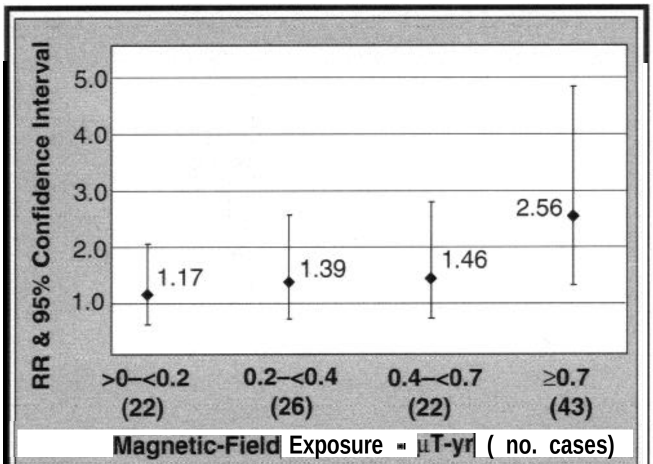


Figure 3.9. Relative risk of brain cancer for utility workers exposed to increasing levels of 60-Hz magnetic fields for the past 2–10 years (1 µT = 10 mG). Source: Savitz and Loomis (1995).

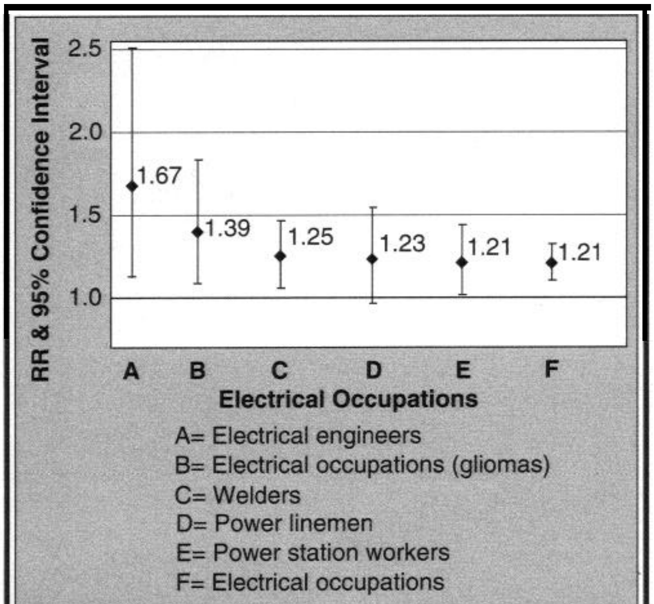


Figure 3.10. Relative risk of brain cancer for electrical workers from a meta-analysis of results of 29 published studies.
Source: Kheifets et al. (1995).

Kheifets et al. (1995) concluded that results of their meta-analysis could be interpreted in at least three ways: 1) there is no association between occupational exposure to EMF and brain cancer, 2) there is truly a small effect of exposure, or 3) there is a true large exposure effect but it primarily involves a small number of preconditioned individuals, or potentially affects all individuals and depends on the presence of some other factor(s). Authors of the study said that their results are evidence against the first interpretation, provide some evidence to support the second interpretation, and provide no clues to factors in the third interpretation.

Occupational: Breast Cancer

In the U.S., the incidence rate for breast cancer in women is about 110 cases in 100,000 women per year, compared to about 1 case in 100,000 men per year (Ries et al. 1994). Carcinomas (cancers arising from epithelium) that develop in male breasts are histologically indistinguishable from those in females, although the relative frequencies are different (Thomas 1993). The proportion of carcinomas in male breasts with estrogen receptors is also higher than in females.

There have now been at least 20 occupational studies that have specifically provided data about electrical occupations and breast cancer risk (Table 3.6). Stevens (1987,1993) suggested a possible mechanism to explain how EMF could affect the development of breast cancer. This possible mechanism involved suppression of melatonin, a hormone which has been reported to have oncostatic properties. Suppression could be caused by the increasing amount of light at night in dwellings in industrialized countries, and by exposure to EMF. Wertheimer and Leeper (1982) had previously reported elevated breast cancer risks in women living near power lines. Matanoski et al. (1989, 1991) reported finding two cases of breast cancer in male telephone central office technicians. This was a more than sixfold elevation in risk of male breast cancer, although it was not statistically significant.

In addition to the studies in Table 3.6, there are probably several more that included all cancers but that did not mention specific occupational data on male breast cancer because it is so rare. For example, in a study of 4203 cancer deaths in the male Canadian labor force, there were only 3 breast cancer deaths (Howe and Lindsay (1983). The report did not identify the occupations in which the breast cancers occurred. Of the studies in Table 3.6,12 involved male breast cancer. Half of these reported elevated risks, but in only three of the studies were the findings statistically significant. The statistical power of these studies tends to be low because of the small numbers of male breast cancers.

The study in the U.S. by Demers et al. (1990, 1991) reported the largest number of male breast cancer cases (33) for electrical workers. Risk of breast cancer was highest for the group consisting of electricians, telephone linemen, and electric power workers (OR= 6.0,1.7-21). Risks were also highest for men who began work be-

Table 3.6. A summary of studies that reported data about breast cancer in workers exposed to EMF.

Study/Location	Subjects/Exposure	Selected Breast Cancer Results
Puntoni et al. (1979), Italy	Mortality (1960- 1975) among >2000 male shipyard workers by occupation.	There were no cases of breast cancer for electricians or for electrical welders.
Vagero et al. (1985), Sweden	139 cancers (1958-79) in male & female telecommunications workers.	For women, breast cancer SMR= 60, 30-130 (7 cases). No breast cancer cases listed for men.
Sorahan et al. (1985), U.K.	Cancers (1970-81) among male & female semiconductor plant workers.	For women SMR= 32 (2 cases), SRR= 68 (9 cases). No breast cancers observed for men.
Matanoski et al. (1989, 1991), U.S., NY	Cancer among 50,582 telephone linemen by occupation (1976-80).	For central office technicians SIR= 650, 79-2350 (2 cases).
Oemers et al. (1990,1991), U.S.	227 male breast cancer cases from 10 cancer registries by occupation.	ORs for: electrical workers 1.8 (33 cases), electric trades & related 6.0* (13 cases).
Tynes & Anderson (1990), Tynes et al.(l992) Norway	Cancer among 37,945 male electrical workers compared to national rates.	For electrical workers SIR= 2.07*, 1.07-3.61 (12 cases).
Rosenbaum et al. (1990, 1994), U.S., NY	71 male breast cancer cases (1979-88), exposure to heat & EMF by job.	For estimated occupational EMF exposure, OR= 0.7, 0.3-l .8 (6 cases).
Loomis (1992), U.S.	250 male breast cancer deaths (1985-88) from 24 states by occupation.	Electrical workers: <65 years old OR= 2.2 (3 cases), >65 years old OR= 0.4 (1 case).
Guenel et al. (1993), Denmark	Cancer cases among 2.8 million men and women by occupation.	O/E for continuous magnetic-field exposure: men 1 .36 (2 cases), women 0.88 (55 cases).
Loomis et al. (1994a), U.S.	Breast cancer deaths (1985-89) for female electrical workers in 24 states.	ORs for: electrical workers 1.38* (68 cases), telephone install/repair 2.17* (15 cases).
theriault et al. (1994), Canada, France	4151 cancer cases (1970-89) for male electric utility workers. PEM.	O/E= 0.85 (7 breast cancer cases) for all workers combined.
Floderus et al. (1994), Sweden	Cancers in male railway workers (1961-79) & magnetic fields (16.6 Hz).	For the 2 highest-exposure jobs (engine drivers & conductors) RR= 4.9*, 1.6-15.7 (3 cases).
Tynes et al. (1994c), Norway	Cancers in female radio/telegraph operators (1940-89).	For all women SIR= 150*, for those with more than 20 years of work RR= 2.19".
Tynes et al. (1994b), Norway	Cancers (1953-91) among 5088 men at 8 hydroelectric companies.	For all men: SIR= 137, 3-763 (1 case).
Oosemeci & Blair (1994), U.S.	Cancer deaths (1984-89) among women in the telephone industry.	MORs: Engineers/technicians 2.7*, 1.3-6.0 (9 deaths); mechanics/repair 1.6,0.8-3.2(9 deaths).
Savitz & Loomis (1995), U.S.	Cancer deaths (1950-88) in 138,905 men at 5 electric utilities. PEM.	For all men: SMR= 80, 29-174 (6 cases). Breast cancer RR was not reported in an internal study.
Cantor et al. (1995), U.S.	Breast cancer deaths (1984-89) for 33,509 female electrical workers.	ORs for high probability of ELF: white women 1.09, 1.02-1.2; black women 1.28*, 1.1-1.6.
Coogan et al. (1996), U.S.	6888 new female breast cancer cases from 4 states by occupation.	ORs high potential of magnetic-field exposure: premenopausal 1.98, postmenopausal 1.33.
Fear et al. (1996), U.K.	7981 cancer cases for male and female electrical workers (1981-87).	For male electrical workers PRR= 129, 71-217. For female electrical workers PRR= 89, 72-l 12.
Tynes et al. (1996), Norway	50 breast cancer cases among 2619 female radio & telegraph operators.	Female radio/telegraph operators SIR= 1.5*, 1 .1 -2.0; ages 50-54 yr SIR= 2.5*, 1.3-4.3.

Abbreviations: **ELF=** extremely low frequency, **MOR=** mortality odds ratio, **O/E=** observed/expected, **OR=** odds ratio, **PEM=** personal exposure measurements, **PMR=** proportional mortality ratio, **PRR=** Proportional registration ratios, **RR=** relative risk, **SIR=** standardized incidence ratio, **SMR=** standardized mortality ratio, **SRR=** standardized registration ratio (O/E x 100)

* statistically significant (confidence intervals are not always given because of space limitations)

fore age 30, and who were exposed to EMF for at least 30 years before cancer was diagnosed (for the highest exposure group, OR= 7.4, 1.6-34). There was no significant trend, however, for increasing risk with increasing duration of work in an EMF-exposed job. As with most of the studies in Table 3.6, exposure was estimated by job titles, and no exposure measurements for EMF were made.

Risk for breast cancer was elevated 29 percent for male electrical workers in the U.K. (14 cases), but it was not statistically significant (Fear et al. 1996). In that same study there were 83 cases of breast cancer among female electrical workers, with a 10 percent deficit in risk, but it also was not statistically significant.

A Norwegian study found that, based on 12 cases of male breast cancer, risk was doubled for a group of 12 electrical occupations (Tynes and Andersen 1990, Tynes et al. 1992). Within the group, risk was elevated significantly for electrical transport workers (SIR= 396, 108-1014), and nonsignificantly for electricians (SIR= 219,7 l-5 12). Authors of the study said that their results should be interpreted with caution because of the small numbers of cases in the study.

Neither of the two studies that included measurements of personal magnetic-field exposures found an elevated risk of male breast cancer (Theriault et al. 1994, Savitz and Loomis 1995). In each study there were only about a half dozen cases of male breast cancer. Because of these small numbers, breast cancer risks were not reported for individual electrical occupations in these studies.

Two studies reported statistically significant risks of breast cancer in female electrical workers, based on analyses of death certificates from the same source for 24 states (Dosemeci and Blair 1994, Loomis et al. 1994a). Dosemeci and Blair (1994) studied cancer mortality (1984-89) only for female telephone industry workers, and looked at four occupational groups. They did not relate these groups specifically to EMF exposures. Breast cancer risks were elevated, one significantly so, in two of the groups that seem generally to fit in the "electrical occupation" category as used by other researchers (Table 3.6).

Loomis et al. (1994a) found that, out of 27,882 deaths in women from breast cancer from 1985-89, only 68 women had occupations that they classified as a type of electrical worker. Risk for these electrical workers was elevated, but it was on the borderline of statistical significance (OR= 1.38, 1.04-l .82). For specific occupations, only one, (telephone installers-repairers-line workers), had an adjusted risk that was statistically significant (OR= 2.17, 1.17-4.02).

In an editorial, Trichopoulos (1994) reviewed the Loomis et al. study and related research, and he generally took a skeptical view about the possibility that EMF affect the occurrence of breast cancer. Wertheimer and Leeper (1994b) commented that Trichopolos should have also pointed out that likely exposure misclassification in the negative breast cancer studies can bias the results toward the null (i.e., no effect).

Malkin and Moss (1994) suggested that the breast cancer risk for telephone workers found in the study by Loomis et al. (1994a) may have been confounded by ionizing radiation from radium bromide contained in some vacuum tubes. They also questioned whether telephone pole workers have elevated magnetic-field exposures. In response, Loomis et al. (1994b) acknowledged that future studies should examine additional factors, and they cited research that found that telephone workers did have elevated magnetic-field exposures.

The study by Loomis et al (1994a) also prompted correspondence from Cantor et al. (1995). These researchers had recently completed a study of the same death certificate data base (with one more year of data) although they had focused on radiofrequency fields. They extended their study by having an industrial hygienist code occupations by possible exposure to power-frequency fields. They also reported results separately for white and black women, with only the latter showing statistically significant risks of breast cancer (Table 3.6).

Cantor et al. (1995) concluded that their studies and those of Loomis et al. (1994a), ruled out the possibility of a very high risk of female breast cancer from exposure to magnetic fields. However, they added that a possible modest elevation in risk cannot be addressed by these data.

Breast cancer risk was elevated significantly for women who worked at sea as radio and telegraph operators, especially for those of ages 50 years or more (SIR= 1.8, 1.1-2.7) (Tynes et al. 1996). The women were exposed to fields at radio-frequencies (405 kHz-25 MHz), and at 50 Hz. For the latter, measurements showed that body exposures to magnetic fields near the radio sets were only about 0.1-0.2 µT (l-2 mG). Significant elevated breast cancer risks were also found in the study for long duration of shiftwork.

Goldberg and Labreche (1996) reviewed 115 studies of possible occupational risk factors for female breast cancer, of which seven involved electrical workers. They concluded that there was limited evidence for associations with the pharmaceutical industry, and with employment as cosmetologists and beauticians. The reviewers also found associations for employment as chemists and for jobs with exposure to EMF; however, methodology problems with the studies precluded any definite conclusions.

Occupational: Total Cancer

At least 34 studies have looked at total cancer mortality or incidence in one or more electrical occupations (Table 3.7). Of the 3 1 studies that involved male workers, about 12 reported one or more statistically significant positive risks. These significant positive risks ranged from about 1.06 to 2.76. At least five studies reported one or more statistically significant negative risks for total cancer and electrical work (range 0.50-0.83). Six studies included total cancer for female electrical workers Vagero and Olin 1983, Vagero et al. 1985, Sorahan et al. 1985, Guenel et al. 1993, Tynes et al. 1994c, Dosemeci and Blair 1994, Tynes et al. 1996). Only the Dosemeci and Blair (1994) study reported a statistically significant elevated risk (Table 3.7) for an occupation that might include elevated exposures to EMF, although occupations in the study were not defined in such a way.

Of the six studies that included measurements of personal exposures, two reported statistically significant elevated risks. The risk for total cancer found in the > 90th-percentile exposure group by Armstrong et al. (1994) was due primarily to an excess of lung cancer. In this study, assumed exposure (as measured with Positron meters), was to high-frequency pulsed magnetic fields. There is some uncertainty, however, about what the exposure meters actually measured in the high-frequency channel (Guttman et al. 1994, Maruvada and Jutras 1994).

Savitz and Loomis (1995) found that total cancer mortality showed a small but statistically significant increase (up to 19%) for increasing duration of employment in magnetic-field-exposed jobs as measured by AMEX meters. Three of the highest exposed occupations (linemen, electricians, power plant operators) showed risks that ranged from 0.99 to 1.12, Risks increased with increasing total magnetic-field exposure (RR= 1.22, 1.09- 1.37, for the highest magnetic-field exposure category with 505 cases). In this study, total cancer risk was influenced in part by a statistically significant increase in brain cancer.

Baris et al. (1996b) conducted further analyses of data on cancer and personal EMF exposures from the Quebec portion of the Canada-France study by Theriault et al. (1994). They found that utility workers had smaller risks for total cancer compared to the general population (Table 3.7). They attributed these findings to the healthy worker effect, or possibly to an under-assessment of mortality. The workers at the Ontario utility in the Canada-France study showed no significant risks for total cancer associated with exposures to EMF (Miller et al. 1996).

Occupational: Other Cancer Types

Several additional cancer types have been included in studies of electrical workers. Many of these are the same studies summarized in Tables 3.4-3.7 for the cancer types discussed in the above sections. The sections below summarize results of studies reporting positive effects for seven additional cancer types. The numbers of studies that did not report statistically significant risks are given, but they are generally not summarized. This is not because such studies are less important, but because of space limitations. Many of these negative studies reported elevated risks that were not statistically significant, in some cases possibly because of small numbers of cases.

Lymphoma

Out of about 34 electrical-worker studies that included lymphoma, about six reported at least one statistically significant risk. Guralnick (1963) combined U.S. data on lymphoma with lymphosarcoma and various neoplasms of the lymphatic and hematopoietic system. Only for stationary engineers was there a statistically significant risk (SMR= 152, $p < 0.05$). Risk was not elevated for six electrical occupations combined. Dubrow and Wegman (1984) found significant elevated risks for lymphoma in electrical engineers in Massachusetts (SMR= 300, $p < 0.01$), and for lymphosarcoma in electricians (SMR= 331, $p < 0.01$).

In the study by Milham (1985), a group of five EMF-exposed electrical occupations from Washington state had a combined elevated risk for all lymphatic and hematopoietic cancers (PMR=139, $p < 0.01$). Within the group, only power-station operators had a statistically significant elevated risk (PMR= 195, $p < 0.01$). Among employees of an electric utility in Taiwan, the risk of leukemia and lymphoma combined was significantly elevated (O/E= 2.00, $p < 0.01$) (Lin 1987). Lymphoma risk was significantly elevated in New York telephone cable splicers (SIR= 359, $p < 0.05$), and nonsignificantly in central office technicians (SIR= 194, $p > 0.05$) (Matanoski et al. 1989). Workers in electric-power industries in Sweden had an elevated lymphoma risk (SIR= 130, $p < 0.05$), as did power plant engineers/technicians (SIR= 470, $p < 0.05$) (Linet et al. 1993).

Table 3.7. A summary of studies of total cancer in workers exposed to EMF.

Study/Location	Subjects/Exposure (men unless noted otherwise)	Selected Results -Total Cancer
Guralnick (1963), Wertheimer & Leeper (1979) U.S.	U.S. mortality in 1950 by job titles from death certificates.	SMRs: electrical workers 115*, electricians 122*, stationary engineers 130*, power station 53*.
Puntoni et al. (1979), Italy	Mortality (1960-75) for >2000 shipyard workers by job title.	Based on two control populations, electricians RR= 1.30, 1.54; electric welders RR=1.19, 1.47.
Beaumont & Weiss (1980), U.S.	114 cancer deaths (1950-76) of welders who worked in metal trades.	For welders SMR= 0.98.
Vagero & Olin (1983), Sweden	Cancers in 73,102 male and female workers in the electronics industry.	For women RR= 1.08, 1.01-l .15 (1009 cases), for men RR= 1.15*, 1 .l 0-l .20 (1855 cases).
Howe & Lindsay (1983), Canada	4203 cancer deaths among 10% of the Canadian labor force (1965-73).	For electrical workers, data shown only for telegraph operators, SMR= 199".
Cammarano et al. (1984), Italy	15 cancer deaths in 270 men who worked at a power plant (1960-69).	For all workers SMR= 198*, 11 l-326, for workers > 10 yr work SMR= 276*; 143-482.
Vagero et al. (1985), Sweden	Cancers in 2918 male and female telecommunications industry workers.	For women SMR= 98 (37 deaths), for men SMR= 103 (102 deaths).
Barregard et al. (1985), Sweden	6 cancers (1958-83) among workers at a chlorine production plant (DC EMF).	O/E= 0.8, 0.3-l .9.
Sorahan et al. (1985), U.K.	Cancer deaths/cases for 1807 men and women at semiconductor plants.	SMRs: women 67 (14 deaths), men 174 (11 deaths); SRRs: women 113, men 155, both 122.
Milham (1985), U.S., WA	2649 cancer deaths among electrical workers (1950-l 982).	For all electrical occupations PMR= 106*.
Olin et al. (1985), Sweden	24 cancer deaths for 1254 electrical engineers from 1930-79.	For electrical engineers, SMR= 50*, 30-70.
Tornqvist et al. (1986), Sweden	699 cancers (1961-79) in 10,061 linemen and power station operators.	Linemen SMR=l10 (236 deaths), power station operators SMR=l00 (463 deaths).
Lin (1987), Taiwan	180 cancer deaths (1971-85) for electric power utility employees.	For all employees, O/E= 1.15*.
Lin (1988), Taiwan	129 cancer deaths (1976-86) at a telephone/telegram company.	For all employees, O/E= 1.01.
Guberan et al. (1989), Switzerland	Brain cancer deaths and cases (1970-84) among electricians and painters .	For a total of 1948 electricians: SMR= 114 (52 deaths), SIR= 92 (78 cases).
Matanoski et al. (1989), U.S., New York	Cancer among 50,582 telephone linemen by occupation (1976-80).	SIRs for: cable splicers 181* (40 cases), central office technicians 115 (96 cases).
Koifman et al. (1989), Brazil	Cancer deaths in electric power workers, and exposure level.	SMRs were significantly elevated at all magnetic field exposure levels (SMR range 129*-201*).
Forastiere et al. (1989), Italy	Cancer deaths in 406 workers at 2 power plants.	For all workers SMR= 112 (16 deaths).
Melkild et al. (1989), Norway	30 cancer cases among welders at a shipyard (1953-86).	For welders, O/E= 1.22.
Spinelli et al. (1991), Canada	Cancer deaths and cases in 4213 aluminum plant workers (1954-85).	For all workers, SMR= 92 (95 deaths), SIR= 95 (158 cases).
Tynes et al. (1992), Norway	3806 cancers in 37,945 electrical workers.	For electrical workers, SIR= 106*, 103-l 09.

Abbreviations: **O/E=** observed/expected, **OR=** odds ratio, **PEM=** personal exposure measurements, **PMR=** proportional mortality ratio, **RR=** relative risk, **SIR=** standardized incidence ratio, **SMR=** standardized mortality ratio , **SRR=** standardized registration ratio (O/E x 100).

* statistically significant (confidence intervals are not always given because of space limitations)

Table 3.7. A summary of studies of total cancer in workers exposed to EMF. (Continued)

Study/Location	Subjects/Exposure (men unless noted otherwise)	Selected Results -Total Cancer
Sahi et al. (1993), U.S., CA	773 cancer cases among electrical workers at an electric utility. PEM.	RRs for: ail electrical workers 1.08, electricians 0.85, linemen 1 .1 7, plant operator 1 .1 9.
Guenel et al. (1993), Denmark	Cancer cases in men and women with occupational magnetic-field exposure.	O/Es for potential magnetic-field exposure: women 0.98 (210 cases), men 1.04 (846 cases).
Nakagawa & Koana (1993), Japan	818 cancer deaths among 32,545 electric railway workers.	For electric power facilities, SMR= 54*.
Theriault et al. (1994), Canada, France	4151 cancer cases (1970-89) among 223,292 men at 3 utilities. PEM.	For magnetic field-exposure > median, OR= 1 .01, 0.91-l .1 3 (2158 cases).
Tynes et al. (1994c), Norway	Cancers in 2619 women who worked as radio/telegraph operators.	SIR= 114,96-1 34.
Armstrong et al. (1994), Canada, France	2679 cancer cases (1970-88) in men at 2 utilities and pulsed EMF. PEM.	For cumulative exposure, > 90th percentile, OR=l.39*, 1.05-l .85 (301 cases).
Tynes et al. (1994b), Norway	Cancers in men who worked at 8 hydroelectric companies.	For > 30-yr employment SIR= 115*; >35 µT yr, SIR= 105. Installation electricians SIR= 140*.
Dosemeci & Blair (1994), U.S.	Cancer deaths (1984-89) for women in the telephone industry.	MORs: Engineers/technicians 2.1*, 1 .1 -3.9 (19 deaths); mechanics/repair 1.3, 0.7-2.2.
Savitz & Loomis (1995), U.S.	Cancer deaths in 138,905 men at 5 electric utilities (1950-86). PEM.	AH workers SMR= 86 (4833 deaths). Magnetic field exposed jobs, RR= 1 .1 9*, 1 .1 l-l .29.
Baris et al. (1996b), Canada	466 cancers (1970-88) at an electric utility in Quebec. PEM.	For total cohort SMR= 83*,76-91. Above-background magnetic fields SMR= 93, 78-l 11.
Miller et al. (1996), Canada	1484 cancer cases (1970-88) at an electric utility in Ontario. PEM.	Male electrical workers >345 V/m-yr, OR=0.98, 0.76-1.27; >71 mG-yr, OR= 1.01, 0.82-1.24.
Tynes et al. (1996), Norway	140 cancer cases among 2619 female radio & telegraph operators.	Female radio/telegraph operators Si R= 1.2, 1.0-l .4.
Aifredsson et al. (1996), Sweden	630 cancer cases among electric railway workers.	For male locomotive engineers RR= 0.9, 0.8-1 .0; for conductors RR= 1.0, 0.9-l .2.

Abbreviations: **MOR=** mortality odds ratio, **O/E=** observed/expected, **OR=** odds ratio, **PEM=** personal exposure measurements, **PMR=** proportionate mortality ratio, **RR=** relative risk, **SIR=** standardized incidence ratio, **SMR=** standardized mortality ratio , **SRR=** standardized registration ratio (O/E x 100).

* statistically significant (confidence intervals are not always given because of space limitations)

Among the many studies that did not find significant elevated lymphoma risks were large studies that included personal magnetic-field exposures (Sahl et al. 1993, Theriault et al. 1994, Savitz and Loomis 1995, Baris et al. 1996b).

Lung Cancer

About 29 studies of electrical workers reported results for lung or respiratory cancer, and about 11 of these reported at least one statistically significant risk increase. In the U.S. study by Guralnick (1963), five electrical occupations combined had a significant risk for cancer of the trachea, bronchus, and lung (SMR= 128, p< 0.01). Risk was also elevated significantly for two of the occupations (stationary engineers, SMR= 159. p< 0.0 1: electricians, SMR= 13 1, p< 0.0 1). Electricians in New York also had a significant increase in lung cancer risk (RR=2.1, p= 0.03) (Houten et al. 1977).

Electricians who worked in an Italian shipvard had a more than fourfold increased risk of death from cancer of the lung, bronchus, and trachea (RR= 4.72, p< 0.05,6 cases) (Puntoni et al. 1979). Asbestos exposure was widespread in the shipyard, although electrical welders did not have a statistically significant increased risk for lung cancer. Welders in the Seattle. Washington area with long work experience did have a significant elevated risk of respiratory cancers (SMR= 169, p< 0.01) (Beaumont and Weiss 1980). Men who worked in the Swedish electronics industry also had a significant elevated risk of cancer of the trachea, and lung (RR= 1.52, 1.35-1.72) Vagero and Olin 1983).

Blair et al. (1985) found a significant deficit in the risk of cancer of the lung and bronchus for U.S. military veterans who were electrical engineers (SMR= 68, p< 0.05). In that study, risk was elevated for electricians but it was not statistically significant (SMR= 118, p > 0.05). In Sweden, risk for cancer of the lung and trachea was reduced significantly for power-station operators (SMR= 70,50-90) Tormqvist et al. 1986). Risk for power linemen was also reduced, but it was on the borderline of statistical significance (SMR= 70,40-100).

Male electrical workers in the U.K. had a significant deficit in lung cancer risk (PRR= 85,81-89). The researchers suggested that the lower risk may reflect a lower smoking rate among electrical workers.

For workers in Italian thermoelectric power plants who were less than 60-years old, lung cancer risk was significantly increased (SMR= 247, 108-487) (Forastiere et al. 1989). Welders who had worked at a Norwegian shipyard for l-5 years had a significant risk of lung cancer (O/E= 5.6, p< O.Ol), but risk was not increased in welders who had worked for more than 5 years (O/E= 0.58) (Melkild et al. 1989). Installation electricians at hydroelectric power companies in Norway had significant increased lung cancer risks (SIR= 188, p< 0.05) (Tynes et al. 1994b). Risks were not increased for power-supply electricians (SMR= 79), or for electric line workers (SMR= 84).

Armstrong et al. (1994) reported a strong association between lung cancer and exposure of electric utility workers in Canada and France to high-frequency pulsed magnetic fields. For combined data from two utilities, the odds ratio increased to 3.11, 1.60-6.04 in the highest exposure group. For the utility in Quebec the risk was much higher (OR= 6.67,2.68-16.57). Both findings were statistically significant. Authors of the study said that the results suggest a causal association; however, they identified factors that do not support such an association. This included little previous evidence for this association, uncertainty about what the personal exposure meters actually measured, and no evidence that the utility workers had elevated lung cancer risk compared to the general population.

Additional analyses of data for Quebec from the Canada-France study again showed that exposure to pulsed magnetic fields was associated with an elevated lung cancer risk (Baris et al. 1996b). However, as compared to the general population, the risk was smaller and not statistically significant (for above-background exposure to pulsed fields SMR= 121, 85-169).

Urinary, Bladder, Kidney Cancer

There have been at least 27 studies of electrical workers that reported data on cancers of the urinary system, bladder, or kidney. Four of these reported statistically significant elevated risks for bladder cancer, and three reported risks for kidney cancer.

For U.S. workers in six electrical occupational groups combined, the risk for bladder cancer was elevated significantly (SMR= 140, p< 0.05) (Guralnick 1963). Risk was elevated significantly for only one of the individual occupations: motormen (SMR= 286, p< 0.05). The risk for electricians was nearly doubled, although it was not statistically significant (SMR= 190, p> 0.05). Bladder cancer risk was elevated significantly for workers at an aluminum reduction plant in Canada (SMR= 169, 106-257) (Spinelli et al. 1991). In Norway, the incidence of bladder cancer among electrical workers was also elevated significantly (SIR= 123,1 1O-138) (Tynes et al. 1992). Male electrical workers in the U.K. had a small but statistically significant elevated risk of bladder cancer (PRR= 110, 101-120).

Two studies reported significant elevated risks for kidney cancer in electrical engineers. For electrical engineers in Massachusetts, risk of kidney cancer was more than doubled (OR= 2.77, p< 0.05) (Dubrow and Wegman 1984). In a study from the U.K., electrical engineers had a 15-fold increased risk of death from kidney cancer (RR= 15.2, 1.7-136) (Magnani et al. 1987). This finding was based on four deaths of electrical engineers from various industries. For workers with assumed exposure to electromagnetic fields, risk of kidney cancer was also elevated significantly (RR= 1.9, 1.1-3.2). In the same study, electricians had about a threefold elevated risk of kidney cancer, and it was on the borderline of statistical significance (RR= 2.9, 1.0-8.3). For workers in Norwegian hydroelectric power plants who were employed more than 30 years, risk of kidney cancer was elevated significantly (SIR= 160, p< 0.05) (Tynes et al. 1994b). For workers in that study with the highest estimated cumulative magnetic-field exposure, the risk was smaller and not statistically significant (SIR= 116, p> 0.05).

Stomach Cancer

Three studies reported statistically significant increased risks of stomach cancer for electrical workers out of about 27 studies that have reported on this cancer type. In a lo-percent sample of the Canadian labor force, linemen and servicemen showed a significant increased risk for stomach cancer (SMR= 233, p< 0.05) (Howe and Lindsay 1983). At one electric power company in

Brazil, workers who had the highest estimated exposure to EMF had a significant elevated risk for stomach cancer (SMR= 213, 102-392) (Koifman et al. 1989).

Armstrong et al. (1994) found significant elevated risks for stomach cancer in utility workers in Canada and France exposed to high-frequency pulsed fields (OR= 3.26,1.44-7.38 for exposure > median, O-20 years before diagnosis). A later analysis of data from the Quebec part of the study found that, compared to the general population, stomach cancer risk was less for workers exposed to above-background pulsed fields (SMR= 22, 1-122) (Baris et al. 1996b). Among workers at eight Norwegian hydroelectric power companies, risk of stomach cancer was elevated, but it was on the borderline of statistical significance (SIR= 130,99-169) (Tynes et al. 1994b).

Skin Cancer, Melanoma

Cancers of the skin are the most common cancer in the U.S., but most are highly curable (ACS 1996). Melanoma is the most serious type of skin cancer because it is highly malignant and commonly spreads to other parts of the body. There have been about 28 studies of skin cancer and electrical workers; some of these reported data on melanoma and other skin cancers separately. Five of these studies reported statistically significant elevated risks for melanoma. Among workers in the Swedish electronics industry, there was a significant elevated melanoma risk for men (RR= 1.35, 1.05-1.76), but not for women (Vagero and Olin 1983). For workers in a semiconductor factory in the U.K., women, but not men, had a significant melanoma risk (SRR= 440, p< 0.03) (Sorahan et al. 1985).

The risk of non-melanoma skin cancer was slightly but significantly elevated for male electrical workers in the U.K. (PRR= 109,102-l 19) (Fear et al. 1996). Risk of melanoma in that study of electrical workers was also elevated for both men (PRR= 118,94- 147) and women (PRR= 127, 55-251), but neither was statistically significant.

Two studies reported elevated melanoma risks for workers in the telecommunications industry. In one of these, Swedish men had a significant risk for melanoma (SMR= 250, 110-490) , and the risk was also elevated in women but it was not statistically significant (SMR=280,80-720) (Vagero et al. 1985). In the other study, Canadian men had a significant risk (O/E= 2.7, 1.31-5.02); there were no melanoma cases among female workers (De Guire et al. 1988).

Men who had worked for more than 30 years at a hydroelectric company in Norway had a significant elevated risk of skin cancer (SIR= 203, p< 0.05) (Tynes et al. 1994b). Men who had the highest estimated cumulative exposure to magnetic fields had a significant risk of melanoma (SIR= 224, p< 0.05). Melanoma risk was also increased significantly for power-supply electricians (SIR= 208, p< 0.05).

Two studies reported statistically significant decreased risks, including a study of men who worked at an aluminum reduction plant in Canada (for skin cancer, SIR= 51,38-67) (Spinelli et al. 1991). In the large study by Theriault et al. (1994), risk of melanoma was significantly reduced for men with above-median exposure to magnetic fields, and with O-20 years of exposure relative to diagnosis (OR= 0.49, 0.26-0.94). For all men with above-median exposure, risk was also decreased but not significantly (OR= 0.86, 0.49-1.48). However, at one of the three utilities in the study, melanoma risk was elevated fourfold, although it was not statistically significant (OR= 3.98, 0.44-36.01).

Prostate Cancer

At least 23 studies of electrical workers have reported results for prostate cancer, of which, about four reported statistically significant risks. Out of four electrical worker occupations from Massachusetts, motion picture projectionists showed a significant elevated risk for prostate cancer (OR= 8.01, p< 0.001) (Dubrow and Wegman 1984). Prostate cancer risk was elevated significantly in machine shop welders in Finland (O/E= 2.5, o< 0.05), but not in platers, machinists, or in pipefitters (Tola et al. 1988). For telephone central office technicians in New York, prostate cancer risk was elevated significantly (SIR= 348, p< 0.05) (Matanoski et al. (1989). In that study risk was also elevated for telephone cable splicers but it was not statistically significant (SIR= 438, p> 0.05).

In Quebec, risk of prostate cancer was significantly elevated in electrical workers with 10 or more years employment (OR= 2.38, 1.13-5.01) and in railway transport workers with less than 10 years employment (OR= 4.47,1.26-15.83) (Aronson et al. 1996). For railway workers with 10 or more years employment, the risk was smaller and not significant (OR= 1.81, 0.71-4.58). Welders and flame-cutters with 10 or more years employment also had an elevated risk for prostate cancer, but it was on the borderline of statistical significance (OR= 2.13, 0.95-4.78).

Eye Cancer

About six studies of electrical workers have reported data on eye cancer or disease, and only one reported statistically significant elevated risks. Male electrical and electronics workers in the U.K. had significant risks for eye cancer in 3 out of 8 years from 1968-70 (Swerdlow 1983). Proportional registration ratios for the 3 years were 714 ($p < 0.01$), 444 ($p < 0.05$), and 571 ($p < 0.05$), based on a total of 13 cases. Other occupations that had significant elevated risks for eye cancer in this study included administrators and managers (41 cases), and professionals, technical workers, and artists (72 cases).

Gallagher et al. (1985) studied 90 cases of ocular melanoma from western Canada, and they did not find significant elevated risks for the electrical occupations as reported by Swerdlow (1983). They did find that indoor workers in general had significant elevated risks. Out of 4833 cancers among men at five U.S. utilities, Savitz and Loomis (1995) found six benign neoplasms of the eye and brain (SMR= 55,20-120), and 39 neoplasms of unspecified nature of the eye and brain (SMR= 117,83-160). Singewald et al. (1973) gave eye examinations to 10 linemen over a 9-year period and no eye problems were reported.

Occupational: Summary

The previous sections have summarized results of about 113 studies of cancer and electrical workers. This large body of research is difficult to synthesize because the studies are so diverse. Although several of the studies used similar categories of "electrical workers," others used unique groupings to estimate EMF exposure. Only a few of the studies used meters to measure personal exposures to magnetic fields-exposures to electric fields have seldom been measured in cancer studies.

Even those studies than did include personal exposures to EMF, they only provided data about present-day exposures-usually only a time-weighted average. To calculate cancer risks, many assumptions still have to be made about how to define "exposure," and how to estimate individual exposures that occurred in the past. Thus exposure misclassification is a potential problem in these studies. In general, in a study where exposure misclassification is random (occurs with about the same frequency for "exposed" and control groups), the result is that the risk estimate derived from those groups is biased toward the null (Hutchison 1982, Savitz 1995). This means that the real risk is probably larger than the risk estimated in the study.

Several occupational cancer studies considered possible factors other than EMF that could have been the cause of elevated risks found in the studies. In general, controlling for confounding factors did not greatly change results for EMF. For example, in the Canada-France study, Theriault et al. (1994) estimated exposures to chemical and physical agents listed as carcinogenic or possibly carcinogenic by the International Agency for Research on Cancer, and by the American Conference of Governmental Industrial Hygienists. There was little confounding by these chemicals, as the odds ratios for magnetic fields changed little after they were adjusted for chemical exposures. In the large study of five U.S. utilities, Savitz and Loomis et al. (1995) also found no evidence for confounding of their results for magnetic fields.

Figure 3.11 provides a quick reference of the numbers of occupational cancer studies for each cancer type summarized in this chapter. The figure also gives an indication of the numbers of studies that reported statistically significant elevated risks. As mentioned in the above sections, many of the studies that did not find statistically significant results did find elevated risks.

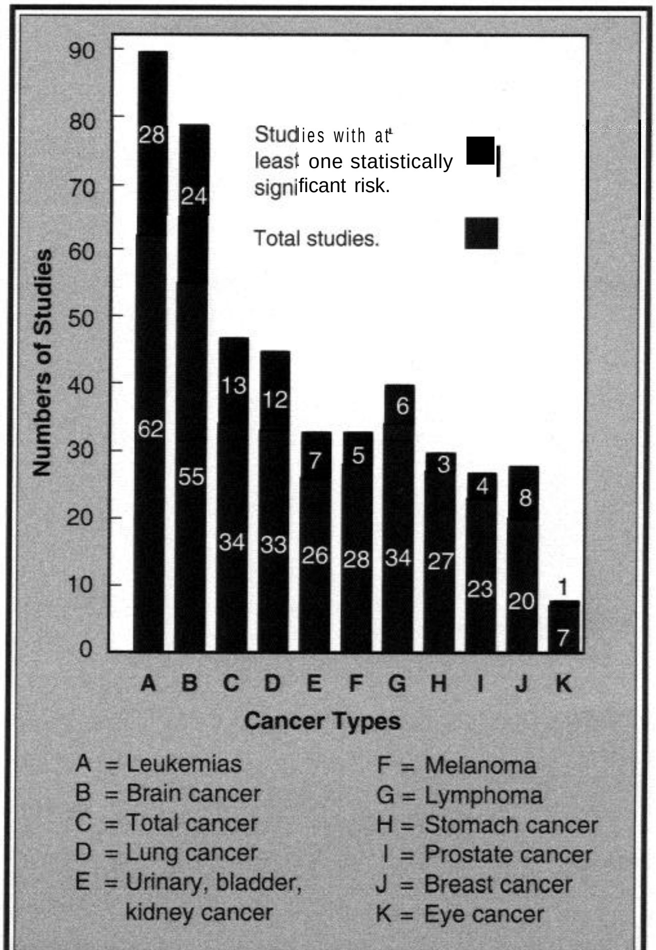


Figure 3.11. Numbers of studies of electrical workers included in this chapter by cancer type. Graph also shows numbers of studies reporting at least one statistically significant risk.

Even with the large number of studies that has been conducted, scientists still are uncertain about the cause(s) of the elevated cancer risks for electrical workers reported in this body of research. One of the most recent, and largest of these studies by Savitz and Loomis (1995: 133) stated that, "Firm conclusions regarding whether magnetic fields cause cancer, based on our study alone or on the entire literature, are not yet possible." Those authors advised against more studies unless they can more accurately assess historical exposure, or can specify more biologically relevant, testable hypotheses.

In a review of the EMF occupational studies, Wilson and Stevens (1996) concluded that the studies suggest that something associated with electrical occupations increases the risk of leukemia, brain cancers, breast cancer, and possibly melanoma. Regardless of whether the causal factor(s) turns out to include magnetic fields, those authors suggested that industrial professionals approach the issue with some caution.

Occupational: Cancer in Workers' Children

In addition to the studies described above of cancer in workers exposed to EMF, some studies have also looked for associations between cancer in children, and the occupation of their parents. Table 3.8 summarizes 12 studies that have reported on cancer risks in the children of parents who were assumed to have been exposed to EMF.

Six of the studies in Table 3.8 included mothers. and only one reported a statistically significant association. For women who worked at home with sewing machines during pregnancy, their children had a more than fivefold elevated risk of developing acute lymphoblastic leukemia, and the risk was statisticallv significant (Infante-Rivard 1995). Authors of the study had initially attributed their findings to organic dust and synthetic fibers present during fabric sewing. However. after learning that electric sewing machines produce very

Table 3.8. A summary of studies of cancer in children of workers exposed to EMF.

Study/Location	Subjects/Exposure	Selected Child Cancer Results
Sanders et al. (1981), U.K.	6920 child cancer deaths (1959-63 & 1970-72) and fathers' occupations.	For electrical occupations: 1959-63, PMR= 95 (120 deaths); 1970-72, PMR= 107 (89 deaths).
Hemminki et al. (1981), Finland	948 child cancer cases (1969-75) and parents' occupations.	Transport & communication workers: mothers OR=1 52, fathers OR=1.22.
Spitz & Johnson (1985), U.S., TX	157 child deaths from neuroblastoma (1964-78) and fathers' occupations.	ORs: electrical workers 2.14*, 1.05-4.35 (17 deaths), electronics workers 11.75*, l-40-98.55.
Nasca et al. (1988), U.S., NY	338 child cancer cases (1968-77) and parents' occupations.	Parents' with electromagnetic field exposure at childs' birth, OR= 1.61, 0.83-3.11 (19 cases).
Wilkins & Koutras (1988), U.S., OH	491 child brain cancer deaths (1959-78) and fathers' occupations.	Electrical assembling, installing, repairing, OR= 2.7*, 1.2-6.1 (19 deaths).
Johnson & Spitz (1989), U.S., TX	499 child CNS cancer deaths (1964-80) and fathers' occupations.	Electricians OR= 3.52, 1.02-12.08 (7 deaths); construction electricians OR=1 0.05*,1.17-86.29.
Wilkins & Sinks (1990), U.S., OH	1 IO child brain cancer cases (1975-82) and parents' occupations.	Nonionizing radiation: father OR= 3.2*, 1 .1 8.8 (13 cases); mother OR= 2.1, 0.6-7.3 (5 cases).
Wilkins & Hundley (1990) U.S., OH	101 child neuroblastoma cases and fathers' occupations.	Depending on how EMF exposure was defined, ORs ranged from 0.5, 0.2-1.2 to 1.9, 0.4-9.7.
Bunin et al. (1990), U.S., PA	104 child neuroblastoma cases (1970-79) and fathers' occupations.	EMF exposure, narrow definition: for preconception exposure OR= 1.3, 0.4-4.1.
Olsen et al. (1991), Denmark	1747 child cancer cases (1968-84) and parents' occupations.	Total child cancers by father's occupation: electrician OR= 0.8, welder OR= 1 .0.
Kuijten et al. (1992), U.S., NJ, DE	163 child astrocytoma cases (1980-86) and parents' occupations.	Father's: definite EMF exposure, OR= 1 .1, 0.4-3.1. electrical repair, OR= 8.0*, 1.1-356.1
Infante-Rivard (1995), Spain	128 child cases of acute lymphocytic leukemia and mothers' occupations.	Working at home with sewing machine, OR= 5.78*, 1.27-26.25.

Abbreviations: CNS= central nervous system, **OR=** odds ratio, **PMR=** proportionate mortality ratio

* statistically significant (confidence intervals are not always given because of space limitations)

strong magnetic fields (Sobel et al. 1994), they reinterpreted their study as possibly being magnetic-field related.

Five studies reported statistically significant elevations in cancer risk in children of fathers who had some occupational exposure to EMF. However, the exposure classifications used in the studies varied widely, and no two of the studies reported significant risks for the same exact electrical occupation, or group.

In a review paper, Gold and Sever (1994) concluded that the evidence is suggestive for increased risks of neuroblastomas and CNS cancer in children of electrical worker fathers. However, because low frequency EMF are not known to be mutagenic, the potential mechanism by which paternal exposure to EMF could cause cancer in offspring is not known.

Comparative Cancer Risks and Conclusions About Research

The previous sections have described cancer risks reported in a large number of studies of people exposed to EMF. To help place these risks in perspective, this section provides some information on other cancer risk factors that have been reported in the scientific literature. The information in Table 3.9 is presented to show in general how the magnitudes of the relative risks for EMF compare to some of these other factors. The information is not intended to imply that risks for EMF are more or less important or acceptable than these other factors. The latter are value judgments that will vary among individuals, and among organizations (see Chapter 5 for more on risk assessment).

Several scientific committees have reviewed the epidemiological evidence involving EMF and cancer, and many of these are summarized in Appendix A. None of the reviews concluded that EMF have been shown to be the cause of the increased cancer risks reported in some studies. However, several reviews recommended prudent or precautionary measures to reduce or prevent exposures to EMF because of the uncertainty that exists in the evidence. A number of reviews of this evidence have also been published in scientific journals, and some of the most recent ones are summarized below.

Verschaeve (1995:246) concluded that,

"Overall, the available human data on EMF and cancer (especially leukemia, brain and breast cancer) are too inconsistent to establish a cause-and-effect relationship, but there is enough evidence of association to raise concern.. . . The available information only allows ELF EMF to be classed as possible carcinogens to humans, with a higher probability in occupational exposures."

A review by Hardell et al. (1995) classified epidemiological studies of EMF and cancer into five groups: no association, probably no association, possible association, association, or no conclusion. Hardell et al. (1995:3) concluded that,

"... there are possible associations between (i) an increased risk of leukaemia in children and the existence of, or distance to, power lines in the vicinity of their residence, (ii) an increased risk of chronic lymphatic leukaemia and occupational exposure to low frequency electromagnetic fields and (iii) an increased risk of breast cancer, malignant melanoma of the skin, nervous system tumors, non-Hodgkin lymphoma, acute lymphatic leukaemia or acute myeloid leukaemia and certain occupations."

Foster and Mouldern (1996: 102) summed up their views with,

"... we conclude that there is still no substantial evidence that power frequency magnetic fields cause or promote cancer.. . . The strongest responsible claim that can be made to the contrary is that such a hazard might exist, although it cannot be clearly identified in present studies."

Stevens (1996:290) observed that,

"... the weight of evidence supports an association of proximity to power lines and risk of, at least childhood leukemia, and the weight of evidence supports an association of putative occupational exposure and increased risk of leukemia and brain tumors. It is important to determine if these associations are causal."

In a review of causes of cancer in the U.K. Sir. Richard Doll (1996: 18 l), whose epidemiological research helped establish the link between smoking and lung cancer, had this to say about studies of cancer and exposure to magnetic fields:

"The numbers of cases in the best studies are small, but we must, I think, conclude that the possibility of a risk from such exposures exists, and that we urgently need research to determine whether it does exist or not. The fields concerned are almost wholly man-made and, if the risk is real, there will certainly be an opportunity of reducing them, though at considerable social cost."

Electric Power Consumption and Cancer Trends

The research summarized in this chapter, although not conclusive, suggests that residential and occupational exposure to EMF increases the risk of cancer. Some scientists who question this possibility argue that if EMF really did affect cancer, then national cancer rates should

Table 3.9. Some examples of cancer risks reported for factors other than EMF.

Cancer Type	Risk Factor	Relative Risk	Comments	References
Lung	Smoking†	5.5-23.9*	Range for 1-9 to 40+ cigarettes per day, US. veterans	Fraumeni & Blot (1982)
Lung	Environmental tobacco smoke†	1.19* 1.38*	U.S. nonsmokers U.S. nonsmokers, highest exposed groups	EPA (1992b)
Lung	Home radon	1.20 1.20 1.80"	U.S. nonsmoking women, highest exposure Sweden, nonsmokers, highest exposure Sweden, all subjects, highest exposure	Alavanja et al. (1994) Pershagen et al. (1994)
Lung	Asbestos†	2.55 6.08	Insulation workers 1 O-l 4 yr employment Insulation workers 30-34 yr employment	Selikoff et al. (1979)
Hematopoietic Leukemia Leukemia	Benzene†	3.93* 1.36 5.00*	U.S. chemical workers U.S. male petrochemical workers U.S. natural rubber workers	Wong (1987) Waxweiler et al. (1983) Infante et al. (1977)
Leukemia	Smoking†	1.09 1.34*	Pooled estimate, 9 case-control studies Pooled estimate, 6 cohort studies	Siegel (1993)
Leukemia	Hot dogs	1.3 9.5*	Child's consumption of >1 per week Child's consumption of >12 per month	Sarasua & Savitz (1994) Peters et al. (1994)
Leukemia	x rays†	1.6	Prenatal x rays of twins	Harvey et al. (1985)
Leukemia	Home pest strips	3.0*	Child leukemia in homes where pest strips used during fast 3 months of pregnancy	Leiss & Savitz (1995)
Breast	Alcohol†'	1.11* 1.38*	Women, 1 drink/day (meta-analysis) Women, 3 drinks/day (meta-analysis)	Longnecker (1994)
Breast	x rays†	0.8 1.4 2.0	Men with chest x rays every 6-10 yr Men with chest x rays every 2 yr Men with chest x rays more than every yr	Thomas et al. (I 994)
Breast	Environmental tobacco smoke†	3.1*	Women exposed to tobacco smoke for at least 1 hr/day for at least 1 consecutive yr	Morabia et al. (1996)
Breast	Oral contraceptives†	1.7*	For women ages 25-34 yr who used oral contraceptives for at least 1 yr	Rosenberg et al. (1996)
Bladder	Water disinfection	1.8*	For people in Colorado with 30 or more yr exposure to chlorinated surface water	McGeehin et al. (1993)
Bladder	Occupation	2.69* 5.37*	Men in machine trades Homemakers	Anton-Culver et al. (I 992)
Brain	N-nitroso corn-pounds x rays†	3.3* 2.3* 2.5*	Child tumors: mother burned incense, mothers' high intake of cured meats Child tumors: >5 full-mouth dental x rays	Preston-Martin et al. (1982)
Brain	x rays†	21.7*	Child tumors after leukemia treatment	Neglia et al. (1991)
Brain	Petrochemicals	2.63*	Men with 15-yr employment	Waxweiler et al. (1983)
Melanoma	Fluorescent light	1.77 1.92*	Men with 21-30-yr occupational exposure Men with > 31-yr occupational exposure	Walter et al. (1992)
Melanoma	Sunlight†	2.3*	Women in San Francisco who never used sunscreen	Holly et al. (1995)

* Finding is statistically significant.

' There was a statistically significant dose-response.

†Factor is generally considered to be a known cause of cancer, although not necessarily of all types, and under conditions in these examples.

Pure alcohol does not cause cancer in animals but it seems to cause cancer in humans in combination with other factors, e.g., smoking.

Oral contraceptives also have a protective effect against ovarian and endometrium cancers.

have increased greatly, because of the rapid increase in per-capita consumption of electric power (Adair 1991, Jackson 1992, ORAU Panel 1992, Poole and Trichopoulos 1991). Although this argument seems to have some logical appeal initially, other scientists have pointed out flaws in the argument which are summarized below (Delpizzo 1990, Savitz 1993, Wertheimer and Leeper 1992, Heath 1996).

Adair (1991) compared child leukemia incidence rates in Connecticut for 1940-80, with U.S. per capita electric power use during this period. Leukemia rates remained fairly stable, but power use increased 12-fold. Adair concluded from this comparison that child leukemia is not caused by electromagnetic fields, and that poor quality studies that show otherwise are wrong. Jackson (1992) contended that the absence of appreciable changes in cancer death or incidence rates in the U.S. since 1900 also shows that EMF pose no significant hazard to the average person.

Researchers in three other countries also examined cancer rates in relation to electric power consumption by the use of ecological studies. In Greece, deaths from childhood leukemia from 1976-89 were compared to increases in electric power consumption during this period (Petridou et al. 1993a). Although mortality rates decreased during this period, there was a suggestion that the rate was slowing as power consumption increased (0.249 deaths per 100,00 children per year for every increase of electric power consumption equal to 1 MWhr per child per year). The finding was not statistically significant, and the authors of the study said that the results did not strongly support the hypothesis linking EMF to cancer.

Researchers in Canada found that provinces with the highest residential electric consumption rates also had higher rates of childhood cancer (Kraut et al. 1994). The study looked at the period 1971-86, which was a time period when there were significant increases in incidence rates for overall child cancer and for child brain cancer. Authors of the study acknowledged that a major limitation of their study, and all similar ecological studies, is that no information is available on actual field exposures. This is a major flaw in the approach because historic data are not available on human exposures to EMF. As discussed below evidence shows that the average magnetic field in the home has little or no relation to home electric power consumption.

A study in Japan found that among 47 administrative divisions, there was a statistically significant inverse correlation between deaths from leukemia and other cancers in males and electric power consumption per capita (Sokejima et al. 1996). For example, in the division with the lowest per capita electric power consumption, the death rate for leukemia was about 10 per 100,000 population. In the division with the highest consumption, the death rate was about 4 per 100,000. After adjustment for expenditures per person the correlation was still significant. Therefore, the researchers concluded that the correlation was likely to be independent of socioeconomic factors related to income. The researchers assumed that average exposure to EMF should correlate with average electric power consumption per person in a given area. However, they cited no evidence to support the assumption. No correlation was seen in the study for per capita electric power consumption and all causes of death in males.

It is true that since the introduction of electric power in the late 1890s the use of electricity by homes, businesses, and industries has increased at a rapid rate. Even in the more recent period from 1950 to 1991, per-capita electricity sales in the U.S. increased almost fivefold (Kujawa et al. 1992). However, the assumption that average human exposure to EMF has also increased at the same rate is probably not correct.

There is no question that exposures to EMF increased after electric power was first introduced, because strong AC fields at 50/60 Hz basically did not exist before that time (the earth produces mainly DC fields). However, through time there is evidence to indicate that many exposures to EMF may have decreased for people who were using electricity. For example, early buildings were wired in a way that kept the hot and neutral wires separated (called knob and tube wiring). This type of wiring produces stronger EMF than modern wiring in which the two wires are usually right next to each, separated only by insulating material. In a study of homes throughout the U.S., average magnetic fields in homes with modern wiring were about 25 percent lower than the fields in older homes with knob and tube wiring (Zaffanella 1993).

Wertheimer and Leeper (1992) pointed out the importance of the modem use of nonconducting elements in plumbing systems (e.g., plastic pipe) in reducing magnetic fields. This practice greatly reduces magnetic fields from return currents on plumbing, and from net currents on distribution lines-both of which are significant contributors to magnetic fields in buildings. Delpizzo (1990) also observed that many modem appliances such as radios and TV sets with transistors draw less current than older appliances that used high-power vacuum tubes. Three studies have also shown that there is no significant association between home electric energy consumption, and residential magnetic-field intensity (Zaffanella 1993, Kaune et al. 1987, Lee et al. 1996).

Another problem is that historic cancer rates and trends are subject to many uncertainties, and there are differing interpretations as to the underlying causative factors. Reliable data on U.S. cancer incidence rates are only available from about the early 1970s (Savitz 1993). Such data, therefore, are not generally available for the period when electric power was being introduced and when new exposures to EMF were occurring.

Figure 3.12 shows some U.S. cancer incidence rates for 1973-91 as reported by the SEER program (see page 3-3) of the National Cancer Institute. These cancers are those most often associated with EMF exposures in the studies reviewed in this chapter. During this period the incidence rate for the two most common cancers in children increased (Ries et al. 1994). For acute lymphocytic leukemia in children of all races, both sexes, and ages O-14 years, the incidence rate increased 20 percent. For child cancers of the brain and nervous system, the incidence rate increased 38.4 percent. For leukemia for all ages, the incidence rate decreased by 11.3 percent from 1973-9 1. For brain and other nervous system cancers, the incidence rate increased 24.6 percent during this period. For people aged 65 years and over, the incidence rate for brain and nervous system cancers increased 54.4 percent. In comparison to these cancer rates, from 1973-9 1, per capita electricity sales increased by about 35 percent (Kujawa et al. 1992).

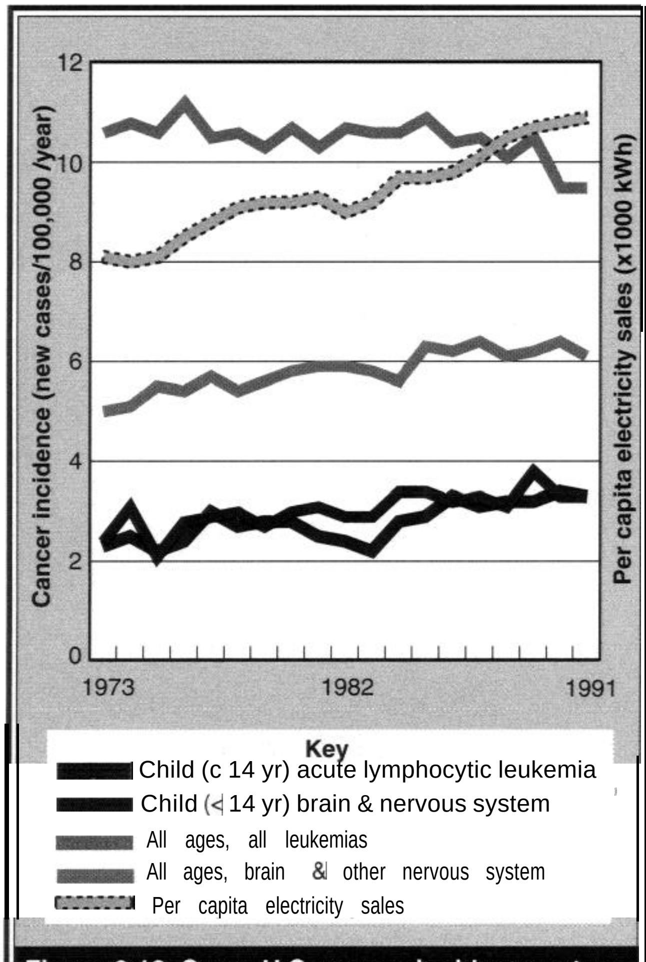


Figure 3.12. Some U.S. cancer incidence rates for children and all ages for 1973–91, and per capita electricity sales during the same period. Sources: Kuja et al. (1992), Ries et al. (1994).

Most of the data in Figure 3.12 are not consistent with the hypothesis that cancer rates do not reflect changes in electric energy consumption. This is not to say, however, that this crude analysis proves that the increase in electricity consumption is causally associated with cancer. Likewise, for the reasons discussed above, it does not seem appropriate to suggest that this simple type of analysis is evidence to dismiss the possibility that EMF are cancer risk factors.

Although we have focused on electric power, another important consideration is that many other significant societal changes have occurred during the time that electric power has been increasing in use. Some of these-such as synthetic chemicals, drugs, medical treatments, and lifestyle and diet-have also changed greatly over the last 100 years. These and other factors alone, or in combination, may act to increase or decrease cancer rates. Savitz (1993) believed that using secular trends to distinguish a moderate or a no effect of EMF on health from among all these other factors, cannot be done.

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Chapter 4

Effects of EMF on Animals and Plants

Summary

- Since the 1960s large numbers of studies have been done of animals exposed to EMF in laboratories. These in vivo studies were mostly intended to provide data to help assess the potential for adverse effects of EMF on people,
- Many effects of EMF have been reported on animals in laboratory studies, but relatively few have been independently replicated. Much current interest is focusing on effects on the hormone melatonin, and on dancer promotion. The laboratory animal studies to date have nut firmly established the existence of any hazardous effects from levels of EMF as found typically in the environment.
- Many studies have also been done on effects of EMF on cells and tissues. These *in vitro* studies are often designed to explore possible mechanisms to explain how EMF may cause biological effects. Areas of current interest include melatonin, gene expression, and carcinogenesis.
- Many scientists believe that the cell membrane is a basic site fur biological interactions with EME Several possible mechanisms to explain biological effects of EMF have been proposed.
- Studies of plants growing near transmission lines generally found no adverse effects of EMF on overall growth, Tips of tree branches growing close to transmission-line conductors can be damaged by corona in strung electric fields. Some laboratory studies found that specific combinations of AC and DC magnetic fields can affect plant growth.
- In special studies, honeybee hives were adversely affected by electric currents and shucks induced by electric fields from large transmission lines.
- Some studies have been dune of wildlife and domestic animals exposed to EMF and relatively few effects have been reported. Studies are continuing on a possible effect of EMF from a **500-kV** line an the immune system of sheep.

Background

This chapter provides an overview of the large body of research on the possible effects of power-frequency EMF on animals, cells and tissues, and plants. This research has been done since the 1960s and includes studies done in laboratories and in natural environments. The laboratory animal studies (in vivo) span a large number of biological areas, including behavior, stress, growth, reproduction, hormones, cardiovascular system, nervous system, immune system, and cancer. Studies of EMF and cells and tissues (in vitro) include carcinogenesis, gene expression, mutagenesis, and cell communication and growth. A primary purpose of the laboratory studies is to provide information to supplement the human studies described in Chapters 2 and 3 to allow for a hazard assessment of EMF.

A smaller number of studies has been done of EMF and animals and plants in natural environments. These include studies of livestock, wildlife, insects, and plants living near transmission lines. Other natural environment studies have looked at animals and plants exposed to low-frequency EMF from a U.S. Navy communication antenna. In two studies, livestock were exposed to simulated transmission line-fields inside buildings.

This chapter begins with an introduction to basic exposure considerations for laboratory studies of EMF.

Laboratory Studies

These studies were done primarily to help assess the potential for EMF to cause biological effects in humans, and to investigate possible mechanisms for such effects. It is, therefore, important to understand how exposures in the laboratory relate to exposures that people may receive. This process is complicated by a lack of agreement among scientists about what exposures to EMF are most biologically relevant, and by fundamental problems in extrapolating from results of studies of animals and cells, to humans.

EMF Exposure Considerations

Chapters 2 and 3 provided an introduction to the basic ways that EMF interact with people and animals. This section provides more specific information that is useful for understanding the results and limitations of laboratory studies. The design and conduct of a laboratory study of EMF is a complex undertaking that requires the combined efforts of biologists, engineers, and physicists.

As described in Chapter 1, there are several parameters that are needed to characterize EMF in addition to simply the field intensity. Valberg (1995) listed several such characteristics that he believed should be considered, when applicable, to fully describe the fields present in laboratory experiments involving magnetic-field exposures. These characteristics are listed below:

- **Exposure Intensity and Timing**
- **Magnetic-field intensity**
- **Timing and duration of exposure**
- **Repetition of exposure periods**
- **Circadian time of exposure**

- **Frequency-Domain Characteristics**
- **Field oscillation frequency**
- **Harmonic content**
- **Intermittency**
- **Turn-on turn-off transients**
- **Time coherence**

- **Spatial (Geometric) Characteristics**
- **Polarization (circular, linear)**
- **Orientation of AC and DC magnetic fields**
- **Spatial homogeneity**

- **Combined EMF Exposure**
- **Superimposed electric fields**
- **Earth's static (DC) magnetic field**
- **Incidental, unplanned EMF exposure**

- **Laboratory System Characteristics**
- **Cell culture system geometry**
- **Size, number, movement of animals**
- **Accessory non-EMF exposures**

For studies that include electric-field exposures, the same parameters should apply. To date, relatively few published papers on studies of EMF have provided such comprehensive information about fields used in the studies.

The sections below discuss some additional considerations specifically related to electric- and magnetic-field exposures in laboratory studies.

Electric Fields

In vivo studies. Most early interest in the possible health effects of electric power facilities involved electric fields. A large number of studies of laboratory animals have been done of power-frequency electric fields. A basic electric-field exposure system consists of two horizontal parallel plates, one of which is grounded and one of which has voltage applied. This arrangement produces a vertical electric field between the plates, where animals are placed during exposure (Fig. 4.1). This is, therefore, similar to the electric field beneath a transmission line which is also primarily vertical. The electric-field strength depends on the amount of voltage on the plate, and on the distance between the plates.

The strength of the electric field used in laboratory studies, has often been selected so that it has some application to human exposure to environmental fields. This requires taking into account the fact that conducting objects, including animals, perturb electric fields. As a result, the strength of an external electric field impinging on the surface of an animal or human depends on the size and shape of the body. Likewise, the body current induced by an electric field is greatly influenced by body size and orientation. This means that, in general, animals must be exposed to stronger electric fields than the field of interest for human exposure. For example, Figure 4.2 compares the surface field, induced body current, and short-circuit current for a human and two kinds of animals standing in a IO-kV/m electric field. Because humans have a relatively narrow and tall body shape, all three parameters are much greater compared to those of the animals. However, if the person were sitting down or bending over, the surface field and the internal current would be reduced. Likewise, when rats stand on their hind legs, the fields and currents are greater than those shown in Figure 4.2.

The kind of information in Figure 4.2 has been used by some researchers to scale the electric field used in laboratory animal studies, so that it more closely matches electric-field strengths for human exposures. For example, a rat would have to be exposed to an electric field of about 119 kV/m, to produce about the same amount of induced current across the chest as a person would receive standing in a 10-kV/ml electric field (about the maximum field beneath a large transmission line).

Plastic rodent cages can lower the exposure to electric fields in laboratory studies, especially when they are dirty (Free et al. 1981, Baum et al. 1991). The type of bedding, and the amount of soiling also produce some shielding of the electric field. There is mutual shielding when animals are close together which can further reduce electric-field exposure. In most papers on electric field studies, only the unperturbed electric field level is given (i.e., the field without the animals or cages present). The actual exposure may vary greatly among studies depending on the amount of shielding that may be present.

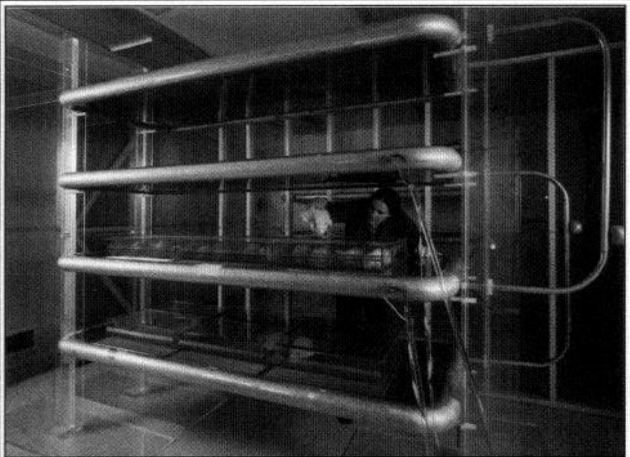


Figure 4.1. This is a parallel-plate system used for exposing laboratory animals to power-frequency electric fields. An electric field is produced between a horizontal metal plate that is connected to voltage, and a horizontal plate that is connected to ground. Voltage is turned off when personnel enter the room. Photo courtesy of Battelle Pacific Northwest Labs.

An animal's interaction with an electric field is also influenced by the design of cages and feeding and watering devices. Unless care is taken, animals can receive shocks inside the cage, and biological effects attributed to electric fields *per* se may actually be caused by shocks. Also, the possible production of noise, vibrations, or ozone from the electric field source must be considered. With proper methodology, these factors can largely be eliminated. These types of confounding factors may have been present to varying degrees in some of the early research on power-frequency electric fields. More detailed information on proper techniques for the generation and measurement of 60-Hz electric fields in laboratory studies can be found in a report by Misakian (1984).

