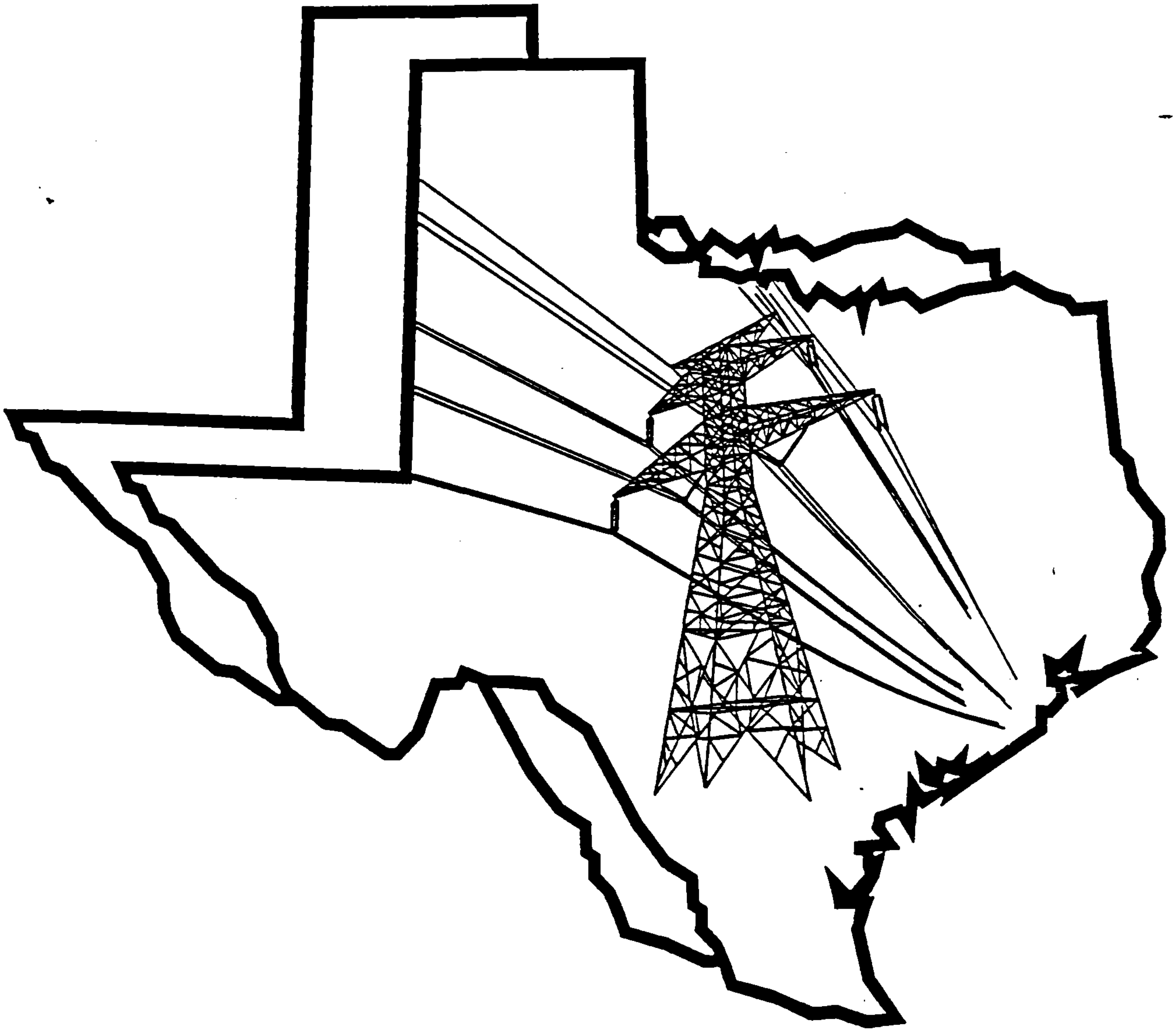
HEALTH EFFECTS OF EXPOSURE TO POWERLINE-FREQUENCY ELECTRIC AND MAGNETIC FIELDS

ELECTRO-MAGNETIC HEALTH EFFECTS COMMITTEE



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PREFACE

The Electro-Magnetic Health Effects Committee has completed its initial examination of the literature and research involving electric and magnetic fields (EMF) and public health. This report is the result of three years of work by the Committee and represents a thorough study and analysis of the EMF issue. This report contains the Committee's review of EMF engineering and exposure assessment, epidemiologic studies, experimental studies, judicial issues, regulatory issues, and policy issues, and includes the Committee's recommendations to the Public Utility Commission of Texas. The conclusions and recommendations in this report represent the consensus of the Committee, and do not necessarily reflect the opinions of the Commission or the Commission Staff.

The Committee was originally proposed by a Commission task force that was organized to review the rules, practices, applications, and forms concerning transmission line certification in Texas. The task force identified numerous on-going studies concerning EMF and public health and believed that this issue required additional monitoring by qualified individuals. In February 1988, the task force recommended that the Commission appoint a Committee to study the EMF issue and report its findings annually to the Commission. The Committee met for the first time in January, 1989.

The Public Utility Commission of Texas recognized the increase in concerns regarding exposure to EMF and its potential effects on human health. The Commission agreed with the task force recommendations and on April 18, 1988, resolved that a Committee be appointed to study the literature and monitor the research concerning the possible health effects of exposure to electric and magnetic fields.

The Commission originally selected seven members and added an eighth member in September 1989. The members of the Committee represent the research community, the public health community, and electric utilities. They hold credentials in medicine, epidemiology, biology, engineering, health physics, bio-statistics, and public policy. The Committee members have served as volunteers and have not been reimbursed by the Commission for travel expenses or for the significant amount of time each member has devoted to this project. The Public Utility Commission of Texas owes the Committee members its sincere thanks and appreciation for the exceptional effort and commitment to this project.

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1. Introduction and Background

On April 18, 1988, the Public Utility Commission of Texas (PUC) established the Electro-Magnetic Health Effects Committee for the purpose of addressing the possible health effects of powerline-frequency electric and magnetic fields. The Committee was charged with the responsibility for researching the literature, monitoring on-going research, and reporting their findings annually to the Commission. This Committee was established as an independent review body which has served without compensation. Committee members were drawn from the research community, the Texas Department of Health, and suppliers of electric services. They are familiar with the scientific literature on electric and magnetic fields (EMF) and the methodology employed in this area. This report is the result of their efforts.

The report is divided into this Overview and major sections on the following topics: (1) Introduction and Background, (2) Engineering and Exposure Assessment, (3) Epidemiology of Health Effects and Exposure to EMF, (4) Experimental Studies, (5) Judicial Issues, (6) Regulatory Issues, and (7) Policy Issues and Options. In addition, appendices to the text are included.

Before the 1970's, health issues associated with electricity were limited to safety issues related to electrical shock. Then writers of a few reports from Eastern Europe suggested certain health effects in individuals exposed to electric and magnetic fields. In the mid-1970's, the State of New York began a 5-year, $5-million EMF research program. By the late 1980's, the scientific literature contained many EMF reports. The uncertainty inherent in such work has caused public concern because of the suggestion of cancer and other health effects.

Although public concern over EMF health effects has focused principally on transmission lines, such fields are produced by all electrical devices in everyday use.

Electric and magnetic fields are produced by voltage differences and current flow changes in electric transmission lines. Electricity generation and transmission is accomplished in three stages: (1) generation and passage through a step-up transformer, (2) transmission through high-voltage lines, and (3) passage through a step-down transformer and transfer to lower-voltage distribution lines. Alternating current (60 Hertz, or cycles per second) is standard in North America.

Electric and magnetic fields have been the subject of scientific study since the 19th century. Energy content from EMF is much lower than that from ionizing radiation (such as x rays) and is too low to cause heating effects. Even so, observations of some biological effects combined with findings from epidemiologic studies have increased the public's concern about possible human health effects. It is not clear which properties of the EMF environment among many should be measured, e.g., field intensity, duration of exposure, etc. In addition, it is clear that home appliances can produce magnetic fields as strong or stronger than those from transmission lines. Nonetheless, the public generally views involuntary exposure to be more of a health hazard than voluntary exposure. Research into this important issue is continuing largely through the efforts of the U.S. Department of Energy and the Electric Power Research Institute. Many uncertainties remain. This report concentrates on scientific, regulatory, and judicial aspects of EMF.

2. Engineering and Exposure Assessment

Demonstration of a cause-and-effect relationship between observed health effects and exposure to EMF is basically dependent on the accurate assessment of exposure to EMF and the resulting absorbed dose to cells, organs, and body. The electric and magnetic fields resulting from the everyday use of alternating current are complex, varying in properties such as wave shape, frequency, harmonic content, and transients (spikes). In vivo laboratory studies on animals and in vitro studies on cells, as well as epidemiologic studies, have failed to clearly identify any single field exposure parameter as a major agent in the induction of adverse health effects. The usual problems associated with applying data obtained from laboratory animals to humans are particularly important in the evaluation of EMF health effects. Furthermore, field measurements of exposure to electric and magnetic fields are by necessity limited to a determination of basic environmental properties. Most exposure assessments to date have been based on long-term average exposure rates. In this process, important data may not be recorded, and effects of exposure (dose) rate may be missed.

The Institute of Electrical and Electronic Engineers (IEEE) has established standards for methods used in measurement of EMF from power transmission lines. Development of standard methods for measuring EMF in other environments, such as residences, is needed. Various instruments to measure EMF are available commercially. These are capable of reliable measurement of individual EMF parameters, but no one measurement system exists for completely characterizing EMF in the environment.

Regardless of the imperfect (and perhaps inaccurate) nature of current exposure assessment methods, data so obtained are essential to the scientific evaluation of possible health effects. In the laboratory, conditions of EMF exposure can be carefully controlled. Assessing the exposure of the public to EMF is, however, beset by a multitude of complicating factors that determine the effect of the fields as well as actual exposure. This situation causes confusion when an effort is made to apply causal relationships established in controlled laboratory studies to human populations.

In situations where it is difficult or impossible to make actual EMF measurements, exposure rate estimates can be generated by appropriate computer calculations. Reliable programs exist for calculation of EMF in the vicinity of power transmission lines, and more capable programs designed to calculate magnetic fields in the more complex residential indoor environment are under development.

When potential health effects of EMF from transmission lines are evaluated, background EMF needs to be considered. The average natural magnetic field of the earth at Texas latitudes, which is static in contrast to such fields in most "technologically enhanced" environments, is around 500 milliGauss (mG).

The natural electric field in the atmosphere is 130 volts per meter near the earth's surface. As in the case of the natural magnetic field, the natural electric field is essentially static, while electric fields due to use of electricity in the home or proximity to power transmission lines are alternating at a rate of 60 Hertz.

The magnetic field (flux density) directly beneath a 345-kV transmission line carrying an average load is about 130 mG. Design of transmission lines can strongly affect the magnitude of the EMF generated by the lines. Generally speaking, raising the height of a line above the ground reduces the strength of EMF outside the rights-of-way. Burying transmission cables, however, does not assure a significant reduction in the exposure to magnetic fields.

It has recently been found that the average magnetic field intensity within a U.S. home ranges from 0.5 to 1.0 mG and that average residential electric fields range from 5 to 20 volts per meter. Operating electric appliances, for example, an electric can opener, may generate a magnetic field up to 20,000 mG nearby. The normal combination of distance from an appliance and infrequent use reduces the possible significance of this source of EMF exposure.

3. Epidemiologic Studies of EMF Exposure

Epidemiology is the study of the incidence and distribution of human disease and injury. Epidemiologists organize the study of the complex process of disease causation in terms of the disease agent, the environment, and the host. Epidemiologic studies are organized into two types: descriptive and analytic. Descriptive epidemiologic studies explore patterns of disease in whole populations (correlational studies) or specific subgroups in a population (cross-sectional studies). Analytic studies characterize subjects that do or do not have a specific disease (case-control studies) or subjects who share a common risk factor for a disease (cohort studies). Of major concern in all types of epidemiologic studies is the potential for bias and confounding factors. Bias is avoided by stringently defining subject selection criteria and maintaining quality control over measurement procedures. Confounding factors are accounted for by understanding the complex interrelationships between exposure and disease.

In epidemiologic studies of EMF and cancer, scientists have attempted to define the incidence and distribution of health effects in populations exposed to electric and/or magnetic fields. However, the effectiveness of these studies has been limited by the use of indirect, imprecise, and/or inaccurate measures of exposure. Uncertainty in exposure measurements is magnified by the absence of a plausible biological effect mechanism in any EMF-cancer association and by the difficulty of formulating a dose-response relationship. No proper measure of EMF exposure has been defined.

The exposure assessment methodologies currently in use are surrogate or indirect measures of exposure, exposure models, and field measurements. Indirect EMF exposure measures which have been used are wire configuration codes, job titles, and census codes (indicators of occupation). Exposure models based on historical data have been used to project exposure values. Field measurements provide screening information for short-term exposures but may not give good indications of average long-term exposures.

Various categories of wiring configurations have been devised by researchers to substitute as measures of exposure in homes. These include, for example, very high current configurations (VHCC) and ordinary low current configurations (OLCC), both of which are dependent on the proximity of a dwelling to specific types of powerline wiring configurations.

Job titles have also been used as surrogates for exposure to EMF. Occupational epidemiologic studies have focused on telecommunications workers, electrical engineers, and other occupations considered to be exposed to EMF. However, actual exposures in these groups were largely unknown and were assessed on the basis of exposure categories. One study attempted to determine actual occupational exposures by using portable dosimeters for measuring individual exposures to EMF. Even within a single job category, considerable variability in field exposures was found.

Field measurements have shown some promise when used in comparison with wiring configurations and for linking spot measurements to 24-hour average magnetic fields. However, a single 24-hour measurement may yield imprecise results. A model based on measurement data seems to provide a better index than the measurements alone.

Exposure assessment studies are also subject to confounders. Subjects may be exposed to carcinogens in the environment as well as to EMF. A true confounder will be related to both EMF and cancer. In one EMF study, traffic density was studied as an indirect measure of exposure to vehicle emissions and benzene (both related to cancer), and a statistically significant association between cancer and traffic density was found. In another study the "wire code effect" was most pronounced among females, older children, those living in multi-family housing, disadvantaged persons, and those whose mothers smoked during pregnancy. These outcomes indicate the importance of other factors in correlation with cancer risk.

In order to assess the results of epidemiologic studies of EMF, one must consider both internal and external validity. Internal validity is concerned with the criteria, procedures, attention to confounders, and chance that go into designing and performing a study. External validity is concerned with how the results of a study can be generalized and whether the study addresses the causal nature of the association between EMF and disease.

After confirming that a study is internally valid, epidemiologists follow several guidelines to aid in the determination of external validity. These include strength, consistency, specificity, temporality, dose-response gradient, biological plausibility, coherence of evidence, and effect of intervention. The magnitude of risk ratios or strength, for example, can be used to partially assess the external validity of an epidemiologic study. Risk ratios less than 2.0 are likely to be affected by bias or confounding; risk factors greater than 5.0 are more likely to reflect a true increase in risk. A causal hypothesis may be further strengthened when experimental evidence is available. Laboratory or experimental studies completed under controlled conditions provide valuable data regarding the generality of a hypothesis that is being considered.

An essential component of epidemiologic evidence in the study of human cancer and its causes is time trends for various cancers. In the United States, such data have been compiled by the American Cancer Society back to 1930. Data for the years 1930-1987 for various cancer sites including lung, leukemia, brain, breast, and total cancers for males and females and adults and children were compiled for this report. One of the important findings in these data is the effect of the shifting age distribution of U.S. population. Total cancer mortality rates appear to have doubled over the last 50 years, but when adjusted for changing age distributions, the rate increases by only about 20% over the same time interval. An increase in the size of older age groups necessarily leads to an increase in the number of people dying of diseases associated with old age, which include cancer. In addition, the total age-adjusted cancer mortality rates change dramatically when lung cancer deaths are subtracted. Mortality rates for cancer minus lung cancer have remained nearly constant for males and have actually decreased for females over the period of study.

Of particular importance to this study are the findings for male adult leukemia and brain/central nervous system (CNS) cancers, and male and female childhood leukemia, brain/CNS, and total cancers. Mortality rates for all these cancer sites were undergoing substantial increases prior to the exponential growth period (beginning in 1945) in U.S. electric power consumption. In general, mortality rates for these cancers began to level off or decline after the period of rapid increase in electric power consumption.

In previously published reviews of EMF epidemiologic studies which are cited in this report, results from both residential and occupational settings were analyzed. Two initial studies of EMF and disease were done by Wertheimer and Leeper in 1979 and 1982. In the former study, the authors found a excess of high-current wiring configurations near former homes of children who had died of cancer, and in the latter study, the authors found an increase in adult cancer mortality associated with high-current wiring configurations. Other EMF reviews included a study of residential childhood leukemia and exposure to EMF with a summary odds ratio of 1.33, a residential exposure study of childhood cancer of the CNS with an odds ratio of 2.44, an occupational exposure study for leukemia with a risk estimate of 1.18, an occupational exposure study for myeloid leukemia with a risk estimate of 1.46, and several other occupational exposure studies. Many of the studies mentioned in the reviews cited in this report lacked precise assessments of exposure. One study for male breast cancer among telephone workers reported a standardized incidence ratio of 6.5, which has been interpreted to lend support to the proposal that EMF increases cancer risks by interfering with melatonin production. However, melatonin production may be independently affected by the shiftwork of the subjects.

Childhood cancers associated with residential EMF exposures were explored in five studies. Two of the five studies exploring associations of EMF with total childhood cancers reported significant associations with odds ratios of 2.22 and 2.10. With regard to childhood leukemia, none of the studies showed a consistent association with EMF, but two produced odds ratios of 2.35 and 2.10. The findings for childhood tumor of the CNS were also inconsistent with only one study producing a moderately elevated odds ratio of 2.86.

Adult cancers associated with residential exposures were evaluated in five studies. Only two out of the five studies produced significant results. One reported an association of EMF with total cancer (odds ratio of 1.28) and associations for lymphomas, cancer of the CNS, uterus, and breast. The other reported a significant association with lung cancer. In addition, four of the five studies reported weak associations of EMF with adult leukemia.

This report evaluates occupational EMF studies in association with all cancer sites, leukemia, tumors of the CNS, melanoma, and other cancer sites. In addition, this report evaluates several studies which examined the associations between paternal occupations having potential for EMF exposures and childhood cancers and adverse effects on reproduction. This report also evaluates 15 studies of the association of occupational exposures with all cancer sites. Because of differences in definitions, methodology, and other inconsistencies, it was impossible to determine any causal relationships. Leukemia incidence among occupationally exposed individuals has been given the most attention, and results for this site are suggestive of a causal association. Among 15 studies of leukemia and EMF, several have yielded weak, but statistically significant, results. However, problems with confounding factors and inaccurate exposure assessments limit the usefulness of the leukemia results. Cancer of the CNS has also received increased attention. Studies of this site have been beset with the same problems as the leukemia studies, and half of the studies have produced inconclusive results. Significant results were reported for associations of job categories with malignant melanoma and eye cancer, but not for testicular cancer. Finally, three of six studies of childhood cancer/paternal occupation which were evaluated in this report showed significant results. Five studies were completed on adverse reproductive effects, and in three of these studies statistically significant associations were found with spontaneous abortion, frequency of abnormal pregnancy, and congenital malformation.

Adding to the public's concern over cancer and EMF has been the misuse of cancer epidemiologic data. Because cancer incidence data are generally unavailable, time-trend studies are usually based on mortality rates. Mortality rates can be expressed in several ways, but in order to present a true picture, two factors affecting such presentations must be taken into account: data must be age-adjusted to account for shifting age distributions in the population of the U.S., and improvements in medical care which have dramatically decreased the proportion of the population dying from infectious diseases must be heeded. Consideration of these two factors produces a much different view of the present importance of cancer as a cause of death. In addition, no positive correlation is seen between age-adjusted cancer mortality trends and increases in U.S. electric power consumption, which one would expect to see if an EMF relation exists. (Lung cancer, of course, remains at the top of the list for cancer mortality.)

Utilizing cancer statistics, risk managers in Federal regulatory agencies seek to achieve protection of public health and the environment while responding to the requirements of the Office of Management and Budget, defending the technological and economic feasibility of a proposed action, and following legislative mandates. Ultimately, risk managers respond to specific problems based on assessments which are formed using accepted scientific criteria. However, several models for risk assessment have evolved. New approaches to risk assessment are being formulated which recognize the importance of a scientific approach to risk decisions.

Historically, the attention surrounding EMF grew out of public concern in the 1960's for the aesthetic and nuisance problems related to high voltage transmission lines. Reports in the late 1960's and early 1970's by Soviet scientists concerning possible health effects of EMF changed the focus of public concern. Western scientists failed to confirm the Soviet findings, except that a study in Denver in the late 1970's seemed to confirm the earlier studies. Negative findings did not ease public concerns.

In conclusion, much disagreement exists over the relationship, if any, between EMF and disease. Available epidemiologic evidence has produced limited conclusions. Findings related to leukemia remain suggestive, and associations with cancer of the CNS and other cancer sites are inconclusive.

In order to improve the quality of future EMF epidemiologic studies, the Committee offers several recommendations. The exposed population must be well defined. There should be more than one reference cohort. More work needs to be done to accurately assess the complex nature of EMF exposure. New EMF measurement technologies need to be explored. The relationship, if any, between residential wiring configurations and EMF exposure needs to be studied. The biological basis of any health effects in humans needs further study. Epidemiologic results should provide guidance for new experimental studies. Special care must be taken in future studies to control for confounders and to avoid internal inconsistencies.

4. Experimental Studies of EMF Exposures

The Committee examined the results of numerous laboratory experiments, comprising in vivo (alive) studies of EMF effects on animals (e.g., rats, baboons) and in vitro (test tube) studies at the cellular level. These studies focused on animal behavior, cancer initiation and promotion, developmental and growth effects, endocrine system and immunity and cell-cell (membrane) interactions.

While the quantity and quality of EMF research have improved dramatically in recent years, the EMF effects data base is still in a state of infancy when compared to the research literature on other potential environmental exposure risks. Although laboratory studies generally provide a greater opportunity to control extraneous variables than do epidemiologic and field studies, many opportunities still exist for sources of error to enter into even the best designed study. It is possible that the EMF literature, like most scientific literature, contains false positives and false negatives. The Committee has found that the scientific literature on EMF contains results of laboratory studies that were performed under a variety of exposure metrics (e.g., frequencies, field intensities, exposure duration, earth's static magnetic field). Thus, the inconsistencies and contradictions of study findings may be due to unknown errors and/or the numerous aforementioned laboratory conditions. This circumstance makes it difficult to sort through the literature, interpret the evidence, and draw definite conclusions with respect to EMF effects.

Nonetheless, the Committee believes that, based on its evaluation of the laboratory and epidemiologic literature, there is at this time no conclusive evidence to suggest that EMF due to electric power transmission lines poses a human health hazard. The Committee believes that this conclusion is basically corroborated in other EMF literature summaries and background reports prepared by expert scientific and research panels.

The following observations can be summarized on the basis of the studies evaluated by the Committee:

The interaction of variables which control actual exposure to EMF is poorly understood. Undoubtedly, the inconsistencies and contradictions found in the scientific literature are due, at least partly, to this fact.

Under certain circumstances, animals and humans can detect and avoid electric fields. However, no research to date has presented any conclusive evidence that these fields, detected or not, produce any deleterious and/or long lasting impacts on animal or human behavior.

One of the current models for carcinogenisis involves two steps, initiation and promotion. The initiation step involves direct or indirect permanent damage to the cell's genetic material (DNA). Ionizing radiation and certain chemicals have been identified as cancer initiators. Promotion is characterized by uncontrolled cell growth (tumor formation) after exposure to an initiator, which causes or allows the expression of genetic damage. Neither electric nor magnetic fields are energetic enough to cause damage to DNA, and it is generally accepted that power frequency fields are not cancer initiators. However, scientists have suggested that EMF may be a cancer promoter. No firm conclusions can be drawn on the promotion theory at this time. Hypotheses are only now being advanced. Additional information is clearly needed.

Most of the EMF studies reviewed by the Committee found no teratogenic effects during embryonic development or during postnatal growth. A few studies do show effects. Some show effects only under "pulsed" fields, which are not normally associated with 60-Hz alternating current transmission. Certain studies show effects using one animal strain, but no effects with another. A high incidence of effects is observed in the controls of various studies, making interpretation of the data difficult. Overall, these laboratory studies tend to lead to the conclusion that there is no proven detrimental effect on prenatal development or postnatal growth from exposure to EMF.

It has been suggested that exposure to EMF can affect animal immune systems. Whole-animal studies have not shown such an effect, but certain cellular studies indicate possible effects. Hypotheses need to be developed and tested before any definitive conclusion can be drawn.

Several studies suggest that EMF exposure causes changes in the function of animal endocrine systems. For example, reduction in night-time melatonin production and alteration of biological rhythm have been recorded in animals exposed to 60-Hz fields. Numerous physiological effects due to melatonin reduction have been hypothesized, but the potential health effects due to such reduction needs further investigation.

Many in vitro studies have shown no effect on cells exposed to EMF, while others have shown positive effects. Although the results of these studies are complex and inconclusive, a growing number of positive findings imply that, under specific conditions, EMF can produce cellular changes. For example, levels of calcium which is involved in the regulation of numerous physiological processes have been shown to be affected in several test systems. The significance of these results is unknown.

Although effects have been observed at the cellular level, with most being attributed to changes occurring at the cell membrane, the actual biophysical and/or biological mechanism is unknown. Various mechanisms have been postulated, but all are speculative. More research is needed to evaluate these mechanisms. If a mechanism is established at the cellular level, this will support the positive laboratory and epidemiologic studies.

5. Judicial Issues

Although the EMF health effects issue is still actively debated in scientific circles and the public press, it has been a factor in several types of judicial proceedings for some time. An increase in judicial proceedings on this issue is expected. As used here, "judicial" includes siting, zoning, condemnation, and tort proceedings. The PUC is concerned only with transmission line siting considerations.

An early concern about EMF health effects was expressed during Public Service Commission hearings in New York in the mid-1970's on a proposed 765-kV transmission line. Since then, many proceedings have involved presentation of evidence relative to the EMF health effects question. Over 200 proceedings involving EMF cases related to power transmission and substations have been reported. Of more local interest, nine Texas electric utilities have reported one or more proceedings where EMF or other health effects issues were raised.

Review of the information available on EMF-related judicial proceedings shows that, to date, little weight has been given to EMF health effects claims by objectors, intervenors, and plaintiffs. Due to public perceptions of potential hazards and scientific interest, however, the EMF issue is assured continued involvement in judicial proceedings. To respond to these continuing concerns, the utilities are developing strategies including keeping up with EMF-related research, complying with regulations regarding the planning and siting of facilities, surveying public awareness about EMF health effects, and developing public education and information programs.

6. Regulatory Issues

As powerline-frequency transmission grids have expanded, so have the health concerns of those citizens living, working, or going to school close to power lines. Some citizens believe that regulations are necessary to protect public health. Such regulations are being contemplated and enacted in some states.

Several approaches to regulations can be considered for controlling power line placement. Specific circumstances may dictate which approach is used. When adopting regulations, a government agency may use a standard (an acknowledged criterion for comparison) or a limit (a specified level which is restrictive). Other options are to use a guideline (an optional standard or limit) or a criterion statement (usually a document for making informed decisions about regulations). Ordinarily, regulations which are protective of health are based upon health risk assessments, an approach which takes into account all the evidence and weighs benefits versus risk to assign an acceptable level of safety.

If health-based regulations designed to protect the public or exposed workers are contemplated for transmission line siting, explicit health data are required. At present, however, no such data exist, nor is there any other rational approach for setting exposure regulations to protect public health. Before occupational regulations can be adopted, a consistent health effect must be found which is related to a measure of EMF exposure (such as frequency, intensity, or time). The necessary basic EMF data would then be combined with the so-called "healthy worker" criteria which define possible exposure time on the job and basic human physiological quantities. Similarly, biological evidence, quantification of dose, and risk assessment information must be available to set regulations for populations. Any regulations written in the absence of the mentioned data would offer no protection and could possibly hinder further investigations into real health effects.

International organizations such as the World Health Organization, the International Radiation Protection Association, and some countries (the United Kingdom and Australia) have addressed the EMF issue. These groups have found that the scientific data suggesting health effects due to long-term environmental EMF exposure are not persuasive.

In the United States, the Congress, several federal agencies, a few institutes, and some national associations have performed some preliminary work on the EMF issue. Although the federal government has no clear mandate or authority to take regulatory action concerning 60-Hz EMF and the existing evidence does not compel immediate action, some federal action has occurred. Congress has hosted hearings to collect testimony on the issue; the U.S. Environmental Protection Agency has conducted a review of EMF scientific literature; the U.S. Department of Energy has maintained a strong research program in the area of basic EMF science; the U.S. Department of Transportation is evaluating "maglev" trains; and several other agencies have maintained a more limited involvement in the area. Organizations like the National Council on Radiation Protection and Measurements and the American National Standards Institute have not pursued the issue at a rigorous level but may do so when the scientific results become less speculative. Associations like the National Association of Regulatory Utility Commissioners and the Conference of Radiation Control Program Directors have urged greater federal involvement.

At present, the only generally applied national standard for EMF is the National Electric Safety Code, which deals with reducing shock hazards from transmission lines. This code is not intended to provide protection from possible long-term health effects due to chronic exposure.

Because of the lack of federal leadership on the EMF issue, the states have responded individually. The result is varied and lacks consistency. The states' responses have fallen into four categories: (1) take no action, (2) study and report on the issue, (3) fund research, and/or (4) use regulatory authority to establish standards. At least one common thread runs through these efforts: In the absence of a firm dose-response relationship or intended results, no method for evaluating the benefit of EMF standards is available. In the body of this report, the Committee details the actions taken by seven states.

Texas powerline siting problems are similar to those in other states. In some cases siting permit applications have been contested, and the applicants have been taken to court. A health-based standard would have simplified the siting process by providing design criteria to achieve compliance. Without clear evidence upon which to develop a health-based standard, the Commission may make use of Section 23.44 of the Public Utility Regulatory Act, which addresses new construction. Section 23.44 is based on American National Standards Institute (ANSI) and National Electric Safety Code (NESC) standards. If EMF standards are issued by ANSI and/or NESC, the Commission could readily adopt them as guides. A question remains, however, about regulatory jurisdiction over city-owned utilities in siting questions. Another option for the PUC is to defer to the Texas Department of Health which has the ultimate responsibility for developing statewide health standards.

7. Policy Issues and Options

The current status of scientific evidence regarding EMF health effects is unclear. There is no definitive indication that EMF exposure can affect health, and there are no data that establish convincingly that it does not. In fact, as is often the case in situations involving very low probability cause/effect relationships, it may not ever be possible to prove an effect or the lack of an effect.

With respect to the EMF health effects issue, state legislatures find themselves in a quandary. Acceptance of false positive conclusions may result in a significant expenditure of taxpayers' money and divert attention from efforts to seek the true source of any increased risk. By contrast, not acting on false negative conclusions is likely to be interpreted by the public as irresponsible disregard for citizens' safety. Therefore, it seems reasonable to expect legislatures to actively support efforts to resolve the conflict.

Regulatory agencies normally address scientific uncertainty, such as the EMF health effects question, through procedural mechanisms similar to those used in the courts and legislatures. The details of the mechanisms vary considerably depending on the nature of the regulatory agency and its legislative charter. Political pressures to "do something" about the EMF issue may result directly or indirectly in the search for regulatory relief, especially if no action is achieved at the judicial or legislative levels.

In at least 17 states, legislative or administrative agencies have formally considered the possibility of health effects as a result of EMF exposure. Responses range from dismissal of the question due to lack of evidence (Wyoming) to codification of formal EMF limits in transmission lines (Florida). Courts and legislatures are actively considering actions in several states.

Different responses and their rationales are tied to different views of what constitutes the key problem in the EMF debate. There have been at least four different ways to define the EMF "problem", each with distinctive views of the scientific evidence, of the proper role for science to play, and of the proper perception of risk. More importantly, each definition carries a policy prescription along with it. In the absence of a conclusive body of scientific findings that would provide a firm grounding for deciding which of the four ways of constructing the problem is the most appropriate, one is left to decide largely on the basis of pre-existing beliefs and values that each of us brings to the EMF issue.

In this instance, the values of experts alone may provide too narrow a basis for legitimating one definition of the problem over others. Recognizing this limitation, the Committee recommends that, until science can provide a clearer path, state officials should engage the public in open discussions of both the evidence to date and the public values that influence its interpretation.

CONCLUSIONS AND RECOMMENDATIONS

The following are the Committee's overall conclusions and recommendations regarding standards, siting criteria, research, and public education.

1. Standards

1.1 Conclusions

The Committee has examined much of the current EMF scientific literature. Many epidemiologic studies have investigated the possibility of an association between disease and residence near installations transmitting electricity. Epidemiologic studies have most frequently investigated the possibility of an association between various types of cancer and exposure to EMF. To date, the results from these epidemiologic studies have been inconsistent and inconclusive.

The results of the laboratory studies evaluated by the Committee are also inconsistent and in some cases inconclusive. However, it is apparent that under specific exposure conditions, biological changes do occur. It appears that many variables (e.g., frequency, intensity, exposure duration, field orientations) can affect the results of these studies, which undoubtedly play an important part in the inconsistencies reported in the literature.

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. In general, the Committee's evaluation is corroborated by other EMF literature summaries and background reports.

The Committee concludes that at present there is insufficient evidence regarding human health effects of EMF to provide the basis for a health-based standard. The Committee can find no reason to create arbitrary numbers to use as a desired level of exposure, because the use of such numbers cannot be argued or defended on the basis of scientific evidence. The primary objective of the Committee is the protection of public health, and the Committee can find no scientific argument to support standards, either through guidance or through regulatory criteria.

The Committee has reviewed various state EMF standards. However, the use of numbers for an arbitrary standard in the absence of scientific justification sets a de facto risk level which is not supported by available evidence. Use of such numbers, which is strictly political, can generate a false sense of security, diverting resources from evaluating a genuine risk associated with some other environmental factor.

The Committee concludes that regulatory activities should be divorced from the EMF issue, at this time, and that the Public Utility Commission of Texas (PUC) take action regarding the EMF health effects issue only when, or if, action can be justified on a public health basis. If such action is required, the Committee concludes that the issue be referred to the Texas Department of Health (TDH), since the PUC does not have authority over all EMF sources (e.g., appliances, home wiring). The TDH is the state agency with authority in health matters.

1.2 Recommendations

The Committee recommends that neither the PUC nor other state authorities attempt to set EMF standards through guidelines, regulations, or legislation.

Should new evidence emerge establishing a clear association of human health effects from EMF exposure, justifying promulgation of standards, the Committee recommends that the EMF issue be referred to the Texas Department of Health.

2. Siting Criteria

2.1 Conclusions

The Committee concludes that at present, the existing criteria used by the PUC for siting transmission lines appear to be adequate. The Committee concludes that a plan for engineering interventions is not warranted at this time. The Committee noted that "prudent avoidance" in siting of transmission lines has been the de facto philosophy in the PUC criteria since 1976, by avoiding population centers, historical sites and existing facilities. Matters of safety and rights-of-way criteria have influenced the selection of routes. Based on current evidence, the Committee finds this approach adequate and acceptable.

2.2 Recommendations

The Committee recommends that the PUC continue its policy of de facto "prudent avoidance" in the siting of transmission lines. We further recommend that, at this time, the PUC not expand existing routing criteria to include concerns regarding health effects of EMF exposures.

3. EMF Research

3.1 Conclusions

While the quantity and quality of EMF research have increased, the EMF effects data base, however, is still in a "state-of-infancy" when compared to the research literature on risks to other environmental exposures. Continued research will help to reduce the current level of ambiguity inherent in EMF findings, while increasing the certainty of research results and confidence in research conclusions. The Committee concludes that the research agenda developed and funded by the Electric Power Research Institute (EPRI) should continue together with enhanced federal funding. A considerable number of large and well-designed studies are currently under way. These studies offer the potential of more conclusive information than exists at present. Increasing the number of studies without a coherent research plan is not likely to contribute to resolving the current inconsistencies in available research results. A carefully coordinated and comprehensive national research agenda with adequate funding from a mix of governmental and non-governmental sources is needed.

The Committee also notes the need for a more systematic review of available research results to resolve the inconsistencies in the published studies and to identify areas of needed research. Most reviews of available evidence conducted to date have not employed rigorous review criteria and quantitative methods such as those used in meta-analysis. Such reviews would entail extensive reanalysis of data from studies specifically selected because they satisfy study design criteria. A review of this type was beyond the resources available to this Committee.

The application of limited state resources to the EMF issue cannot be justified at this time, when more direct public health benefits can be derived from other uses.

3.2 Recommendations

The Committee recommends that the PUC continue to review research findings from on-going studies of the association of EMF with human health effects as these data become available. The PUC should continue this review through the Committee on EMF Health Effects.

The Committee recommends that Texas not develop a specific EMF research program at this time.

4. Public Forum

4.1 Conclusions

Since the mid-1970's, EMF has been an issue in over 200 legal proceedings involving the electric utility industry in the U.S. Approximately 75% of these occurred during siting of electrical facilities, primarily transmission lines, and during condemnation proceedings.

The Committee recognizes that the EMF health issue is often introduced in legal proceedings (e.g., hearings). When EMF health effects concerns are addressed in this setting, the expense and delays in siting decisions are unwarranted. The quasi-judicial role of a state regulatory agency may facilitate the establishment of a better arena than the judicial arena for the expression of differing views and conflicting evidence. The Committee recognizes that, regarding transmission lines, the PUC has jurisdiction. However, transmission lines are not the only source of EMF exposure. It is anticipated that a public forum sponsored by an appropriate state agency, addressing all exposures, would provide a nonadversarial setting for the review of concerns regarding the EMF health effects issue.

4.2 Recommendations

The Committee recommends that the Texas Department of Health assume the leadership role in sponsoring any public informational meetings for the exchange of EMF information. Such meetings, if deemed necessary, can be scheduled in conjunction with the release, by the PUC, of the Committee's annual reports.

5. Education Of The Public

5.1 Conclusions

The Committee has not addressed the important need for public education regarding risk assessment, as this was beyond the scope of its work. However, the Committee recognizes the need for follow-up research and education in public risk perception and risk communication in conjunction with dissemination of risk information to the public.

The Committee also did not investigate the question of personal options such as prudent avoidance. However, with the present uncertainty regarding the association of EMF exposure with health effects, there is no clear indication regarding what specific aspects of EMF exposure should be avoided.

The public needs to be informed about the EMF health effects issue, and involved in the discussion of concerns arising from this issue. At present, the TDH and utility companies do respond to public concerns regarding potential health effects of environmental exposures by speaking to public groups and by distributing written information. Some electric utility companies also make EMF measurements for their customers.

5.2 Recommendations

The Committee recommends that electric utility companies and the TDH continue to be responsive to the public's need to have general information regarding potential EMF health effects, and continue to provide needed information through brochures, audiovisual presentations, and field measurements.

1.0 INTRODUCTION AND BACKGROUND

1.1 Introduction

The Public Utility Commission of Texas (PUC) recognized the increased concerns regarding exposure to powerline-frequency (i.e., 50 and 60-hertz) electric and magnetic fields (EMF) and their possible effects on human health. On April 18, 1988, the Commission resolved that a Committee (i.e., Electro-Magnetic Health Effects Committee) be appointed to research the literature and monitor the on-going research on the health effects of electric and magnetic fields from electrical transmission and distribution lines, and report annually their findings to the Commission. Committee members were originally appointed in December, 1988 and met for the first time in January, 1989. In May, 1989 the Committee issued an Interim Report. Additional members were added in 1989 and 1990. The following report represents the first complete review, and will be up-dated with new research findings, conclusions and recommendations on an annual basis.

The members of this Committee represent the research community, the state public health agency and the suppliers of electric services. The members hold credentials in medicine, epidemiology, biology, biochemistry, engineering, health physics, political science and biostatistics. Committee members are familiar with the current scientific EMF literature, and are actively engaged in reviewing hundreds of documents and published EMF research findings.

This Committee is similar to others that have performed literature reviews and made recommendations regarding possible health effects from these fields. However, it differs in one major respect: the Committee was established because of the foresight of the Public Utility Commission of Texas and not by legislative or judicial mandates.

The Committee has neither been placed under a deadline to produce a recommendation nor has it been funded to conduct its review or conduct new research. It serves as an independent review body to evaluate scientific evidence and to provide recommendations and advice to the Commission on the possible health effects associated with EMF exposures.

This report is divided into seven major sections: Introduction and Background, Engineering and Exposure Assessment, Epidemiology of Health Effects and Exposure to EMF, Experimental Studies, Judicial Issues, Regulatory Issues, and Policy Issues and Options.

1.2 Background

Until recently, serious inquiry about biological effects associated with electricity was limited to safety issues, primarily those identified with electrical shock. Several events in the 1960s and 1970s prompted inquiry about the biological effects of exposure to electric and magnetic fields (EMF). Reports from the Soviet Union in the early 1960s suggested neurological and cardiovascular effects in workers exposed to electric and magnetic fields. The controversy increased in 1974 when the New York Public Service Commission began hearings on a proposed 765 kilovolt (kV) transmission line, resulting in the New York Electrical Utilities funding a 5-year, $5-million EMF research program. Many articles concerning biological effects of exposure to electric and magnetic fields have appeared in the technical literature during the past two decades. Many more have been published in the popular press. These events have increased the public's concern over possible health effects when exposed to EMF.

Electric fields are produced by the voltage applied to a wire and are measured in volts per meter (V/m). Magnetic fields are produced by the current flowing through a wire and are measured in terms of gauss (G). The amount of power that a line transmits is the product of its voltage and current. Power systems are designed to hold voltages relatively constant, while currents increase and decrease depending on the power demand. Therefore, for a given voltage the electric field will remain relatively constant over time, but the magnetic field will increase or decrease depending on power demand.

There are basically three stages in generating electricity and moving the electricity from the electric stations to the end user (Figure 1-1). First, electricity is generated at an electrical generating station at about 20,000 volts (20 kilovolts). The power is then passed through a transformer which increases the voltage so that the power can be transported with minimal losses. In the second stage, electricity is transported over high voltage transmission lines (i.e., 69 to 765 kV).

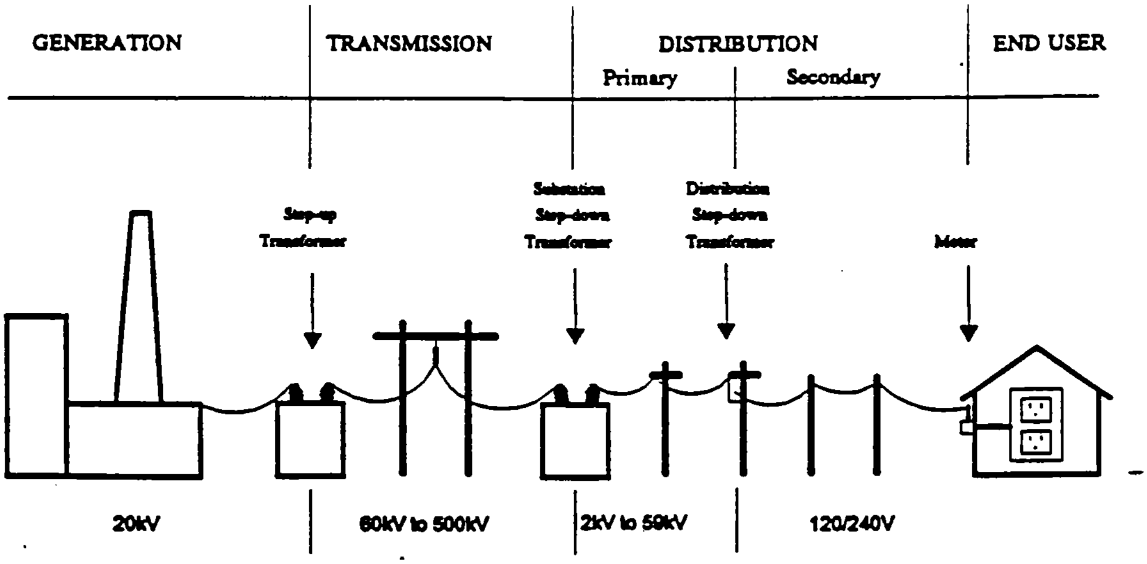


Figure 1-1. Schematic illustration of the stages in an electrical system used to transfer power from the generator via transmission and distribution lines to an end user. (Modified from Office of Technology Assessment Report-Biological Effects of Power Frequency Electric and Magnetic Fields).

Currently in the United States there are more than 300,000 miles of alternating current (AC) powerlines ranging from 115 to 765 kilovolts (kV). However, 500 kV is the highest operating voltage currently used in Texas.

Transmission lines connect to substations where the voltage is reduced and power is transferred to lower-voltage distribution lines. In the third stage, distribution lines deliver power locally to individual users. The distribution system is composed of two voltage levels. One is a "primary" circuit (2 to 59 kV) that delivers power from a substation to a distribution transformer. From there the power flows through a "secondary" circuit to an end user. The "secondary" circuit voltage is low enough (120/240 volts) to operate household electrical appliances, lights, etc.

The electricity we use in our homes, offices, etc. is alternating current (AC) in contrast to direct current (DC) which is like that produced by batteries. Alternating current does not flow in one direction, but instead alternates back and forth. The current used in North America alternates back and forth 60 times per second, which is called 60 hertz (60 Hz), compared with 50 times per second (50 Hz) in Europe and other countries.