In vitro studies. Parallel-plate exposure systems can also be used to expose cells and tissues to electric fields, although there are some limitations. Kaune et al. (1984) calculated that the maximum electric field that be induced into cell suspensions through air from parallel plates is about 0.01 V/m. This internal field strength is at least lo-times smaller than the maximum electric field induced in a person standing in the maximum electric field beneath a transmission line (Kaune and Phillips 1980). By using dielectric material such as glass or polypropylene instead of air, electric fields of 0.2 V/m have been induced into cell suspensions with parallel-plate systems (Kaune et al. 1984).

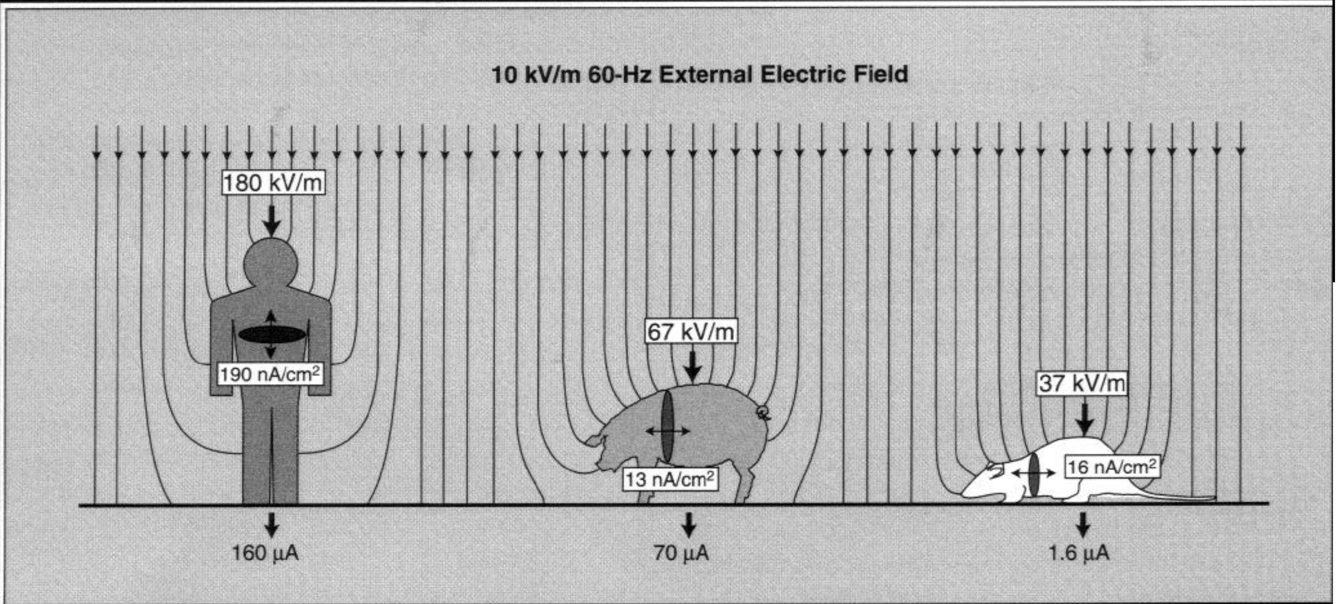


Figure 4.2. Grounded human, swine, and rat in a 10 kV/m vertical electric field showing enhanced field at the top of the body (kV/m), induced axial current averaged across the chest (nA/cm²), and short circuit current to ground (µA) (not to scale). Source: Kaune and Phillips (1980).

Other researchers have injected current onto electrodes that are placed directly into the cell suspension media to produce strong internal electric fields (Marron et al. 1986). The electric field strength can be calculated from Ohm's law by dividing the current density by the conductivity of the culture medium. This approach raises the possibility that metal ions from electrodes could contaminate the cell media. Some researchers used insulated electrodes (Greenebaum et al. 1979), or have used agar bridges to isolate the electrodes from the media (Reese et al. 1988). Figure 4.3 shows two basic types of electric field *in vitro* exposure systems.

Another approach for producing *in vitro* electric-field exposure is to induce an electric field in the culture medium with an external AC magnetic field (Kaune et al. 1984, Mullins et al. 1993). With this method, electrodes do not need to be in contact with the experimental medium. Researchers have also used RF/MW frequencies amplitude modulated at 60-Hz or other low frequencies to induce electric fields in cell and tissue cultures (Blackman et al. 1985a).

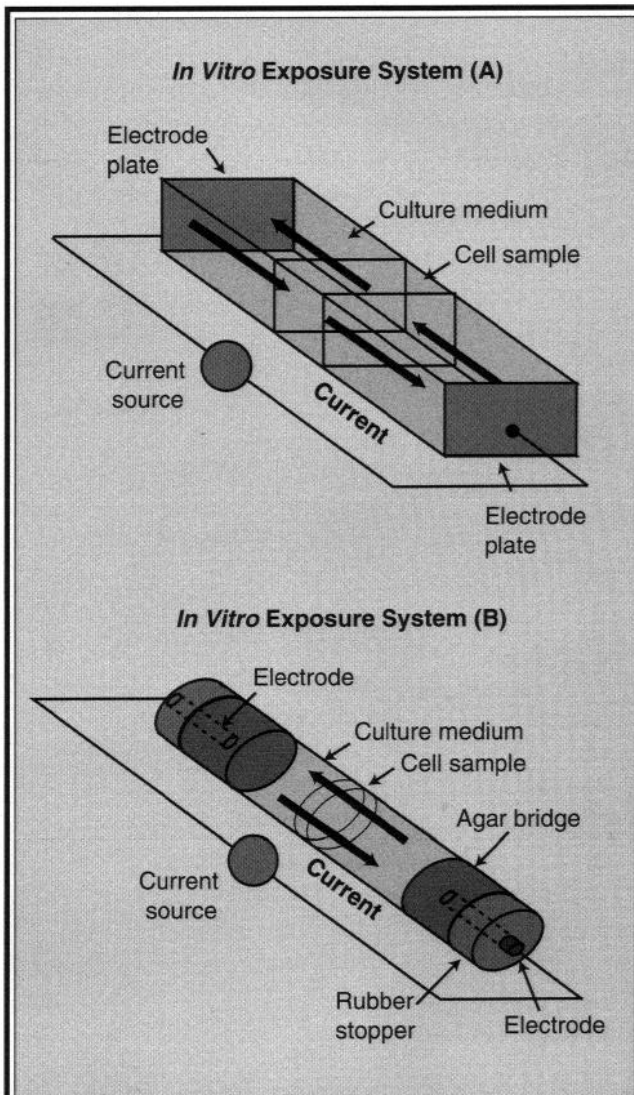


Figure 4.3. Simplified examples of two types of systems for exposing cells/tissue to 60-Hz electric fields. In (A) the electrodes are in direct contact with the culture medium. In (B) the electrodes are separated from the culture medium by agar bridges. Sources: Adapted from Reese et al. (1988), and Misakian et al. (1993).

Magnetic Fields

***In vivo* studies.** As interest in power-frequency magnetic fields began to increase, systems were developed for exposing animals to both electric and magnetic fields (Miller et al. 1989, Baum et al. 1991) and to magnetic fields alone (Wilson et al. 1994a, Stuchly et al. 1991, Mitsuru et al. 1993). These systems were often based on work by Merritt et al. (1983) who described specifications for current-carrying square coils that could be used to generate uniform magnetic fields. Figure 4.4 shows one design for a system for exposing laboratory animals to both electric and magnetic fields. The vertical electric field is produced by parallel-plate electrodes as described above. A horizontal magnetic field is produced from current in the square vertical coils that surround the system. Exposure systems can also be designed to produce vertical or circularly polarized magnetic fields (Shigemitsu et al. 1993, Baum et al. 1991).

Animals do not perturb the magnetic field, so there is no need to consider scaling factors for direct magnetic-field effects. However, the internal electric field that is induced by an external AC magnetic field is influenced greatly by body size and shape. If induced electric fields are of interest, it is, therefore, necessary to apply some scaling factor when laboratory animals are used in studies to obtain information about possible effects of magnetic fields on humans. Feero (1989) suggested that as a first-order approximation, magnetic field scaling factors should equal the linear dimensions of body sizes.

Stuchly et al. (1991) scaled magnetic-field exposure in a laboratory study by assuming that the maximum current loop radius is proportional to the cube root of the body mass (volume). If the average human body mass is assumed to be 70 kg (154 lb), and the average body mass for a mouse is 25 g (0.9 oz), then the scaling factor is about 14. Therefore in their study, on the basis of body mass, exposing mice to a magnetic field of 2 mT (20 G), is similar to exposing people to a field of about 0.15 mT (1.5 G).

Weiguo et al. (1994) concluded that weight-based scaling for 60"Hz magnetic field exposure is not as accurate as scaling based on induced currents from human and rodent models. For example, for the human-

Figure. 4.4. A system developed to expose laboratory animals to 60-Hz EMF. The electric field is produced by voltage on the parallel plate electrodes (metal tubing). The magnetic field is produced by current in the vertical rectangular coils (inside white plastic pipes).
Photo courtesy of Battelle Pacific Northwest Labs.

mouse comparison, the two scaling methods may vary by 1.7 times or more assuming homogeneous tissue conductivity. However, even bigger differences would be expected if heterogeneous conductivity models (which are more realistic) were used.

In vitro studies. Systems for exposing cells and tissues to power-frequency magnetic fields often use circular wire loops of many turns called Helmholtz coils (Misakian 1984). In a basic system, cell or tissue samples are placed within the magnetic field between two coils. The magnetic field is not perturbed by common materials used to contain the samples (e.g., glass or plastic). However, the shape of the container does affect the currents and electric fields induced in the medium within the container (Misakian et al. 1993).

Kirschvink (1992) discussed design considerations for improving the uniformity of magnetic fields produced by Helmholtz-coil exposure systems. He also recommended the use of double-wrapped coil systems. These systems have two sets of wire wrapping for the coils instead of one. When currents in the two wires are parallel, they add together and produce a magnetic field. When current is equal and opposite in the wires, they cancel and no field is produced; this arrangement can be also used for sham control exposures.

The magnetically induced current in a circular container perpendicular to the field is zero at the center, and progressively increases in strength to a maximum around the outer edge of the container. This phenomenon can be used to separate effects from the magnetic field *per* se, from effects due to induced currents and electric fields. If cell samples are placed in concentric circular wells separated from each other, all cells are exposed to the same magnetic flux density, but they are exposed to induced electric fields of differing intensity (Misakian et al. 1993).

The type of magnetic-field polarization that is used also affects the magnitude and oscillation of induced currents and electric fields in the cell medium. Both linear and circular polarization have been used for *in vitro* studies of power-frequency magnetic fields (Misakian 1991).

Studies of Laboratory Animals

The number of laboratory animal studies that have been done on power-frequency EMF is even more ex-' tensive than the epidemiologic studies reviewed in Chapters 3 and 4. It is, therefore, not feasible to include all known studies. Instead, the most often cited studies will be described. References are given to reviews of the laboratory research for readers who want more information about studies on a particular topic.

The laboratory animal research is grouped into 10 categories: 1) behavior, 2) stress, 3) growth, 4) reproduction and development, 5) melatonin, 6) other hormones, 7) cardiovascular system, 8) nervous system, 9) immune system, and 10) cancer and mutagenesis. For most categories, studies are further divided into electric- field studies, magnetic-field studies, and studies of combined electric and magnetic fields. As in previous chapters, the research is presented in a rough chronology reflecting the development of research issues.

Behavior

The behavior of animals can be a sensitive indicator of effects of exposure to environmental agents. Some behaviors are simple predictable reflexes, and others are influenced by past experience (Eckert 1988). Many behavioral tests measure locomotor activity by use of such methods as activity wheels, residential maze, or the open field. In the latter, for example, an animal's movements over a grid-lined floor are recorded.

Other animal behavioral tests involve conditioning using positive or negative reinforcers. For example, an animal given a mild shock paired with an audible tone will eventually respond aversely to the tone in the absence of the shock (McFarland 1993).

Operant conditioning is a widely used type of behavioral test. In these tests an animal is trained to perform a task (e.g., pull a lever, peck a button) to obtain a food reward (McFarland 1993). A wide variety of operant tests is used in which animals are trained to respond only under certain conditions, for example only when a certain sound or field is present. Tests are also used in which animals are rewarded when they respond in specific intervals of time. The timing of the response can be studied to determine whether some stimulus like EMF affects the timing or pattern of the response.

Other studies examine the behavior of animals as they perform day-to-day activities associated with feeding, grooming, sleeping, reproducing, and caring for young. Observations may involve isolated animals, or animals that are interacting as part of a social group. As with other research discussed in this chapter, behavioral research on EMF is primarily focused on assessing the potential hazardous effects of these fields. Behavioral effects seen in studies of EMF may mean that animals are simply aware of the fields and they are responding to their presence. Of more importance from a potential hazard viewpoint are behavioral changes that may represent a direct physiological effect of EMF on the functioning of the neuromuscular system.

Electric field. One of the earliest studies in the U.S. of 60-Hz electric fields and laboratory animals focused on animal behavior (Moos 1964). That study found that nighttime activity levels were increased when mice were exposed to 60-Hz fields of 0.8-1.2 kV/m. Since then, several other laboratory studies of power-frequency electric fields have also reported changes in behavior of mice, rats, baboons, and swine. Table 4.1 summarizes several of these studies.

Most of the studies used stronger field strengths than those used in the study by Moos (1964), and it was clear early on that strong electric fields could greatly affect behavior because of shocks, if precautions were not taken. In the study by Knickerbocker et al. (1967) with fields of about 160 kV/m, mice were shocked when they attempted to drink from water bottle nipples. The electric field had to be turned off for a time each day to allow the animals to drink. Researchers in that study also reported that corona could be heard from the mice when they attempted to stand on their hind legs.

Some studies have attempted to determine the lowest 60-Hz electric-field strength that animals can detect. The combined detection range for rats reported by two research groups using different methods was 3-13.3 kV/m (Stern et al. 1983, Stern and Laties 1985, Sagan et al. 1987). This is very similar to the 60-Hz electric-field detection threshold for baboons (5-15 kV/m) (Orr et al. 1995a). The detection threshold for pigeons was between 10.5 and 21 kV/m (Cooper et al. 1981).

Detection of electric fields is presumably mediated at least in part by surface stimulation of feathers, fur, and vibrissae. Weigel and Lundstrom (1987) found that the vibration of vibrissae in an electric field is influenced by relative humidity.

At least two studies found that animal detection of 60-Hz electric fields is not caused only by hair vibration. Stell et al. (1993) found that blowing air over rats (to cause hair movement) did not eliminate the animals' ability to detect electric fields. A cutaneous receptor was found in the cat's paw that responds to 60-Hz electric fields (Weigel et al. 1987). These studies show that there may be other biological receptors that are sensitive to 60-Hz electric fields.

In addition to detection, some studies used shuttle-box systems to determine whether animals would avoid electric fields if given the opportunity to do so. Swine tended to avoid 30-kV/m fields (Hjeresen et al. 1982), and rats tended to avoid fields of 60 kV/m and above (Hjeresen et al. 1980). In contrast, the latter study also found that during the light period, rats apparently preferred to be in 60-Hz electric fields of 25 or 50 kV/m. Bayer et al. (1977) found that female rats preferred to build their nests outside of a lOO-kV/m 50-Hz field. The lowest level at which females would leave their nest was about 10-20 kV/m. Le Bars et al. (1983) reported that rats did not avoid eating in a 50-kV/m field compared to a area with no field.

Strong 60-Hz electric fields of up to 65 kV/m were not aversive to baboons (Rogers et al 1995b), although some studies showed that certain social behaviors were temporarily affected by electric-field exposure (Coelho et al. 1991, Easley et al. 1992). Three behaviors that seemed to be affected, although not always significantly, were called passive affinity, tension, and sterotypy. Those researchers suggested that electric fields of 30-60 kV/m affected the baboon's central nervous system by unknown mechanisms. They added that there were insufficient data to determine whether such effects might be deleterious.

Magnetic field. Several laboratory studies have looked for behavioral responses of animals to magnetic fields at or near the frequency of electric power (Table 4.2). Female pigmented rats (Long-Evans Hooded) appear to be able to detect 60-Hz magnetic fields of at least 0.22 mT (2.2 G), although lower flux densities were

Table 4.1. A summary of studies of behavior of laboratory animals exposed to electric fields.

Study/Location	Species/Exposure (60-Hz vertical, unperturbed, unless noted)	Selected Behavior Results
Moos (1964), U.S.	Groups of 1 O-1 7 male mice 6-wk old exposed/not exposed l-30 days to 0.8-I .2 kV/m. No controls.	Mechanical counts showed that during the night mice were significantly more active during field-on times, compared to field-off times.
Knickerbocker et al. (1967) U.S.	22 male mice exposed 10.5 months to 160 kV/m, 6.5 hr/day. No water during exposure. 22 controls.	Subjective observations: exposed animals reacted to the strong electric field, and tended to sleep more than controls.
Gavalas-Medici & Day-Magdaleno (1976), U.S.	Groups of 4-5 monkeys were exposed to 7-, 45., 6O-, & 75Hz horizontal fields of up to 56 V/m peak to peak.	Exposure to fields at frequencies of 7 & 75Hz but not 60-Hz significantly modified a lever-press response in monkeys.
Bayer et al. (1977), Sander et al. (1982), Germany	6 male rats 6-wk old exposed to 50-Hz 100 kV/m for 1 yr; 6 controls. 5 female rats to 100 kV/m for 1 -wk.	Male activity (measured automatically) lower in exposed, but they spent more time gnawing on food holders. Females avoided fields .10 kV/m.
Smith et al. (1977), U.S.	8 male rats were exposed to a 25.kV/m horizontal field fur 6 wk. 8 controls.	When tested after the fifth week of exposure, there was a tendency for the exposed rats to show greater exploratory activity.
Shandala et al. (1979), Russia	400 rats were exposed to 50-Hz fields of 10, 15, or 20 kV/m for 1-4 months for 20-320 min per day. Controls.	In tests before, during, and after exposure, fields of 15 & 20 kV/m significantly affected the latent period of conditioned reflexes to bells/buzzers.
Babovich & Kuzyarin (1979), Russia	Male rats were exposed to 50-Hz fields of 7, 12, or 15 kV/m for 4 months for 30 min per day. Controls.	Significant effects on the rats' working capacity (swimming with load) in 15lkVlm and on the latent period of conditioned reflex in all fields.
Graves et al. (1979) Cooper et al. (1981) U.S.	6 pigeons were trained to peck a food key and then tested to determine if they could detect an electric field.	A conditioned suppression test showed that pigeons detected a field at a level of between 10.5 and 21 kV/m at head height.
Hjeresen et al. (1980), U.S.	Groups of 8 male rats were exposed to fields from 0 to 105 kV/m in 45min periods, and one 23.5-hr period.	In 45-min tests rats significantly avoided .90 kV/m, and tended to avoid .60 kV/m. Fur 23.5 hr, .75 kVlm avoided, 25 or 50 kVlm preferred.
Rosenberg et al. (1981), U.S.	34 male deermice, ungrounded, and 21, grounded, exposed to IOO-kV/m over four l-hr periods at l-hr intervals.	Activity (measured automatically) increased significantly during the inactive phase of the circadian cycle for the first exposure period.
Hjeresen et al. (1982), U.S.	17 small female swine exposed to 30-kV/m for 3438 hr (mean) before 2l-hr behavior testing. 15 controls.	Swine spent significantly more time in the shielded part of their pen than in the part exposed to 30-kV/m.
Rosenberg et al. (1983), U.S.	5 groups of 12 deer mice were exposed at inactive period for l-hr to fields from IO-75 kV/m at 1 -hr intervals. 8 controls.	Mice showed significant arousal only at first exposure to .50 kV/m as measured by activity, CO, production, and 0, consumption.
Le Bars et al. (1983), France	Rats, mice, rabbits, and guinea pigs exposed to 50-Hz 50 kV/m field.	No changes observed in general behavior, or in distribution of rats' use of feeding areas in fields of 0 to 50 kV/m (no behavioral data shown).
Savin & Kuz'micheva (1985), Russia	Male rats were exposed to 50-Hz fields of30or100kV/mfor1 hror1 hr&20 min per day for 9 days. Controls.	Exposure to both field levels led to a significant slowing of the development of a conditioned reflex activity to sound but not to light.
Stern et al, (1983), Stern and taties (1985), U.S.	19 male & 5 female rats were trained to press food levers, and used in tests to measure detection of electric fields.	Threshold of field detection for males was generally between 4-10 kV/m and for females the detection threshold was about 3-10 kV/m.
Creim et al. (1984), U.S.	Groups of 8 male rats were exposed to fields of 34-133 kV/m in taste-aversion experiments.	Consumption of saccharin in presence of the field did not lead to taste aversion learning (field did not cause gastrointestinal distress).
Blackwell & Reed (1985), U.K.	20 male mice were exposed fur 3O-min/ day for 5 days to 50-Hz fields af 50-400 V/m peak to peak. 20 controls.	No effects on exploratory behavior or on emutionality as measured by movement and excretion during 2 min on an open field arena.

Table 4.1. A summary of studies of behavior of laboratory animals exposed to electric fields. (Cont.)

Study/Location	Species/Exposure (60-Hz vertical, unperturbed, unless noted)	Selected Behavior Results
Weigel & tundstrom (1987), U.S.	Snouts of 12 rats were exposed to a 5U-kV/m field periodically from spring through winter, and vibrissae observed.	The number of vibrissae that vibrated depended on % relative humidity-above 39% no more than 1 vibrated; at 25%, half of them vibrated.
Sagan et al. (1987), U.S.	16 male rats were trained and used in 2 tests to measure their detection of electric fields of various strengths.	Threshold of field detection for males was generally between 7.9-13.3 kV/m. Rats were trained to detect tones to receive water.
Stern & laties (I 989), U.S.	3 male and 2 femaie rats were trained to press a lever to turn off a 9U- or 100-kV/m field to study aversive stimuli.	Rats did not reliably turn off the electric field but they did turn off an incandescent lamp which was apparently an aversive stimulus.
Coelho et al. (199l), Easley et al. (1991,1992), U.S.	8 young adult male baboons were exposed to 30 kV/m, or to 60 kV/m for 12 hr/day for 6 wk. 8 controls.	Systematic observations indicated that baboon behavior was significantly affected, reflecting a stress response to the field.
Stell et at. (1993), U.S.	6 male rats were trained to detect electric fields, and tested to see if moving air affected detection.	Moving air did not affect field detection suggesting that movement of hair, vibrissae, or skin is not the main mechanism for field detection.
Orr et al. (1995a), U.S.	6 male baboons were trained to push a button in the presence of a 60-Hz electric field to measure field detection.	The average field detection threshold for male baboons was 12 kV/m and the range among subjects was 5-15 kV/m.
Rogers et al. (1995a), US.	12 male baboons pushed a button within certain times fur food. 6 wk at 30 & 60 kV/m, 12 hr/day. 12 controls.	In 2 studies, baboons significantly decreased responding "work stoppage" to test cues on the first day of exposure. No effects over 6 wk.
Rogers et al. (1995b), U.S.	6 male baboons were trained to obtain a food reward in the presence of a light and/or an electric field.	In 7 studies, no strong evidence that baboons perceived fields up to 65-kV/m field as aversive, and exposure did not affect operant responding.

not tested in the study by Smith et al. (1994). A strong 60-Hz field of 3.03 mT (30.3 G) was not found to be aversive to rats (Lovely et al. 1992). This field level was selected by the researchers because it induces currents in a rat that exceed the current induced by a 130-kV/m electric field. Rats avoid strong electric fields (Hjeresen et al. 1980). Therefore, the results of the magnetic-field study suggest that field avoidance is mediated by factors other than induced current, e.g., by sensory stimulation effects.

Sander et al. (1982) found no evidence that rats avoided spending time in a strong 50-Hz magnetic field of 5 mT (50 G). In that study, a field-exposed cage and a nonexposed cage were connected by a tube through which the rats could move freely.

Another study found no evidence that male albino rats (Sprague-Dawley) could detect a 0.2 mT (2 G) 45Hz magnetic field (Marr et al. 1973). There are several differences between this and the study by Smith et al. (1994), including sex and type of rat, field frequency, and differences in the type of tests used in the studies.

Male rats exposed to 50-Hz magnetic fields of 0.04 mT (0.4 G) showed increased rearing activity and trends for an increase in ambulation, and less defecation (Rudolph et al. 1985). It is not known whether these effects were associated with field detection, or with other mechanisms.

Some behavioral studies of rats reported interactions between AC magnetic fields and other factors. The rate and pattern of the performance of rats in a behavioral test was affected only when rats were exposed to a specific combination of 60-Hz and DC magnetic fields (Thomas et al. 1986). No effects were seen with either field alone. The study was a test of a cyclotron resonance theory (Liboff 1985); the fields used in the study were selected to correspond to the mass ratio for lithium ions. A later study by Stern et al. (1996) did not replicate the findings of Thomas et al. (1986). An earlier *in vitro* study by Blackman et al. (1985b) found effects of combined AC and DC magnetic fields on calcium efflux from chick brain. Even if cyclotron resonance is not the mechanism responsible for effects seen in the rat study, those authors pointed out the importance of considering the geomagnetic field when assessing effects of 60-Hz fields.

Specific combinations of AC and DC magnetic fields affected the performance of rats in seeking food rewards in a radial arm maze (Lovely et al. 1994). Also,

Table 4.2. A summary of studies of behavior of laboratory animals exposed to magnetic fields.

Study/Location	Species/Exposure (60-Hz, horizontal unless noted)	Selected Behavior Results
Grissett (1971), U.S.	3 squirrel monkeys were for 42 days to a 45-Hz field of 1 .O mT (10 G).	Field exposure had no consistent effects on the monkey' rates of lever-pressing to obtain food.
Marr et al. (1973), U.S.	7 pigeons and 4 male rats were trained for behavioral tests and exposed to 0.2 mT (2 G) vertical fields (rats, 45 Hz).	Pigeons: the field did not affect temporal discrimination during tests, and it was not detected. Rats: a 45Hz field was not detected.
de Large (1974), U.S.	2 male & 2 female rhesus monkeys were exposed to a 15- or a 45-Hz field of 0.82-0.93 mT (8.2-9.3 G).	Field exposure had no consistent effects on the operant behavior of monkeys (rates of lever-pressing to obtain food).
Smith & Justesen (1976), U.S.	39 male mice (2 strains) in groups of 3 were exposed to a vertical 1.7 mT (17 G) field for 2-min periods over 48 hr.	Locomotor activity increased in both strains during field exposure; the pigmented strain was more reactive to the field.
Silny (1976), Germany	Rats were exposed to a 50-Hz 50-mT (500-G) field for 1 wk.	Rats could freely leave the magnetic field area if they found it aversive. At most, the field caused only a weak irritation in the rats.
Clarke & Justesen (1979), U.S.	A test of the ability of 4 chickens to detect a vertical 60-Hz modulated 2450 MHz 1.7 mT (17 G) field.	A conditional suppression test suggested that chickens could detect the field but possible cues from vibration or heating could not be ruled out.
Sander et al. (1982) Germany	In 8 tests with 2 rats each, rats could select cages in a 50-Hz vertical field of 5 mT (50 G), or a nonexposed cage.	Little difference was found between amount of time spent by rats in the field-exposed and the nonexposed cages (data not shown in paper).
Davis et al. (1984), U.S.	14 female mice were exposed to a 1.65 mT (16.5 G) field for 72 hr. 14 controls.	No effects of field exposure were seen on locomotor activity, memory of electroshock avoidance task, or response to seizure agent.
Rudolph et al. (1985) Germany	Groups of 8 male rats were exposed to a 50-Hz, 0.04-mT (0.4-G) field for 4 hr. 8 controls per experiment.	Rats exposed to the field at the beginning of the light phase showed 40% more rearing activity than the controls No effects for dark phase.
Thomas et al. (1986), Liboff et al. (1989), U.S.	5 male rats were exposed for 30 min before I-hr tests to 0.05-.5 mT (.5-5 G) fields with/without a DC field-O.026 mT.	Exposure to both 60-Hz and DC fields, affected rate & pattern of rats' response in a reinforcement test. No effect seen with either field alone.
Ossenkopp & Kavaliers (1987a, 1987b), U.S.	Male mice were treated with morphine and exposed to 0.05-0.15 mT (.5-I .5 G) fields for 60 min. Controls.	Significant dose-response reduction of the pain-reducing effect of morphine (behavior on a warm hotplate) at night. No daytime exposure effect.
Ossenkopp & Cain (1987), U.S.	Male rats were exposed to fields of 0.05-0.185 mT (0.5-I .85 G) and treated wiith a seizure-inducing drug. Controls.	Fields of I-l .5 G significantly reduced the lethality of the drug-induced seizures. Fields of 0.5 and 1.85 G had no significant effects.
Lovely et al. (1992), U.S.	32 male rats. A 3.03-mT (30.3-G) vertical field present in part of the box.	Rats did not avoid that part of the shuttle box exposed to the magnetic field.
Trzeciak et al. (1993) Poland	Male and female rats were exposed to 50-Hz fields of 8 mT (80 G) 2 hr/day for 20 days, and tested at 3 time points.	Both sexes exposed to the field showed significantly lower levels of irritability, and no effects on exploratory behavior or locomotion.
Smith et al. (1994), U.S.	5 female rats were trained and exposed to 0.2-I ,9-mT (2-I 9-G) vertical fields for 3 min in tests for field detection.	A conditioned suppression test showed that rats detected the field as a cue to stop food-lever pressing to avoid a brief electrical shock.
Lovely et al. (1994), U.S.	Learning was studied in rats trained to obtain food in an 8-armed radial maze exposed to combined AC & DC fields.	Rats made more search errors in 0.05 mT (0.5 G) 60 Hz & 0.027 mT (0.27 G) DC fields; fewer errors in 0.05 mT 60 Hz & 0.048 mT DC fields.
Prato et al. (1996), Canada	Groups of 10-l 2 land snails exposed to a 60-Hz 299-uT (peak) (2.9-G) magnetic with DC field of 78 µT (780 mG).	AC + DC magnetic field exposure reduced effect of drug on snails' response to a hot plate. Field effect may be through direct field detection.
Stern et al. (1996), U.S.	5 male rats exposed to 60-Hz & DC fields as in Thomas et al. (1986).	Behavioral effects of AC + DC fields found by Thomas et al. (above) not found in this study.

mice exposed to a 0.75-mT (7.5-G) 50-Hz magnetic field tended to make more errors in finding food in a maze compared to the control mice (Sienkiewicz et al. 1996).

Another rat study in Table 4.2 reported an interaction between a 60-Hz magnetic field and mortality from drug-induced seizures (Ossenkopp and Cain 1987). The drug was PTZ (pentylenetetrazol) administered at a dose of 55-60 mg/kg. The lethality from seizures was reduced when male rats were exposed to fields of 0.1-O. 15 mT (1.0-I .5 G), but no reduction was seen with stronger fields. Lovely et al. (1996) also found a trend for reduced mortality from PTZ-induced seizure in rats exposed to a 0.1 mT (I G) 60-Hz magnetic field. In the study by Ossenkopp and Cain (1987), a 0.1 -mT (I-G) field had no effect on novelty-elicited seizures in Mongolian gerbils. An earlier study with male mice found no effect of a l .65 mT (16.5 G) 60-Hz magnetic field on severity of seizures induced by PTZ at a dose of 75 mg/kg (Davis et al. 1984).

A behavioral study with mice also reported an interaction between a drug (morphine) and a 60-Hz magnetic field (Ossenkopp and Kavaliers 1987a, 1987b). Another study of mice found that their relative activity levels while exposed to a 60-Hz magnetic field were higher for a pigmented strain compared to albino mice (Smith and Justesen 1976). Those authors suggested, however. that the finding may have been confounded by other variables.

Strong 45-Hz magnetic fields had no effects on the behavior of two species of monkeys (Grissett 197 I. de Lorge 1974). The animals were trained to press a lever to obtain food, and field exposure had no significant effects on the monkeys' performance of this task.

Combined fields. Some of the earliest behavioral studies of combined AC electric and magnetic fields were done for frequencies of 45 and 75 Hz, instead of the electric power frequencies (50/60 Hz). The former were associated with frequencies of a planned U.S. Navy submarine communication project (at various times the project was called *Sanguine,* Seafarer and ***ELF). Sev***eral species were studied that were exposed to electric fields of I O-20 V/m and magnetic tields of 0.2 mT (2 G) (Coate et al. 1970). In some of the tests, bluegill fingerling fish and Eastern painted turtles reacted to the onset of the tields in water. Reactions were not observed for young and adult rats, or for mallard ducklings. Adult rats and their offspring conceived and raised in the combined fields did not differ from controls in their performance in avoidance and escape learning tests.

In other Navy-sponsored studies, rhesus monkeys were exposed to l mT (IO G) magnetic fields and weak electric fields of up to a few 10s of V/m at frequencies of 10, 45, and 60 Hz (de Lorge 1973a, 1973b). Exposure to these fields produced no consistent effects on the monkeys' performance in various behavioral tests.

Adult rats that were exposed perinatally to 60-Hz fields of 30 kV/m (vertical), and 0.1 mT (1 G) (circularly polarized) showed altered behavior in responding to tests (Salzinger et al. 1990). Forty-one male rats in two experiments were exposed to EMF throughout their mother's pregnancy, and for the first 8 days after they were born. The rats were trained to press a lever, and as adults they gradually began to respond at lower rates compared to unexposed controls. No effects were found on general activity levels of the exposed rats.

Performance on a simple motor task was studied in six monkeys (pigtailed macaques) exposed to 60-Hz EMF of 3 kV/m and 0.01 mT (0.1 G), 10 kV/m and 0.03 mT (0.3 G). and 30 kV/m and 0.09 mT (0.9 G) (Wolpaw et al. 1989). Exposure occurred during three 21-day periods. Compared to four control monkeys, exposure to combined EMF had no effects on the monkeys' performance of a task to obtain water. There were also no indications that the fields were disturbing to the animals.

Another study found no effects on the feeding rhythm of two squirrel monkeys exposed to 60-Hz EMF of 2.6 kV/m and 0.1 mT (1 G) (Sulzman and Murrish 1986). A slight lengthening of the feeding period was seen in three of nine monkeys exposed to 26 kV/m and 0.1 mT (1 G), and in three of four monkeys exposed to 39 kV/m and 0.1 mT (1 G). In these studies, the animals served as their own controls during the field-off periods. The researchers suggested that the results from their laboratory study might not occur in natural outdoor environments where numerous cues are available to time biological rhythms.

As summarized in Table 4.2 rats exposed to both an AC and a DC magnetic field showed a change in performance on a behavioral test (Thomas et al. 1986). No such effects were found when the same researchers exposed rats to combined 60-Hz EMF of I kV/m and 0.05-0.5 mT (0.5-5 G) (Thomas et al. 1984).

Orr et al. (1995b) studied operant behavior of baboons exposed for 6 weeks to 60-Hz EMF of 6 kV/m and 50 μT (0.5 G), and 30 kV/m and 100 μT (I .O G) (Fig. 4.5). No significant effects of either of the combined exposures were found on the performance of baboons in selecting the correct button to match a flashing light (match to sample test). There was also no evidence of a "work stoppage" which was found by Rogers et al. (1995a) in a previous study of baboons exposed to an electric field.

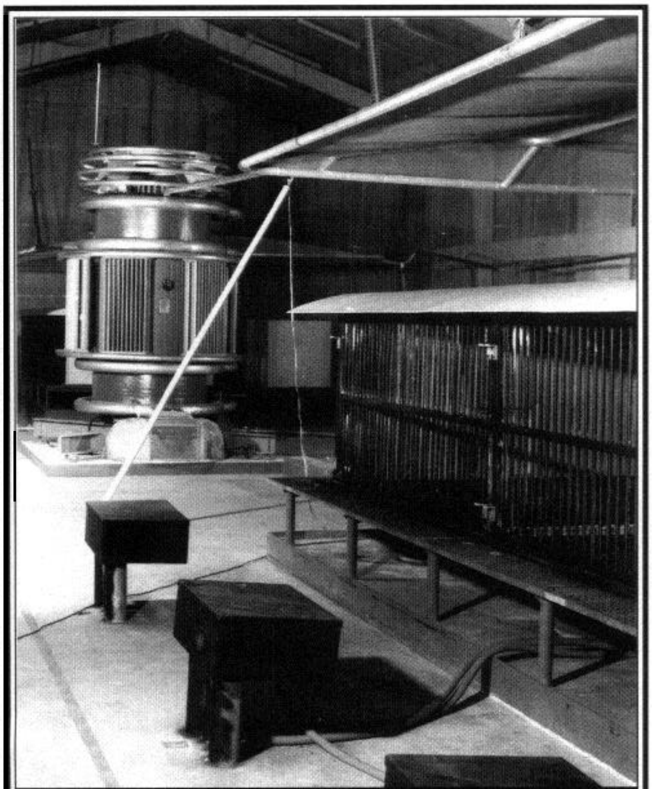


Figure. 4.5. Facilities for exposing baboons to 60-Hz EMF. Cages (right) are under a metal screen that produces an electric field. The large object in the back is a series resonant inductor for supplying high voltage to the screen. Large current-carrying wire loops around the facility produce a magnetic field. Photo courtesy of Southwest Research Institute.

The social behavior of male baboons was also studied by the same research group using the same combined EMF as in the above study (Coelho et al. 1995). Neither of the combined EMF exposures resulted in clear effects on passive affinity, tension, or stereotypy behaviors found in an earlier studies of electric fields (Coelho et al. 1991). However, exposure to combined 6 kV/m and 50 µT (0.5 G) EMF did result in overall decreased behavioral performance rates compared to pre- and post-exposure periods. Exposure at the higher combined field intensities, 30 kV/m and 100 µT (1 G), did not produce the same effects seen with the lower intensities, or effects seen in earlier studies with electric fields only. The researchers said that it was not clear whether the absence of effects at the higher levels were due to prior exposure to the lower levels, or to an inhibitory effect of the 100-µT (1-G) magnetic field on the effects from the 30-kV/m electric field (Coelho et al. 1995).

Observations were made of the general behavior of sheep raised in the 60-Hz EMF beneath a 500-kV transmission line (Lee 1992). The observations were made at 15-minute intervals during 24-hour periods once a month for 9 months. Compared to sheep raised in a control area, there were no noticeable effects of exposure on the percentage of time spent by the sheep in resting, feeding, standing, walking, or drinking.

Stress

Stress has been defined by Selye (1974: 14) as, "... the nonspecific response of the body to any demand placed upon it." He added that it makes no difference whether the stress-producing agent is pleasant or unpleasant. Selye (1974) referred to damaging or unpleasant stress as "distress." By these definitions stress cannot be avoided, but excessive stress (distress) should be avoided if possible.

Response of animals to environmental stressors can be divided into two general kinds of physiological reactions (Dantzer and Mormede 1983). First are the short-term emergency reactions characterized by release of hormones such as epinephrine (adrenaline) from the adrenal medulla. Second is the long-term reaction originally referred to as the "general adaptation syndrome" by Selye (1936). In this syndrome, deleterious effects including death occur when an animal is no longer able to adapt to chronic stress.

Hormones involved in the stress reaction include ACTH from the pituitary which causes the adrenal cortex to secrete corticosteroids-cortisol and corticosterone. Sheep, monkeys, and humans primarily secrete cortisol: whereas birds, rats, and mice secrete mainly corticosterone (Ganong 1981). Measurement of the so-called stress hormones identified above, as well as other possible stress indicators have all been used in studies to determine whether exposure to EMF causes excessive stress in laboratory animals.

Electric field. The early studies of behavior of animals exposed to strong electric fields described above (e.g., Knickerbocker et al. 1967) reported adverse reactions of animals to the fields. Marino et al. (1976b, 1977) were among the first to specifically propose that exposure to power-frequency electric fields caused a stress response in laboratory animals. Their research, however, found that rats exposed to 15-kV/m electric fields had lower levels of corticoids compared to controls. This is opposite to the normal increase in these hormones expected in animals responding to stress.

There have now been several laboratory studies that have measured corticosterone in animals exposed to power-frequency electric fields (Table 4.3). One of these also found a decrease in the level of the hormone in rats, but a decrease was not found in a replicate experiment (Free et al. 1981). Those authors suggested that the inconsistent results of their two studies, may have

Table 4.3. A summary of studies of stress in laboratory animals exposed to electric fields.

Study/Location	Species/Exposure (60-Hz vertical, unperturbed, unless noted)	Selected Behavior Results
Marino et al. (1976b, 1977), U.S.	154 male rats in 10 experiments were exposed to 15 kV/m for 1 month. 179 controls.	In some experiments, exposed animals showed depressed body weight, water consumption, and corticoids-interpreted as stress response.
Marino et al. (1979a, 1979b), U.S.	Fibula bone fractured in 80 male rats and rats were then exposed to fields of 1 or 5 kV/m for 14 days. 78 controls.	Fracture healing was slower for 5 kV/m at 14 days but not for 1 kV/m. Authors concluded result is evidence that electric field is a stressor.
Graves et al. (1979), Hackman & Graves (1981), US.	Male mice (35/group) exposed to 25 or 50 kV/m for 6 wk and 35 controls. 220 mice (0,25, & 50 kV/m) exposed 2 hr.	Exposed mice had significantly higher WBCs. Corticosterone was significantly increased 5 min after start of exposure, but not over 6-wk.
Free et al. (1981), U.S.	Male rats were exposed for 30 days (1 study) and 120 days (2 studies) to a 98-kV/m field. Controls.	In one 120-day study body and adrenal weights, and corticosterone were significantly decreased. Adrenal weight significantly higher in the other 120-day study. No effects in the 30-day study.
Seto et al. (I 982a, 1982b), Hsieh et al. (1983), U.S.	3 generations of male rats (more than 300 individuals) were exposed to a 80 kV/m field, Controls.	Exposed rats had increased adrenal weights, and > 25% increased levels of corticosterone. Authors suggested the field is a mild stressor.
McClanahan and Phillips (1983), U.S.	Fibula bone was fractured in male rats and rats were exposed to a 100 kV/m field for 14-26 days. Controls.	Fracture healing was slower at 14 days for exposed rats as found by Marino et al. (see above). No effect on bone strength at 26 days.
Portet et al. (I 984), Portet & Cabanes (1988), France	50-Hz 50-kV/m: 20 male rats exposed for 4 wk; 28 pregnant rabbits exposed during and/or after pregnancy. Controls.	Rats: corticosterone & ACTH higher in exposed rats, but not significantly. Mothers & young rabbits: no effects on corticosterone or ACTH.
Quinlan et al. (1985), U.S.	Male rats were exposed for 1 or 3 hr to a IOO-kV/m constant or intermittent (16 sec on/ 16 sec off) field. Controls.	No significant effects of exposure were found on corticosterone levels.
Behari et at. (1986), India	20 male rats were exposed to a horizontal 50-Hz 5 kV/m field for 2-3 months. 20 controls.	Exposed animals ate and drank less and had differences in electrocardiograms compared to controls-interpreted as stress responses.
Quinlan et al. (1987), U.S.	Blood samples were taken from male rats every 14 sec during 1 -hr exposures to a 80 kV/m field. Controls.	No significant effects of exposure were found on corticosterone levels.
Leung et al. (1990), U.S.	Study I : female rats exposed to a 40-kV/m field from gestation to adulthood. Study 2: female rats exposed in utero to 14 wk to IO-I 30 kV/m. Controls.	Females exposed to 40-I 30 kV/m had increased deposits of brown material (possibly from Harderian gland) on nose and ears. The deposits may reflect a response to stress.
Coelho et al. (1991), Easley et al. (1991,1992), U.S.	8 young adult male baboons were exposed to 30 kV/m, or to 60 kV/m for 12 hr/day for 6 wk. 8 controls.	Systematic observations indicated that the baboons' behavior was significantly affected, reflecting a stress response to the fields.
de Bruyn & de Jager (1994), Republic of South Africa	6 generations of mice were exposed to a 50-Hz IO-kV/m field from conception until death.	Adult males had significantly higher daytime corticosterone levels, and significantly increased mean adrenal lipids, suggesting chronic stress.

been because the exposed and control animals showed different corticosterone cyclic patterns, which would affect levels measured at a single time point.

Of the three studies in Table 4.3 that showed increased corticosterone, one found that the increase in male mice only occurred for a few minutes after the electric field had been turned on (Graves et al. 1979, Hackman and Graves 1981). In another study, adult male mice showed increased levels of daytime corticosterone during long-term exposure to electric fields (de Bruyn and de Jager 1994). Levels were not elevated at night, but authors of the study concluded that the electric field acted as a chronic stressor. No effects on corticosterone were found in that study for female mice, or for young male mice. Male rats exposed long-term to electric fields had increased corticosterone levels, and increased adrenal gland weights, which led the researchers to conclude that electric fields are a mild stressor (Hsieh et al. 1983).

No effects on corticosterone were found with short-term electric-field exposures on rats in the studies by Quinlan et al. (1985, 1987). Those authors pointed out the importance of considering the many extraneous factors that can cause stress in laboratory animals. If not controlled for, such factors can confound the effect that may be attributed to electric field exposure.

In addition to hormones, other measures have been cited by some researchers as evidence that electric fields can cause stress in laboratory animals. These include slowing of body growth and bone fracture repair (Marino et al. 1977, 1979a, 1979b), food and water consumption (Behari et al. 1986), changes in animal behavior (Easley et al. 1991, 1992), and secretion of material that has been associated with response to stress (Leung et al. 1990). Although two studies found that fracture repair is slowed in rats exposed to 60-Hz electric fields (Marino et al. 1979a, 1979b, McClanahan and Phillips 1983), normal bone growth is not affected (McClanahan and Phillips 1983) or may even be slightly increased (Walker et al. 1982).

All of the studies cited above that reported a stress response in rats were conducted with electric-field strengths that were within or above thresholds for field detection (Table 4.1). Some were also done with field strengths above levels shown in other studies to be aversive to rats (Table 4.1). If electric-field stress responses in rats and other species are due primarily to detection of an unpleasant stimulus, this is of interest for human exposure. Most people are seldom exposed to power-frequency electric fields that are detectable.

Magnetic field. Few laboratory studies have looked for indications of stress in animals exposed to power-frequency magnetic fields. Picazo et al. (1996) found that rhythmicity of the daily cortisol plasma concentration in mice was altered with chronic exposure to a 50-Hz 15-pT (150-mG) magnetic field. This, along with histological changes in the adrenal gland, suggested to the researchers a possible response of the mice to stress. A long-term study of sheep raised beneath a 500-kV transmission line found no evidence that cortisol secretion was affected by exposure to 60-Hz EMF (Thompson et al. 1995).

Growth

Growth is influenced by many factors, including genetics, food and water consumption, food content, age, health, and a wide variety of environmental factors including temperature. Controlling and accounting for these factors in studies of EMF is challenging. Not all studies report sufficient details to allow an assessment of whether these factors influenced study results. The presence of induced currents on water and feeding devices in animal cages can greatly affect food and water intake. In some studies, exposure systems were designed to minimize induced currents; in other studies, fields were turned off at times to allow animals time to drink.

Electric field. Several studies that looked at growth of laboratory animals exposed to electric fields are summarized in Table 4.4. Most of the studies reported some changes in growth in field-exposed animals, but results often appear to be inconsistent within and among studies. Marino et al. (1976a) reported that at least some of the effects on growth of mice in their pilot study may have been related to induced currents on food and water devices. Steps were taken to reduce problems from induced currents in their later study (Marino et al. 1980), and there was a trend for increased weight of exposed animals compared to controls.

Margonato et al. (1993) suggested that their early studies that found decreased growth of rats exposed to 100-kV/m fields, may also have been due to induced currents on drinking devices. In their later study water was provided to animals only when the electric field was turned off, and no effects on growth were found (Margonato et al. 1993). Sikov et al. (1984) designed their exposure system so that rats exposed to a 100-kV/m field did not receive shocks while eating or drinking. No effects on growth were reported in that study.

Exposure in the large four-generation mouse study by Smith et al. (1981) was assumed to be at 100 kV/m. However, after the study was published, the researchers discovered that, because of a problem with a transformer, the field was only 120-250 V/m (Phillips 1982). The study points out the high variability in growth rates that typically occur in animal populations. The 128 litters in the study were consistently different in weight both for exposed and control groups. The study also shows the difficulty of detecting a possible small effect of electric-field exposure when growth rates are changing daily.

Statistical tests can be used to determine the probability that differences between exposed and control groups are due to chance. However, it is a matter of subjective judgment by the researchers about how to interpret statistically significant differences that appear to be inconsistent. As an example, Marino (1990) analyzed results of eight multigeneration studies of mice exposed to 60-Hz electric fields, including those conducted in his laboratory and those conducted by Smith et al. (1981). The study by Marino et al. (1976a) was not included because of problems associated with induced currents on drinking devices.

Table 4.4. A summary of studies of growth of laboratory animals exposed to electric fields.

Study/Location	Species/Exposure (60-Hz vertical, unperturbed, unless noted)	Selected Growth Results
Knickerbocker et al. (1967), U.S.	22 male mice were exposed to a 160-kV/m field for IO-5 months and mated with unexposed females. Controts.	Average weights of mate offspring of exposed males were consistently lower than controls. The effect was small but statistically significant
Durfee et al. (1976), U.S.	315 young chickens were exposed to I-, IO-, or 3600-V/m fields for up to IO wk of age. 283 controls.	No significant effects of exposure were found on the growth of young chickens.
Le Bars & Andre (1976), France	Rabbits were exposed to a 50-Hz 50-kV/m field for 100 days.	The first 9 wk after birth; no effect of exposure on weight gain. After a disease outbreak, exposed rabbits grew slower than controls.
Dumanskiy et al. (1976), Russia	100 male rats exposed for 4 months to 50-Hz fields of 0.1-5 kV/m. 20 controls.	Exposed rats showed a trend for increased growth rates.
Marino et al. (1976a), U.S.	3 generations of mice were exposed to fields of 10 kV/m (horizontal) or 15 kV/m (vertical). Controls.	At 35 days old: vertical field, fower weights fur all 3 generations-may have been shuck related horizontal field, lower weights for 2 generations
Mathewson et al. (1976), U.S.	48 rats were exposed to 45Hz fields of up to 100 V/m. 48 controls.	No significant effects of exposure were found on growth.
Marino et al. (I 976b, 1977), U.S.	154 male rats in IO experiments were exposed to 15 kV/m for I month. 179 controls.	In 3 of the IO experiments final body weight in exposed rats was significantly tower than in controls-a trend fur tower weight in all exposed I.
Bayer et al. (1977), Germany	6 male rats 6-wk old were exposed to 50-Hz 100 kV/m for 1 yr.	Growth decreased slightly but significantly in rats exposed to 25 & 100 kV/m but not IO kV/m
Cerretelli et al. (I 979), Itaty	50 male rats exposed in groups to 50-Hz fields of 10, 25, and IOU kV/m for 35 or 48 days (8 HR/DAY 50 controls.	In 31 studies, exposed rats (but nut mice) had lower body weights than controls. No effects or weight for second series of 120-day exposures
Marino et al. (1980), U.S.	Three generations of mice were exposed to 3.5-kV/m fields, both horizontal and vertical. Controls.	There was a trend for exposed mice in the third generation to be slightly heavier than controls.
Hifton & Phillips (1981), US.	Rats and mice were exposed to 100-120 kV/m fields for 30-120 days in more than 31 experiments. Controls.	Exposed rats showed a small but significant slowing of growth at 4-8 wk but there was no overall effect of exposure of growth
Smith et al. (1981), U.S.	1400 mice from 4 generations were conceived born and raised in a 120-250 V/m field.	Effects of exposure on growth, if any, were transient, not readily reproducible, and easily masked by other environmental factors.
Seto et al. (1983), U.S.	176 rats were exposed to 80-kV/m fields from conception to about 120 days of age. 174 Controls.	There was a slight but significant delay in growth of young exposed rats from 4-8 wk, but not after 8 wk.
Le Bars et al. (1983), France	Male and female rats exposed to 50-Hz 50-kV/m for up to 3 months. Controls.	The growth rates of the exposed rats were slightly but not significantly less than controls.
Sikov et al. (1984), U.S.	Offspring of female rats exposed to a 100-kV/m field during gestation and for 8-25 days after birth. Controls.	No significant effects of exposure were found on the growth of young rats.
Portet et al. (1984), Portet & Cabanes (1988), France	50-Hz 50 kV/m: 20 male rats exposed for 4 wk; 28 pregnant rabbits exposed during and/or after pregnancy. Controls.	No effects of exposure were seen on growth of young male rats or on newborn rabbits exposed from gestation until 6-wk of age.
Sikov et al. (1987b), U.S.	Female swine (FU) and offspring (f1) exposed to 30-kV/m. F0 & Fl bred twice to nonexposed males. Controls.	No effects on mothers' growth during gestation Birth weights of first female young of Fls were 15% less than controls. No effect on later growth
Margonato et al. (1993), Italy	140 male rats (13-wk old at start) were exposed to 50-Hz fields of 25 or 100 kV/m for 280-1240 hr. 80 controls.	No effects of exposure were seen on growth of male rats.

Together, the studies reported 51 (out of 168) statistically significant differences in weight. Of these, in 29 cases the exposed animals were heavier than the control mice, and in 22 the exposed mice were lighter than the controls. Thus the results do not show a consistent dose-response pattern. Some researchers would view the results as evidence of no effect of electric field exposure on the growth of mice. Marino (1990) however. suggested that both increases and decreases in weight are possible, depending on conditions present in each experiment. Overall, Marino concluded that the results of his analyses provide evidence for an effect of electric field exposure on growth of mice of about 6.6 percent.

Magnetic field. The growth of 374 young chickens exposed to 60-Hz magnetic fields of 0.8 or 3.0 mT (8 or 30 G) was compared to that of 361 control chickens (Durfee et al. 1975). Through 10 weeks of age there were no statistically significant differences in growth between the two groups. Thirty-days of exposure to a 1.02-mT (10.2-G) 60-Hz vertical magnetic field had no effect on body or bone growth in 14 male rats (Simmons et al. 1986). The rats were exposed for 12 hours per day (half were exposed during the dark phase, and half were exposed during the light phase). Their growth was compared to six control rats. There were also no effects on the growth of 20 pregnant rats exposed for 24 hours per day for 20 days to a 50-Hz magnetic field of 30 mT (300 G) (Mevissen et al. 1994).

Nine male mice exposed 1 week for 23 hours per day to a very strong 60-Hz magnetic field of 0.11 T (1100 G) lost an average of 3.77 percent of their body weight (Fam 1981). During the same time 9 control mice gained an average of 4.76 percent in body weight.

Growth through 30-days of age was studied for 184 young male and female mice exposed during gestation to a 50-Hz 20-mT (200-G) magnetic field (Sienkiewicz et al. 1994). Compared to 168 control mice, there were no overall effects of magnetic-field exposure on growth. For exposed males, their average weight at 30 days of age was slightly less than that for the controls, and the difference was statistically significant. Picazo et al. (1996) found that growth increased significantly in male mice chronically exposed to a 50-Hz 15-µT (150-mG) field.

Two hundred and fifty-six male rats in two experiments were exposed 22 hours per day for 32 weeks to a 50-Hz, 5-µT (50-mG) magnetic field (Margonato et al. 1995). Compared to 256 controls, there were no effects on growth rate, or on the final weights for the exposed rats.

Combined fields. As part of research for the U.S. Navy's submarine communication project, 30 rhesus monkeys were exposed long-term to combined EMF of 0.2 mT (2 G) and 20 V/m at frequencies that varied randomly between 72 and 80 Hz (Grissett et al. 1977). The most significant finding of the first year of the study was that exposed males gained weight more rapidly than control males. At the end of 1 year, the male monkeys exposed to EMF were about 11 percent heavier than the controls. The weight gain appeared to be primarily in the form of increased mass of upper back and pectoral muscles. At the end of the study EMF exposure totaled nearly 3 years. At that time the growth rates for exposed and control males was no longer significantly different from each other (Lotz and Saxton 1987).

A followup study was conducted by Lotz and Saxton (1987) in which 30 monkeys were exposed to the same levels of EMF as used in the study by Grissett et al. (1977). In the second study, male monkeys had a slightly higher growth rate during puberty compared to controls, but it was not statistically significant. Authors of the study suggested that possible effects on growth could be related to increased testosterone secretion caused by current stimulation of the scrotum while a monkey was sitting on the cage floor.

Reproduction and Development

Possible effects of power-frequency EMF on reproduction and development have been of primary interest since the earliest studies of EMF were conducted. A large number of such studies has now been conducted by researchers in several countries. Animals are generally considered to be more sensitive to effects of environmental agents during early stages of development, especially before birth. The term developmental toxicity has been used to describe effects during the early stages of development (Rommereim 1989). Such effects, which include abnormal changes in structure or function, are called teratologies.

Laboratory animals are studied to provide data for assessing whether some agent like EMF may cause reproductive or developmental effects in humans. In general, however, there are many limitations to applying results of animal studies to assess reproductive risks in humans (Brent et al. 1993). Also agents that cause developmental toxicity in animals at very high doses may not be relevant to human exposures to the agent.

The studies of EMF described below were done with a wide range of field intensities, and looked at many end points. Possible effects of exposure to EMF were studied for time periods that included breeding, gestation, and early development of the young. Several of the studies included multiple generations of animals exposed to EMF.

Electric field. Table 4.5 summarizes several studies of reproduction and development in animals exposed to electric fields in laboratory experiments. One of the earliest studies to report effects on reproduction from a power-frequency electric field was done in Russia (Andrienko 1977). That study reported a variety of adverse reproductive effects in male and female rats exposed to a moderate strength 50-Hz electric field of 5-kV/m. However, the paper gave no information about the electric-field exposure system, or about how the animals were fed and watered. The reproductive effects reported by the Russian researchers were generally not found by the other studies of rats in Table 4.5. These include three large multigeneration rat studies (Seto et al. 1984; Rommereim et al. 1989, 1990).

Marino et al. (1980) reported that survival rates decreased in the offspring of mice exposed to 3.5 kV/m 60-Hz fields. This effect was not reported in three other studies of mice (Knickerbocker et al. 1967, Smith et al. 1981, Savin and Sokolova 1985). About the only consistent effect found in the large multigeneration study by Smith et al. (1981) was a delay in the age at which incisor teeth erupted in young mice. At 10 days of age, the number of mice with erupted incisors was about 19-25 percent less for exposed animals compared to controls (combining all data for both sexes).

When two generations of female miniature swine were exposed to a 30-kV/m 60-Hz electric field for 20 hours per day, and bred to unexposed boars, significant increases in fetal malformations and birth defects in offspring were found (Fig. 4.6) (Sikov et al. 1987a, 1987b). The results, however, were not consistent among breedings, or among generations. To obtain data on fetal malformations, some swine were sacrificed at 100 days of gestation, and others were allowed to give birth to provide breeding animals for the next generation. There were no consistent differences between exposed and control groups for litter size, fetal mass, or mass of fetal organs. Some of the teratology results from this complex multigeneration study are summarized in Table 4.6.

At the first breeding of the second generation female swine (Fl) that were born and raised in the electric field, most of the animals refused to mate with the unexposed boar (Sikov et al. 1987a). Breeding had to be temporarily suspended. There were no such problems with the control females at first breeding. Because of inconsistencies in the results of the study, the researchers could not conclude that the electric field was the cause of the various reproductive effects that were found.

The researchers that conducted the swine study conducted a followup multigeneration study with rats, in an attempt to see whether similar reproductive effects would occur in another species (Rommereim et al. 1989). Some teratology results of the rat study are shown in comparison with the swine study in Table 4.6. Results of the first rat experiment produced results that were very similar to the swine study. For the first breeding, there was no significant difference in fetal malformations between exposed and control rats. In the second breeding, the proportion of litters with malformations was threefold higher in the exposed group compared to controls, although it was not statistically significant. Also, as in the swine study, the first breeding of the second-generation rats produced a significant increase in malformations in the exposed animals. When the rat study was repeated (experiment 2), the results of the first rat experiment were not replicated (Table 4.6).

Rommereim et al. (1987) suggested that the differences in the results of the two rat experiments may have been from random or biological variation. They may also indicate that the threshold for the effects is near a field strength of IOO-kV/m. The researchers concluded that rats are not a good model for assessing the factors that may have been involved in producing the effects found in the swine study. No further electric-field studies of miniature swine were done.

Rommereim et al. (1990) did conduct another extensive electric-field reproduction study with rats. Groups of 68 female rats each (FO generation) were exposed to vertical 60-Hz fields of 10, 65, or 130 kV/m, and mated with unexposed males. Some of their female offspring (F 1 generation), after being exposed for 3 months, were mated with a new group of unexposed males. After 20-days of gestation, the F1 females were killed and their fetuses examined.

On a per-fetus basis, there was a significantly higher number of malformed fetuses in the Fl females exposed to 65 kV/m compared to the controls. No such effect was seen in the females exposed to 10, or to 130 kV/m. The researchers said that one could argue that this result is a “window effect,” but they could identify no biological explanation for such a possibility. The numbers of young born per litter, and their mortality rates, were not affected by exposure. The weights of the exposed FO mothers were slightly depressed during gestation, and during the lactation period.

Effects on reproduction and development seen in some studies of animals exposed to electric fields may have been influenced by the animals’ perception of the field by skin, hair, or feather stimulation. Graves et al. (1985) attempted to eliminate complications from spark

Table 4.5. A summary of studies of reproduction of laboratory animals exposed to electric fields.

Study/Location	Species/Exposure (60-Hz vertical, unperturbed, unless noted)	Selected Reproduction/Development Results
Knickerbocker et al. (1967), U.S.	22 male mice,1 0.5 months at I60-kV/m mated to unexposed females. Controls.	In second month, exposed group litters were low compared to controls, but not in a replicate.
Andrienko (1977), Russia	270 female and 230 male rats were mated and exposed to 50-Hz 5-kV/m for 4.5 months. Controls.	Effects associated with exposure: increase in time from mating to birth, lower birthweight, higher postnatal deaths and birth defects.
Cerretelli et al. (1979), Italy	Male rats were exposed to 50-Hz 100 kV/m fields for up to 8 hr/day for 48 days and mated to control females.	No effects of exposure on: mating behavior, number of pregnancies, number and weight of fetuses, birth defects, testes weight, sperm.
Fam (1980) Canada	Adult mice exposed 4500 hr and offspring beginning at 3-wk old exposed 2000 hr to a 240-kV/m field. Controls.	No effects on adult fertility or on survival of young. Exposed young males grew faster and females grew slower than controls.
Marino et al. (1980), U.S.	3 generations of mice, 3.5 kV/m fields, horizontal & vertical. Controls.	There was a trend for exposed mice to have lower survival to age 21 days
Smith et al. (1981) U.S.	1400 mice from 4 generations were conceived born and raised in a 120-250-V/m field. Controls.	No effects of exposure on fertility, total births, litter size, sex ratio, mortality, testes/vaginal development. Age for incisor eruption delayed.
Le Bars et al. (1983), France	Female rats exposed 8 hr/day to a 50.Hz 50-kV/m field. Controls.	No significant exposure effects on reproductive cycles or on number of fetuses per female.
Seto et al. (1984), U.S.	4 generations of rats, 80-kV/m field through postnatal development.	No effects of exposure on fertility, fecundity, nurturing, survival, sex ratio, or on birth defects.
Burack et al, (I 984), U.S.	Postnatal development of rats with prenatal exposure to 80-kV/m. Controls.	Possible effects on delay in eye opening, ear flap separation, poor male mating performance.
Sikov et al. (1984), U.S.	During 3 studies, rats were exposed to IOO-kV/m during mating, gestation and up to 25 days after birth. Controls.	No effects on: female reproductive performance, viability or size of fetuses, survival of young. Transient behavioral effects were seen in young.
Portet et al. (1984), Portet & Cabanes (1988), France	3 groups of 7 pregnant rabbits exposed to 50-Hz 50-kV/m during and/or for 6-wk after young born. 7 control mothers.	For 6-wk old young rabbits there were no significant differences between exposed and controls in body or organ weights.
Savin & Sokolova (1985), Russia	5 generations (2677 mice), 50-Hz 200-kV/m, 2 hr/day during mating, gestation, 2 months postnatal. Controls.	No consistent effects were seen on: live embryos per female, sex ratios, body size, young per litter, birth defects, or survival.
Graves (I 985), U.S.	Chicken eggs were exposed during incubation to fields of 0. I-I 100 kV/m. 20,000 subjects including controls.	No effects on growth, development, weight or mortality of embryos, or l-day old chicks. No effects on weight or behavior of 6-wk chicks.
Sikov et al. (1987a,1987b), U.S.	Female swine (FO) and offspring (FI) were exposed to a 30-kV/m field. There were 2 matings with unexposed males for each generation. Controls.	FO: no increase in malformations or birth defects from first mating, increase in malformations from second mating. FI: increase in birth defects from first mating, no effects for second mating.
Rommereim et al. (I 987), US,	Followup to above swine study. 2 studies of female rats of 2 generations in a IOO-kV/m field. F0, 2 matings with unexposed males, 1for F0. Controls.	Study 1: FO, no increase in malformations for first mating, trend for increased malformations for second mating. FI, increased malformations. Study 2 no increase in malformations for FO, FI .
Rommereim et al. (1989), U.S.	Female rats and offspring exposed to fields of 112 or 150 kV/m. Controls.	Exposure had no effects on mating, numbers of litters, or on weight of offspring.
Rommereim et al. (1990), US.	Pregnant rats and offspring exposed to fields of IO, 65, or 130 kV/m. Controls.	No effects on fertility or survival, Significant increase in fetal malformations only at 65 kV/m.
Kowalczuk & Saunders (1990), U.K.	IO male mice, 2 wk at 20 kV/m 50-Hz, mated to unexposed females. 10 controls.	No significant effects of exposure of males on pregnancy rates, or in survival of embryos.
de Jager et al. (1993), Rep. of South Africa	17 male mice, 50-Hz IO-kV/m, conception to 60 days or 18 months. 22 controls.	Epididymai sperm counts significantly higher in the exposed mice at 60 days and at 18 months.

Figure 4.6. Researchers at the Battelle Pacific Northwest Laboratories conducted a long-term study of Hanford miniature swine exposed to a 60-Hz 30-kV/m electric field. Two generations of exposed females were mated with unexposed males. Photo courtesy of Battelle Pacific Northwest Labs.

Table 4.6. A comparison of studies of fetal malformations in swine and rats, and birth defects in swine exposed to 60-Hz electric fields. Swine were exposed to a 30-kV/m field, and rats were exposed to a 100 kV/m field. Sources: Swine study, Sikov et al. (1987b); followup rat study, Rommereim et al. (1987).

Animals/breeding	Breeding age/time exposed (months)	Litters with malformations (%) Exposed	Litters with malformations (%) Control	Litters with birth defects (%) Exposed	Litters with birth defects (%) Control
Swine					
First generation (FO)					
First breeding	22/4	2/7 (28.6 %)	4/7 (57.1 %)	18/7 (38.9 %)	10/2 (20.0 %)
Second breeding	36/18	12/16 (75.0 %*)	2/7 (28,6 %)	— —	— —
Second generation (FI)					
First breeding	18/18			20/28 (71.4 %*)	4/12 (33.3 %)
Second breeding	28/32	19/27 (70.3 %)	8/11 (72.7 %)	— —	— —
Rats, Experiment 1					
First generation (FO)					
First breeding	4/1	1/22 (4.6 %)	0/21 (0.0 %)		
Second breeding	7.2/4.2	6/20 (30.0 %)	2/20 (10.0 %)		
Second generation (FI)					
First breeding	3/3	6/37 (16.2 %*)	1/42 (2.4 %)		
Rats, Experiment 2					
First generation (FO)					
Second breeding	7.2/4.2	1/27 (3.7 %)	2/24 (a.3 %)		
Second generation (F I)					
First breeding	3/3	1137 (2.7 %)	3/37 (8.1 %)		

* The higher percentage of litters with fetal malformations or birth defects in exposed animals compared to control animals is statistically significant.

discharges and peripheral stimulation by studying chicken embryos. Large numbers of eggs were exposed to 60-Hz electric fields of up to 100 kV/m through the 21-day incubation period (Fig. 4.7). No effects of field exposure on developing embryos were seen in this study.