Although the major public concern has been associated with EMF exposure from transmission lines, EMF are also present whenever electricity is used. As electricity is generated at electrical generating stations and transferred to homes via transmission lines, substations and distribution lines, EMF are produced. But these fields are also produced in homes, offices and other buildings, due not only to the proximity of the transmission and distribution lines, but due to electrical wiring in the facility and the use of electrical appliances (e.g., can openers, hair dryers, video display terminals, toasters, electric blankets). Thus, the sources of exposure to fields are numerous, exposure to fields is ubiquitous and if a true human health hazard exists, the response will need to be comprehensive, involving society as a whole.

Electric and magnetic fields are not something new. Scientists have had a good understanding of them since the nineteenth century. For example, processes in the earth's core give rise to the earth's magnetic field. Unlike the alternating fields associated with transmission lines and appliances, the earth's magnetic field does not alternate, but is static.

The EMF from powerlines and appliances are of extremely low energy and frequency. They are markedly different in frequency (i.e., Hz) from ionizing radiation (e.g., gamma rays, xrays, ultraviolet rays) in the electromagnetic energy spectrum (Figure 1-2). Not only is the energy in the 60-Hz frequency not great enough to cause ionization, there is not even enough energy to heat tissue as is the case for microwaves. The non-ionizing and athermal (i.e., non-heating) characteristics of EMF produced from 60-Hz frequencies are two of the reasons why some scientists believe that these fields could not induce biological changes. However, biological changes

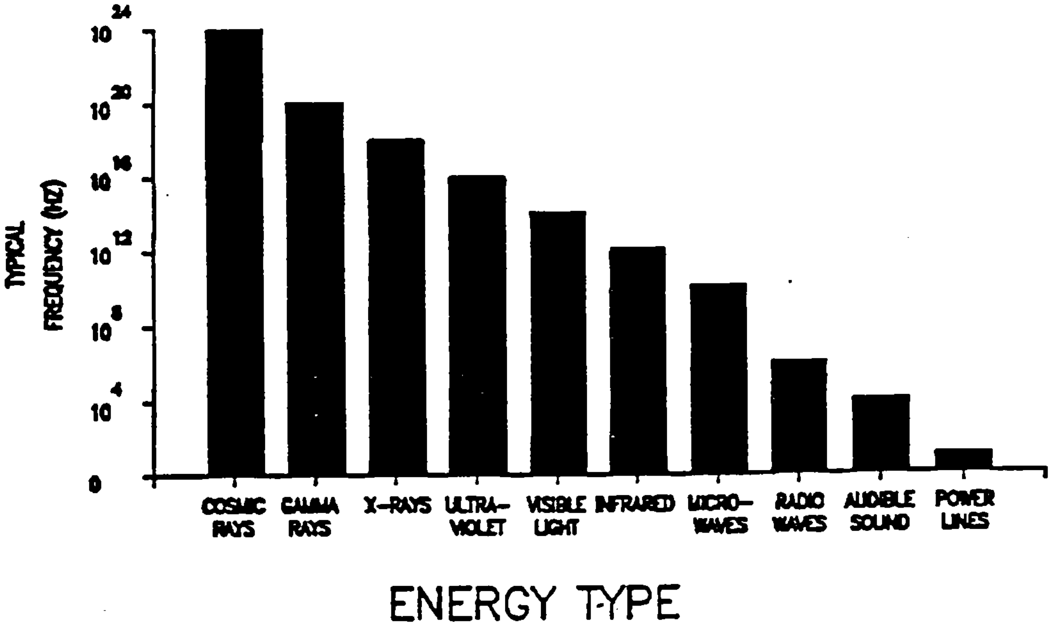


Figure 1-2 The electromagnetic spectrum

have been observed, under experimental exposure conditions, and these observations have increased the concern for possible human health effects.

Electric fields can be easily blocked by trees, buildings, earth and other objects. However, magnetic fields are not easily blocked and can pass through buildings, earth, and humans.

Some individuals have presented the contention that EMF exposure to electrical appliances is just as great a potential health hazard as exposure to EMF produced from transmission lines. Because the intensity of EMF decreases rapidly as one moves away from a source, the fields at the edge of the rights-of-way for a transmission line (since the source is 25' to 40' above the ground) may not be much greater, and in certain cases may be less than, the fields next to an electrical appliance (e.g., oven, hair dryer, electrical shaver, can opener), especially for magnetic fields. Such comparisons are of value, but field intensity is only one of the important variables to be considered in evaluating potential health effects. Exposure duration (i.e., acute vs. chronic) must also be considered. Since most appliances are used infrequently and for short duration, their exposure may be of less importance. Also, it is realized that the public perceives involuntary exposure (e.g., transmission line) to be more of a health hazard than voluntary exposure (e.g., appliances).

During the past decade, extensive research programs evaluating the possible health effects of exposure to EMF have been performed in the U.S. The U.S. Department of Energy (DOE) and the Electric Power Research Institute (EPRI) have sponsored much of this research. These studies have helped answer many unknowns, but many questions remain. Notwithstanding these unknowns in the scientific data base, these uncertainties have triggered public, regulatory, and judicial involvements. This report evaluates the EMF scientific literature and addresses the regulatory and judicial involvement in the issue.

2.0 ENGINEERING AND EXPOSURE ASSESSMENT

2.1 Introduction

Studies of the possible effects of power-line frequency electric and magnetic fields on health are hampered by problems in measuring exposure. Exposure should not be confused with dose. Exposure is the simultaneous occurrence of some agent (e.g., electric or magnetic fields) in the presence of a subject (e.g., human), whereas dose is the amount of agent actually interacting with the subject. Dose inherently involves a thorough understanding of the cause and effect relationship between the agent and biological effect. Currently, science is only beginning to understand this relationship between electric and magnetic fields and their interaction with biological systems. In this section the acronym EMF will be used for electric and magnetic fields.

The essence of exposure assessment is determining, through direct measurement or estimation, the amount of a causal agent occurring in the subject's environment. The assay of this agent is often called the "metric of exposure"--the quantity that explicitly is related to dose and the one we want to measure. Ideally, science must first identify the mechanism by which the agent affects the subject before we know what to look for. For example, if a subject drinks a glass of chocolate milk and then breaks out in a rash, what caused the rash? Was it the milk, the chocolate, some by-product of the reaction between the milk and chocolate, the color of the mixture, or the material from which the glass was made? Most exposure assessments have assumed that the average magnetic or electric field strength found in the subject's environment is the "metric of exposure." Yet, several studies, both in vitro (cellular) and in vivo (animal), have suggested other aspects of the electric and magnetic fields, besides average field strength, may be the measure sought.

Like with the host of properties associated with the glass of chocolate milk, any one of the properties manifested in the EMF environment could be the metric of exposure. For example, associated with every field are aspects of wave shape, frequency, harmonic content, and transients (spikes), and, if transients are present, their host of properties. Furthermore, the exposure metric could be the variability of the field or perhaps the number of times the subject passes in and out of the field. The exposure metric could be the occurrence of fields in certain windows of frequency and/or amplitude, or even more complex, some type of interaction between the strength and orientation of an external field and the earth's magnetic field. Animal and cellular studies have not clearly identified any single metric of exposure. Exposure assessments have been relegated to measuring only the convenient and simple properties of an environment due to the obscurity of the metric and the scarcity of sophisticated instrumentation necessary to measure aspects more complex than time average field strengths.

Many exposure assessments to date have relied on average exposure during a sampling period. Inherent in the averaging process is a loss of information; the more subtle aspects of EMF, such as windows, transient exposure, etc., are obscured when instantaneous field values are averaged. Also averaging fails to portray any temporal variations.

Exposure assessment is important to epidemiologists, biologists, and regulators. To correlate a disease with a suspected agent, epidemiologists must be able to measure the difference in exposure among the subjects for the metric of interest and for a host of possible confounders present in a real environment. To investigate a suspected interaction, biologists must be able to design experiments that accurately mimic exposure in the real environment. If their extrapolations of laboratory experiments to the real environment are to be believable, they must be able to simulate accurately and control the exposure of their subjects to the suspected agent. And finally if science does identify a public health hazard, regulators must be able to identify explicitly which aspects of EMF are threatening public health and at what level those aspects should be limited.

2.2 Summary

The Committee has reviewed the major elements of exposure assessment through reviewing the literature, examining computer models and communication with manufacturers and users of EMF measuring equipment. We find that for making survey measurements of EMF associated with powerlines, commercial instrumentation is readily available and acceptable standards, specifying how these measurements should be made, have been published. However, for measuring exposure, only a few choices of commercially available instruments exist, and the instrumentation to make thorough and intensive engineering measurements must be custom assembled. Also, there are no standards to specify how exposure and engineering measurements should be made.

When it is impossible or not feasible to actually measure exposure, EMF exposure can be estimated by using computer models, spot measurements, and surrogates. Several computer programs exist to accurately estimate field levels for the simplistic geometries usually found around transmission lines. The Electric Power Research Institute (EPRI) is currently developing a program to calculate magnetic fields found in the more complex residential geometries composed of distribution circuits, house wiring, and ground return paths. EPRI has also developed a program to estimate exposure based on time-weighted averages of field strength. Under controlled conditions, spot measurements may be combined with the subjects' activity patterns to estimate exposure. Surrogates must be used with great care since they often suggest other factors besides powerline EMF, which may be associated with cancer.

Preliminary studies show that electric fields in the home are not greatly affected by outside powerlines, but these line may be important contributors to interior magnetic fields. EMF in the work place is similar to that in the home. High current devices appear to be more prevalent in the work place than high voltage devices, so higher magnetic fields are more likely than electric fields. Little data exists on EMF in other areas.

2.3 Electric and Magnetic Field Fundamentals

2.3.1 Introduction

This section lays a foundation of the basic concepts about electric and magnetic fields fundamental to understanding exposure assessment. The reader already possessing a basic understanding of powerline fields may wish to skip this section and refer to it or the glossary as needed.

2.3.2 Basic Electrical Concepts

The source of both electric and magnetic fields is electric charge. Charge can be either positive or negative. Like charges repel and opposite charges attract. This electric force acting between charges is about a billion-billion-billion-billion times (10^{36}) stronger than the force of gravity between the two charges.

A conductor is any material that allows electrons to move freely and to redistribute charge. At some level of voltage, most materials become conductors. Metals are the best conductors. When electrons in a material are not free to move, the material is called an insulator. This property of opposing the movement of electrons is called resistivity. In a wire, resistivity is expressed as resistance and is measured in Ohms. An ideal conductor has zero resistance and an ideal insulator has infinite resistance.

Current is the movement of charge through a conductor and is measured in Amperes (A). A circuit is created when a continuous path for the current is formed. With direct current (DC), like that produced by a battery, the current flows in one direction at a constant level; whereas with alternating current (AC) both the level and direction of the flow change periodically with time. Frequency is the number of these complete cycles that the alternating current undergoes in one second and is expressed in cycles-per-second or Hertz (Hz). Electrical power systems in North America operate at 60 Hz, while 50 Hz is predominate elsewhere, including all of Europe. For 60-Hz alternating current, 60 complete cycles occur every second with the current's direction reversing during each cycle.

Conceptually similar to water being pumped through a pipe, electrical current is "pushed" through a conductor by a difference in electric "pressure" or potential between the ends of the conductor. This difference in potential is measured in volts and is called voltage. With alternating current, both the voltage and current vary sinusoidally, as Figure 2-1 shows.

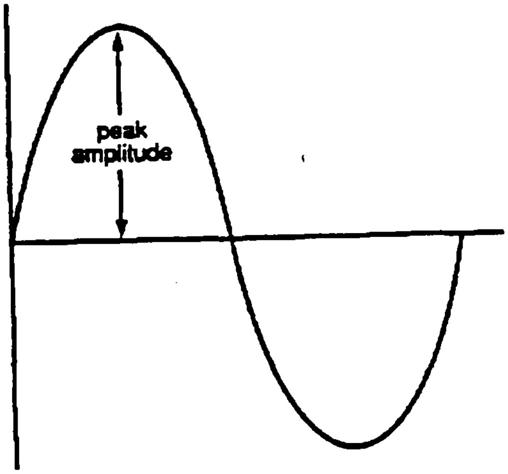


Figure 2-1. Alternating sinusoidal wave shape for current or voltage. The quantity flows one direction during the first half of the cycle and reverse direction during the second. (EPRI, 1989)

2.3.3 Field Concepts

A set of values of a physical quantity at different points in space can be represented as a field. An example of a simple field is the temperature across the State of Texas at noon on January 1, 1990. Each geographic point in the state has associated with it a measurable value of temperature. By associating a temperature reading with every reporting point in the state, we could construct a temperature field.

The above example is a scalar field, where the property being measured is a value easily read on a single scale. More pertinent to the electric or magnetic fields is the idea of a vector field, where each point not only has a value associated with it, but the value is oriented in a specific direction. One example of a vector field is the trajectory of each fragment of a hand grenade during an explosion. A snapshot would show that each piece of shrapnel is travelling at a specific speed in a certain direction. We can describe the explosion in terms of this vector field. Another example of a vector field is the pattern formed by water spraying from the end of a fire hose. A vector field describing the flow will consist of the speed and direction of each molecule of water at every point in the flow.

2.3.4 The Electromagnetic Spectrum

As shown in Figure 2-2, the electromagnetic spectrum encompasses the frequency range of all electromagnetic energy. Near the bottom of the spectrum are extremely low frequency (ELF) waves like powerline fields and near the top are very energetic cosmic rays. In the middle of the spectrum, in a small frequency band, is visible light; different frequencies of light produce different colors. Below visible light are frequencies that produce infrared, microwave, and radio waves, while above visible light are ultraviolet, x, gamma, and cosmic rays. The product of frequency and wavelength of electromagnetic radiation is always a constant–the speed of light. Therefore, the higher the frequency the shorter the wave length. A 60-Hz power frequency has a corresponding wavelength of 5,000 kilometers (about 3,000 miles). In comparison, the wavelength of a television transmission is about 3 meters.

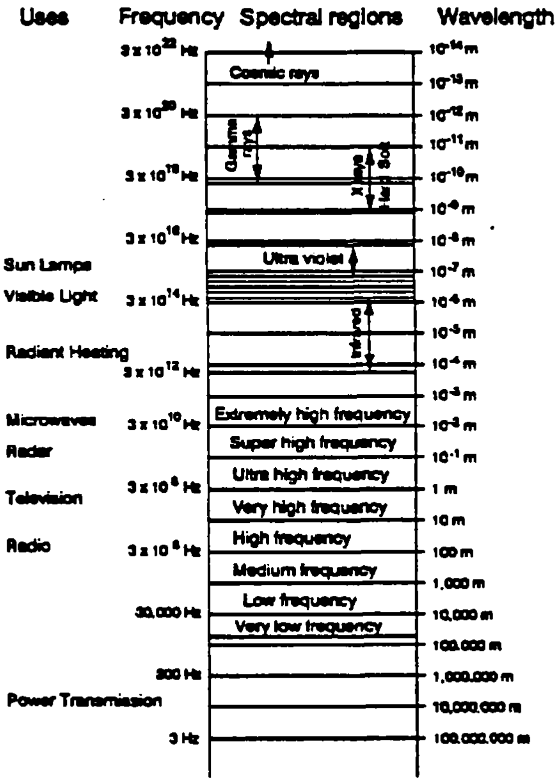


Figure 2-2. The electromagnetic spectrum shown by frequency and wavelength. At a frequency of 60 Hz and a wavelength of 5,000 km, powerlines are at the bottom of the figure. Frequencies less than 300 Hz are designated as extremely low frequency (ELF). (EPRI,1989)

The way the electric and magnetic fields from a source of electromagnetic energy appear to an observer depends on the distance to the source in comparison to the wavelength of that source. When the distance from the source is large compared to its wavelength, the electric and magnetic fields are linked together as electromagnetic radiation. The area where this linking occurs is called the "far" or "radiation" zone. At anything greater than atomic distances, visible light will always appear as a radiation.

When the distance from the source is small with respect to wavelength, the electric and magnetic fields appear as separate quantities. Earth based observers are always in the so called "near" or "static" zone of power frequency fields because of their long wavelength. Therefore, power frequency fields behave as separate, independent, non-radiating electric and magnetic fields. So when studying power frequency fields, we consider the electric and magnetic fields as separate quantities and not as electromagnetic radiation.

2.3.5 Electric and Magnetic Fields

Electric and magnetic fields are vector fields. Within the field, the electrical force produced by the field on a unit charge can have a different magnitude and direction at each point in space and time. These fields are defined by the forces exerted on electrical charges.

Electrical charges cause electric fields, which can be described in terms of electric field strength (E) with units of volts per meter (V/m). The electric field is defined by the force it exerts on a static unit of charge. The electric field is a function of the voltage of the source–the higher the voltage the stronger the field. Transmission line electric fields are typically measured in thousands of volts (kilovolts) per meter (kV/m).

Moving electrical charges cause magnetic fields. Just as the electric field is defined by the force exerted on a stationary unit of charge, the magnetic field is defined by the force exerted on a moving unit of charge. The magnetic field is usually measured in terms of its magnetic flux density (B), although some instruments may be calibrated in magnetic field strength (H). The magnetic field strength and flux density are related to each other by a permeability constant (μ) i.e., $B=\mu H$. The most common units of magnetic flux density are the gauss (G) and tesla (T) and for magnetic field strength it is the ampere/meter (A/m). Table 2.1 shows the equivalence between units. Powerline magnetic fields are usually described in terms of thousandths of a gauss (milligauss or mG) or millionths of a tesla (microtesla or μT).

Table 2.1 - Equivalence Between Magnetic Field Units

Units	G	mG	T	μT	A/m
G	1	1000	0.0001	100	80
mG	0.001	1	10^{-7}	0.1	0.08
T	10^{4}	10^{7}	1	10^{6}	800,000
μT	0.01	10	10^{-6}	1	0.8
A/m	0.0125	12.5	1.25×10^{-6}	1.25	1

The electric field at a point is a function of the voltage of the source and the distance to the source. The electric field strength increases as the voltage is raised or the distance to the source is reduced. Because utilities design their systems to maintain powerline voltage levels within a fairly narrow range over time, the electric field at specific point from a particular powerline will vary little with time and can almost be considered constant.

The magnetic field is independent of the voltage, but depends on current in the conductor and the distance to the conductor. The magnetic field increases with more current and increases the closer you get to the source. Unlike the electric field, the magnetic field from a powerline exhibits a great temporal variability since it is a function of the circuit loading, which varies by time of day and season of the year.

The magnetic field drops off with increasing distance from the source. The electrical and physical characteristics of the source dictate how rapidly this decrease occurs. Generally, magnetic field levels will decrease according to one of three relationships with distance: inversely with distance, inversely with the square of distance, or inversely with the cube of distance. Figure 2-3 illustrates these three relationships for a source of the same strength. Doubling the distance will decrease the field to one-half under the inverse relationship, to one-quarter under the inverse squared, and to one-eighth under the inverse cubed. The conditions under which these relationships occur will be discussed later.

Earth's Electric Field. The earth possesses an essentially static electric field, which is vertically-directed with a strength about 130 V/m near the surface. It is caused by the separation of charge between the earth and the ionosphere. Together they form a capacitor with the earth being the negatively charged plate and the atmosphere being the positively

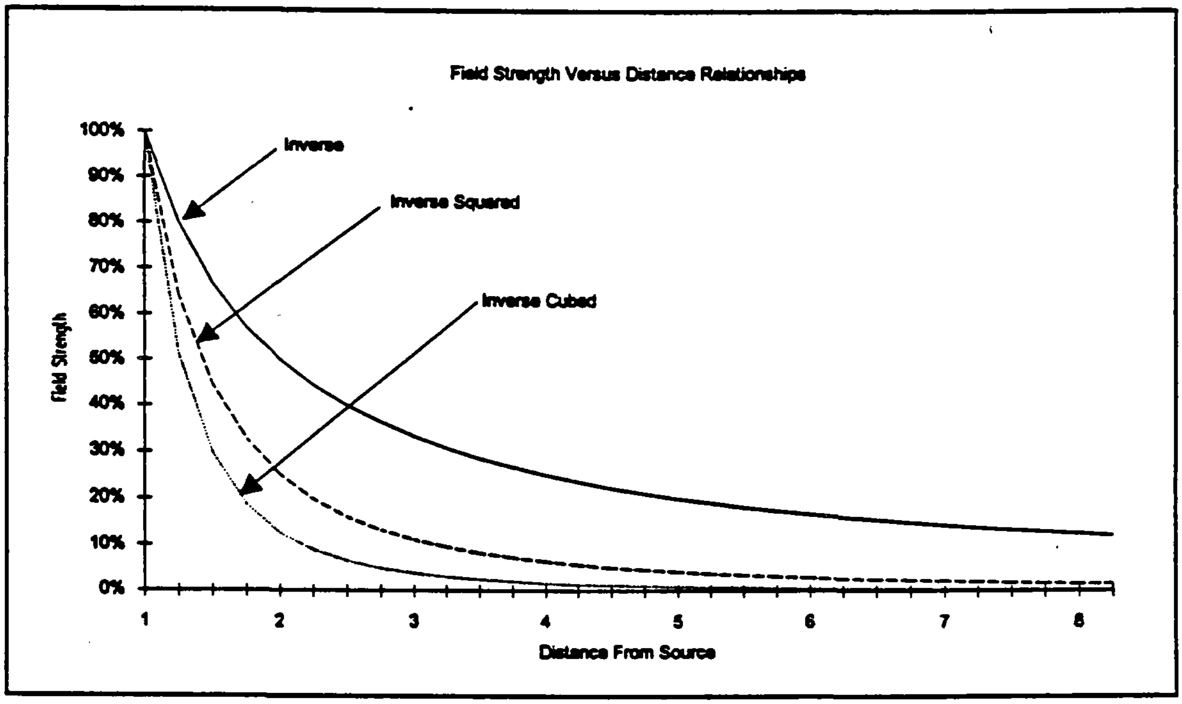


Figure 2-3. Field strength varies with distance from the source according to inverse, inverse-squared or inverse-cubed relationships.

charged plate. Lightning maintains the potential difference by transferring the excess charges. On average, about 2000 thunderstorms are occurring at any time, and there are about 100 lightning flashes per second worldwide. The field follows a diurnal cycle as shown in Figure 2-4. Fields of 10 kV/m or higher can occur during thunderstorms. (EPRI, 1989)

Earth's Magnetic Field. The earth also possesses an essentially static magnetic field. Current flowing through the earth's molten interior is believed to be the source of the geomagnetic field. Its magnetic flux density averages about 500 mG at middle latitudes, but varies between the equator and the poles. The vertical component of the geomagnetic field is greatest at the magnetic poles, reaching about 670 mG and falls to zero at the magnetic equator. Conversely, the horizontal component's maximum of about 330 mG occurs at the equator and is zero at the magnetic poles. (EPRI, 1989)

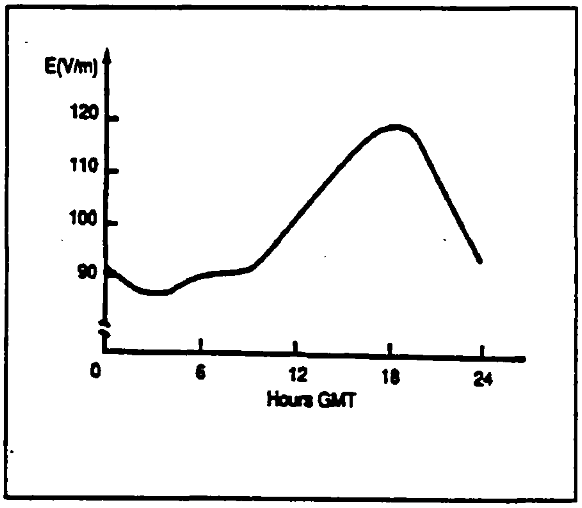


Figure 2-4. Average diurnal variation of the atmospheric potential gradient. The peak occurs near 7 p.m. Greenwich Mean Time (GMT) and is associated with peak thunderstorm activity around the globe (EPRI, 1989).

Man-made Power Frequency Fields

Overhead Transmission Lines. The most common means of transporting electric power is by overhead alternating-current transmission lines. Transmission lines are often grouped by their design operating voltages. Two groups are high voltage (less than 345 kV) and extra high voltage (345 kV and above). A typical transmission line has three phase conductors per circuit. Multiple, or "bundled," conductors for each phase are used at higher voltages to control corona-related effects (such as audible noise) or to increase power handling capability on heavily loaded lines. Figure 2-5 shows a typical transmission line. In each phase conductor, the sinusoidal voltage or current wave is out of phase with the other two phase conductors by one-third of the wavelength.

The transmission line is said to be balanced if the vector sum of the phase voltages and phase currents add up to zero. Ideally no currents will be flowing in the shield wires or the ground. Because of differences in the electrical characteristics of each phase and the differing amounts of single phase load attached to each phase, transmission lines are seldom precisely balanced. Even under balanced conditions, some current will be induced into the shield wires, unless they are isolated into short segments.

Transmission lines are identified by their nominal

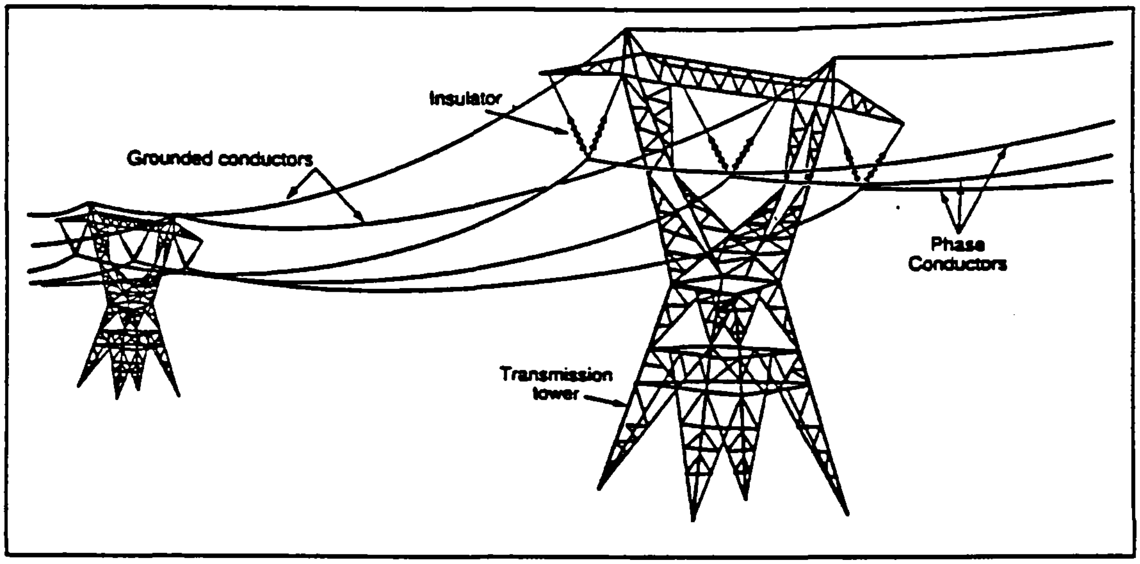


Figure 2-5. A typical three-phase single-circuit AC transmission line. (EPRI,1989)

phase-to-phase voltage. Typical nominal voltages in Texas are 69, 115, 138, 230, 345, and 500 kV. In practice, actual operating voltage will be within a few percentage points of the nominal voltage.

Electric fields near transmission lines are usually calculated or measured at a height of 1 m above the surface. The strength of the electric field from a transmission line is dependent on three factors: the operating voltage of the line, the height of the conductors above the ground and the distance from the line to the point of measurement. Figure 2-6 shows the electric field profiles for a 500-kV, 345-kV, 230-kV, and 138-kV single-circuit transmission lines. Because the field profile is symmetrical about the center of the transmission line for symmetrical arrangements of the phase conductors, often only one-half of the profile is shown. The calculations assume an open, flat surface in the area about the transmission line. Conducting objects such as vegetation, buildings or fences will "perturb," or distort the electric field.

The electric field that permeates space surrounding a transmission line can be described as a rotating vector field. The electric field at each point in space may have a different magnitude and direction and varies cyclically at the powerline frequency. The loci of the field vector describes an ellipse, with the maximum electric field occurring along the semi-major axis and the minimum electric field occurring along the semi-minor axis. Figure 2-7 shows the field ellipse.

Electric current in the transmission line phase conductors produces a magnetic field. Figure 2-8 shows calculated magnetic flux densities profiles at 1 meter above the ground for different transmission lines. The peak magnetic field beneath a 500-kV line carrying 2,150 megawatts (MW) is about 450 mG. For a single-circuit 345-kV transmission line carrying 1,050 MW is about 330 mG. The peak magnetic field for a 230-kV line carrying 350 MW is about 170 mG and the peak magnetic field for a 138-kV line carrying 112 MW is about 95 mG.

Unlike the electric field, the presence of most objects does not perturb the magnetic field thus making shielding very difficult.

For balanced conditions, the transmission line's magnetic field will decrease with the square of the distance from the line. Generally transmission line phase currents will be better balanced than distribution line phase currents. If an unbalanced condition occurs, the resulting magnetic field would be proportional to the degree of unbalance in the phase currents (i.e., the net current) and would decrease as distance between the line and point of interest increases.

The design of the transmission line will influence the strength of the power frequency fields under and next to the transmission line. The parameter of transmission line design having the most effect on the strength of

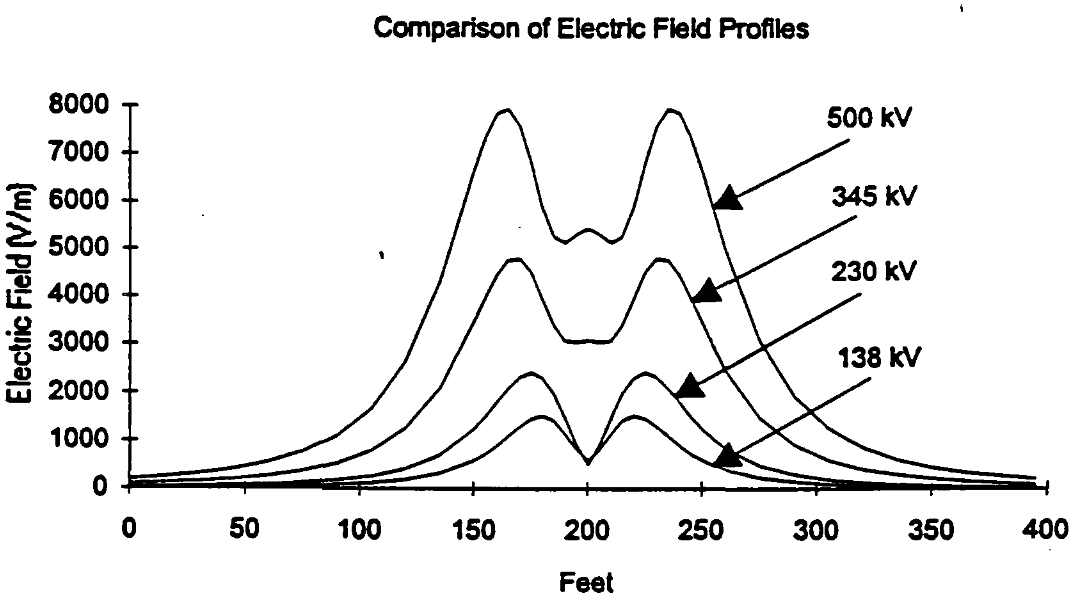


Figure 2-6. The maximum electric field lateral profile for 500-kV, 345-kV, 230-kV, and 138-kV transmission lines. The profiles are symmetrical about center of the line (located at 200 ft.). Conductors are at minimum clearance conditions and the field measured at 1m above the ground.

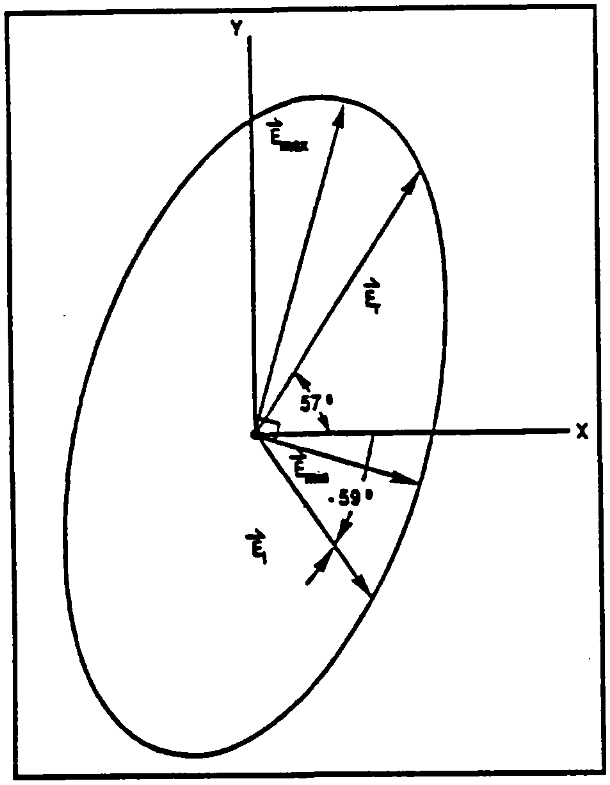


Figure 2-7. The electric field ellipse at a point in space. The maximum field occurs along the semi-major axis and the minimum along the semi-minor axis. The field vector rotates at the power frequency. (EPRI, 1982)

fields is the height of the conductors above ground. Figures 2-9 and 2-10 show the electric and magnetic field profiles for a single circuit 345-kV transmission line with conductor heights of 33', 43', 53', and 63'. As the figures show increasing the height of the conductors lowers the field strength under the line.

But, the distortion of the electric field by the earth produces a curious effect: raising the conductors slightly increases the electric field's strength at points greater than a certain distance from the line. This distance is called the critical distance. Figure 2-11, which shows the resultant electric field profiles for the two extremes (33' and 63'), more clearly shows this effect. With increasing conductor height, the electric field strength decreases at those points located less than the critical distance, the electric field stays the same at the critical distance, and it increases at distances greater than the critical distance.

The critical distance depends on the distance between phase conductors and the diameter of the phase bundles. The significance of the critical distance is that in cases where it is desirable to reduce the electric field at some point on the ground, conductor height must be increased for points within the critical distance (i.e., usually locations within the right-of-way) but decreased for points greater than the critical distance (i.e., usually locations outside the right-of-way).

Since the magnetic field is unaffected by the presence of the ground, this critical distance phenomena does not affect the magnetic field profiles. Magnetic field intensities, for all points on the ground, will always be reduced with increased conductor height.

Another parameter of transmission line design affecting only the electric field strength is the size of the phase conductors. Figures 2-12 and 2-13 shows the effect on the magnetic and electric fields respectively of doubling and halving the 18 inch bundle spacing. Decreasing the diameter of the phase conductors or, for bundled phases, decreasing the bundle spacing decreases the electric field strength, but has no effect on the magnetic field strength. Drastic changes are required to affect significantly the electric field at ground level, and the opportunities for manipulating phase diameter are limited by mechanical, electrical, and cost constraints.

The distance between phases can affect the electric and magnetic field levels. Figures 2-14 and 2-15 show the effect on the electric and magnetic field profiles, respectively, for the same transmission line with different phase spacings of 37.5', 27.5', and 17.5'. The canceling effect of one phase upon the others suggests that more compact lines will have lower fields at ground level. The amount of compaction is limited by the corona performance, tower construction and spacing, and National Electric Safety Code's clearance considerations. The orientation or configuration of the phases also can have a significant impact on the ground level fields. Figures 2-16 and 2-17 show the electric and magnetic field profiles for three possible phase configurations: vertical, horizontal (flat), and an equilateral (delta). All three configurations have the same phase spacing (27.5') and minimum conductor height (33'). The vertical and flat configurations have the highest maximum ground-level electric field under the line while the delta has the lowest. The electric field outside the right-of-way is lowest for the vertical configuration and highest for the flat. The flat configuration has the highest maximum ground-level magnetic field and the broadest profile, whereas the delta and vertical present lower maxima and more compact profiles. But, vertical configured lines require the tallest towers and therefore are the most expensive.

For transmission lines composed of more than one circuit, the phase sequencing can have a dramatic effect on the ground level fields. Also using a lower voltage distribution circuit beneath a transmission circuit can sometimes raise or lower ground level fields.

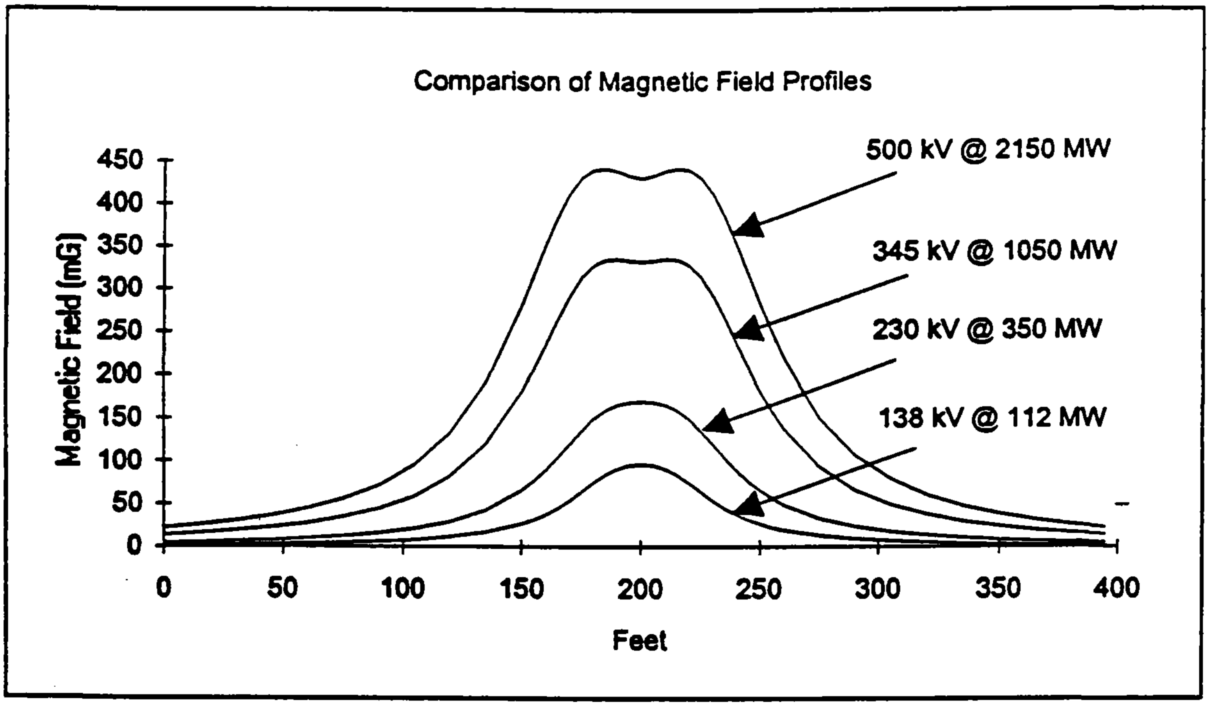


Figure 2-8. The maximum magnetic field lateral profile for 500-kV, 345-kV, 230-kV, and 138-kV transmission lines. Lines are at maximum operating load of 2150, 1050, 350, and 112 Megawatts, respectively. Conductors are at minimum clearance conditions and field measured at 1m above ground.

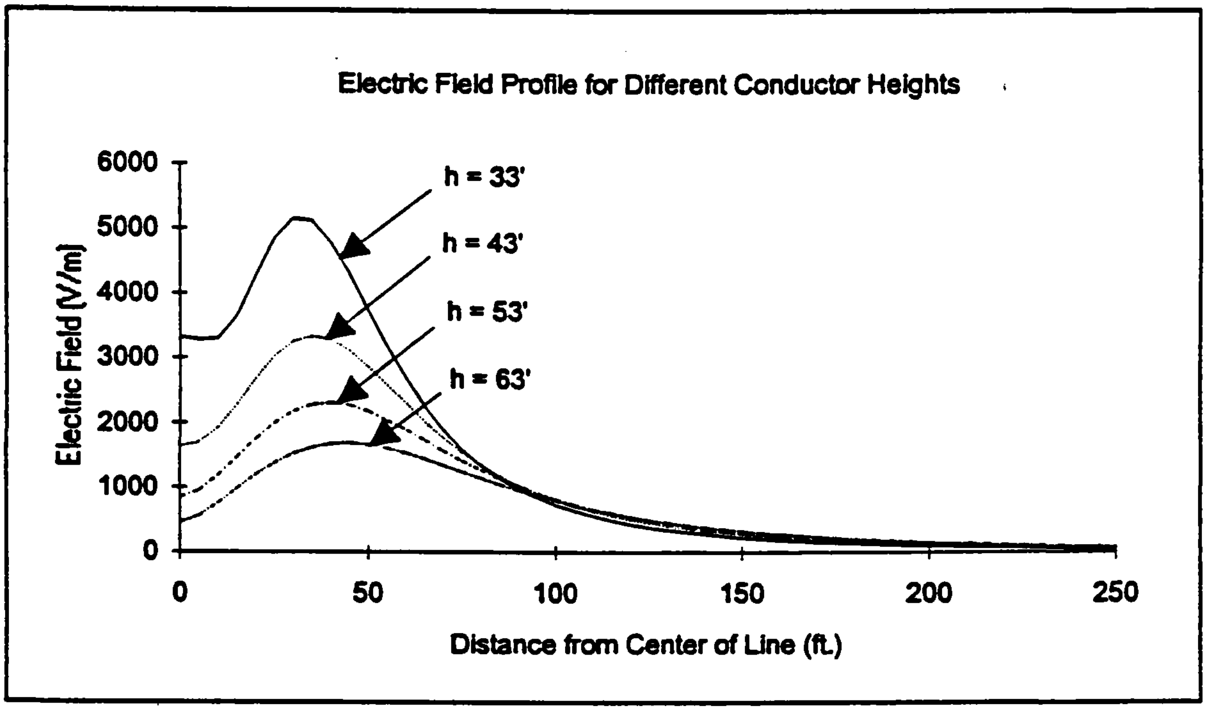


Figure 2-9. Electric field profiles at 1m above ground for single-circuit 345-kV transmission lines with conductors 63, 53, 43, and 33 feet above the ground. The profiles are symmetrical about center of line and only one side is shown.

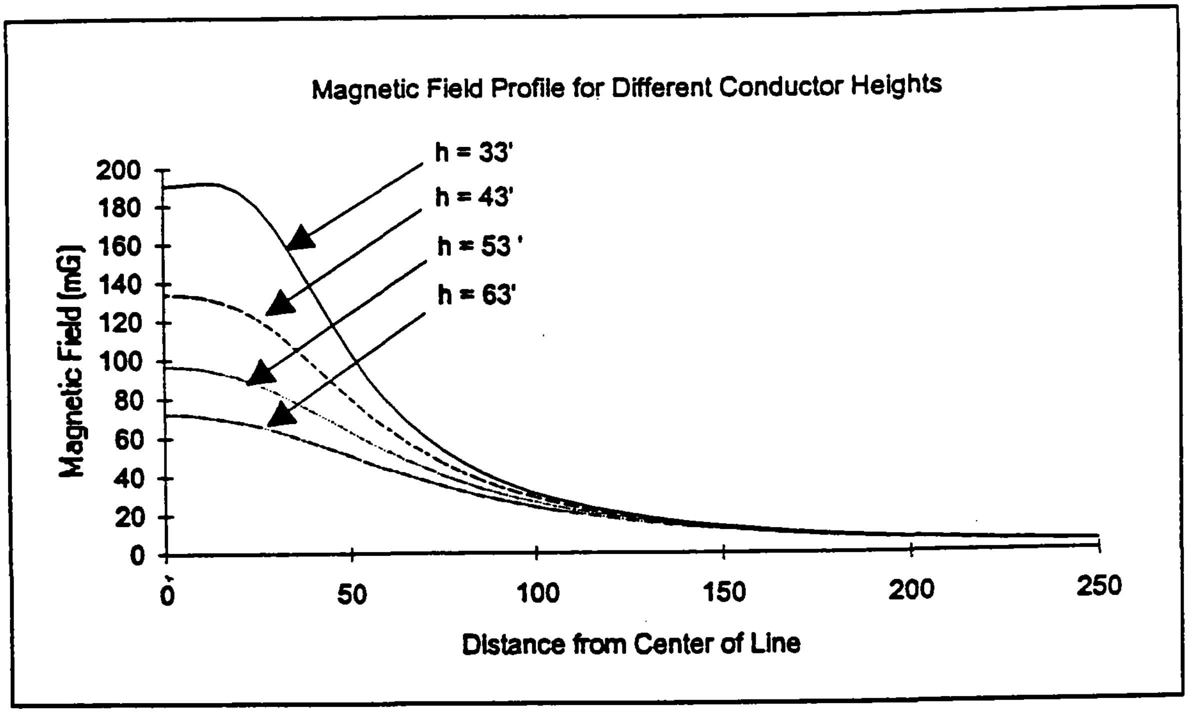


Figure 2-10. Magnetic field profiles at 1m above ground for single-circuit 345-kV transmission lines with conductors 63, 53, 43, and 33 feet above the ground. The profiles are symmetrical about center of line and only one side is shown.