Magnetic field. Chicken embryos were also among the several species used in studies of power-frequency magnetic fields (Table 4.7). Finnish researchers found that in their studies, the threshold for adverse developmental effects from 50-Hz magnetic fields was around 1.2 µT (12 mG) (Juutilainen 1986, Juutilainen et al. 1987). There was no indication of a dose-response effect, with fields of 1.25 µT (12.5 mG) and 12.5 µT (125 mG) producing about the same percentage of abnormalities. Most of the abnormalities involved the neural tube, and both minor and severe abnormalities were elevated in exposed embryos.

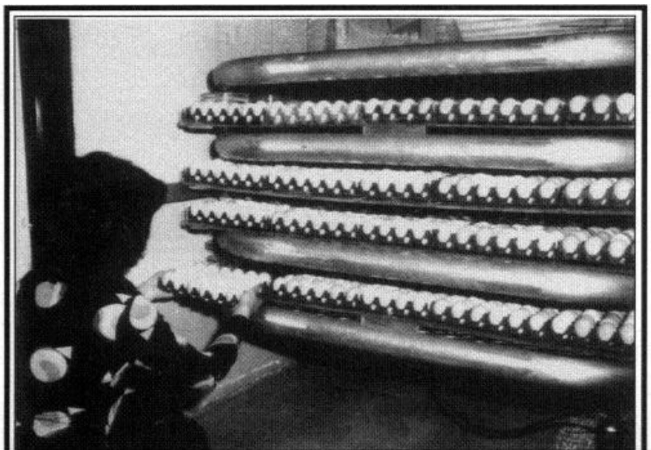


Figure 4.7. Researchers at Pennsylvania State University studied more than 20,000 chicken embryos and young chicks exposed to 60-Hz electric fields of up to 100 kV/m.
Photo courtesy of Pennsylvania State University.

Martin (1992) found no increases in abnormalities when chicken embryos were exposed to a 60-Hz magnetic field of 1.05 µT (10.5 mG). This level is slightly below the threshold for effects noted in the above Finnish studies. Martin (1988) had previously found that a 1-µT (10-mG) (peak) pulsed magnetic field did cause a significant increase in abnormalities in developing chick embryos (pulse characteristics: 2-ms (millisecond) rise and fall times, 500-ms duration, and a 100-Hz repetition rate).

Interest in pulsed magnetic fields and chicken embryos developed after Spanish researchers first reported adverse effects of 0.5-ms pulsed fields of 100 and 1000 Hz (Delgado et al. 1982). Six independent research laboratories used identical equipment and methods in an attempt to provide definitive information of the effect (Berman et al. 1990). They used a pulsed magnetic field with the characteristics as defined above in the research by Martin (1988). Only two of the six laboratories found statistically significant increases in developmental anomalies. Together, however, the combined results showed that the incidence of anomalies was about 25 percent greater than in the controls.

Although the researchers concluded that their overall results appeared to confirm earlier reports of effects on developing embryos, they could not explain the inconsistent results among the six laboratories. In a reanalysis of the study, Handcock and Kolassa (1992) found that the inter-laboratory variation in the exposure effect from unmeasured factors was at least as large as the exposure effect. Martin (1992) also pointed out that the one laboratory that found no effect on anomalies, had used a chicken strain different from those used by the other laboratories.

Of the seven studies in Table 4.7 that used mice, four reported various effects on development. In one study, only one of several measures of physical postnatal development of mice was affected by prenatal exposure to a 60-Hz magnetic field (Sienkiewicz et al. 1994). Compared to controls, exposed male mice (but not females) were significantly lighter in weight at 30-days of age. Exposed mice also performed the air righting reflex earlier, and stayed on a rota-rod treadmill for less time than controls. No significant differences were seen in eight other behavioral tests. Authors of the study concluded that a 60-Hz magnetic field is not a behavioral teratogen.

Picazo et al. (1995b) reported that in male mice exposed to a 50-Hz magnetic field, testicular weight and testosterone levels were increased. De Vita et al. (1995) reported an effect on sperm of mice exposed to a 50-Hz magnetic field, but the effect occurred in only one of the six time-points that were studied.

Picazo et al. (1995a) found changes in skeletal muscle in female mice exposed to a 50-Hz magnetic field. Two studies of rats also reported that the incidence of minor fetal skeletal anomalies was increased in animals exposed to 50-Hz magnetic fields (Huuskonen et al. 1993, Mevissen et al. 1994). In both studies, the skeletal malformations primarily involved the ribs, and they were of a type that would probably not impair later development of the fetuses (Mevissen et al. 1994). The incidence of skeletal and other fetal malformations was not increased in rats exposed to 60-Hz magnetic fields (Rommereim et al. 1996).

Lloyd et al. (1993) found some statistically significant differences in reproduction of sheepshead minnow fish reared in an aquarium in a 60-Hz magnetic field

Table 4.7. A summary of studies of reproduction of laboratory animals exposed to magnetic fields.

Study/Location	Species/Exposure (60-Hz horizontal unless noted)	Selected Reproduction/Development Results
Fam (1981), Canada	1 male mouse exposed .6500 hr in an electromagnet to 0.11 J (1100 G) and bred to 7 unexposed females. 1 control.	There were no significant differences between exposed and control progenies for mean weights, numbers born, or numbers survived.
Ramirez et al. (1983), Spain	*Drosophila* flies and eggs were exposed to a 50-Hz field of 1 mT (10 G). Controls.	Flies showed a significant avoidance of the field for egg laying. Mortality of exposed eggs was significantly higher than that for controls.
Cameron et al. (1985), U.S.	27 fertilized Medaka fish eggs were exposed to a 0.1 -mJ (1 -G) circularly polarized field for 48 hr. 26 controls.	By 51 hr after exposure there was an average 18-hr delay in embryo development compared to controls. No developmental abnormalities.
Juutilainen & Saali (1986), Finland	20 chicken embryos were exposed to 50-Hz vertical fields of up to 0.125 mT (1.25 G) for 48 hr. 20 controls.	For fields of 12.5 mG & 1.25 G the numbers of abnormal embryos were about twice as high as for controls and statistically significant.
Juutilainen et al. (1987), Finland	365 chicken embryos were exposed to 50-Hz vertical fields of up to 0.125 mT (1.25 G) for 48 hr. 77 controls.	Significant increases in abnormal embryo development found above a threshold of about 11.3-12.5 mG. No effect on development rate.
Zimmerman et al. (1990), U.S.	Sea urchin eggs were exposed 4 min after insemination to a rotating 0.1-mT (1 -G) field for 23 hr. Controls.	Compared to controls, exposed eggs had a I-hr delay in embryonic development between 18- & 23-hr points. No developmental defects found.
Martin (1992), Canada	40 chicken embryos were exposed to a 1.05 µT (10.5 mG) field parallel to long axis of the egg for 48 hr. 40 controls.	Neither bipolar nor unipolar sinewave fields caused an increase in malformations in developing embryos during 48 hr.
Huuskonen et al. (1993), Finland	70 pregnant rats were exposed to a 50-Hz 1 2.46-µT (124.6-mG) field for 20 days. 70 controls.	The incidences of minor fetal skeletal anomalies, and of live fetuses per litter were significantly higher in the exposed rats.
Lloyd et al. (1993), U.S.	Reproduction of sheepshead minnow fish in a 60-Hz I-l .25 mT (10-12.5 G) field. Group I started as juveniles, group II as embryos. Controls.	Survival of group II embryos reduced 7.7%, group II fish at 26-56 days 4-6% longer, egg production lower in 1 of 3 trials, lower embryo survival of 1 batch from group II. (See text.)
Yasui et al. (1993) Japan	70 male & female mice, 50-Hz field of 0.5 or 5 mT (5, 50 G) during development, mating, gestation. Controls.	No significant exposure effects on fetal survival, internal abnormalities, or sex ratio. Exposed fetuses had fewer external abnormalities.
Kowalczuk et al. (1994) U.K.	90 pregnant mice were exposed to a 50-Hz vertical field of 20 mT (200 G) for 17 days. 86 controls.	No effects of exposure were found on mating, fertility, or on fetuses: weight, sex ratio, number alive, number of external anomalies
Lazetic & P-Nadj (1994), Yugoslavia	2 generations of rats were exposed to a 50-Hz field of 100-500 µT (I-5 G) 7 hrlday 5 days/wk. Controls.	Significant exposure effects: postnatal mortality and weight were slightly increased, the number of young born per mother was decreased.
Mevissen et al. (1994), Germany	12 pregnant rats were exposed 24 hr/day for 20 days to a 50-Hz field of 30 m J (300 G). 12 controls.	The number of minor fetal skeletal anomalies was more than twice as high in exposed rats compared to controls. No effects on mothers.
Sienkiewiz et al. (1994), U.K.	184 offspring of female mice exposed during gestation to a vertical 50-Hz field of 20 mT (200 G). 168 controls.	No significant effects on ear attachment, tooth eruption, eye opening, hair coat, or sexual maturity. Effects in 2 out of IO behavioral tests.
De Vita et al. (1995), Italy	30 male mice 8-10 wk old were exposed for 2 or 4 hr to a 50-Hz 1 .7-mT (17-G) field. 30 controls.	Sperm assessed by flow cytometry at 7, 14,21, 28, 35, & 42 days after exposure. A significant effect found only at 28 days after 4-hr exposure.
Picazo et al. (1995a, 1995b), Spain	Second-generation male & female mice (30/group) exposed to a 50-Hz 15-µT (150-mG) field. 30 controls/group.	Exposed females: calcium in skeletal muscle significantly decreased. Exposed males: testicular weight & testosterone increased.
Rommereim et al. (1996), U.S.	96 female rats exposed 20 hr/day to 20 days gestation to 1 mT (10 G) or 0.61 µT (6.1 mG) in 2 replicates. 96 controls,	Malformation incidence did not differ among groups. Mean live number of fetuses significantly lower in 1 mT group in replicate A only.

compared to a those in a control aquarium (Table 4.7). However, the researchers said that because the effects were not seen consistently, the effects could not be positively attributed to field exposure.

Combined fields. Part of the early research for the U.S. Navy's submarine communication project included a study of fertility of rats exposed to electric fields of 10 or 20V/m, combined with magnetic fields of 0.1 or 0.2 mT (1 or 2 G) at frequencies of 4.5 or 75 Hz (Coate and Reno 1970). The study included first and second generations, with a total of about 300 rats exposed to EMF and 90 controls. No consistent differences between exposed and control rats were found for mating behavior, conception rates, or the number and appearance of live fetuses. For all data combined, exposed animals had a lower fertility index, but it was not statistically significant. The young of the second-generation exposed group had a significantly higher survival rate compared to controls.

In another Navy-sponsored study, three male beagle dogs were exposed at night, 5 days per week for 3 weeks to 45 or 75-Hz fields of the same intensities as in the above study (Teeters and Coate 1970). In addition to field exposure, the dogs received a 0.5 mA current (45 or 75 Hz) injected through two electrodes (one in a front leg and one in a hind leg). Sperm count was quite variable, but there were no apparent effects related to exposure on sperm morphology or motility.

Benz et al. (1987) conducted several reproductive toxicology studies with mice exposed to combined 60-Hz EMF of 1 mT (10 G) and 50 kV/m, and 0.3 mT (3 G) and 15 kV/m. In studies of possible dominant lethal mutations, no significant consistent differences between exposed and controls were found for impregnation, viable embryos, early or late deaths, corpora lutea, or preimplantation losses. There were also no such differences for several endpoints in multigeneration studies, and in cytogenetic studies (including sister chromatid exchanges).

In a study with two types of experiments, female rats and their young were exposed to combined 60-Hz vertical electric fields of 1 or 100 kV/m, and elliptically polarized magnetic fields of 0.1 or 1 .O mT (1 or 10 G). In one experiment, young rats were exposed for 7-8 hours per day for 1, 2, or 3 weeks (Gona et al. 1993). Rats exposed to 1 kV/m and 1 .O mT (10 G) had a small but statistically significant decrease in cerebellar mass, but overall body growth was not affected. The rats exposed to these field levels also had cerebellum DNA and RNA levels significantly higher than in the controls at ages 6 and 13 days, but not at 20 days. For rats exposed to 100 kV/m and 1 mT (1 G), DNA and protein levels were lower than for controls at 8 days of age, and were higher at 22 days of age. There were no morphological differences in the developing cerebellum between exposed and control rats at any field combination.

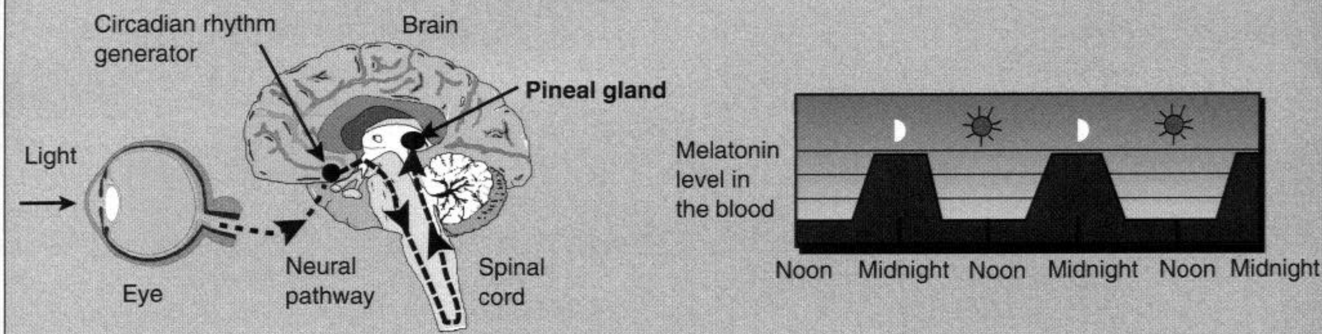
In the second experiment, pregnant female rats were exposed 23-hours per day from days 5 to 19 of pregnancy, and their young were examined at 0, 5, 12, and 19 days postnatally (Mang et al. 1993). There were no significant differences between exposed and control young rats for overall growth, or for physical abnormalities. There was a small decrease in cortical weight for rats exposed to 1 kV/m and 1 mT (10 G), and a small increase in cortical weight for rats exposed to 100 kV/m and 1 mT (1 G). For rats exposed to 1 kV/m and 1 mT (10 G) there were small reductions in DNA, RNA, and protein levels from the neopallium (the cortical gray and underlying white matter). There were no morphological differences in the developing neopallium between exposed and control rats at any field combination.

The developing brain was examined in another study of EMF, but the experimental subjects were chicken embryos (Blackman et al. 1988). Fertilized eggs were exposed continuously during incubation to either 50- or 60-Hz vertical electric fields of 15.9 V/m (72 eggs at each frequency for each of two experiments). Brain tissue from 1.5-day-old chicks was then exposed for 20 minutes to 50- or 60-Hz combined EMF of 15.9 V/m, and 0.073 µT (0.73 mG). For brain tissue from chicks incubated in a 60-Hz electric field and then exposed to 50-Hz EMF *in* vitro, there was about a 40 percent increase in calcium ion efflux from brain tissue. This effect occurred in both experiments, and was not found for the other frequency combinations. A third experiment was conducted in which egg positions in the exposure system were reversed and the same results were found.

Melatonin

Endocrinology is the study of certain glands and their secreted chemical messengers called hormones that regulate physiology and behavior (Norris 1985). Endocrine glands secrete hormones directly into the blood stream. Hormones produce effects at extremely low concentrations. The endocrine system is essential for an organism to function and to adapt to its environment.

Melatonin is a hormone found in vertebrates, invertebrates, and even in plants (Balzer and Hardeland 199 1, Reiter and Robinson 1995). In mammals melatonin is produced primarily by the pineal gland in the brain, although smaller amounts may be produced elsewhere, including the Harderian and lacrimal glands in some species (Reiter 1989a.) In birds melatonin is produced in the eye and in the pineal (Underwood et al. 1984).



The nightly secretion of the hormone **melatonin** by the pineal gland is driven by a circadian rhythm generator in the brain. Light regulates the generator so that melatonin secretion by the pineal matches the day-night cycle. (Melatonin is also found in many species without a pineal, such as insects, plants, and even one-celled organisms.)

Melatonin levels are very low during the day, and increase rapidly at night. The secretion corresponds to the length of the night. This provides biological information about the time of day, and the time of year.

Figure 4.8. In vertebrates the hormone melatonin is secreted mainly by a small gland attached to the brain called the pineal. Melatonin secretion occurs at night, so it provides a biological measurement of day-length and season. One proposed biological mechanism for EMF involves an effect on melatonin.

The pineal secretes melatonin into the blood on a cyclic basis that typically corresponds to the cycle of darkness (Figs. 4.8, 4.9). However, the secretion is driven by a circadian rhythm generator called the suprachiasmatic nuclei (SCN) (Tamarkin et al. 1985). Even in constant darkness, the generator causes melatonin to be secreted for a period of time about every 24-hours (this is called free running) (Tamarkin et al. 1985). Normally, the SCN is regulated by the daily light-dark cycle through neural stimulation from the retina, so that melatonin secretion occurs during the daily dark period.

In the pineal gland, melatonin is synthesized from serotonin through a complex series of steps that occur in structures called pinealocytes (Reiter 1989b). Melatonin and serotonin are classified as indoleamines because they are derived from the amino acid tryptophan. The melatonin synthesis process is shown in a simplified form in Figure 4.9. This information is provided because some EMF research discussed below has examined some of the key enzymes (NAT and HIOMT) in this process.

Secretion of melatonin provides biological information about the length of the night. This can also be interpreted by organisms' physiology to provide information about the season of the year. Thus the melatonin signal provides critical information to species that breed only at certain times of the year, so that their young are born during favorable environmental conditions (Tamarkin et al. 1985). Sheep and other seasonal breed-

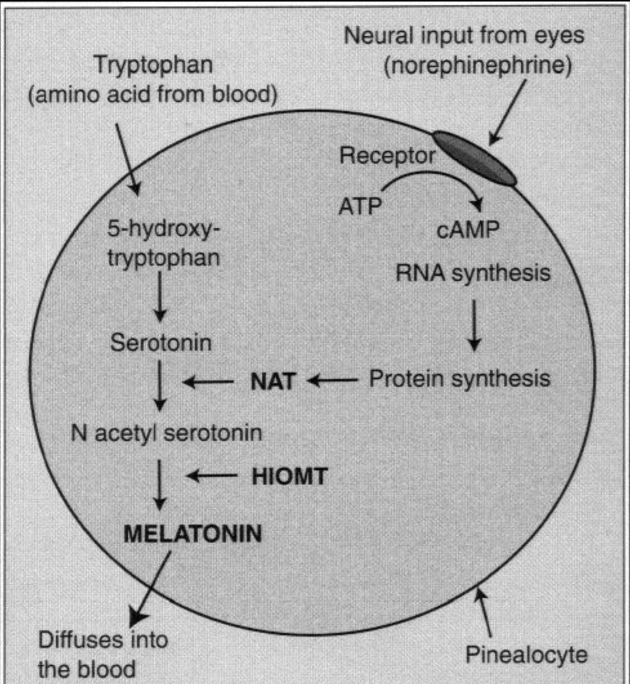


Figure 4.9. Simplified process for melatonin synthesis in pinealocytes of the pineal. Tryptophan is converted to serotonin, and enzymes NAT and HIOMT convert serotonin to melatonin. The process occurs mainly in darkness when norephinephrine interacts with pinealocyte receptors leading to synthesis of NAT, the rate-limiting enzyme in melatonin synthesis.
Sources: Wilson et al. (1981), and Reiter (1989).

ers can be "tricked' into breeding at atypical times of year by artificially manipulating the melatonin signal (Kennaway et al. 1987, Paterson and Foldes 1994).

Melatonin has many other influences on biological functions and processes, in addition to regulating seasonal breeding. In humans, melatonin may affect the sleep-wake cycle, mood and behavior; contribute to "jet lag"; help fight cancer; and may help slow the effects of aging (Reiter and Robinson 1995). Recent books, articles, and news about melatonin's purported beneficial effects, have led to a rapid growth in the sale of melatonin as an over the counter "wonder drug" (Reiter and Robinson 1995, Cowley 1995). Some scientists, however, believe that some of the claims about the beneficial health effects of melatonin misrepresent the scientific research that has been done to date (Turek 1996).

Several factors are reported to contribute to the pattern of nocturnal melatonin secretion (Reiter 1989c, 1993). These include age, genetics, and several external environmental factors. Included among the latter are light, stress, alcohol, and EMF. Light at night can have the most dramatic effects on suppressing melatonin levels at night. However, there is considerable variation among species as to the light intensity required to suppress melatonin (Reiter 1985). Laboratory rats require only a brief exposure to very weak white light for melatonin to be suppressed. In comparison, humans require much stronger light intensities for melatonin suppression (Lewy et al. 1980, Laakso et al. 1993).

The continued interest in EMF and melatonin is largely due to suggestions by some scientists that melatonin may be one mechanism for explaining how EMF could affect carcinogenesis in humans (Stevens 1987, 1993; Wilson et al. 1989, 1990). There is evidence that 60-Hz magnetic fields can lower melatonin's natural ability to slow the growth of breast cancer cells (Liburdy 1993~). Reports that power frequency EMF could affect melatonin secretion were first made in the early 1980s. Since then, many more studies have been conducted. The studies with animals are summarized in Table 4.8 and in the sections below. Later sections in this chapter also describe cellular studies of EMF and melatonin. Studies of EMF and melatonin in humans are described in Chapter 2; DC field studies are described in Chapter 6.

Electric field. Wilson et al. (1981, 1983) first reported that nocturnal pineal melatonin was reduced significantly by about 55-75 percent in adult male rats exposed to 60-Hz electric fields. Similar effects were seen for fields of 1.7 and 65 kV/m, with no indication of dose response. The effect appeared after about 3 weeks of continuous exposure, and recovery occurred within about 3 days after exposure ended. In these studies, levels of the melatonin rate-limiting enzyme NAT (Fig. 4.9) were also decreased, and there was a trend for an increase in the pineal hormone 5-methoxytryptophol (5-MTOL). Synthesis of both melatonin and 5-MTOL requires the enzyme HIOMT (Fig. 4.9), but only melatonin requires NAT. The researchers, therefore, suggested that the effect on melatonin seemed to involve a "biochemical lesion" in the activity of the NAT enzyme.

The above research group extended their findings in adult rats, and showed that nocturnal pineal melatonin was also decreased in young male rats exposed to 60-Hz electric fields of as low as IO-kV/m (Reiter et al. 1988). In this study, however, statistically significant reductions (55-65 %) in melatonin occurred at only one of three time-points during dark (4 hr after lights out).

In later studies the researchers were unable to replicate their earlier findings of a large decrease in pineal melatonin in adult male rats (Sasser et al. 1991). Another research group also found no effects of a 60-Hz electric field on pineal melatonin, NAT, or HIOMT in male rats (Grota et al. 1994). However, nocturnal serum melatonin levels were reduced significantly by about 20 percent in that study. The researchers said that this finding suggested that tissue uptake or degradation of melatonin was affected by 60-Hz electric field exposure.

Magnetic field. Several research groups have studied melatonin in laboratory animals exposed to power-frequency magnetic fields (Table 4.8). Most studies of melatonin and EMF included long-term exposure of animals in the dark period. Yellon (199 l), however, reported that in Djungarian hamsters, an acute 15minute exposure to a 60-Hz magnetic field in the light period led to delays in the onset and a reduction in the peak pineal and serum melatonin in the subsequent dark period. Serum melatonin levels in the exposed hamsters were about 40-60 percent less than in the controls.

Yellon (1996) was unable to consistently replicate the effects on melatonin from acute magnetic-field exposures (during long-day light exposures effects were found in three of five studies; with short day exposures, effects were found in both of two studies). Yellon (1996) also found that a daily 15-minute magnetic-field exposure for 3 weeks did not affect nocturnal melatonin patterns, or sexual maturation in hamsters.

Matt et al. (1994) also found that an acute 15-minute exposure to a 0. I-mT (1-G) 60-Hz field significantly reduced pineal melatonin levels in male hamsters. Acute exposures of male rats to the same field level for 15 or 60 minutes did not affect either pineal or serum melatonin concentrations (Reiter et al. 1996).

Table 4.8. A summarv of studies of melatonin and animals exposed to power-freauencv EMF.

Study/Location	Species/Exposure/Night Samples	Selected Results
	Electric Field Studies (60-Hz vertical)	
Wilson et al. (1981, 1983), U.S.	40 male rats (2 studies) exposed for 30 days to I .7-I .9 kV/m, or to 60 kV/m. Samples 4 hr after dark. 40 controls.	Nocturnal pineal melatonin and NAT significantly decreased after exposure, and 5-MTOL significantly increased after exposure.
Wilson et al. (1986), U.S.	40 adult male rats were exposed for 1, 2, 3, or 4 wk to a 65-kV/m field. Samples 4 hr after dark. 46 controls.	A significant depression in nocturnal pineal melatonin after 3 wk of exposure. Levels recovered in c 3 days after exposure ended.
Reiter et al. (1988), U.S.	Male rats exposed from conception to 23 days; 10,65, or 130 kV/m. Samples 4, 6, & 8 hr after dark. Controls.	Nocturnal pineal melatonin was significantly reduced at all field strengths at one time-point (4 hr after dark). Phase delayed by about 1.4 hr.
Anderson et al. (1988), U.S.	Young adult rats were exposed to a field of 200 V/m. Controls.	Exposure did not cause a depression in nocturnal melatonin, suggesting threshold for 60-Hz electric field effect between 0.2-2 kV/m.
Sasser et al. (1991), U.S.	23 male & 23 female rats exposed to a 65kV/m field for 30 days. Samples 3, 5, & 7 hr after dark, 46 controls.	No significant exposure effects on pineal melatonin in male rats. Pineal melatonin in females significantly increased 7 hr after dark.
Grota et al. (1994), U.S.	Male rats (in 3 studies) were exposed to a 65-kV/m field for 30 days. Samples 4 hr after dark. Controls.	No exposure effects on nocturnal pineal melatonin, NAT, or HIOMT. A significant reduction in nocturnal serum melatonin.
	Magnetic Field Studies (60-Hz vertical unless noted)	
Yellon (1991), U.S.	Adult hamsters exposed to a 0.1 -mT (I-G) field for 15 min, 2 hr before dark. Samples 6 times after dark. Controls.	After exposure during light period, a significant decrease in nocturnal serum melatonin and a reduced duration of nocturnal pineal melatonin.
Kato et al. (1991,1993), Japan	Male rats, circularly polarized 50-Hz fields I-250 µT (1 O-2500 mG) for 6 wk. Samples 6 hr after dark. Controls.	Compared to controls, plasma & pineal melatonin reduced significantly at all field levels during day & night. No differences among field levels.
Kato et al. (1994a), Japan	48 male rats exposed 6 wk to circularly polarized 50-Hz field of 1 µT (IO mG). Samples 6 hr after dark, 48 controls.	Nocturnal plasma melatonin was significantly reduced by exposure, and returned to control levels within 1 wk after exposure ended.
Kato et al. (1994b), Japan	48 male pigmented rats, 50-Hz circularly polarized 1 PT (10 mG), 6 wk. 48 shams (.02µT), 60 controls (.014pT).	Nocturnal pineal & plasma melatonin significantly reduced 15-16% in exposed vs. shams. Exposed & shams also less than controls.
Kato et al. (1994c), Japan	Male rats exposed 6 wk to horizontal or vertical 50-Hz fields of 1 µT (10 mG). Samples 6 hr after dark. Controls.	There were no significant effects of exposure on either plasma or pineal melatonin in contrast to effects from circularly polarized fields.
Yellon (1994), U.S.	Adult hamsters exposed to a 0.1 -mT (1 -G) field for 15 min 2 hr before dark. Samples 5 times after dark. Controls.	Exposure significantly decreased nocturnal and serum melatonin in 2 of 3 studies. Effects at specific times of night were not consistent.
Yellon et al. (1994), U.S.	Juvenile hamsters exposed to a 0.1 -mT (1 -G) field for 15 min 2 hr before dark, daily for 7 days. Controls.	The nocturnal melatonin rhythm of juvenile hamsters on long-day photoperiods was affected by daily 15-min exposures.
Matt et al. (1994), Wilson et al. (1994b), U.S.	Male hamsters exposed to a 0.1 mT (1 -G) field for 15 min, 2 hr before dark. Samples 3 & 5 hr after dark. Controls.	Pineal melatonin was significantly reduced in hamsters in short-day photo periods and that were not photorefractory.

Abbreviations: **5=MTOL=** 5-methoxytryptophol (a pineal hormone), **HIOMT=** hydroxyindole-0-methyltransferase (enzyme in synthesis process for melatonin and 5-MTOL), **NAT** (also called SNAT) serotonin N-acetyltransferase (rate-limiting enzyme in melatonin synthesis).

Table 4.8. A summary of studies of melatonin and animals exposed to power-frequency EMF. (Cont.)

Study/Location	Species/Exposure/Night Samples	Selected Results
	Magnetic Field Studies (Cont. 60-Hz vertical unless noted)	
McCormick et al. (1994a), US.	Rats & mice (12/sex/group) exposed to 0.2 µT (2 mG) to 1-mT(l O-G) fields continuous or on/off for 10 wk. Controls.	Magnetic field exposure had no clear effects on nocturnal pineal or serum melatonin, or on pineal NAT
Loscher et al. (1994), Germany	36 female rats exposed 9 wk to 50-Hz horizontal field of 0.3-l µT (3-10 mG). Samples 4 hr after dark. 36 controls.	Nocturnal serum melatonin levels were significantly reduced in rats exposed to the gradient magnetic field.
Setmaoui & Touitou (1995), France	54 male rats 1, 10,1 00 µT(IO, 100, 1000 mG) 50-Hz horizontal, 12 hr or 30 days. Samples 6 hr after dark. 18 controls.	30 days: pineal melatonin & NAT significantly depressed in IO- & l 00-PT fields. 12 hr: same effects only at 100 µT. No effects on HIOMT.
Bakos et al. (1995), Hungary	IO male and IO female rats exposed to 50-Hz fields of 5 or 500 µT (50 mG or 5 G) for 24 hr. Self controls.	Compared to pre- and post-exposure times, there were no significant effects of exposure on a melatonin metabolite (aMT6s) in urine.
Yellon (1996), U.S.	Adult hamsters exposed to a 0.1 -mT (1 -G) field for 15 min 2 hr before dark, daily for 3 wk. Controls.	Pineal & serum melatonin were not affected in adult hamsters on short-day photoperiods; exposed daily for 15 min to a magnetic field.
Reiter et al. (1996), U.S.	Male rats exposed to a horizontal 0.1 mT (1 G) field for 15 or 60 min 2 hr before dark, or 3 hr during dark.	No effects of exposure were seen for rising (3 hr after dark) or peak (5 hr after dark) pineal or serum melatonin levels.
Bakos et al. (1996), Hungary	5 male rats exposed for 24 hr to a 50-Hz 1 00-µT (l-G) horizontal field, and 5 rats exposed to a l -µT (l 0-mG) field.	No significant difference was found in the amount of nocturnal 6-sulphatoxymelatonin in urine between the two groups of rats.
Mevissen et al. (1996a, 1996c), Germany	Serum: 21 female rats, 13 wk to a horizontal 50-Hz IO µT (100 mG) field + DMBA; 16 DMBA-treated female rats, 9 & 12 wk to a 50 µT (500 mG) field. Pineal: 9 rats, field only; 9 rats field + DMBA. Sham controls.	For 100 mG field: significant 30% decrease in serum melatonin in field+DMBA group compared to DMBA only, no effect on pineal melatonin. For 500 mG field serum melatonin slightly lower in field group, but not statistically significant.
	Studies of Combined Electric and Magnetic Fields (60 Hz)	
Lee et al. (1993), U.S.	10 female sheep exposed 10 months to 500-kV line, 4 µT (40 mG) & 6 kV/m. Samples every 0.5-l hr. 10 controls.	No significant effects of 24 hr/day EMF on nocturnal serum melatonin amplitude, duration or phase as measured over eight 48-hr periods.
Lee et al. (1995), U.S.	15 female sheep exposed 10 months to 500-kV line, 3.8 µT (38 mG) & 6.3 kV/m. Samples every 0.5-l hr. 15 controls.	No significant effects of 24 hr/day EMF on nocturnal serum melatonin amplitude, duration or phase as measured over eight 48-hr periods.
Rogers et al. (1995c), U.S.	3 male baboons, 6 wk to horizontal 50-µT (500=mG), & vertical 6 kV/m, or 100 µT (1 G) & 30 kV/m, 3 controts.	No significant effects of 12 hr/day EMF during tight period on nocturnal metatonin levels with fields turned on & off slowly to avoid transient3
Rogers et al. (1995d), U.S.	2 male baboons, 21 days to horizontal 50 µT (500 mG), & vertical 6 kV/m, or 100 µT (1 G) & 30 kV/m. No controls.	With variable exposures 0.5-23.5 hr/day and rapid on-off field switching, mostly during the light phase, significant day & night melatonin suppression compared to pre-exposure levels.

Abbreviations: **5MTOL=** 5-methoxytryptophol (a pineal hormone), **aMT6s** (urinary 6-sulphatoxymelatonin, the major melatonin metabolite), **DMBA=** 7, l2-dimethylbenz(a)anthracene (a tumor initiator), **HIOMT=** hydroxyindole-O-methyltransferase (enzyme in synthesis process for melatonin and 5-MTOL), **NAT** (also called SNAT) serotonin N-acetyltransferase (rate limiting enzyme in melatonin synthesis).

Kato et al. (199 I, 1993) found that l-250 µT (0.0 1–2.5 G) circularly polarized 50-Hz magnetic fields depressed plasma and pineal melatonin levels in male albino (Wister-King) rats during night and day. In the studies, the control tests were not done concurrently with the field-exposure tests. The researchers did not say whether comparing exposed/control data collected at different times of the year might have affected their results. No effects were seen when the researchers used 1-µT (IO-mG) horizontal or vertical magnetic fields (Kato et al. 1994~). Kato et al. (1994b) also found that nocturnal plasma and pineal melatonin were significantly reduced when pigmented rats (Long-Evans) were used. In that study, both the exposed and sham-exposed rats had significantly lower nocturnal and daytime melatonin levels compared to controls. The shams were exposed to a stray field of 0.02 µT (0.2 mG) when the exposure facility was energized. The controls were tested about 1 month before the exposed/sham tests were done, and without the facility energized in an ambient field of 0.014 µT (0.14 mG). The researchers did not say whether by comparing the exposed and sham rats to the controls that were tested at a different time period, their results could have been affected.

Selmaoui and Touitou (1995) also found that a 1 -µT (IO-mG) 50-Hz horizontal magnetic field had no effect on nocturnal serum melatonin levels in male rats. When they used stronger horizontal fields of 10 or 100 µT (100 or 1000 mG), both serum melatonin and pineal NAT levels were significantly reduced by 30-40 percent. Serum melatonin levels were also reduced significantly by 20 percent in female rats exposed to horizontal 50-Hz magnetic fields of 0.3-l µT (3-10 mG) (Loscher et al. (1994). In a later study, these researchers found a 30 percent reduction in serum melatonin in female rate exposed to a 10 µT (100 mG) 50-Hz magnetic field; no effect was seen on pineal melatonin (Mevissen et al. 1996a).

Exposure of male and female rats and mice to 60-Hz magnetic fields of 2 µT-1 mT (20 mG – 10 G) had no effects on nocturnal serum or pineal melatonin, or on pineal NAT (McCormick et al. 1994a). Exposure included continuous (18.5 hours/day), and intermittent (1 hour on, 1 hour off).

Two studies measured the excretion of a melatonin metabolite in the urine of rats exposed to 50-Hz magnetic fields (Bakos et al. 1995, 1996). With this technique, small laboratory animals do not have to be killed at a single time-point, as is required when melatonin is measured in serum or in the pineal. Instead, urine can be collected without disturbing the animals, and melatonin production over the whole night or day can be estimated. There was no indication in the study that the amount of excretion of the melatonin metabolite in rats was affected by 24-hour exposure to a 50-Hz magnetic field.

Combined fields. Two research groups studied melatonin in animals exposed to combined 60-Hz electric and magnetic fields. One group studied melatonin in baboons exposed to 60-Hz EMF in a specially constructed exposure facility (Fig. 4.5). The baboons were fitted with a special jacket and catheter apparatus so that blood samples for melatonin measurements could be taken automatically. In three studies, three baboons were exposed to different levels of EMF (Table 4.8) for 12 hours per day during the light period for 6 weeks (Rogers et al. 1995c). The fields were turned on and off slowly to prevent transients. Under these conditions there were no statistically significant differences in nocturnal melatonin between exposed and control baboons.

In another study two baboons were exposed to EMF on a variable schedule, and the fields were turned on and off rapidly, therefore, transients were produced (Rogers et al. 1995d). Exposure occurred mostly during daytime over a 21-day period. The baboons served as their own controls. Melatonin levels were compared between pre-exposure, and exposure conditions. In contrast to the previous studies with EMF turned on and off slowly, in this study nearly complete suppressions in nocturnal melatonin occurred with baboons exposed to rapidly switched fields. The suppression was evident after 9 days of daytime exposure. The researchers considered their results as preliminary because they needed to be replicated in a more extensive experiment.

In a replicated study, female lambs were exposed for 10 months to 60-Hz EMF beneath a 500-kV transmission line (Lee et al. 1993, 1995). Melatonin was measured in blood samples taken at 0.5-3-hour intervals during eight 48-hour periods. Figure 4.10 is an example of the melatonin pattern in the sheep during a 48-hour period in May (for clarity, variation among the sheep at each measurement point is not shown). At that time the sheep had been exposed to the 500-kV line for 4 weeks. As is typical for species in general, melatonin secretion increased rapidly in the evening, and rapidly decreased near sunrise. No statistically significant differences were found in melatonin patterns between sheep raised beneath the 500-kV line, and sheep raised in a control area.

Other Hormones

This section reviews studies of EMF and other hormones that were not already covered in previous sections on stress and melatonin. Table 4.9 summarizes some basic information about the specific hormones that are mentioned in this section.

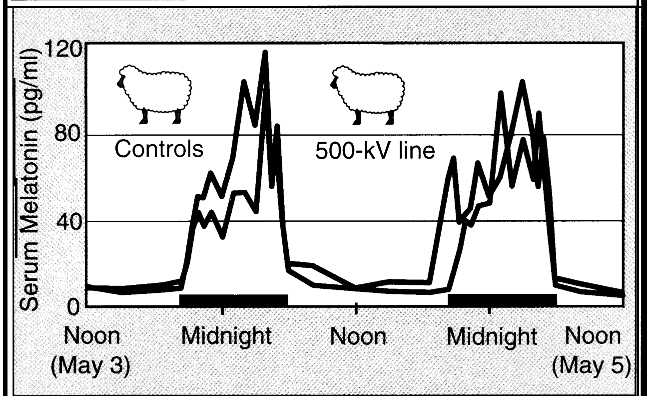


Figure. 4.10. An example of the mean 48-hour pattern of melatonin in serum from 10 sheep raised in EMF from a 500-kV transmission line, and in 10 sheep in a control area. The blue bars are sunset to sunrise. Combined data from eight 48-hour periods over 10 months showed no statistically significant differences in the melatonin patterns between the two groups of sheep. Source: Lee et al. (1993).

Electric field. Dumanskiy et al. (1976) studied thyroid gland function in rats exposed for 4 months to 50-Hz electric fields of 0.1-5 kV/m. The uptake and secretion of radioactive iodine (I- 13 1) was significantly slower in the exposed rats. Measurements of ratios of certain serum proteins (globulins) were interpreted as evidence that serum T_4 levels were also reduced in exposed animals.

Free et al. (198 1) studied several hormones in rats exposed to 60-Hz electric fields. For 19 adult male rats exposed for 30 days to a 98-kV/m field 68-kV/m effective), no effects were seen on serum levels of testosterone, FSH, LH, TSH, GH, or T,. In the first of two studies with 120-day exposure, the exposed rats showed statistically significant decreased levels of testosterone compared to controls. In the second study, the decrease was on the borderline of statistical significance. FSH levels were also decreased in the first study, but not significantly.

Free et al. (198 1) also exposed weanling males from 20 to 56 days of age to a 60-Hz electric field of 80-kV/m (effective). Hormone levels were similar between exposed and control rats, but there were large cyclic variations, and possible phase shifts at certain stages of development. This was most apparent for FSH and LH. The researchers said that exposure to electric fields may produce some variable and intermittent effects on the endocrine system of the rat. The changes did not result in harmful effects, and were within the normal range.

Table 4.9. Some basic information about the mammalian hormones mentioned in the text.

Hormone	Main Source	Some Important Actions
Follicle-stimulating hormone (FSH)	Anterior pituitary	In males: increases sperm production In females: stimulates growth of ovarian follicles
Growth hormone **(GH)** (Somatotropin)	Anterior pituitary	In males and females: stimulates protein synthesis and tissue growth including growth of the long bones
Luteinizing hormone (LH)	Anterior pituitary	In males: stimulates testosterone secretion In females: maturation of ovarian follicles, ovuiation, corpus luteum formation, progesterone secretion
Prolactin **(PL)**	Anterior pituitary	In males: stimulates sex accessory structures In females: increases mammary gland growth, milk synthesis
Thyroid-stimulating hormone (TSH)	Anterior pituitary	In males and females: increases synthesis and secretion of thyroid hormones
Progesterone	Corpus luteum	In females: maintain uterine secretion, maintain pregnancy
Insulin	Pancreas	In males and females: promotes uptake of glucose (sugar) by cells, regulates blood sugar level
Testosterone, Dihydrotestosterone **(DHT)**	Testes	In males: development of reproductive structures and secondary sexual characteristics
Estrogens (estradiol, estriol, estrone)	Ovary	In females: development and maintenance of the female sex organs and sexual characteristics
Triiodothyronine **(T,)** Thyroxine **(T,)**	Thyroid	In males and females: influence reproduction, growth, differentiation, and metabolism

Sources: Norris (1985), Eckert (1988).

Several hormones were studied in young rats and rabbits exposed to 50-Hz electric fields of 50 kV/m (Portet et al. 1984, Portet and Cabanes 1988). For 25 male rats exposed 8 hours per day for 4 weeks, there were no significant effects on serum levels of TSH, or T,. Levels of T_3 were slightly, but significantly, decreased compared to controls. Female rabbits in groups of 7 were exposed from the last 2 weeks of gestation, until 6 weeks after birth, and no significant effects on the above hormones or on insulin were found.

Quinlan et al. (1985) looked at some hormone levels in male rats after short exposures (1 or 3 hr) to a 100-kV/m 60-Hz electric field. Exposure included both continuous, andintermittent (16 sec on, 16 sec off). For l-hour exposure (either continuous or intermittent) there were no effects on prolactin, TSH, or GH. With 3-hours of intermittent exposure, GH levels were increased significantly compared to controls. A similar effect on GH was seen with continuous exposure, but it was of borderline significance.

A long-term endocrinology study of rats exposed to 50-Hz electric fields for up to 18 percent of their life span was conducted by Margonato et al. (1993). Adult male rats were exposed in groups of 20 for 8 hours per day to fields of 25 or 100 kV/m. Plasma levels of LH, FSH, and testosterone had high variation among individual animals, but there were no statistically significant differences in mean levels between exposed and control groups.

Magnetic field. Kato et al. (1994d) measured plasma testosterone in male rats exposed for 6 weeks to 50-Hz circularly polarized magnetic fields of 1, 5, or 50 µT (10, 50, 500 mG). Rats were exposed continuously except for 2 hours on 2 days per week, when cages were cleaned. In three experiments with 269 rats, there were no statistically significant differences in testosterone levels between the exposed and the control rats.

In another study, testosterone and insulin were measured in rats exposed to 50-Hz magnetic fields for 0.5-24 hours, or for 23 hours per day for 11 days (Navakatikyan et al. 1994). For these times, groups of 10 to 12 rats were exposed to flux densities of 10,50, or 250 µT (0.1, 0.5, 2.5 G). For the 0.5-hour exposure, serum testosterone was increased only at the highest flux density, while with the 12-hour exposure, testosterone increased at all three flux densities. With the 24-hour exposure, testosterone decreased at the low and high flux densities. No effects on testosterone were seen with the 1 l-day exposure. Serum insulin levels were found to decrease only at the middle and high flux densities for the 1 l-day exposure. The researchers suggested that this pattern of results could be a response to stress.

Serum testosterone was measured in 30 young male mice exposed until the age of 6 weeks to a 50-Hz 15-µT (150-mG) magnetic field (Picazo et al. 1995b). Testosterone levels were significantly increased in the exposed animals by about 21 percent, as compared to the controls. The study also found that the size and weight of the testes were also significantly greater in the exposed mice.

Combined fields. Thirty rhesus monkeys (17 males, 13 females) were exposed to combined EMF of 20 V/m and 0.2 mT (2 G) modulated between 72 and 80 Hz (Lotz and Saxton (1987). Exposure occurred for 22 hours per day from when the monkeys were 1 to 54 months of age. Levels of progesterone in females and testosterone in males increased at the expected time of development, and there was no significant difference between the exposed and control groups. The exposed males did show a trend for higher testosterone levels during the period of early development. There were no statistically significantly differences between groups for mean levels of estradiol, and DHT.

A long-term study of female lambs raised in the 60-Hz EMF from a 500-kV transmission line included measurements of serum progesterone (Lee et al. 1993). Ten spring-born lambs under the line were exposed for 10 months to a mean electric field of 6 kV/m, and a mean magnetic field of 4 µT (40 mG). Progesterone was measured in blood samples taken twice weekly beginning when the lambs were 19 weeks old. Progesterone levels increased sharply at the normal time in the fall in both the line and control lambs, marking the onset of puberty. There was no significant difference in the mean age at puberty between the two groups.

Cardiovascular System

This section describes research on the effects of EMF on the cardiovascular system of laboratory animals. This system, also called the circulatory system, consists of the heart and the networks of blood vessels. Table 4.10 summarizes terminology about blood cells and plasma chemistry used in describing results of research covered in this section. Red blood cells (erythrocytes) contain molecules of hemoglobin which transport oxygen. White blood cells (leukocytes) fight infections through a variety of ways; they are further described in a later section on the “ Immune System.” Platelets are involved in the process of blood clotting. Figure 4.11 shows the basic electrocardiogram (electrical activity of the heart) which has also been included in some research on EMF.

Table 4.10. Some basic terminology about blood cells and plasma chemistry to aid in understanding studies in the section on the cardiovascular system. Sources: Ganong (1981), Gersh (1992), Cleve (1992).

- **Blood Cells (45%** of blood)
  - **Red blood cells** (RBC, erythrocytes)
    Hematocrit (red blood cell volume as a fraction of total blood, also called VPRC- volume of packed cells)
    Hb (hemoglobin concentration)
    MCH (mean corpuscular hemoglobin)
    Reticulocyte (immature red blood cell)
  - **White blood cells** (WBC, leukocytes)
    Basophils, eosinophils, neutrophils, monocytes, lymphocytes
  - **Platelets**

- **Plasma** (55% of blood, mostly water)
  - **Plasma** (fluid containing the blood cells)
  - **Serum** (fluid that separates from clotted blood)
  - **Plasma proteins** (e.g., albumin, fibrinogen, immunoglobulins, cholesterol, ceruloplasmin)
  - **Electrolytes** (e.g., sodium, potassium, calcium)
  - **Products for synthesis, or of metabolism** (e.g., urea nitrogen, iron, creatine, glucose, pyruvic acid, uric acid, amino acids, triglycerides, SGOT-serum glutamic oxaloacetic transaminase, LDH-lactic dehydrogenase, CPK-creatine phosphokinase, alkaline phosphate, GGTP-gamma-glutamyl transpeptidase)
  - **Other substances** (e.g., respiratory gases, hormones, cholinesterase, nutrients)

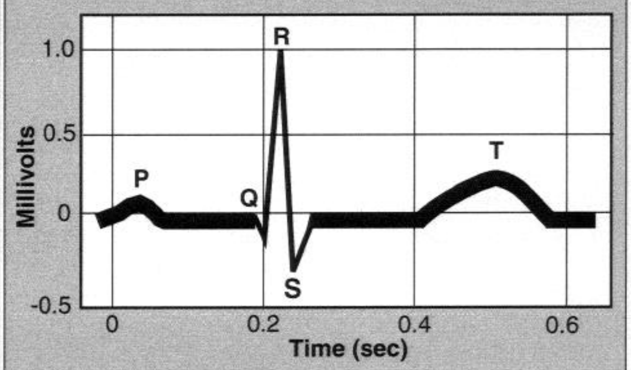


Figure 4.11. The basic pattern of the electrocardiogram (ECG) (human) which shows the electrical activity of the heart. Mammals and birds have four-chambered hearts (two atrials, and two ventricals). Source: Ganong (1981).

Electric field. Most EMF research on the cardiovascular system has involved electric fields (Table 4.11). A wide variety of effects of electric fields on the cardiovascular system has been reported, but several studies also reported no effects. The findings of studies reporting effects have not always been consistent.

Ragan et al. (1983) reviewed results of about a dozen of the early studies of electric fields on blood and serum. They found that the studies with electric fields of 10-100 kV/m showed indications of increases in neutrophils, eosinophils, SGOT, LDH, glucose, and urea nitrogen, and decreases in lymphocytes. They added, however, that few of the studies used appropriate sham-exposed control animals, some used inappropriate statistical tests, and few of the studies were replicated.

In their own studies, Ragan et al. (1983) did not find any consistent effects of 120-day exposures to 60-Hz lOO-kV/m fields on blood cells or on serum chemistry in rats. They did find some statistically significant effects in some of their individual studies, and they pointed out the importance of replication and appropriate statistical analyses.

Morris et al. (1989) also reviewed research on electric fields and hematology. They suggested that the effects reported in some studies could be viewed as either statistical artifacts, or as real biological effects that were undetected in most studies that used small sample sizes. Morris et al. (1989) used two formal methods to combine results of 40 experiments on blood and serum chemistry by six research groups, including the studies by Ragan et al. (1983).

In their analyses, Morris et al. (1989) considered 15 end-points that were addressed in the studies. The results of their combined analyses indicated possible decreases in total proteins, albumin, lymphocytes, and percent lymphocytes. Possible increases were seen in glucose, neutrophils, percent neutrophils, lymphocytes, and eosinophils. Morris et al. (1989) concluded that the combined results strongly suggests the presence of consistent effects on some end-points. They recommended long-term studies to help determine whether the effects have any impact on the well being of exposed animals.

Four of the studies in Table 4.11 reported effects of electric-field exposure on the ECG. Two of these involved rats (Meda et al. 1972, Behari et al. 1986), one involved dogs (Cerretelli et al. 1979), and one involved chicks (Carter and Graves 1975). Of these, two reported effects on the heart rate, and two found no effects. Hilton and Phillips (1980) found no significant effects of acute or long-term exposure to 80- or lOO-kV/m fields on the ECG or heart rate of rats. While collecting data during

Table 4.11. A summary of cardiovascular system studies of laboratory animals in electric fields.

Study/Location	Species/Exposure (60-Hz vertical, unperturbed, unless noted)	Selected Cardiovascular Results
Meda et at. (1972), Itaiy	12 mice 5 rats and 5 Guinea pigs (all males) exposed to 50-Hz 10 kV/m field (9 hr on, 3 hr off) for 1000 hr. Controis.	Rats: neutrophils, eosinophils increased; lymphocytes decreased. Mice: ECG P-R interval longer, QRS complex increased.
Carter & Graves (1975), U.S.	20 newly hatched chicks exposed to 40 or 80 kV/m for 22-24 days. ECG recordings after exposure. 20 controls.	ECGs recorded after exposure to hen call or 500-Hz tone. Most chick heart rates significantly higher in exposed compared to controls.
Dumanskiy et ai. (1976), Russia	100 male rats were exposed for 4 months to 50-Hz fields of 0.1-5 kV/m. 20 controls.	Significant effects in blood of exposed rats: cholinesterase decreased 34-38%, glucose increased, nitrogen and urea increased.
Le Bars & Andre (1976), France	Rabbits and rats were exposed to a 50-Hz 50-kV/m field for 24-70 hr, and for 8 hr/day for 30-100 days. Controls.	Rabbits, 100-day exposure: significant increase in leukocytes, anemia. Increase in blood urea: rabbitt 24-hr exposure, rat 100-day exposure.
Mathewson et al. (1976), U.S.	48 weanling male rats were exposed to 45-Hz fields of up to 100 kV/m for 28 days. 48 controls.	No significant effects of exposure were found on complete blood counts, and selected plasma biochemical assays.
Silny (1976), Germany	Rats were exposed to 50-Hz 80-kV/m and cats to 60-kV/m fields. Exposure & postexposure 4 hr each. Controls.	The cardiac frequency increased IO-20 % from exposure, growing steadily in rats and oscillating in cats. The changes were within normal values.
Marino et al. (I 976b, 1977), U.S.	154 male rats in IO experiments were exposed to 15 kV/m for 1 month. 179 controls.	Serum albumin was significantly higher (9-28%), and serum gamma globulin was significantly lower in exposed rats compared to controls
Bayer et al. (1977), Sander et al. (1982), Germany	Rats were exposed nearly continuously for 1 year to a 50-Hz IOO-kV/m field.	No significant exposure effects on hematocrit, leukocyte concentration, WBC, heart rate, ECG. Leukocyte volume was reduced 30%.
Cerretelli et al. (1979), Italy	Dogs, rabbits, and rats exposed to 50-Hz fields from 1 O-1 00 kV/m. Tests before and after exposures.	No effects of 80 kV/m on rabbit heart functions. Threshold of IO kV/m for effects on dog heart rate and on blood components of rats & dogs.
Graves et al. (1979), U.S.	Mice were exposed for short term (2 hr), and long term (2-6 wk) to 25 or 50 kV/m fields. Controls.	No significant changes were seen in blood cell composition that indicated an effect of exposure.
Babovich & Kozyarin (I 979), Russia	Male rats were exposed to 50-Hz fields of 7, 12, or 15 kV/m for 4 months for 30 min per day. Controls.	Significant effects in blood of exposed rats: cholinesterase, glucose, copper, nitrogen and urea increased; iron decreased.
Shandala et al. (1979), Russia	400 rats were exposed to 50-Hz fields of IO, 15, or 20 kV/m for I-4 months for 20-320 min per day. Controls.	Significant effects in blood of exposed rats: glucose, ceruloplasmin, nitrogen and urea increased; cholinesterase decreased.
Fam (1980), Canada	Adutt mice exposed 4500 hr and offspring beginning at 3-wk old exposed 2000 hr to a 240-kV/m field. Controls.	Significant effects females: WBC, Hgb, & MCH decreased, band increased; both sexes, aibumin, urea nitrogen, cholesterol increased.
Hilton & Phillips (1980), U.S.	Rats exposed 20 hr/day for 30 or 120 days, or for 1 or 8 hr to 80 or 100 kV/m. Males used in exposures , 30 days and females for 120 days. Controls.	No significant effects after 8 hr-120 day exposures on ECG (P-R interval, QRS duration), heart rate, blood pressure; no effects on blood pressure or heart rate during 1 hr exposure to 100 kV/m.
Ragan et af. (1983), U.S.	Groups of IO-20 female rats exposed to I 00 kV/m fur 15,30,60, or 120 days (replicated studies). Controls.	No consistent significant effects of exposure on RBC, reticulocytes, leukocytes, neutrophils, lymphocytes, or on serum components.
Le Bars et al. (1983), France	Male & female rats (normal & hairless), 50-Hz 50 kV/m field for 8 or 14 hr/day for 100 days or 3 months. Controls.	No significant effects on blood cells. Some significant effects on serum chemistry but only a small increase in urea consistently in normal rats.
Ragan (I 985), U.S.	3 generations of miniature swine (FO, FI 'F2) were chronically exposed to a 30-kV/m field. Controls.	No significant effects on blood of F0 or Ft. F2 at 42 days: reticulocytes increased in both sexes; Mb, RBC, VPRC decreased in exposed males.

Table 4.11. A summary of cardiovascular system studies of laboratory animals in electric fields. (Cont.)

Study/Location	Species/Exposure (60-Hz vertical, unperturbed, unless noted)	Selected Cardiovascular Results
Seto et al. (1986), U.S.	3 generations of rats (135) conceived, burn, & raised 120 days in a 80=kV/m field on for 21 hr/day. 135 controls.	Of 13 blood cell parameters 3 were significantly reduced in exposed rats (% reduction): WBC (7%), lymphocytes (<7%), eosiniphiis (24%).
Behari et al.(I986), India	20 male rats were exposed to a horizontal 50-Hz 5 kV/m field for 2-3 months. 20 controls.	ECGs 30 min after exposure ended. Amplitude of R and T waves in exposed rats significantly different from controls. No effect on heart rate.
Margonato et al. (1993), Italy	140 male rats (13-wk old at start) were exposed to 50-Hz fields of 25 or 100 kV/m fur 280-1240 hr. 80 controls.	No significant differences were found between exposed and control groups for hematology or serum chemistry.

acute exposure, the researchers used grounded wire braid to shield cannulas and transducers to avoid induced currents on these devices from the electric field.

Magnetic field. Blood and serum were studied in four rhesus monkeys exposed to 15 or 45-Hz magnetic fields of 0.82-0.93 mT (8.2-9.3 G) for several days (de Lorge 1974). No consistent changes associated with exposure were found on WBC, monocytes, eosinophils, polycytes, lymphocytes, and bands. Possible effects were seen on triglycerides, LDH, and CPK, which the researcher said encouraged further measurements.

Silny (1985) studied heart functions of cats and dogs exposed to 50-Hz magnetic fields. No changes were found in the ECG or skin temperature of cats exposed to a 50-mT (500-G) horizontal magnetic field. For dogs, changes in the ECG were seen when the animals were exposed to very strong magnetic fields of more than 2 T (20,000 G). Exposure to the fields caused body spasms and a run of ectopic heart beats in the dogs (rapid premature beats).

Male mice exposed to a 50-Hz, 20-mT (200-G) horizontal magnetic field for 7 days showed no effects of exposure on peripheral blood components, or on cells from bone marrow (Lorimore et al. 1990). The 18 exposed and 18 control mice were sampled in groups of three each on 6 days up to 18 days post-exposure. Blood cell components studied included hematocrit, neutrophils, eosinophils, monocytes, and lymphocytes. The researchers suggested that long-term exposure studies were required to establish whether magnetic fields affect the blood system.

A long-term study was done by Picazo et al. (1994), in which six female mice were exposed for 3 months to a 50-Hz horizontal magnetic field of 0.1 mT (1 G). As compared to six control mice, no effects of exposure were found on hematocrit, neutrophils, eosinophils, or on basophils. Statistically significant differences between the two groups were found for WBC, lymphocytes, monocytes, and blast cells (immature cells). Because of a reduction in WBC (leukopenia), and an increase in blast cells and young lymphocytes, the researchers diagnosed the condition as lymphocytic aleukemic leukemia. They added that the type of mice used in the studies do not normally develop tumors before 6 months of age.

Picazo et al. (1995c) conducted a larger study in which two generations of mice were exposed to a 50-Hz 15-µT (150-mG) horizontal magnetic field. The first generation was exposed from age 6 weeks, for 14 weeks, at which time they were mated. Exposure continued through gestation until the mice in the second generation were 14 weeks old. Blood samples were taken from females of each generation as adults (first generation 12 exposed, 12 control; second generation 30 exposed, 30 control). No statistically significant differences between exposed and control groups were found for any blood parameter measured (i.e., hematocrit, RBC, Hb, MCH, WBC, or platelet counts). Significant differences were found between control mothers and daughters for hematocrit, Hb, and WBC. For exposed mothers and daughters, significant differences were found for Hb and platelet counts. Picazo et al. (1995c) interpreted the WBC results as indicating a moderate leukopenia in exposed females of the second generation.

No effects were found on the blood of nine male mice exposed 1 week for 23 hours per day to a strong 60-Hz magnetic field of 0.11 T (1100 G) produced by an electromagnet (Fam 1981). Blood parameters studied in the exposed mice and in nine controls included WBC, RBC, Hb, MCH, platelets, lymphocytes, monocytes, eosinophils, basophils, and six blood proteins.

Margonato et al. (1995) conducted replicated studies of male rats exposed 22 hours per day for 32 weeks to a 50-Hz magnetic field of 5 µT (50 mG). No statistically significant differences between exposed and control rats were found for several blood parameters. These included: RBC, VPRC, Hb, WBC, eosinophils, lymphocytes, monocytes, neutrophils, uric acid, cholesterol, and alkaline phosphate.

Some effects on blood components were found in 12 male mice exposed to a 5-µT (50-mG) 50-Hz magnetic field for 90 days (B.-Faivre et al. 1995). Before exposure there were no statistically significant differences in five white blood cell types between the exposed mice and 12 controls. At 20 days of exposure, significantly lower levels were found in exposed mice for leukocytes, lymphocytes, monocytes, and eosinophils (but not neutrophil polynuclears). Red blood cells and hemoglobin were also measured at 20 days, and both were significantly reduced in the exposed mice (Bonhomme 1994). At 43 days, only eosinophils were depressed, and no differences were seen at 63 days. At the end of the 90-day period, all the cell types except lymphocytes were significantly lower in exposed mice. The researchers interpreted the lack of differences during mid-exposure as hematopoietic compensation.

Combined fields. Eight beagle dogs were exposed at night, 5 days per week for 3 weeks to 45 or 75-Hz fields of 10 V/m and 0.1 mT (1 G), or 20 V/m and 0.2 mT (2 G) (Teeters and Coate 1970). In addition to field exposure, the dogs received a 0.5-mA current (45 or 75 Hz) injected through two electrodes (one in a front leg and one in a hind leg). Many blood cell and serum parameters were measured in the dogs. The researchers concluded that none of the changes seen in these parameters appeared related to exposure. Seven of the eight exposed dogs showed one or more elevations in blood pressure during or after exposure (five of these were elevation of diastolic pressure). One of two control dogs also showed blood pressure elevations during the same periods.

Thirty rhesus monkeys were exposed 22 hours per day for 1 year, to combined EMF of 0.2 mT (2 G) and 20 V/m at frequencies that varied randomly between 72 and 80 Hz (Grissett et al. 1977). A large number of blood and serum parameters was measured; only a few showed differences between exposed and control monkeys that were at or near a level of statistical significance. Urea nitrogen, glucose, GGTP, and triglycerides were decreased in exposed males. (Exposed males also grew at a significantly faster rate than controls.) The researchers said that they were not prepared to call the observed effects either harmful or helpful.

Lotz and Saxton (1987) conducted followup research to the above study by Grissett et al. (1977). In the followup study, 30 monkeys were exposed for about 1 year to the same levels of EMF as in the previous study. Analyses of blood samples included RBC, WBC and individual white cell types, Hb, hematocrit, and MCH. There were no statistically significant differences between the exposed and control groups for any of the 11 blood parameters that were measured.

Another study with monkeys (pigtailed macaques) exposed to combined EMF also found no significant exposure effects on blood (Wolpaw et al. 1989). In this study, six male monkeys were exposed to 60-Hz EMF of 3-30 kV/m, and 0.01-0.09 mT (0.1-0.9 G) for three 2 l-day segments. Data were also collected on these monkeys during pre- and post-exposure periods, and on four control monkeys not exposed to EMF. More than 20 blood cell and serum parameters were measured and no statistical evidence for exposure effects was found (no blood data were shown in the paper, however).

Nervous System

The vertebrate nervous system consists of the central nervous system (CNS, brain and spinal cord) and the peripheral nervous system (nerves carrying information to and from the CNS) (Ganong 198 1, Alberts et al. 1989). Neurons are basic nerve cells that carry information throughout the nervous system (Fig. 4.12). Within a neuron, signals are carried by electrical impulses. In some cases, signals are also transmitted electrically between neurons through gap junctions. In most cases, signals are transmitted chemically across the small gaps between neurons (synapses). Neurotransmitters are chemicals that carry signals across synapses. Acetylcholine is a common neurotransmitter and neurons that release acetylcholine are termed cholinergic. Neurotransmitters derived from amino acids are called biogenie amines-serotonin, and catecholamines (epinephrine, norepinephrine, dopamine).

The brain is divided into several functional and structural areas, including the cerebellum, which is involved with coordination and movement. The cerebellar cortex contains three layers, including a middle layer of Purkinje cells which are among the largest neurons. A Purkinje cell may receive inputs from more than 100,000 other neurons (Alberts et al. 1989).

Other parts of the brain included in some studies of EMF are the hypothalamus (regulation of hormones, temperature, hunger, sleep), hippocampus (involved with memory), and the striatum (involved with motor control). Functioning of the neurons is associated with changing voltages and currents. The overall electrical activity of the brain can be measured with an electroencephalogram (EEG). Different EEG frequency and voltage amplitude patterns are associated with various physiological conditions. An EEG is, therefore, analyzed on the basis of voltage and frequency.

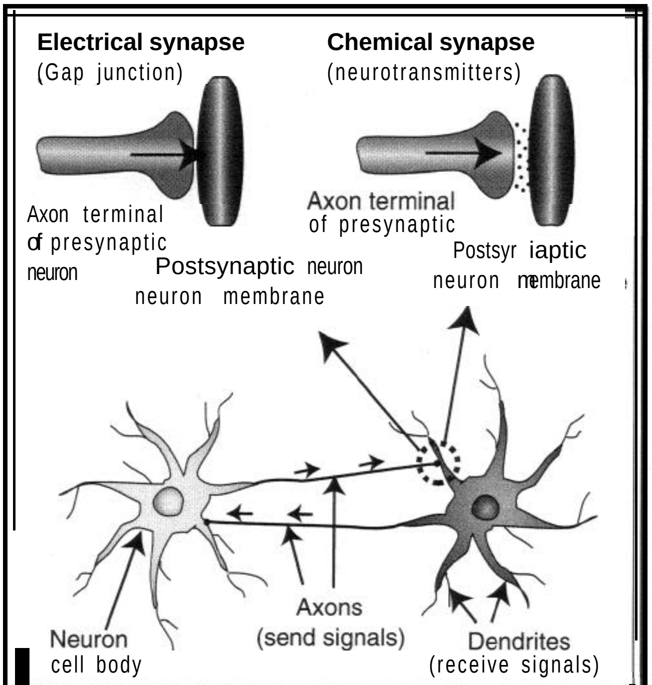


Figure 4.12. The basic process for the transmission of nerve impulses between neurons. At electrical synapses, impulses directly flow between cells in electrical contact through gap junctions. Most synapses are chemical, where neurotransmitters carry signals across the small gaps between cells.
Sources: Ganong (1981), Alberts et al. (1989).

Electric field. Several studies that looked at possible effects of power-frequency electric fields on laboratory animals are summarized in Table 4.12. One of the first such studies included EEG recordings of chicks after they had been exposed for 8 days (Carter and Graves 1975). For most analyses of the EEG data, there were no significant differences between exposed and control groups. The researchers said that the few significant differences for average power spectrums could have been due to chance. There were no group differences when EEG power spectrums were collapsed into eight frequency bands. Some differences were found for coefficients of variation in some frequency bands. The authors offered no comments on the possible biological significance of the finding.

Silny (1976) studied the EEGs of cats and rats exposed to 50-Hz electric fields. Four frequency bands were examined; alpha (8-13 Hz), beta (14-24 Hz), delta (0.5-4 Hz), and theta (4-8 Hz). The recordings were made with electrodes implanted in the brain. During field exposure there was a gradual decrease in the average density of the instantaneous power in all four bands. The decrease reached about 50 percent and it was most apparent in the right cortex. The researchers attributed the EEG effects to a change in excitation in the animals.

The largest study of nerve function in rats was done by Jaffe et al. (1980). Segments of nerves removed from rats were subjected to several tests to measure synaptic transmission, and peripheral nerve function. Only one, the conditioning test (C-T) response, was significantly and consistently different between exposed and control groups. This test measures the excitability and refractory period of synapses. The researchers said that the C-T results suggested that electric-field exposure caused an increase in neuronal excitability in rats.

A study in which rabbits were exposed outdoors to electric fields and corona effects (noise, UV light) in a substation reported effects (lamellar bodies) on the structure of Purkinje nerve cells in the cerebellum (Hansson 1981). Presumably the rabbits were also exposed to magnetic fields in the substation; however, only electric field levels were measured in the study. No effects on Purkinje cells were found in rabbits in the substation that were covered with a metal screen to shield the electric field (the screen probably had little effect on magnetic fields).

In followup studies, Hansson et al. (1987) exposed rabbits in a laboratory to an electric field of the same level as that in the substation study. The effects on Purkinje cells in rabbits, mice and rats were less apparent in the laboratory study. The researchers suggested that some of the earlier effects in the substation may have been influenced by weather and malnutrition.

Another laboratory study with rats also found a few small lamellar bodies in Purkinje cells of rats exposed to electric fields, and none were found in the control rats (Albert et al. 1984). In a study with rabbits, no differences in Purkinje cells were found between electric-field-exposed and control groups (Portet et al. 1984).