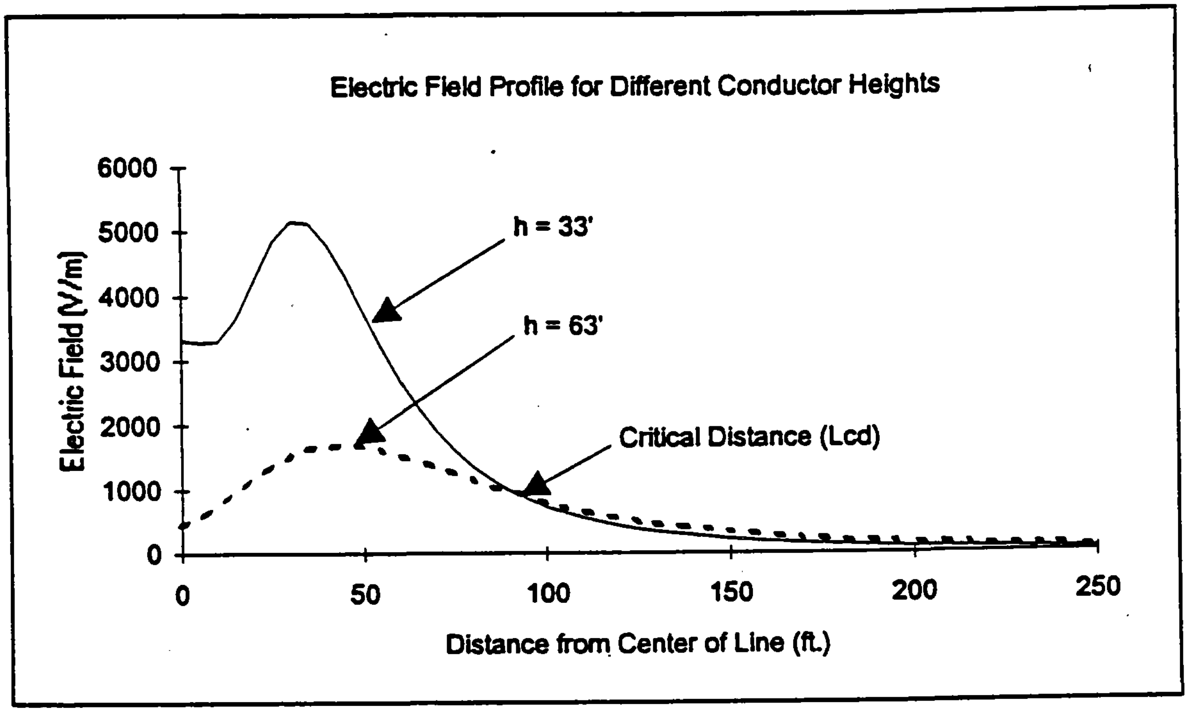


Figure 2-11. Critical distance (L_{cd}) for electric field from a 345-kV transmission line. The intersection of the field profiles occurs at L_{cd}. Increasing conductor height lowers E-field inside Lcd but raises E-field outside of L_{cd}.

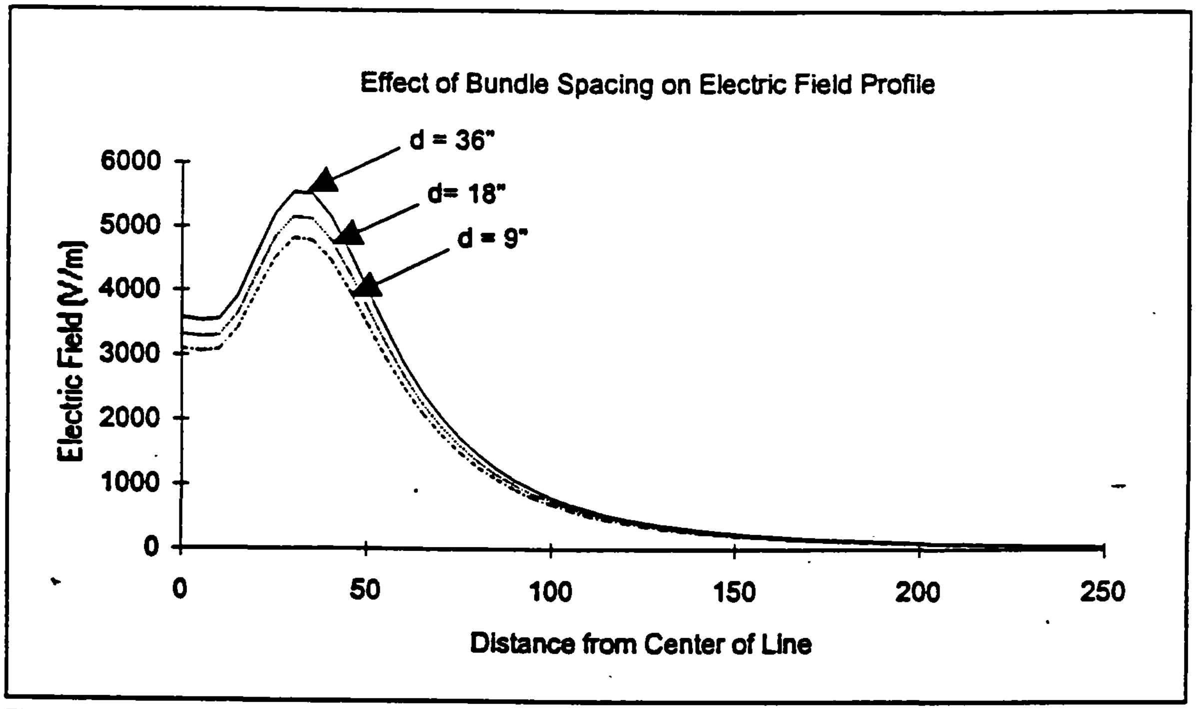


Figure 2-12. Electric field profiles for phase conductor bundle spacings of 9, 18, and 36 inches for a single-circuit 345-kV transmission line. Lines with smaller conductors (i.e., closer bundle spacing) have lower electric fields.

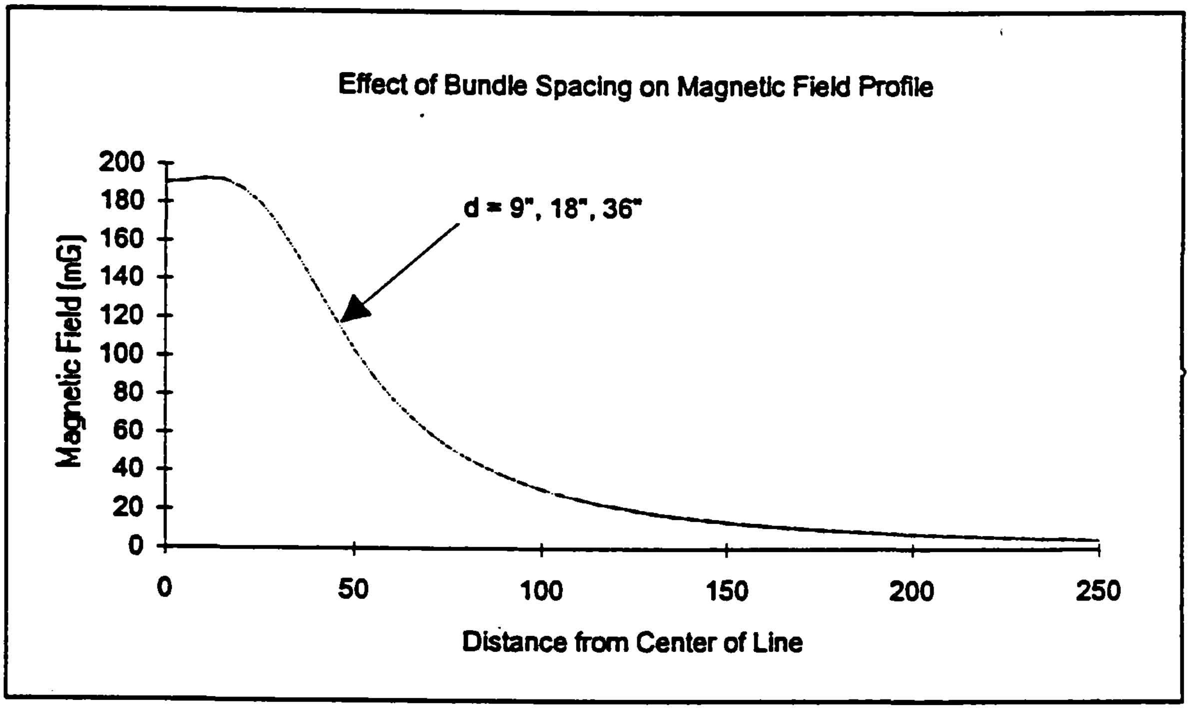


Figure 2-13. Magnetic field profiles for phase conductor bundle spacings of 9, 18, and 36 inches for a single-circuit 345-kV transmission line. Conductors size (i.e., bundle spacing) has no effect on magnetic field strength.

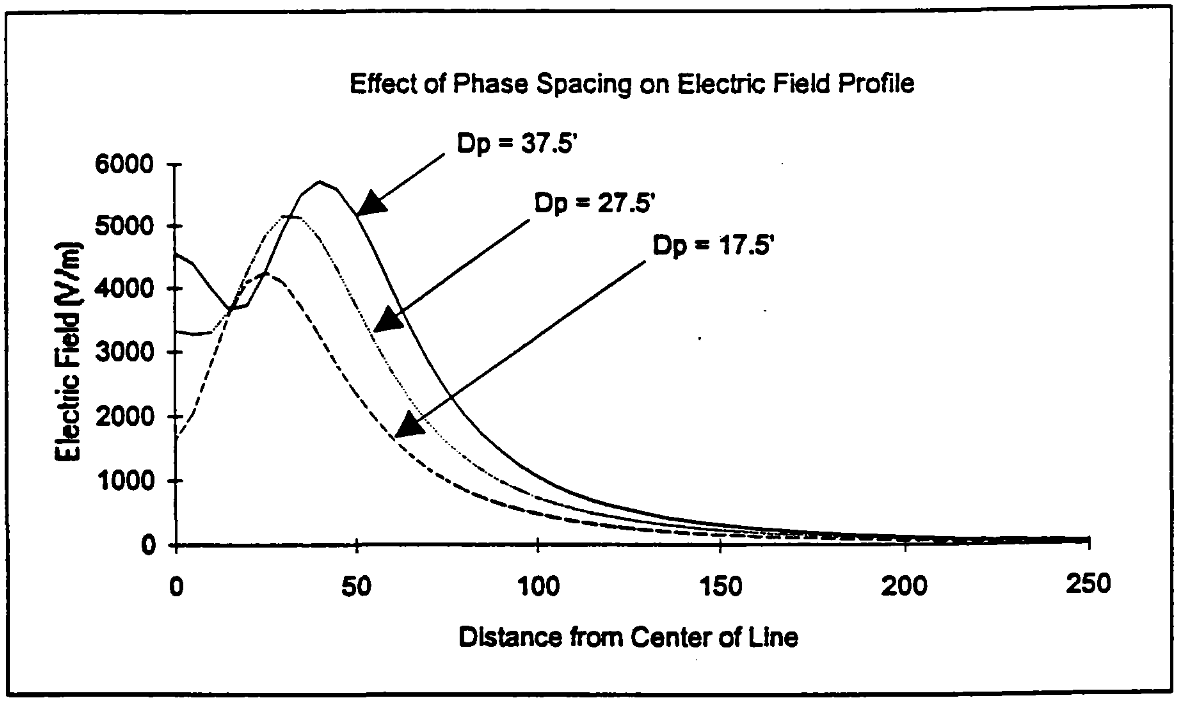


Figure 2-14. Electric field profiles for phase conductor spacings of 17.5, 27.5, and 37.5 feet for a single-circuit 345-kV transmission line. Compact transmission lines (narrower phase spacings) have lower electric fields.

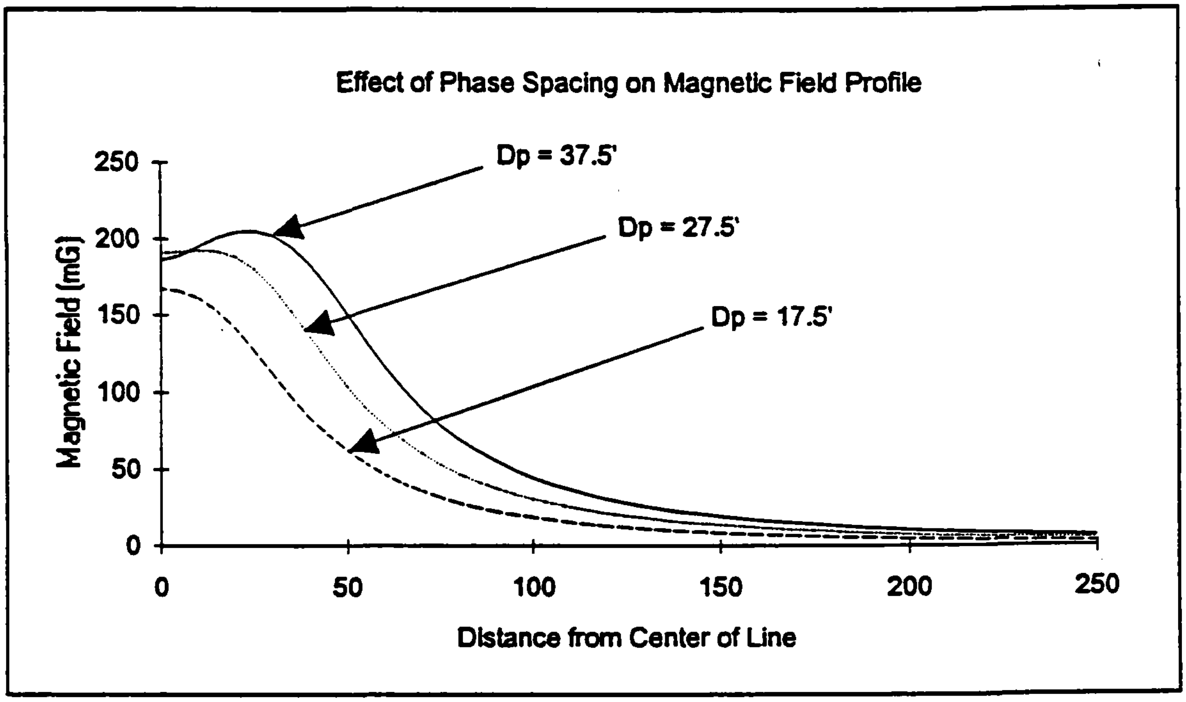


Figure 2-15. Magnetic field profiles for phase conductor spacings of 17.5, 27.5, and 37.5 feet for a single-circuit 345-kV transmission line. Compact transmission lines (narrower-phase spacings) have lower magnetic fields.

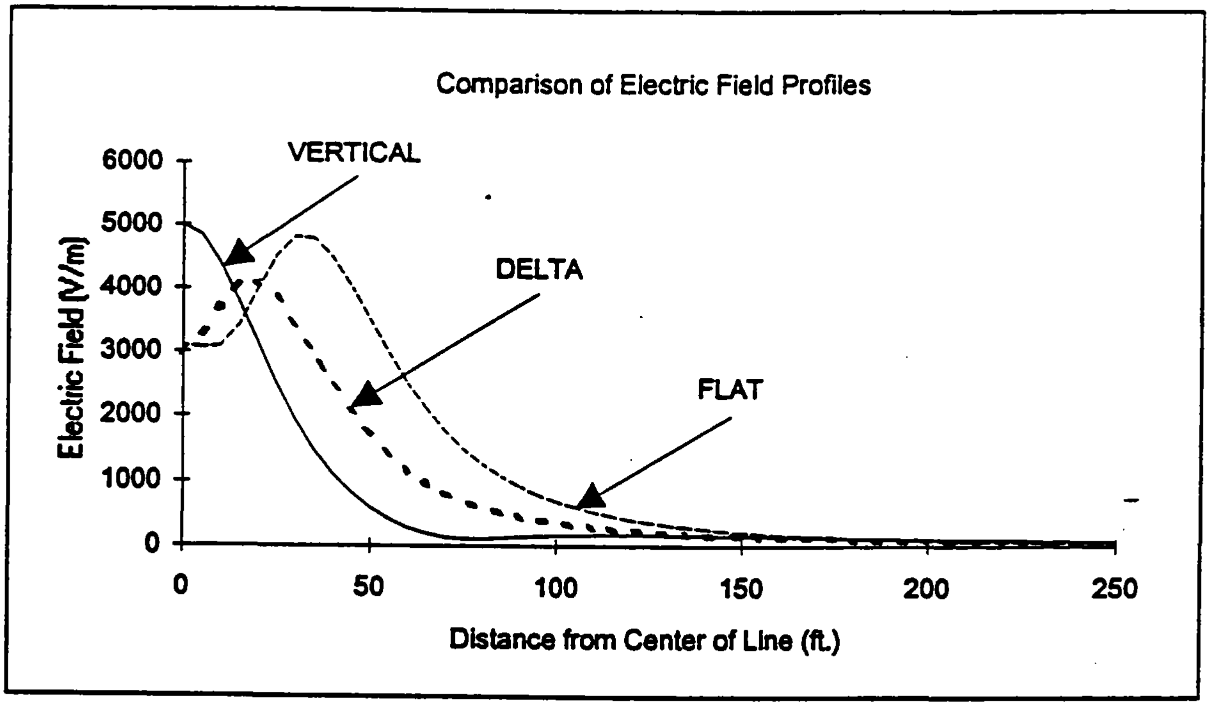


Figure 2-16. Electric field profiles for single-circuit 345-kV transmission lines with flat (horizontal), delta (equilateral) and vertical phase geometries. The phase spacing and minimum conductor height is the same for each configuration.

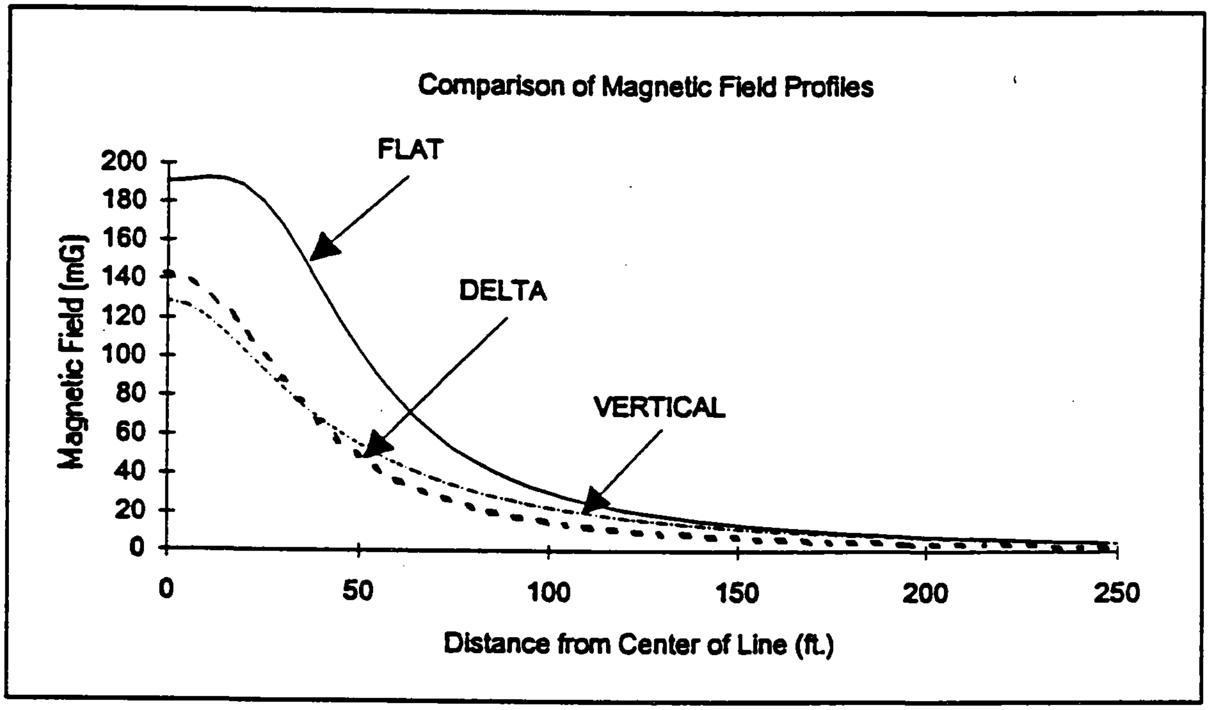


Figure 2-17. Magnetic field profiles for single-circuit 345-kV transmission lines with flat (horizontal), delta (equilateral) and vertical phase geometries. The phase spacing and minimum conductor height is the same for each configuration.

Fields Near Underground Conductors. Placing conductors underground rather than suspending them overhead from towers or poles changes the characteristics of the fields. Underground conductors rely upon rubber and plastic materials for insulation instead of air; therefore, the phase conductors can be located much closer together than is possible with overhead lines. Sometimes all three phase conductors are combined into a single cable. With the conductors closer together, the fields tend to be lower due to the canceling effect from the phase differences among the conductors. The electric field is further reduced or eliminated by the earth, or in the case of a cable, a grounded shield which sometimes encircles the phase conductors. Although the fields can be lower, people can be in much closer proximity to the underground conductors than overhead, so exposure levels may be similar to those of overhead transmission lines. Thus putting conductors underground may not necessarily guarantee that exposures would be reduced.

Transmitting power through underground cables is tremendously more expensive than using overhead transmission lines. Not only do high voltage underground cables themselves cost more per foot and are more expensive to install than overhead transmission lines, but due to the higher capacitive reactance found in cables, more circuits will be required to carry the same amount of power.

Fields in the Home Environment. Any use of electricity will produce electric and magnetic fields. Electric field levels measured at the center of different rooms, typical of housing in United States, are shown in Table 2.2, while Table 2.3 lists levels measured 30 cm (about 1 foot) away from various home appliances. The data in the tables are from limited measurements and should be considered anecdotal. They do suggest the general range of levels that may be encountered in the home, although wide variability should be expected. Preliminary measurements, (Bracken, 1988), indicate that the electric fields found in residences result from internal sources (house wiring, appliance, etc.) rather than external sources such as transmission and distribution lines.

Table 2.2 - 60-Hz electric field levels at the center of various rooms in a typical U.S. home. (Source: WHO, 1984)

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

Table 2.3 - Typical 60-Hz electric field levels at 30 cm from 115-V home appliances. (Source: WHO, 1984)

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

The magnetic field produced by most appliances is from a loop of wire or many-turn coil. Necessarily, because of the compact size of most appliances, the diameter of this loop or coil is small and achieves high magnetic fields with either high currents or multiple turns. At distances larger than the diameter of the coil the field approximates a three dimensional dipole field (Monitor Industries, undated) and decreases with the cube of the distance (see Figure 2-3), therefore falling off very quickly.

Table 2.4 shows the magnetic flux densities at distances of 3 cm, 30 cm and 1 m from several appliances. At 30 cm, levels range from 0.03 μT to 30 μT (0.3-300 mG). Notice how rapidly the magnetic field decreases with increasing distance. Unlike electric field levels in the home, magnetic flux densities close to some household appliances are higher than encountered under transmission lines (EPRI, 1989). However; when comparing the time-duration exposure to appliance fields, two points must be considered:

Table 2.4 - 60-Hz magnetic flux densities near various appliances. (Source: WHO, 1987)

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

- *Appliance fields, generally, exist only a small fraction of the time--most appliances are off more than they are on.*

- *Because the fields of most appliances fall off rapidly with distance, the areas in which the fields are elevated due to operation of the appliances are small compared to the total living area.*

Residential background magnetic fields, away from appliances, range from 0.05 to 1 μT (0.5-10 mG) (EPRI,1989). Figure 2-18 shows the major sources of magnetic fields, which are distribution lines, residential grounding systems, unusual wiring configurations within the residence, and nearby transmission lines. The following will discuss each of these sources.