Nerve function was studied in three generations (FO, Fl, F2) of miniature swine that were chronically exposed to a 60-Hz 30-kV/m electric field (Jaffe 1985). Peripheral nerves removed from seven exposed FO mothers and from 7 controls at 100 days of gestation were subjected to several tests. Only two tests showed consistent differences between the exposed and control swine. Nerve conduction velocity in certain nerve fibers (C-fibers) was slower, and nerve recovery from high-frequency stimulation was consistently (but not significantly) less in the exposed animals.

Synaptic function in the swine was tested in 12 exposed and 5 control Fls, and in 22 exposed and 12 control F2s. Of several tests that were done, only one showed consistent differences between exposed and controls. Nerves removed from exposed swine showed

Table 4.12. A summary of nervous system studies of laboratory animals exposed to electric fields.

Study/Location	Species/Exposure (60-Hz vertical, unperturbed, unless noted)	Selected Nervous System Results
Carter & Graves (1975), U.S.	Newly hatched chicks exposed for 8 days to 40 or 80 kV/m (25 chicks each field level). 25 controls.	EEG 6-8 hr after exposure. Significant ave. power spectrums: 4/512,40 kV/m; 17/512, 80 kV/m. Possible effects in some frequency data.
Silny (1976), Germany	Rats were exposed to 50-Hz 80-kV/m and cats to 60-kV/m fields. Exposure & postexposure 4 hr each. Controls.	The instantaneous power density of the EEG in four frequency bands decreased by about 50% during field exposure.
Jaffe et al. (I 980), U.S.	144 mate rats exposed 20 hr/day for 30 days to IOO-kV/m field. Controls.	Nerve tissue removed from rats was tested. Only synaptic nerve transmission was significantly and consistently affected by exposure.
Jaffe et al. (1981), U.S.	45 male rats exposed 20 hrlday for 30 days to IOO-kV/m field. 43 controls.	Muscle function in rats tested. Only recovery from fatigue of slow-twitch muscles was significantly, consistently affected by exposure.
Hansson (1981), Sweden	14 rabbits exposed from gestation to 7.5 wk, 50-Hz 14 kV/m (with or without conona) in a substation. 7 controls.	Many lamettar bodies in Purkinje nerve cells of the cerebellum in field-exposed rabbits-not in controls. Possibly augmented by malnutrition.
Michaelson et al. (1981), U.S.	Male rats were exposed for 1 or 3 hr to a IOO-kV/m field, continuous or interrupted. Controls.	Brain levels of dopamine, dopa, and norepinephrine were significantly higher in exposed rats than in controls. No effect on epinephrine.
Jaffe et al, (1983), U.S.	114 male rats exposed from conception to 1 I-20 days of age to 65 kV/m (effective). Controls.	Exposure had no effect on the visual evoked response (a test of the developing nervous system).
Portet et al. (1984), France	3 rabbits exposed from last 2 wk of pregnancy until 6 wk after birth of young to 50-Hz 50 kV/m. 2 controls.	Purkinje cells of cerebellum were very similar between exposed and control rabbits, and all were normal (no statistical tests reported).
Atbert et al. (1984), U.S.	Female rats exposed 20 hrlday for 30 days; mated and exposed for 21 days after birth to 100 kV/m field. Controls.	A few small lamelfar bodies were found in Purkinje cells only in exposed rats. No conclusions because of sample size, data variability.
Jaffe (1985), U.S.	3 generations of miniature swine (FO, FI, F2) were chronically exposed to a 30-kV/m field. Controls.	7 exposed FOs; 1 peripheral nerve test showed a significant difference from controls. 51 Fls & F2s; 1 synaptic nerve test showed an effect.
Blackwell (1986, 1987), U.K.	Male anaesthetized rats exposed to 15, 30, and 50-Hz peak-to-peak fields of 100 V/m.	Small but statistically significant effects on the time but not rate-of-firing of some spontaneously firing brain neurons at 15 & 30, but not 50 Hz.
Hansson et al. (1987), Sweden	Brain cells from rabbits, rats, mice, and swine, laboratory-exposed to electric fields of various levels. Controls.	The dramatic effects on Purkinje cells in rabbits in a substation (Hansson 1981) generally not seen, but some indications of exposure effects.
Vasquez et ai. (1988a, 1988b), U.S.	36 male rats exposed 20 hrlday for 4 wk to a 65-kV/m (39 kV/m effective) field. 36 controls.	Significant exposure effects on diurnal rhythms of several biogenic amines & metabolites in the striatum and hypothalamus of the brain.

increased conduction velocities up to 25 percent for the B and C components of the postsynaptic compound action potential. The result was only statistically significant for the B-fibers of the F2s. (This test basically measures electrical changes associated with the signal received by a postsynaptic neuron that was sent by a presynaptic neuron-see Fig. 4.12.)

Vasquez et al. (1988a, 1988b) studied the diurnal patterns of biogenic amine neurotransmitters and their metabolites. They took brain samples from rats sacrificed at 4-hour intervals over 24 hours. Four weeks of electric field exposure affected diurnal patterns of DOPAC (dopamine metabolite) in the striatum; and of norepinephrine, dopamine, and 5-HIAA (serotonin metabolite) in the hypothalamus. No effects were seen on serotonin, and no effects were seen on amine neurotransmitters in the hippocampus.

Magnetic field. Cats exposed to a 50-Hz 50-mT (500-G) magnetic field showed a short-term decrease in the power density spectrum of the EEG after the field was turned on (Silny 1985). The effect was associated with the hippocampus, and the response was followed by a rapid adaptation.

Exposure to a 50-μT (.500-mG) 60-Hz magnetic field brought a delayed development of dopamine receptors in the brain striatum of lo-day-old rats (Hagino et al. 1992). The rats were exposed to the field beginning during gestation. Surprisingly, the effect was also seen in rats exposed to a very weak field of only 0.07 μT (0.7 mG). The researchers suggested that the weak AC field may have been in a similar direction as the earth's DC field.

Lai et al. (1993) studied sodium-dependent high-affinity choline uptake (HACU) in the brain of male rats exposed for 45 minutes to 60-Hz horizontal magnetic fields of up to 1 mT (10 G). In cholinergic neurons, HACU is the rate-limiting enzyme in the synthesis of the neurotransmitter acetylcholine. The study found that HACU was reduced in the frontal cortex and in the hippocampus with exposure to magnetic flux densities of 0.75 mT (7.5 G) and above. Other tests done in the study indicated that the effect on HACU was mediated by endogenous opioids in the CNS.

In replicated studies by Margonato et al. (1995), male rats were exposed 22 hours per day to a 50-Hz magnetic field of 5 μT (50 mG). After 32 weeks of exposure, no statistically significant differences between exposed and control rats were found for several neurotransmitters and some metabolites. These included: norepinephrine, dopamine (and two metabolites), and serotonin (and one metabolite). These substances were measured in four brain regions-hypothalamus, hippocampus, striatum, and cerebellum.

Combined fields. Based on visual analyses, there were no differences in EEGs between controls and eight beagle dogs exposed at night, 5 days per week for 3 weeks to 45 or 75-Hz fields (Teeters and Coate 1970). Field intensities for the exposed dogs were 10 V/m and 0.1 mT (1 G), or 20 V/m and 0.2 mT (2 G) In addition to EMF, the exposed dogs received a 0.5~mA current (45 or 75 Hz) injected through two electrodes (one in a front leg and one in a hind leg).

Seegal et al. (1989) studied neurotransmitters in six male monkeys that were exposed to 60-Hz EMF of 3-30 kV/m, and 0.01-0.09 mT (0.1-0.9 G) for three 21-day segments. Data were also collected on these monkeys during pre- and post-exposure periods, and on four control monkeys not exposed to EMF. Neurotransmitters were measured in cerebrospinal fluid after each 21-day period. In the exposed monkeys, levels of metabolites of dopamine and serotonin (HVA and 5-HIAA, respectively) declined significantly 20-30 percent during exposure as compared to pre-exposure levels. During post-exposure, levels of HVA, but not 5-HIAA, returned to pre-exposure levels. No changes in these metabolites were seen in the control monkeys.

The monkeys in the above study were also used in a study of evoked potentials (EP) (Dowman et al. 1989). EPs are time-varying changes in voltage measured on the skin that reflect an animal's response to some stimulus. This study used auditory (sound clicks), visual (light flash), and somatosensory (mild shocks) stimuli. Exposure to EMF at intensities as in the above study had no effects on the early or mid-latency periods of EP components. The researchers said that this suggests that exposure had no effects on peripheral or central sensory pathways. There was a significant decrease in the amplitude of the late components of the somatosensory EP during exposures to 10 kV/m and 0.03 mT (0.3 G), and 30 kV/m and 0.09 mT (0.9 G). The researchers said that the functional significance of the finding is unknown, and they do not know whether there was a change in perception of the stimulus.

Exposure to 60-Hz EMF was associated with some effects on development and maturation of the rat brain (Gona et al. 1993, Mang et al. 1989). These studies were described previously in the section, "Reproduction and Development."

Immune System

The immune system protects the body from potentially harmful foreign infectious agents that may be bacterial, viral, fungal, parasitic, or tissue (Alberts et al. 1989, Campbell 1990, Rose 1993). The system is normally able to distinguish body molecules from foreign molecules, and when this ability breaks down autoimmune diseases can occur.

The basic nonspecific immune defenses include the skin, mucous membranes, inflammatory responses, and certain white blood cells such as macrophages that engulf foreign material. The specific immune defense mechanisms respond to foreign material (germs) termed antigens which are mostly proteins. A class of white blood cells called lymphocytes are involved in immune specificity. They are found in the blood and lymph, and in organs including the thymus, lymph nodes, and spleen.

The antigen response begins when an APC (antigen-presenting cell, e.g., a macrophage) displays a piece of an ingested antigen on its surface (Fig. 4.13). Lymphocytes called helper T-cells that have receptors on their surface that recognize and bind to a specific antigen bind to the APC. This results in proliferation of a population (clone) of identical T-cells for that antigen. Helper T-cells also cause B-lymphocyte cells to produce immu-

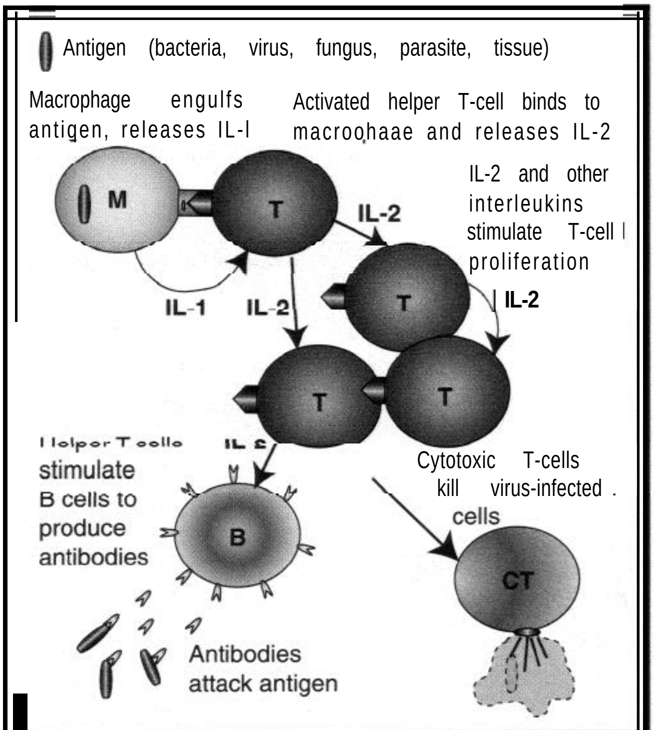


Figure 4.13. Simplified specific immune response to a pathogen (antigen). Ingestion of antigen and release of interleukin-1 (IL-1) by macrophages activates helper T-cells (CD4$^+$). CD4$^+$ cells produce IL-2 leading to proliferatioı of CD4$^+$ cells. CD4$^+$ cells stimulate B cells to produce antibodies and cytotoxic T-cells (CD8$^+$) to help attack the antigen. (See text.)
Sources: Alberts et al. (1989), Campbell (1990).

noglobulin (Ig) proteins called antibodies (humoral immunity), and stimulate specialized lymphocytes called cytotoxic T-cells (cell-mediated immunity), both of which attack a specific antigen in a variety ways. The ability of T-cells to bind to specific cells is facilitated by surface receptor proteins (e.g., CD3 on all T-cells, CD4 on helper T-cells, CD8 on cytotoxic T-cells). A + indicates a cell that expresses these receptors, e.g., CD4+ is a helper T-cell.

During the immune response, proteins called interleukins (IL) are secreted by various cells. These chemical mediators help stimulate cell proliferation. For example, IL-l secreted by macrophages early in the immune response helps activate the CD4+ cells. The activated CD4+ cells then produce IL-2, which increases proliferation and activity of more CD4+ cells. IL-2 also helps to initiate development of lymphocyte-like cells called natural killer (NK) cells. More than a dozen interleukins have so far been identified.

Cell-mediated immunity is often studied in *vitro* by the use of mitogens. A mitogen is some material that causes mitosis, i.e., cell division. Some mitogens stimulate T-cell proliferation, others stimulate B cells, and others stimulate both cell types. Some commonly used mitogens are plant lectins (proteins with binding sites that recognize specific sugar-residue sites). Some examples include Concanavalin A (Con-A) (from jack beans), PHA (from red kidney beans), and pokeweed mitogen (PWM). Lipopolysaccharide (LPS) is also used as a mitogen, and keyhole limpet hemocyanin (KLH) is used to stimulate antibody production.

Another immune defense system is called complement. This is a group of proteins that circulate in the blood and, when activated by the onset of the immune response, help destroy foreign microorganisms.

Electric.field. In two early Russian studies, exposure to 50-Hz electric fields affected certain components of the immune system in rats. In one of these studies male rats were exposed 30 minutes per day for 4 months to fields of 7, 12, or 15 kV/m (Babovich and Kozyarin 1979). The exposed rats showed a significant increase in degranulation of basophils after being injected with brain tissue from another animal. Degranulation is a process that occurs in basophils and other granulocyte-type white blood cells during the antigen-antibody response (Ganong 1981). Another test suggested the development of an autoimmune condition. Both effects were also found in the other study in which rats were exposed 20-320 minutes per day for l-4 months to fields of 10,15, or 20 kV/m (Shandala et al. 1979). There were also differences in complement between exposed and control rats after immunization.

Cerretelli et al. (1979) studied the resistance of mice to infection after the mice had been exposed S-hours per day for 42 days to a 50-Hz 25-kV/m electric field. Mice (228 males and 108 females) were injected with a *Staphylococcus* bacteria, and 72-hours after injection, there was no difference in the percent mortality between the exposed and control mice (72 hours corresponded to the time of maximum virulence of the bacteria).

Another immunological study of mice was done with exposure to a weak 60-Hz electric field of 150-250 V/m (Morris and Ragan 1979, Morris and Phillips 1982). (The published papers on these studies state that exposure was 100 kV/m; this was later found to be an error because of a transformer problem-Morris and Phillips 1983.) No significant differences were found between exposed and control mice for antibody response to keyhole limpet hemocyanin (30- or 60-day exposure), or for mitogen-stimulation response of spleen cells (90- or 150-day exposure). Mitogens studied included Con-A, PHA, LPS, and PWM. In later studies by these researchers with actual exposures of 100 kV/m, no effects on immune system responses were seen (Anderson 1991).

In two experiments, mice were exposed to a 50-Hz 50-kV/m electric field for 2.5 months, and then exposed to a bacterial infection *(E. coli)* (Le Bars et al. 1983). In the first experiment, there were no significant differences between exposed and control mice in their response to the infection. In the second experiment, the variation in weight was greater in the exposed mice. The researchers also vaccinated male rats with diptheric antitoxin 15 and 18 days after the start of electric-field exposure. Tests conducted after 17 more days of exposure indicated that the mean antibody strength was significantly lower in exposed rats. Another study showed that exposed female rats did not respond to immunization in the same way as controls. Le Bars et al. (1983) also tested tuberculin sensitivity in guinea pigs exposed to a 50-kV/m field, and no significant differences were found between exposed and control groups.

Immunological tests were conducted on three generations of miniature swine (FO, Fl, F2) exposed to a 30-kV/m 60-Hz electric field (Morris 1985). Serum immunoglobulins (IgG, IgM) were measured several times in the parental generation (FO) up to 22 months of exposure, in Fl fetuses at 100-days gestation, in Fl females after 32 months of exposure, and in F2 weanlings at 1.5 and 6 months of age. The only statistically significant result was for exposed FOs at 100 days of pregnancy, when IgG levels were 24 percent higher than controls (IgM levels were 28 percent lower, but not significantly). Mitogen response studies were done on FOs and Fl fetuses at 100 days of gestation, and on 42-day-old Fl weanlings. Several T- and B-cell specific mitogens (Con-A, PHA, LPS, PWM) were used on cells from peripheral blood lymphocytes, the spleen, and from lymph nodes. In all of these mitogen tests, there were no statistically significant differences between exposed and control groups.

De Jager and de Bruyn (1994) studied the life expectancy of mice exposed to a 50-Hz 10-kV/m electric field for 20 hours per day. Although they did not report any findings specifically for the immune system, they speculated that a shortening of life expectancy found in exposed mice may have been influenced by a lowering of resistance to illness and infections. The first generation of field-exposed mice had a statistically significant 33-percent-higher death rate by 18 months compared to the controls. In the second generation, the exposed mice had a 13-percent-higher death rate than controls by 18 months, and a 20-percent-higher death rate by 24 months. These rates for the second generation, however, were not statistically significant.

Magnetic field. Immune system parameters were studied in mice exposed to a 60-Hz 2-mT (20-G) magnetic field (McLean et al. 1991). The study also looked at tumor promotion in mice treated with a subthreshold dose of a carcinogen called DMBA (7,12-dimethylbenz(a)anthracene). Co-promotion was studied by also treating some animals with a tumor promoter (TPA). (Tumor results of this study are described in the following section on cancer.)

After field exposure for 6 hours per day for 21 weeks, there were no statistically significant differences in NK (natural killer cell) activity between mice exposed to the magnetic field and DMBA (no TPA) and control mice (DMBA, no field, no TPA). Some differences in NK activity were found between the field and non-field exposed groups treated with TPA, but they were not statistically significant. Among the animals with DMBA+TPA and exposed to the field, there were more enlarged spleens and abnormally high blood-cell counts than in the nonexposed animals.

Mandeville et al. (1995) conducted several immune system studies of rats born and raised for different periods of time in 60-Hz magnetic fields of 2 pT to 2 mT (20 mG to 20 G). With 6-weeks of exposure, there were significant decreases in exposed rats for CD5+, CD4+, and CDS+ cells, and a significant increase in NK cells. No significant effects were seen on secretions from macrophages, although H_2O_2 production was consistently higher in exposed rats. Effects seen on the immune system showed a dose-response pattern with increasing exposure level. Studies by these researchers of 3-month exposures produced essentially the same effects on the cell types noted above. In addition, IL-2 levels were decreased and TNF (tumor necrosis factor) was increased in exposed rats. With 6- and 9-month exposures, only NK cell activity continued to be increased in exposed rats. The researchers said that their study illustrates the adaptability of the immune system to an environmental stressor.

The in vitro proliferation of spleen lymphocytes in response to Con-A was markedly reduced when seven female rats were exposed for 13 weeks to 50-Hz magnetic fields of 50 or 100 µT (0.5 or 1 G) (Mevissen et al. 1996b). Proliferation of lymphocytes in response to Con-A increased with 2- and 4-week exposures to the 100-µT (1-G) field, but there were no effects after 8 weeks. No effects on proliferation were found in response to stimulation of cells with PWM.

Combined fields. The immune system was included in two studies of baboons exposed to combined 60-Hz EMF (murthy et al. 1995). In a pilot study, six adult male baboons were exposed 12 hours per day for 5 weeks to fields of 6 kV/m and 50 µT (500 mG). Blood samples were taken before, during, and 6 weeks after exposure and the animals served as their own controls. Four of the eight parameters studied showed statistitally significant reductions during exposure-CD4+ (T helper cells), IL-2 receptor expression, and T-cell proliferative responses to PHA and PWM. All of these parameters, except IL-2 receptor expression, recovered during post-exposure (i.e., no statistically significant differences between pre- and post-exposure). No significant exposure effects were seen on lymphocytes, CD3+, CD8+, or on the CD4+/CD8+ ratio.

The researchers conducted a second study involving eight baboons exposed for 5 weeks to fields of 30 kV/m and 100 μT (1 G). This study also included eight control baboons. Statistically significant differences for group and exposure-period interaction were seen only for WBC, and for the CD4+/CD8+ ratio. In addition to the other parameters listed in the first study, no effects were seen on B cells, NK cells, or on T-cell proliferative response to Con-A. The researchers concluded that in their studies with 6-week exposures, immune system effects were rapidly reversible. It is not known what might happen with longer exposures.

Immune system parameters were also included in long-term studies of sheep raised in 60-Hz EMF beneath a 500-kV transmission line (Hefeneider 1994, Lee et al. 1997). A primary finding of the studies was a significant decrease in the *in vitro* LPS-stimulated activity of IL- 1 in leukocytes of exposed sheep compared to controls. Exposure in the current study (Christensen et al. 1996) is expected to be completed in 1997. More information on the methods and results of the sheep study are included in a later section on "Environmental Studies."

Cancer and Mutagenesis

Interest in cancer and EMF developed mainly in the 1980s as a result of epidemiological research that reported associations between cancer and living or working around electric power facilities (Chapter 3). Laboratory cancer research followed that involved primarily magnetic fields. A few electric-field studies of cancer and laboratory animals have also been done. This body of laboratory animal research on EMF and cancer is summarized in the sections below. Background information on cancer can be found in Chapter 3.

Results of research on animals is usually considered, along with epidemiologic studies, in assessing the human carcinogenic potential of various agents. The International Agency for Research on Cancer (IARC 1987) found that of 44 agents with sufficient or limited evidence of carcinogenicity to humans, 37 produce cancer in at least one animal species. IARC believes that, for agents that are carcinogenic in animals, it is prudent to regard the agent as presenting a carcinogenic risk to humans. As in many areas of science, however, there is controversy about the proper role of animal research data in assessing potential cancer or other health risks in humans (Ames and Gold 1990, Rall 1991).

In the studies summarized below, several different approaches were used by researchers in attempts to determine whether power-frequency EMF can initiate, promote, or co-promote cancer development in laboratory animals. Some long-term studies looked at incidence of cancer over the typical lifetime of rats and mice, using either standard animal strains, or strains that are prone to develop cancers. In other studies, leukemia cells or viruses were implanted in healthy animals, and the progression of the disease was followed. Several studies used chemicals to initiate or promote skin or mammary tumors. Researchers then looked for promotion, or co-promotion effects of EMF. These chemicals are identified at the bottom of Table 4.13.

Electric field. Schneider and Kaune (1981) studied the possible effects of 60-Hz electric-field exposure on a virus-induced leukemia in chickens. The chickens were exposed to a field of 1.7-1 .9 kV/m (Phillips 1982) until they were 32 days old. Seven days after start of exposure, they were injected with a virus that causes myeloblastic leukemia in birds. The amount of virus used was adjusted to produce about a 50 percent incidence of leukemia. Leukemia development was assessed by measuring the ratio of white to red blood cells, and changes in body weight. In three experiments, there were no statistically significant differences in these parameters between the exposed and control groups.

Female mice that spontaneously develop leukemia were used in two experiments with exposures to 50-Hz 50-kV/m electric fields (Le Bars et al. 1983). In the first experiment 55 mice (5-6 wk old) were exposed 8 hours per day. After 1 year of exposure, all 56 control mice had died but three of the exposed mice were still alive. In the second experiment, with exposures of 18 hours per day, the exposed mice again had lower cumulative mortality than the controls.

Le Bars et al. (1983) also studied the development of chemically induced mammary tumors in female rats exposed to 50-Hz 50 kV/m electric fields. In one experiment 40 rats were exposed 8 hours per day for 7 months, beginning 45 days after treatment with DMBA. The second experiment involved 40 rats exposed for 14 hours per day. Compared to 40 controls in each experiment, there were no significant effects of exposure on the time of tumor appearance, or on the numbers or weights of tumors. There was a greater amount of heterogeneity in the number of mammary tumors per animal among the exposed rats.

Leung et al. (1988) also conducted studies of DMBA-induced mammary tumors in rats exposed to electric fields. In two experiments, a total of 147 female rat pups were exposed to a 60-Hz 40-kV/m electric field. They were treated with DMBA at 54 days of age (7 mg in experiment 1, and 10 mg in experiment 2). Exposure continued for 18 and 23 weeks after treatment. At those times there were no statistically significant differences between exposed and control groups in the numbers of rats that developed mammary tumors. The numbers of tumors in animals with tumors was 35 percent higher in exposed rats than in controls in experiment 1, and 29 percent higher in exposed rats in experiment 2. Neither percentage was statistically significant, but when results of the two experiments were combined, there was a significant increase in tumors per tumor-bearing rat for the exposed group.

Male mice exposed for 24 hours to strong 50-Hz electric fields showed significant dose-response increases in micronuclei formation in bone marrow cells (El Nahas and Oraby 1989). Examination of macronuclei formation tests the potential for cytogenetic effects. Samples were taken at 48,72, and 96 hours after exposure started. No significant increases in macronuclei were found for lOO-kV/m exposure at any time period. After 72 hours, mice exposed to 170 kV/m had increases of 35 percent; with 220-kV/m and 290-kV/m exposures, increases were four to five times greater than controls. All of these increases were statistically significant. Macronuclei formation decreased after 96 hours, but levels in the high-exposure groups were still significantly greater than those in the controls.

De Jager and de Bruyn (1994b) studied the life-expectancy of two generations of mice exposed to a 50-Hz 10 kV/m electric field. The exposed mice had higher death rates than the controls, but there was no increase in the incidence of malignant tumors.

Magnetic field. Several studies of cancer in laboratory animals exposed to power-frequency EMF are summarized in Table 4.13. One of the earliest studies was conducted by Thompson et al. (1988), and it involved implanting leukemia cells in healthy mice. In four experiments, there were no significant differences in survival times between the control mice and those exposed for 2 weeks to a 1 .4-500-μT (14-mG-5-G) field (control survival range, 11.8-13 days; exposed range, 11.3-12.7 days). In a later study, Morris et al. (1994) implanted spleen cells from old leukemic rats into young rats, and exposed the young animals to a 60-Hz magnetic field for 18 weeks. The implanted cells caused leukemia to develop in a short time in control and exposed rats. This study found no effects of magnetic-field exposure on growth or progression of leukemia.

In multigeneration studies, mice were exposed to strong 60-Hz magnetic fields of 25 mT (250 G) from conception up to 418 days of age (mikhail and Fam 1991,1993). Up to 78 percent of the exposed mice developed thymic lymphoma or other cancer-related changes, while only 5-6 percent of the control mice were affected. The effects were also reported to show a direct correlation with the duration of magnetic-field exposure. An unusual aspect of this study is that the control mice were maintained in an area with a relatively strong magnetic flux density of up to 0.05 mT (0.5 G).

McCormick et al. (1994b) also studied lymphoma, but they used a transgenic mouse strain (PIM) that develops the disease after a single injection of the chemical ENU (25 mg ENU/kg of body weight). Results of the study provided no evidence that 60-Hz magnetic fields of up to 1 mT (10 G) stimulated the development of lymphoma in PIM mice.

Another study used ENU to induce brain tumors in young mice by injecting it into their mothers during pregnancy (at 50 mg/kg) (Brugere et al. 1993). Both male and female rats were exposed to 50-Hz fields of 1, 10, or 100 μT (0.01, 0.1, 1 G). No significant differences were seen in mean survival time between the exposed and the control groups.

Swedish researchers conducted two studies to determine whether 50-Hz magnetic-field exposure promoted the growth of liver tumors in male rats (Rannug et al. 1993b, 1993c). An enzyme-altered rat liver tumor model was used in which animals first received a 70 percent hepatectomy and were then injected with the initiator DENA (a combination that produces preneoplastic liver lesions). In the first study, the liver tumor promoter phenobarbital (PB) was added as a positive control to the diet of one group (those treated with DENA, but with no field exposure). In the second study, PB was fed to the rats exposed to the magnetic field. Neither study found any indication that magnetic-field exposure increased liver lesions. In the second study, there was some inhibition of lesion development in some of the field-exposed rats.

At least four research groups have studied possible cancer promotion effects of magnetic fields on chemically induced skin tumors in mice. Canadian researchers (McLean et al. 1991) treated the skin on the backs of mice with the 10 nmol (nanomole) of the chemical carcinogen DMBA. This was a dose below what is required alone to produce tumors. The study used a mouse strain that is sensitive to carcinogenesis (SENCAR). Exposure to a 60-Hz 2-mT (20-G) field did not cause tumors to develop following treatment with DMBA. However, in mice that were also treated weekly with 16.3 nmol of the tumor promoter TPA, skin tumors ap-

Table 4.13. A summary of studies of cancer in laboratory animals exposed to magnetic fields.

Study/Location	Species/Exposure (60-Hz horizontal unless noted)	Selected Cancer Results
Thompson et al. (1988), U.S.	Female mice implanted with leukemia cells. I .4-500-µT (0.014-5-G) fields for 6 hr/ day, 5 days/wk for 2 wk. Controls.	From 4 studies with 112 exposed and 90 control mice, there were no significant group difference: for survival, spleen weight, or body weight.
Beniashvili et al. (1991), Republic of Georgia	Groups of 25 or 50 female rats, 50-Hz 20-µT (200-mG) field for 0.5 or 3 hr/day over 2 yr, plus NMU for some. Controls.	Significantly more rats had mammary tumors in the 3-hr magnetic-field group, with and wthout NMU. Field+NMU also had shorter latent period.
McLean et al. (199l), Canada	32 female SENCAR mice. IO nmol skin DMBA,sume with I µg/wk TPA. 2 mT(20 G) fur 21 wk, 6 hr/day. Controls.	Subthreshold DMBA only, no skin tumors in exposed or control mice; adding TPA, tumors appeared sooner in exposed but not significant.
Stuchly et al. (1992), Canada	48 SENCAR mice, 1 skin DMBA, 1 TPA/week. 2 mT (20 G) 6 hr/day 5 dayslwk for 23 weeks. 48 controls.	After 18 wk of field exposure significantly more exposed mice (25%) had skin tumors compared to controls (8%) but not after 23 wk.
Mikhail & Fam (1991, 1993), Canada	55 third-generation mice exposed to 25 mT (250 G) field from conception to 133,257 days age. Controls.	Exposed mice: 33% malignant lymphoma, 13% premafignant changes, 31% lymphoid hyperplasia. Controls: 5% lymphoid hyperpfasia.
Rannug et al. (1993c), Sweden	10 male rats/group, 30 mg DENA/kg & PB. 50 Hz 0.5 µT-0.5-mT (5 mG-5 G) for 12 wk. DENA & positive controls.	Rats with partial hepatectomy, treated with DENA, and magnetic-field-exposed showed no effects on the growth of preneoplastic liver cells.
Mikhaif& Fam (1993), Canada	41 third-generation mice exposed to 25-mT (250-G) field from conception to 363-418 days age. 36 controls	78% of exposed mice (correlated with exposure duration) and 6% of the controls developed premalignant changes or malignant Iymphoma.
Rannug et al. (1993a), Sweden	30 female mice per group treated with DMBA & exposed to 50 µT or 0.5 mT 50 Hz field for up to 103 wk. Controls.	No significant differences for % mice with skin tumors: DMBA & no field (27%), DMBA + 0.5 mT (37%), DMBA + 50 µT (20%).
Rannug et al. (1993b), Sweden	Groups of 9-10 male rats, 30 mg DENA/kg & PB. 50-Hz 0.5-µT (5mG) or 0.5 mT (5 G) field for 12 wk. Controts.	Rats with partiat hepatectomy+DENA+PB+field exposure gained less weight, and had slight reduction in size & location of liver focal lesions.
Mevissen et al. (1993), Germany	18 female rats, 4 oral 5 mg DMBA. 50-Hz 30 mT(300 G). 36 female rats 50 Hz 0.3-I PT (3-10 mG) 91 days. Controls.	No exposure effect on mammary tumor incidence. Tumors/tumor-bearing rat significantly higher at 30 mT (300 G) in 1 of 2 experiments.
Loscher et al. (1993), Germany	99 female rats, 4 oral 5 mg DMBA doses. Exposed continuously to 50-Hz 0.1 mT (I G) field for 91 days. Controls.	Mammary tumor incidence was 50% higher (and statistically significant) in field-exposed DMBA rats than in nonexposed controls with DMBA.
Yasui et al. (1993) Japan	48 male and 48 female rats/group exposed 2 yr to 50-Hz 5-mT (50-G) or 0.5-mT (5-G) fields. 96 controls.	Exposure for 2 yr to magnetic fields did not increase the incidence of tumors in rats.
Brugere et al (1993), France	ENU injected into pregnant rats. 60 young/group, l-1 00 µT (0.01 -1 G) 50-Hz for nearly 500 days. 60 controls.	No significant exposed/control group differences in mean survival time associated with development of brain tumors induced by ENU.
Loscher et al. (1994), Germany	36 female rats, 4 oral 5 mg DMBA doses. Exposed 24 hr/day, 91 days to 50-Hz 0.3-I µT (3-10 mG). 36 controls.	No significant exposed/control differences for mammary tumor incidence or size; possible reduced tumor latency in exposed rats.
Rannug et al. (1994), Sweden	50 female SENCAR mice/group, DMBA & TPA 105 wk 50 Hz 0.05, 0.5 mT (0.5, 5 G) continuous,1 5 sec on/off. Controls.	No significant exposed/control skin tumor differences; possible dose-response fur on/off exposure, more effect compared to continuous.

Abbreviations: **CR=** circularly rotating magnetic field vector, **DENA=** diethylnitrosamine (a tumor initiator), **DMBA= 7,** 12-dimethylbenz(a)anthracene (a tumor initiator), **ENU=** N-ethyl-N-nitrosourea (produces lymphoma in PIM mice, and brain tumors in rats), **NMU=** nitrosomethyl urea (tumor initiator), **ODC=** ornithine decarboxylase (an enzyme that accompanies tumor promotion), **PB=** phenobarbital (used in this study to promote growth of foci of altered liver cells), **PIM=** mouse strain carrying the *pim* oncogene (develops lymphoma after single injection of ENU), **PMA=** phorbal-12 myrstate-13 acetate (a tumor promoter), **TPA=** 12-0-tetradecanoylphorbol-13-acetate (a tumor promoter), **UV=** ultra-violet light, **UVB=** ultra-violet light with wavelengths from 315-280 nm, **SENCAR=** mouse strain sensitive to carcinogenesis.

Table 4.13. A summary of studies of cancer in laboratory animals exposed to magnetic fields. (Cont.)

Study/Location	Species/Exposure (60-Hz horizontal unless noted)	Selected Cancer Results
Morris et ai. (1994), U.S.	18 young male rats/group implanted with leukemia ceils. 1 mT(10 G) 20 hr/ day to 18 wk. Sham & positive controls.	In general, there were no significant exposed/ control differences in the clinical progression of leukemia in young rats after t8 wk of exposure.
McCormick et al. (1994b), US.	30 PIM mice/group 25 mg ENU.18.5 hr/ day, 0.002-I mT (0.02-10 G) continu-ous & 1 hr on/off, 175 days. Controls.	There were no significant effects of magnetic-field exposure on lymphoma incidence, latency, infiltrative behavior, or tumor-related mortality.
Rhodes et al. (1994), U.S.	100 opossoms exposed to UVB light (36 hr total) & 50 µT (500 mG) CR field 20 hr/day for 8 wk. 100 controls (UVB).	No statistically significant exposed/control differences fur melanoma-related efffects; field group tended to have higher level of indicators.
Juutilainen et al. (1995), Finland	44 female mice, UV light & 50-Hz vertical 0.1 mT (1 G) continuous & 1 hr on/2 hr off 1.26-126 µT 46wk. Controls.	Skin tumors/mouse in sensitive (K2) mice with UV and field was about 0.95 & in K2 UV only 0.4. For normal mice 0.55 & 0.2, respectively.
Baum et at. (1995), Germany	99 female rats, 4 oral 5 mg DMBA. 50-Hz 0.1 mT (I G) field 24 hr/day 91 days. 9 rats field, no DMBA. Controls.	Magnetic field exposure with DMBA did not alter the initiation of mammary tumors, but exposure significantly accelerated tumor growth.
Mevissen et al. (1995), Germany	6 female rats/group, 4 weekly 5 mg oral doses of DMBA. 50-Hz 50 µT (500 mG) field 24 hr/day for 6 wk. 6 controls.	Significant doubling of ODC in mamma of rats exposed to magnetic field similar to ODC from DMBA. Spleen ODC also increased significantly.
Loscher & Mevissen (I 995), Germany	36-99 female rats/group, 4 oral 5 mg DMBA 50-Hz 0.3-100-µT (3-1000 mG) field 24 hr/day, 91 days. 333 controls.	Statistically significant linear increase with field exposure in visibte mammary tumors-50% more tumors than in controls fur 100 µT (1 G).
McLean et al. (1995), Canada	48 SENCAR mice, 1 skin DMBA & 23 PMA treatments. 2 mT (20 G) 6 hr/day 5 days/wk for 52 weeks. 48 controls.	Field exposure significantly increased rate of malignant conversion of chemically induced skin papillomas-8 of 9 affected mice in field group.
Byus et al. (1996), U.S./Canada	60 female SENCAR mice, 1 treatment with DMBA , TPA 2x/wk, 2-mT (20-G) field for 33-43 wk. 60 controls.	incidence of benign papiliomas increased in field exposed mice at 43 wk with lowest TPA dose, reduction in tumor size at high dose 33wk.
Morris et al. (1996) U.S.	80 SENCAR mice/group. 1 DMBA treatment (10 nmol), TPA 2x/wk (0.85-3.40 nmol), 2 mT (20 G) for 20-23 wk.	No statistically significant differences in the incidence of skin tumors between mice exposed to the magnetic field and the sham controls.
Mevissen et al. (1996a, 1996c), Germany	99 female rats, 4 oral 5 mG DMBA treatments & SO-Hz 1 µT (IOO-mG), or 50-µT (500-mG) fieid for 91 days. 9 rats field only.	Visible mammary tumors in field vs. control groups: 10% higher in 100 mG (nut significant), 25.5% higher in 500 mG (statisticaiiy signifi-cant).

Abbreviations: **CR=** circularly rotating magnetic field vector, **DENA=** diethylnitrosamine (a tumor initiator), **DMBA= 7,** 12-dimethylbenz(a)anthracene (a tumor initiator), **ENU=** N-ethyl-N-nitrosourea (produces lymphoma in PIM mice), **ODC=** ornithine decarboxylase (an enzyme that accompanies tumor promotion), **PB=** phenobarbital (used in this study to promote growth of foci of altered liver cells), **PIM=** mouse strain carrying the *pirn* oncogene (develops lymphoma after single injection of ENU), **PMA=** phorbal-12 myrstate-I 3 acetate (a tumor promoter), **TPA=** 12-0-tetradecanoylphorbol-13-acetate (a tumor promoter), **UV=** ultra-violet light, **UVB=** ultra-violet light with wavelengths from 315-280 nm, **SENCAR=** mouse strain sensitive to carcinogenesis.

peared more quickly in the exposed mice. The time difference between the exposed and control groups was not statistically significant. Some other differences between the two groups suggested to the researchers the possible development of leukemia in exposed mice due to suppression of the immune system (see discussion of this study in the section above on the Immune System).

In a later study by these researchers, skin tumors were again studied in SENCAR mice treated with 10 nmol of DMBA and with 4.9 nmol/week of TPA (Stuchly et al. 1992). Following 16-18 weeks of exposure to a 60-Hz 2-mT (20-G) magnetic field, yield and incidence of skin papillomas (benign skin growths) were significantly higher in the exposed group compared to the control group. After 52 weeks of exposure, skin tumors were found in 10.4 percent of the exposed mice and in 12.5 percent of the controls (McLean et al. 1995). However, in 62 percent of the exposed mice, papillomas became malignant (squamous cell carcinomas), compared to only 14 percent in the controls. The researchers cautioned that their experimental design allowed for a 1 in 20 chance of a false positive result.

Researchers in Sweden treated NMRI female mice with 100 nmol of DMBA to induce skin tumors; mice were then exposed for 103 weeks to a 50-Hz 50-, or 500-µT (0.5-, 5-G) magnetic field (Rannug et al. (1993a). TPA (50 nmol, twice every week) was used as a positive control with DMBA (no field exposure). No significant differences were found in the percentage of tumor-bearing mice between animals exposed to both DMBA and the magnetic field, and to those exposed to DMBA with no field. The percentages in these groups (Table 4.13) were also much less than for the DMBA+TPA positive control group (80 %).

In a later study the researchers used SENCAR mice and they added an intermittent magnetic-field-exposure (15 set on/off) to their study design (Rannug et al. 1994). The numbers of skin-tumor-bearing mice in the continuous and intermittent field groups with DMBA (10 nmol) were not significantly different from mice exposed only to DMBA. The intermittent groups, however, had significantly more tumors than the continuous exposure groups (9 vs. 0, respectively). There was also a possible dose response for tumors and the intermittent field. In the positive control group not exposed to the field but treated with DMBA and TPA (33 nmol), 39 mice had skin tumors.

A team of U.S. and Canadian researchers found a 22 percent increase in the incidence of benign skin papillomas in SENCAR mice treated once with 10 nmole of DMBA, twice weekly with 4.1 nmol of TPA, and exposed to a 60-Hz 2-mT (20-G) magnetic field for 43 weeks (Byus et al. 1996). No effect was seen with a higher dose of TPA (8.2 nmol) and a 33-week exposure to the magnetic field.

Other U.S. researchers used the DMBA/TPA skin tumor model and found no effects on tumor incidence in SENCAR mice exposed for 23 weeks to a 60-Hz 2-mT (20-G) magnetic field (Morris et al. 1996). DMBA was applied at a dose of lOnmo1, and TPA was applied twice per week at doses ranging from 0.85 to 3.40 nmol per mouse.

Two other research groups studied magnetic fields as possible promoters of skin tumors, but instead of initiating tumors with chemicals, they used UV light. Rhodes et al. (1994) studied the Brazilian gray short-tailed opossum, because it is susceptible to developing melanoma from exposure to UVB light (melanoma is a highly malignant tumor of melanocytes in the skin). Newborn opossums were exposed to UVB light from fluorescent tubes on alternate days during 17 days. After exposure to a 60-Hz 50-µT (0.5-G) magnetic field for 8 weeks, there were no statistically significant differences between exposed and control animals in the indicators of melanoma. The researchers said that, because of low statistical power, their study provides little support for or against a hypothesis that magnetic fields promote skin cancer.

Juutilainen et al. (1995) used broad-spectrum UV lamps to initiate skin tumors in normal, and in a strain of mice (K2) prone to developing skin tumors. Mice were given 35-minute UV exposures three times a week, and exposed to continuous or to intermittent 50-Hz magnetic fields. After 10 months of exposure the numbers of visible skin tumors per animal were more than doubled in the magnetic field groups for both normal and K2 mice, compared to their controls. The average number of tumors per animal for all groups was less than 1.0. There were no statistically significant differences between the continuous and intermittent field-exposed groups. The researchers said that their preliminary results suggest that a magnetic field may facilitate development of skin tumors initiated by UV light.

Three research groups have studied chemically induced mammary tumors in female rats exposed to 50-Hz magnetic fields. Beniashvili et al. (1991) found significantly more mammary tumors in rats (86%) exposed 3 hours/day to a 50-Hz magnetic field and treated with the tumor initiator NMU, compared to rats treated with NMU but not exposed to the field (54%). The mean latent period of tumor development was also significantly shorter in the field plus NMU group (45.5 days vs. 74.4 days for NMU only). There were also significantly more rats with tumors in the group exposed to the magnetic field 3 hours/day without NMU (28%) as compared to the controls (0%). There were no significant effects for rats exposed to the magnetic field for 0.5 hours/day.

A research group in Germany has conducted a series of studies of mammary tumors and related factors in rats exposed to magnetic fields. The group's first study involved four experiments with DMBA-induced tumors and exposure to 50-Hz or DC magnetic fields (Mevissen et al. (1993). In this study mammary tumor incidence was not significantly increased by either AC or DC magnetic-field exposure. In one experiment, the number of tumors per tumor-bearing rat was significantly increased by about 39 percent in the group exposed to a 50-Hz 30-mT (300-G) field (as compared to reference controls; not significant compared to sham controls). This result was not found when the experiment was repeated.

In a second study the German researchers increased the number of rats per group, and used a weaker 50-Hz magnetic field that more closely approximated human exposure to domestic power-line fields (0.3-l µT, 3-10 mG) (Loscher et al. 1994). No significant differences were found between exposed and control rats in the incidence of DMBA-induced mammary tumors, or in the number of tumors per tumor-bearing animal. The time to the first appearance of tumors was shorter in the field-exposed animals, but not significantly so. The study did find that peak nocturnal melatonin levels were about 20 percent lower in field-exposed rats than in controls.

To further increase statistical power, the number of rats per group was increased further to 99 per group in the next study by the German researchers (Loscher et al. 1993). After 3 months of exposure, DMBA-induced mammary tumor incidence was significantly increased 50 percent in the rats exposed to a 50-Hz 100-µT (1-G) magnetic field. The tumors were also significantly larger in the exposed animals.

The researchers conducted another study with 99 rats per group and 100-µT (1-G) fields, but they added detailed histopathological examinations of DMBA-induced mammary tumors (Baum et al. 1995). As in the previous study by Loscher et al. (1993) the field-exposed group had significantly more and larger macroscopically visible mammary tumors than the control group. However, there were no statistically significant group differences in the incidence of mammary lesions seen in the histological examinations. The researchers said the results showed that magnetic field exposure did not increase the incidence of mammary tumors, instead it promoted growth and development of the tumors.

The German researchers found that exposure of DMBA-treated female rats to a 10-µT (lOO-mG) 50-Hz magnetic field resulted in about a lo-percent increase in visible mammary tumors compared to sham controls (Mevissen et al. 1996a). The finding, however, was not statistically significant. The study did find a statistically significant 30-percent reduction in serum melatonin in the field-exposed rats.

In a study to look at possible mechanisms for magnetic-field effects on mammary tumor growth, the researchers looked at the activity of the enzyme ornithine decarboxylase (ODC) (Mevissen et al. 1995). ODC is involved in the biosynthesis of polyamines for cell proliferation, and it may play a role in tumor promotion. In the study, ODC was increased significantly in the mammary glands and spleen of rats exposed to a 50-Hz 50-µT (500-G) magnetic field. The increase in the mammary glands was similar in magnitude to the increase in ODC in the group treated with the carcinogen DMBA. ODC was not elevated in the liver, small intestine, bone marrow, or ear skin of field-exposed rats.

One of the polyamines (putrescine) for which ODC is a rate-limiting enzyme was increased in epidermal concentrations in 36 K2 mice exposed to a 50-Hz 100-µT (1-G) magnetic field for 24 hours (Juutilainen et al. 1996). ODC activity was lower in the exposed than in the control mice. The researchers suggested that this may have been due to downregulation as a result of increased putrescine levels. After 10 months of exposure there were no effects of exposure on putrescine.

Levels of ODC and polyamines in epidermis and in skin papillomas were not increased in SENCAR mice treated with DMBA and TPA and exposed to a 60-Hz 2-mT (20-G) horizontal magnetic field for 43 weeks (Byus et al. 1996).

The series of German studies of mammary tumors in DMBA-treated rats exposed to magnetic fields were summarized by Loscher and Mevissen (1995). Among 333 control rats there were 170 (51%) macroscopically visible tumors, compared to 207 (62%) tumors in the 333 rats exposed to magnetic fields of all intensities. These percentages were significantly different. The incidence of visible tumors in the field-exposed groups also showed a statistically significant linear increase with increasing flux density (i.e., a dose-response) (Fig. 4.14).

Loscher and Mevissen (1995) concluded that their laboratory findings seem to support some epidemiological studies which found increased breast cancer risks in people exposed to magnetic fields. They added that further laboratory and epidemiological studies were needed, however. The U.S. National Institute of Envi-

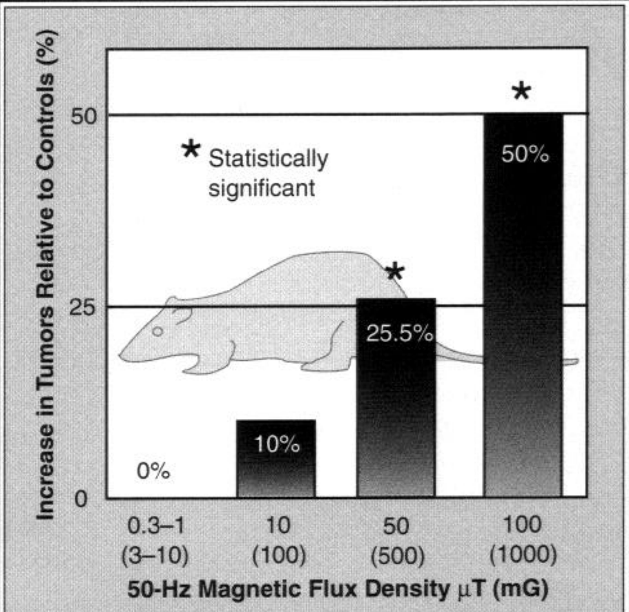


Figure 4.14. Researchers in Germany found that the incidence of mammary tumors induced in rats with the chemical DMBA increased with increasing magnetic flux density. In these studies, a total of 333 female rats was exposed to 50-Hz magnetic fields for 3 months.
Source: Löscher and Mevissen (1995).

ronmental Health Sciences announced in March 1996, that a $1.5 million contract had been awarded to a U.S. Federal laboratory for a study that will attempt to replicate the German tumor promotion studies using both 50- and 60-Hz magnetic fields *(EMF Health & Safety* Digest March 1990:3).

Many of the studies in Table 4.13 were included in a review of EMF animal cancer research by Loscher and Mevissen (1994). Those authors concluded that there is accumulating evidence that magnetic fields induce a carcinogenic response in laboratory animals. However, they added that the existing evidence was insufficient to discern a cause-and-effect relationship. In another review, Anderson and Sasser (1995) concluded that the results of the animal tumor promotion studies are mixed, and the strongest evidence is the area of mammary carcinogenesis. They believed that the studies with animals had not yet confirmed the results of epidemiologic studies which suggest an association between EMF and cancer in humans.

Studies of Cells and Tissues

Studies of cells and tissues conducted outside of the body are called in vitro studies. For research with EMF, these studies are typically used by scientists to obtain information on how these fields interact with biological structures and processes. Thus, *in vitro* research helps to provide information on possible mechanisms to explain effects of EMF reported in studies of humans and animals. However, effects of EMF found on isolated cells and tissues, may not occur in whole organisms where many processes function that could prevent, obscure, or compensate for the effects.

Some Basic Cell Biology

Information in this section is intended to provide a basic introduction to some of the cellular processes that have been the subject of research on EMF. This information is primarily derived from Campbell (1990), and Alberts et al. (1989). The electrical resistance of cell membranes is about 60-2000 times greater than the resistance of the fluid surrounding the cells (Adey 1990). Therefore, currents induced in the body by EMF exist primarily in the small spaces between the cells. Although induced currents are extremely weak, they are present at the surface of cells where many specialized structures are located. These surface projections are important to many functions of the cell, including cell-to-cell communication, and responses to hormones and to cells of the immune system.

Some key components of the outermost membrane (plasma membrane) of animal cells are shown in Figure 4.15. (Plant cells have a cell wall that is not found in animal cells.) The model of the membrane in Figure 4.15 is called "fluid mosaic" because it consists of protein structures in a lipid bilayer that has a consistency about like salad oil. Cholesterol helps keep the membrane fluid. There is a membrane potential of about 0.1 V (inside of the cell is negative), and because the membrane is so thin, there is an enormous electric field of about 10^7 V/m across the membrane (Adey 1990).

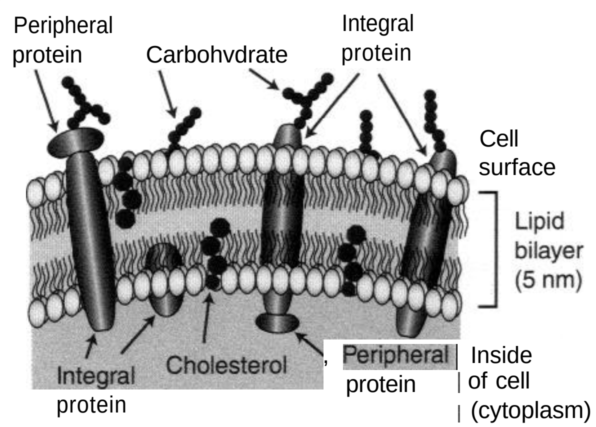


Figure 4.15. Highly simplified cross-section of a cell membrane. The lipid (fat) bilayer blocks most water-soluble molecules. Protein molecules dissolved in the bilayer transport some molecules in and out of the cell. Some also act as receptors for hormones and other molecules. External carbohydrate (sugar) chains may function in cell-to-cell recognition.
Sources: Campbell (1990), Alberts et al. (1989).

Some molecules such as H_2O, CO, and 0, pass easily through the membrane, but it effectively blocks most other molecules and ions. These substances must cross the membrane by specialized means. Some hormones such as estrogen (steroid hormones) are able to pass through the membrane. Other hormones, however, do not directly enter the cell. Instead they bind to specific protein receptors on the cell surface. The weak hormone signal binding to its receptor triggers a process that results in a large response inside the cell that amplifies the hormone signal several million-fold. This process is also known as signal transduction (Liburdy 1995).

An example of cell bioamplification is shown in Figure 4.16 for the hormone epinephrine. This hormone is secreted by the adrenal gland during times of stress

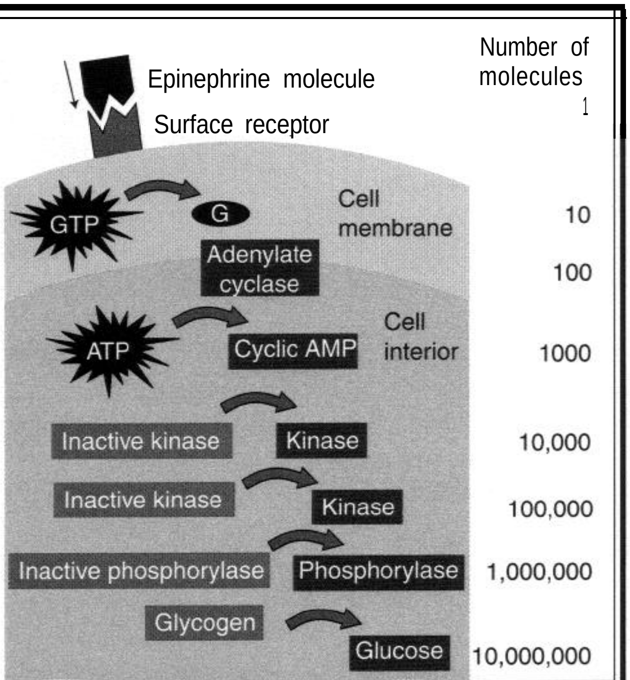


Figure 4.16. An example of how a weak signal (a hormone) is greatly amplified by biological processes. Binding of a single molecule of epinephrine (adrenaline) to its receptor on the surface of a liver cell, sets off a cascade of events in the membrane and in the cell interior. As a result, millions of glucose (sugar) molecules are released from stored glycogen. Source: Campbell (1990).

when the body needs a quick increase in sugar for energy. One source of this sugar is the glycogen stored in liver cells. Figure 4.16 shows the approximate amplification in active molecules that occurs when a molecule of the hormone binds to its receptor on a liver cell leading to release of glucose. A cell may have about 10,000 surface receptors for a particular hormone.

First steps in the bioamplification process involve activation of membrane-bound G proteins and energy-carrying GTP, resulting in an increase in the enzyme adenylate cyclase. This enzyme converts another energy carrier ATP, to cyclic AMP (cAMP). This compound is called a second messenger because it carries the signal from the first messenger (the hormone) into the cytoplasm of the cell. In the cytoplasm, more amplification occurs involving a cascade of enzymes called kinases, and finally the hydrolysis of glycogen releases the sugar glucose.

The receptor binding and amplification process for some hormones involves a second messenger called inositol triphosphate (IP,). This process involves G proteins, enzymes called phospholipase C and protein kinase C, and the protein calmodulin. The process results in the release of calcium stored in the cell which functions as a third messenger. As an example, intracellular calcium is mobilized when an antigen binds to its receptor on T-lymphocytes (Weiss and Imboden 1987).

EMF and Signal Transduction

Many scientists have suggested that a basic site of interaction of induced currents and electric fields is the cell membrane (Bawin and Adey 1976, Adey 1981, Chiabrera et al. 1984, Grattarola et al. 198.5). Such interactions could include effects on signal transduction through alterations in cell surface receptors, or on movement of calcium across membranes. Marron et al. (1983) reported one of the first studies to support this hypothesis. Their study involved amoebae exposed to combined 60-Hz EMF of 1 V/m, and 0.1 mT (1 G). Statistically significant differences in the distribution of the amoebae in layers within the media (partitioning) were seen between exposed and control groups. Because the cells typically partition on the basis of cell surface properties, the results suggested that such properties may have been altered by exposure to EMF. Followup studies showed that exposure to either electric or magnetic fields alone produced different cell surface alterations (Goodman et al. 1988).

Erythroleukemic cells exposed to a 50-Hz 2.5mT (25-G) magnetic field showed changes in the cell surface that were visible with a scanning electron microscope (Paradisi et al. 1993). The proliferative ability of the cells was not affected, however.

Antibody binding to surface receptors (CD3) on human T-lymphocytes was altered by exposure to a 60-Hz magnetic field of 22 mT (220 G) (Liburdy et al. 1993a). The immature T-cells used in the study showed a significant increase in the shedding of peripheral proteins from the cell surface. A large effect was not seen for B-lymphocytes.

Luben (199 1) presented evidence that pulsed magnetic fields affected the signal transduction process of G protein-linked membrane receptors for parathyroid hormone. This mechanism was proposed as a way to explain how pulsed fields are able to affect the healing of bone fractures. In more recent work, Luben (1993) began extending his findings to 60-Hz sine-wave magnetic fields. In preliminary studies, cAMP responses of mouse bone cells to isoproterenol were inhibited by exposure to a 60-Hz 0. 1-mT (1-G) magnetic field. The effect was not as large as that produced by a 1 -mT (1 O-G) pulsed magnetic field.

Schimmelpfeng et al. (1995) also found changes in cAMP levels in mouse cells exposed to a 2-mT (20-G) 50-Hz magnetic field. Levels were found to increase or decrease, relative to controls, depending on the cell concentration. Rodan (1987) found no evidence that 60-Hz currents from agar-electrodes affected levels of adenylate cyclase activated by the binding of parathyroid hormone to its receptor. He did find a small but statistically significant increase in DNA synthesis under certain cell growth conditions.

The expression of cell-surface receptors for transferrin on human colon carcinoma cells was altered by exposure to 60-Hz electric and magnetic fields (Phillips et al. 1986, Winters 1986). Serum transferrin is a glycoprotein that is a major iron-transport protein in the body, and it is a cell growth factor. Exposure to a 0. 1-mT (1 -G) magnetic field alone or in combination with an electric field from a 300~mA/m* current density resulted in receptors being maintained at maximum levels and not regulated by cell density. Exposure to the electric field alone resulted in fewer receptors being expressed as compared to numbers expected based on cell density. In these studies, normal leukocytes and lymphocytes from dogs and from humans were also exposed to the 60-Hz EMF and no effects on cell-surface receptors were found (Winters 1986).

Exposure of human tonsil lymphocytes for up to 60 minutes to a 450-MHz field modulated at 60 Hz did not affect activity of CAMP-dependent protein kinases (Byus et al. 1984). Activity of non-CAMP-dependent kinases was reduced 20-25 percent after 15-30 minutes of exposure. However, activity returned to control levels after 60 minutes of exposure. The researchers said that they could not say whether the transient effect altered any function of the lymphocytes.

Several studies have looked for effects of EMF on calcium ions. As described previously, calcium is a second messenger in cell-signaling mechanisms. Bawin and Adey (1976) found decreased efflux of calcium from isolated chick and cat brain tissues exposed to electric fields at certain frequencies from 1 to 75 Hz (50/60 Hz were not tested) with intensities of 5-100 V/m. In these studies, brain tissue is first incubated in a solution containing radioactive calcium ($^{45}C^{2+}$). The tissue is then rinsed, placed in fresh solution, and then exposed to the magnetic field. The amount of $^{45}C^{2+}$| in the solution released by the tissue is then compared between exposed and control tissues. In similar studies by Blackman et al. (1985a), 50- and 60-Hz combined electric and magnetic fields were used, and increased calcium efflux from chick brain tissue was found. In both of the above studies, effects on calcium efflux showed both frequency and field magnitude "windows" of sensitivity. For 60 Hz, Blackman et al. (1985a) found enhanced calcium efflux for electric fields of 12.4 and 14.1 V/m (unperturbed in air), but not for fields of 8.8, 10.6, or 15.9 V/m. (The exposure system also had a magnetic field component in A/m which can be found by dividing these rms electric fields by 377.)

In later studies, Blackman et al. (1985b) found that the strength of the local geomagnetic (DC) field has an influence on the frequency of the AC fields that are most effective in changing calcium efflux from brain tissue. Further, the AC and DC magnetic fields must be perpendicular to each other for the effect to occur (Blackman et al. 1990). Blackman (1985) suggested that the calcium efflux results found with specific combinations of AC and DC magnetic fields might involve a cyclotron resonance mechanism. This mechanism and related research are discussed in a later section, "Possible Mechanisms for Biological Effects of EMF."

Gunderson et al. (1986) studied calcium efflux from embryonic chick spinal cord tissue exposed to circularly polarized 60-Hz EMF. Tissues were exposed from 20 minutes to 72 hours to fields of 30 kV/m (air equivalent), and 0.1 mT (1 G) (separately, and combined). Exposure for 20 minutes had no significant effects, but after 72 hours exposure to combined EMF, calcium efflux was almost twofold higher in exposed tissue. The finding was on the borderline of statistical significance, and the researchers cautioned that the results were based on a small sample. The researchers also found that neurotransmitter release from rat muscle was significantly increased 12-18 percent by exposure to a 60-Hz linearly polarized magnetic field of 0.1 mT (1 G). The researchers suggested that this finding may have been caused by an increase in intracellular calcium concentration.

Exposure to a 60-Hz amplitude-modulated 450-MHz electromagnetic field resulted in a significant 20-percent inhibition in the ability of cytotoxic T-cells to kill target cells (Lyle et al. 1983). Smaller levels of inhibition were seen with fields at 16, 40, 80, and 100 Hz. The researchers suggested that the effect may have been mediated by a field-caused change in calcium flux or in membrane function. A 42.1-µT (421-mG) 16-Hz magnetic field (50/60 Hz was not tested) in combination with a 23.4-µT (234-mG) DC magnetic field inhibited calcium influx in lymphocytes stimulated with the mitogen concanavalin A (Yost and Liburdy 1992). The effect was not seen with either field alone. The researchers suggested that signal transduction was apparently affected by the combined AC and DC fields.

Lyle et al. (1991) saw a statistically significant 37-percent increase in uptake of labeled calcium ions by mouse spleen lymphocytes exposed to a 20-µT (peak)

(200-mG) 60-Hz magnetic field. Much larger effects on uptake were seen with exposure to a 13.6-Hz magnetic field.

Exposure of human helper T-lymphocytes to an induced 0.1-V/m 60-Hz electric field did not increase the intracellular calcium concentration (Lyle et al. 1993). The intracellular calcium signal was stimulated by a complex of cell-surface molecules involved with transmembrane signaling. Another study also found no effects on calcium uptake by six types of mammalian cells exposed to 50-Hz magnetic fields of 0.1-2 mT (l-20 G) (Garcia-Sancho et al. 1994).

Real time changes in the influx of calcium ions across the cell membrane of human leukemic T-cells exposed to 50/60 Hz EMF were measured by dual-sample florescence spectroscopy (Walleczek et al. 1993). The largest effect occurred with a 50-Hz current that produced a 5-V/m electric field in the media. No effect was seen with 0.1 V/m. A smaller effect (up to 12%) on calcium influx was seen with exposure to a 60-Hz magnetic field of 1 mT (10 G).

Eichwald and Kaiser (1995) reviewed research on effects of EMF on calcium signaling in cells of the immune system. They proposed a model to show that the external fields act on the signaling process between the surface receptors and the G-proteins. The model also showed that different cell responses were possible, depending on specific combinations of internal cell factors and external physical factors.

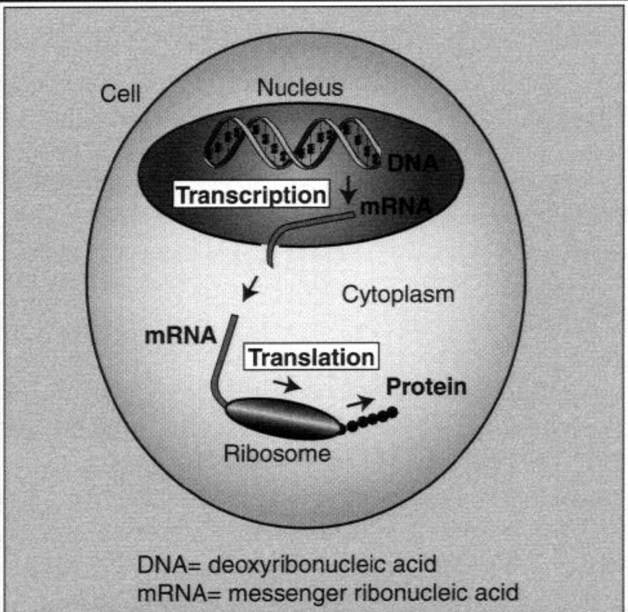


Figure 4.17. Gene expression is the process for making proteins from information in DNA within genes. During *transcription* information in DNA is transferred out of the nucleus by mRNA. *Translation* occurs in the cytoplasm on ribosomes where information on mRNA is used to construct amino acid combinations forming specific proteins. Source: Campbell (1990).

EMF and Gene Expression

The enzymes and other proteins that each cell produces are determined by information contained in the cell's DNA. Through an intricate and highly regulated process, information within a gene's DNA provides the instructions needed by RNA to synthesize specific proteins. The overall process of gene expression leading to protein synthesis is diagrammed in Figure 4.17.

Goodman et al. (1983) first reported that pulsed electromagnetic fields increased transcription activity in fly (Sciara) salivary glands. The researchers expanded their studies to include sine wave fields, and found that transcription was increased in fly salivary glands exposed for 60 minutes to a 72-Hz 1.15-mT (peak) (11.5-G) magnetic field (Goodman and Henderson 1986,1988). Transcription on the X chromosome was measured by counting uptake of radioactive 3H-uridine into RNA transcripts. The researchers suggested that most of the transcriptional activity they observed was probably an increase in preexisting transcription. The results also suggested that mRNA species were affected by field exposure.

Goodman and Henderson (1988) continued their studies on fly salivary gland cells by adding a 1.5-mT (peak) (15-G) 60-Hz sine-wave field, and by looking at polypeptide (protein synthesis). There were qualitative and quantitative differences in the patterns of polypeptides seen that varied by signal type (pulsed or sinewave). For 60-Hz exposure, nine polypeptides found in the controls were absent, and three found at 60-Hz were not found in the controls.

This research group also found changes in RNA transcripts for the genes *c-myc,* and histone H2B, when human HL-60 cells (a promyelocytic leukemia cell line) were exposed for 20 minutes to magnetic fields with frequencies from 15 to 150 Hz (Wei et al. 1990). *C-myc* is an oncogene involved in the early response to mitotic stimuli, and histone H2B is a "house-keeping gene." At 60 Hz, the levels of the two transcripts were increased about twice that of the controls. The largest increase (fourfold) occurred at 45 Hz. Transcript levels of *c-myc* and histone H2B were also increased when I-IL-60 cells were exposed to a 60-Hz electric field of 3 mV/m (Blank et al. 1993).

Exposure of human leukemia HL-60 cells to a 1 -mT (10-G) 60-Hz magnetic field for 30-120 minutes resulted in a 50-60 percent increase in transcriptional rates

(Greene et al. 1991). The rates were measured by counting the uptake of 3H-uridine into RNA. The researchers found that the effect on transcription rates was primarily from the induced electric-field component of the magnetic field.

Exposure to 60-Hz magnetic fields has also been reported to affect gene transcription in yeast cells. Weisbrot et al. (1993) found that two different yeast genes showed different responses to short-term exposure to magnetic fields of 0.8-80 µT (S-800 mG). Transcripts for gene URA3 (responsible for uridine metabolism) showed the greatest increase (2.7 x controls) after 15minutes exposure to a 0.8-µT (8-mG) field. The gene IME2 (involved in meiosis) showed little or no response to magnetic field exposures of up to 90 minutes.

Goodman et al. (1992b) studied transcription in another fly, *Drosophila,* and again found several changes in transcripts for salivary gland chromosomes exposed for 20 minutes to pulsed and sine-wave (60- & 72-Hz) magnetic fields. This species yields more detailed information compared to *Sciara,* because extensive gene mapping for the species has been done. In the study there were 13 regions on chromosome 3R where transcriptional activity was induced or increased by field exposure, compared to unexposed chromosomes.

In further studies with human HL-60 cells, Goodman et al. (1992a) exposed cells to 60-Hz magnetic fields of 0.57-570 µT (5.7-5700 mG), for periods of 10,20, and 40 minutes. Increases in basal levels of normally expressed gene transcripts were found for c-myc, ß-actin, c-src, ß-tubulin, and histone H2B. No effects were seen on a-globin transcripts. The increases were not proportional to either field strength or duration of exposure (i.e., effects appeared in windows). For example, c-myc transcripts were increased most (about 300% more than controls) after 20-minutes exposure to a 5.7-µT (57-mG) field. In a later study, Lin and Goodman (1994) found that 20-minutes exposure of HL-60 cells to a 60-Hz 8-µT (80-mG) field resulted in only a 30-50 percent increase in *c-myc* transcript levels.

Liburdy et al. (1992, 1993b) found a twofold increase in *c-myc* mRNA in mitogen-activated rat thymic lymphocytes exposed to a 60-Hz 22-mT (220-G) magnetic field (induced electric field of 0.17 V/m). The researchers observed that their results confirmed the work of Goodman et al. (1992a) who reported effects of magnetic fields on *c-myc* transcripts in HL-60 cells.

Phillips et al. (1992) found both increases and decreases in gene expression with CEM-CM3 T-lymphoblastoid cells exposed for 15-20 minutes to a O.l-mT (1-G) 60-Hz magnetic field. They used a nuclear run-off assay and found that c-fos transcription increased up to twofold after field exposure. *C-myc* transcription increased 4.7-fold at one cell density (10^6 cells/ml), but did not change at a lower cell density (10^5 cells/ml). C-jun transcription was decreased by 60 percent at the lower cell density, and was not affected at the higher density. Protein kinase C transcription was increased 3.1 -fold at the lower cell density.

Two research groups attempted to replicate the *c-myc* transcription studies of Goodman et al. described above. Lacy-Hubert et al. (1995) exposed human HL-60 cells to 60-Hz fields of 0.57-57 µT (5.7-570 mG) for 20 minutes. Using methods similar to those of previous researchers, as well as modified methods, no significant effects of field exposure were found on *c-myc* transcripts. In the second study, Saffer and Thurston (1995) exposed HL-60 and Daudi cells (human lymphoma cell line) to 60-Hz magnetic fields of 5.7 µT to 10 mT (57 mG to 100 G) for 20-60 minutes. This study also found no significant increases on *c-myc* transcripts in field-exposed cells. Saffer and Thurston (1995) concluded that their study, along with the study by Lacy-Hubert et al. (1995), refute prior claims of magnetic field effects on *c-myc* transcripts.

Marino (1996) challenged the conclusion reached by Saffer and Thurston (1995) and he identified several reasons to invalidate their conclusion that *c-myc* expression is unaltered by magnetic fields. In response Saffer and Thurston (1996) defended their study and suggested that researchers should put the transcription studies behind them and move on to other issues.

C-myc transcripts were not affected in HL-60 cells or in human lymphoid cells infected with Epstein-Barr virus and exposed to 50-Hz magnetic fields (Desjobert et al. 1995). Exposures included magnetic fields of 10 µT (100 mG) or 1 mT (10 G) from 20 minutes to 72 hours.

Kropinski et al. (1994) found no effects of a 2-hour exposure to 60-Hz magnetic field of 3 mT (30 G) on protein synthesis in a bacterial cell *(Escherichia coli).* Dutta et al. (1994) also studied *Escherichia coli;* they found changes in the activity of the cytoplasmic enzyme enolase when cells were exposed for 30 minutes to 16- and 60-Hz EMF. The mammalian gene for enolase was contained within a plasmid in the bacterial cells. (Plasmids are small rings of bacterial DNA into which foreign DNA can be inserted.) Exposure to a 147-MHz field amplitude modulated at 60 Hz resulted in a 28-percent reduction in enolase activity. Exposure to 60-Hz sinewave EMF of 14.1 V/m and 65 nT (0.65 mG) reduced activity of the enzyme by 24 percent. Exposure to the 16-Hz field resulted in enhanced activity. The researchers pointed out that enolase is being tested clinically as a possible way to detect new tumors.

In later studies, Dutta et al. (1995) studied expression of mRNA and enolase protein in chick embryo retina and neuroblastoma cells exposed to 60-Hz electric fields as used in the above study. Statistically significant reductions in enolase activity were found in the exposed neuroblastoma cells, but no significant effects were found for retinal cells.

The ability of mitogen (LPS)-stimulated mouse peritoneal exudate cells to make IL- 1 and IL-2 was not significantly affected by exposure to 60-Hz EMF (Morandi et al. 1994). Cells were exposed for 24 or 48 hours to a 300 V/in electric field, and a 0.3-mT (3-G) magnetic field. The researchers cautioned, however, that because of the small sample size, only relatively large effects could have been detected by the study.

Treatment of rat adrenal tissue with ACTH (adrenocorticotrophic hormone) and exposure for 5.5 hours to a 60-Hz lo-kV/m electric field resulted in a threefold increase in corticosterone production (Lymangrover et al. 1983). The researchers considered this an intensity window effect, because no effects were seen with exposures of 5, 100, or 1000 kV/m. (All of these electric field values are the calculated unperturbed levels.) The researchers estimated that the electric field was about 16.8 mV/m in the cell solution for 1000 kV/m.

A 60-Hz electric field of 1 V/m produced by current from electrodes in the cell media produced increased activity of the enzyme ornithine decarboxylase (ODC) (Byus et al. 1987). ODC is a controlling enzyme in the polyamine biosynthetic pathway, and it is regulated by factors interacting at the cell surface (e.g., hormones). ODC levels are increased in all rapidly growing cells-both normal and cancerous. A l-hour exposure to the field produced a fivefold increase in ODC activity in human lymphoma cells, and two to threefold increases in mouse myeloma cells. Mattsson and Rehnholm (1993) found increases in gene expression for ODC in three mammalian tumor cell lines exposed to a 50-Hz magnetic field of 30 uT (300 mG). The increases ranged from about 20 percent for HL-60 cells, to five-sixfold over control values for ELD cells.

Litovitz et al. (1991) found that a 4-hour exposure to a 10-uT (lOO-mG) 60-Hz magnetic field about doubled the activity of ODC in mouse L929 cells. Cress et al. (1995) could not replicate the finding when cells were exposed to the same magnetic flux density in their laboratory. However, when the cells were exposed to the same flux density in the facilities used by Litovitz et al. (1991), a significant doubling of ODC activity was found.

It appears that the general issue of magnetic fields and gene expression is not resolved. Both positive findings and failures to replicate prior studies continue to be reported. At the 1995 annual review of research on biological effects of EMF, there were at least seven reports on various aspects of gene expression and most reported one or more positive results (W/L Associates 1995). These included new studies by Goodman et al. (1995b) that found that c-myc transcripts in HL-60 cells showed greater responses when 60-Hz magnetic field exposures were intermittent compared to continuous. Ning et al. (1995) found no effects of a 60-Hz magnetic field of 0.1-l mT (l-10 G) on c-myc expression in HL-60, GM1500B, or BL41 cell lines. However, c-myc expression was significantly increased in Daudi and in BL41 95.8 cell lines. The researchers suggested two possibilities to explain why I-IL-60 cells did not seem to affected: 1) they have intact ***c-myc*** (compared to deregulated ***c-myc*** in Daudi), or 2) they lack the Epstein-Barr virus (which is found on BL41 95.8 cells).

Several papers on gene expression were also presented at the 1996 annual meeting of the Bioelectromagnetics Society. Goodman et al. (1996) summarized their past research and suggested that many lines of evidence indicate that 60-Hz magnetic fields increase transcripts for stress genes in cells from humans, flies, and yeast. Other researchers, however, reported that they were unable to find effects of 50- or 60-Hz magnetic fields on gene expression (Mattsson et al. 1996, Buthod et al. 1996, Hui et al. 1996, Owen et al. 1996, Thurston and Saffer 1996) or on protein synthesis (Shi et al. 1996). Some studies of genes reported on at the meeting did find effects of magnetic tields. Miyakoshi et al. (1996) found that in human MEW0 cells (from melanoma) exposed to a strong 50-Hz magnetic field of 400 mT (4000 G), there were increases in mutations at the locus of the ***HPRTgene.*** Studies by Binninger and Ungvichian (1996) have found changes in gene expression in yeast cells. Expression of p53 protein in rat glioma cells was increased up to 40-fold in three of four experiments, following a 3-hour exposure to a 60-Hz magnetic field of 50 uT (500 mG) (Zhao et al. 1996).

EMF and Genetics, Proliferation, and Cancer

Liboff et al. (1984) reported that exposures from 24 to 96 hours to sinusoidal magnetic fields of 15-4000 Hz affected DNA synthesis in human fibroblast cells. Exposure of cells to a horizontal 76-Hz magnetic field with a flux density of 0.023 mT (230 mG) resulted in an increase of up to about 50 percent in uptake of 3H thymidine compared to controls.

The DNA synthesis rate can be a measure of cell proliferation. Cridland et al. (1996) found no effects of 20-uT (200-mG) or 20-mT (200-G) .50-Hz magnetic fields on DNA synthesis of normal human fibroblast cells. Those authors believed that their results were consistent with most other studies of proliferation of cells exposed to magnetic fields. Hirakawa et al. (1996) using a cell-free system found that exposure to 5-100-uT (50-lOOO-mG) 60-Hz magnetic fields significantly altered the synthesis of complementary DNA (only the DNA sequences that correspond to genes).

Nordenson et al. (1984) exposed blood from two human volunteers to a .50-Hz 1 mA/cm2 current density in an agar bridge electrode system. No chromosome damage was seen on lymphocytes exposed to the current for 3 hours. Significant increases in chromosome breaks were seen when the researchers exposed blood samples to 10, 3-us long spark discharge shocks with a peak electric field in the samples of 350 kV/m. The frequency of the breaks was similar to that caused by ionizing radiation of 0.75 Gy (Gray).

Paile et al. (1995) used a Helmholtz coil system to expose blood from one human volunteer to 50-Hz magnetic fields of 30 uT, 300 uT, and 1 mT (0.3, 3, and 10 G). No exposure effects were seen consistently on chromosomal aberrations. A weak effect was seen on sister chromosome exchange (SCE, used to detect DNA damage) in one series of experiments, but the finding did not occur in other experiments. There were also no effects on chromosomal aberrations when blood samples were exposed to 10, 2.6-us spark discharges with electric fields of up to 365 kV/m.

When cow lymphocytes were exposed to a 50-Hz current density of 2.4 mA/cm² (16 mV/m induced electric field), the frequency of chromosome aberrations was threefold higher than in the controls (d'Ambrosio et al. 1985). The most frequent aberration was for chromatid breaks (45.4 %), and there were no effects on SCE. In this study the current was induced by external electrodes. In later studies these researchers used an agar-bridge exposure system, and chromosomal aberrations were increased significantly by 52 percent in cow lymphocytes exposed to a 50-Hz current density of 1 mA/cm2 (Scarff et al. 1993). No effects were seen with a current density of 0.1 mA/cm2.

Livingston et al. (1986) found no effects on SCE when human lymphocytes and Chinese hamster ovary (CHO) cells were exposed to 60-Hz EMF. There were also no effects on cell proliferation, DNA synthesis, or on chromosome breaks. The cells were exposed to various combinations of electric-field-induced current densities from 3 to 3000 uA/cm2 and a magnetic field of 0.22 mT (2.2 G). The researchers concluded that EMF exposures had no detectable effects on reproductive integrity of the two types of cells.

Rosenthal and Obe (1989) found that SCE frequencies in PHA-stimulated human lymphocytes were only increased with 50-Hz magnetic field exposure, when the cells were pretreated with alkylating agents. There was, however, a significantly faster cell cycle in the untreated lymphocytes. Flux densities ranged from 0.1 to 7.5 mT (l-75 G). Because only two fixation times were used (48 and 72 hr), the researchers cautioned that the effect may have been due to factors other than the magnetic field (i.e., cell culture factors). In later studies at this laboratory, human lymphocytes were again exposed to a 50-Hz 5-mT (50-G) magnetic field, and a larger number of fixation times was used (Antonopoulos et al. 1995). The study confirmed the previous findings of a faster cell cycle, and no effect on SCE frequencies.

Mitotic rate, SCE, and chromosome breakage were not affected in human lymphocytes exposed to a 60-Hz electric-field-induced current density of 30 uA/cm2, and a O.l- or 0.2-mT (l- or 2-G) magnetic field (Cohen 1986, Cohen et al. 1986). The cells, taken from five men and five women, were exposed to the EMF for 69 hours.

DNA single-strand breaks in CHO cells were not increased by a l-hour exposure to 60-Hz EMF of 1 or 38 V/m, and 0.1 or 2 mT (1 or 20 G) (Reese et al. 1988). DNA single-strand breaks were increased in rat brain cells exposed for 2 hours to 60-Hz magnetic fields at flux densities equal to or greater than 0.1 mT (1 G) (Lai and Singh 1995).

Whitson et al. (1986) studied possible effects of a 60-Hz lOO-kV/m electric field on the ability of human fibroblast cells to repair DNA damage caused by ultraviolet (UV) light. An assay was used that measures the cell's ability to remove the pyrimidine dimers induced by UV light. No effects of field exposure were found on DNA damage repair, or on cell growth or survival.

Frazier et al. (1990) found no indication that repair of DNA single-strand breaks in human lymphocytes caused by ionizing radiation was affected by exposure to 60-Hz EMF. The cells were exposed to an electric field of 20 V/m, to a magnetic field of 1 mT (10 G), or to combined fields ranging from 0.2-20 V/m, and 0.05 -1 mT (0.5-10 G).

Initial studies by Phillips et al. (1995) found increases in the levels of an enzyme associated with DNA repair, when pheochromocytoma cells were exposed to a 60-Hz 0. I-mT (1-G) magnetic field. After 30 minutes of exposure there was a lo-percent increase in levels of the enzyme poly(ADP-ribose) polymerase compared to controls. After l-3 hours of exposure, levels of the enzyme were elevated 70-75 percent.

Cantoni et al. (1995) found no effects of exposures to 50-Hz EMF on the rate of repair of DNA single or double strand breaks induced in CHO cells by hydrogen peroxide. Exposures included electric fields of 0.2-20 kV/m, and magnetic fields of 0.2 uT-0.2 mT (2 mG-2 G).

When CHO cells were exposed to 60-Hz electric fields of 0.15-10.9 V/m induced by a magnetic field, there were no cytotoxic or mutagenic effects, but cell plating efficiency was significantly reduced at 0.7 V/m and above (Frazier et al. 1987). Plating efficiency is the ability of a cell to produce a colony, and it is a measure of cell viability. When the study was repeated using current injected by an agar-bridge system to produce a 3.5-V/m electric field, no effect on plating efficiency was seen. The researchers suggested that either the first finding was an artifact, or the magnetic field was in someway responsible for the effect.

Exposure to a 60-Hz electric-field-induced current density of 300 mA/m2, and a O.l-mT (1-G) magnetic field produced no sustained effects on normal (noncancerous) human cells (Winters 1986). However, exposure to EMF increased proliferation of human colon cancer cells in soft agar more than sixfold over controls (Winters 1986, Phillips and Winters 1987). Cohen (1986) attempted to replicate the effects on colon tumor cells using electric-field induced current densities of up to 3000 mA/m2 and magnetic fields of the same level as in the previous study. In a large number of replicates involving two cell lines, some statistically significant differences between exposed and control groups were found. However, because no consistent pattern was apparent, the researcher concluded that no effects on proliferation of colon cancer cells were demonstrated in his study.

Tabrah et al. (1994) used the Ames short-term mutagenic test to study possible mutagenic effects of 60-Hz magnetic fields. They used a specific strain of bacteria (*Salmonella typhimurium*, strain TAlOO) and azide ion as a agent that causes mutations in the bacteria. With a 48-hour exposure to a 0.2-mT (2-G) magnetic field, the number of azide-induced mutant bacterial colonies was increased significantly 14 percent compared to controls. There was no significant difference in the number of mutant colonies when the bacteria were grown inside the non-energized coil (no magnetic field), compared to bacteria outside the coil.

One type of effect on chromosomes from ionizing radiation was significantly enhanced with exposure to a 1.4-mT (14-G) 60-Hz magnetic field (Hintenlang 1993). Following an exposure of up to 3 Gy of radiation, human lymphocytes were exposed to the field during the 48-hour culture period. With this combination of exposures, the frequency of near-tetraploid metaphase cells increased (with a non-linear dose response) with increasing magnetic-field strength. These types of cells were not seen with exposure to the magnetic field alone, to radiation alone, or in non-exposed cells. The researchers said that tetraploid cells (cells with four instead of two sets of chromosomes) are frequently not viable; therefore, their formation may not lead to severe biological consequences. Dicentrics and, apparently, other types of chromosomal aberrations were not increased by magnetic-field exposure in the study.

Luben et al. (1994) found that two protein tyrosine kinases were activated in human leukemia cells after only a 5-minute exposure to a 0. 1-mT (1-G) 60-Hz magnetic field. The kinases activated (Zyn and sck) are associated with certain cell surface receptors involved with growth and death of leukemia cells. The researchers said that their results suggest that magnetic fields could influence the growth or differentiation of already mutagenized clones of cells.

The hormone melatonin has been found to have the ability to inhibit the growth of certain tumors, including estrogen-responsive human breast cancer cells in culture (Cos et al. 1991). When cultured human breast cancer cells (MCF-7) and melatonin were exposed to a 60-Hz 1.2-uT (12-mG) magnetic field, melatonin's ability to inhibit tumor cell growth was blocked (Liburdy et al. 1993c). The magnetic field had no effect on growth of the tumor cells in the absence of melatonin. When the cells were grown in the ambient 0.19-0.253-uT (1.9-2.53-mG) 60-Hz magnetic field in the laboratory, at day 7 there were 18-27 percent significant reductions in cell growth when melatonin was present in the culture. When the cells were exposed to a 1.2-uT (12-mG) vertical magnetic field, there was no significant difference in growth between cells with melatonin and those without melatonin (i.e., melatonin's inhibitory effect on tumor cells had been blocked). Melatonin used in the study was at physiological concentration of 10^{-9} M.

The results of the above study by Liburdy et al. (1993a) was essentially confirmed by Blask et al. (1993b). The latter found that a 60-Hz 1.5-uT (15-mG) magnetic field blocked melatonin's ability to inhibit growth of human MCF-7 breast cancer cells. The effect, however, was influenced by cell culture conditions. Blask et al. (1993a) also studied the effect in two cell incubators which produced different magnetic field levels. In three experiments, melatonin inhibited tumor cell growth by 38-53 percent in the incubator with a 60-Hz magnetic field of 1.68 uT (16.8 mG). Inhibition was only 12-29 percent in the incubator that produced a stronger field of 10.9 uT (109 mG). The growth of control cells was also 36-percent higher in the high-field incubator. This suggested that the magnetic-field may have promoted growth of the tumor cells independent of an effect on melatonin.

Blask et al. (1993a) also found that the action of the antitumor drug Tamoxifen was not affected in either of the two incubators tested. Harland and Liburdy (1994) found that a 1.2-uT (12-mG) 60-Hz magnetic field did reduce Tamoxifen's ability to reduce proliferation of MCF-7 breast cancer cells.

The melatonin studies by Liburdy et al. (1993a) were also confirmed by Blackman et al. (1996). The latter researchers found that a 1.2uT (12-mG) 60-Hz magnetic field completely blocked the oncostatic action of melatonin. As in the studies by Liburdy et al. (1993a) the effect was found with MCF-7 human breast cancer cells.

Some Reviews of EMF *In* Vitro Research

In a review of research on EMF and molecules and cells, Goodman et al. (1995a) concluded that the evidence suggests that cell processes are affected by weak EMF. Although post-transcription effects do not seem to occur, the review found good evidence for transcription effects. The latter, however, have no apparent disruptive effects on routine physiological processes. DNA does not appear to be affected. If EMF are involved in carcinogenesis, they are more likely involved in promotion rather than initiation.

McCann et al. (1993) conducted a critical review of 55 published papers on *in vitro* and *in vivo* research on possible genotoxic effects of EMF. They concluded that the preponderance of the evidence does not show that EMF (DC and ELF) have a clear potential for causing genotoxic effects. They added that such effects may occur in some situations involving factors such as spark discharges, shocks, or corona.

Possible Mechanisms for Effects of EMF

Although many scientists believe that the cell membrane is a primary site for biological interactions with EMF (Liburdy 1995, Adey 1996), there are widely differing opinions about how, and at what field intensities such interactions occur. A major point of discussion is how or whether environmental 60-Hz EMF can cause effects when the electric fields that they induce are generally smaller than the natural electrical noise in the body (i.e., the signal-to-noise ratio is less than 1.0). The term "kT" is used to refer to thermally induced electrical noise (k= Boltzman's constant, T= absolute temperature).

Based on calculations for a single spherical cell, Adair (1991) concluded that biological effects of ambient EMF are virtually impossible because their potential effects are masked by natural noise. Pilla and Markov (1994) observed that Adair's (1991) calculations were based on a oversimplified model. When Pilla and Markov (1994) used a cell-array model of tissue, an induced electric field as low as 0.1 mV/m could be detected in the presence of thermal noise. Gailey (1996) also calculated that elongated cells and cells connected by gap junctions had substantially higher membrane potentials induced by external fields than did spherical cells. He found that 60-Hz magnetic fields below 10 uT (100 mG) can induce cell membrane potentials that can exceed thermal electrical noise.

Astumian et al. (1995) calculated that signal averaging and AC-DC rectification could improve the signal-to-noise ratio. However, they concluded that a 100 mV/m induced field was needed to exceed the noise level in a reasonable period of time (they believe that it may take from hours to days for cells to recognize weak fields above noise levels). Polk (1993) calculated that the minimum field needed to exceed thermal noise was 4.1 mV/m, and Tenforde (1993) calculated the minimum field at 10 mV/m.

Three possible mechanisms are summarized below that have been widely discussed as possible explanations for the biological effects reported in research on EMF. More details on these and other potential mechanisms can be found in reports by Valberg (1994), and Liburdy (1995).

Resonance mechanisms. The studies summarized above that reported "window" effects of magnetic fields on the movement of cellular calcium prompted scientists to consider mechanisms to explain the effects. Cyclotron resonance is one proposed mechanism for explaining how specific frequency and amplitude combinations of AC and DC magnetic fields influence movement of calcium through channels in cell membranes (Blackman 1985, Liboff 1985, Liboff and McLeod 1988). Basically, by this hypothesis the forces exerted by magnetic fields on moving charges causes ions to move through membrane ion channels in a circular spiraling (helical) motion. The AC resonance frequency (f_c) for this to occur for a specific ion is given by the formula:

$$f_c = QB / 2\pi m$$

where,
m= ion mass, Q= ion charge, B= DC magnetic flux density.

For example, for a resonant frequency of 60 Hz and for calcium ions (Ca++), the required DC magnetic field is 78.4 uT (784 mG) (Liboff et al. 1987). The ion cyclotron resonance mechanism for explaining effects of magnetic fields has been questioned on a number of grounds, primarily on the basis of the significant friction effect of fluids on ion movement (Durney et al. 1988, Halle 1988, Sandweiss 1990).

Attempts to verify the cyclotron resonance mechanism experimentally have been mixed. Smith et al. (1987) found support for the mechanism in studies of calcium ions and motility of diatoms (one-cell organisms that show changes in motility related to calcium concentrations). Results of two other studies of diatoms did not support the mechanism (Parkinson and Sulik 1992, Prasad et al. 1994). Liboff et al. (1987) reported that calcium uptake by human lymphocytes increased as predicted with exposure to cyclotron resonance conditions, but attempts by Prasad et al. (1991) to replicate the study were unsuccessful. Parkinson and Hanks (1989) found no changes in cytosolic calcium in four cell lines exposed to cyclotron resonance conditions. Liboff and Parkinson (1991) found no changes in calcium or in five other ions when turtle colonic tissue was exposed to cyclotron resonance conditions.

Another resonance mechanism, ion parametric resonance, was proposed by Lednev (1991) to explain biological effects of weak magnetic fields. This theoretical and highly complex model was extended by Blanchard and Blackman (1994), and by Engstrom (1996). This model in general involves effects of magnetic fields on energy levels of a charged oscillator, which could be a calcium ion bound to a protein such as calmodulin. This in turn affects the ion's interactions with ligands (molecules such as hormones that bind to cell surface receptors).

Adair (1992) was highly critical of Lednev's proposed mechanism, and he identified several reasons to support the view that the mechanism cannot operate. Bruckner-Lea et al. (1992) studied calcium binding to calmodulin under conditions similar to parametric resonance, and they saw no effects of the magnetic fields. Trillo et al. (1996) studied a rat cell line under resonant magnetic field exposures for hydrogen ions (H+) , and their results were in general agreement with predictions of the ion parametric resonance model.

Magnetite. As discussed in Chapter 1, people and animals are essentially transparent to 60-Hz magnetic fields because biological tissue is nonmagnetic. (Magnetic fields do induce electrical currents.) However, tissue from humans and several other species have been found to contain the ferromagnetic material magnetite (Fe_3O_4) (Kirschvink et al. 1992b). In some species, magnetite seems to have a biological function such as in facilitating orientation and migration of certain aquatic bacteria along the DC magnetic fields of the earth (Frankel and Blakemore 1989). In the chiton, a marine mollusk, a hard layer of magnetite covers the teeth on the feeding organ allowing the animal to scrape algae from rocks (Kirschvink 1989). Magnetite has also been found in human brain tissue in implied amounts of 5-100 million crystals per gram of tissue (a few hundred micrograms of magnetite in an adult) (Kirschvink et al. 1992a, 1992b). The biological function, if any, of magnetite in humans is not known at this time.

Magnetite interacts with external magnetic fields more than a million times more strongly than other material in the body, and Kirschvink et al. (1992a) have proposed that magnetite may be involved in some reported effects of such fields. Kirschvink et al. (1992a) suggested that magnetite oscillating in a 60-Hz magnetic field could exert enough force to open or close cell membrane ion channels. They estimated that a magnetic field of at least 0.14 mT (1.4 G) would be required to exceed the thermal noise level and affect ion channels.

Adair (1993) calculated that 60-Hz magnetic fields of 5 uT (50 mG) or less cannot affect biological structures holding magnetite because their effects are smaller than thermal agitation. He suggested that effects of 60-Hz fields are possible at intensities larger than the earth's field. Polk (1994) believed that the model used by Adair (1993) had limited validity to pertinent biological systems. Polk calculated that 60-Hz magnetic fields as low as 2 uT (20 mG) could produce detectable effects on magnetite.

Radical pair reactions. One established mechanism for biological effects of strong DC magnetic fields involves effects on recombination of radical pairs (Walleczek 1995, Grissom 1995, Brocklehurst and McLauchlan 1996). Radicals are atoms or molecules that have one or more unpaired electrons as a result of a break in a molecular bond. They are formed in pairs, therefore, they are called radical pairs. Radicals are highly reactive with very short lifetimes, and they are normally formed during many biochemical reactions. Reactivity is determined by the spin state of the outer-shell electrons. Strong magnetic fields can modify the spin state resulting in a change in reactivity (Walleczeck 1995). DC magnetic fields of at least 1 mT (10 G) are typically required to affect recombination of radical pair. In theory, AC magnetic fields of about the same magnitude in the presence of a DC field may also produce effects (Polk 1996).

There are differing views by scientists about whether the radical-pair mechanism may have any relevance to explaining the many reported biological effects of relatively weak magnetic fields. Adair (1996) calculated that magnetic fields weaker than the earth's field cannot significantly affect biologic processes by effects on radical-pair recombination. Walleczek (1995) suggested that not enough is known about how living organisms interact with magnetic fields, and that more research is needed to determine whether the radical pair mechanism could explain health effect of fields , 1 uT (10 mG).

Environmental Studies of Plants, Wildlife, and Domestic Animals

This section describes studies of EMF that have been conducted in natural environments. These include studies of transmission lines and studies of U.S. Navy submarine communication antennas at sites in Wisconsin and Michigan. Also included are studies of plants conducted in laboratories, and a study of dairy cows conducted in an indoor facility.

The communication antenna included both buried cables and overhead conductors suspended about 12 m (40 ft) above ground on wood poles (Zapotosky et al. 1996). The antennas carried 150-300 A of current and the operational frequency was shifted between 72 and 80 Hz (76-Hz center frequency). Magnetic flux densities in the antenna study sites were 0.02-4.5 uT (0.2-45 mG) and electric fields were 0.01-40 V/m.

Plants

The possible effects of electricity on plants have been studied since the 18th century (Wheaton 1970, Diprose et al. 1984). Most of the early interest was in the possible use of electricity to increase crop yields. Some investigators claimed big increases in crop production by exposure to AC and DC fields and currents. Others, however, using similar methods, could find no effects. Many of the early studies were poorly controlled and technical details of the electrical test setups were sketchy.

Laboratory Studies

Beginning in the mid-1970s research programs were initiated specifically to investigate the possible effects of 60-Hz electric fields on plant growth. A team of researchers from the Westinghouse Electric Corporation and Pennsylvania State University studied 85 plant species grown in a laboratory while exposed to electric fields of up to 50 kV/m (Bankoske et al. 1976, McKee et al. 1978). This group later studied crops (alfalfa, fescue, corn, wheat) grown in a greenhouse in a 30-kV/m electric field (McKee 1985). Overall, germination and plant growth and productivity were not affected by exposure to the electric field.

Sharp-pointed plant parts on some species in the Penn-State studies exhibited minor tip damage, beginning at field intensities of 15-20 kV/m. The strength of an electric field is greatly enhanced around sharp-pointed conducting objects such as a grass leaf. This happens because the field lines of force are drawn to and converge around such objects. If the field is strong enough, corona can occur, producing heat and drying of leaf tips. In contrast, rounded plant parts were not damaged in the study by even the 50-kV/m fields.

In a laboratory study at the University of Rochester, effects of an electric field on root growth were studied (Miller et al. 1979). Electrodes were placed in the water medium containing the roots. A 40-50 percent decrease in growth was detected with electric field strengths of 360-430 V/m in the water medium. The researchers pointed out that it is impossible to induce electric fields of this strength in water or soil if the electrode is in air (such as a transmission line), because the field strength required would exceed the breakdown strength of air.

The effects found in the University of Rochester studies were believed to be due to a decrease in root-cell elongation rather than to any change in the proportion of cells in mitosis (Brulfert et al. 1985). The studies also suggested that normal cell membrane functions were altered but not blocked by the strong electric fields.

Another laboratory study reported that a 1-kV/m 60-Hz field had no effect on germination rate of sunflower seeds, but that a 5-kV/m field seemed to reduce the rate by an average of 5 percent (Marino et al. 1983). However, the effect was observed in only 4 out of 11 replicates of the study. Although the effect was small and inconsistent, the researchers concluded that plant physiology can be altered by weak fields involving non-thermal mechanisms (other than air ionization).

Krizaj and Valencic (1989) exposed water cress plants to 50-Hz magnetic fields of 1.2-18 mT (12-180 G). The plants were grown in Petri dishes placed inside horizontal coils. Root growth increased most in 6-mT (60-G) fields, and shoot growth increased in 12-mT (120-G) fields. Both root and shoot growth significantly decreased in fields above 12 mT (120 G). In fields above 3 mT (30 G), effects of temperature became dominant, and the researchers said that their results were due to a combination of magnetic fields and temperature changes.

Ruzic et al. (1992) exposed chestnut buds to 50-Hz magnetic fields of 1.2, 3.2, and 5.9 mT (12, 32, 59 G) for 28 weeks inside a Helmholtz coil. In one treatment group, exposed plants showed significantly more growth than controls in June at all field levels, but significantly less growth in August in the 3.2-mT (32-G) field. Growth was significantly increased in the 5.9 mT (59 G) field in November/December. For September and November, no significant differences were seen. In another treatment group no significant differences between exposed and control plants were seen at any time of year. The researchers interpreted these seemingly inconsistent results as a season-dependent effect of magnetic fields.

Tobacco callus was exposed for 7 days to 50-Hz currents from electrodes in the growth medium (Mihai et al. 1994). The callus is an asynchronous culture of mostly undifferentiated cells. With exposure to currents of 0.3-1.0 uA, there was a 50 percent increase in mass growth. The researchers suggested that the induced electric field may interact at the membrane level, stimulating metabolic processes.

Pumpkin and morning glory plants showed increased growth when exposed to a 6-uT (60-mG) 60-Hz magnetic field for 6-3 1 days (Czerska and Casamento 1994). The plants were exposed inside of a Helmholtz coil. The abstract of the study provided no numerical data on the results.

Smith et al. (1993) studied growth of the common garden radish exposed for 21 days to combined 60-Hz and DC magnetic fields tuned to cyclotron resonance conditions for calcium or potassium ions. The 60-Hz field was set at 40 uT (400 mG) peak-to-peak, and the DC field for calcium was 78.3 uT (783 mG), and for potassium it was 153.3 uT (1533 mG). Plants exposed to the calcium-tuned fields grew significantly larger than the controls, and those exposed to potassium-tuned fields tended to show inhibited growth. In plants exposed to the 60-Hz field with a zero DC field, no statistically significant effects were seen. The researchers believed that their results demonstrate that plant growth can be significantly altered by exposure to specifically tuned AC and DC magnetic fields. They acknowledged, however, that it is difficult to imagine a mechanism for the opposite effects seen on growth in their study.

Davies (1996) used the same magnetic field conditions for calcium as in the study by Smith et al. (1993), to study growth of radish, mustard, and barley. In three replicates, the exposed radish plants were always significantly taller, and had significantly heavier dry stem weight than the controls. For eight other growth measurements, results for radish were not consistent among replicates. Mustard plants showed no response to magnetic field exposure, and only a few inconsistent effects were seen in barley plants. The researchers believed that their study represented an independent replication of the studies of radish by Smith et al. (1993). The reasons for the general lack of effects on the other two plant species are not known

Outdoor Studies

A few studies have been done of plants growing near transmission lines. The American Electric Power Service Corporation sponsored research conducted by Purdue University and the University of Notre Dame (Hodges et al. 1975, Hodges and Mitchell 1979, Greene 1979, Roy and King 1983, Hodges and Mitchell 1984). Corn and other crops commonly grown in Indiana were studied near 765-kV lines in electric fields of up to 12 kV/m, and near a UHV test line in a field reaching 16 kV/m. Overall results of the studies indicated that the transmission lines had no noticeable influence on the growth or productivity of the crops. Some crops growing in the maximum electric-field area of the test line had some leaf tip damage from induced corona. However, overall plant growth was not impaired.

Greene (1983) studied mitotic activity (cell division) in the tips of onion roots grown in containers beneath the UHV test line in Indiana. He concluded that this activity was not affected by exposure to air electric fields of 15.5 kV/m for 15 days.

By contrast, research in Tennessee indicated that corn grown beneath a 500-kV line showed lower yields in electric fields of up to 8.5 kV/m, compared to corn grown in plots shielded from the field (Hilson et al. 1983). However, other crops (cotton, soybeans, clover) and trees (tulip poplar, loblolly pine) showed no effects. The researchers concluded that data for the corn study were insufficient to reach definite conclusions and that further investigation was warranted.

Parsch and Norman (1986) published a brief report on a study of crop growth near a 500-kV transmission line in Arkansas. No differences in yields of rice and soybeans were found between crops growing under the line and crops growing away from the line. Cotton yield was about 15 percent less under the line. The authors could not determine whether the effect was related to electric or magnetic fields, or to ineffective aerial application of agricultural chemicals to crops near the line.

BPA sponsored long-term research involving plants growing near a 1200-kV prototype line in Western Oregon (Rogers et al. 1979, 1980; Warren et al. 1981; Lee and Clark 1981; Rogers et al. 1982). The research, conducted by Battelle Pacific Northwest Laboratories, included trees, shrubs, grasses, and crops. Branches of some Douglas-fir trees purposely left growing as close as 12 m (40 ft) to the 1200-kV line were damaged by induced corona (Fig. 4.18). The effect was not seen on Oregon white oak (they have rounded leaves in contrast to the sharp-pointed fir needles). Height growth in red alder and in Douglas-fir trees purposely planted directly beneath the line was also reduced, as corona damaged branch tips (Rogers et al. 1984a).

Figure 4.18. Corona induced on a Douglas-fir tree purposely left growing close to the BPA 1200-kV prototype line. Heat from corona can cause damage to sharp-pointed plant parts. The same effect also occurs if trees grow too near 500- or 765-kV lines. The photograph was taken with a night vision device.

This "self-pruning" effect has also been found in trees that grew too close to 500-kV and 765kV lines (Zaffanella and Deno 1978, Miller and Kaufman 1978). For the 1200-kV line, slight damage was noted in treetops as far as 18 m (60 ft) from the line. For a commercial 1200-kV line, trees within this distance would likely be removed during construction of the line. Shrubs growing beneath the 1200-kV line were not affected by the electric field.

Barley and peas were grown under the 1200-kV line in plastic tubes (lysimeters) filled with uniform soil mixtures. Electric field strength during 5 years of study ranged between 7 and 12 kV/m. Although weather and natural variability accounted for wide differences in crop production among the years, no consistent differences were found to indicate that the 1200-kV line affected plant growth. Germination studies showed no effects of the line on the viability of pea and barley seeds.

Growth of pasture grasses beneath the 1200-kV line was not inhibited by electric fields of up to lZkV/m (Rogers et al. 1984b). Growth was compared among plants shielded by wire mesh from the field, plants covered by simulated shielding, and plants exposed directly to the field. Researchers in Japan also found no effects of a 7.7-kV/m electric field on growth of wheat (Endo et al. 1979). The plants were grown in pots beneath an outdoor test line.

In Italy researchers grew wheat outdoors in .50-Hz electric fields of 5 and 12 kV/m (Conti et al. 1989). Plants were maintained using normal farming conditions, and the plants were exposed for several generations. Initial results showed no significant differences between exposed and control plants for germination, growth, weight, or chlorophyll content.

Extensive long-term studies of natural vegetation were conducted in Michigan and Wisconsin for the US. Navy's communication antennas (Zapotosky et al. 1996). Some of these studies showed enhanced growth of trees near the antenna (Reed et al. 1993). When measured growth was compared to expected growth models, aspen and red maple showed increased diameter growth, and red pine had increased height growth. Theses findings were for trees growing in 76-Hz magnetic fields of 0.1-0.7 uT (l-7 mG). No effects on growth were seen for northern red oak and paper birch.

Other studies suggested that the communications antenna may have stimulated the production of algae in a river in Michigan (Zapotosky et al. 1996). Prior to energization of the antenna, the chlorophyll biomass was larger at the control site than at the antenna site. After energization, biomass tended to be higher at the antenna site by 30-70 percent.

Insects and Other Invertebrates

Reports in the early 1970s from Europe indicated that power lines had caused harmful effects in honeybee colonies in wooden hives under the lines (e.g., Wellenstein 1973). Because of the reported effects on bees, both BPA and the Electric Power Research Institute initiated research with honeybees in 1977. The BPA study was part of the 1200-kV research program conducted by Battelle Northwest (Rogers et al. 1982) (Fig. 4.19). The EPRI study was done by Bioconcem near a 765-kV line in Illinois (Greenberg et al. 198 1).

Both studies confirmed that transmission-line electric fields can affect honeybees inside wooden hives. A most noticeable effect was excessive propolization

Figure 4.19. Studies of the BPA 1200-kV prototype transmission line showed that electric fields can adversely affect honeybee colonies inside wooden hives. The effects are due to induced currents in the hive. As a precaution, BPA recommends that hives should not be placed beneath high voltage tranmission lines.

within the hive. Propolis is a resinous material, normally collected from various plants and used as a sealer by bees. There were also decreases in colony weight gains, increased irritability and mortality, and poor overwinter colony survival.

Since wood is not a perfect insulator, a current is induced in a wooden hive placed in an electric field, whether there are metal parts in the hive or not. The strength of the current is influenced by the electric field strength, hive height, and moisture conditions. Long-term automatic monitoring at the BPA 1200-kV prototype site showed that current in a given hive varies daily and seasonally. Some effects become noticeable when induced current exceeded 0.02-0.04 mA. Depending on hive height, this occurred in field strengths between 2 and 4 kV/m. Effects were most evident in electric fields of 7-12 kV/m.

The effects found in honeybee colonies are most likely caused by frequent shocks experienced by bees while inside the hive (Greenberg et al. 1985, Bindokas et al. 1988). The effects can be prevented by placing a grounded wire screen over the hive, which greatly reduces the electric field and current flow through the hive. The use of a standard metal hive cover, connected by wire to a ground rod, also mitigated effects on a colony placed beneath the 1200-kV prototype.

The shielding studies indicated that the effects were not caused by the bees flying through an external electric field of up to 11 kV/m. Greenberg et al. (1981) also concluded that a 7-kV/m field outside the hive had no impact on colonies shielded by wire. In a related study, the electric field did not prevent insects from pollinating clover planted beneath the 1200-kV line (Warren et al. 1981). The study design could not reveal subtle effects, if present, on pollination.

Although AC transmission-line electric fields can affect honeybee colonies, the magnetic field appears to have no significant effect. This was shown in a study of a 765-kV line in which grounded wire screen was placed over hives to eliminate the electric field (Greenberg et al. 1981). The magnetic field easily penetrates the screened hive. The performance of honeybee colonies in the screened hives under the line was no different than that of colonies in the control area.

The effects found in the above studies have, to our knowledge, not generally been reported by beekeepers in the U.S. As a precaution, BPA recommends that bee hives not be placed on a 500-kV right-of-way, especially near mid-span between towers where the electric field is strongest. If for some reason a person wants to locate hives near BPA transmission lines, BPA will provide information on methods for mitigating the kind of effects found in the research described above.

Orlov (1990) reported on studies of insect movement and behavior near a 500-kV transmission line and a test transmission line in Western Siberia. The distribution of numbers of insects and other invertebrates caught in traps was not correlated with electric-field strength from the 500-kV line (electric field near the ground was about 15 kV/m). Mosquito attacks on mice placed under the test line decreased at 7 kV/m, and stopped at 40-kV/m. Bee visits to flowers beneath the test line did not decrease until the electric field was raised to 50 kV/m. At 100 kV/m insects stopped visiting the flowers.

Studies of the Navy communication antennas included several studies of invertebrates (insects, worms, amoebae, slime molds). No consistent long-term changes due to operation of the antenna were detected (Zapotosky et al. 1996). Researchers found a possible short-term reproductive effect on one worm species (significantly faster plant-soil decomposition during one study period), and some possible effects on honey bees. The latter included possible effects on certain aspects of how bees constructed their hives, and on over winter mortality (higher near the antenna). There was no consistent pattern of higher mortality at the antenna sites, however. A long-term study of stream-dwelling insects found that natural physical factors were more important causes of seasonal and yearly changes in insect communities, than were possible effects of EMF from the communication antenna (Stout and Rondinelli 1995).

Coghill and Gerasimov (1996) studied earthworm populations beneath and near a 132-kV transmission line (no levels of EMF were given). The biomass of earthworms beneath the line (77 g/m^2) appeared to be similar to biomass away from the line (52-120 g/m^2).

Wildlife

This section addresses the possible effects of EMF on wild birds, mammals, and fish. Emphasis in most of the studies involving powerlines was on the effects of the right-of-way, and only rarely was specific attention given to possible field effects (see papers in Amer and Tillman 1981, and Crabtree 1984). However, this research does suggest that, compared to effects of construction and maintenance, any effects of EMF on wildlife are subtle and difficult to identify (Lee et al. 1979).

In the typical situation where mammals or birds are within or beneath vegetation, that vegetation largely shields them from a transmission-line electric field. When mammals such as deer and elk move through areas of low-growing vegetation, they may be subject to induced body currents, shocks, and perception effects. Because the larger animals are normally grounded to a degree through their feet, it is unlikely that they experience shocks in these fields. It is possible that some wildlife species are able to detect weak induced currents. Based on studies with laboratory animals, wildlife may be able to detect electric fields through such means as hair or feather stimulation (e.g., Cooper et al. 1981, Stem et al. 1983). Research to date, however, has not shown that these fields adversely affect wildlife behavior or health.

Mammals

Goodwin (1975) observed no apparent effects of the EMF from a 500-kV transmission line in Idaho on movement of deer and elk. Animal movement was studied by direct observation, track counts, and by time-lapse photography. Some animals were attracted to the cleared right-of-way for feeding. However, during the hunting season, game animals tended to avoid the right-of-way and other similar clearings during daylight.

Schreiber et al. (1976) examined the effects on small mammals of a right-of-way in Tennessee containing two 500-kV lines. In hardwood forests, small mammals were more abundant on the cleared right-of-way than in the adjacent forest. In pine forests, the reverse occurred. In both areas, the right-of-way was used by some species not present in the adjacent forest. The most common species was the short-tailed shrew. Other common species were the white-footed mouse, pine vole, and Eastern chipmunk. Use of the various areas by small mammals appeared to be strongly influenced by vegetation composition and distribution, which affects cover and food availability.

Small mammals were studied for several years as part of a research program for the BPA 1200-kV prototype (Rogers et al. 1980, Warren et al. 1981). No adverse electric field effects on mammals were found. Chipmunks and deermice were the most frequently captured species. Animals were most abundant on the right-of-way and in the nearby control areas during the first 2 years of construction and operation. Mammal abundance on the right-of-way and control areas declined in subsequent years. After initial right-of-way clearing, tall brush had become re-established on the right-of-way, thus shielding small mammals from the electric field.

Studies were conducted of deer-mice and chipmunks living near the submarine communication antenna in Michigan (Zapotosky et al. 1996). Animals were kept in large open enclosures near the antenna and in control areas. Female deermice were allowed to give birth and to rear their young in the enclosures. The age at eye-opening stayed fairly constant in the young in the antenna group, but it increased steadily in the control group. The researchers suggested this difference could indicate an effect of exposure to EMF, but they could not say whether it was a detrimental effect. There were no apparent effects on age at incisor tooth eruption, or on overall body growth rates.

Maximal rate of oxygen consumption was used as a measure of overall physiological fitness and winter thermoregulatory capacity of deermice living near the communication antenna (Hill et al. 1993a). Although the oxygen consumption was lower in years when the antenna was operational compared to preoperational years, there were no significant differences between the antenna and the control groups.

Possible effects of the communications antenna on homing ability of deermice and chipmunks were studied by trapping animals and releasing them away from their home area. Based on frequency of recaptures in their home areas, there were no significant effects on homing ability (Zapotosky et al. 1996).

Birds

Studies of song birds near transmission lines also indicate that vegetation on the right-of-way, rather than electric or magnetic fields, is the primary factor influencing usage and behavior (e.g., Rogers et al. 1980, Anderson et al. 1977, Kroodsma 1984). For birds, however, some additional considerations arise.

Where transmission lines cross open country, some birds such as hawks and eagles often use the towers for perching and nesting (Howard and Gore 1980). Although there are some shielding effects from tower parts, birds nesting on these structures can be exposed to EMF for long periods. Birds nesting on BPA transmission lines were studied to determine whether there are harmful effects from energized lines. A sample of hawks nesting on 500-kV and 230-kV line towers produced about the same average number of young as were reported for hawks nesting in trees and cliffs (Lee 1980) (Fig. 4.20).

Figure 4.20. A hawk nesting on a transmission line tower. The steel tower can shield much of the electric field, but a strong magnetic field can be present around such nests. A small study found birds nesting on BPA towers produced about the same number of young as typically reported for nests at other sites.

Large birds such as eagles can be electrocuted if they contact a conductor and grounded hardware, or if they contact two conductors (different phases). These problems are generally associated with distribution lines of 12-69 kV (Olendorff et al. 1981). Transmission-line conductors are usually far enough away from other conductors or hardware that bird electrocutions seldom occur. Special line designs have been developed for protecting raptors and other birds from power-line electrocutions. These are described in a report distributed by the Raptor Research Foundation (Olendorff et al. 198 1).

Birds are apparently able to use the earth's DC magnetic field as an orientation aid (Hong 1995). Some studies have produced evidence indicating that birds can perceive AC magnetic fields at strengths comparable in magnitude to those of the earth's DC fields (e.g., Larkin and Sutherland 1977). Whether such fields disrupt avian flight orientation, provide environmental location information to flying birds, or have no effect at all is not clear. During migration, birds must routinely fly over probably hundreds (or thousands) of electrical transmisson and distribution lines. We are not aware of any evidence to suggest that such lines are disrupting migratory flights.

Research on bird collisions with BPA transmission lines did not suggest that transmission line EMF cause noticeable disorientation in flying birds. Most waterfowl and other birds during low altitude flight typically react to the presence of transmission lines by altering flight direction or altitude to avoid colliding with the lines (Lee 1978, Meyer and Lee 1981, Beaulaurier et al. 1984).

Periodic counts of birds near the submarine communication antenna and in control areas in Wisconsin revealed no effects of EMF on overall bird abundance or numbers (Hanowski et al. 1993). Several individual bird species did show significant differences in abundance between antenna and control sites. The researchers attributed most of these to differences in habitat, and they believed that it was unlikely that the differences were from the antenna EMF.

Studies were also conducted of free-living tree swallows that nested in boxes placed near the communication antenna and in control areas (Hill et al. 1993b, Beaver et al. 1993, Zapotosky et al. 1996). No effects attributable to EMF were found for abnormalities in embryos, or for growth, development, or mortality of young birds. There was also no indication that the mortality rate of adult swallows was affected by nesting near the antenna. Tests of the ability of adult swallows to return to their nest boxes after being released 30 km (18.6 mi) away showed some differences between the antenna and the control groups. These differences occurred both before and after the antenna was in full operation, and the researchers concluded that exposure to EMF was, therefore, not the cause. The homing speed of birds returning to the antenna site did gradually decrease during full operation of the antenna, but the researchers were unable to explain the reason(s) for this finding.

Fish

A lo-kV/m transmission-line electric field in air produces a field in water of around 1 mV/m (Miller and Kaufman 1978). This field tends to be even less because conductor clearances are often higher than minimum over navigable waters. Also, streams and rivers are often in a narrow topographical depression and thus partially shielded. In this last situation, support towers may be located at higher elevations, resulting in large conductor clearances over the water. The magnetic field from a transmission line is not reduced in water.

Some fish are known to be sensitive to very weak, low-frequency electric and magnetic fields in water. Sharks and some other species have special organs (ampullae of Lorenzini) for detecting biofields from other fish and probably the earth's fields (Kalmijn 1966). For example, skates were shown to respond to 5-Hz square wave fields of only 1uV/m, and stingrays oriented to uniform electric fields as small as 500 nV/m (1 nanovolt = one-billionth of a volt) (Kalmijn 1982).

American eels and Atlantic salmon reportedly can also perceive low-frequency electric fields of 7-70 mV/m (McCleave et al. 1974). However, 45- to 75-Hz electric fields up to 20 V/m had little, if any, effect on behavior of bluegill fry (McCleave et al. 1974, Coate et al. 1970). A 62-mT (620-G) 50-Hz magnetic field suppressed the swimming activity of goldfish, and the effect remained for a few days after field exposure had stopped (Arisawa et al. 1994).

Fish populations were studied at a site in Michigan where the submarine communication antenna crossed a river (Zapotosky et al. 1996). As compared to fish at another site along the river, there were no significant differences for species diversity, biomass, or condition. The studies also found no indication that EMF had affected fish movement beneath the antenna, although the researchers pointed out that only large-scale changes in movement could have been detected.

Domestic Animals

Livestock

Utility operating experience and results of research generally show that transmission-line electric fields do not affect livestock behavior or health (Lee and Reiner 1983). Livestock of all types can often be seen feeding or resting beneath transmission lines. Occasionally utilities receive reports that a transmission line was related to some livestock illness or death. Typically, when these reports are investigated, or when livestock owners are surveyed, no evidence is found to substantiate such reports (Ware 1974, Busby et al. 1974).

A survey of livestock owners living near a 765-kV line in Indiana was sponsored by American Electric Power Service Corporation (Amstutz and Miller 1980). Included in the survey were owners of beef and dairy cattle, sheep, hogs, and horses on 11 farms. Farmers were interviewed bi-monthly, and periodic inspections were made by a veterinarian. The 765-kV line produced electric fields on some of the farms of up to 12 kV/m. Magnetic fields measured on two farms were 1.2-5.6 uT (12-56 mG) beneath the line. The survey found no evidence that health, behavior, or performance of livestock were affected by transmission-line EMF.

A 6-year-long study in Ohio investigated 55 dairy farms located near 765-kV transmission lines (Williams and Beiler 1979). There was no indication that the presence of the lines had any long-term effects on milk production. After the lines had been constructed, the incidence of calf mortality and birth defects per farm increased. The researchers believed that this may have been a reflection of a trend for larger herd sizes per farm during the study period. The dairy operators interviewed during the study believed there was no evident change in health problems after the lines were energized.

Studies in Sweden were prompted because of reports that cattle fertility decreased on two farms following energization of 400-kV transmission lines (Algers et al. 1981). In pilot studies involving 36 herds near 400-kV lines and where artificial insemination was used, no effects on cattle fertility were found, compared to a control group. A larger study was conducted that involved 106 farms throughout Sweden (Hennichs 1982). The study, conducted primarily by mail survey, found that, on the average, cows exposed to 400-kV lines for more than 15 days per year did not have decreased fertility. The maximum 50-Hz electric field strength beneath 400-kV lines measured on 11 farms in Sweden was 5 kV/m; magnetic field levels were not reported (Algers et al. 1981).

To obtain more definitive information on fertility, Swedish researchers conducted an experimental study (Algers and Hultgren 1987). Fifty-eight cows were placed in pens crossed by a 400-kV, 50-Hz transmission line. Another 58 cows were maintained in control areas away from the line. During the 120-day exposure period, the electric field averaged 4 kV/m, and the average magnetic field was 2 uT (20 mG). Breeding was done with artificial insemination. None of the fertility parameters studied were affected by exposure to the 400-kV line. These included the estrous cycle, number of inseminations per pregnancy, and conception rates.

Each summer during 1977-1981, cattle behavior was studied near the BPA 1200-kV prototype line (Rogers et al. 1982) (Fig. 4.21). Each year five different steers were placed in a pasture where the animals could range both beneath and away from the line. The location of the cattle throughout the day was monitored with time-lapse cameras. Forage, salt, and water consumption were also measured. The line was alternately turned on and off at times during the study. The animals showed no reluctance to graze or drink beneath

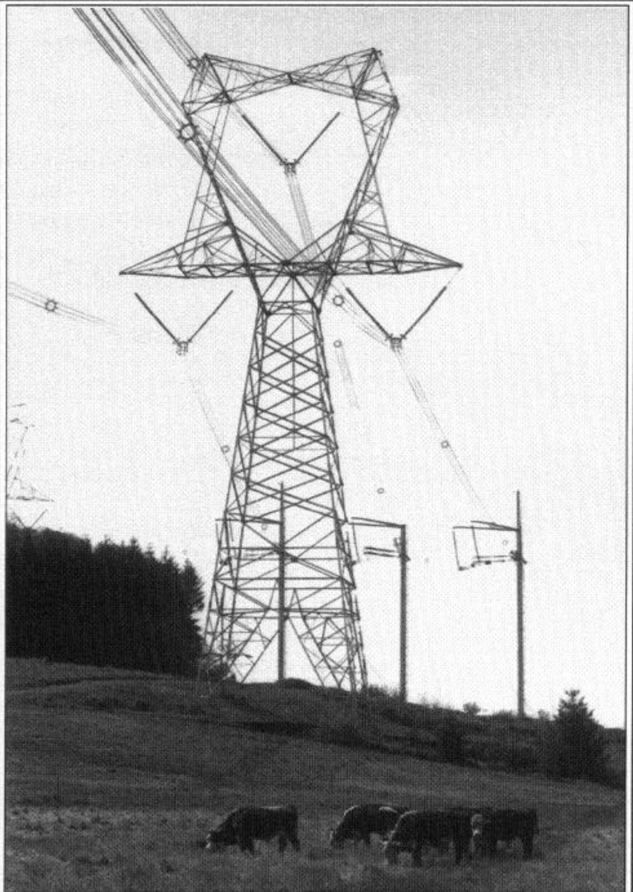


Figure 4.21. Cattle showed no obvious reluctance to eat or drink beneath the BPA 1200-kV prototype line in electric fields of up to 12 kV/m. Time-lapse photography suggested that cattle spent slightly less time beneath the line when it was energized compared to when it was turned off.

the line, which produced a maximum electric field of 12 kV/m (the test line carried no load so there was no magnetic field). A refined statistical analysis of the 1980-81 data indicated the cattle spent slightly more time near the line when it was turned off. This may indicate a reaction of the cattle to audible noise from corona, or to the electric field. During the 1980 study of the 1200-kV line, one steer died of a bacterial infection. The other cattle studied, in this and other years, remained healthy and no abnormal conditions developed.

In Iowa, a study was done of crossbred swine purposely raised beneath a 345kV transmission line (Mahmoud and Zimmerman 1983). The line produced a maximum electric field of 4.2 kV/m (the magnetic field level was not reported). The behavior and performance of 30 swine under the line over a 91-day period were compared to those of 30 control animals located away from the line. No effects of the line were found on body weight, carcass quality, behavior, or feed intake. A second phase of the study involved reproduction. Findings indicated no effect of the 345-kV line on pregnancy rate, frequency of birth defects, or on weight gain of young (Mahmoud and Zimmerman 1984).

In 1990, researchers from Oregon State University began long-term experimental studies of groups of lO-15 sheep raised in the EMF produced by a BPA 500-kV transmission line in Western Oregon (Lee et al. 1993, 1995). The same numbers of sheep were raised in a control area located about 229 m (750 ft) from the line. The mean 60-Hz electric field in the line pen was about 6 kV/m, and the mean magnetic field was about 4 pT (40 mG). In the control pen, levels of EMF were two orders of magnitude smaller than the levels in the line pen.

The sheep studies have focused on melatonin, reproductive cycles, growth, stress, and the immune system. Some results of the studies have been summarized in previous sections dealing with those respective topics. In addition, no significant differences were found between the line and control sheep for wool growth or for body weight gain (Thompson et al. 1995). Only for immunology was a possible effect of EMF on sheep in the study found (McCoy et al. 1993, Lee et al. 1996). Followup studies by the Portland Veterans Affairs Medical Center on interleukin- 1 (Fig. 4.13) for which possible effects were seen, and on other components of the immune system are expected to continue through at least 1998 (Christensen et al. 1996). Sponsors for this phase of the research include EPRI and the Korean Electric Power Research Institute (KEPRI).

Sheep in the studies are raised in pens beneath the transmission line, and in a control area away from the line. Figure 4.22 shows one of the pen designs used in the studies. In the most recent studies, an additional pen was constructed beneath the transmission line. The existing line pen was covered with metal screen which greatly reduced the electric field but had no effect on the magnetic field. This design is intended to provide data to help clarify whether possible effects found on the immune system are associated with the electric or the magnetic field.

In another study of sheep, 44 animals were infected with bovine leukemia virus and maintained in a pen beneath a 345-kV transmission line in Iowa for over 5 years (Miller and Lamont 1996). Another 44 sheep were infected with the virus and raised in an low-exposure area 152 m (500 ft) from the line. The abstract of the study included no information on levels of EMF in the

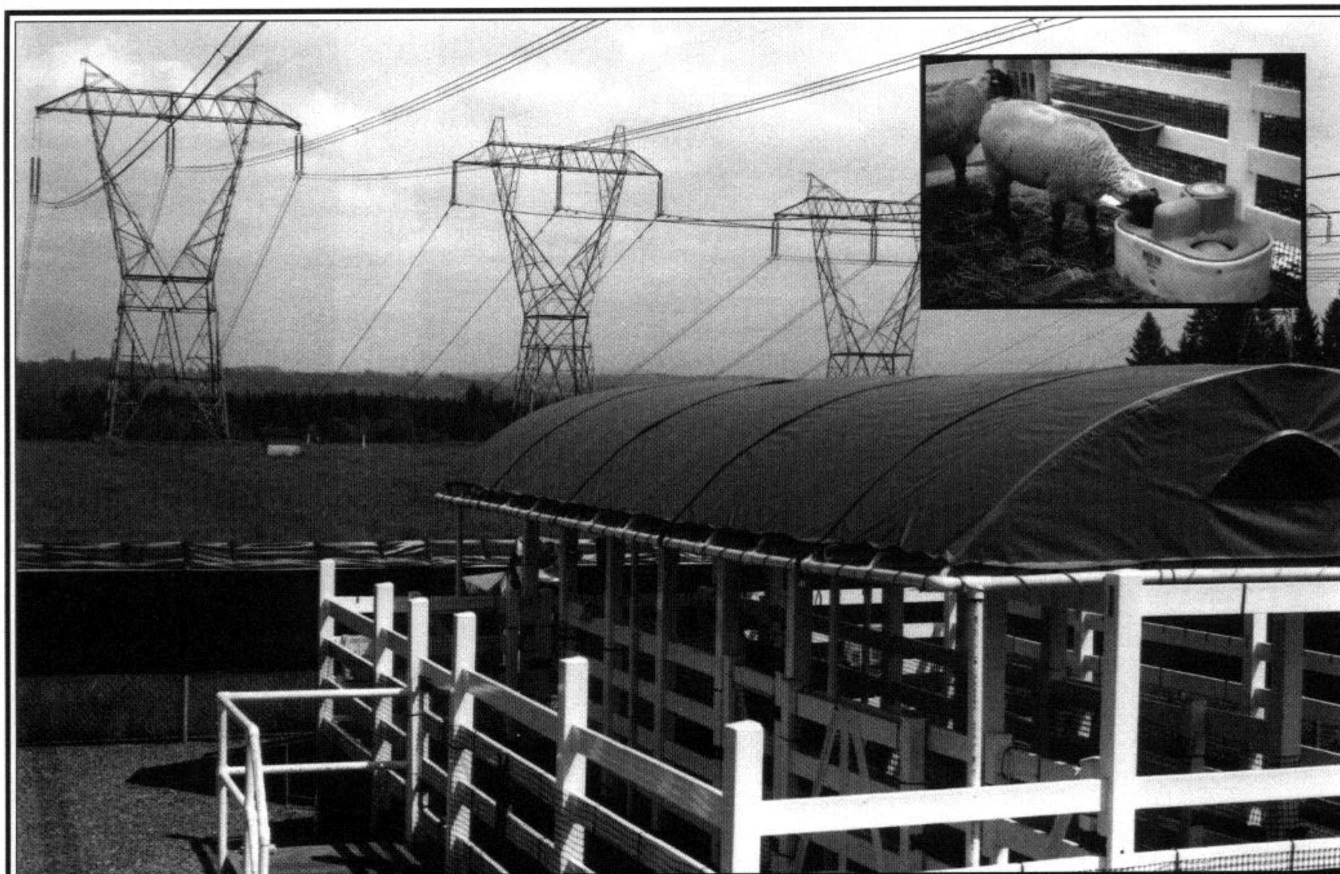


Figure 4.22. Since 1990, studies have been conducted of sheep raised in the EMF from high-voltage transmission lines near the BPA Ostrander substation in Western Oregon. The pens have grounded metal screen floors, and all other parts of the pens are made of plastic to minimize shielding of the electric field. No effects of EMF were found on melatonin, growth, stress, or on reproductive cycles. Followup studies are investigating possible effects on the immune system.

two areas. Through 5.5 years of study, 14 sheep under the line had developed lymphosarcoma or lymphatic leukemia, compared to 17 sheep that developed these conditions in the low exposure group. The difference between the two groups was not statistically significant.

In a study in Canada 16 Holstein cows were exposed to 60-Hz EMF while they were confined to individual stalls in an exposure building (Burchard et al. 1996). The cows were exposed to a vertical electric field of 10 kV/m combined with a magnetic field of 30 uT (300 mG). Exposures lasted for 28 days in two replicates, and the cows served as their own controls during 28-day field off periods.

Analyses of periodic blood samples taken from the cows showed no significant effects of field exposure on levels of serum cortisol or progesterone. Samples of milk taken once per week showed no effects of exposure on uncorrected milk yield. When yield was corrected for 4 percent fat content, a statistically significant increase in yield of 9.1 percent occurred during field exposure. The fat content of the milk increased from 4.06 to 4.43 percent during exposure. The researchers said that the size of the change was biologically important, but it was within the range of normal variability (Burchard et al. 1996)

Although not specifically an effect of EMF from power lines, "stray voltages" on equipment in barns have been found to affect adversely the health and production of dairy cows and other livestock (Gustafson and Albertson 1982). The sources of the voltages, which result in annoying shocks, include ground faults, improper wiring, and unbalanced loads on electrical distribution systems. Methods are available for identifying the sources and for mitigating problems caused by stray voltages (Lefcourt 1991). This issue remains controversial, however, especially with dairy farmers in Minnesota and Wisconsin. In 1996 the Minnesota legislature approved $370,000 for 2 years of a possible 5-year research program on the electrical environment of dairy farms (*EMF Health & Safety Digest* May 1996, pages 12-13).

Other Species

Studies were conducted for 2 years on the movement of five beagle dogs beneath a 50-Hz lOOO-kV test line in Italy (Conti et al. 1985, 1989). The dogs were kept in a large open pen where electric-field strength ranged from 1 to 18 kV/m. Based on data from time-lapse photographs, the dogs showed no avoidance of areas with the highest electric-field strengths. There were also no significant changes in blood parameters in the dogs over the 2-year period.

Reif et al. (1995) studied the risk of lymphoma in dogs exposed to residential 60-Hz magnetic fields in Colorado. The study was prompted by the studies of humans which reported increased cancer risks in homes with elevated magnetic fields (see Chapter 3). The researchers reasoned that dogs living in such homes should be exposed to the same risks. They compared 93 cases of canine lymphoma with 137 controls by classifying homes based on nearby power-line wiring configurations. Some magnetic-field measurements were also made. The highest lymphoma risk was found for dogs that lived in homes classified as very high current (crude OR= 6.81, 95% CI 1.63-28.5; adjusted OR= 13.43,95% CI 1.76-102.7). For dogs exposed to magnetic fields of 0.2 uT (2 mG) and above (measured on the sidewalk) for 6 or more years, lymphoma risk was elevated threefold but it was not statistically significant. The researchers suggested that dogs may act as sentinel species for effects of environmental exposures.

Various effects were reported on rabbits kept in cages in the electrical environment (EMF and corona effects) of a high-voltage substation in Sweden (Hansson 1981). Effects reported on Purkinje nerve cells were described in an earlier section on the "Nervous System." The rabbits exposed to the strongest electric field (14 kV/m) showed poor weight gains, and they were inactive compared to the control rabbits. In a later report Hansson et al. (1987) suggested that some of the earlier effects might have been influenced by weather and malnutrition.

Chickens were raised for about 1 year beneath the Italian IOOO-kV test line in 50-Hz electric fields of up to 15 kV/m (Conti et al. 1989). No gross changes related to field-exposure were seen in mortality, body weight, egg weight, fertility, or on the growth rate of chicks. The researchers conducted additional studies of chickens exposed to 50-Hz electric fields of 5 kV/m for 8 hours per day, or to 12-kV/m for 3 hours per day. These studies showed no statistically significant effects of exposure on egg production, or on the growth of chicks.