The power distribution lines that gird the alleys and streets of residential neighborhoods are a source of magnetic fields in the home environment. These lines consist of both primary and secondary conductors (wires). Three separate sources of magnetic fields can be identified for distribution lines: balanced currents in primary wires, balanced currents in secondary wires, and net current that is the vector sum of all individual wire currents.

The primary carries power from a step-down transformer at the substation to the pole-top transformers on the distribution line. The primary may include a neutral wire, which may or may not be connected to the secondary neutral wire. The secondary carries power from the pole top transformer to the customers' service drops. The secondary usually consists of two energized wires at the nominal residential voltage of 120 V (240 V between the two wires) and the neutral, which is at ground-potential (zero volts). The secondary serves several residences, while service to each home is supplied via a service drop, which is generally a three-wire line connected to the secondary conductors.

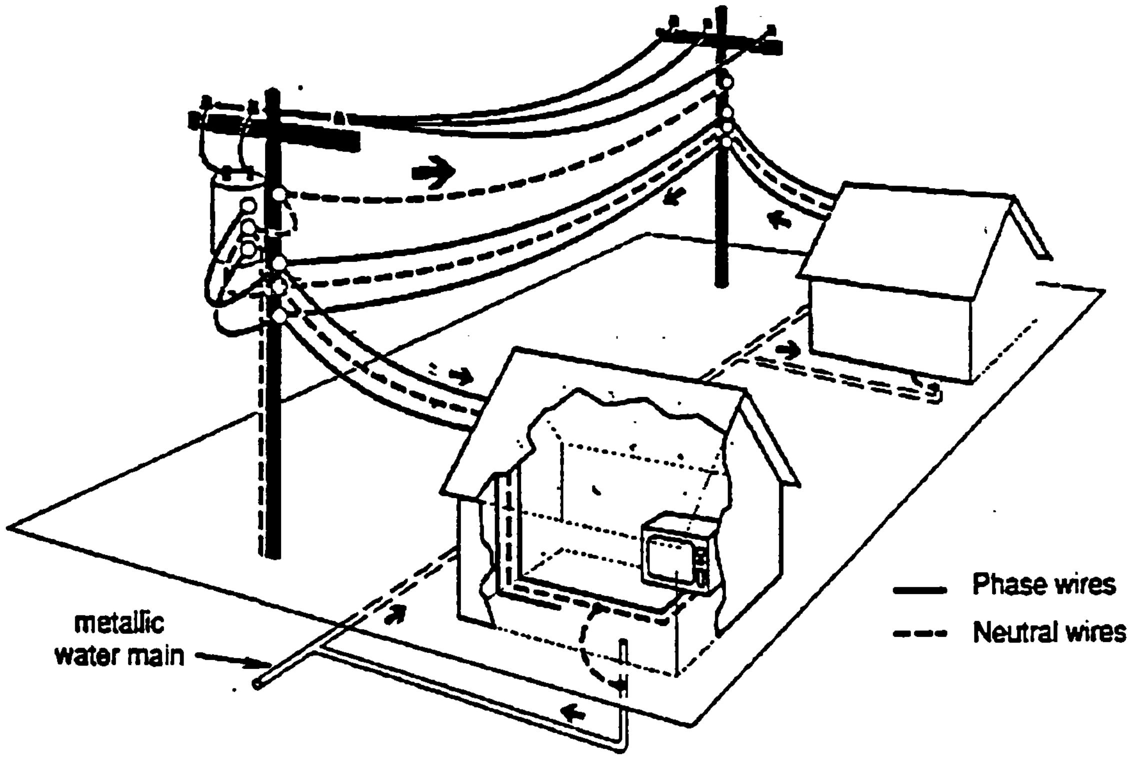


Figure 2-18. Residential magnetic field sources include appliances, grounding systems and overhead distribution lines (primary, secondary, and net current). Other possible sources are unusual wiring, underground cables and nearby transmission lines.(EPRI, 1989)

Safety precautions and engineering practice dictate the number, location, and type of grounds in the distribution system, but these multiple ground connections provide multiple return paths for the load current. The primary's neutral is grounded at each distribution transformer and at regular intervals along the line. If a portion of the load current returns through any of these ground paths instead of through the neutral conductor, an unbalanced condition will occur and a net current will exist, producing a magnetic field in the residence.

As mentioned earlier, the fields from balanced currents decrease proportional to the square of distance, whereas the fields from unbalanced currents (i.e., net current is not zero), decrease proportional to distance. At locations far from the line, the net current becomes a major contributor to the magnetic field. Therefore predicting the magnetic field level at such locations based only on balanced conditions often underestimates the actual level if a net current is present. The magnetic field caused by a net current in the distribution system will be more uniform throughout a residence than that caused by balanced currents.

The grounding system at the residence can be a very significant source of magnetic fields in the home environment. It consists of the connections between the service drop's neutral wire and the electrical ground at the residence. A common safety practice is to ground the neutral wire at the service entrance by connecting it to a metallic water pipe. This allows neutral current from household appliances to return through both the service drop neutral and the ground connection to the water line (Figure 2-18). The current returning on the water pipe (the ground current) flows to the water main, and then to neighboring water pipes and service drop's neutrals. While done for safety reasons, grounding the neutral wire at the service entrance can cause large current loops that are a source of magnetic fields.

The amount of the house current flowing back to the distribution system through water pipes or other ground return paths may be small. However, if some of the current does return by a way other than the neutral wire, it most likely will be through the water pipe. Ontario Hydro Research (Mader, 1989) has shown that they can predict residential magnetic fields by combining a measurement of the outside ambient magnetic field with the magnetic field calculated to be produced by ground paths currents. They calculate the ground path magnetic fields by measuring the current in the water pipe. Other possible ground return paths are through cable television lines, telephone lines, ground rods, connections to steel reinforcing rods in concrete floors and foundations, and equipment connected to ground.

Ground currents produce a very non-uniform magnetic field within the living space of a residence because of the widely differing distances and convoluted routings of the grounding system's current paths. The field also varies greatly in time since the ground current changes every time a 120-V appliance operates.

House wiring is generally not a significant source of magnetic fields. When the supply and return currents are equal, the opposite fields cancel and produce very little field at distances of more than a few inches from the wiring. In other situations, which may not violate any electric codes, more than one supply or return path is present. This might happen when controlling one socket of a duplex outlet from a remote light switch, wiring adjacent outlets from different sources but using only one neutral return for both, and controlling one light fixture from two switches.

Two methods of wiring may be commonly found in houses: Romex cable and "knob and tube." Modern practice is to use Romex cable, which combines supply, return and ground wires closely together in one cable. Older houses may contain "knob and tube" wiring, which uses discrete supply and return wires often separated by several inches and supported in the attics and walls by a series of porcelain standoffs (knobs) and insulating tubes. Experience has shown that houses with knob and tube wiring generally have higher fields.

However, by far the most common situation found in house wiring that results in unbalanced currents is connecting the neutral to ground at a location in the residence besides the service entrance. In houses with metallic plumbing, the neutral is usually connected to the plumbing by a ground strap. Some current may flow through the ground strap back to the transformer serving the house, resulting in an unbalanced condition.

Electrical appliances (garbage disposals, ice makers, whirlpool baths, refrigerators, etc.) connected to the plumbing also may provide additional ground return paths for the neutral current. These can produce multiple current loops and be a source of magnetic fields within the home.

Table 2.5 - Residential magnetic field source characteristics. (Source: EPRI, 1989)

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

EPRI (EPRI, 1989) has summarized (Table 2.5) the residential magnetic field characteristics for different sources. The table includes appliances as field sources and observations on the harmonic content of the fields.

2.3.6 Field Measurement Fundamentals

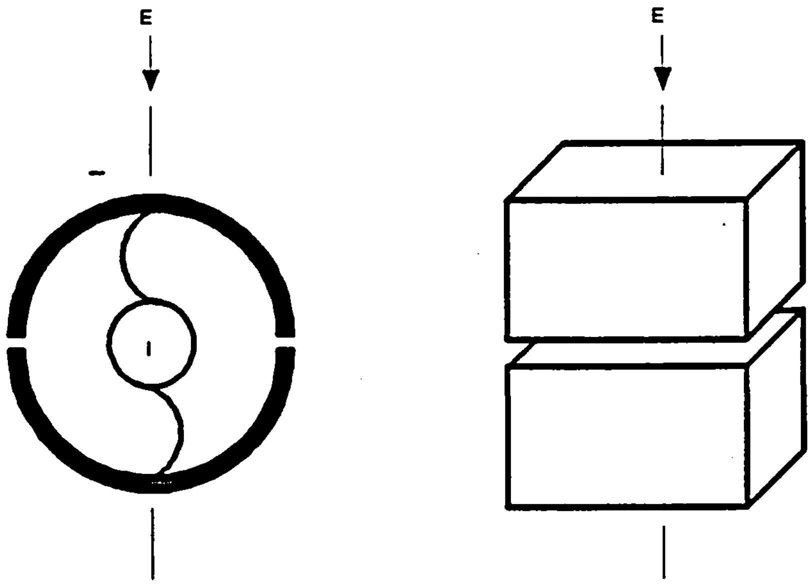
Although the type and purpose of a measurement dictates the type of equipment used, all instruments rely on a few fundamental principles to detect and measure EMF. Electric fields can be measured by three types of field meters as Figure 2-19 shows: the free body meter, the ground reference meter and the electro-optic meter. The free body meter measures electric field strength by metering the current or time varying charge induced between the halves of a dipole probe (see Figure 2-20). For many instruments the case itself is the probe. The free body meter is self contained, allows measurements above a ground plane, and does not require a known ground reference. The ground reference type meter measures the electric field strength by metering the current flowing between a probe placed in the field and a known ground reference. Its use is restricted to measurements on flat grounded surfaces. The electro-optical meter uses the Pockels effect to measure electric field strength. The Pockels effect is the change in refractive properties of certain crystals in the presence of an applied electric field and is proportional to the first power of the electric field strength. Although compact, the electro-optical meter lacks sensitivity in fields of less than 5 kV/m and is expensive. The free body and ground reference meters have been available commercially for about the last fifteen years, whereas the electro-optical meter only recently.

Magnetic field meters operate by detecting the voltage induced into a probe by the magnetic field. The probe element is a shielded wire coil. When the coil encounters a time-varying magnetic field, a voltage will be induced in the coil based on Faraday's Law of Induction (see Figure 2-21). The device can be made more sensitive by increasing the number of turns in the coil. The induced voltage is proportional to magnetic flux density perpendicular to the plane of the coil. The probe may be composed of a single element or three orthogonal elements that simultaneously measure the magnetic fields in all three geometric planes.

Hall-effect Gauss meters, which measure magnetic flux density from DC to several hundred hertz, are also available, but because they suffer from low sensitivity and from saturation effects due to the earth's magnetic field, authorities do not recommend their use (Misakian, 1988).

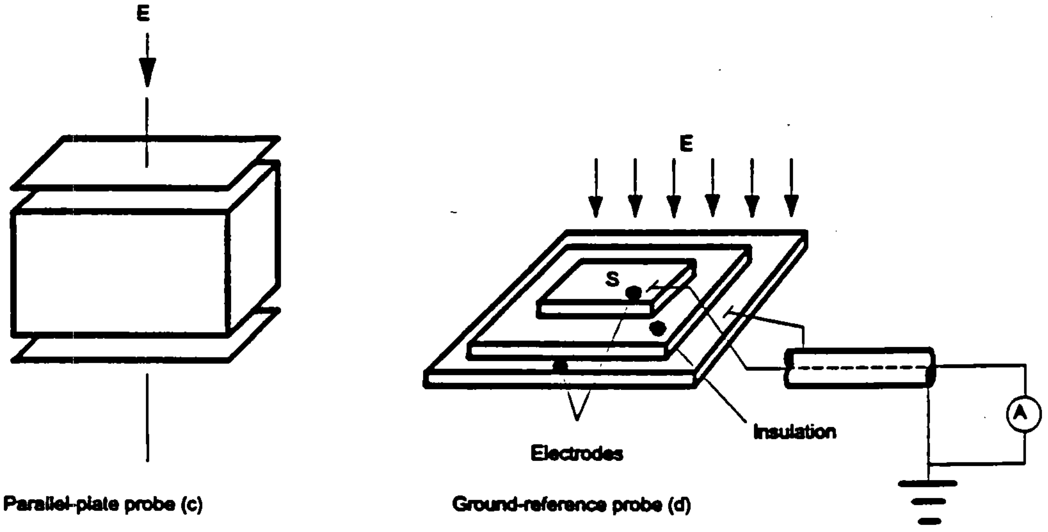
2.3.7 Cyclotron Resonance

To explain some inconsistent and ambiguous results of bioeffects experiments, some scientists have postulated a complex interaction between the earth's DC magnetic field and an external AC magnetic field (i.e., from a powerline). At specific combinations of intensity and orientation of the two magnetic fields, it is suggested that certain charged molecules (ions) of biological significance exhibit a resonance phenomena at frequencies near the powerline frequency. This phenomena is known as cyclotron resonance.



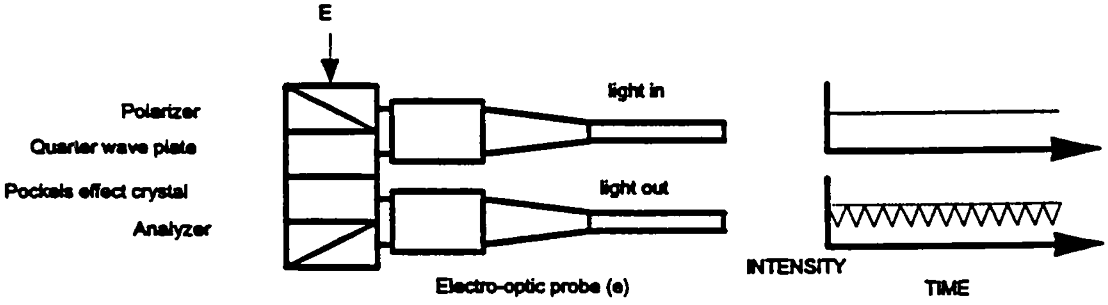
Spherical probe (a)

Box-type probe (b)



Parallel-plate probe (c)

Ground-reference probe (d)



Electro-optic probe (e)

Figure 2-19. Illustrations of three types of electric field meters:

1. free body: (a),(b),(c)
2. ground reference: (d)
3. electro-optical: (e)

(IEC, 1987)

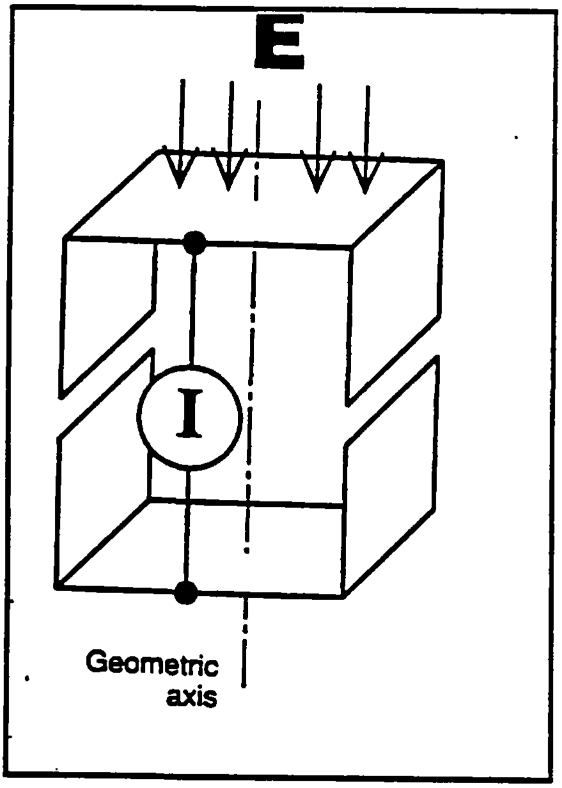


Figure 2-20. Diagram of a free body electric field meter. The device measures the current induced between its two isolated conducting halves. The induced current is proportional to the strength of the electric field. (EPRI, 1989)

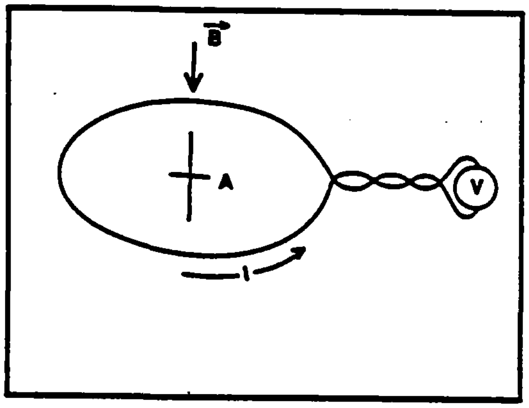


Figure 2-21. Diagram of a magnetic field meter. The voltage (V) induced in the coil will be proportional to the flux density (B) of the external magnetic field. (EPRI, 1991)

2.3.8 Biological Scaling of EMF

The establishment of precise exposure of EMF in laboratory studies on animals and tissue samples is complicated. Since EMF interaction in experimental animals can be very different from humans, it is often necessary to scale the field to duplicate the suspected conditions to mimic human exposure levels. For example, investigators might use a 65-V/m electric field on rats to simulate the same exposure of a 10-V/m field on humans, whereas they might use a 35-V/m field if the study was being done with pigs. The electric field level used in a study will depend on the size, shape and posture of the exposed subject, the particular electric parameter (electric field, induced current, or induced current density) being investigated, and the degree to which the exposed subject is grounded.

The electric field is perturbed by conducting objects in the field. Conducting objects can act to increase locally the electric field intensity. The amount of this concentration depends on the shape and size of the objects and the orientation of that object to the electric field. The field intensity above the head of a standing grounded person, may be as much as 15 to 20 times the unperturbed field (EPRI, 1988), whereas the field above the backs of pigs or rats is increased seven or four times, respectively. Concentration effects vary based on the specific part of the body and the subject's posture, but in general, the concentration of the electric field will be greatest about those surfaces with smaller radii of curvature.

The amount of current induced in an exposed subject depends on the strength of the surface electric field on the subject's body, the conductivity of the subject's tissue in which the current flows and how well the subject is grounded. To accurately simulate biological effects caused by current, allowances for the differences between the conductive cross-section to the induced current of the human and subject's bodies must be made. The level of the electric field can be adjusted to get the same current density, which is the amount of current flowing through a given unit of area. Internal current density varies among different animals in a way similar to the variation of surface electric field strength. Thus the strength of the applied electric field will depend on the type animal and also the desired current density.

The magnetic field is unperturbed by presence of biological materials; still in exposure studies, the strength of the magnetic field must be adjusted to compensate for the differences in the perimeters of the human's and exposed subjects' bodies. Faraday's law, which relates the induced electric field to the external magnetic field, can be used to calculate the appropriate magnetic field levels for various body radii.

2.4 Exposure Assessment Fundamentals

2.4.1 Introduction

This section develops a working definition of exposure assessment and was adapted from materials prepared by Robert M. Patterson, Temple University for: Seminar on New EMF Epidemiologic Results And Their Implications, October 16-19, 1990. Its objective is to create an understanding of the basic goals of exposure assessment rather than to list strict criteria or performance guidelines. From these goals, detailed guidelines and criteria could be derived as needed. It also discusses the general tools and strategies of exposure assessment, and describes the particular instruments used with EMF. Data from EMF exposure studies are used to explain what is known about the sources and nature of exposure to these agents.

2.4.2 Exposure v. Dose

Exposure (of a person to an agent) is the joint occurrence in space and time of the person and the agent. It is different from dose, which is the amount of the agent interacting with the person. As expressed by the Council on Environmental Quality (CEQ, 1989), "dose is the concentration or quantity or risk agent reaching tissues, organs or cells within the exposed organisms where damage may occur." Applying this distinction, one could be exposed momentarily to a vapor that is toxic when inhaled and, by not breathing, have no dose. One could be exposed to a systemic, poisonous chemical spilled on the skin, but unless it is absorbed through the skin there is no dose and no effect.

A human exposure assessment gives a qualitative and quantitative picture of the exposure of people to agents. In general, exposure assessments try to define "(1) substances that target organisms, species, or environments; (2) the intensity of exposure; (3) in what way; (4) for how long; and (5) under what conditions" (CEQ 1989).

2.4.3 Reasons for Exposure Assessments

The reason for making exposure assessments can be placed in two broad categories, described as routine and novel.

Routine assessments are common in environmental regulatory compliance activities and in the day-to-day practice of industrial hygiene. They are conducted when the effects of an agent are known. The techniques of the assessment are often prescribed.

Assessments in the novel category occur when little is known about either the agent or its effects, or both. They can provide new information to further our understanding of the agent. For example, an exposure assessment might seek to define where the agent occurs, in what amounts, and under what conditions, or it might try to define who is exposed and the detail of their exposure. In the latter case, it could be an integral part of a health effects study that is looking for a cause and effect relationship. There may be little guidance as to how or even what to measure. Most extant assessments of EMF exposure are in this category.

An assessment for regulatory compliance is relatively straightforward because the agent and the techniques for measuring it are given. When trying to link environmental exposures to an effect, however, there is normally a well-defined effect but little notion of the cause. The effect might be an increase in a certain disease in a population. The causative agent, however, can be very difficult to determine because of the variety of exposures of those with the disease. Even with a strongly suspect agent, adequate exposure assessment becomes critical in identifying a cause and effect relationship. The better the exposure data, the more surely a true link can be uncovered.

The causative agent may be identified by using epidemiologic studies. Causality cannot be established until certain supportive characteristics of association between an agent and a disease is demonstrated. The characteristics include strength, consistency, specificity, temporal relationship, biological plausibility, and coherence of evidence. However, because of time, cost, inherent difficulty, or other constraints, exposure assessment is often the study element done with least accuracy. In fact, as discussed later, the parameter that should be measured is sometimes not even known.

According to a report by the Office of Science and Technology (1985), "exposure assessment is often the most resource-demanding portion of the (risk) evaluations..." The Task Force on Environmental Cancer and Heart and Lung Disease (1981) has stated, "Many authorities agree that the weakest link in our understanding of the environmental health studies is our knowledge of human exposure."

2.4.4 Elements of an Exposure Assessment

With a definition of exposure and an appreciation of the importance of exposure assessment, the elements of an exposure assessment can be simply stated: *Measures of exposure should mimic the receptor's experience of interest.* From this statement, volumes could be filled with cookbook instructions covering nearly every conceivable situation. However, that is not necessary or even desirable. An exposure assessment can be designed with two keys: the first is knowing what to mimic; the second is knowing how to mimic it. This is explored using a common example.

Suppose that an exposure assessment is to be made of indoor, ambient temperature (like EMF, a physical agent). Guidelines are found describing rules for setting out a monitor to measure air temperature in a dwelling, and they state that the monitor shall:

- operate continuously
- be located at a height of 1.5 meters above the floor,
- be placed on an inside wall, away from drafts and direct sunlight and provide an electrical signal reflecting its measurement.