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Chapter 5

Other Health, Safety, and Environmental Considerations for AC Fields and Corona

Summary

- In the U.S., no formal government health risk assessment for EMF has been done, and there are no national standards for exposure to 60-Hz EMF This is largely because EMF to date have not been shown to represent a health hazard, the first step in a risk assessment process. Several Federal agencies have been involved in research and issues involving EMF. A national research and communication program on EMF was created in 1992 called "EMF RAPID."
- Several state and local government organizations have established standards or guidelines for EMF produced by power lines. In most cases these take the form of actions to reduce EMF from new lines based on various interpretations of a concept called "prudent avoidance."
- Numerical exposure levels for EMF have been developed by a U.S. professional society, and by some international organizations. These levels are based on criteria other than results of recent epidemiologic studies on EMF. The levels are much higher than typical exposures to EMF received in residential or occupation environments.
- There are several safety issues that should be considered in assessing the overall environmental effects of transmission-line EMF These include possible effects on cardiac pacemakers, flammable materials, blasting, irrigation, and shocks from fences and structures.
- Corona on transmission lines produces audible noise, ozone, and radio and television reception interference. Lines are typically designed to reduce these effects to acceptable levels
- Although most of the research described in this book deals with hazard assessment, there is also a large body of research and clinical experience with beneficial medical uses of EMF Whether effects of EMF are beneficial or adverse seems to depend on the specific characteristics of the fields and the exposures"

Introduction

This chapter covers several diverse aspects of AC fields, including risk assessment. standards and guidelines, medical applications and special field effects cases. The latter include effects on cardiac pace-makers, flammable materials. irrigation equipment. and fences and structures"

This chapter also describes corona effects of AC transmission lines. These effects include audible noise. radio and television reception interference. and ozone.

Risk Assessment

A primary use of the data developed by the many research programs described in Chapters 2-4 is to provide a basis for assessing the possible health risks associated with living or working near power lines and other electrical equipment. Risks can be defined as quantitative measures of hazard consequences. i.e.. the chance of sornething bad happening (Hohenemser et al. 1983). Hazards are the threats to humans and what they value.

For example, riding in an automobile is hazardous. Risks can be defined by such measures as the probability (chance) of being involved in a fatal traffic accident during a lifetime. A probability can ranee from 0 (no chance of the hazard occurring) to 1.0 (the hazard is certain to occur). In the driving example. the average risk of being killed in a traffic accident over a lifetime is about 0.01, i.e., I percent (Wilson 1996). Said another way, about 1 out of every 100 people at risk will be killed in automobile accidents. Your individual risk, of course, depends on many factors, including how much you drive, whether you wear a seat belt, how carefully you drive, and so on.

Risks have been formally estimated for many aspects of our technological society, such as for exposure to toxic chemicals and ionizing radiation. and for auto safety devices (Covello and Merkhoffer 1993). In such cases, prior experience or research has confirmed that hazards exist. In many cases the causes of death are not as obvious as a traffic accident. For many things that may cause death, disease, or accidents, the term “risk factor” is loosely used (Rodricks 1994, Last 1995). This term was used extensively in Chapter 3 in discussing results of cancer epidemiology studies. The cause(s) of most individual cancers usually are not known, even though a person may have been exposed to some factor(s) considered to be causes of cancer (e.g., smoking or ionizing radiation). However from experience and review of research, physicians may be able to identify possible factors that could have contributed to development of a specific cancer case. A risk factor may be a known or potential cause of a disease, or it could be correlated with other factors that are the true cause(s).

As described in this and previous chapters, no hazards have been confirmed for EMF exposures of people or animals (except for the special cases of some cardiac pacemakers and honeybee hives). There is ongoing debate about whether EMF are risk factors for cancer or other diseases. The American Cancer Society (1996) includes EMF under the heading of “unproven risks.” Thus, there have been relatively few attempts to conduct formal health risk assessments for EMF.

There are similarities and differences between the scientific controversy over biological effects of EMF, and other well-known controversies such as those over ionizing radiation, microwaves, and toxic chemicals. For the latter three, there is no debate over the existence of confirmed hazardous effects above certain levels of exposure. However, there is continuing controversy over low-level exposures. For example, although biological effects of ionizing radiation have been studied for several decades, scientists still disagree about the public health implications of long-term exposure to low levels of radiation (Goldman 1996, Puskin and Nelson 1996, Nussbaum 1996).

The controversy and continued interest about EMF is basically over whether the mostly small effects observed in some studies are caused by EMF, and, if they are, whether there are any significant consequences for public or worker health. This situation also applies to many other potential risk factors in our society (Covello and Merkhoffer 1993, Rodricks 1994).

Table 3.9 in Chapter 3 gives some examples of relative risk levels for some confirmed and possible environmental cancer risk factors as reported in epidemiological studies. Comparative studies could also be listed for other potential health risks associated with EMF such as reproductive effects. Notice in Table 3.9 that some confirmed risk factors tend to have the high relative risks. This means that the factor is considered an important cause of the particular type of cancer. Smoking, for example, is believed to be the main cause of lung cancer. When several factors may cause a disease, relative risk (i.e., the degree of association) is weaker for any one of the factors (Lilienfeld and Lilienfeld 1980). For example, excessive alcohol use and smoking are both important causes of oral cancer. Relative risks for each factor, however, are smaller than for the two factors combined. In general, it becomes very difficult to establish causation when relative risks are small (e.g., below 3).

To estimate actual population risks, assumptions have to be made that include estimating the size of the exposed populations. One early estimate about potential risks of 60-Hz magnetic fields was made by the Science Panel for the New York Power Lines Project (Ahlborn et al. 1987). The Panel, extrapolating from the study by Savitz (1988) suggested that 10-15 percent of childhood cancer cases could be due to magnetic fields from high-current power lines. In terms of mortality, this could amount to around 200-300 deaths per year. The Panel’s estimate assumed that about 20 percent of children live near high-current power lines. Carpenter (1994) suggested that exposure to magnetic fields from appliances may account for another 10-15 percent of childhood cancer.

Morgan et al, (1987) conducted preliminary studies to structure the problem of assessing EMF health risks. They acknowledged that scientific uncertainty about biological effects of EMF precluded them from conducting a formal risk assessment. Those researchers found that a major problem was attempting to define exposure as applied to EMF. In more recent studies Morgan and Nair (1992) assessed various exposure “effects functions” for EMF by holding a structured workshop with research scientists. These functions included frequency windows, intensity windows, time-averaged fields, cumulative fields, switching fields, binary fields, and AC-DC fields. Scientists in the workshop did not rule out any of these functions as having a role in some of the reported biological effects of EMF.

Florig (1992) found that the risks reported in epidemiological studies of workers exposed to EMF represent a small fraction of the total risk of death for those occupations. However, he said that the risks reported in studies of workers and of children exposed to EMF are above a threshold where some regulatory agencies on occasion have acted to reduce risks from other agents.

Zhang (1995) observed that although risks reported in epidemiological studies of EMF are not extremely high, population risks may not be negligible because exposures to EMF are so common. He suggested that risk assessment for EMF is, therefore, warranted. His studies showed that such assessments are now possible, at least with models requiring the lowest levels of scientific information.

Wilson (1996) calculated cancer risks related to magnetic field exposure for the U.S. population. For purposes of his calculations, he first assumed that risks for brain and breast cancer, and for leukemia found in some studies are correct. He next made assumptions about population exposures to magnetic fields, and then he calculated that on average, field exposure could contribute to about 9300 cases of cancer per year. Wilson (1996) suggested that the number could be lo-fold greater if magnetic field exposure contributed to development of other cancer types. It is important to point out that a cause-and-effect link between EMF and cancer has not been established, and that information on population exposures to EMF is incomplete.

A hazard identification/risk assessment model will be a central component of the U.S. National EMF research program (EMF RAPID) (see the following section) (The EMF Interagency Committee 1995). The assessment will use results from all relevant research and, if a health hazard is found to exist, efforts will be made to quantify the magnitude of the risks to human health. Results of the risk assessment and of related research under EMF RAPID are expected to be included in a report to Congress in late 1997. Although it is not clear what specific form the EMF RAPID risk assessment will have, the U.S. EPA and some other Federal agencies have used a four-step model of risk assessment (Fig. 5.1). Questions about EMF have mainly focused on the first step, which tries to determine how likely an agent is to be a human carcinogen. EPA uses a "weight of evidence" approach to assess the potential for carcinogenicity (Fig. 5.2) although adjustments to the categories are allowed based on specific cases (EPA 1986).

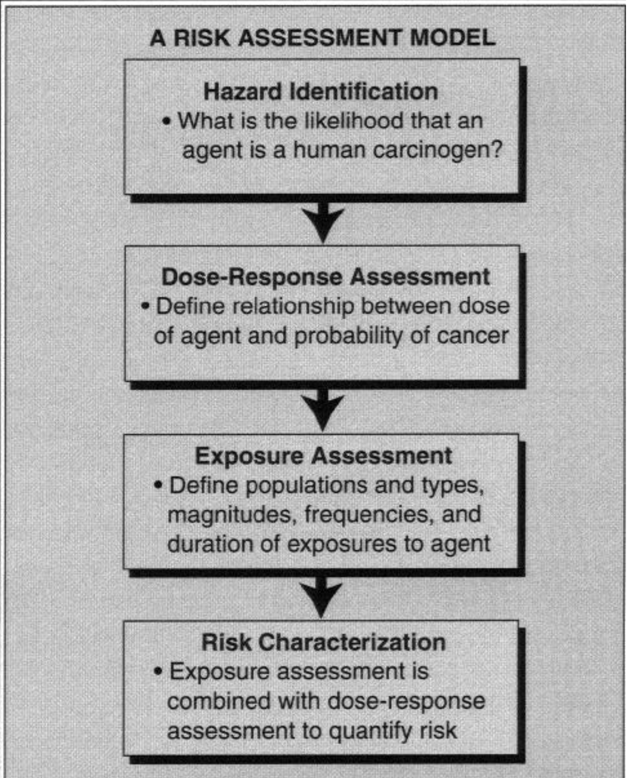

Figure 5.1. The basic risk assessment model used by the U.S. Environmental Protection Agency and some other agencies to assess cancer risk of environmental pollutants.
Source: EPA (1986).

Human Evidence	Animal Evidence: Sufficient	Limited	Inadequate	No Data	No Evidence
Sufficient	A	A	A	A	A
Limited	BI	BI	BI	Bi	BI
Inadequate	B2	c	D	D	D
No Data	B2	C	D	D	E
No evidence	B2	C	D	D	E

Some Examples:

Class A: Human Carcinogens
Arsenic
Asbestos
Benzene

Class B: Probable Human Carcinogens

B1: Limited Epidemiologic Evidence
Cadmium
Creosote
Formaldehyde

B2: Sufficient Animal Evidence
DDT
PCBs
Dioxin

Class C: Possible Human Carcinogens
Methyl chloride
Saccharin
Trichloroethane

Figure 5.2. Overall scheme to categorize the weight of evidence of the human carcinogenicity of a chemical as announced in 1986 by the U.S. Environmental Protection Agency. The assignments are for illustrative purposes and actual assignments may be adjusted.
Sources: EPA (1986), EPA June (1988) cited in *Microwave News* May/June (1990).

On April 23, 1996 EPA issued a proposal to revise its 1986 guidelines for cancer risk assessment *(Federal Register* June 25, 1996).

When risks or potential risks are identified, then additional considerations arise about risk acceptability and risk management. Determining acceptable levels of risk involves judgements about desired levels of safety, and of the benefits and costs of various measures to manage risks (Fischhoff et al. 1981, Leiss and Chociolko 1994, Rodricks 1994). The judgements of technical experts, industries, regulatory agencies, and the public may vary widely on these issues. Communication among all of the interested parties in an important component of the overall risk analysis process (Lundgren 1994, National Research Council 1989).

Although at present it is difficult to develop actual health risk estimates for exposure to power-line EMF, some work has been done on assessing how people perceive risks. In general, a person's perception of a risk is influenced by such factors as knowledge of the subject, whether the risk is voluntary or involuntary, and the perceived benefits (Slavic et al. 1980). Therefore, the importance that people place on various risks varies greatly among individuals.

In terms of the siting and construction of transmission lines, perceived risks are an important concern. Risk assessment for power-line EMF needs to incorporate not only the results of biological research, but should also consider social perceptions and concerns. Early research was conducted at Carnegie-Mellon University on methodology for risk assessment applicable to transmission lines (Morgan et al. 1985a, 1985b).

The public's beliefs about the seriousness of potential risks of EMF are significantly influenced by the content of information that they receive. MacGregor et al. (1994) found that people's concerns about EMF were raised after they read a brochure that the researchers believed carefully presented the scientific uncertainty about EMF. Although scientists may accept uncertainty as a part of the scientific process, people concerned about whether something is safe may see uncertainty as a reason to be concerned until more is known.

One measure of the degree of scientific uncertainty about the risks of EMF on human health comes from a panel of scientists assembled by the Harvard Center for Risk Analysis (Graham and Putnam 1995). The 17 panel members were from the fields of medicine, public health, engineering, biology, physics, and risk analysis. They were asked to rate how confident they were about whether exposure to EMF on the job caused certain types of cancers (0= no confidence, 100= complete confidence). Their ratings for breast cancer ranged from about 2 to 80; for leukemia and for brain cancer their ratings ranged from about 6 to 7.5.

Policies, Standards and Guidelines

Federal and National Activities

There are no national standards in the U.S. for exposure to 60-Hz electric or magnetic fields. However, requirements of the *National Electrical Safety Code* for induced currents place some upper limits on field strength for power lines.

Environmental Protection Agency (EPA)

In 1975, the U.S. Environmental Protection Agency (EPA) issued a request for information *(Federal Register*, March 18, 1975) on health and environmental effects of transmission lines. EPA wanted to determine whether guidance was needed for electric field-standards for transmission lines of 700 kV and above. The report on the final analysis of the information received concluded as follows: "However, the work which has been performed to date has not provided convincing evidence that any threat to the public health or welfare has been caused by existing [electric field] exposure levels" (Janes 1980:X).

The EPA released a draft report in 1990 that reviewed research on EMF and cancer (EPA 1990). Although the draft was prepared for scientific review and marked "do not quote or cite" it was widely discussed, cited, and quoted by scientists, the utility industry, other agencies and the public *(Microwave News* May/June 1990, Nov./Dee. *1990; Transmission/Distribution Health & Safety Report* March 31, 1990). Controversy surrounded release of the draft over questions about why language in an earlier version classifying EMF as a Group Bl carcinogen (i.e., a probable carcinogen, see Fig. 5.2) was dropped. The draft released for review did not include a specific classification, instead, it said that 60-Hz magnetic fields are a possible but not proven cause of cancer.

The draft 1990 EPA report on EMF and cancer was reviewed by a subcommittee of an EPA Science Advisory Board. The committee concluded that the draft had serious deficiencies and needed to be rewritten to correct internal inconsistencies that made it difficult to tell what EPA's position was on EMF (SAB 1992). The committee also reviewed evidence on EMF and cancer and concluded that,

... some of the epidemiological evidence is suggestive of an association between surrogate measurements of magnetic field exposure and certain cancer outcomes.. . . This lack [of information on appropriate exposures], together with limited understanding of possible biological mechanisms, prevents the inference of cancer causality from these associations at this time" (SAB 1992: 1).

As of 1996 a revised version of the 1990 draft EPA report on EMF and cancer had not been released. An EPA official said that due to budget uncertainties, the report will not come out in the foreseeable future (Microwave News Jan./Feb. 1996). EPA has no official position on prudent avoidance of EMF exposures, and suggests individuals must decide whether they want to take actions to reduce potential health risks (EPA 1992).

National Council on Radiation Protection and Measurements (NCRP)

The National Council on Radiation Protection and Measurements (NCRP) was formed in 1964 by the U.S. Congress as a non-government, non-profit organization. The Council's charter is to assess environmental and health effects of radiation and to make recommendations about radiation protection and measurements. In 1984, EPA commissioned the NCRP to conduct a critical appraisal of the world-wide literature on health effects of EMF. The review was to provide EPA with updated information for presumably another assessment as to the possible need for exposure guidance. NCRP Scientific Committee 89-3, consisting of about a dozen scientists with expertise on EMF, was assembled to conduct the review. The review was finally expected to be submitted for approval in late 1996 (Tenforde 1996). Some draft material from the NCRP review was prematurely released in 1995 (Anonymous 1996).

Bonneville Power Administration (BPA)

The Bonneville Power Administration (BPA) began an active program of research and public communication on EMF in 1974. At that time BPA was an agency within the U.S. Department of the Interior. In 1977, BPA became one of the five power marketing agencies within the newly created U.S. Department of Energy. In 1975 BPA adopted transmission-line design levels for 60-Hz electric fields. No such levels have been established by BPA for magnetic fields

BPA criteria for allowable electric-field strengths are intended to result in a low probability of human perception or annoyance from field effects. Therefore, the levels are normally much lower than those needed to meet requirements of the *National Electrical Safety Code* (NESC). BPA 500-kV transmission lines are allowed a maximum electric field of 9 kV/m on the right-of-way as measured at 1 m (3.3 ft) above ground. BPA's maximum allowable electric field at the edge of the right-of-way is 5 kV/m. However, the maximum calculated edge-of-right-of-way field strength for BPA 500-kV lines is typically around 2-3 kV/m.

The NESC specifies that induced currents from transmission lines not exceed 5 mA. BPA policy is to limit induced current to below annoyance levels (2 mA) for conductive objects permanently located on or near the right-of-way. This is done by grounding fences and other objects or by reducing electric field strength by increasing conductor-to-ground clearance.

To meet the NESC 5 mA limit (for induced currents from the largest anticipated vehicles), BPA limits the electric field to 5 kV/m at highway crossings. Across shopping center parking lots, the field is limited to 3.5 kV/m so that the current induced into sedans and pickup trucks is generally not perceptible (1 mA or below). The electric field strength is further limited to 2.5 kV/m across commercial or industrial parking lots so that induced current is less than the annoyance level (2 mA) for personnel working around large trucks.

In 1988 following release of the results of the second childhood cancer study in Denver, Colorado (Savitz et al. 1987). BPA conducted a review of its practices for dealing with EMF issues. As a result BPA adopted interim guidance on EMF which was published in the 1989 edition of this publication (Lee et al. 1989), and in the transcript of the 1990 Congressional hearing on EMF (Lee 1990). Included in the 1988 BPA Interim Guidance on EMF were provisions that EMF should be one of the considerations in the design and location of new transmission facilities, and that public and employee exposure to EMF should not be increased where practical alternatives exist. The BPA guidelines on EMF were reviewed and revised in 1992 (Lee et al. 1993), and in 1995 (Table 5.1).

For many years BPA, like most utilities, actively encouraged multiple uses of its transmission line rights-of-way. Such uses included parks, playgrounds, trails, and soccer and softball fields. Because of continuing controversy about the potential for health effects of EMF, in 1990 BPA placed a 2-year moratorium on new uses of its rights-of-way property rights that may increase human exposures to EMF. Existing uses were not affected by this action. No significant problems were encountered during the first 2 years of the moratorium. Because issues about EMF are still unresolved, the moratorium is ongoing until such time as the status of the controversy changes, or other factors indicate that the moratorium should be discontinued or modified.

The moratorium means that for rights-of-way where BPA owns all of the property rights, new requests for uses that are likely to increase exposures to EMF will not be approved. For rights-of-way where BPA has an easement, new requests for such uses will not be approved if they infringe on BPA's property rights, e.g., rights to prohibit structures such as baseball backstops. In all other cases where BPA property rights do not prohibit the proposed use, BPA provides the requestor with information on EMF issues so that the requestor can make an informed decision about whether to proceed with the proposed use.

Table 5.1. BPA strategy on EMF (Feb. 1995).

Issue: There continues to be significant uncertainty about the potential health effects from electric and magnetic fields. Scientists and others do not agree on how to interpret the available information, and public concern is sincere.
Response: BPA believes the concerned public and its employees need to know about and understand the EMF issue.
Desired Results: BPA is recognized as a credible source of information onEMF and a utility responsive to public concern and to changes in the science.

To implement its STRATEGY on EMF, BPA adopts the following GUIDELINES governing its practices with regard electric and magnetic fields.

1 Staffing: Maintain a high level of professional knowledge and internal capability in the area of EMF.

2 Communication:
- Create, gather and share educational information on EMF. Communicate respectfully sincerely, and responsively with employees and the public.
- Inform and involve affected customers and the public in BPA project deve topment,
- Explore with employees ways to reduce exposures in carrying out their jobs.

3 Research: Support research and development associated with EMF and transmission facilities that directly relates to accomplishing BPA's desired results.

❑ Transmission Facilities:
- Consider EMF as an important factor with other design and siting factors for new and upgraded transmission facilities. BPA will take reasonable low-cost steps to minimize field exposure for these facilities while taking into account operation and maintenance considerations.
- *Consider modifying existing facilities upon request and at no cost to BPA System reliability, operation, maintenance, and safety should not be adversely affected and there should be no adverse impact on others.

5 Participate with Others: Participate with professional entities, the scientific community, utilities, governmental bodies and others in the development of the EMF issue.

6 Evaluation: Monitor and evaluate EMF activities and make decisions based upon the value of the results.

Western Area Power Administration (WAPA)

In 1990, the Western Area Power Administration (WAPA) adopted an EMF issue position statement (WAPA 1990). WAPA is a power marketing agency within the U.S. Department of Energy. WAPA investigates alternative transmission-line design and siting approaches to reduce public exposure to EMF. WAPA supports research on EMF and gathers and shares information on EMF with employees and the public.

Tennessee Valley Authority (TVA)

The Federal Tennessee Valley Authority (TVA) adopted interim guidelines on EMF in 1994. TVA takes "... sensible, practical measures in its day-to-day business activities to reduce EMF levels that result from the construction of new transmission facilities and those in the workplace" (TVA 1994). Where practical, TVA routes new lines to reduce EMF near homes, schools, and other densely populated areas. TVA conducts and monitors research on EMF, provides measurements of EMF, and provides information about EMF to employees and the public.

Congressional Hearings

The first of two congressional oversight hearings on the possible health effects of transmission lines was held on October 6, 1987 (microwave News Sept./Oct. 1987, Jan./Feb. 1988). The hearing was prompted, in part, by media and public interest in the recently announced results of the study by Savitz et al. (1987) of cancer in children living near power lines in Denver. The Subcommittee on Water and Power Resources heard testimony from several scientists, including Dr. Savitz, who had conducted research on EMF. Others providing testimony included a Congressman, and representatives of the U.S. Department of Energy, and the U.S. Environmental Protection Agency.

The second hearing was held on March 8, 1990, before the Subcommittee on General Oversight and Investigations of the House Committee on Interior and Insular Affairs (Committee on Interior and Insular Affairs 1990). The subcommittee chairman said that the purpose of the hearing was to consider implications of recent research that he believed strongly suggested an association between EMF and cancer and other health effects. The subcommittee heard testimony from research scientists, citizens, utilities (including BPA), and sponsors of research on EMF. As in the previous hearing, there was a wide range of viewpoints about the research findings and related policy implications.

Congressional Office of Technology Assessment (OTA)

In 1989 the Congressional Office of Technology Assessment (OTA) prepared the report, *Electric Power Wheeling and Dealing Technological Considerations for Increasing Competition.* One of the background papers, on the biological effects of EMF, was prepared by researchers at Carnegie Mellon University (Nair et al. 1989). Included in the paper were five policy alternatives for dealing with uncertainties about health effects of EMF. Of these, the "prudent avoidance" strategy has since been widely adopted by utilities, regulators, and individuals as a general way to deal with EMF issues (Morgan 1994, Sahl and Dolan 1996). The strategy has also been criticized and rejected by some individuals and organizations (Ekfeldt 199 1, Hafemeister 1995).

As defined in the OTA report by Nair et al: (1989:78-79), prudent avoidance meant "... taking steps to keep people out of fields, both by rerouting facilities and by redesigning electrical systems and appliances. By prudence we mean undertaking only those avoidance activities which carry modest costs." Prudent avoidance is discussed further in the sections below on national, state and local activities concerning EMF.

The OTA (1995) also prepared a report entitled *Risks to Students in School,* which included a section on EMF. The report summarized pertinent epidemiological research and research on EMF in schools, and described EMF issues at selected sites. The report gave no recommendations specifically related to EMF and schools.

Regarding risks, the report found that, "In comparison to other environmental risks described in this report, EMF is among the most uncertain" (OTA 1995:167). The other environmental risks considered included school materials (lead, pesticides, chemicals, supplies, lab materials), infectious diseases, indoor air quality (asbestos, radon, other air contaminants), hazardous waste sites, and noise.

American Conference of Governmental Industrial Hygienists (ACGIH)

The American Conference of Governmental Industrial Hygienists (ACGIH) first included subradio frequency EMF in the 1991-1992 edition of its "Threshold Limits" booklet (ACGIH 1991a). ACGIH is a professional society and not a government agency. It develops threshold limit values (TLVs) and biological exposure indices for chemicals and physical agents for use by practicing industrial hygienists. ACGIH states that the occupational values they provide are not a fine line between safe and dangerous levels, and the values should not be used by anyone not trained in the discipline of industrial hygiene.

For 60-Hz EMF the TLVs are 25 kV/m, and 1 mT (10 G). Information on the rationale for these levels is provided by ACGIH in a separate publication (ACGIH 199 lb). In brief, the levels are based on keeping currents induced by EMF at or near currents that occur naturally in the body. Table 5.2 gives more information on the TLVs for EMF from the 1996 ACGIH booklet.

Table 5.2. American Conference of Governmental Industrial Hygienists Threshold Limit Values for 60-Hz EMF. Source: ACGIH (1996).

Electric Field	Magnetic Field
Occupational exposure for l-100 Hz should not exceed:	Occupational 60.Hz exposure should not exceed the ceiling value:
25 kV/m	1 mT[a] (10 G)
Prudence dictates the use of protective devices (e.g. suits, gloves, insulation) in all fields above 15 kV/m.	For frequencies below 300 Hz, exposure of the extremities can be increased bv a factor of 5.
For workers with cardiac, pacemakers, maintain 60-Hz exposure at or below 1 kV/m.	For workers with cardiac pacemakers, maintain 60-Hz exposure at or below 0.1 mT (1 G).

[a] This rms magnetic flux density is calculated for frequencies of l-300 Hz from the equation:
B_{TLV} (mT) = 60/f, where f is the frequency in Hz.

Oak Ridge Scientific Panel

The U.S. Department of Labor (DOL) in 1989 requested the Committee on Interagency Radiation Research and Policy Coordination (CIRRPC) for assistance in evaluating the potential health effects of EMF (ORAU Panel 1992). CIRRPS subsequently asked Oak Ridge Associated Universities to form a scientific panel to review research on EMF. The 1 l-member panel concluded in their report that there was no convincing evidence that ELF-EMF are demonstrable health hazards (ORAU

1992). The panel also found no justification for a major expansion of the national research effort to investigate health effects of EMF.

National EMF Program

A national 5-year program of research and public communication on EMF was established on October 24, 1992 by section 2118 of the *Energy Policy Act of 1992* (42 USC 13478). The $65 million dollar program is funded by Federal and matching non-federal funds. The program is called EMF RAPID (EMF Research and Public Information Dissemination Program). EMF RAPID is defined as a comprehensive program to determine whether exposure to EMF from generation, transmission, and use of electricity affects human health.

EMF RAPID is the responsibility of the U.S. Department of Energy, and the National Institute of Environmental Health Sciences. An Interagency Committee, and an Advisory Committee are involved in overseeing the program. In 1995 there were 39 EMF health effects studies underway as part of EMF RAPID being done by researchers who received grants under the program, and by government researchers (EMF Interagency Committee 1995). Large numbers of a public information booklet on EMF have also been distributed as part of the program. Although EMF RAPID was to have been completed in 1997, it now appears that the program could be extended to 1998 *(EMF Health & Safety Digest* April 1996). Final reports on the program are to be prepared by the Interagency Committee and by a committee formed by the National Academy of Sciences.

National Research Council (NRC)

The National Research Council (NRC) is the principle operating organization of the National Academy of Sciences (NAS) and the National Academy of Engineering. The NRC is a private, non-profit organization that provides science and technology advice under a congressional charter. The U.S. Congress in 1991 asked the NAS to review research on EMF and determine whether the research was sufficient to assess the health risks from exposure to EMF. The U.S. Department of Energy entered into an agreement with the NRC to convene a committee of 16 scientists to prepare a report on EMF.

The conclusions and findings of the NRC committee's report were released in late October 1996 (only the report's executive summary was available at the time of this writing). The committee found that,

"Based on a comprehensive evaluation of published studies relating to the effects of powerfrequency electric and magnetic fields on cells, tissues, and organisms (including humans), the conclusion of the committee is that the current body of evidence does not show that exposure to these fields presents a human-health hazard" (Committee on the Possible Effects of Electromagnetic Fields on Biological Systems 1996) (more conclusions of the committee are included in Appendix A).

The committee said that more research is needed to resolve some research issues. This includes identifying the causative factor(s) responsible for the association found between child cancer and proximity of homes to power lines.

Three of the committee members included the current and past presidents of the Bioelectromagnetics Society; they issued a press release at the same time that the NRC report was released. Luben et al. (1996) stated that,

"The most important aspect of this report is that it establishes that even under the most strictest possible standards of proof, there is a reliable, though low, statistical association between power lines and at least one form of cancer [childhood leukemia]. This fact in itself shows that we need to do more to find out why this relationship exists" (see also Appendix A).

Another committee established by the NAS will review the results of the national EMF research program (EMF RAPID).

State Activities

Several states have addressed the EMF issue, usually during regulatory proceedings for proposed transmission lines. This has resulted in some states establishing electric field limits; however, apparently only three states (Oregon, Florida, and Montana) have formally adopted rules or standards. The state standards and guidelines are summarized in Table 5.3. Additional background information on some of the state activities on EMF is summarized below. More information on EMF activities at the state and local level can be found in reports by Gulliver and Vito (1993), Merritt (1994) and by the Environmental Law Institute (1996).

Arizona

Although the state of Arizona apparently has no formal policies on EMF, in 1992 the Phoenix-based Salt River Project (SRP) outlined its position on EMF, which included adopting prudent field management (SRP 1992). This was defined as taking prudent steps to manage fields around sources wherever possible as long as there is a potential for health effects from EMF. When

Table 5.3. A summary of state standards and guidelines for transmission-line EMF.

State	Electric Field On R.O.W.	Electric Field Edge R.O.W.	Magnetic Field On R.O.W.	Magnetic Field Edge R.O.W.
Delaware [a]	8 kV/m	2 kV/m	—	20 μT (200 mG)
Florida	8 kV/m [b] 10 kV/m [c]	2 kV/m		15 μT [b] (150 mG) (max. load) 20 μT [c] (200 mG) (max. load) 25 μT [d] (250 mG) (max. load)
Minnesota	8 kV/m	—	—	—
Montana	7 kV/m [e]	1 kV/m		
New Jersey	—	3 kV/m	—	—
New York	11.8 kV/m 11 kV/m [f] 7 kV/m [e]	1.6 kV/m		20 μT (200 mG) (max. load)
Oregon	9 kV/m	—	—	—

[a] Adopted by Delmarva Power Co.
[b] For lines of 69 to 230 kV
[c] For 500-kV lines
[d] For 500-kV lines on certain existing R.O.W
[e] Maximum for highway crossings
[f] Maximum for private road crossings
R.O.W = Right-of-way

siting new transmission facilities, SRP avoids schools, daycare centers, and other public facilities wherever practical. SRP supports research on EMF and provides information on EMF to customers and the public.

California

In 199 1 the California Public Utilities Commission began an investigation of its potential role in mitigating possible health effects of EMF from power systems and cell phone towers (California EMF Consensus Group 1992). A 17-member EMF consensus group representing various stake holders was formed to propose interim procedures and utility-funded research requirements. The group's report submitted to the PUC in 1992 contained several recommendations involving research, education, and policy pertaining to EMF (California EMF Consensus Group 1992).

In 1993 the California PUC adopted interim measures on EMF based on recommendations from the consensus group *(EMF Health & Safety Digest* Nov.-Dec. 1993). The measures applied to the five investor-owned utilities in California. The measures included no-cost and low-cost steps to reduce EMF levels, uniform EMF measurements programs, a $1.489 million education program, and a $5.6 million research program. The measures did not include numerical state standards for EMF.

The California State Department of Education in a 1989 publication defined limit distances for locating schools near transmission line easements, and they were revised in 1993 (Lowrey 1994). The revised limits from the edge of transmission line easements are as follows:

- 100 ft for 50-133-kV lines,
- 150 ft for 220-230-kV lines, and
- 350 ft for 500-550-kV lines.

In defining these limits the Education Department acknowledged that no scientific consensus exists supporting reports of EMF on people. However, they cautioned that, " Nevertheless, school districts must take a conservative approach when reviewing sites near power transmission line easements" (Lowrey 1994). The Department further suggested that when evaluating potential school sites near transmission lines, the selection team should ask whether other sites are available, and should ask the power company about possible plans to build more or larger lines on the right-of-way.

Colorado

The Colorado Public Utilities Commission in 1992 adopted the concept of prudent avoidance with respect to planning, siting, constructing, and operating transmission lines *(EMF Health & Safety Digest* Nov.-Dec. 1992). Prudent avoidance was defined as, "... striking a reasonable balance between the potential health effects of exposure to magnetic fields and the cost and impacts of mitigation of such exposures, by taking steps to reduce the exposure at reasonable or modest cost."

Discussions between the Public Service Company of Colorado and university researchers led to establishment in 1991 of the Universities Consortium on Electromagnetic Fields. The Consortium prepared a literature review that concluded although no health effects of EMF have been established, more research is needed (Universities Consortium on EMF 1992). The review contained no recommendations for policies or standards.

Connecticut

In a 1992 report on EMF to the Connecticut Department of Health Services, a scientific committee concluded that it would be inappropriate for public authorities to recommend prudent avoidance (Academy Ad Hoc Committee 1992). The committee also recommended against adopting any existing EMF exposure guidelines, or adopting more stringent guidelines.

The Commissioner for the Connecticut Department of Health Services (DHS) took exception to some of the statements in the Academy report. Commissioner Addiss (1992) said in a letter that, ". . .(DHS) is concerned that the overall tone of the review may imply that exposures to electromagnetic fields (EMF) may be dismissed as a potentially significant public health issue." An ongoing Connecticut Interagency EMF Task Force recommended "voluntary exposure control" relating to individuals' use of electrical appliances, and endorsed the State Siting Council's "best management practices for EMF" (Interagency Task Force Studying EMF 1995).

Delaware

The Delmarva Power Company adopted EMF limits for transmission facilities in 1990 (Transmission/ *Distribution Health C? Safety Report* Dec. 1990). They are not official state limits, but Delmarva is the only electric utility in Delaware. The electric field limit is based on avoidance of human detection of the field. The magnetic field limit is based on fields produced by existing lines in the state.

Florida

In 1985, an interdisciplinary Science Advisory Commission in Florida evaluated the potential for adverse health effects of exposure to transmission-line fields. In a final report submitted to the state of Florida, the Commission concluded that it is unlikely that 60-Hz electric and magnetic fields can lead to public health problems (FEMFSAC 1985). The commission found no scientific basis for recommending risk management strategies such as limiting the electric field strength at the edge of the right-of-way.

In 1986, another Advisory Panel was appointed to advise the Florida Department of Environmental Regulation (DER) on electric and magnetic fields. Because of uncertainties raised by more recent research, the Panel concluded that it would be prudent to keep long-term field exposures to the population to low values (Parker et al. 1987). The Panel recommended that, when possible, new transmission lines be routed outside of residential areas. Interim standards for both electric and magnetic fields were also recommended.

The Florida Environmental Regulation Commission (ERC) subsequently recommended that the DER adopt the interim standards recommended by the Advisory Panel. For electric fields, these levels were l-2 kV/m at the edge of the right-of-way, and 8 kV/m maximum on the right-of-way. For magnetic fields, the recommended levels for the edge of the right-of-way were 10 uT (100 mG) for maximum loads, and 5 uT (50 mG) for normal load conditions. In the final standards adopted by the Florida ERC in early 1989 (Table 5.3), magnetic field levels were different from those recommended by the advisory panel.

The DER sponsored a study of options to further reduce the magnetic fields from transmission lines used in Florida. The study identified transmission-line designs that had lower edge of right-of-way magnetic fields than present designs, had low support-structure cost, and had acceptable appearance (Oppel and Stewart 1993).

Hawaii

The Hawaii Department of Health adopted a prudent avoidance policy in 1991 that called for new power lines to be constructed with engineering controls to reduce EMF exposures *(EMF Health & Safety Digest* Feb. 1994). In 1994 the department revised its policy on EMF to define prudent avoidance to mean, ". . . that reasonable, practical, simple, and relatively inexpensive actions should be considered to reduce exposure."

In 1994 the Hawaii Public Utilities Commission (HPUC) also adopted prudent avoidance during a process of approving a 138-kV transmission line *(EMF Health & Safety Digest* May 1994). The HPUC definition of prudent avoidance included a statement that, "Prudent avoidance applied to EMFs suggests adopting measures to avoid EMF exposures when it is reasonable, practical, and relatively inexpensive to do so."

Illinois

A House Resolution (HR 1064) adopted in 1989 by the Illinois General Assembly instructed the Illinois Department of Health, and the Illinois Environmental

Protection Agency to assess health risks of EMF. The two agencies prepared a review of research on EMF that was completed in 1992 (IDPH, IEPA 1992). The review concluded that no scientific consensus had been reached on the possibility of health effects of EMF, and that without sufficient information, health risks of EMF could not be properly determined. The review also found that it was not possible to set standards for EMF, or to say whether any field level is safe or dangerous. However, the review encouraged utilities to take prudent measures to reduce EMF when routing transmission lines.

Maryland

In 1989 the Maryland Public Service Commission ordered annual reports to be made about information on possible health effects of EMF. The fifth report in the series reviewed studies published in 1993-1994 (Information Ventures, Inc. 1994). The report concluded that even with the newest research, it is still not possible to make definitive conclusions about the potential health effects of EMF. The report also found that electric utilities in most cases had limited their mitigation for EMF to the least expensive alternatives.

Minnesota

The Minnesota Environmental Quality Board (MEQB) specifies in construction permits that the maximum transmission-line electric field shall not exceed 8 kV/m at 1 m (3.3 ft) above the ground on the right-of-way (Banks et al. 1977). The MEQB funded a review of research and issues involving EMF to assist the Board in regulatory decisions for new electric energy facilities, and to serve as a public information document (Sheppard 1994). The report found that health effects of EMF had not been conclusively demonstrated. However, although the possible risk to individuals was considered to be relatively small, the report said that the risk is still large enough to require control if the risk from EMF is proven to be true.

Montana

Public concerns about potential health effects developed in Montana in the early 1980s because of a proposed BPA 500-kV transmission line. In 1984, the Montana Board of Natural Resources and Conservation adopted a state standard for electric field strength for new transmission lines constructed in residential and subdivided areas. In that state, the field strength shall not exceed 1 kV/m at the edge of the right-of-way, although affected landowners can waive the standard (Jamison 1986). The field at road crossings cannot exceed 7 kV/m. Both levels are for 1 m (3.3 ft) above the ground.

The Montana standard does not apply to existing transmission lines. In that state 230-kV and 500-kV lines have operated for many years with edge-of-right-of-way field strengths greater than 1 kV/m. The Montana I-kV/m standard is based on a consultant's report (Sheppard 1983) that indicated considerable flexibility and uncertainty in attempting to define a single electric-field criterion. No limits on transmission-line magnetic fields were recommended by Sheppard (1983).

Ohio

In 1992, the Ohio Power Siting Board adopted prudent practice rules for transmission lines *(EMF Health & Safety Digest* April 1993). Among the rules for new lines were requirements that utilities provide information on levels of EMF, identify sensitive areas such as schools, and estimate the population exposed to proposed lines. A companion document to the rules defined prudent avoidance as "... appropriate efforts taken, to find ways of meeting the needs for new transmission capacity while limiting population exposure." The Ohio rules were influenced in part by a draft model state siting act developed by the Keystone Center that included a policy statement on EMF (see discussion below) *(EMF Health &Safety Digest* Nov.-Dee 1992).

Oregon

An administrative rule for transmission line electric fields was adopted in 1980 by the Oregon Energy Facilities Siting Council (OAR-80-055). The electric-field standard of 9 kV/m applies to areas that are accessible to the public. It is basically a safety standard to reduce risks of electrical shocks and burns. The standard applies to transmission lines of 230 kV or more, longer than 16 km (10 mi), and crossing more than one city or county in the state.

Oregon initiated a process in 1988 to review the adequacy of the electric-field standard and to consider the need for a magnetic-field standard. A committee of five scientists and engineers was assembled to review research and other issues involving EMF. The committee's report was completed in 1990 (Panel on 60-Hz Electric and Magnetic Fields 1990). The report did not result in actions by the state of Oregon to change the electric field standard, or to set a magnetic-field standard.

Because of public concern about EMF the Oregon Legislature passed a bill in 1991 that directed the Facility Siting Council to form another committee to review EMF issues. The committee recommended that monitoring of EMF issues should continue, and that low-cost ways to manage EMF exposures should be explored. The committee believed that it was premature to set health-based EMF limits (EMF Committee 1993).

New Jersey

The New Jersey Commission on Radiation Protection (1981) set an interim guideline of 3 kV/m for the electric field at the edge of transmission line rights-of-way as measured 1 m (3.3 ft) above ground. The Commission found that no verified incidents of adverse human health effects at electric field strengths at or below 3 kV/m. The level was also not expected to constitute an economic hardship for transmission-line constructors in New Jersey.

In 1993 new rulemaking efforts for EMF began in *New* Jersey ***(EMF Health & Safety Digest*** October 1993, June 1995). Several types of rules have been identified during the process; however, to date none have been adopted in New Jersey. Proposals included a magnetic-field limit in the 0.2-20 uT (2-200 mG) range, 50 percent reductions in magnetic field strength for new lines, keeping exposures as low as reasonably achievable, prohibitions against constructing recreational areas within rights-of-way, and placement of signs alerting people about EMF.

New York

The New York State Public Service Commission conducted extensive hearings from 1975 to 1977 on the potential health and environmental effects of proposed 765kV transmission lines (see a review by Scott-Walton et al. 1979). In the final decision, the New York Commission concluded that, "Although the record before us is, in many ways, reassuring-it does not show that the electric and magnetic fields of the lines as proposed will produce effects endangering human health and safety-it contains unrefuted references of possible risks that we cannot responsibly ignore" (SNYPSC 1978:39).

The Commission decided in 1978 to require that the width of rights-of-way for new 765-kV lines be set so that electric field strength at the right-of-way edge would not exceed that produced by existing 345-kV lines (about 1.6 kV/m). (In some other states, 765-kV lines operate with electric fields of 3-4 kV/m at the edge of the right-of-way.) Also, the New York Power Authority was ordered to fund a program of biological research on electric and magnetic fields.

The New York research program on electric and magnetic fields was completed in 1987 (Ahlbom et al. 1987). In evaluating this program, the New York Public Service Commission concluded that the program was not able to provide a definitive answer about potential health risks of transmission lines (Power Lines Evaluation Task Force 1988). The New York PUC also concluded that, even though magnetic fields have not been shown to be hazardous, an interim magnetic field standard was needed. In 1990 an interim magnetic-field limit for the edge of transmission-line rights-of-way was adopted by the New York PUC. The 20-uT (200-mG) limit was based on surveys of 345-kV transmission lines in the state, assuming winter normal conductor ratings.

Rhode Island

An EMF Task Force was established in Rhode Island in 1991 by an executive order from the governor ***(EMF Health & Safety Digest*** Jan. 1993). The Task Force contracted for a study of the cost-effectiveness of measures to reduce human exposures to EMF from transmission lines. The report focused on 115-kV and 345-kV lines, and on other conditions specific to Rhode Island (Commonwealth Associates, Inc. 1992). Several methods and their relative costs were described for reducing magnetic fields from overhead and underground transmission lines.

The Task Force submitted recommendations in 1992 that included a recommendation that the state Energy Facility Siting Board be assigned regulatory responsibility for transmission lines (EMF Task Force 1992). Legislation was subsequently passed that implemented this recommendation, and a recommendation to continue the operation of the Task Force ***(EMF Health & Safety Digest*** Jan. 1993). The 1992 Task Force report contained no recommendations for standards or guidelines for EMF.

Texas

In Texas, a committee charged with reviewing EMF research and issues recommended that neither the Texas Public Utility Commission (TPUC) nor other state agencies should set standards or guidelines for EMF (Electro-Magnetic Health Effects Committee 1992). The committee did recommend that the TPUC should continue its ***de facto*** policy of prudent avoidance in the siting of transmission lines.

The Lower Colorado River Authority (LCRA) adopted a policy on EMF in 1993 (LCRA 1993). When siting transmission facilities, wherever practicable, facilities are located in areas least affected by EMF exposures. LCRA also attempts to use reduced-EMF designs, and openly communicates about EMF with employees, customers, and the public.

Virginia

Joint Resolutions passed by the Virginia General Assembly in 1985 and in 1993 required annual reports on the status of research on EMF. The eleventh annual report concluded that based on the results of research on EMF through 199.5, it is not possible to state with any certainty whether there is a risk from EMF, or from living near transmission lines (Wasti 1996).

Washington

The 1989 Washington Legislature passed Senate Bill 5275 that directed the Washington State Institute for Public Policy to review studies on the possible health effects of EMF. The Institute's report found the studies on EMF to be inconclusive but cause for concern (Sykes and Li 1990). The report cited recommendations from the California Public Utility Commission that could serve as a reference for Washington (the California activities are reviewed above).

Another Senate Bill (6771) was passed in 1990. The Bill mandated the establishment of a task force to investigate techniques to limit EMF exposures from the distribution and transmission of electric power. The task force report, completed in 1992, described a variety of design and location alternatives to reduce human exposures to EMF (Electric Transmission Research Needs Task Force 1992). The report also recommended several topics for future research.

Wisconsin

The Wisconsin PUC (WPUC) began addressing EMF in its Advance Plans in 1989 (Wisconsin Electric Utilities' EMF Task Force 1994). Although the WPUC acknowledged that no health risks of EMF had been confirmed, because of public concerns utilities were directed to take several actions. These included providing public information and in-home EMF measurements, considering EMF exposures to the public when planning new transmission lines, and reporting on distribution designs that reduce EMF. One of the utility recommendations in 1994 for Advance Plan 7 stated that, "The utilities will include EMF as a factor to consider in siting and designing new facilities and will, wherever practical, make efforts to reduce exposure to magnetic fields" (Wisconsin Electric Utilities' EMF Task Force 1994).

Keystone Center

The Keystone Center is a national non-profit organization involved in public policy issues and in science education. In addition to the state activities summarized above, the Keystone Center used a structured process involving about 28 participants from across the U.S. to develop a draft model state siting act for transmission facilities (Keystone Dialogue Group 1992). Participants reached consensus that scientific concern about potential health effects of EMF was sufficient to warrant a pro-active approach to dealing with issues involving EME There was also consensus that efforts were needed to find ways of increasing transmission capacity without increasing population exposure to EMF.

The draft Keystone report contained a policy statement on EMF which included the suggestion that, "... until scientific findings are more conclusive, facilities should be designed and located using methods to mitigate, to the extent practicable, involuntary exposures to the public." There were specific requirements that applicants for new transmission lines should describe actions evaluated to minimize exposure of the public to EMF, and estimates should be made of changes in exposure that may occur for each transmission option considered.

Local Government Activities

A small number of cities and counties have adopted ordinances or have other taken other actions aimed at regulating transmission line EMF. In almost all of these cases the actions were taken in response to local controversies that developed over proposed transmission line construction projects. In a review of these local actions on EMF, McNeal (1995) argued that some of the actions provide local governments and planners with flexibility, while others compound an already confused issue. She suggested that policies that involved prudent EMF reduction approaches were preferable to setbacks, numerical standards, or siting restrictions.

A report by the American Planning Association suggested that planning departments consider the need for EMF regulations before proposals for new lines in their communities are made (Slesin et al. 1991). The report suggested that,

"Following the doctrine of prudent avoidance, all we can recommend at this time is that the regulation be sufficiently rigorous to allay public concerns while at the same time allow for the provision of electric power in an efficient manner."

The report suggested that communities require transmission line projects to have an EMF mitigation plan.

Ashland, Oregon

In 1991, the Ashland City Council adopted a resolution on the siting and construction of electrical facilities within the city (Resolution no. 91-15). The resolution acknowledged that biological effects of EMF may be correlated with potential health effects, that BPA had adopted interim guidelines on EMF, and that the city supports public disclosure of the potential health risks of EMF. The council adopted a policy of prudent avoidance which assumed that EMF may present a health risk.

The Ashland resolution called for city employees to be trained regarding avoidance of unnecessary exposure to EMF, and for public information and education about EMF. The city is also to develop data on EMF levels from distribution-line feeders. For new electrical facilities, affected citizens will be informed about projected EMF, The resolution also states that public exposure to EMF should not be increased where practical alternatives exist.

Bellevue, Washington

The utility section of a 20-year comprehensive plan adopted by the city of Bellevue in 1993 recommended that future utility development should seek "... a reasonable balance between potential health effects and the cost and impacts of mitigating those effects.. ." *(EMF Health & Safety* Digest Jan. 1994). The following were among the recommendations in the plan:

UT39: Require the undergrounding of all new electrical distribution and communication lines where it is reasonably feasible. Encourage the undergrounding of all existing electrical distribution and communication lines where it is reasonably feasible.

UT44: Avoid, when reasonably possible, locating overhead lines in greenbelt and open spaces as identified by the Parks, Recreation and Open Space Plan.

Ut 49: Encourage the undergrounding of existing distribution and communication lines, especially in residential areas, by facilitating the development of local improvement districts (UDs) or other means.

The Bellevue City Council decided not to include prudent avoidance language in the plan as had been recommended by a citizen's committee. The Council believed that to mandate prudent avoidance would be too limiting and specific for a long-range plan *(EMF Health & Safety* Digest Jan. 1994).

Brentwood, Tennessee

Ordinance 91-3, adopted by the city of Brentwood in 1991, established requirements for establishing design specifications for transmission lines in the city. The ordinance states that it is incumbent on the city to protect public health and safety, and that, "... a reasonable doubt exists as to potential long-term health effects produced by electromagnetic fields and emerging evidence does not allow for the categorical denial of risks."

The ordinance requires that transmission lines of 120 kV or larger, "... shall not allow spillage of the electromagnetic fields (EMFs) associated with such transmission lines in excess of 4 milligauss beyond the legal right-of-way boundaries ... ." Existing transmission lines in the city are to be brought into compliance within 5 years.

Camas, Washington

In 1995, the Camas City Council adopted an ordinance (No. 2030) on EMF that is based on prudent avoidance. The Council found that scientists could not establish or eliminate a link between EMF and health effects, and that EMF from transmission lines may constitute an involuntary risk to people on property abutting such lines. Prudent avoidance was defined in the ordinance as follows:

"... those practices and standards which serve to minimize exposure to electrical and magnetic fields, and include but are not limited to purchasing additional right-of-way, altering line configuration, selection of alternative routes, utilizing capacity in existing transmission facilities, underground, shielding, public education, research and testing, and discouraging siting near sensitive areas and structures."

The ordinance requires that new transmission lines be designed, built, and operated using prudent avoidance measures, and that,

"... applicants shall identify the 4 mG magnetic field line associated with the proposed installation. The mG contour shall be identified as the line coinciding with normal winter loading which shall be further defined as being 80% of the line's peak capacity."

New transmission lines are to be installed underground (except in certain industrial areas) unless the Council finds that exposure to EMF and impacts on land values and esthetics can be reasonably mitigated. All new distribution lines in residential areas are also to be placed underground.

When land is developed, the ordinance says that EMF exposures should be a consideration. It defines target levels to minimize exposure as not to exceed 0.4 uT (4 mG), and 1.6 kV/m. The ordinance also specifies setback distances from transmission lines for facilities where children assemble. These distances are the same as those defined by the California Department of Education (see above discussion of California activities). The ordinance further states that sensitive-use structures (e.g., homes, schools, hospitals) should be setback from transmission facilities, and that transmission lines should not be located in sensitive-use areas (e.g., parks, recreational areas) where practical alternatives exist.

Eugene, Oregon

The Eugene Water and Electric Board (EWEB) sponsored a study of planning issues involving EMF in the siting of electric power facilities (Banks 1996). The purpose of the study was, ". . . to create a framework for developing recommendations that use interagency collaboration, public participation and appropriate land use planning to site electric facilities and minimize EMF exposure."

The study concluded that EWEB should work more closely with the city of Eugene on EMF issues, and that EWEB should continue to apply prudent avoidance policies for EMF. The study recommended that EWEB should not apply EMF exposure standards at this time, but that additional prudent avoidance strategies should be investigated. Other recommendations called for EWEB to research the most effective means for educating the public about facility siting, and for soliciting public participation in the siting process.

Irvine, California

A zoning ordinance (90-23) passed by the city of Irvine in 1990 included restrictions on transmission-line EMF. Section 838.4, I-8 of the ordinance requires that,

"... the applicant shall indicate on the [tract] map [for Planning Area 381 the 4 milligauss magnetic fields contour line. No residential living area or child care building shall be developed between the Southern California Edison right-of-way and the magnetic field contour line."

The ordinance states that the magnetic field is to be based on the typical annual mean load on the transmission line, or the medium load if the annual mean is not available. Applications for permits for residential and child care uses must also include information on typical residential magnetic field exposures in Southern California. The ordinance makes provisions for changing the 4 mG contour level, or accepting alternate mitigation measures based on this information.

Sandy City, Utah

An ordinance (no. 96-9) passed by Sandy City Council in 1996 requires that new transmission lines in the city be placed underground. The ordinance also requires that transformers be grouped where possible, and screened with vegetation or by other appropriate methods. The removal of existing transmission facilities was not required. The Council concluded that, "Overhead power lines pose a health risk to the community, but the full scope of such risks cannot be accurately measured." The council also believed that power lines decrease property values and affect scenic values. The council said that these factors justify a prudent avoidance standard. Prudent avoidance was defined in much the same way as in the Camas, Washington ordinance described above.

A survey of residents in Sandy City found that a majority strongly favored requiring that new lines in the city be placed underground even if it costs considerably more money to do so. Most residents also seemed to be willing to pay some of the added costs.

Whatcom County Washington

Citizens concerned about a proposed 230-kV transmission line in Whatcom County petitioned to have residents vote on an initiative to restrict the construction of transmission lines in the county (Transmission/Distri*bution Health* h *Safety Report* Sept. 1990). The initiative passed, and the Whatcom County code was revised to limit the construction of transmission lines with voltages greater than 115 kV. The code section on conditional uses (20.82.020) under public utilities reads in part:

"Except on land where such permits have already been granted or in those districts classified as industrial, no conditional use permit shall be granted for electrical power transmission lines carrying more than 115,000 volts."

Wilmette, Illinois

In 1991 the town of Wilmette passed an ordinance that restricted 60-Hz magnetic fields to 0.2 uT (2 mG) at the property line of a remodeled Chicago Transit Authority station *(Transmission/Distribution Health & Safety Report* Jan. 1991). Later that year the town adopted a resolution of prudent avoidance which stated in part that,

"Government can educate the public concerning EMF issues, assist residents in identifying and controlling exposures within their homes, identify and reduce (in cooperation with Commonwealth Edison) any unusually high magnetic field levels caused by the electric power distribution system.. . ." *(TransmissiodDistribution Health & Safety Report* Oct. 1990).

International Activities

World Health Organization (WHO)

A committee formed in the early 1980s by the World Health Organization (WHO) to review electric-field studies concluded that, in terms of intermittent exposures, there was no need to limit access to areas where the electric field strength is less than 10 kV/m (WHO/IRPA 1984). As for long-term public exposures, the committee found no evidence for pathological effects resulting from field exposure. However, because of effects reported in some studies, they recommended that efforts be made to limit electric-field exposures to levels as low as can be reasonably achieved. The committee did not recommend any specific field-strength standard.

Another WHO committee conducted a review of research on magnetic fields. The review concluded that the epidemiological studies which had been done as of the mid-1980s raised important questions that should be addressed by future studies with adequate statistical power (WHO/IRPA 1987). The review also found that there was an urgent need for well-designed experimental laboratory studies on the carcinogenic effects of magnetic field exposure.

In June 1996 the WHO announced that it was beginning a 5-year international project to assess the health and environmental effects of DC, power frequency, and radio frequency EMF (EMF *NEWS* July 1, 1996). Information for the project will come from 23 countries and six international organizations. The project will produce four reports on EMF issues, and will encourage more focused research for developing better health risk assessments.

IRPA/INIRC, ICNIRP

An international organization formed in 1977 that worked in cooperation with WHO on nonionizing radiation was the International Non-ionizing Radiation Committee of the International Radiation Protection Association (IRPA/INIRC). The two WHO publications on electric and magnetic fields described in the above section above along with more recent reports, provided the scientific basis for interim guidelines on 50/60-Hz EMF developed in 1989 by the IRPA/INIRC. The guidelines were published in 1990 (Table 5.4).

In 1989 the Australian National Health and Medical Research Council adopted the IRPA/INIRC guidelines on EMF that are shown in Table 5.4 (Australian Radiation Laboratory 1989).

Table 5.4. IRPA/INIRC guidelines on limits of human exposure to 50/60-Hz EMF.
Source: IRPA/INIRC (1990), ICNIRP (1993). [a]

Exposure	Electric Field	Magnetic Field
Occupational:		
Whole working day	10 kV/m	0.5 mT (5 G)
Short-term [b]	30 kV/m	5.0 mT (50 G)
For limbs	—	25.0 mT (250 G)
General Public:		
Up to **24 h/day**	5 kV/m	0.1 mT (1 G)
A few hr/day	10 kV/m	1.0 mT (10 G)

a The International Non-Ionizing Radiation Committee of the International Radiation Protection Association (IRPA/INIRC), in 1992 became the International Commission on Non-Ionizing Radiation Protection (ICNIRP).

b For electric fields of IO-30 kV/m, field strength (kV/m) x hours of exposure should not exceed 80 for the whole working day. Whole-body exposure to magnetic fields up to 2 hours per day should not exceed 5.0 mT (50 G).

The limits in the IRPA/INIRC (1990) guidelines are based on levels of EMF that would induce body currents that are at or slightly above naturally occurring body currents (up to about 10 mA/m2). The following summaries were provided that related induced currents and reported biological effects:

- between 1 and 10 rnA/m2, minor biological effects have been reported;
- between 10 and 100 rnA/m2, there are well established effects, including visual and nervous system effects;
- between 100 and 1000 mA/m2, stimulation of excitable tissue is observed and there are possible health hazards;
- above 1000 mA/m2, extra systoles and ventricular fibrillation can occur (acute health hazards).

In 1992 the IRPA/INIRC became the International Commission on Non-Ionizing Radiation Protection (ICNIRP). At the first meeting of the ICNIRP in 1993, the members confirmed the guidelines published in 1990 by the former organization (ICNIRP Press Release, May 12, 1993). The ICNIRP (1993) found that,

"The most recent data reflect some improvements in methodology in laboratory studies and in epidemiological studies of both occupational and general populations. After careful consideration of this evidence, the

Commission concludes that the data related to cancer do not provide a basis for health risk assessment of human exposure to power frequency fields."

The IRPA/INIRC also worked with the International Labour Organization on a guide to protection of workers from power frequency EMF (IRPA/INIRC 1994). The guide described EMF research, and suggested ways that workers' exposure to EMF can be controlled.

European Committee for Electrotechnical Standardization (CENELEC)

In 1995, a prestandard on human exposure to low-frequency EMF (O-10 kHz) was published by the European Committee for Electrotechnical Standardization (CENELEC) (Table 5.5). It is intended to be applied on a provisional basis. A decision on whether it will be converted to a European standard will be made in 3 years after its publication. The prestandard is based on established short-term biological effects of EMF, including stimulation of electrically excitable cells and heating. CENELEC acknowledges that there are reports of possible long-term health effects from EMF levels lower than those in the prestandard. However, because adverse effects have not been established, the reports do not provide a basis for restricting exposure to EMF.

Table 5.5. CENELEC[a] prestandard on human exposure to low-frequency EMF (only 50/60 Hz shown). Source: CENELEC 1995.

Exposure	Reference Levelsb	
	Electric Field	Magnetic Field
Workers:		
50 Hz	30 kV/m[c]	1.6 mT[d] (16 G)
60 Hz	25 kV/m[c]	1.3 mT[e] (13 G)
General Public:		
50 Hz	10 kV/m	0.64 mT[f] (6.4 G)
60 Hz	10 kV/m	0.53 mT[g] (5.3 G)

a European Committee for Electrotechnical Standardization.

bThese ensure compliance with basic restrictions: induced current for workers= 10 mA/m*, contact current= 3.5 mA; induced current for public= 4 mA/m^2, contact current= 1.5 mA.

c These levels may be exceeded, subject to the time restriction given in the formula below, and to the basic restriction on induced current density, in situations where the field is predominantly perpendicular, rather than parallel, to the body. The limits to the total time, t, within any 8-hour period, that may be spent above a particular field level, E (in kV/m), subject to the maximum fields in the table is given by, $t < 80/E$.

d For limbs, 25 mT (250 G) is allowed for workers at 50 Hz.

e For limbs, 20.8 mT (208 G) is allowed for workers at 60 Hz.

f For limbs, 10 mT (100 G) is allowed for the public at 50 Hz.

g For limbs, 8.3 mT (83 G) is allowed for the public at 60 Hz.

Individual Countries

In addition to the international organizations summarized above, some countries have also adopted standards or guidelines, or have taken other actions involving power-frequency EME Many of these can be found in reviews by Polk and Postow (1996), and by Sahl and Murdock (1995). Because activities of various organizations in Sweden are often cited in discussions of EMF, a summary of developments involving EMF in that country is presented below.

Sweden

To date, Sweden has not established national health-based numerical standards for transmission line EMF. It appeared that Sweden would adopt such standards following research released by Feychting and Ahlbom (1992), that showed increased cancer risks in people living near Swedish transmission lines. At that time the Swedish National Electrical Safety Board (SNESB) issued a statement saying that, ". . . the Board in the future will act on the assumption that there is a connection between exposure to power frequency magnetic fields from power lines and childhood cancer, when preparing regulation on electrical installations " (SNESB 1992). The statement also said that the Board was initiating a review that could result in limits on magnetic fields in the range of 0.2-1.0 uT (2-10 mG).

In addition to the SNESB, other government agencies involved in decisions on EMF include the National Board of Occupational Safety and Health; National Board of Housing, Building and Planning; National Board of Health and Welfare; and the Radiation Protection Institute. After a review, in 1994 these agencies concluded that, ". . . knowledge regarding how weak magnetic fields affect humans is currently insufficient to set limits. Suspicion of a connection is however sufficient to recommend caution" (SNESB 1994). The Swedish agencies went on to conclude that the guidelines below should be followed if they can be implemented within reasonable costs:

- Strive to site power lines and electrical facilities in such a way that magnetic fields are reduced;
- Avoid building new homes, schools, daycare centers, etc. in close proximity to existing power lines which have significant magnetic fields, if alternative sites are available:
- Strive to limit significant fields in existing homes, schools and workplaces.

In a more recent publication for decision makers, the Swedish agencies responsible for EMF again rejected the need for limits or other compulsory restrictions on exposures to EMF (Swedish Agencies 1996). They also concluded, however, that a certain amount of caution may be justified with regard to magnetic field exposures.

Guidelines and standards have been developed in Sweden for EMF produced by computer monitors. These are equipment performance measures, not specifically health exposure limits. These measures have been developed by the Swedish Board for Technical Accreditation (SWEDAC, formerly MPR), and the Swedish Confederation of Professional Employees (TCO) (Table 5.6). The Swedish performance measures have been widely adopted by makers of computer monitors.

Table 5.6. Swedish performance levels for EMF (5 Hz–2 kHz) produced by computer monitors.
Sources: SWEDAC (1990), TCO (1991), Swedish Standards Institution (1995).

Organization	Electric Field	Magnetic Field
SWEDAC		
MPR II [a]	25 V/m	0.25 µT (2.5 mG)
MPR III [b c]	≤ 10 V/m	0.2 µT (2 mG)
TCO [b]	10 V/m	0.2 µT (2 mG)

a Measured 50 cm (20 in) in front of the screen.
b Measured 30 cm (12 in) in front of the screen.
c For performance level A (there are three levels, A-C).

In 1993, the Swedish Trade Union Confederation adopted a program of action involving magnetic fields in the workplace. A trade union goal was that workers' exposure does not exceed an average level of 0.2 uT (2 mG), and that temporary exposures to high magnetic fields be minimized as much as possible.

Field Effects: Special Cases

Cardiac Pacemakers

Under some circumstances, voltages and currents from such things as automobile ignition systems and household appliances can interfere with the operation of implanted cardiac pacemakers (Sowton 1982, Sager 1987). Instruction manuals accompanying pacemakers typically describe the precautions that should be taken by people who have these devices. We know of no published report of a case where a transmission line has harmed the wearer of a pacemaker.

Early pacemaker models that pulsed the heart at a preset rate (asynchronous type) were less likely to be influenced by electrical interference. The newer and more widely used pacemakers (synchronous) are normally in the off mode (inhibited), and send electrical pulses to the heart only when the normal heartbeat slows or stops. These pacemakers function by sensing the electrical activity (R-wave, see Fig. 4.11) produced when the heart beats. Electrical interference in some cases may mask the R-wave. If this occurs, R-wave inhibited pacemakers are designed to revert to pulsing in a regular (asynchronous) mode even though the heart may be functioning normally. Reversion is basically a safety feature. Cardiologists do not agree on whether prolonged operation in the asynchronous mode constitutes a health hazard (Bridges and Frazier 1979).

The sensitivity to electrical interference (e.g., voltage) depends not only on the pacemaker type but also on how it is implanted in the body. The pacemaker is placed beneath the skin and one or two wire leads are inserted through veins to the heart. Electrical current in the body causes a voltage difference between the leads of a pacemaker. Body current can be induced by electric and magnetic fields, or can enter directly through contact with electrical appliances (leakage current) or with charged objects near a transmission line.

Implants with bipolar leads (two wires) are unlikely to be affected by transmission line fields because leads are usually close together (resulting in a small voltage). Depending on the distance between the pacer unit and the single lead, some monopolar implants could revert to asynchronous operation when the wearer is on an EHV line right-of-way (Bridges and Frazier 1979). This would not apply to persons temporarily exposed while inside vehicles because the metal vehicle largely shields occupants from the electric field. It is unlikely the weak magnetic field from a 500-kV line would affect pacemaker operation.

The Florida Science Advisory Commission recommended that the U.S. Food and Drug Administration be urged to revise testing procedures so as to exclude pacemaker designs whose operation is affected by transmission line fields (FEMFSAC 1985: 180). The Commission estimated that, as of the mid-1980s only l-3 percent of the estimated 350,000 – 500,000 pacemaker patients in the U.S. may be at some risk from 60-Hz electric fields.

In a study in the U.K., 10 volunteer patients with a monopolar, multiprogrammable pacemaker (Medtronic 5985) were exposed to a 20-kV/m, 50-Hz electric field (Butrous et al. 1982). Body currents in the field were up to 0.3 mA, but the pacemakers did not revert to the asynchronous mode nor were any other effects found. The researchers expanded the study to include 35 patients and 16 pacemaker models representing 6 companies (Butrous et al. 1983a). Again, the Medtronic unit was not affected by fields to 20 kV/m. However, all the other makes exhibited some response to the field, with most responses occurring in fields of 5 kV/m or above.

Butrous et al. (1983b) also reported on two cases where pacemakers in electrical substation workers were affected by 50-Hz electric fields. In one case, a Telectronics 174 Programmable pacer reverted to the interference mode in a 2.5-kV/m field. In the other case, a Cordis 334 A pacer produced inappropriate pacing in fields above 13 kV/m. The problems were corrected by the use of a protective suit.

Researchers from the University of Rochester evaluated the performance of various pacemaker models in 11 volunteer patients while in a 345-kV substation (Moss and Carstensen 1985). The seven pacemaker models from four manufacturers were tested in electric fields ranging from 2 to 9 kV/m. The study found various alterations in pacemaker function in three models from two manufacturers (Cordis 190A, 190F and Cardiac Pacemakers, Inc. 0505). The alterations were detected by monitoring instruments. The patients, who were not life-dependent on their pacers, essentially reported no symptoms. However, the researchers pointed out that, for certain other pacemaker patients, the effects observed in the study could result in serious problems. They also indicated that because some models were not affected, it is possible for manufacturers to design pacemaker circuits to eliminate potential problems from 60-Hz interference.

Studies were conducted in Finland of 15 pacemaker patients with 12 different pacemaker models exposed to 50-Hz EMF under controlled conditions (Valjus 1996). For patients with bipolar implants and pacers set for normal sensitivity, no abnormal pacings were observed in electric fields of up to 8 kV/m and magnetic fields to 45-90 uT (0.45-0.90 G). Of the four subjects with bipolar implants and pacers set for high sensitivity, none experienced premature or inhibition of pacing in electric fields of 1.2-1.7 kV/m. In a strong electric field of 7-8 kV/m, one of the four subjects experienced an inhibition of pacing.

For subjects in the Finnish study with unipolar implants set for high sensitivity, the highest frequency of interference involved 9 out of 12 subjects who experienced premature pacing in the strong electric field. The lowest frequency of effects occurred with 1 of 15 unipolar implant patients (and regular pacer sensitivity) experiencing either premature or inhibited pacing in the moderate electric field. One of the unipolar patients with high sensitivity experienced abnormal pacing in the magnetic field. The researchers concluded that, “Tailoring the pacemaker features according to individual needs diminishes the necessity to restrict the patients’ activities in surroundings with elevated electromagnetic fields” (Valjus 1996:90).

As a precaution, persons with pacemakers who may have reason to be outdoors near high-voltage transmission lines should consult with a physician to determine whether their particular type of pacer may be susceptible to 60-Hz interference.

Flammable Materials

In designing an electric transmission system, one concern is the possibility that a spark discharge could ignite a flammable mixture, such as gasoline vapor. Theoretically, such an incident could occur if a vehicle were fueled under a transmission line. However, no case of a flammable mixture being ignited has been reported for a BPA transmission line. BPA sponsored a study to determine the conditions under which an ignition might occur (Engle 1982).

For gasoline vapor to ignite, it would require a voltage of l-2 kV between the fuel can and a large vehicle. To achieve these conditions, the vehicle would have to be well-insulated and, the pouring spout well-grounded, and a spark would have to occur where the fuel air mixture was close to optimal. The chances that all these conditions would be met is slight.

The distance between the transmission line conductors and highway and road surfaces normally is increased to provide adequate clearances for automobiles, buses, and trucks. This reduces the field strength at ground level and even further reduces the likelihood that an ignition could take place.

As a conservative precaution, vehicles should be at least 21 m (70 ft) from a transmission line when refueling. If a vehicle must be refueled closer, the operator should first connect the fuel can by a jumper wire to some metal on the vehicle (well away from the fuel inlet), *before* removing the vehicle’s fuel cap.

Blasting

This general discussion on blasting near transmission lines is taken verbatim from a recent report from the IEEE Subcommittee (1985:30).

"Explosives are frequently detonated by electric energy carried by long wires from a battery. There have been instances of premature detonation caused by radiated fields from nearby radio transmitters or microwave antennas. A number of devices and procedures can be used to prevent such a potentially catastrophic event. Typically these involve the use of a filter to block out radio-frequency energy. However, these filters will not block out power-frequency interference. Reduction of this interference is possible with shielded cables which lead to the blasting caps. Mitigation procedures with shielded cables must be carefully followed to be effective. Alternatively, nonelectric detonating devices exist which are not sensitive to transmission line fields."

BPA contracted for a study of the safety aspects of electrical blasting near high-voltage transmission lines (Bracken 1985). Several parameters that may constitute a "high level" of hazard were identified.

These were:

- Direct contact of the blasting wires (after detonation) with transmission line conductors.
- Current induction into the blasting wires from transmission line magnetic fields.
- Magnetic field induction caused by switch ing or other transmission line disturbances.
- Lightning within 16 km (10 mi) of electrical blasting circuits.

Blasting within 300 m (1000 ft) of a high-voltage transmission line should be confined to nonelectric systems. All blasting operations, regardless of location, should employ a qualified blaster who complies with all Federal, state, and local regulations.

Persons planning to detonate explosives near a BPA transmission line should notify the nearest BPA office well in advance. The layout of electrical circuits for blasting near the right-of-way should be cleared with that office.

Irrigation Equipment

Metal irrigation systems near transmission lines pose a potential shock hazard because they are large and at times they can become insulated from ground. However, with simple precautions, the hazards can be eliminated. These precautions are discussed in a report available from BPA (Nichols 1978). Great care should be exercised when handling lengths of metallic pipe near any overhead power line. The pipe should be kept in a horizontal position (Fig. 5.3). The big danger near any power line is the chance of electrocution if a person were to up-end a section of pipe into or near the conductors. Electricity from a 500-kV line can flashover l-2 m (3-7 ft) through air to a grounded object.

When moved manually, irrigation systems usually are laid on soil. This ground contact means that they present little or no shock hazard. To minimize the occurrence of nuisance shocks, or electrical contact with conductors, pipe should be unloaded from vehicles at least 15 m (50 ft) from the center of a transmission line.

In general, no equipment or vehicle should be higher than 4.3 m (14 ft) when directly under a BPA transmission line. This limitation can be exceeded in some cases. Persons who need specific information on safe working distances for a particular BPA transmission line should contact the nearest BPA office.

Mobile irrigation systems that move on wheels (such as the wheel-line and center pivot type) can develop voltages if well-insulated from ground and if parked parallel to a high-voltage transmission line. However, in realistic situations, it is difficult to get a high degree of insulation. The insulation is influenced by the type of

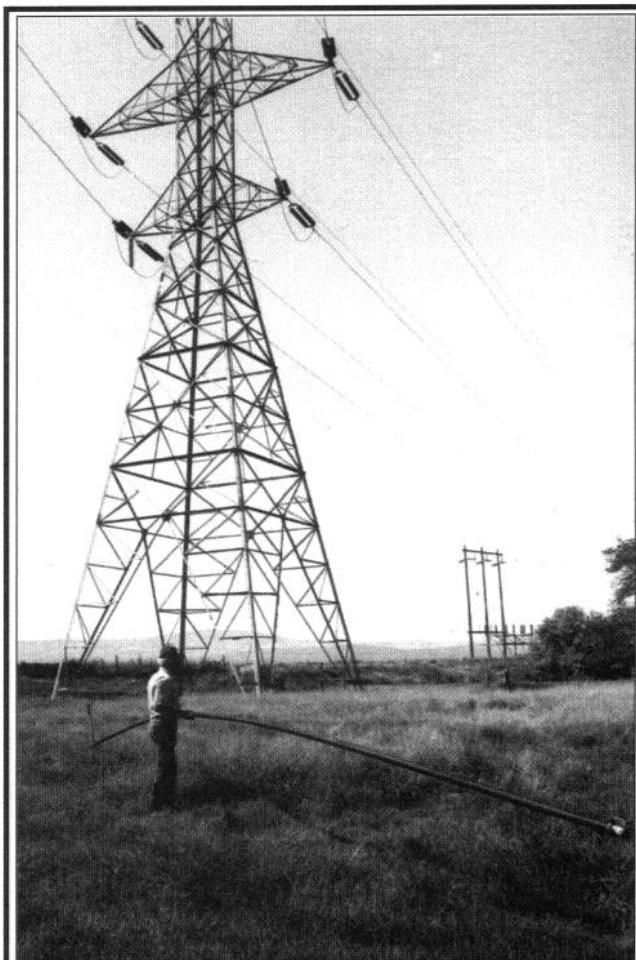

Figure 5.3. Irrigation pipe and other large objects should always be moved in a horizontal position when near an overhead power line.

wheels (metal or rubber), moisture conditions in the soil, and other contact points to ground, such as the central pivot point on a circular system.

All irrigation systems should be operated at distances sufficient to avoid direct contact between the water stream and conductors. A solid (continuous) stream of water should never be directed on or near the conductors. When contact between a well-broken water stream and transmission-line conductors cannot be avoided, the distance between the conductors and the irrigation nozzle should exceed the minimum distances listed in Table 5.7.

Table 5.7 gives suggested clearances between transmission-line conductors and solid-stream high-pressure irrigation nozzles. If the water stream is broken, there is actually a greater margin of safety if the distances in Table 5.7 are adhered to. Because of the small size of a Vermeer (impulse) system, no problems should occur due to induced voltages; however, extreme care should be taken in moving these systems to avoid tipping them into the conductors.

Fences and Metal Structures

In general, induced voltages on fences and structures can be reduced to safe, low levels by grounding at intervals and by using metal fence posts with proper bonding to the posts. For very long fences parallel to a transmission line, it may be necessary to break the electrical continuity. BPA routinely installs proper grounding for all fences and structures when new transmission lines are constructed. Persons who may have questions about grounding practices for objects close to BPA transmission lines should contact the nearest BPA office.

CORONA EFFECTS

Corona occurs in regions of high electric-field strength on conductors, insulators, and hardware when sufficient energy is imparted to charged particles to cause ionization (partial breakdown) of the air (Fig. 5.4). Corona may result in radio and television reception interference, audible noise, light, and production of small amount of oxidants (ozone and nitrous oxides). How-

Table 5.7. Suggested minimum electrical clearances from transmission lines for solid water streams. (Crest current= 2 mA, water resistivity= 11.7 ohm-m, water pressure= 80 psi.)

Nozzle Diameter cm (in)	Conductor-to-Nozzle Clearance m (ft)				Centerline of Power Line-to-Nozzle Clearance [a] m (ft)			
	115-kV line	230-kV line	345- kV line	500-kV line	115-kV line	230-kV line	345- kV line	500- kV line
1.9 (3/4)	12 (40)	14 (45)	17 (55)	18 (60)	17 (55)	23 (75)	27 (90)	32 (105)
2.2 (7/8)	17 (55)	18 (60)	18 (60)	20 (65)	21 (70)	27 (90)	29 (95)	34 (110)
2.5 (1)	18 (60)	20 (65)	20 (65)	21 (70)	23 (75)	29 (95)	31 (100)	35 (115)
2.9 (1 1/8)	21 (70)	23 (75)	24 (80)	26 (85)	26 (85)	32 (105)	35 (115)	40 (130)
3.5 (1 3/8)	24 (80)	27 (90)	29 (95)	31 (100)	29 (95)	37 (120)	40 (130)	44 (145)
4.1 (1 5/8)	27 (90)	29 (95)	31 (100)	34 (110)	32 (105)	38 (125)	41 (135)	47 (155)
4.9 (1 15/16)	35 (115)	37 (120)	40 (130)	43 (140)	40 (130)	46 (150)	50 (165)	56 (185)

[a] These values are based on phase-to-phase spacing of 4.6 m (15 ft) for 115 kV, 9.1 m (30 ft) for 230 kV, 10.7 m (35 ft) for 345 kV, and 13.7 m (45 ft) for 500 kV.

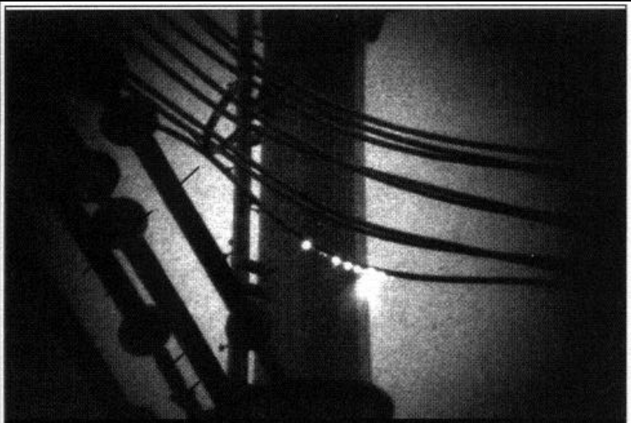

Figure 5.4. Corona visible on the conductors of a test transmission line as seen through a night vision device. Corona at times can be seen with the unaided eye on dark nights as a glow around transmission line conductors, mainly when they are wet. Corona causes audible and high-frequency noise.

ever, engineers can and do produce line designs that keep the generation of corona and its effects within limits generally acceptable to the public.

Another source of radio and television interference is arcing across small gaps in loose hardware (Loftness 1977). Arcing, which may occur at any voltage, will not be discussed here because it is not unique to high-voltage lines. It can be prevented by good design and proper maintenance.

At higher elevations, the breakdown strength of air is less than that at sea level, so the incidence of corona discharge increases. For all corona-generated noise, a BPA study confirmed that with each 300 m (1000 ft) increase in elevation, noise increases by about 1 dB (Chartier et el. 1987). To standardize reporting, all noise levels in this section are for a line located at sea level.

Corona is created during all types of weather, when air ionizes near isolated irregularities (e.g., nicks, scrapes, insects) on the conductor surface of operating transmission lines. Raindrops, fog, snowflakes, and condensation add to the isolated corona sources that exist in fair weather. Foul weather, therefore, causes a significant increase in corona activity on AC lines and the audible noise and radio noise produced by it. The noise is generally caused when drops of water form on the surface of the conductor.

Audible Noise

Description and Comparative Levels

Audible noise produced by transmission-line corona is a hissing, popping, or crackling sound. Near an AC line, a 120-Hz hum is occasionally superimposed. The sound level near a transmission line depends on the ambient noise level present, on the electric-field strength at the conductor surface (conductor geometry and operating voltage), and on the weather. Transmission-line audible noise is usually measured in decibels (dB) on what is called the "A Scale," which models how the human ear perceives sound. Figure 5.5 shows some typical sound levels in dB(A) for various environmental sources.

With the introduction of .500-kV transmission lines in the 1960s audible noise became an environmental concern. The first .500-kV lines constructed by BPA had one 6.4-cm (2.5-in) diameter conductor for each phase. Audible noise on the right-of-way averaged about 62 dB(A) during rain for these lines. Experience showed that, with average line noise of approximately 53- 59 dB(A) at the edge of the right-of-way, some complaints can be expected from persons living near the line. Numerous complaints can be expected when levels are above 59 dB(A) (Perry 1972). Because of problems with audible noise, BPA began using 500-kV designs with multiple subconductors per phase, which greatly reduced corona effects. Some of the older 500-kV lines with single conductors were reconductored to a newer design with three subconductors per phase (Yasuda and Dewey 1980).

Figure 5.6 shows calculated average audible noise levels during steady rain for typical 230-kV and 500-kV transmission lines. Transmission-line audible noise decreases at a rate of about 34 dB as distance from the line doubles. For example, 45 dB(A) at 30 m (100 ft) decreases to 41- 42 dB(A) at 61 m (200 ft). Trees, buildings, and other large objects near a line tend to reduce this sound further. It is estimated that a sound, as heard by the human ear, is cut in half with a 10 dB(A) decrease in the sound level.

The range of ambient (background) noise levels, and the variety of sources, is very large. In areas remote from human development, levels as low as 15-20 dB(A) may be measured. In urban areas, levels may reach 80-90 dB(A). High noise levels occur even in the natural environment; for example, waterfalls may produce levels of 85 dB(A) or higher (EPA 1974). During rain, ambient noise levels average 30-70 dB(A) in rural areas (Miller 1978).

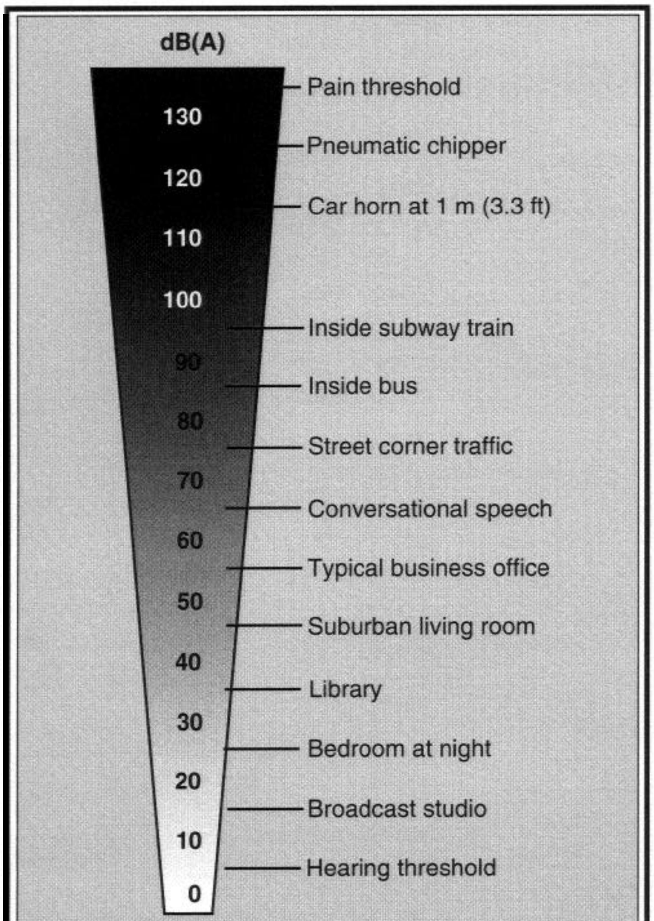

Figure 5.5. Some examples of common sound levels. The decibel levels (dB) are measured on the "A" scale, which models human hearing. Source: Comber et al. (1982).

Noise Standards

BPA's typical single-circuit 500-kV design using three subconductors per phase produces an average noise (L_{50}) of 49 $\pm$2 dB(A) at the edge of the right-of-way during rain. The A-weighted average sound level for 24 hours, with a 10 dB penalty for the time between 10 p.m. and 7 a.m., is termed L_{dn} (day-night). Assuming rain for 17 percent of the time (e.g., Western Oregon), noise from the latest BPA 500-kV design is around 49 L_{dn}. This is less than the 55 L_{dn} level, below which the EPA feels no effects on public health and welfare will occur (EPA 1974). BPA's 500-kV noise policy limits the L_{50} level during rain to 50 dB(A) or less, where a rain rate of 0.8-5.0 mm/hour (0.03-0.2 in/hr) occurs more than 1 percent of the time.

Three states within the BPA service area have noise standards that pertain to transmission lines. In Washington, transmission lines are Class C EDNA (Environmental Designation for Noise Abatement) noise sources. Applicable limitations are 60 dB(A) during day and 50 dB(A) at night for Class A EDNA receivers, which include residential areas (Washington Administrative Code Chap. 173-60). Oregon noise control regulations (OAR 340.35) limit noise to 50 dB(A) at night for noise-sensitive property such as residential areas. Montana requires that noise from transmission lines not exceed 50 L_{dn} at the edge of the right-of-way in residential and subdivided areas (ARM 36.7 3507). However, the affected landowner can waive this requirement. BPA works with state and local agencies to determine the compatibility of transmission line noise with current and planned noise regulations.

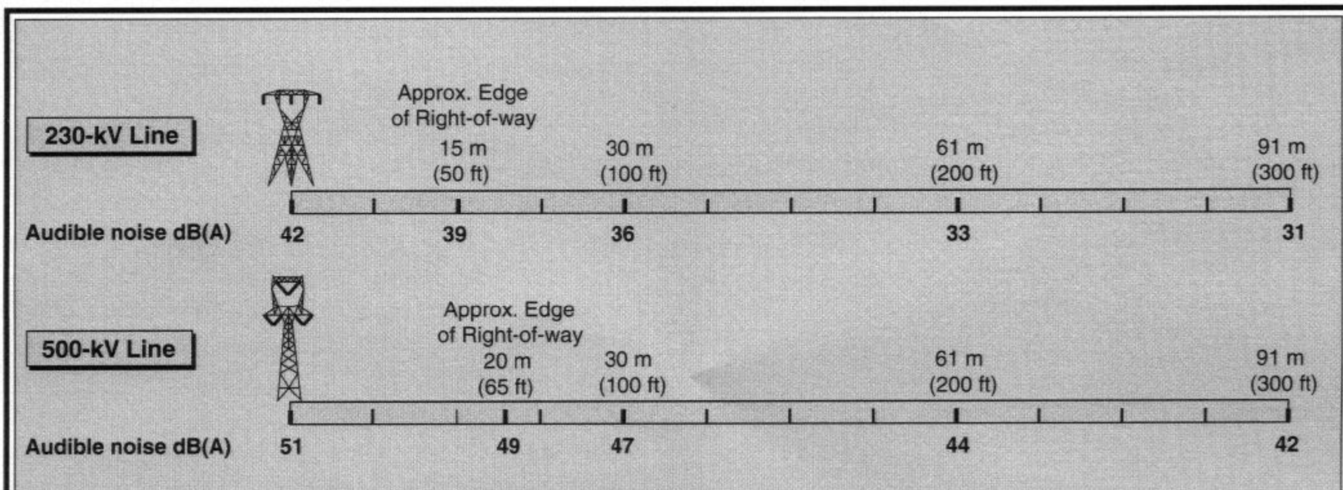

Figure 5.6. Typical audible noise levels during rain at various distances from BPA transmission lines as measured at 1 m (3.3 ft) above ground level. Actual noise levels depend on the line design. Fair weather noise levels are typically about 25 dB(A) lower than during rain.

Human Studies

Some laboratory research has been done to measure human response to transmission-line audible noise. Molino et al. (1979) studied people's reactions to maximum corona noise levels as found within a transmission-line right-of-way, i.e., 54-62 dB(A). The people tested found these noise levels as aversive as other environmental sounds (e.g., air conditioner, traffic) that were 3 dB(A) higher in noise level.

Pearsons et al. (1979), in a preliminary study, compared human response in a laboratory to corona noise of around 4.5 dB(A) with responses to other noises such as those from lawnmowers, dishwashers, and rain. This study also indicated that annoyance from corona noise is greater than annoyance from other noises of the same level. Corona noise needed to be 10 dB(A) lower to be judged as annoying as other environmental sounds. The higher annoyance properties of corona noise appear to be related to its high-frequency components.

A preliminary study involving reactions of residents to the noise produced by actual transmission lines was done in California. Fidel1 et al. (1979) interviewed 403 people living near 230-kV and 500-kV lines and transformer substations. Only 2 percent of the people spontaneously mentioned power lines or transformers as noises heard in their neighborhoods. Overall, transmission line noise did not interfere with listening to radio or TV, nor did it startle or frighten people or interfere with sleep. We are not aware of similar studies done in areas that experience heavy precipitation and, therefore, greater corona noise.

Wildlife Studies

During rainy weather, when corona noise is highest, domestic animals and many kinds of wildlife are often seen on or near 500-kV rights-of-way. Goodwin (1975) used track counts, direct observation, and time lapse photography to study the effects of a BPA 500-kV line in northern Idaho on migrating deer and elk. Portions of the line were constructed with a single conductor per phase. Goodwin found that line noise levels up to 68 dB(A)-the highest level he measured-did not deter elk, deer, and several other species from crossing or foraging on cleared rights-of-way in a manner consistent with their use of other forest clearings. Lee and Griffith (1978) also reported no effects of audible noise on wildlife inhabiting areas near a +-400-kV DC line and near SOO-kV AC lines.

Picton et al. (1985) found that a 500-kV double-circuit transmission line did not act as a barrier to elk using a high-elevation winter range in Montana. However, elk use of grassland habitat near the line appeared to be less than that in surrounding grassland. The effect was in part related to the transmission line access road and to towers, both of which removed some habitat. Audible noise from the line may also have contributed to the decreased habitat use. The L_{50} noise level on the right-of-way during precipitation was around 60 dB(A). Other factors also affected elk distribution, however, including weather, and cattle grazing near the line.

Two older reports (Klein 197 1, Villmo 1972) mentioned that, in Scandinavia, reindeer herders claimed that noise from power lines (no voltages or levels stated) adversely affected reindeer behavior and that the animals were reluctant to cross under newly constructed power lines. It is not clear, however, whether the cleared right-of-way or factors other than noise were responsible for the reported effects. Overall, it appears unlikely that BPA transmission line noise results in any significant effects to wild or domestic animals. (See discussions in: Lee and Griffith 1978, Dufour 1980.)

Radio and Television Interference

Corona also generates high-frequency noise called electromagnetic interference (EMI) which can disrupt radio and television reception in some cases. EM1 is the static sometimes heard over an automobile radio when driving beneath high-voltage transmission lines.

The same designs that have been used to decrease audible noise (e.g., multiple conductors) have also served to reduce EMI. Over 90 percent of the EM1 attributed to power lines is caused by arcing across gaps in hardware and can be corrected (Loftness et al. 1981).

Because BPA's high-voltage lines are designed for low audible noise levels, BPA does not design its transmission lines for a specific radio interference (RI) or television interference (TVI) level. In 1971, the IEEE Radio Noise Subcommittee published a Radio Noise Design Guide which, in essence, recommends a radio noise limit. Figure 4 of the document (reproduced here as Fig. 5.7) shows the range of operating conductor surface electric fields (gradients) and conductor size for single or bundle conductors for comparable noise levels. Industry experience has shown that lines that have been designed and built with conductor surface gradients that fall below the top curve in Figure 5.7 have successfully avoided both radio and audible noise and TVI. The conductor surface gradient on BPA's new generation of 500-kV lines falls well below this curve.

Foul-weather TVI due to corona is usually limited to occasional residences within about 183 m (600 ft) of a transmission line, where broadcast signals are weak. In outer fringe (weak signal) areas, interference may

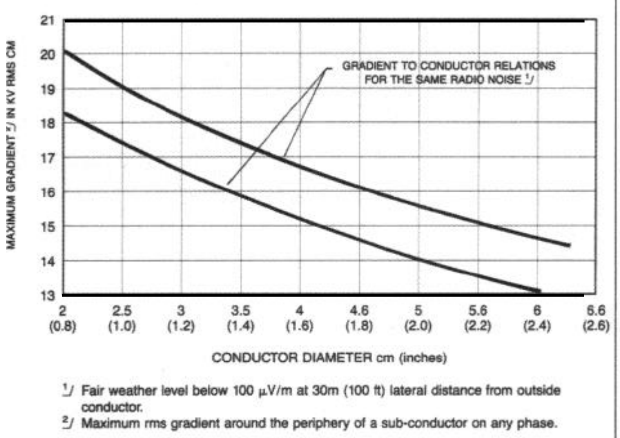

Figure 5.7. Ranges of operating gradient and sizes for single or bundle transmission line conductors for comparable noise levels.
Source: Adapted from IEEEE Radio Noise Subcommittee (1971).

occur in some cases at distances of 457 m (1500 ft) or more (Loftness 1977). In areas with strong broadcast signals, TV1 is usually not a problem, even when receiving antennas are at the edge of the right-of-way.

TV1 occurs most frequently in TV channels 2 to 6. The problem primarily involves the picture, which is amplitude modulated (AM), rather than the frequency modulated (FM) sound. FM reception is inherently more free from static. FM radio is also not usually affected by transmission-line corona, although RI can develop with AM radios (Loftness 1980).

Federal Communications Commission (FCC) regulations require that incidental radiation devices (such as transmission lines) be operated so that no harmful RI is produced. Further, FCC regulations require that the operators of these devices eliminate such interference (FCC Rules and Regulations, Part 15, Section 15.25).

BPA policy is to comply with FCC requirements and each complaint about EM1 is investigated. If a BPA transmission line is found to be the source of television interference with reasonably good reception, measures are taken to restore the picture to a quality as good or better than that before the interference. Depending on the individual situation, corrective measures may include one of the following (Loftness et al. 1981):

- Improving the receiving antenna system;
- Installing a remote antenna;
- Installing an antenna for TV stations not previously received but which are less sensitive to TVI;
- Connecting to an existing commercial TV cable system, or;
- Installing a translator station.

Correcting for residential AM radio interference usually involves installing a new antenna for the radio. Overall, BPA receives very few RI or TV1 complaints. Essentially, all legitimate complaints are satisfactorily corrected.

Although not a corona effect, magnetic fields from power lines and other electrical sources can cause interference patterns on computer monitor screens (Baishiki and Deno 1987, Baishiki et al. 1990). The interference causes oscillating or jittering patterns in text and graphics material that can be distracting to the user. The amount of interference depends on the frequency and level of the interfering magnetic flux density, and on the type and design of the monitor. Methods have been developed for reducing this kind of interference (Melik 1996).

Ozone

During corona, chemical reactions take place in the small volume of air immediately surrounding a conductor. These reactions include the production of small amounts of ozone (0,) and nitrous oxides (NO_x). This discussion will be confined to ozone, because the amount of nitrous oxides produced by transmission lines is considerably less than the amount of ozone and NO_x has not been an issue (Roach et al. 1974).

Ozone is a naturally occurring, though unstable, form of oxygen. Its peculiar odor can be detected in concentrations as low as 0.01 ppm (parts per million by volume) by persons with keen smell. Most people detect ozone at 0.02 ppm (Jaffe 1967). At such low levels, however, ozone odor detection diminishes rapidly and a person becomes unable to notice the ozone during a lengthy period of exposure.

Ozone occurs naturally in the atmosphere, diffusing slowly to sea level from the ozone layer 21- 26 km (13-16 mi) above the earth's surface. This layer is a major source of ozone. Another major source is the action of sunlight on nitrogen dioxide, an important component of automobile exhaust. An electrical discharge through oxygen can dissociate oxygen molecules into free oxygen; some of these molecules then recombine to form ozone. Lightning and electrical discharges from transmission lines, however, produce only minor amounts of ozone.

Average ozone concentrations usually reported for rural areas are between 0.01 and 0.03 ppm. In some rural areas, however, ozone concentrations exceeding 0.1 ppm have been measured (Coffey and Stasiuk 1975). Concentrations of 0.5 ppm occur in cities such as Los Angeles and reportedly stem from the action of sunlight on emissions from autos and industrial combustion. The national primary air quality standard for ozone is 0.12 ppm (EPA 1979).

When this review was first prepared in 1975, there was considerable interest about the amounts of ozone generated by transmission lines (e.g., Young 1974). Extensive research projects have been conducted since that time. They show that the amount of ozone produced by even the largest lines in operation (765 kV) is insignificant. (See reviews in: SNYPSC 1978, Scott-Walton et al. 1979, Janes 1980.) BPA monitored ozone levels near a 1200-kV prototype line for 2 years and found no increase in ambient ozone levels due to the line (Bracken and Gabriel 1981).

Calculations of ozone production from transmission lines show why such production is generally not measurable. For example, with a rain rate of 2.5 mm (0.1 in) per hour and no wind, a double-circuit 500-kV line would increase ambient ozone concentrations at ground level by no more than 0.00135 ppm. This assumes that the line is on terrain that is at 12 19 m (4000 ft) elevation. At 1830 m (6000 ft) elevation, ozone production would be about l-1/2 times this level. At lower elevations it would be proportionately less.

Ozone concentrations produced by transmission lines appear to be too low to have any significant effects on humans, animals, or plants.

Medical Applications of EMF

Most of the research described in this book was designed to provide data for helping assess the potential hazardous effects of power-frequency EMF. There is also a large body of research and extensive clinical experience on uses of many types of electric and magnetic fields for beneficial purposes (Marino 1988; Becker 1990; Bassett 1993, 1994, 1995; Rubik et al. 1994).

The possible medical applications of nonthermal, nonionizing electric and magnetic fields can be grouped into eight categories as follows (Rubik et al. 1994):

- bone repair,
- nerve stimulation
- wound healing,
- treatment of osteoarthritis,
- electroacupuncture,
- tissue regeneration,
- immune system stimulation,
- neuroendocrine modulations.

The most well-known use of EMF for healing is the use of pulsed electromagnetic magnetic fields (PEMF) for stimulating bone growth in fractures that are slow to heal. (See Fig. 1.5 for a comparison of pulsed and other waveforms.) These types of fractures are often treated surgically with bone grafts or with metal support implants. In the U.S. about 20 percent of the 100,000 slow-healing fracture unions each year are treated with PEMF (Bassett 1995). This method has been in use since the early 1970s and several devices that produce PEMF used in these applications are approved by the U.S. Food and Drug Administration (FDA) (Polk 1996). However, Rubik et al. (1994) pointed out that many such devices sold before the passage of the Medical Device Law in the late 1970s were "grandfathered" by the FDA (they automatically received FDA approval). The safety and effectiveness of devices in this category were not established by the FDA as is done for newer products.

Pulsed magnetic fields were first used in fracture repair applications because they induced electric fields that were similar to natural fields produced through transduction of mechanical to electrical energy (Bassett 1994). The PEMF used in current-day applications, however, are less similar to electrical signals produced by mechanical stress (Polk 1996). For example, the PEMF in some devices consists of 72 pulses per second; the magnetic field for each pulse changes from 0 to 3.5 mT (35 G) in 380 ps, and decreases back to 0 in 4.5 ms. The fields are generated from coils placed around the fracture site, and pulses can be delivered automatically by small-battery operated units. DC currents are also used in fracture repair applications by injecting currents from electrodes attached to the fracture site.

In addition to bone, the ability of EMF to aid healing of soft tissue (skin, nerve, and tendon) has been studied in animals and experimentally in humans (Sisken and Walker 1995). These studies also indicate that effects are specific, and depend on the nature of the EMF signal. There is more controversy about whether EMF are effective in soft tissue healing, and there are no devices approved by FDA for this purpose except for experimental uses (Polk 1996).

Both DC and radio-frequency fields are used in combination in magnetic resonance imaging devices that are used to provide high resolution diagnostic scans of the body (WHO/IRPA 1987) (Fig. 5.8). The DC fields used in these devices range in strength up to 1 T (10,000 G) or more.

The use of EMF for beneficial medical applications is counter to the orientation of most of the research on EMF that is directed at hazard evaluation (Becker 1990). In dealing with this issue, Bassett (1994) stressed that the biological effects of EMF are specific and depend on the nature of the EMF signal. He argued that it is not appropriate to lump all types of EMF together in terms of their effects, just as it is not appropriate to lump all drugs together. As an example, although pulsed magnetic fields can increase fracture healing, two studies discussed in Chapter 4 found that 60-Hz electric fields slowed fracture healing (Marino et al. 1979, McClanahan and Phillips 1983).

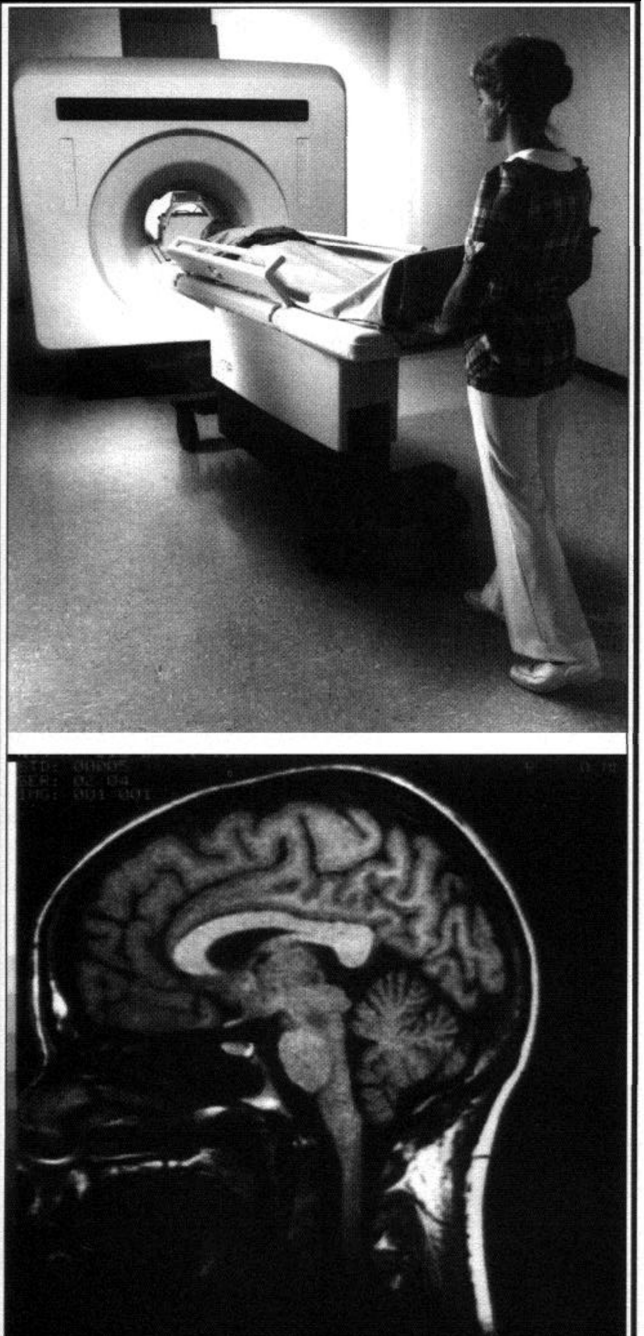

Figure 5.8. A combination of DC and radio-frequency AC magnetic fields are used in magnetic resonance imaging devices. These devices produce high-resolution pictures of internal body parts Source: General Electric Co.

Overall, the research and use of EMF in medical applications provides further evidence that such fields can produce biological effects, and the effects can be either adverse or beneficial. Pilla and Markov (1994) pointed out, however, that PEMF used in medical applications produce significantly larger induced electric fields than environmental EMF.

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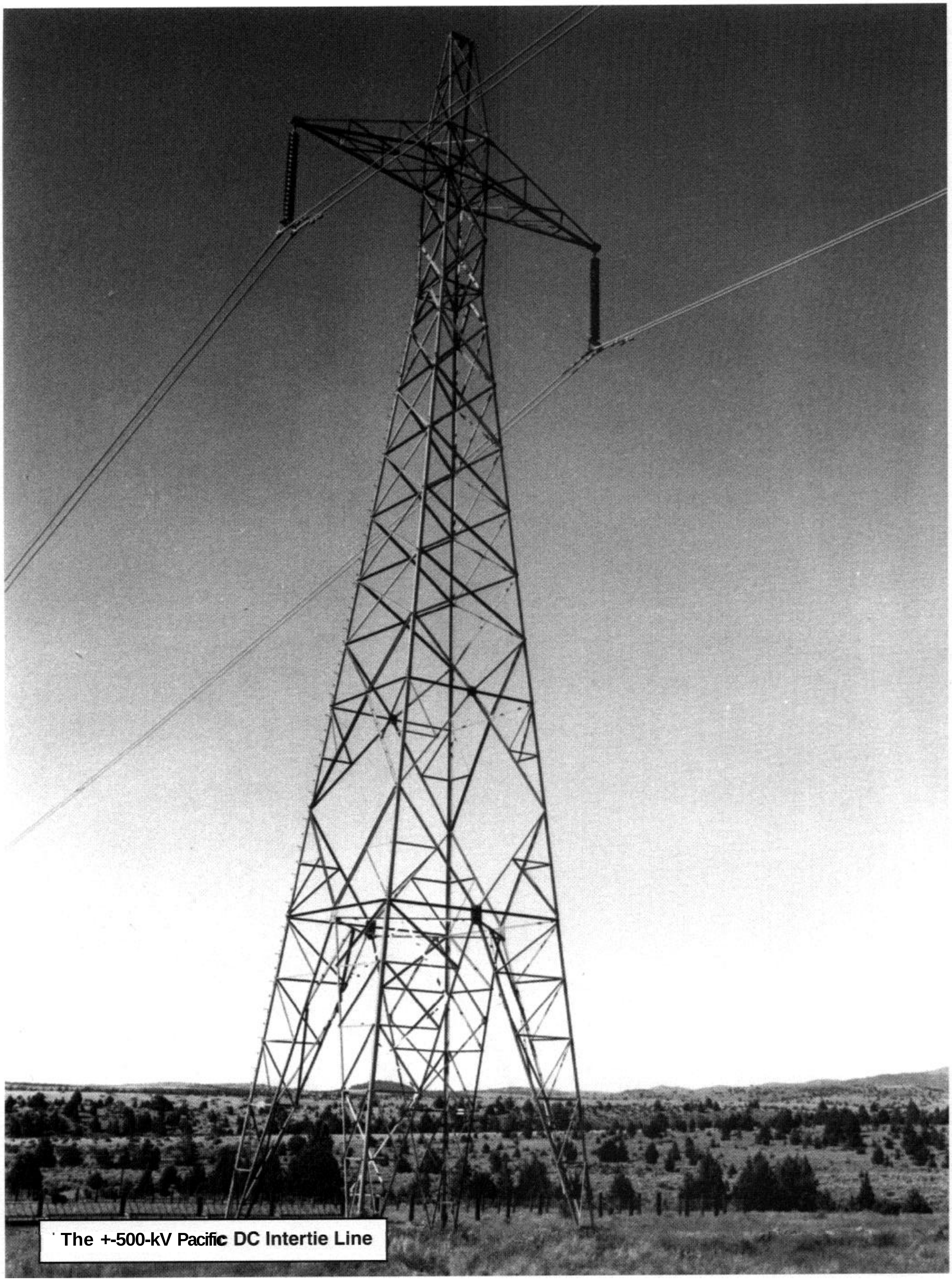
PART 2

Direct-Current (DC) Transmission



The +-500-kV Pacific DC Intertie Line

Chapter 6

Direct-Current (DC) Transmission: Effects of EMF, Air Ions, and Corona

Summary

◆ DC transmission lines can have advantages over AC lines when large amounts of power need to be transmitted over very long distances. However, the costs for terminal stations used for converting between AC and DC are very high. There are only seven DC transmission lines in North America. DC links are also sometimes used in substations to tie adjacent AC electric power systems together.

- Compared to AC transmission lines, the electrical environment of a DC line is more complex and variable. Some of the air ions produced by corona on the positive and negative conductors of a DC line are carried away from the line by wind. The ions form a space charge that adds to the electric field produced by voltage on the conductors. Although the electric fields from DC lines are numerically much larger than from AC lines, DC electrical effects are typically less than for AC.
- Magnetic fields from a DC transmission line add to or subtract from the earth's DC field, depending on the orientation of the line and on the direction of current flow on the line. The fields from a DC line do not induce currents in objects, unless the object is moving or the field is being turned on or off.
- Compared to AC, relatively few studies have been done specifically to assess the possible health and environmental effects of EMF from DC transmission lines. A primary issue with DC lines is the possible biological effects of air ions. Scientific reviews of air ion research typically conclude that adverse human health effects have not been conclusively established.
- As with AC lines, corona on DC transmission lines produces audible noise, small amounts of ozone, and radio and television reception interference. While corona on AC lines is usually highest during precipitation, for DC lines corona is generally highest during fair weather.

Introduction

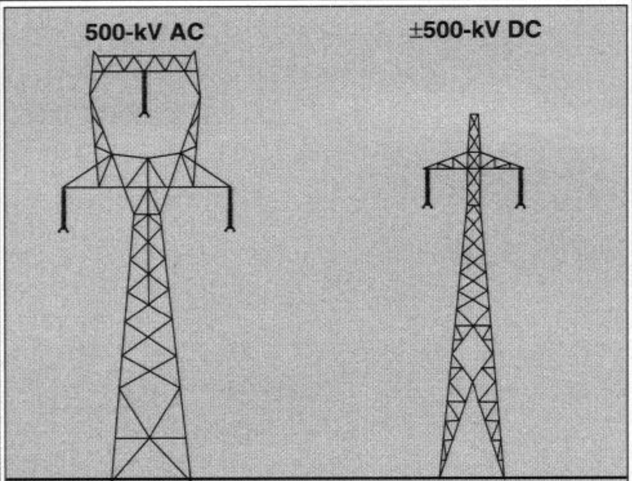
In 1882, the first commercial electrical distribution system developed in the U.S. by Thomas Edison was a DC (direct-current) system. The use of DC, however, was limited to short distances because it was difficult to convert between high transmission and low distribution voltages. With the development of AC (alternating-current) generators, transformers, and other equipment, AC became established by the early 1900s as the dominant technology for both distribution and transmission.

Engineers knew that DC had advantages over AC for some applications, and research continued on ways to improve DC technology. In the 1930s equipment was developed for economically converting between high-voltage AC and DC. A 30-kV, 27-km (17-mi) DC line was constructed in New York in 1936 (Hingorani 1978). The first EHV DC line in the United States was energized in 1970 between The Dalles. Oregon. and Los Angeles, California.

The voltage for a DC line is usuallv referenced as ± indicating the voltage from each of teh two poles (conductors) to ground. However, a DC line can also be referenced by the voltage difference between the positive and negative poles. For instance, a ±500-kV DC line can also be called a 1000-kV DC line. Similarly. a ±400-kV line is the same as an 800-kV DC line.

Advantages of DC electric-power transmission include lower power losses because the current is not continuously reversing direction as in an AC system. (On an AC system this is called reactive power loss.) DC transmission lines are also less expensive to build. A bipolar DC line needs only two sets of conductors (compared to three for an AC line), requires smaller towers and fewer insulators, and might require a narrower right-of-way than an equivalent AC line. Figure 6.1 compares a 500-kV AC transmission line with a ± 500-kV DC line.

Although DC lines may be economical, the extensive facilities on each end of a DC line needed to convert between high power AC and DC is very expensive.



500-kV AC		±500-kV DC
41.1 m (135 ft)	**Average Height**	35 m (115 ft)
351 m (1150 ft)	**Average Span**	351 m (1150 ft)
46 m (150 ft)	**Right-of-Way**	46 m (150 ft)
2600 MW[a]	**Power Capacity**	3100 MW[b]

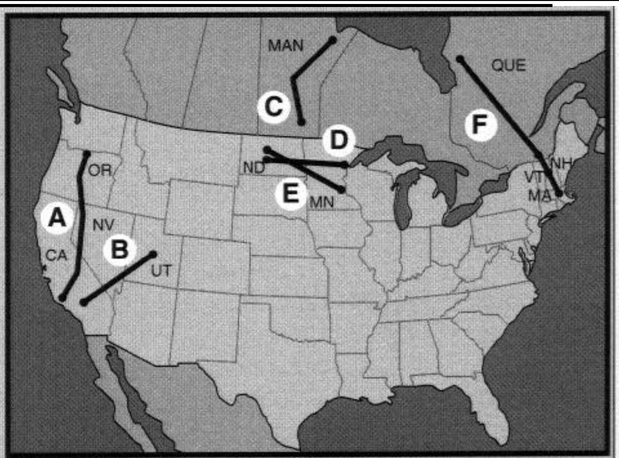
a The AC Intertie line could carry about 3900 MW if the two subconductors per phase were changed to larger-diameter subconductors, three per phase.
b The DC Intertie line with the two subconductors could carry about 4000 MW if the terminal station capacity were expanded.

Figure 6.1. A comparison of typical structures used for the 500-kV AC Intertie transmission lines, and typical structures used on the ±500-kV DC Intertie line. Newer BPA 500-kV AC lines have smaller towers (see Fig. 1.3).

Therefore, HVDC (high-voltage direct-current) transmission lines are usually practical only when large blocks of power are to be transmitted over long distances, with no need to tap power off along the way. (DC links that involve no transmission lines are also sometimes used in substations to interconnect adjacent AC power systems.) These are exactly the conditions in the Western U.S. that led to the constrnction of the first commercial +-400-kV DC transmission line in North America.

The Celilo-Sylmar DC line, energized in 1970, transmits surplus electrical power 1361 km (846 mi) from the Pacific Northwest to the Pacific Southwest. The Pacific DC Intertie, as the line is also called, operated at +-400 kV until 198.5, when the voltage was upgraded to +-500 kV (Lee and Burns 1987, Chartier et al. 1989). This increased the power capacity of the line to 2000 MW. In 1989, the current-carrying capacity of the line was increased and the power capacity then increased to 3 100 MW.

There are seven DC overhead transmission lines operating in North America (Fig. 6.2). In other countries, there are about nine overhead DC transmission lines of 400 kV or larger (Piwko 1994). The highest voltage commercial DC line operates at +-600 kV in Brazil. Research was done in Massachusetts (Johnson 1984) and in Montreal, Canada, (Maruvada et al. 1981) on DC transmission lines of over +-1000 kV. BPA investigated the possible use of 500-kV AC/DC hybrid lines (Chartier et al. 1981).



Map	Name	Voltage
A.	Pacific Intertie	+-500 kV
B.	Intermountain	± 500 kV
c.	Nelson River I Nelson River II	± 463 kV ± 500 kV
D.	Square Butte	± 250 kV
E.	CU (Cooperative Power Assoc., United Power Assoc.)	± 400 kV
F.	Quebec-New England I & II	± 450 kV

Figure 6.2. Overhead DC transmission lines in North America.

Since 1963, BPA has periodically operated a HVDC test facility at The Dalles, Oregon. From 1984 to 1987, BPA engineers also conducted long-term monitoring of the electrical performance of the Pacific Intertie line before and after it was upgraded to +-500 kV (Chartier et al. 1989). This research, coupled with many years of operational experience with the Pacific DC Intertie, provides the basis for much of the discussion in this section. BPA experience is based on a DC line in the semi-arid climate of Central Oregon. There may be variations in the magnitudes of effects in more humid climates. However, the basic principles of DC transmission phenomena are the same in both cases.

This chapter provides only a summary of information on DC transmission lines. More details of the technical characteristics of DC transmission can be found in publications by Hill et al. (1977), Bracken (1979), Johnson (1982, 1984), Piwko et al. (1994), and by Litzenberger and Varma (1996).

The Electrical Environment of DC Transmission Lines

Like AC transmission lines DC lines produce EMF and corona. However, there are major differences between the electrical environments of the two types of lines. The EMF from DC lines are static like the fields produced by the earth and by batteries. Like a battery, the two conductors on a bipolar DC line are negative and positive. The conductors on an AC line are continuously changing between positive and negative (120 times a second for a 60-Hz line). DC lines are also able to operate with one conductor (either positive or negative) in what is called monopolar operation. In this case, the earth supplies the return current path.

With AC lines air ions produced by corona tend to stay close to the conductor because they are alternately attracted and repelled as voltage on the conductor alternates between positive and negative. The air ions produced by corona on DC conductors that are of the same polarity as the conductor are repelled away from the conductor (Fig. 6.3). Some of these ions move away from the DC line and form a "space charge" that enhances the DC electric field produced by voltage on conductors.

At least six measures can be used to describe the electrical environment of a DC transmission line:

- ion current density (i) in A/m2;
- ion concentration (space charge density) (p) in C/m3;

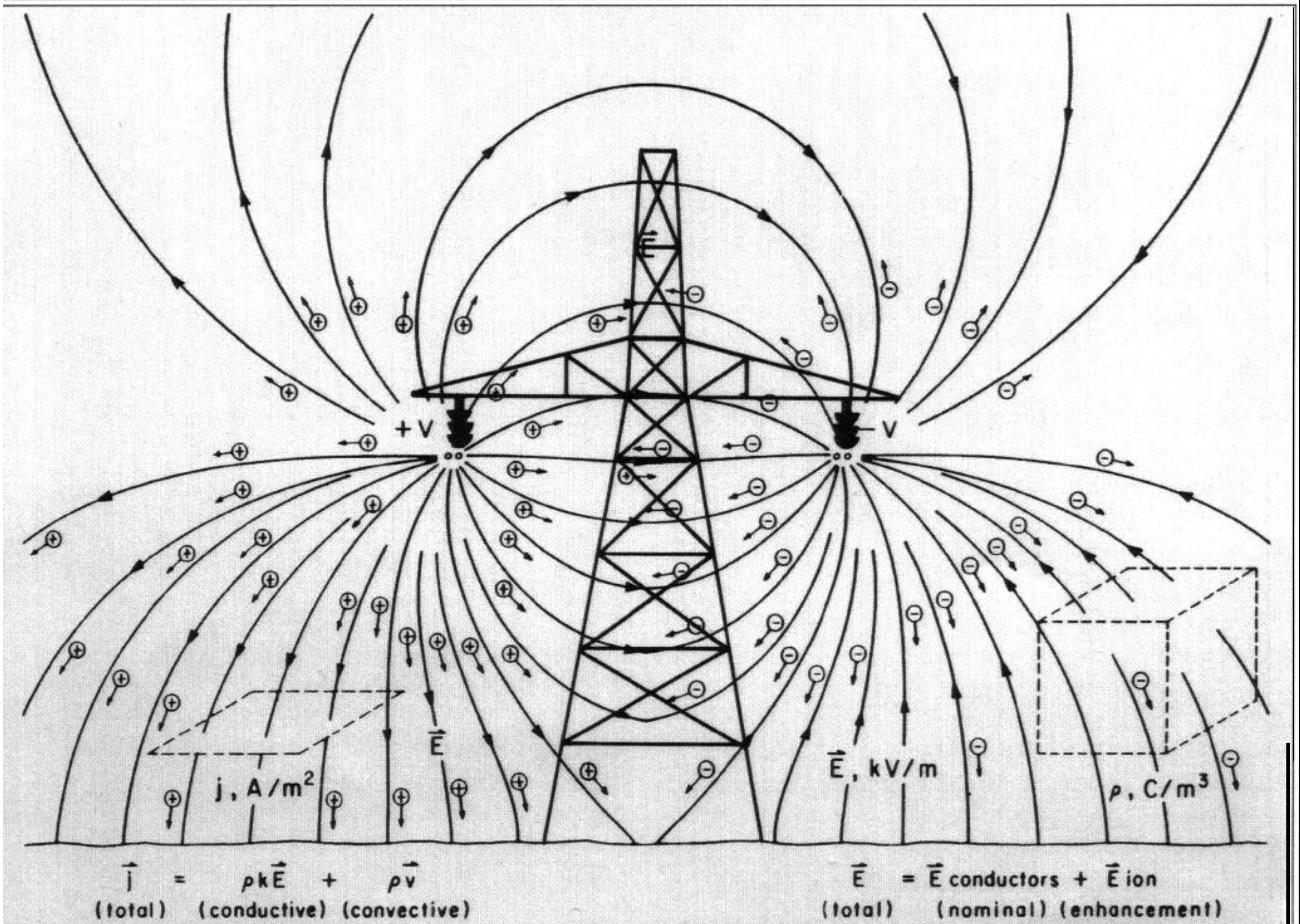


Figure 6.3. Diagrammatic depiction of the air ion and electric field environment of a DC transmission line. Source: Bracken (1979).

- electric fields (E) in kV/m produced by voltage on the conductors (nominal) and the space charge (enhanced);
- a static magnetic field (B) produced by current carried by conductors;
- small AC fields caused by the AC/DC conversion process;
- corona effects (high frequency and audible noise, ozone, light).

This complex DC electrical environment is further explained in the sections below.

Air Ions and DC Fields

Air ions are natural components of the atmosphere. They are basically molecules with either extra electrons (negative ion) or with missing electrons (positive ion) and are formed through collisions among particles. Air ions are produced by such things as storms, sunlight, waterfalls, radioactive materials, corona, cosmic rays, and blowing dust. Some highly charged windstorms, such as the Santa Ana of California, occur regularly.

Clean rural air typically contains around 500-2000 small positive ions/cm3 and a slightly smaller number of negative ions (Kotaka 1978). Polluted city air contains depleted levels of small air ions but high levels of large air ions (aerosols). Near waterfalls, negative air ion concentrations of 35,000 ions/cm3 have been measured (Krueger 1980). Johnson (1982) reported that air ion concentrations in a residential room rose from 800 ions/cm3 to 27,600 ions/cm3 when nine candles were lit.

It is important to keep in mind that air ions occur in extremely small concentrations. For example, Krueger (1980) estimated that, in rural air, there may be only one air ion for every 10 quadrillion uncharged air molecules. Some scientists have questioned how air ions could have significant biological effects if they occur in such minute concentrations.

When an AC line is in corona, air ions formed in the process are alternately repelled and attracted, as voltage polarity changes on the conductors at 60 Hz. Therefore, there is little movement of these ions away from an AC conductor. However, voltage polarity (positive or negative) is constant on a DC line conductor. Also, HVDC lines are typically in constant corona. During corona, ions move away from the conductor of like polarity and are attracted to the conductor of opposite polarity (e.g., positive ions are repelled by the positive conductor and attracted to the negative conductor). Some of the corona-generated ions do not reach the oppositely charged conductor. Instead, they drift away from the DC line and enhance the ambient air ion concentrations (Bracken 1979).

Thus, the electrical environment of a DC line is more complex and variable than that of an the AC line. Likewise, techniques for measuring and calculating HVDC transmission electrical parameters are complex because of effects of air ions. Ion concentrations constitute a "space charge" that contributes to the electric field from a DC line.

Negative ions do recombine with positive ions but, overall, DC conductors in corona create ion currents and space charge of like polarity near each conductor. At ground level, space charge enhances the electric field above the nominal electric field due to voltage on the conductors.

An electric field profile for a DC transmission line is shown in Figure 6.4. Space charge contributes significantly to the total electric field near a DC line. This enhancement represents a near maximum value, and occurs only under relatively calm conditions. This total electric field due to space charge is highly variable be-

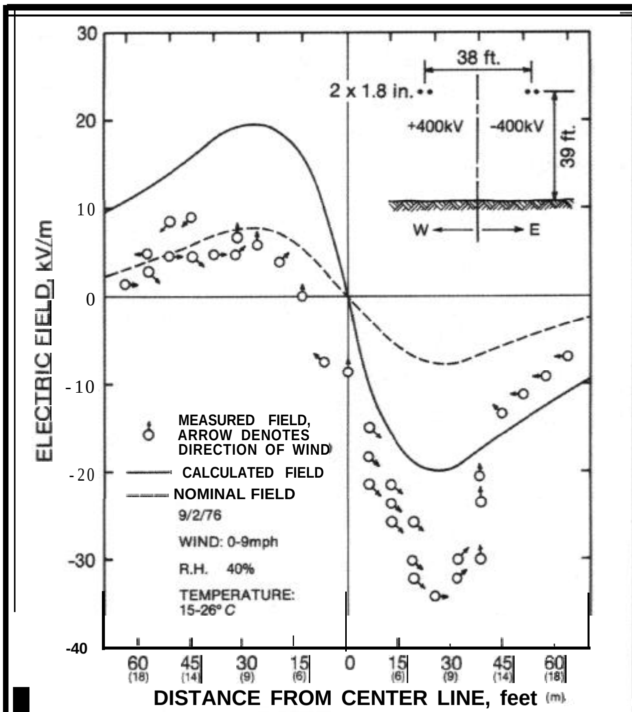


Figure 6.4. Calculated total electric field (due to voltage on conductors and ion space charge) and nominal field (due to voltage only) near ground for a ± 400-kV DC transmission line. Field measurements made on one day show how movement of ions by wind greatly influences the electric field.
Source: Bracken et al. (1978).

cause wind disperses the ions and the total field fluctuates between the maximum and the nominal value. Momentary readings above the calculated maximum are, therefore, not surprising, in view of the significant dependence of ion movement on wind.

Early research with DC lines involved electrical measurements on and near the right-of-way where small air ions are thought to predominate, Ions can also attach to water and dust particles to form charged aerosols. The aerosols can be carried away from a DC line by wind for considerable distances. A study in Minnesota found that charged aerosols (and small air ions) were still measurable above ambient at distances of at least 1.6 km (1 mi) downwind from a +-400-kV DC transmission line (Hendrickson 1985). Measurements of off-right-of-way aerosol concentrations have also been made at the High Voltage Transmission Research Facility in Massachusetts (Johnson 1984).

In 1984, BPA initiated a project to obtain more information about the electrical environment on and off the right-of-way of the DC Intertie (Char-tier et al. 1989). The study, in Central Oregon, included long-term monitoring of electric field and ion levels out to 610 m (2000 ft) from the DC line (Fig. 6.5).

A summary of electric field measurements from the BPA study of the +-500 kV DC Intertie line in Central Oregon is presented in Figure 6.6. Electric-field and air-ion levels varied greatly depending on weather conditions. For all weather conditions combined, the mean positive ion concentration was 29.7 kions/cm^3 and for negative ions it was 33.4 kions/cm3. During rain these levels increased to 24.1 kions/cm3, and -55.9 kions/cm3, respectively. Both electric field and ion levels were found to be 2-3 times higher on the negative side of the line than on the positive side. Previous studies of DC test lines (which carried no current) did not show this imbalance. As expected, average levels were higher dnring foul weather than during fair weather. DC electric

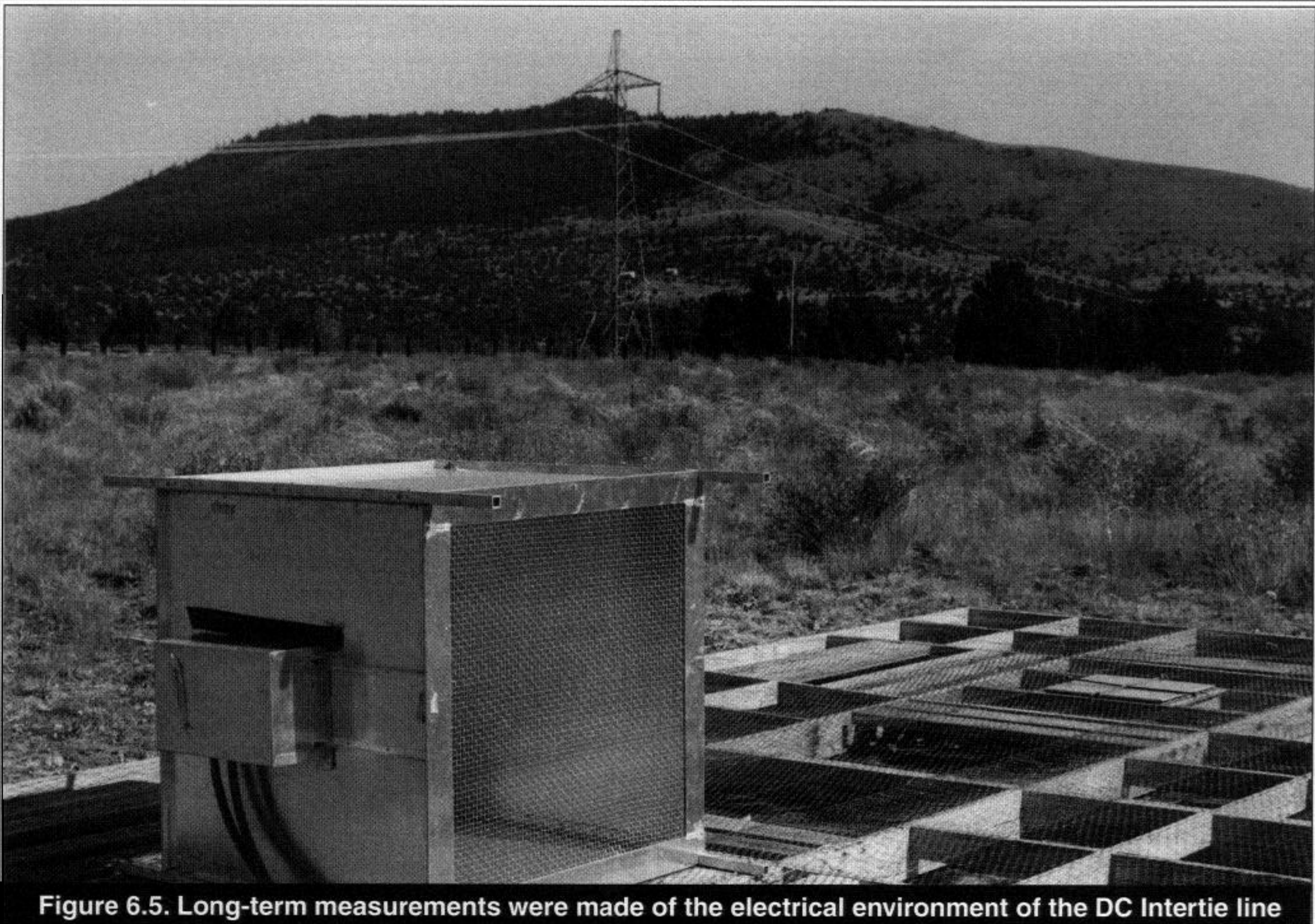


Figure 6.5. Long-term measurements were made of the electrical environment of the DC Intertie line near Grizzly Mt. in Central Oregon. The box-like device is a space charge cage used to measure air ions and charged aerosols at distances out to 610 m (2000 ft) from the line. A 1 m (3.3 ft) square Wilson plate used to measure the DC electric field is located in the wood framework to the right of the cage. Source: Chartier et al. (1989).

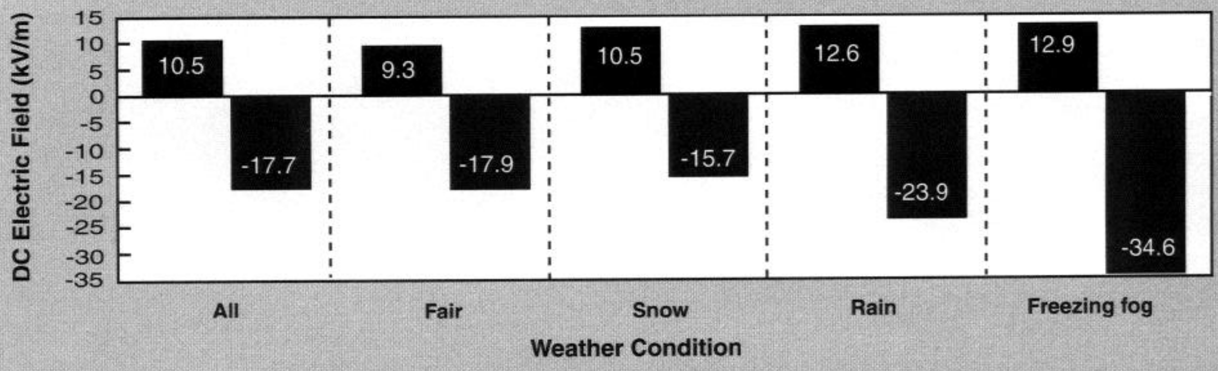


Figure 6.6. Summary of mean DC electric fields measured beneath the positive and negative conductors of the ±500-kV DC Intertie during different weather conditions. The measurements were made in 1986 in Central Oregon at a site where the conductors were 12.2 m (40 ft) above the ground. Source: Chartier et al. (1989).

fields and air ions from the line were detected at 6 10 m (2000 ft) from the line a small percentage of time. (This is the farthest distance that measurements were made.)

Long-term measurements of DC fields and air ions were made in New Hampshire for the +-450-kV Quebec-New England line (T.D. Bracken, Inc. 1993). The median DC electric fields beneath the positive and negative conductors for all weather conditions combined were about 8.5 kV/m, and -5 kV/m, respectively. Maximum fields (levels exceeded 5% of the time) were two to three times greater than the median levels. Conductor-to-ground clearance at the measurement site was about 17 m (56 ft). The median concentrations of positive air ions at two test sites were 15 and 26 kions/cm3, and 5 and 9 kions/cm3 for negative ions. The electric fields and air ion concentrations from the Quebec-New England DC line were higher for the positive conductor, in contrast to the DC Intertie, which produced higher negative fields. The exact reasons for this difference are unknown. One reason might be the difference in the electric field at the surface of the conductors between the lines (26 kV/cm for the Intertie vs. 17 kV/cm for the New England line) (T.D. Bracken, Inc. 1993).

When the Quebec-New England DC line in New Hampshire was operated with only the positive conductors energized (positive monopolar), the median electric field was 12.2 kV/m. During negative monopolar operation, the median electric field was -8.7 kV/m (T.D. Bracken, Inc. 1993). Both of these levels are greater than the corresponding positive and negative fields given above for the line in bipolar operation.

Long-term measurements were also made of the electrical environment of the Nelson River HVDC transmission lines in Manitoba (Norris-Elye et al. 1995). The two parallel bipolar DC lines operate at different voltages (Fig. 6.2) with the negative poles on the outer positions, and the positive poles adjacent to each other. For all seasons and weather conditions combined the highest median positive and negative DC fields in the right-of-way were about 13 kV/m and -10 kV/m. The corresponding maximum fields (exceeded 5% of the time) were about 30 kV/m and -27 kV/m, respectively. DC electric fields were higher during wet weather than during fair weather.

For all seasons and weather conditions combined the highest median concentration of positive ions on the right-of-way of the Nelson River DC lines was about 35 kions/cm3, and about 20 kions/cm3 for negative ions. The corresponding highest maximum ion concentrations were about 125 kions/cm3, and about 80 kions/cm3, for positive and negative ions, respectively.

Equal DC and AC field strengths do not produce the same electrical or biological effects. The field coupling to organisms or objects for the two cases are entirely different. In the DC case, the electric field coupling is resistive, with charge carried by natural and corona-generated ions. For AC, the coupling is capacitive and induced currents are the result of the changing electric field. Typically, the DC current coupled to an object is several orders of magnitude smaller than the induced current in an AC field of comparable amplitude. Electromagnetic induction does not occur from DC, because the current that causes the magnetic field moves in one direction.

The maximum DC magnetic field produced by the DC Intertie with 3100 A of current is about 34 uT (340 mG) beneath the line. However, the magnetic fields from a DC transmission line can either add to or subtract from the earth's DC horizontal and vertical magnetic fields, depending on the direction that current is flowing on the line (Raleigh 1988). The Inter-tie is located in a generally north-south position (Fig. 6.2), and power can flow in either direction on the line. When power is flowing from north to south, the line's vertical magnetic field is in the opposite direction from the earth's magnetic field. In this case, the field from the line subtracts from the earth's vertical field near the line (in an area about the width of the right-of-way). At distances farther from the line, the line's magnetic field add to the earth's magnetic field. These additions and subtractions are reversed when power flow on the intertie line is from south to north.

When power flow on the Intertie is from north to south, the line's horizontal magnetic field increases the earth's horizontal magnetic field on the west side of the line, and decreases it on the east side of the line. These conditions are reversed when current is flowing from south to north.

Corona Effects

Corona activity and effects (noise, ozone, light) occur whenever the electric-field strength on the conductor surface exceeds the breakdown strength of air. For AC transmission lines, corona activity is greatest during heavy precipitation because the water droplets concentrate the electric-field strength. With DC lines, however, radio and audible noise generally decrease during foul weather, when ions formed near DC conductors tend to suppress the formation of positive corona streamers. Studies of a DC test line in Massachusetts indicated that insects deposited primarily on the positive conductor, and that this was a primary and significant corona source in summer during fair weather (Johnson 1984).