Based on these guidelines, a monitor is positioned and operated to assess (and react to) air temperature.

Of course, this monitor is a thermostat for operating a home heating and cooling system. Consider how it might be deployed given the objective of mimicking the experience of interest. That experience is our comfort, which relates to the temperature in the room. The mimicking is done by measuring temperature with a thermostat, which then drives the furnace or air conditioner accordingly. The thermostat is not placed on the ceiling because no one occupies that space. It is not placed on an outside wall because it is relatively cold (or hot) there. Similarly, no one ordinarily sits in drafts. The thermostat should be located to mimic one's experience of air temperature and thermal comfort in the home. Sometimes, one thermostat is not adequate because of variability in the home environment, and two thermostats are used. That is just a response to spatial variability of temperature; additional locations are added to be sure that the experience of interest is continually mimicked. The point is that the same advice expressed by the guidelines can be obtained by thinking about what is to be mimicked by measurements.

With that broad idea of the objective of an exposure assessment, consider the latter part of the above statement, i.e., the "experience of interest." This is sometimes expressed (or obfuscated) as the "exposure metric." The exposure metric tells what characteristic of exposure is being measured. It might be the time-averaged value, the peak value, the time that the value exceeds some stated level, or something else. The time-averaged concentration, the peak concentration, and the amount of time that the concentration exceeds a given level are all different exposure metrics. Depending on the agent, the values in each case may be expressed in units, such as parts per million, milligrams per cubic meter, or milligauss. Consider the experience of interest in terms of another familiar example, exposure to carbon monoxide.

An exposure assessment for carbon monoxide might be made with a personal monitor, a device that one can wear and that measures ambient concentrations. One choice could be that it measures the average of all concentrations over some long time period, such as days. However, the body responds to carbon monoxide on a shorter time scale, so perhaps it would be appropriate to measure over a shorter period. Carbon monoxide exposure can be measured essentially continuously, but the body may not respond rapidly enough to warrant continuous measurement. Besides, a peak level that occurs during exhalation would not really matter. Some intermediate time scale would then be best, and it need be no shorter than the time it takes to complete a breath. Thus, a rational basis for an assessment of human exposure to carbon monoxide might be: the experience of interests is the average concentration over the time it takes to complete one breath. (A monitor that sampled only the air inhaled would be even better but difficult and expensive to produce.) Because the action of carbon monoxide in the body is known, and because an indicator of exposure persists, this example can be carried further.

The ambient level relates to the experience of interest for exposure, but the real experience of interest for assessing the effects of carbon monoxide exposure is the level at which it has combined to form carboxyhemoglobin in the blood. From the earlier definitions, that would really be an assessment of dose, not exposure. Hence, a better assessment would be based on dose, because that is where the biological effects are produced. Notice, however, that the mechanism must be understood first. Knowing nothing about carboxyhemoglobin, one would assess exposure to carbon monoxide.

The best assessment is conducted by the bodies of those exposed. Blood carboxyhemoglobin level mimics the experience of interest better than monitoring could ever do because it reflects not only the level of exposure but also the body's response. It acts as an "internal monitor." The emergence of biological monitoring in the practice of industrial hygiene is based on uncovering similar responses to other agents. An internal monitor for EMF would greatly increase confidence in epidemiologic studies of hypothesized health effects from EMF.

Carbon monoxide is an easy example for exposure or dose, because the mechanism for its effects is known. EMF is more difficult because of the "illusory nature of reported effects". As with most environmental agents, EMF exposure can be recorded as time-averaged measurements. With conflicting laboratory results, with reports of effects in windows of power, frequency and temperature, and with conflicting results from epidemiologic studies, an exact idea of what should be measured does not exist. After considering ambiguous results, some researchers have speculated that the experience of interest is not the field frequency or intensity per se, but rather may be movement in and out of a field of some undetermined parameters. Given the range of possibilities that this notion uncovers, the parameters probably are indeterminable as well as undetermined. This seems to arise from a faith that a cause-and-effect relationship certainly exists, and we can uncover it if we just measure the right way.

2.4.5 Exposure Assessment Tools

Exposure assessments can use one or a combination of three basic tools: surrogates, models, and monitoring (CEQ, 1989). Surrogates are "stand-ins" for the actual agent, and they are assumed to have attributes that relate to the agent under study. For example, wire codes are surrogates for actual exposure to background residential magnetic fields. Models are used to estimate or predict exposure from basic, available information and, for EMF, physical principles. Monitoring would be expected to come closet to replicating exposures.

Exposure Surrogates. Instead of monitoring exposure directly, a substitute or surrogate is often used. An exposure surrogate is defined as a factor that is used to represent exposure to an agent when a direct measure of exposure is not available. Number of cigarettes smoked per day is a surrogate for exposure to cigarette smoke. A stationary monitor collects surrogate data for the exposure of a mobile population. (In the extreme, one might argue that virtually all exposure assessment uses surrogates.) Surrogates find wide and often creative application in health effects studies. Their use in EMF studies is illustrative and is outlined here.

Probably the most familiar surrogate for EMF exposure of the general population is the wiring configuration of the electric power distribution network. It was used by Wertheimer and Leeper (1979) in their original study of childhood cancer and has since been used repeatedly by them and others (e.g., Fulton et al., 1980; Wertheimer and Leeper, 1982; Savitz et al. 1988; Severson et al., 1988). The basic idea is that magnetic field intensity is directly related to current and proximity to the source. Because thicker wires can carry more current than do thinner wires, and because field intensity decreases away from a source, it is presumed that higher magnetic fields occur closer to thicker lines. Wertheimer and Leeper (1979) divided their study population into groups having presumably different magnetic field exposures according to factors that included wire thickness, voltage rating, and proximity of nearby lines.

Others have employed source strength and distance in different ways. Some studies have used distance from sources such as transformers and substations as well as from overhead lines (Strumza, 1970; McDowall, 1986; Coleman et al., 1985). Some studies of workers have used the strength of the source, for example the voltage of equipment at the work place (Knave et al., 1979; Nordstrom et al., 1983).

For studies of workers, however, the most commonly used exposure surrogate has been occupational classification, such as electrician, electronics worker, electrical engineer or welder. Virtually all published occupational studies to date have used this surrogate (e.g., Milham, 1982, 1985a, 1985b; Wright et al., 1982; McDowall, 1983; Coleman et al., 1983; Calle and Savitz, 1985; Pearce et al., 1985; Tornqvist et al., 1986; Spitz and Johnson, 1985; Olin et al., 1985; Stern et al., 1986). It is not known whether workers in their so-called "electrical occupations" are in fact exposed to elevated EMF levels. They are, of course, exposed to other agents, such as welding or soldering fumes and solvent vapors, which might be confounding exposures. An exposure assessment based merely on surrogates is at best speculative.

Exposure Models. The distinction between surrogates and models can be difficult to draw. Somewhat as exposure assessment blends into dose assessment, surrogates blend into models. The wiring configuration code might be thought of as a crude model for EMF exposure because it has some physical foundation: thicker wires carry more current, which produces higher field levels. Computer-generated models for estimating electric and magnetic field exposure levels have been developed by the Electric Power Research Institute (EPRI) and other groups, including the Bonneville Power Administration.

EPRI has developed the "EXPOsure CALCulation" model, EXPOCALC, for transmission line electric and magnetic fields. It is working on another, called RESICALC, for distribution lines and residential sources. EXPOCALC calculates field levels near transmission lines and incorporates a time-activity model (discussed below) for estimating exposure. Model inputs include the environmental setting and the physical and electrical parameters of the line; outputs include contour maps of field intensity and exposure histograms. RESICALC is similar in concept, but it will focus on the home and include the effects of distribution lines, household wiring, and unbalanced return currents through water pipes.

Kaune (1987) has built a model of magnetic field levels based on a sample of Seattle residences, using statistical relationships between wiring configurations and measured field levels. The most important input to this "empirical regression model" is the number of service drops near the residence. Distance from distribution lines correlates only weakly with measured fields. It is important to note that a statistical model based on data collected in one locale may not be valid elsewhere.

Exposure Monitors. EMF monitoring instruments have advanced very rapidly in recent years, due largely to work by EPRI. Their technical bases of operation was described in the section 2.3.6.

Monitors may be classified as survey or personal, depending on their design and intended use. Survey monitors require an operator and are suitable for stationary measurements. Personal monitors do not require an operator and can be worn on the body, continuously measuring fields to which one is exposed.

Many companies manufacture monitors and section 2.5.3 describes in detail several instruments that are commercially available. They differ in how they record measurements. Some, useful mainly for surveys, indicate only the instantaneous field intensity, perhaps on a dial, with no way of recording or averaging. Some average all field levels over time. They yield an exposure metric of time-averaged levels, expressed with units of kV/m or mG, which could be used to distinguish among average exposures of workers. If the length of time of exposure is noted, the total, integrated exposure could be expressed by multiplying the average by that length of time, with units of (kV/m) hr or mG hr. The more sophisticated instruments of this type collect data separately for different field level ranges; for example, <2 kV/m, 2-4 kV/m, 4-7 kV/m, and so on. Rather than averaging all exposures, they average in each of the ranges.

The Average Magnetic Field Exposure Meter, or AMEX, is illustrative of a simple, time-integrating, personal monitor for magnetic field exposure. Developed by EPRI, the AMEX measures exposure by storing the charge related to the current induced by the magnetic field in each of three, mutually perpendicular coils. The total charge is proportional to the product of the field intensity and the exposure time. i.e. integrated exposure.

Other devices can give continuous readings of the field intensity. When connected to a recording device, such as a chart or tape recorder, they can collect data over time or space for later analysis. The most sophisticated instruments now include a built-in computer to control data recording and recovery. An example of the state-of-the-art is the EMDEX, also developed by EPRI. The EMDEX uses three orthogonal coils to measure the magnetic field, and it is capable of sampling at rates from about once each second to about once every five and one-half minutes, giving a range of collection frequency that might be matched to environmental conditions.

2.4.6 Exposure Assessment Strategies

Using the objective of mimicking the experience of interest, some broad exposure assessment strategies can be developed. First, though, it is recognized that not all EMF exposure is continuous. So, lacking an exposure metric, the ideal exposure assessment would yield continuous data on the exposure of the population being studied. The simplest way to do this would be by equipping everyone with a personal, continuously recording monitor. But what happens when someone engages in an activity during which the monitor cannot be worn? What if the size of the study population is greater than the available number of monitors or the resources to use them? Now something less than the continuous, population-wide ideal must suffice. How this is done is what exposure assessment strategies are about: coming as near the ideal as possible under the technical constraints of available monitoring methods and the resource constraints of time, money, and subjects.

Exposure was defined earlier as requiring a person and an agent to be at the same place and time. A continuous personal exposure monitor essentially accompanies a person everywhere and continuously measures the amount of agent. The same measured data could be generated by knowing the concentrations of the agent at all times and places, and then superimposing these on the person's movements. Instead of using a monitor that moves with the person, stationary monitors that record everywhere continuously would be used (at least everywhere that the person goes). Variations and blends of these two approaches—personal continuous monitoring (or possibly modeling or use of surrogates), or continuous monitoring of locations combined with knowledge or assumptions about a person's activity (again, with possible use of modeling or surrogates)—encompass exposure assessment strategies for EMF. Historical assessments must rely on the latter approach. The exact details are the result of the study constraints and the investigator's imagination.

Instead of continuous data, average or instantaneous data are usually gathered. Instantaneous data, also called grab samples, reflect the conditions at one location and time, for example, spot measurements in the center of a room. Average data are referred to as integrated samples and can be averaged in space or time, or both. Many grab samples can be compiled into an integrated sample, if conditions are assumed to be constant or smoothly varying between samples. When data are collected in the center of a room and used to represent the conditions throughout the room or residence, spatial averaging has been assumed. Implicit time averaging is assumed when measurements taken only periodically are used to represent continuous exposure. (True spatial averaging of some chemical pollutants in air can be done with sophisticated sensing techniques; an equivalent capability does not exist for EMF.)

Another approach employs survey techniques, similar to an opinion poll: Individuals are singled out as being representative of the larger population, and their exposure is monitored. The results are extrapolated to the larger population.

Still another approach uses time-activity patterns (patterns of how and where people spend their time) with measurement data from different "microenvironments," or separately identifiable locations. Microenvironments are defined so that exposure characteristics can be assumed similar within specific microenvironments, such as homes, but dissimilar between microenvironments, such as between homes, substations, and offices. Monitoring studies characterize levels of the agent for each microenvironment; activity patterns can be developed by sociological research. The time-activity patterns tell where people are and how long they spend there, while the microenvironment data supply the exposures. When combined, they yield an assessment of time-averaged exposure.

Each new exposure assessment offers the opportunity for a unique strategy. The major danger in this, however, is that the ability to compare the results of different studies can be compromised by differences in how exposure is assessed. That is why it is important for new studies to include the techniques of previous ones and for protocols to evolve to a common point. However, since we do not know which, if any aspect of EMF is bioactive, or could be the agent, using standard measurement techniques might preclude identification of the true agent, if such exists.

2.4.7 Confounders

A confounder is an agent that is associated with both the presumed, causative agent and the effect being studied. Confounders are important considerations in exposure assessments because of their possible role as the true causative factor. Many potential confounding factors have been identified that are relevant to epidemiologic studies of EMF. When occupational classification is the exposure surrogate, the association may be confounded by exposures to other agents such as solvents. In community studies that rely on wiring configuration codes for exposure assessment, results may be confounded by other urban environmental factors that have the same routing and usage density features as electric distribution lines. These factors could include air pollution from local street traffic, gas lines, potable water and sewer lines, or telephone lines. Not all of these might be plausible confounders. On the other hand, benzene is a known carcinogenic component of automobile exhaust and may be a confounding factor. Well-designed studies include exposure assessments of plausible confounders for all study subjects.

2.4.8 Conclusion

Exposure assessments are performed to document levels of agents having known effects or to elucidate suspected ones. While vital to health effects studies, good exposure assessments are often lacking, in large part due to their inherent difficulty. We can design an ideal exposure assessment by following the simple notion that our measurements should mimic the receptor's experience of interest. For EMF studies the important experience of interest is unclear, although the practice has been to measure time-averaged levels, as is done with other environmental agents.

Tools for marking exposure include surrogates, models, and monitors. Surrogates, which are substitutes for a measure of exposure to the real agent, have often been used in exposure assessments. EMF exposure monitors have become rapidly more sophisticated in recent years and are finding wide use in a number of epidemiologic studies.

Starting with the ideal assessment, strategies can be designed that accommodate technical and resource limitations. However, exposure data are sufficiently variable that careful exposure assessments will be needed to identify any health effects on EMF.

2.5 Measurements

This section will examine the types of measurements performed in assessing fields and exposure, review any recognized standards for measuring fields from powerlines, and survey commercially available instruments used to make measurements.

The objective of a study will largely prescribe the EMF measurement. The extent, accuracy, and duration of the data collection will dictate the type of instrumentation used. The measurements may be covered by an existing standard that further specifies the type equipment and procedure used.

2.5.1 Measurement Categories

Three specific categories of measurements (Dietrich, 1988) are often made: survey measurements to find the field strength at specific locations at a specific time, exposure measurements to estimate the exposure of a subject over time, and engineering measurements to more completely characterize the nature of the fields in an environment.

Survey Measurements. Survey measurements find the strength of EMF at a specific point-in-space and instant-in-time. Often measurements will be done serially at several points on a path perpendicular to the transmission line to find the line's lateral field profile. Maximum and minimum field strength may be determined by rotating the measuring probe about the field ellipse. The instant-in-time nature of these measurements precludes detecting long term variations of the field quantities. The serial nature of these measurements allows temporal variations occurring during the measurements to confound determination of an accurate field profile.

The equipment most often used for survey measurements is the self-contained free body meter. The meter may have probes to measure electric fields or magnetic fields. The meter provides either an analog meter movement or a digital display to show the root-mean-square (RMS) value of the measured quantity. Survey meters have no recording capability, although some may offer outputs for stand alone recorders. They are point-in-space and instant-in-time devices. Selective electronic filtering permits only the measurement of 60-Hz powerline frequency fields. But, some meters allow overriding the selective filtering, enabling measurement of harmonics or other frequencies beyond the fundamental frequency.

Exposure Measurements. Exposure measurements introduce the time parameter into the field measurement regime to find the extent of exposure to power frequency fields that a subject experiences. Such measurements are of primary importance to human and animal exposure studies. The most accurate way to measure exposure for human subjects is to outfit the person with a recording exposure monitor. An alternative method is to take survey measurements of all areas that the subject is likely to frequent during a normal daily routine and to record the time spent in each area. Although limited in applicability for human subjects, this method is suitable for caged animal studies. The equipment designed to make exposure measurements is specialized based on the application. Some devices that are to be worn emphasize light weight and compact size while retaining measurement capability.

Engineering Measurements. Engineering measurements go beyond the single point-in-space and instant-in-time approach used by survey measurements and the periodic sampling or time weighted averaging used in exposure measurements. If, as discussed in the introduction of the exposure assessment (section 2.1), the true metric of exposure turns out to be more complicated than average field level, these more extensive measurements will be necessary to find the presence and amount of the particular property.

Engineering measurements attempt to more completely characterize the EMF environment at a location over a long duration. Engineering measurements may include field strength, field polarization, field orientation, temporal variations, spatial variations, harmonic content, wave shape, transient content, and source identification. Engineering measurements would be required to assess the subject's exposure to fields of specific windows of frequency and amplitude, or the occurrence of complex interactions between field strength and orientation of the powerline's fields and the geomagnetic field.

The equipment employed for making engineering measurements is specifically designed and customized to the problem under study. A typical system would consist of multiple sensors (each specially fabricated) designed and calibrated to interface with a multichannel data acquisition system.

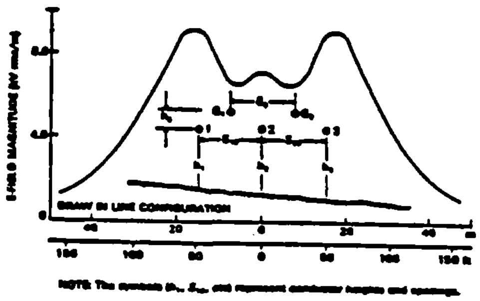
2.5.2 Measurement Standards

The Institute of Electrical and Electronic Engineers (IEEE) first published a standard in 1979 for making measurements of powerline electric and magnetic fields entitled "IEEE Recommended Practices for Measurement of Electrical and Magnetic Fields from AC Powerlines." More recently, IEEE revised this standard (ANSI/IEEE, 1987) and the American National Standard Institute (ANSI) has approved it. The standard establishes a uniform procedure for conducting survey measurements of powerlines and calibrating instruments, or more specifically as stated in the standard:

> "The purpose of this standard is to establish uniform procedures for the measurement of power frequency electric and magnetic fields from alternating current (ac) overhead powerlines and for the calibration of the meters used in these measurements. A uniform procedure is a prerequisite to comparisons of electric and magnetic fields of various overhead powerlines. These procedures apply to measurement of electric and magnetic field levels close to the ground. They also can be tentatively applied to electric field measurements near an energized conductor or structure with the limitations outlined in . . . this standard."

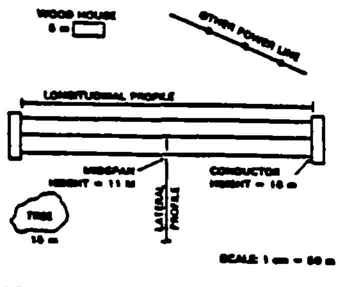
For measuring electric fields, the standard specifies the use of a free body meter, and for measuring magnetic fields, a shielded coil probe connected via a shielded cable to a shielded detector. Acceptable calibration equipment and procedures for both instruments are prescribed by the standard.

As Figure 2-22 shows, the electric field measurement procedure is to make several measurements along a line perpendicular to the powerline (lateral profile) and along a line parallel to the powerline (longitudinal profile). First, measurements of the lateral profile should be made at mid-span where the conductors are closest to the ground. Measurements should be made from the center of the line to at least 30 m (100 ft.) beyond the outside conductor. At least five equally spaced measurements should be made under the phase conductor. Complete profile measurements should commence in the region of interest beyond the outside conductor and progress successively to the opposite side of the right-of-way.



NOTE: The symbols $h_{..}$, $S_{..}$ and represent conductor heights and spacings.

Example of Lateral Profile of Vertical *E*-Field Strength at Midspan



Typical Plan View with Heights of Permanent Nearby Objects

Figure 2-22. Lateral profile and plan view of IEEE standardized procedure for conducting survey measurements of the electric and magnetic fields from powerlines.

(ANSI/IEEE, 1987)

Next, the longitudinal profile of the electric field should be made, beginning at mid-span at the point (as determined from the lateral profile) of the greatest field strength. Measurements at five nearly equal consecutive increments along a path parallel to the line should be made in both directions from the mid-span point for a total distance equal to one span.

Magnetic field measurements are made using the same procedure as for the electric field's lateral and longitudinal profiles. The standard specifies that all measurements (both electric and magnetic fields) be made with the sensor at the height of 1 m above the ground.

The standard specifies that the combined errors due to all sources (calibration, temperature effects, interference, operator proximity, etc.) should not exceed 10% for both electric and magnetic field measurements.

Recently the International Electrotechnical Committee has also published a standard (IEC, 1987) for measuring power frequency electric fields. The IEC standard is similar to the IEEE standard, with the exception that IEC recognizes the electro-optical electric field meter, which is not widely used in the United States.

While these two standards address survey type measurements, no published standards exist that specify procedures for making exposure and engineering type measurements.

2.5.3 Commercial Instrumentation

A review of manufacturers' literature shows that several magnetic field meters and a few electric field meters are commercially available. Although the Committee's review of commercially available instrumentation is not exhaustive, it does indicate what is on the market and the capability of the equipment. Microwave News (Microwave News, 1989) published an extensive summary list of commercial instruments and that summary is shown in Table 2.6. Most of these instruments are for making survey-measurements, while only a couple are available for making exposure-measurements, and none are available for making engineering-measurements. Please refer to the fundamental section for a description of the measurement principles used in these instruments.

Survey Instruments. Survey instruments measure power frequency fields at a single point-in-space and instant-in-time. Several instruments are commercially available.

Although no longer being manufactured, one of the most widely used and versatile survey instruments is the "Deno" Power Frequency Field Meter (Electric Field Measurements Co., 1985). It is a multi-function instrument–a free-body electric field meter with accessory probes and inputs for measuring other field quantities. Besides electric and magnetic fields, the instrument can measure space potential, and the open-circuit voltage and short-circuit currents induced in objects by the fields. The unit's measurement range is from 1 to 100,000 V/m for electric fields and 0.125 to 12,500 mG for the magnetic flux density. The instrument reads magnetic field strength in A/m, which must be multiplied by the conversion factor of 12.5 to obtain magnetic flux density in milligauss.