Audible noise produced by a DC line is generated primarily by corona streamers on the positive conductor. This results in an impulsive "popping" noise. The DC line noise levels are generally lower than those for comparable AC lines. The L,, fair weather noise level (edge of right-of-way) calculated for the +-500-kV DC Intertie is 40 dB(A). However, Hill et al. (1977) pointed out that, while AC line noise is generally of short duration (foul weather), the noise from a DC line is essentially continuous.

Radio-frequency noise from a DC line is also greatest during fair weather; the positive conductor is the primary source. During rain, DC radio noise decreases by 2-9 dB when the conductors become thoroughly wet. Although DC lines can occasionally cause interference with radio reception, television reception interference has generally not been reported. As with AC lines, BPA's policy is to correct radio or television reception problems if a BPA line is involved.

Studies of the BPA HVDC Test Line by Battelle Northwest Laboratories showed that ozone production from the line was not measurable during fair weather (Droppo 1979). With a slight wind parallel to the conductors and during precipitation, small amounts of ozone from the line could be detected at conductor height on some occasions at +-500-kV. Studies of a +-400-kV DC transmission line in Minnesota and North Dakota also showed that ozone production was insignificant (Krupa and Pratt 1982).

Field Effects

It must be emphasized that, for DC lines, the electric-field strength alone does not characterize the electrical effects. The direct current that is intercepted by a person or object is of more significance because it can readily be compared with the DC threshold of perception and let-go levels.

Shock tolerance levels for DC are much higher than for AC (IEEE W.G. 1972, Hill et al. 1977). The mean threshold for perception of DC by men is 5.2 mA; for women, the value is 3.5 mA. In comparison, AC perception levels for men and women are around 1.0 mA and 0.7 mA respectively. Direct currents of 62 mA and 41 mA represent the release current for 99.5 percent of men and women, respectively. These are analogous to the 9 mA and 6 mA values for AC let-go current. The let-go or involuntary muscle contraction reaction does not occur with DC, but with high currents it becomes very painful to release a current-carrying conductor. Hence the term "release current" refers to a psychological rather than a physiological limit.

The ion current intercepted by persons or objects beneath DC lines is many times below the human perception level. Measurements made at The Dalles Test Site in total DC electric fields of 40 kV/m showed only 3-4-uA of current intercepted by a person with arms raised directly beneath the +-600-kV DC line (Hill et al. 1977). The maximum measured current from a 13.7-m (45-ft) tractor trailer under a similar test line in Canada was about 50 uA with a 12-m (40-ft) conductor-to-ground clearance, and 150 uA with conductor-to-ground clearance of 10 m (33 ft) (Morris et al. 1967).

Near a DC transmission line, charge will accumulate on an insulated object, causing a voltage difference with respect to ground. DC voltage is a function of the charge buildup, but it cannot exceed the corona limiting voltage of the object. For example, barbed wire fences will not assume a voltage higher than 25 kV, because at that voltage corona occurs at the tips of the barbs and the voltage stabilizes. Even this voltage level is very rare, because it requires extreme conditions of dryness.

Table 6.1 shows data from The BPA Dalles Test Site on fences and a metal roof. Typical levels of current and stored energy are given, along with the associated shock sensation for spark discharges. These stored energies can be compared with the DC shock experienced when touching a door knob after walking across a nylon carpet. For a carpet shock, the energy level is typically around 3-4.5 millijoules (mJ). Thus, a fence 40-m (130-ft) long on the right-of-way could reach this level of stored energy in very dry weather. The .50-mJ shock from a 240-m (787-ft) fence on the right-of-way parallel to the line and 4.6 m (15 ft) outside the conductor could be classed as a definite annoyance. A 250-mJ shock is very uncomfortable. However, the 1500 m (5000 ft) of parallel fence on a transmission line right-of-way which would be required for this level is a rare occurrence. In any event, one metal post attached to the fence is sufficient to drain the energy below perceptible levels.

It is BPA practice to ground fences on and adjacent to certain transmission line rights-of-way. Several metal grounding posts are usually used. A 186-m2 (2000-ft2) building, 30 m (100 ft) from the line (simulated by a metal roof) poses no problems as far as stored energy or short-circuit current magnitudes are concerned.

Tests made by BPA with vehicles on soil, asphalt, and concrete surfaces show that present-day tires are semi-conducting and have a sufficiently low resistance to ground to limit the potential on vehicles to several hundred volts. Thus, the vehicle will not store enough energy to ignite gasoline or deliver a shock.

All these examples point out why there is such a low probability of receiving shocks near a DC transmission line, To date, we are not aware of any complaints from the public about electrostatic shocks due to the DC Intertie line in Oregon.

Subjective tests with nine men in conditions of 60 percent relative humidity at The Dalles Test Site indicate that, when an individual is well insulated from ground, a DC electric field of 22 kV/m can be perceived as a slight tingling of the scalp (Hill et al. 1977). Test site personnel indicated that perception levels and field strengths are both affected by humidity. With normal footwear, BPA personnel have reported that, on rare occasions, with the line at +-500 kV, significant stimulation of head hair occurred in fields greater than 30 kV/m.

Blondin et al. (1996) studied human perception of DC electric fields and ion currents such as produced by DC transmission lines. The studies were conducted with men and women seated indoors within a special exposure chamber. The researchers said that the field detection values found in their study for seated subjects could be applied to a person standing beneath a DC line by multiplying the values by 0.8. Relative humidity in the chamber varied from 6 to 40 percent (it varied from lO-25% for 38 of the 48 subjects). Psychophysical methods derived from signal-detection theory were used to measure perception.

On the average, the subjects could detect a 40-kV/m DC field; about a third could detect a 25-kV/m field. The simultaneous presence of air ions at high current densities (60-120 nA/m2) facilitated the detection of the

Table 6.1. Results of tests made on barbed wire fencing and a m[illegible]e to the BPA ±600-kV DC test line at The Dalles, Oregon.

Object	Distance from Line	Average Current	2 mJ (Barely perceptible)	5 mJ (Perceptible)	50 mJ (Annoying)	250 mJ (Very uncomfortable)
			Length or Size of Structure to Attain Energy (shock sensation) Shown			
Single strand of barbed wire fence with 6-m (20-ft) post spacing.[a]	4.6 m (15 ft)	1.3 μA/m (0.36 μA/ft)	20 m (67 ft)	40 m (131 ft)	240 m (787 ft)	1500 m (4920 ft)
	17 m (56 ft)	0.6 μA/m (0.17 μA/ft)	600 m (1968 ft)	1 km (0.6 mi)	7 km (4.3 mi)	10 km (6.2 mi)
Metal roof on wood posts.[b]	30 m (98 ft)	0.2 μA/m² (4 μA/200 ft²)	186 m² (2000 ft²)			

a Resistance of each wood post= 860 Mohm, capacitance= 7.5 pF/m (2.3 pF/ft).

b Resistance of each wood post= 860 Mohm, capacitance= 100 pF per 18.5 m³ (200 ft²) of metal.

electric field. Ten percent of the subjects could detect a 21-kV/m field with no air ions, and they could detect a 12-kV/m field with a 60 nA/m2 ion current density. The subjects perceived the DC electric field as a tingling or itching sensation of the skin or hair.

Biological Effects

Background and Issues

As discussed above, the small currents intercepted by people or animals near a DC transmission line appear to be insignificant. Also, compared to AC lines, it is less likely that the electric field from DC lines can be perceived by people or that nuisance shocks will occur. Operational experience with DC transmission lines in general has been very good. Personnel who have worked near the BPA +-600-kV DC test line have reported no harmful effects from the line.

Some public awareness of DC transmission lines developed in the late 1970s and early 1980s largely as a result of controversy surrounding the CU +-400-kV line in Minnesota (Ames 1978, Casper and Wellstone 198 1). The CU (Cooperative Power Association, United Power Association) line extends 708 km (440 mi) from a power plant in Western North Dakota to a point near the Twin Cities in Minnesota (Fig. 6.2). Strong and sometimes violent public opposition to the line occurred in parts of Minnesota during the planning and construction processes. Persons opposing the project believed that the line was not needed, and they did not like the way land was acquired for the right-of-way (McConnon 1984). By the time the line was constructed, the only remaining issues were health and safety related to DC fields, air ions, and ozone (Casper and Wellstone 1981).

Studies by the Minnesota Environmental Quality Board (Banks et al. 1977) and the Comptroller General of the United States (1979) found no evidence to indicate that DC lines pose a threat to human health. However, after the +-400-kV CU line was first energized, some people surveyed in Minnesota reported that the line caused adverse effects on themselves and their livestock (Genereux and Genereux 1980). Other persons surveyed experienced no effects.

A Science Advisory Committee formed by the State of Minnesota found that the survey was flawed. A majority of the Committee also concluded that there was no indication that the +-400-kV DC line presented a risk to human health from short-term exposure (Bailey et al. 1982, 1986). (See Brambl 1982 in Table 6.2 for a minority viewpoint.) The advisors also recommended that studies be done of livestock and crops raised near the DC line.

The Minnesota Environmental Quality Board subsequently sponsored a statistical study to determine whether dairy cattle were affected by the +-400-kV CU line. Data were obtained by examining records from a Dairy Herd Improvement Association from before and after the line was energized. In comparing farms near to and away from the line, no differences were found on milk production, calving intervals, rate of culling for reproductive problems, and incidence of abortions (Martin et al. 1986).

By contrast, little controversy over the CU line developed in North Dakota, where two-thirds of the line is located (McConnon 1984). Although in North Dakota the conductors are actually closer to ground and the DC electric field is therefore stronger, health effects from the line have generally not been reported in that state.

The Minnesota Science Advisors were reconvened in 1986 to consider results of electrical monitoring studies of the CU line, and to review results of recent biological research. The Advisors concluded that the newer information still indicated that there was little likelihood for either acute or chronic health effects of air ions or DC electric fields (Bailey et al. 1986). The Advisors acknowledged, however, that long-term research on possible DC effects was still limited.

We are not aware of any reports of health effects from persons living or working near the DC Intertie line. A health survey of residents near the line in California did not reveal any perceived effects attributable to the line (Nolfi and Haupt 1982). The survey compared persons living near the +-400-kV DC line with persons farther away. Residents were questioned about perceived overall health and about health problems experienced during time periods of 2 weeks, 1 month and 12 months preceding the survey. The DC line was undergoing routine maintenance at times during the survey, which complicated interpretation of the results. The survey was sponsored by the state of Vermont, where interest developed in DC transmission because of the proposed Quebec-New England DC line.

Overall, there appears to be no evidence that the electric fields and ions of DC lines pose any hazards to public health (Banks and McConnon 1987). A monitoring study in Minnesota and North Dakota found that ozone production from the +-400-kV DC line was also insignificant (Krupa and Pratt 1982). Gatchel et al. (1981) suggested that the health effects reported from some people in Minnesota (described above) may be related to stress, apparently associated with controversy over the line, or perceived hazards.

Air Ions and DC Fields

Laboratory Animals

Although there is a large body of laboratory research on air ions and DC fields (e.g., Krneger and Sigel 1978, Kotaka 1978, Sulman 1980, Charry and Kavet 1987, Simon 1992), few studies have been done specifically for DC transmission lines. The Electric Power Research Institute (EPRI) sponsored some laboratory research relevant to DC lines.

One EPRI-sponsored study was done in the laboratory where Dr. A.P. Krueger conducted many well-known studies of air ions, In the study, no effects of air ions were found on growth of male mice or on their resistance to influenza virus (Kellogg 1982). After 2 years, serum glucose levels were slightly lower in female mice exposed to 2×10^3 ions/cm3 (monopolar) than in mice in grounded cages (no ions or field) (Kellogg et al. 1985). The levels were highest in mice exposed to a 2-kV/m field. The +-electric field groups had the longest median survival time (MST). MST was lowest in mice exposed to negative ions ($2x10^3$ – $2x10^5$ ions/cm^3); however, the group exposed to high positive ions ($2x10^5$ ions/cm3) had an MST longer than the grounded cage group. (See reviews of this study in Bailey et al. 1986.)

A second study was conducted at the Institute for Basic Research in New York. Researchers there reported no effects of air ions at $5x10^5$ ions/cm3 on levels of the neurotransmitters, serotonin, norepinephrine, and dopamine in rats (Bailey and Charry 1987, Charry and Bailey 1985). Exposures ranged from 2 to 66 hours. The New York studies also found no effects of air ions ($5x10^5$ ions/cm3), or l2kV/m DC electric fields on the behavior of rats (Bailey and Charry 1986).

Researchers at the Battelle Pacific Northwest Laboratories studied the behavior of 380 male rats exposed to DC electric fields and air ions (Fig. 6.7). A shuttlebox experiment was used to determine whether rats would avoid a strong DC electric field, or high ion concentrations, The studies showed that rats spent significantly less time in the exposed side of the box at field strengths of -55,55 and 80 kV/m, but not at -36,30 or 42.5 kV/m (air ion concentration was held constant at $1.4x10^6$ ions/cm3 for the positive fields, and $-1.4x10^6$ ions/cm3 for the negative fields) (Creim et al. 1993). The tendency of rats to avoid +-55-kV/m DC electric fields was not significantly affected by varying the air ion concentration between $2x10^3$ and $2.5x10^6$ ions/cm^3.

Figure 6.7. This is a system developed by Battelle-Northwest to expose rodents to DC electric fields and air ions such as produced by DC transmission lines.
Photo courtesy of Battelle Pacific Northwest Labs.

In other studies Battelle researchers used 56 male rats to determine whether +-75-kV/m DC electric fields and $\pm 2x10^5$ ions/cm3 produced taste aversion (Creim et al. 1995). Rats will stop eating or drinking a favored item if it is accompanied by unpleasant effects such as stomach pain. In this study no such aversion to saccharin-flavored water occurred in the presence of the DC electric fields and air ions. The researchers concluded that the avoidance of strong DC electric fields by rats found in their earlier study (Creim et al. 1993) must occur through mechanisms other than by those that would cause taste aversion.

DC fields do not induce currents into stationary objects (including people and animals) as do AC fields. However, currents are induced at the instant that DC fields are turned on or off, and currents are induced when people or animals are moving in DC fields (Rosen 1994). Many studies have been conducted of animals exposed to DC fields. A wide variety of biological effects has been reported, but many have not been confirmed or refuted (Simon 1992). A review by the World Health Organization concluded that, although transient effects of DC magnetic fields have been reported on animals, no irreversible effects have been reported from fields of up to 2 T (20,000 G) (WHO/IRPA 1987). A few examples of studies of animals exposed to DC fields are summarized below.

Fam (198 1) exposed 21 male and 21 female mice for 5000 hours to a 340-kV/m DC electric field. The offspring of these animals were exposed for 2000 hours to the strong electric field. For exposed males, drinking water consumption was consistently lower than for the controls, and there was a trend for males to grow slightly faster than controls. There were no significant differences between exposed and control groups in the numbers of young born or in their survival. Some differences between exposed and control groups were noted in hemoglobin and white blood cell populations for females. Tissue samples were taken from a few animals from each group and no unusual findings attributable to electric field exposure were found.

Prenatal and postnatal development was studied in mice after intrauterine exposure to a 1 -T (10,000-G) uniform DC magnetic field, or to a gradient magnetic field of 2.5 T/m with a maximum field of 1 T (10,000 G) (Sikov et al. 1979). Data were obtained on litter size, prenatal mortality, gross malformations, and on several measures of development and neuromuscular status. Although some significant differences between exposed and control groups were found, they did not appear in study replicates. The researchers said that the small number of litters in the study, however, precluded them from making any firm conclusions about possible effects of the magnetic field.

Al-Maliki (1994) studied behavior and reproduction in the offspring of mice that had been exposed throughout their life to a DC magnetic field of 76,655 gamma (766.55 mG). For the young male mice from the exposed group , the incidence of fighting with other males was drastically inhibited. Some other social behaviors were also significantly reduced in this group. The study also found that none of six exposed female offspring became pregnant after mating with six exposed males. The six control females not exposed to the magnetic field bred normally, although no data were shown. The researchers said that the reasons for the infertility were not known and further investigation was needed.

As discussed in Chapter 4, there has been considerable interest in the possible biological interactions of weak, combined AC and DC magnetic fields. This is largely due to studies described earlier involving efflux of calcium from chick brains (Bawin and Adey 1976). Attempts by other researchers to replicate the calcium efflux effect found that the local DC magnetic field of the earth influences the frequency of the AC field that is most effective in producing the effect (Blackman et al. 1985).

Another study reported that when rats were exposed to 50 uT (500 mG) 60-Hz magnetic fields while in a DC field of 26 uT (260 u T the animal's ability to judge time intervals was affected (Thomas et al. 1986). The effect was reversible about 1 hour after exposure ended. Another research group, however, was not able to replicate the results of this study (Stem et al. 1996).

Resonance phenomena have been proposed to explain reported biological effects of combined AC and DC magnetic fields (Liboff 1985, Lednev (1991). Other efforts to replicate studies that reported effects with resonance-type exposures are described in Chapter 4 in the section "Possible Mechanisms for Effects of EMF."

As described in Chapter 4, a major focus of research for AC fields involves the hormone melatonin. Several studies have also been conducted to see whether DC fields can affect this hormone. Welker et al. (1983) found that nocturnal concentrations of melatonin and of the pineal enzyme SNAT were quickly depressed in laboratory rats when the horizontal component of the earth's DC magnetic field was inverted. Similar effects were found when they increased the intensity of the DC field to twice that of the earth's field.

The findings of Welker et al. (1983) were confirmed by other research groups (Olcese et al. 1985, Olcese and Reuss 1986). These studies used laboratory exposure facilities to rotate the earth's DC magnetic field by 50 degrees which increased the field intensity to about 0.1 mT (1 G) (about double the earth's field). After a 30-minute exposure to the altered DC magnetic field, nocturnal melatonin was reduced significantly in two strains of rats, but not in golden hamsters.

Stehle et al. (1988) found that pineal melatonin and SNAT in albino Mongolian gerbils were decreased following a 30-minute exposure to a 0.03-mT (0.3-G) DC magnetic field. In contrast, neither parameter was affected in pigmented gerbils. Stehle et al. (1988) cited other studies that reported that pigmented animals lack retinal melatonin, and albino rats have more active pineals than pigmented rats.

Reuss and Semm (1987) studied melatonin synthesis in pigeons by changing the horizontal component of the 0.03-mT (0.3-G) earth field to 0.04 mT (0.4 G). A 55-minute exposure to the changed field resulted in a 60-percent reduction in nocturnal melatonin and SNAT concentrations. The activity of the enzyme HIOMT was not affected.

In vitro studies have also found evidence that the pineal responds to changes in DC magnetic fields (Semm 1983). In the guinea pig about 20 percent of the cells in the pineal responded to artificial changes in the earth's DC magnetic field. Cell activity returned to normal when the field was returned to the ambient level. In pigeons about 30 percent of the pineal cells showed a response to changes in the DC magnetic field.

A combination of an AC magnetic field (33.7 Hz) and a DC magnetic field tuned to ion-cyclotron resonance conditions for Ca^{2+} and applied for 2.5 hours to isolated rat pineals significantly reduced melatonin concentrations in those glands (Lerchl et al. 1990).

In a study by Lerchl et al. (1991) the rapid change in switching a DC magnetic field on and off, rather than the presence of the field appeared to be responsible for a decrease in pineal melatonin in rats. Those authors suggested that the effect on melatonin was associated with eddy currents induced in the animals from the transients caused by switching.

Environmental Studies

Environmental studies of DC lines are useful because they deal with exposures that actually exist from operating lines. If effects are found, however, it may be difficult to determine what aspect(s) of the field and corona environment may have caused the effects (Lee 1979).

BPA sponsored a small study in Oregon that involved natural vegetation, crops, and wildlife living near the +-400-kV DC Intertie (Griffith 1977, Lee and Griffith 1978). Some slight differences were found in the abundance and diversity of wildlife on and off the right-of-way. These differences were attributed to effects of construction that changed vegetation composition and patterns on the right-of-way. No effects of the DC line were found on wheat growing on the right-of-way. Cattle were also frequently observed feeding or resting near the line. The principal researcher conducting the study spent hundreds of hours on the DC line right-of-way and never perceived the electric field and never experienced any shocks.

Japanese researchers studied wheat growing beneath a DC test line (Endo et al. 1979). A DC field of up to 19.5 kV/m was reported to have had no effect on growth or yield of the wheat. However, in reviewing this study, the Minnesota Science Advisors (Bailey et al. 1982) suggested that the data indicated that the DC field did appear to affect plant growth and yield.

An extensive, long-term environmental study of the DC Intertie in Central Oregon was conducted by Oregon State University from 1985 to 1988 (Lee et al. 1986, Raleigh 1988). BPA and a group of nine other utility organizations sponsored the experimental study, which involved beef cattle and crops raised on the right-of-way of the +-500-kV DC Intertie (Fig. 6.8). The study was designed to simulate ranching and farming conditions. The growth and reproduction of 100 beef cows and two crop species raised under the line were compared to those of control groups raised in an area away from the line.

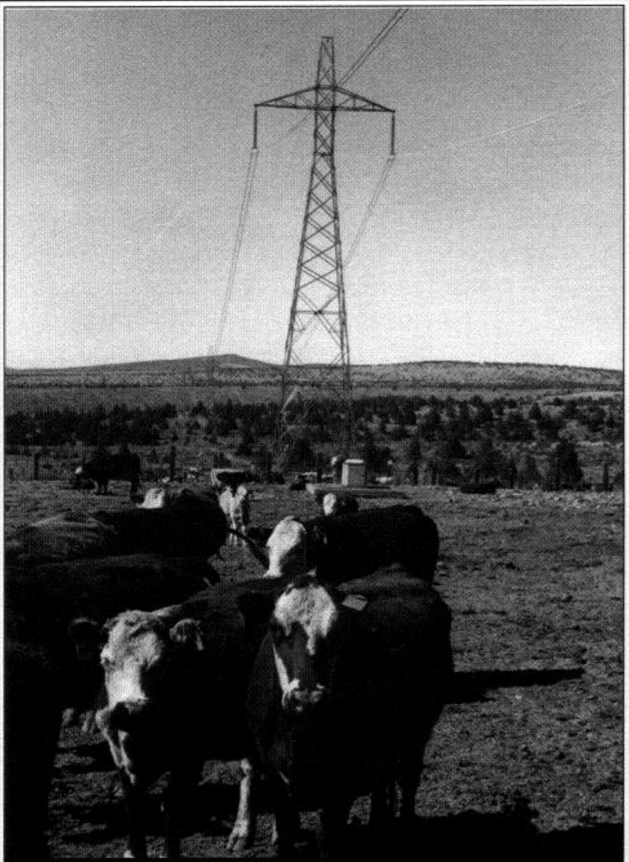


Figure 6.8. Oregon State University conducted a 3-year study of beef cattle raised beneath the ±500-kV DC Intertie and in a nearby control area. The study was done in Central Oregon and it involved growth, reproduction, and behavior.

Results of the study showed no statistically significant differences in growth or reproduction between the cattle raised under the line and the control animals (Angel1 et al. 1990). Behavioral studies indicated that from 5 to 11 percent fewer cattle occupied areas directly under the DC line conductors (Ganskopp et al. 1991. Such a small effect would not be noticeable in a normal ranching operation. This finding could not be correlated with either the electric field or the audible noise produced by the line. There were also no differences in yield of alfalfa or wheat between the line and control areas. A few small and inconsistent differences in crop growth were found, but the causes could not be determined.

Orientation/Navigation

A large body of evidence suggests that several species, ranging from bacteria to fish and possibly humans may have some ability to detect and make use of the earth's DC magnetic field (Blakemore et al. 1988, Kalmijn 1988).

Birds may to be able to use information from the earth's DC magnetic field as one aid to navigation (Gould 1980, Southern 1988). Birds exhibit behavioral and neural sensitivities to changes in DC magnetic fields as weak as 200 nT (2 mG) or less (Beason and Semm 1994). This is less than 0.5 percent of the earth's total magnetic-field intensity. This ability to detect changes in weak magnetic fields may be related to the presence of magnetic material (magnetite) known to exist in the tissues of birds, bees, and other animals.

When homing pigeons were exposed to slowly alternating magnetic fields of up to 0.06 mT (0.6 G) for a few hours before release, their initial orientation was disturbed (Papi et al. 1983). However, the birds seemed to compensate quickly for the disturbance, and their homing performance was not affected.

Other studies raised some doubts about the ability of birds to detect weak magnetic fields. Moore et al. (1987) tested the ability of four pigeons to detect changes in an earth-strength magnetic field varying between 0.01 and 10 Hz. The birds were trained to contact a response key to obtain a water reward. Even with extensive training, none of the birds was able to distinguish between the constant and changing field.

Another similar study tested the ability of six pigeons to detect changes in a DC magnetic field of up to 3 times the normal strength of the earth's field (Alsop 1987). Results indicated that the birds could not distinguish between the static or fluctuating applied fields and the ambient earth field. The researchers suggested that if birds can actually detect weak magnetic fields, far more elaborate study designs may be needed to measure this phenomenon.

Human Health

There are some claims that negative air ions can have a therapeutic effect, at least for some sensitive people. Commercial negative ion generators are sold that supposedly produce a more healthful home or office environment (Field 1976, Sulman 1980). Negative ions have also been used in the treatment of burns, allergies, and other medical problems (Charry 1984, Sulman 1980).

The "sick building syndrome," referring to worker discomfort in office buildings, has been suggested to be, in part, caused by a deficiency of negative ions. A study by Finnegan et al. (1987), however, found no evidence that the use of negative ion generators had any effect on the comfort or well-being of the 26 people in the study.

The serotonin hypothesis has been advanced to explain certain reported effects of air ions. Krueger and Sigel(1978) believed that small positive ions, when inhaled, cause release of the brain hormone serotonin. In contrast, negative ions speed the removal of this hormone from the blood. The presence of serotonin is associated with a variety of minor ill effects. The unpleasant effects of desert winds on weather-sensitive people have also been attributed to ions and/or charged particulates and release of serotonin (Sulman 1980).

Bailey (1982) challenged the factual basis of the assumption that air ion effects are due to alterations in serotonin metabolism. He believed that the serotonin hypothesis has not been rigorously tested. A study by Beardwood et al. (1987), however, on research with rats exposed to positive ions did not refute the hypothesis. Kavet et al. (1985) advanced another hypothesis for explaining effects attributed to air ions. They proposed that such effects are mediated by certain neuroendocrine cells which are found in the respiratory epithelium. They indicated that studies are needed to test the hypothesis.

Charry (1987) reviewed 33 air ion studies involving human physiology and behavior, and 18 studies on human biomedical responses. He found that, while a large variety of effects has been reported, there is no overall agreement among the findings. Many of the studies were flawed by design and methodology problems. Many studies reported no effects of exposures to air ions. Charry concluded that it appears that air ions can affect human biological responses, but the effects are small and usually disappear after exposure ends.

The relatively limited epidemiological research on DC magnetic fields was reviewed by Simon (1992). Most of the research involved occupational exposures, and no clear pattern of health effects was apparent. Effects reported in some studies included discomfort and pain in strong fields of 2-4 T (20,000-40,000 G), a slight decrease in white blood cell counts, and an excess of deaths from pancreatic cancer and leukemia. There were problems in some studies with how magnetic field exposure was measured, and in some studies the number of study subjects was small. Nevertheless, Simon (1992) suggested that the possible risks warrant further investigation.

Most of the research involving cancer and exposure to EMF has focused mainly on AC fields (Chapter 3). There have been suggestions that the local geomagnetic field may interact with power-line AC fields to influence cancer risks in people living near such lines (Liboff and McLeod 1995, Bowman et al. 1995).

Summary

Many of the various effects reported from studies of air ions and DC fields remain controversial with scientists. In general, much of this research cannot be directly applied to a DC transmission line. In most studies, ion and DC field levels are relatively constant for long periods. In contrast, ion concentrations, distributions, and fields are constantly changing near a DC line. Likewise, people and animals typically are not stationary. In many air ion papers, it is also difficult or impossible to determine exactly what type and concentration of ions were present and the actual exposure experienced by the test subjects.

Other than the questionable reports from Minnesota, persons living or working near DC commercial and test lines have generally not reported either adverse or beneficial effects from air ions or DC fields. Overall, research indicates that it is unlikely that fields or air ions as produced by DC lines cause any hazardous effects. Table 6.2 is a summary of conclusions from several reviews of the literature involving the biological effects of air ions.

Standards and Guidelines

The American Conference of Governmental Industrial Hygienists established Threshold Limit Values (TLVs) for DC electric and magnetic fields (ACGIH 1995). Routine occupational whole-body exposure to DC magnetic fields should not exceed 60 mT (600 G), and exposure to the extremities should not exceed 600 mT (6000 G) on a daily time-weighted basis. A flux density of 2 T (20,000 G) is recommended as a ceiling value for DC magnetic fields. People who have cardiac pacemakers or similar medical devices should not be exposed to DC magnetic fields exceeding 0.5 mT (5 G). For DC electric fields, the ACGIH TLV calls for occupational exposure not to exceed 25 kV/m. The ACGIH points out that the above values for DC fields are guides, and not a fine line between safe and dangerous levels.

In 1995 a prestandard on human exposure to low-frequency EMF (O-10 kHz) was published by the European Committee for Electrotechnical Standardization (CENELEC). It is intended to be applied on a provisional basis. A decision on whether it will be converted to a European standard will be made in 3 years after its publication. The prestandard is based on established short-term biological effects of EMF including stimulation of electrically excitable cells and heating. CENELEC acknowledges that there are reports of possible long-term health effects from EMF levels lower than those in the prestandard. However, because adverse effects have not been established, the reports do not provide a basis for restricting exposure to EMF.

For whole-body exposure to DC electric fields (O-O.1 Hz) predominantly parallel to the body CENELEC (1995) sets a basic restriction for workers at 42 kV/m (peak). This is also the reference level for worker exposure to DC electric fields. The reference level electric field E (in kV/m), may be exceeded subject to the time restriction, t (in hours), given by the formula: t **I** 112/E. This is the time limit within any S-hour period that workers may spend above any particular field level, subject to the basic restriction level.

For worker whole-body exposure to DC magnetic fields (O-O. 1 Hz) the CENELEC basic restriction is 2 T (20,000 G). Above this level there is the possibility of vertigo, nausea, cardiac arrhythmia, and impaired mental function. For whole-body continuous exposure during a work day, DC magnetic field exposure is restricted to a time-weighted average of less than 0.2 T (2000 G), For exposure of the limbs, 5 T (50,000 G) is allowed.

For exposure of the general public to DC magnetic fields, the CENELEC reference level is 14 kV/m. The DC magnetic field reference level for the general public is 0.04 T (400 G), and for limbs 100 mT (1000 G) is allowed.

Table 6.2. Some conclusions from reviews of research involving the biological effects of air ions.

Bailey et al. (1982:8):
"In summary, while air ions appear to affect some biological processes in animals, plants, and microorganisms, there is insufficient reason to believe that acute exposures to air ions are harmful or injurious. As far as is known, all effects that have been described in animals and humans are quite mild and fully reversible, usually within a few hours. However, there are insufficient data to determine what effects, if any, might be observed with exposures to high ion concentrations over extended periods of time."

Bailey et al. (1986):
'There still appears to be little likelihood that either chronic or acute exposure to small air ions and static electric fields at levels measured either on or downwind of the right-of-way of the dc line cause adverse health effects. The scientific literature since 1982 is similar to the earlier literature in that the evidence for biological effects of air ions is still inconsistent. Certain authors have begun to address the question of chronic exposure. However, these studies are not conclusive and would need to be replicated before their results could be accepted."

Banks et al. (1983:66):
"In summary, it can be concluded, based on a more detailed examination of those studies meeting reasonable criteria for acceptable scientific quality, that the effects on biological and behavioral responses in both animals and humans are for the most part small in absolute magnitude and are transient (i.e., the effects disappear after subjects are removed from the ion condition). The exception to the above are the series on the course of respiratory infection in mice . . . . These findings taken as a whole indicate that there is no scientific basis at present for asserting that small air ions are a threat to human or animal health."

Brambl (1982:MW6):
'The conclusion of this minority report is that it is more likely than not that the CPANPA HVDC transmission line represents a potentially significant hazard to human health and welfare. Since the air ions produced by this line (or their products) are the most probable agent of this hazard, the concentration of air ions in the vicinity of this line (beyond the right-of-way) should be reduced to ambient levels by any of several technical modifications of the transmission line that are now available."

Charry (1987:i46):
"Based on a detailed examination of those studies meeting such minimum standards [of scientific quality], the following conclusions seem reasonable: (1) there appear to be effects of ions on biological and behavioral responses in both animals and humans; (2) when these effects occur, they are for the most part small in absolute magnitude; and (3) the effects that have been observed are for the most part transient (the effects disappeared after subjects were removed from the ion exposure condition)."

Dow Associates (1980:3-54):
"For air ions, the strongest statement that can be made is that they do have biological effects. Extrapolations to the power line environment are extremely difficult to make. . . . there are no substantive laboratory or 'real life'studies describing what the role of intervening variables, such as fluctuations in ambient air conditions, might be."

Frazier and Preache (1980:113):
"In summary, the questions of bioactivity of small air ions and the role of 5HT [serotonin] metabolism in such effects are still controversial issues. . . . In any event, the reports of adverse effects of sometimes relatively short exposures to environments containing excess positive ions (some of which are based on ion densities that occur in nature in unusual weather conditions and will almost certainly occur in the vicinity of HVDC transmission lines), it is important for the objectives of the proposed experimental design that some of the lines of investigation suggested by the air ion literature be pursued [sic]."

Table 6.2. Some conclusions from reviews of research involving the biological effects of air ions. (Cont.)

Kellogg (1984:132):
"Certainly the scientific literature contains a core of well-controlled studies which have clearly demonstrated air ion effects of physiological relevance to conditions found in both natural and man-made environments. Nevertheless, because many early workers neglected to pay strict attention to the experimental details required in this type of research, much uncertainty still exists about many reported air ion effects."

Sheppard (1983: I I l-22):
"The evidence from either laboratory or human studies is so deeply flawed by methodological or experimental problems that one can conclude there is no sound body of literature on the biological effects of air ions. Nevertheless, a few isolated research reports, primarily in the area of animal physiology, suggest possible air ion effects using ion concentration greater than would be found beneath the HVDC transmission line."

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Appendix A

This appendix summarizes several reviews of health effects research on EMF published in the previous 5 years (since 1991). This cutoff date covers the time immediately before and after the widely reported Nordic epidemiologic studies of magnetic fields and cancer began to be published (see Chapter 3). The reviews are separated into two major categories: 1) reviews conducted by or for government organizations, and 2) reviews or position statements by professional or private organizations. For each review where applicable, selected conclusions are given about the findings of health research, and recommendations or comments on the need for EMF exposure reduction. The reviews are presented in chronological order. Additional published reviews on specific areas of research on EMF are included in previous chapters.

Reviews by or for Government Organizations

Reference/Organization	Health Effects	Exposure Reduction/Prevention
Gibbs (1991:57,162), for the New South Wales Government, Australia	"It has not been scientifically established that electric fields or magnetic fields created by the electric power system in New South Wales (or by any electric fields or magnetic fields of extremely low frequency) initiate or promote cancer or have any other harmful effects on humans. However, it has not been scientifically established that such fields are not harmful."	"It has not been established that electric fields or magnetic fields of power frequency are harmful to human health, but since there is some evidence that they may do harm, a policy of prudent avoidance is recommended."
California EMF Consensus Group (1992:18,49), for the California Public Utilities Commission	"There is consensus that scientific reviews to date have concluded that data from epidemiology, whole animal studies, and cellular experiments are not sufficient to conclude that the statistical associations reflect a cause and effect relation. In addition, it is agreed that the accumulated scientific evidence does not allow an assertion that significant health risks do not exist."	"All members of the Consensus Group agree that, given the public concern and scientific uncertainty over whether or not EMF causes adverse health effects, utilities should take no-cost and low-cost measures to reduce fields."
Connecticut Academy of Science and Engineering (1992:7,9), for the Connecticut Department of Health Services	"Absolute proof of the occurrence of adverse effects of ELF fields at prevailing magnitudes cannot be found in the available evidence, and the same evidence does not permit a judgement that adverse effects could not occur, as is true for any putative hazard without a solid base of evidence."	"The academy concludes that it would be inappropriate -- given the above conclusions -- for public authorities to recommend prudent avoidance."
ORAU Panel on Health Effects of Low-Frequency EMF (1992:ES-II), for The Committee on Interagency Radiation Research and Policy Coordination	'This review indicates that there is no convincing evidence in the published literature to support the contention that exposures to extremely low-frequency electric and magnetic fields (ELF-EMF) generated by sources such as household appliances, video display terminals, and local power lines are demonstrable health hazards."	Recommendations on EMF exposure reduction/prevention were not specifically addressed in this review.

Reference/Organization	Health Effects	Exposure Reduction/Prevention
EPA Science Advisory Board (1992:1), for the U.S. Environmental Protection Agency	"The Subcommittee has concluded that some of the epidemiological evidence is suggestive of an association between surrogate measurements of magnetic field exposure and certain cancer outcomes. In such studies, the existence of confounders is always a possibility, but since no common confounder has yet been identified, the existing evidence cannot be dismissed. . [lack of sufficient data] prevents the inference of cancer causality from these associations at this time."	Recommendations on EMF exposure reduction/prevention were not specifically addressed in this review.
Illinois Dept. of Public Health and Illinois Environmental Protection Agency (1992:vii,53), for Illinois State Legislature	"Because some studies have identified positive associations between ELF field exposure and certain health effects, while others have not, the data obtained to date are far from conclusive. They are suggestive enough, however, to justify much more research into the question of whether ELF fields may have any adverse impact on human health."	"Electric utilities are encouraged to take prudent measures in the reduction of ELF field exposures by such actions as providing larger rights of way, avoiding schools and population centers, and using low-field transmission line configurations when routing power transmission lines in the future."
Universities Consortium on EMF (1992:2), contract with the Public Service Company of Colorado	"Taken together, the conclusions from this review highlight the absence of health effects directly related to 60 Hz alternating current EMF on humans. It is equally clear that the book is not closed. Several questions remain unanswered that should be addressed in carefully conducted research by qualified investigators who are knowledgeable in the problems and pitfalls of this type of research."	Recommendations on EMF exposure reduction/prevention were not specifically addressed in this review.
Panel on Electromagnetic Fields and Health (1992:3,81), for the Victorian Government of Australia	"The scientific studies, although conflicting, suppot-l the view that it is possible that children exposed to extremely low frequency magnetic fields are at a greater risk than other children of developing cancer, and that it is possible that adults so exposed are at greater risk than others of developing certain forms of cancer, namely, leukaemia, lymphoma and brain tumors. Some studies suggest that exposure to such fields creates other risks, e.g., reproduction and of foetal injury, but other studies contradict this suggestion. It has not been shown that it is probable that any of the risks exist."	"The dual base of the uncertainty of the science and the concerns of the community lead the panel to support a policy of prudent avoidance. While the public health implications, if any, of electromagnetic fields are not yet known, the Panel does not believe that there are no appropriate responses which can and should be taken under the circumstances."
Electro-Magnetics Health Effects Committee (1992:xxi), for the Public Utility Commission of Texas	"The Committee believes that, based on its evaluation of the existing EMF research, the evidence at this time is insufficient to conclude that exposure to EMF from electric power transmission lines poses an imminent or significant public health risk."	"The Committee recommends that the PUC continue its policy of de ***facto*** 'prudent avoidance' in the siting of transmission lines."
Advisory Group on Non-ionising Radiation (1992: 132), U.K. National Radiological Protection Board	"In the absence of any unambiguous experimental evidence to suggest that exposure to these electromagnetic fields is likely to be carcinogenic, in the broadest sense of the term, the findings to date can be regarded only as sufficient to justify formulating a hypothesis for testing by further investigation."	Recommendations on EMF exposure reduction/prevention were not specifically addressed in this review.

Reference/Organization	Health Effects	Exposure Reduction/Prevention
The ELF Electromagnetic Fields Committee (1992:6), the Health Council of the Netherlands for the Dutch Minister of Housing, Physical Planning, and Environment	'There is at present insufficient scientific proof that chronic exposure to ELF EMF with low field strengths as found in the domestic or professional environment results in adverse health effects."	"Exposure to ELF EMF with field strengths considerably higher than those that occur in the domestic environment but may be present in certain industrial work areas can result in acute health effects. The committee therefore recommends the development of standards for the maximum exposure to ELF EMF."
Expert Group on Non-ionising Radiation (1993a:70),The Danish Ministry of Health	"The expert group believed that neither the earlier nor the latest studies offers sufficient documentation to characterize 50 Hz magnetic fields in homes adjacent to high-current electricity supply plants as a cancer-inducing factor among children. The studies described do not, however, allow this assumption to be dismissed."	"The group, therefore, finds no scientific reason for establishing standards with respect to high-current plants."
Expert Group on Non-ionising Radiation (1993b:95,96), The Danish Ministry of Health	"The task force concluded that the Nordic studies confirm the suspected correlation between exposure to ELF magnetic fields and the occurrence of leukaemia. The suspicion should now be refuted or confirmed by studies based on morbidity registers and precise exposure evaluation. The task force finds that the most recent studies have not increased the suspicion of a possible link between occupational exposure to low-frequency electromagnetic fields and an increased occurrence of brain cancer."	Recommendations on EMF exposure reduction/prevention were not specifically addressed in this review.
Guenel and Lellouch (1993:46), French National Institute of Health and Medical Research (INSERM)	"Among the effects considered in the present report, those that concern health in general, depression and suicide, reproduction, cancer in the children of exposed subjects, were evoked as a result of a very few discordant studies, often with a methodology highly subject to criticism. At present there does not seem to exist any serious argument that permits the implication of electric and magnetic fields in these pathologies. . . . In conclusion, the epidemiologic results presently available do not permit the exclusion of a role for magnetic fields in the incidence of leukemia, particularly in children."	Recommendations on EMF exposure reduction/prevention were not specifically addressed in this review.
Advisory Group on Non-ionising Radiation (1993:67,68), U.K. National Radiological Protection Board	"The Group concluded that the three new occupational studies (from Sweden, Denmark, and Norway) strengthened the evidence for believing that some groups of workers in industries where exposure to electromagnetic fields may have been elevated have an increased risk of leukaemia, but not brain cancer. . . . These new studies add little to those previously reviewed by the group. Two new residential studies were also reviewed (from Sweden and Denmark). . . They do not establish that exposure to electromagnetic fields is a cause of cancer, although they provide weak evidence to suggest that the possibility exists."	"The views of the Advisory Group have been noted in the formation of restrictions on human exposure to electromagnetic fields developed by the Board, although at present epidemiological studies do not provide an effective basis for quantitative restrictions on exposure to electromagnetic fields."

Reference/Organization	Health Effects	Exposure Reduction/Prevention
The EMF Committee (1993:6), for the Oregon Energy Facility Siting Council	"Low levels of EMF are known to affect living things. However, it is not known if these effects are harmful to humans."	"The EMF Committee encourages exploration of low-cost ways to reduce or manage EMF exposure during this time of uncertainty. The EMF Committee believes it is premature to set 'health based' limits for exposure to low levels of 60 Hertz EMF at this time."
ORAU Panel on Health Effects of Low-Frequency EMF (1993:13), for The Committee on Interagency Radiation Research and Policy Coordination	". in our opinion, the evidence presented in these [two new Swedish] studies is not sufficiently compelling to alter the conclusions of the [1992] ORAU report."	Recommendations on EMF exposure reduction/prevention were not specifically addressed in this review.
Swedish National Electrical Safety Board (1993)	"In the light of the previous presented epidemiological studies, in particular the Swedish study 'Magnetic fields and cancer in people residing near Swedish high voltage power lines' by Maria Feychting and Anders Ahlbom, the Swedish National Board for Electrical Safety has revised the previous assessment of health hazards to the extent that the Board in the future <u>will act on the assumption</u> [emphasis in original] that there is a connection between exposure to power frequency magnetic fields from power lines and childhood cancer, when preparing regulation on electrical installations."	"The Swedish National Board for Electrical Safety will in consultation with representatives from the parties concerned, such as the Department of State, various authorities, research institutes and electricity utilities, analyse more closely the immediate risk and consider proposals for new regulations on electrical safety, if such should prove necessary."
The National Radiation Laboratory (1993:3), New Zealand Department of Health	"A reported weak association between the incidence of childhood leukaemia and proximity to high current carrying lines has led to intense study of this issue. There is yet, however, no conclusive proof that exposure to the ELF fields commonly encountered has any effect on health."	Recommendations on EMF exposure reduction/prevention were not specifically addressed in this review.
Swedish National Electrical Safety Board (1994)	"During the spring of 1994, those organizations [Swedish government organizations involved with EMF] concluded that knowledge regarding how weak magnetic fields affect humans is currently insufficient to set limits. Suspicion of a connection is however sufficient to recommend caution."	"Therefore, these guidelines should be followed in housing planning and construction if they can be implemented within reasonable costs: strive to site power lines and electrical facilities in such a way that magnetic fields are reduced; avoid building new homes, schools, day care centers, etc., in close proximity to existing power lines which have significant magnetic fields, if alternative sites are available; strive to limit significant fields in existing homes, schools, and workplaces."
Swedish National Board of Health and Welfare Working Group (1994)	"The existing epidemiological data cannot be used to support any definite conclusions as to whether exposure to electromagnetic fields increases the cancer-risk in any organ system. However, the possibility of there being a link between exposure and risk cannot be ruled out; especially with regard to child leukemia. . . There is no convincing epidemiological or vivisectional evidence for there being a link between exposure to electromagnetic fields and miscarriage, low birth-weight or malformation of children."	Recommendations on EMF exposure reduction/prevention were not specifically addressed in this review.

Reference/Organization	Health Effects	Exposure Reduction/Prevention
Advisory Group on Non-ionising Radiation (1994:79), U.K. National Radiological Protection Board	"Two residential studies of childhood cancer previously reviewed were from Sweden and Denmark. A further study from Finland has now been examined. The Group has concluded that all these studies were well controlled and substantially better than those that previously reported associations with childhood cancer. The studies do not establish that exposure to electromagnetic fields is a cause of cancer but, taken together, they do provide some evidence to suggest that the possibly exists in the case of childhood leukemia. The number of affected children in the studies is, however, very small."	Recommendations on EMF exposure reduction/prevention were not specifically addressed in this review.
Information Ventures, Inc. (1994:x-9), for Maryland Department of Natural Resources and Public Service Commission of Maryland	"Research on the potential health effects from exposure to power frequency EMF has continued at a modest level over the past year [June 1993-June 19941 and recently published studies have made important contributions to elucidating the nature of biological effects and to determine the possible implications of EMF exposure on human health. However, it is still not possible to arrive at definitive conclusions regarding the health effects from EMF exposure, based on the existing body of scientific evidence."	Recommendations on EMF exposure reduction/prevention were not specifically addressed in this review.
The Interagency Task Force Studying EMF (1995:4), for the Connecticut General Assembly	"No definitive cause and effect relationship between exposure to EMF and an increase in health risk has been established. The evidence available to us at this time is not sufficient to say whether or not a risk exists."	"We now think that the term 'prudent avoidance' is not sufficiently clear with respect to intent. [DPHAS] and theTask Force are advocating a strategy that calls for a pro-active program of providing information to the community about EMF and factors to consider if concerned individuals decide to reduce their exposure. We term that approach Voluntary Exposure Control."
The Criteria Group for Physical Factors (1995), for the Swedish Government	"The Criteria Group for Physical Risk Factors notes that animal experiments do not give sufficient support for a relationship between cancer and exposure to magnetic fields. Epidemiological studies show a certain credible, but weak, support for the hypothesis of an association between brain tumours and certain forms of leukemia and magnetic field exposure. An overall evaluation of both animal and epidemiological studies is that occupational exposure could possibly be a human carcinogen."	"The Criteria Group summarizes the situation such that the scientific data base is insufficient to develop limits of exposures.This does not exclude other steps to reduce exposure - based e.g. on some form of strategy of caution."
Wasti (1996:18), Virginia Department of Public Health for the Virginia General Assembly	"The preponderance of evidence for an increased risk of cancer in humans from exposure to EMF presented in the epidemiologic studies published so far, taken individually or collectively, can best be construed as tenuous, and does not allude to an inordinate hazard. The results of laboratory studies conducted on cells, tissues, and in experimental animals have shown that under certain conditions, exposure to EMF can produce changes in behavior and nervous system activity, alteration in biological rhythms and the production of certain hormones. However, it is not possible to infer that these effects are precursors of adverse health effects in humans."	Recommendations on EMF exposure reduction/prevention were not specifically addressed in this review.

Reference/Organization	Health Effects	Exposure Reduction/Prevention
Exposure of the Public to Non-ionising Radiation Ad Hoc Working Group (1996), for the European Commission	"Most biological studies suggest that exposure to low frequency electric and magnetic fields does not have any significant effects on mammalian development. Similarly, there is no persuasive evidence that ELF electromagnetic fields are able to influence any of the accepted stages in carcinogenesis. Effects on initiation are extremely unlikely suggesting that if there is an effect it will be at the level of promotion or progression. Here, the evidence remains confused, but with no clearly reproducible effect."	"It is important that biological, epidemiological and dosimetric research relevant to the health effects of non-ionising radiation exposure is continuously reviewed by international and national bodies with responsibilities in radiation protection. Based on the results, guidance and limits of exposure should be revised as necessary. Scientific bodies should continue to rely only on scientific data relating to well-established health effects of non-ionising radiation."
Swedish Agencies (1996), Guidante for Decision Makers	"The above mentioned groups of experts all come to the conclusion that exposure to low-frequency magnetic fields cannot be convincingly shown to entail elevated risks of cancer. Certain epidemiological studies, however, provide some cause for suspecting that there may be a connection with particular forms of cancer. . Every year in Sweden about 40,000 people develop cancer. According to some estimates, not more than about 100 of these cases might be related to exposure to magnetic fields."	"The research findings presented hitherto afford no basis for and cannot be said to justify any limit values or other compulsory restrictions on low-frequency electrical and magnetic fields. We do not know [which aspects of field exposure may possibly entail hazards], but even so we have come to believe that a certain amount of caution may be justified where exposure to low-frequency magnetic fields is concerned. **If measures generally reducing exposure can be taken at reasonable expense and with reasonable consequences in all other respects, an effort should be made to reduce fields radically deviating from what could be deemed normal in the environment concerned. Where new electrical installations and buildings are concerned, efforts should be made already at the planning stage to design and position them in such a way that exposure is limited"** [emphasis in original].
Committee on the Possible Effects of Electromagnetic Fields on Biological Systems (1996:executive summary), National Research Council for the U.S. Department of Energy. See also **Luben et al.** (1996) on page A-9.	"Based on a comprehensive evaluation of published studies relating to the effects of powerfrequency electric and magnetic fields on cells, tissues, and organisms (including humans), the conclusion of the committee is that the current body of evidence does not show that exposure to these fields presents a human-health hazard. Specifically, no conclusive and consistent evidence shows that exposures to residential electric and magnetic fields produce cancer, adverse neurobehavioral effects, or reproductive and developmental effects. An association between residential wiring configurations (called wire codes, defined below) and childhood leukemia persists in multiple studies, although the causative factor responsible for that statistical association has not been identified. No evidence links contemporary measurements of magnetic-field levels to childhood leukemia."	Recommendations on EMF exposure reduction/prevention were not specifically addressed in this review.

Reviews or Position Statements by National or International Professional and Private Organizations

Reference/Organization	Health Effects	Exposure Reduction/Prevention
American Conference of Governmental Industrial Hygienists, Inc. (1991: PA-60, PA-62)	"Overall, the epidemiological studies on the possible correlation between cancer risk and residential exposure to electromagnetic fields do not support the conclusion of a strong association. . For workers in electrical occupations, the available information indicates that these individuals have a small elevation in the risk of cancer , especially leukemia and brain tumors. However, a causal link between occupational exposure to power-frequency fields and cancer has not been established."	"In view of the presently available evidence based on experimental research with cellular and animal systems, as well as limited data from human exposures under controlled laboratory conditions, a TLV [threshold limit value] for sub-RF magnetic fields has been established that limits the maximum induced current density within the human body to 10 mA/m2 (rms)."
Walborg (1991:97,99,102), for the National Electrical Manufacturers Association	"Epidemiological evidence is presently insufficient to indicate a causal relationship between exposure of human populations to power frequency electromagnetic fields and any increased risk of cancer. Attempts to demonstrate an effect of power frequency electromagnetic fields on carcinogenesis in experimental animal models have been largely unsuccessful, except for an equivocal promotional or cocarcinogenic effect on chemically induced mammary carcinogenesis in the rat."	" any consideration to institute regulations regarding human exposure [to electromagnetic fields] would be premature."
Miller et al. (1993:40), for the Kansas Electric Utilities Research Program	"In conclusion, we are still in the discovery phase of whether EMFs or another toxin possibly related to power line proximity can induce or promote the development of a specific cancer. Only with time and a lot more research can we answer this question."	Recommendations on EMF exposure reduction/prevention were not specifically addressed in this review.
Health Effects institute (1993:9), HEI's proposed EMF Research Plan	"The strongest indication of a human health effect of exposure to EMF is from epidemiologic studies reporting an increased incidence of cancer. Results to date have been suggestive, but they have not provided conclusive evidence that EMF exposure increases risk for any type of cancer."	Recommendations on EMF exposure reduction/prevention were not specifically addressed in this review.
The Swedish Trade Union Confederation (1993: 14)	"An increasing number of studies-not least in Sweden-show links between occupational exposure to magnetic fields and certain forms of cancer. The fact that as yet it is not known how this biological effect functions and the fact that it is not yet regarded as proved that a link exists must not prevent the trade unions from trying to protect our members' health."	"The increasingly confirmed relationship between magnetic fields and cancer means that a principle of caution must be applied. Unneccessary exposure should be avoided and new environments be designed and equipped so that employees' exposure to magnetic fields is minimized."
American Industrial Hygiene Association (1993:2)	"At present, the AIHA finds that the lack of replicated studies, an accepted interaction mechanism in the laboratory studies, and an absence of significant associations with measured fields in the epidemiological studies, make it impossible to come to a definite decision regarding the magnitude of health effects associated with exposure to ELF"	"Good industrial hygiene and public health practice suggests that when there are conflicting data (as previously noted in this Position Statement) a cautious approach is recommended.The AIHA also supports the need for more research to close the current knowledge gaps."

Reviews or Position Statements by National or International Professional and Private Organizations

Reference/Organization	Health Effects	Exposure Reduction/Prevention
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Walbora (1991:97.99.102). for the National Electrical' Manufacturers Association	"Epidemiological evidence is presently insufficient to indicate a causal relationship between exposure of human populations to power frequency electromagnetic fields and any increased risk of cancer. Attempts to demonstrate an effect of power frequency electromagnetic fields on carcinogenesis in experimental animal models have been largely unsuccessful, except for an equivocal promotional or cocarcinogenic effect on chemically induced mammary carcinogenesis in the rat."	" any consideration to institute regulations regarding human exposure [to electromagnetic fields] would be premature."
Miller et al. (1993:40), for the Kansas Electric Utilities Research Program	"In conclusion, we are still in the discovery phase of whether EMFs or another toxin possibly related to power line proximity can induce or promote the development of a specific cancer. Only with time and a lot more research can we answer this question."	Recommendations on EMF exposure reduction/prevention were not specifically addressed in this review.
Health Effects Institute (1993:9), HEI's proposed EMF Research Plan	"The strongest indication of a human health effect of exposure to EMF is from epidemiologic studies reporting an increased incidence of cancer. . Results to date have been suggestive, but they have not provided conclusive evidence that EMF exposure increases risk for any type of cancer."	Recommendations on EMF exposure reduction/prevention were not specifically addressed in this review.
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American Industrial Hygiene Association (1993:2)	"At present, the AIHA finds that the lack of replicated studies, an accepted interaction mechanism in the laboratory studies, and an absence of significant associations with measured fields in the epidemiological studies, make it impossible to come to a definite decision regarding the magnitude of health effects associated with exposure to ELF"	"Good industrial hygiene and public health practice suggests that when there are conflicting data (as previously noted in this Position Statement) a cautious approach is recommended.The AIHA also supports the need for more research to close the current knowledge gaps."

Reference/Organization	Health Effects	Exposure Reduction/Prevention
AMA Council on Scientific Affairs (1994:9,12), American Medical Association	"That no scientifically documented health risk has been associated with the usually occurring levels of electromagnetic fields; nevertheless, the American Medical Association should continue to monitor developments and issues related to the subject."	"It would seem prudent for any company producing an electric appliance or product to begin planning to reduce the electric and magnetic fields produced by the product. . Physicians may advise that patients themselves can control some of their exposures to electric and magnetic fields. The family that changes its residence has some control over whether the next residence will have an adverse environmental characteristic, such as a high radon level in the living area or a high-voltage powerline or transformer next to the house."
Wisconsin Electric Utilities' EMF Task Force (1994:D22-A-2,D22-C-64), submitted to the Public Service Commission of Wisconsin	"The weight of the scientific evidence indicates that the studies to date, including new studies published since 1991, do not provide sufficient or consistent evidence to conclude that exposure to power line electric and magnetic fields pose health hazards."	"The utilities will include EMF as a factor to consider in siting and designing new facilities and will, wherever practical, make efforts to reduce exposure to magnetic fields."
International Non-Ionizing Radiation Committee of the International Radiation Protection Association, and the International Labour Organization (1994:4)	"Current scientific knowledge suggests that there are no detectable health effects and there is no reason to worry about health impairment due to exposure to electric and magnetic fields associated with the common use of electricity in the household, offices, and industry."	"The problem of present concern is the prevention of electrical accidents rather than the hypothetical risks due to exposure to very low electric and magnetic field strengths."
CIGRE Working Group 36.06 (1995:139)	"Although the recent epidemiological studies have contributed improved data on the possible link between EMF and cancer, the evidence for power-frequency magnetic fields as a cause of cancer is still weak and the risk factor, if any, is likely to be low. However, one must keep in mind that because of the small potential risk involved and the inherent limitations of the epidemiological studies, it may well be that such studies alone may not be able to provide a definitive answer to this important question."	Recommendations on EMF exposure reduction/prevention were not specifically addressed in this review.
American Physical Society (1995)	"While it is impossible to prove that no deleterious health effects occur from exposure to any environmental factor, it is necessary to demonstrate a consistent, significant, and causal relationship before one can conclude that such effects do occur. From this standpoint, the conjectures relating cancer to power line fields have not been scientifically substantiated."	"The costs of mitigation and litigation relating to the power-line cancer connection have risen into the billions of dollars and threaten to go much higher.The diversion of these resources to eliminate a threat which has no persuasive scientific basis is disturbing to us."
The EMR Alliance (1995:1), International organization of citizen action groups involved with EMF	"We believe that electromagnetic field (EMF) radiation is hazardous to life and constitutes a significant threat to the public's health."	"We are in favor of and hope to enhance local, regional, national and international efforts to reduce, mitigate and, where possible, eliminate hazardous exposures to EMF radiation."

Reference/Organization	Health Effects	Exposure Reduction/Prevention
Mild et al. (1996), Presidents of the Bioelectromagnetics Society	“A wealth of published, peer-reviewed scientific evidence indicates that exposure to different combinations of electric and magnetic fields consistently affects biological systems in the living body as well as in laboratories, including: altering the function of nerve cells, changing the density and healing rate of bone, disturbing the balance of important hormones, changing the growth rate and drug sensitivity of cancer cells, modifying the immune system’s ability to fight disease, altering the heart rate.”	“We are also concerned that international standards may be imposed before adequate scientific knowledge is available.”
Heath (1996:42), Vice President of Epidemiology and Surveillance Research at the American Cancer Society	“The weakness and inconsistent nature of epidemiologic data, combined with the continued dearth of coherent and reproducible findings from experimental laboratory research, leave one rather doubtful that any real biologic link exists between EMF exposure and carcinogenicity.”	Recommendations on EMF exposure reduction/prevention were not specifically addressed in this review.
Edison Electric Institute (1996), Position Statement on EMF	“Due to the importance of reliable and economic electric power to the health and well being of society, it is important to resolve issues regarding possible health effects of power frequency EMF, Accordingly, the Edison Electric Institute 1) supports and encourages federal and nonfederal scientific research into possible EMF health effects, exposure assessment, and field management techniques; 2) urges Congress to extend the authorization for the National EMF RAPID Program by one year, through 1998, to ensure the full five years of funding intended by Congress in the Energy Policy Act of 1992; 3) supports continuing dialogue and educational efforts regarding EMF, especially the wide dissemination and open discussion of research results; and, 4) will seek to ensure that EMF policy is based upon the best available scientific information.”	' supports and encourages federal and nonfederal scientific research into exposure assessment, and field management techniques.”
Luben et al. (1996), Press release issued by three presidents of the Bioelectromagnetics Society who were also members of the NRC committee on health effects of EMF. **See** the **Committee on the Possible Effects of Electromagnetic Fields on Biological Systems (1996)** on page A-6.	“Drs. Luben, Anderson and Stuchly agree with the [NRC] report’s key conclusions that the data are not convincing that there is a proven danger to the public from electromagnetic fields-but also that EMF exposure does result in a number of biological effects.They caution against taking the attitude that a lack of confirmed proof at this point in the study of EMF effects means that the question can be ignored. They point out that even in the case of cigarette smoking, it took nearly 50 years after the demonstration of a statistical association with lung cancer for scientists to define a specific cellular mechanism by which compounds in smoke could definitely cause the cellular changes associated with lung cancer.They emphasize that, in the view of scientists, research is the only way to find answers to the unexplained observations such as the apparent link between EMF exposure and some forms of cancer.”	Recommendations on EMF exposure reduction/prevention were not specifically addressed in this statement

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Appendix B

This appendix provides some annotated references that describe various methods for reducing the levels of EMF from electric power facilities, and for reducing human exposures to EMF produced from electrical sources in general. Methods to reduce EMF have been termed *field management, mitigation,* or prudent avoidance by various authors. These methods include actions that utilities can take when designing new facilities, and things that individuals can do to reduce their exposures to EMF. Many utilities now routinely consider "low field" designs when new transmission lines are planned, and some regulatory agencies require such considerations by applicants proposing new power facilities (see Chapter 5). Electric blankets and video monitors used with computers are examples of appliances that have been redesigned by manufacturers to produce lower fields than older models. The need for field reduction, however, remains somewhat controversial because scientists have generally not concluded that EMF cause adverse health effects. Some individuals and organizations argue that it is, therefore, premature to implement measures to reduce exposures to EMF.

Publications on Methods for Reducing Exposures to EMF

Clairmont B. (principal author). 1994. *Handbook of Shielding Principles for Power System Magneticfields.* TR-103630-Vl. Final report April 1994 in two volumes. Prepared by General Electric Company for Electric Power Research Institute. Palo Alto, California. Available from EPRI Distribution Center, 207 Coggins Drive, P.O. Box 23205, Pleasant Hill, CA 94523. Telephone (510) 934-4121.

"Volume 1 introduces the topic of magnetic field management, describes basic management principles, details the concept of shielding using wire currents, and provides the following practical information: examples of applications, a survey of commercially available ferromagnetic materials, a list of suppliers of materials and services, a discussion of technical symbols and units, and a glossary. Volume 2 describes the various numerical techniques used for computing shielding effectiveness of high-permeability or high-conductivity materials, including an overview of the commercially available numerical software packages. In addition, this volume discusses the use of multiple layers of high-permeability or high-conductivity materials, magnetic materials properties for low-frequency shielding, laboratory measurements of shielding effectiveness, and a description of harmonics and transients."

Commonwealth Associates, Inc. 1992. *Cost-Efectiveness Analysis Mitigation of Electromagnetic Fields.* Prepared by Commonwealth Associates, Inc. for State of Rhode Island and Providence Plantations, Committee to Study the Potential Health Effects of Electromagnetic Fields Emanating from High Voltage Transmission Lines, Cost Effectiveness Subcommittee. Available from Governor's Energy Office, State House, Room 111, Providence, RI 02903-5872. Telephone (401) 277-2850.

"The purpose of this study is to determine the relative cost effectiveness of various design options to reduce human exposure to magnetic fields produced by high voltage transmission lines. The scope of the study is limited to high voltage transmission at 345 kV and 115 kV as presently planned in the state of Rhode Island. The study is specific with regard to Rhode Island topography, demographics, transmission line design, costs and electric utility requirements."

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"Reducing electric and magnetic fields produced by electric transmission and distribution lines is largely a function of different engineering design techniques that lower or eliminate fields. This report emphasizes these engineering techniques and engineering research that may result in a reduction of electric and/or magnetic fields and therefore, exposure. Actions designed to control the proximity of people to electric and magnetic fields are discussed in Chapter 6."

EMF-RAD Consulting and Engineering Ltd. 1994. *Technologies Available to Mitigate Magnetic Field Exposure Due to Distribution Systems.* Prepared for Toronto, Hydro. Available from Stephen Au, Manager System Planning and Engineering Services Department, Toronto Hydro, 500 Commissioners Street, Toronto, Ontario, M4M3N7, Canada. Telephone (416) 591-4671.

"This report describes a study conducted for Toronto Hydro on the subject of technologies to mitigate power-system magnetic fields due to electrical distribution systems. The scope of the study included the policies and actions of utilities operating municipal distribution systems in North America, similar in size and function to those of Toronto Hydro, with respect to the electric and magnetic fields (EMF) issue and the implementation of field mitigation practices."

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"This chapter serves as an introduction to low-frequency electric and magnetic field mitigation and gives an overview of typical field management strategies with an emphasis on magnetic fields."

Horton W.F., Goldberg S. 1995. *Power Frequency Magnetic Fields and Public Health.* CRC Press Inc. Boca Raton, Florida.

"As we show in Chapter eight of this book, field mitigation is both difficult and very costly to achieve. Mitigation on a large scale would be an almost unthinkable economic burden using today's technology. . . . Generally, public agencies have chosen to evoke the principle of prudent avoidance in dealing with the magnetic field-health effects issue. We trace this issue in Chapter nine and follow with an appendix dealing with prudent avoidance on a personal basis."

International Non-ionizing Radiation Committee of the International Radiation Protection Association, International Labour Organization. 1994. *Protection of Workers from Power Frequency Electric and Magnetic Fields, a Practical Guide.* Occupational Safety and Health Series No. 69. IL0 Publications, International Labour Office, CH-1211 Geneva 22, Switzerland.

"The purpose of this book is to provide information on the possible effects of electric and magnetic fields at 50 and 60 Hz on human health and to give guidance on working conditions and procedures that will lead to higher standards of safety for all personnel engaged in the maintenance and operation of power frequency sources. . . . The following topics are covered in the guide: physical characteristics of electric and magnetic fields; measurement and levels of exposure at the workplace; mechanisms of interaction; laboratory studies and observations on working populations; occupational exposure limits; and prevention and exposure control measures."

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"This handbook provides utility engineers with a basic understanding of how transmission line design determines magnetic field levels. Featured in the handbook is a detailed examination of magnetic field levels associated with various line designs along with techniques and strategies for reducing magnetic fields. Possible options include compaction, splitting of phases, transposition, and shielding with wire loops."

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"This report guides the user through the technical background required to mitigate magnetic fields of power transmission lines, the performance of presently preferred designs, and the resulting designs proposed for application in Florida at 230 and 500 kV. Detailed engineering data is given in the appendices."

Oppel L.J. 1994. “Magnetic field Exposure Management.” Pages D22-E-53, in, Wisconsin Electric Utilities’ EMF Task Force. *Advance Plan 7. Technical Support Document 022, Electric and Magnetic Fields.* State Public Service Commission, 4802 Sheboygan Avenue, P.O. Box 7854, Madison, Wisconsin 53707-7854. Telephone (608) 266-5990.

This report reviews magnetic field management techniques for transmission lines, distribution lines, underground power lines, and substations.

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“The EMF Book explains in a straightforward way the scientific research that has prompted concern about EM field and EM radiation health effects, tells you how to look for EM field and EM radiation sources, and explains what you can do to reduce your exposures. You can take steps to protect yourself and your family without knowing every scientific detail about EM fields and EM radiation.”

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“These EMF design guidelines are intended to be used by Edison’s facilities designers. They describe the considerations and methods available for evaluating no-cost and low-cost measures to reduce magnetic fields in new construction. The purpose is to give the designer a portion of the tools and knowledge necessary to assist in determining the most appropriate design for each application.”

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“This Primer is in response to the contemporary interest in magnetic fields from electric power transmission lines. The Primer presents definitions, and discusses magnetic field management options. The audience of this Primer are technical personnel of electric utilities or other organizations involved in the issue of magnetic field from power lines.”

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DOE/BP 2938 December 1996 1 M