The meter features a large analog dial, probes for magnetic field and space potential, and an eight foot insulated handle used to isolate the meter from the effects of the operator's body during electric field measurements. Output jacks on the meter allow the use of an oscilloscope for further analysis of these fields.

When using the meter on its more sensitive magnetic field ranges, the operator must take care to hold the probe motionless while taking readings. Any movement of the probe will cause a saturation of the instrument by the earth's magnetic field. Electric Field Measurement Company (EFMC) of West Stockbridge, MA. formerly sold the meter for about $1200.

EFMC has replaced the "Deno" meter with a low cost electric and magnetic field meter (Electric Field Measurement Co., 1989) consisting of a 3.5 inch general purpose digital multimeter and special electric and magnetic field probes. The probes convert the field values to a voltage signal allowing the actual field quantities to be read directly on the multimeter's liquid crystal display. The probes produce 1 mV of output for 1 mG of magnetic flux density or 1 V/m of electric field strength. The Model M116PLUS can measure electric fields as small as 0.1 V/m and magnetic fields as weak as 0.1 mG. The unit's upper range is over 30 kV/m and a few hundred gauss for the electric and magnetic fields respectively. The M116PLUS costs about $250.

Monitor Industries of Boulder, CO. sells a single-function magnetic field meter (Model 42A) (Monitor Industries, undated) that uses a 6-inch diameter pick-up coil to sense AC magnetic fields. Offering stable low-level measurements, the Model 42A provides true RMS reading with a flat response over a frequency of 40 to 1000 Hz. The design avoids the problem of movement of the probe in the geomagnetic field saturating the instrument. Another interesting feature is an internal speaker allowing a qualitative indication of the frequency content of the magnetic field being measured. This is handy when attempting to identify the various magnetic field sources that might simultaneously be present. The 42A has an optional linear mode in which the meter's sensitivity is proportional to the frequency of the magnetic field–fields of higher frequency give larger readings. The price of the instrument with the optional linear mode is about $325.

Holaday Industries of Eden Prairie, MN produces an extremely low frequency (ELF) field strength meter (Holaday Industries, 1989) that measures both electric and magnetic fields. The sensitivity range of their model HI-3600-02 is 1 V/m to 200 kV/m for electric fields and 1 mA/m to 200 A/m for magnetic fields. It features true RMS detection, automatic ranging, maximum reading hold, and waveform signal output. An interesting option is a fiber optic coupled remote sensor for measuring electric fields without perturbing the field.

Table 2.6 - Gaussmeters and Dosimeters: (Source: Microwave News, 1990)

Company, Address, Contact	Meter Name	Price	Bandwidth (other bands)	Min-Max/ No. of Scales	Accuracy	Size/Weight (in./lbs.)	Options/Comments
F.W. Bell, Inc. 6120 Hanging Moss Rd. Orlando FL 32807 (407) 678-6900 Contact: Steve Dalal	Model 4048 Model 9200 Model 9500 Model 9903	$650 $1,500 $2,800 $5,800	0-12kHz 10Hz-10kHz 20Hz-10kHz 20Hz-50kHz	0.1 G-20 kG/3 10 mG-20 kG/4 1 mG-300 kG/6 1 mG-3 MG/7	2.5% 2.5% 1.0% 1.0%	4x7x1.8/1 8.8x4.5x11/8 14x7.5x14/19 18x7.5x16/36	All models are Hall Effect devices. All can measure DC Fields. All except 4048 can output to an oscilloscope.
Combinova AB, c/o Ergonomics, Inc. P.O. Box 964 Southampton, PA 18966 (215) 357-5124; FAX (215) 364-7582 Contact: Frances George	MFM 10	$6,700	5Hz-10 kHz	0.1 mG-10 G/4	2.0%	15.2x4.4x10/6.6	Data can be stored and transferred to computer.
Electric Field Measurements Box 326 W. Stockbridge, MA 01266 (413) 637-1929; FAX (413) 637-2826 Contact: Dr. Don Deno	Model 116 Model 116+ EMDEX-C	$75 $250 $2,000	60-Hz 60-Hz 40-400 Hz	0.1 mG-200 G/4 0.1 mG-200 G/4 0.1 mG-25 G/4	3.0% 3.0% 3.0%	1.5x1.5x2/0.4 4.75x2.5x9/2 1.8x4.8x6.5/1.3	116 sensor plugs into std. digital multimeter. 116+ includes multimeter. EMDEX stores data. Waveform capture device.
Electric Power Research Institute (EPRI) PO Box 10412 Palo Alto, CA 94303 (415) 855-2581; FAX (415) 855-1069 Contact: Dr. Stan Sussman	3D-AMAX		40-800 Hz	0.35-150 mG/ (not applicable)	5.0%	1x2x4/0.3	Fits in shirt pocket. Requires separate readout unit.
Electromagnetic Design, Inc. 9100 Bloomington Freeway Bloomington, MN 5543, (612) 888-7473 Contact: Rodger Hastings	ACGM-1 ACGM-2	$450 $990	20-150 Hz 20-150 Hz	0.1 mG-9 G/2 0.1 mG-9 G/2	1.0% 1.0%	2x4x7/1 2x4x7/1	Auto Ranging. LCD readout
Holaday Industries, Inc. 14825 Martin Dr. Eden Prairie, MN 55344 (612) 934-4920; FAX (612) 934-3604 Contact: Burton Gran	HI-3600-02	$1,195	50/60-Hz	0.1 mG- 20 G/5	5.0%	1.8x3.5x17/2.8 (with 8" diameter sensor)	Remote readouts. Signal outputs for dB/dt measurements. VDT/VLF version available.
Integrity Electronics and Research, Inc. 558 Breckenridge St. Buffalo, NY 14222 (716) 886-7283 Contact: Tom Valone	IER-109	$595	55-65 Hz	1 μG-2G/4	2.0%	3x4x7/0.9	LCD display, E-field Module and 3-access (sic) probe available. IER-119 available for 50Hz.
MacIntyre Electronics Design Associates, Inc. 11260 Roger Bacon Dr. Reston, VA 22090 (703) 471-1445 Contact: Barbra Vayda	uMAG	$495	0-100 Hz	10 μG-2 G/3	0.5%	4x7.5x2/0.9	Model with earth field neutralization available for $649.00.
Monitor Industries 6112 Four mile Canyon Boulder, CO 80302 (303) 442-3773 Contact: Ed Leeper	Model 42B	$350	40 Hz-1 kHz	0.01 mG-2.5 G/12	7-10%	2.1x3.1x7.8/1.8	Audio speaker. Model 42B-1 with linear frequency response available for $425.00.
Positron Industries, Inc. 5101 Buchan St., St. Montreal, Quebec, H4P-2R9, Canada (514) 345-2200; FAX (514) 731-8662 Contact: SIlvo Frank	Dosimeter 378,101	$1,650	60-Hz (5-20 MHz)	60 μG-4 G/ automatic	5.0%	6x3x1/0.5	Output to computer. Stores 18 days of data. Model 378102 available for 50 Hz.
Safe Computing Company 368 Hillside Ave. Needham, MA 02194 (617) 444-7778, (800) 222-3003 Contact: George Lechner	Safe Meter Professional Meter	$145 $175	20 Hz-30 kHz (5-70 kHz) 5 Hz-1 kHz (1-40 kHz)	1 μG-230 mG/7 0.1 mG-200mG/1	5.0% 3.0%	6x3x4/0.7 5.5x3.3x1.5/0.8	Safe meter readings must be converted to mG with hand held table. Both meters rent for $29.95 per week.
Schaefer Applied Technology 200 Milton St., Unit 8R Needham, MA. 02026 (617) 320-9900, (800) 366-5500 Contact: John Schaefer	Model EM1	$90 (Rents for $40.00/wk)	10 Hz-1 kHz	0.45-10+ mG/1	5.0%	5.5x3.1x1.5/0.8	Specifies level in 1 of 10 ranges between 0.45 and 10mG, or greater than 10mG. Model EM10 has a large remote display.

Company, Address, Contact	Meter Name	Price	Bandwidth (other bands)	Min-Max/ No. of Scales	Accuracy	Size/Weight (in./lbs.)	Options/Comments
Shoden Corp. 2-23 Ojima 1-chome, koto-ku, Tokoyo, Japan (03) 637-7711; FAX (03) 637-7724 Contact: Massy Fujiwara	MFM-12A	$1,700	60Hz (25 Hz- 10 kHz)	0.1 mG- 20 G/3	5.0%	6x4x2/3	50 Hz meter available. Outputs to oscilloscope and recorder are standard.
Sydkraft AB Carl Gustafs Vag 4, S-217 01 Malmo, Sweden (40) 25 58 96; FAX (40) 97 47 74 Contact: Bo Wiberg	MFDM 3D MFDM	$1,895 $9,500	50/60-Hz 50/60-Hz	10 µG- 20 G/5 10 µG- 2 G/ automatic	5.0% 2.0%	16x12x5/2 24x17x8/245	150/180 Hz included. The program can be made to suit different requirements.
Walker Scientific, Inc. Rockdale St. Worcester, MA 01606 (508) 852-3674, (800) 962-4638, FAX (508) 962-4638 Contact: Joe Nowlan	ELF-50 Field Monitor MF-5D Fluxmeter	$180 $1,665	50/60-Hz 0-100 kHz	1 mG-51.2 G/2 0.1 mG-200 kG/3	1.0% 1.0%	6x3.3x1.5/0.5 2.8x8.5x9.3/5	ELF-50 digital displays available for $225.00. For MF-5D, probes designed for specific applications are available.

Sydkraft of Sweden markets separate electric and magnetic field meters (Sydkraft, 1988). The magnetic flux density meter operates over a range of 0.001 to 2,000 µT and is accurate within 5% over the entire range. The manufacturer has provided both an analog and a digital display for displaying values in µT of magnetic flux density. Their electric meter is a free-body meter and covers the range of 0 to 40 kV/m. Electric field strength is displayed directly on a digital display.

Integrity Electronics and Research of Buffalo, NY sells a Model IER-109 magnetic field meter (Integrity Electronics and Research, 1989) that measures magnetic flux density over a range of 2 to 2000 mG. The narrow band response of this unit prevents it from measuring any contribution from harmonics are any frequency removed from 60 Hz. The unit has a sensitivity of 0.001 mG and is accurate within 2%. Other features include audio and visual alarms, a 200-mV chart recorder output for dosimetry, and an optional 3-axis magnetic field probe. The IER-109 sells for about $600 and many accessories are available.

<u>Exposure Instruments</u>. For making exposure measurements three instrument are commercially available: EPRI's EMDEX, Positron's Electromagnetic Dosimeter, and Combinova's MFM10. Although the primary purpose of these instruments is to measure field levels over time, they can also be used for making survey measurements.

EMDEX (Electric and Magnetic Dose Exposure) is a hardware and software exposure assessment package developed by EPRI (EPRI, 1988). The hardware is a compact self-contained electric and magnetic field meter coupled to a microcomputer for periodic recording of the field readings. The software, which runs on an IBM Personal Computer (PC) or compatible, retrieves the field data stored in the instrument's microcomputer and then analyzes and displays the readings.

The EMDEX instrument is compact and portable–it measures about 6.0 x 4.5 x 2.0 inches and weighs 16 ounces. It can simultaneously measure and record the average electric field on the user, the three orthogonal components of magnetic flux density, and the rotational motion of the meter in the geomagnetic field. The electric field meter's measurement range is from 0 to 50 kV/m and the magnetic flux density range is 0 to 25,000 mG. The accuracy over all but the highest tier of the range is 5%. EMDEX has sampling intervals from one per second to one every 5.45 minutes. Standard sample intervals and their resulting data collection durations are shown in Table 2.7.

Table 2.7 - EMDEX Sampling Intervals (Source: EPRI, 1988)

Sample Interval (Time Between Samples)	Approximate Data Collection Time Limit
1 second	10.6 Hrs. (0.4 days)
2.5 seconds	26.5 Hrs. (1.1 days)
5 seconds	53.0 Hrs. (2.2 days)
10 seconds	106.0 Hrs. (4.4 days)
15 seconds	159.0 Hrs. (6.5 days)
30 seconds	318.1 Hrs. (13.2 days)
60 seconds	636.1 Hrs. (26.5 days)

The software allows the user to download the data from the EMDEX instrument to an IBM PC . Once resident in the PC, other programs process and analyze the data, allowing it to be displayed in graphical or tabular form. An example of the graphical display is shown in Figure 2-23.

Although the EMDEX was designed for exposure measurements it is very useful for making survey measurements. Electric Field Measurement Company offers an enhancement package for the EMDEX that includes a bicycle wheel distance measuring device. The EMDEX can be programmed to read field values at an increment of distance as measured by the bicycle wheel. Profiles and contours of powerlines, substations, and even residences can be rapidly made using this feature. The enhancement package will include software to generate field profiles of powerlines and buildings.

The EMDEX is available from and available from Electric Field Measurements (under license from EPRI) for $2000. The enhancement package is $800.

Although not as capable as the EMDEX nor commercially available, EPRI has also developed the Average Magnetic Field Exposure (AMEX) meter. The AMEX is similar in idea to a radiation film-badge dosimeter. It measures integrated magnetic field exposure with a single axis probe worn on the wrist. Measurements from the single axis probe did not capture the subject's true exposure. Consequentially, EPRI is developing (EPRI, 1989) a new version of the AMEX that will have a 3-axis magnetic probe and should solve this problem. A new more compact, improved model of the EMDEX meter called EMDEXII is also under development.

The Electromagnetic Dosimeter is a 5-channel recording dosimeter (Positron Industries, 1990) manufactured by Positron Industries under a license from Hydro Quebec/IREQ. The unit simultaneously measures and records electric field, magnetic field in three axes, and electromagnetic radio frequency (RF) disturbances. The Positron Dosimeter is considerably lighter and smaller than the EMDEX instrument, it is about the size of a Sony Walkman.

The instrument measures and records electric and magnetic fields at power frequencies. The values of the field measurement is stored within 16 separate bin registers. Each bin represents a specific frequency range; therefore, the intensity of the field is indicated by the number of bins filled. The 16 bins are divided

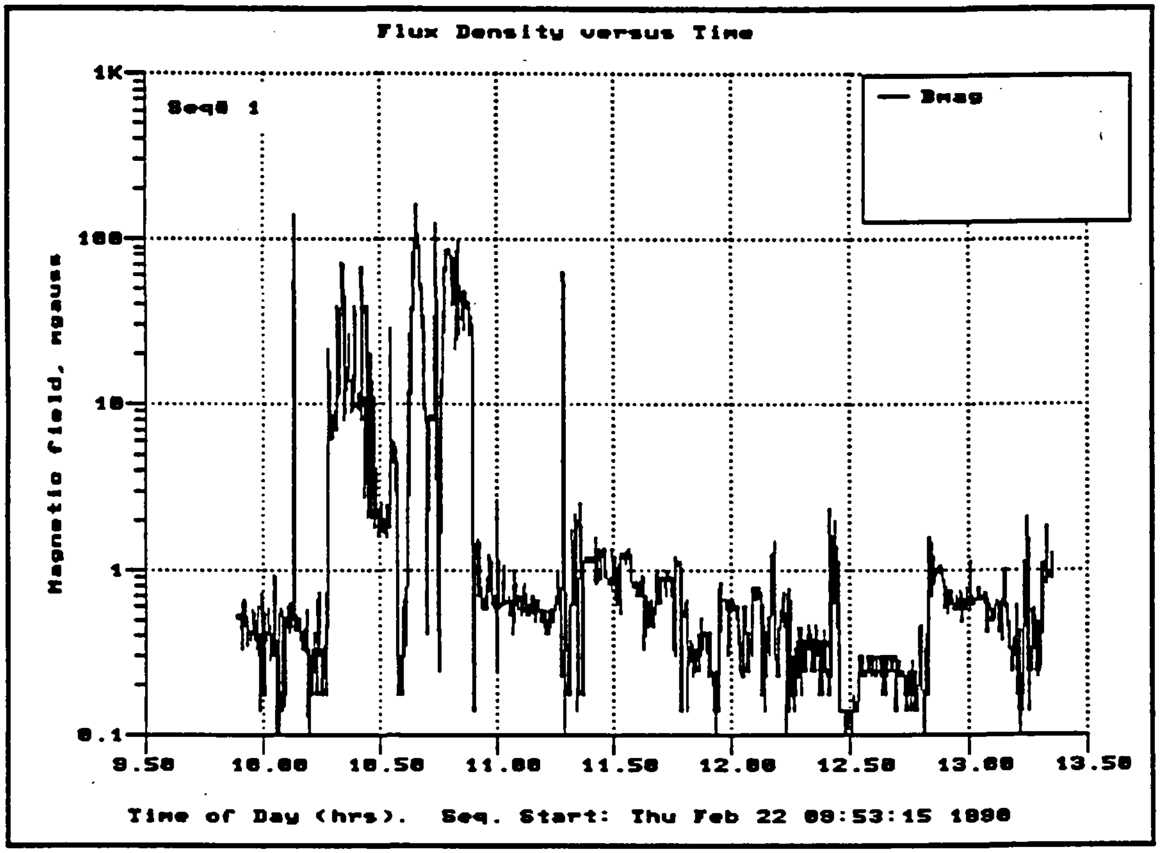


Figure 2-23. Sample output of magnetic field exposure history from Electric and Magnetic Field Exposure (EMDEX) Meter. Data from the meter is download to a personal computer for analysis and graphical display.

in a non-linear manner over the full sensitivity range of the unit. Instantaneous readings of the electric, magnetic, and RF impulse bin levels are displayed on a liquid crystal display (LCD).

The instrument can measure electric fields ranging from 0.61 to 20,000 V/m and magnetic fields ranging from 0.12 to 2000 mG. The magnetic field is measured, recorded, and stored separately for each axis (X,Y,Z). Electric and magnetic fields can be sampled at 1, 5, or 60 second intervals providing continuous recording periods of 8, 24, and 168 hours (7 days), respectively. The fifth channel effectively counts the number of high intensity RF pulses (greater than 200 V/m) occurring in a frequency range of 5 to 20 MHz.

Data from the instrument is download over a standard RS-232 port to an IBM compatible desktop personal computer. Software is provided to display graphs of chronological records of the fields at two different time resolutions, total delivered dosages, average values, as well as histograms of the data.

The Electromagnetic Dosimeter is available for either 50 or 60-Hz frequencies from Positron Industries, INC. of Montreal, Canada. It cost about $1650.

Combinova AB, a Swedish company, manufactures a recording magnetic field meter (Ergonomics, INC., 1989). Their instrument, denoted as MFM 10, is larger (15 x 10 x 4.5 inches) and heavier (6.5 lbs.) than the EMDEX and it only measures magnetic fields. The measurement range is 0 to 10 G with a 2% accuracy. The MFM 10 can store more than 4,000 readings and like the EMDEX download the readings to a PC for analysis. Available from Ergonomics, INC. of Southampton, PA, the MFM 10 costs about $6,800.

Engineering Instruments. The Committee's search did not identify any commercially available systems for performing the very detailed and exhaustive measurements needed to characterize completely the EMF environment. Although the components of necessarily sophisticated systems are available (i.e., field probes, multichannel data loggers, and powerful personal computers or engineering workstations), the Committee made no effort to study the integration of these elements into useful systems. Although most of the components do exist in "off-the-shelf" form, the Committee notes one key ingredient is missing: the software to analyze and make sense out of the vast amount of data required to be collected.

2.5.4 Conclusions

The Committee concludes the following regarding measurement of electric and magnetic fields:

- Field measurements fall into 1 of 3 categories: survey, exposure, or engineering.
- The instrumentation, procedures, and standards (if any) used to make field measurements will depend on the purpose and type of study being performed.
- Standards for making survey measurements of the fields from AC powerlines have been published by ANSI/IEEE and IEC. No standards exist for making exposure or engineering measurements.
- Survey instruments are readily available from several manufacturers for measuring both electric and magnetic fields. Exposure instruments are available, but only from a few manufacturers. Packaged engineering systems are not commercially available.

2.6 EMF Exposure Estimates

Often for a variety of reasons, assessing exposure requires estimating instead of making actual field measurements. This section will describe three methods of estimating exposure: computer models that calculate exposure, the extension of spot measurements to characterize exposure, and substitute properties, called surrogates, which are assumed to be indicative of EMF exposures.

Several situations occur when estimating may be preferable to measurement: when attempting to assess exposure for conditions when measurements are not possible, which is during extraordinary operating conditions not easily created; when attempting to quantify historical exposures, which is necessary in occupational and residential epidemiologic studies; or when the time and expense of making measurements is prohibitive and large amounts of data are required. Three of the most common means of estimating exposures are computer modeling, extrapolations of spot measurements, and the use of surrogates.

2.6.1 Computer Models

Several computer programs are available that calculate the electric and magnetic fields produced by powerlines. An informal survey of Texas utility companies, shows three programs are used predominantly: BPA's CORONA, EPRI's EXPOCALC, and APPA's TRANSPAC.

BPA's *Corona.* The Bonneville Power Administration's Corona and Field Effects Program (CORONA) was first developed as a main-frame computer FORTRAN code for predicting audible noise, radio and television interference and ozone production from AC transmission lines. The program was later extended to calculate corona loss, electric field, space potential, magnetic field, and conductor surface gradients for either AC or DC powerlines. It calculates nominal field values for DC lines, but does not calculate ion-enhanced field effects. The program can calculate the effects from a combination of up to 50 phase or pole conductors and overhead ground wires, but it is unable to analyze hybrid systems consisting of both AC and DC conductors.

With the arrival of more powerful PC's, users ported CORONA from mainframes to IBM PC or compatible systems. Data input to the program can be from either the keyboard or disk files. Input data are a physical description of the line--the number of phase and ground conductors, the number and size of the subconductors making up bundled conductors, and the physical arrangement with respect to some reference datum of the phase and ground conductors. Other data inputs are the line-to-neutral voltage of each phase conductor, the phase currents, and a host of environmental parameters, and sensor height and location data.

The user has the option of generating one or all of the following reports: audible noise, radio interference, television interference, ozone concentrations, corona loss, electric field, and magnetic field. Each report is a tabular listing of the output data. The program does not feature any graphical output capability; however it does offer the option of creating a file of calculated results in data interchange format (DIF). The DIF file can easily be loaded into any one of several popular spreadsheet packages, such as Lotus 123 or MicroSoft's Excel, for generating graphical plots of the powerline's lateral profile.

Appendix A contains CORONA's electric and magnetic field output reports for a typical 345-kV transmission line.

BPA has placed CORONA in the "public domain" and permits it to be freely copied and distributed. The only stipulation is that BPA be credited as the source of the program. It is free to anyone for the asking and in wide use across the country.

APPA's *TRANSPAC.* David R. Brown, INC. has developed, for American Public Power Association (APPA), an extensive set of computer programs (Brown, 1989) for the design and analysis of electric power transmission lines. The programs are divided into three categories: environmental effects, mechanical performance, and electrical performance. The programs run on the IBM PC or compatible with at least 512 K of memory and two floppy disk drives.

The environmental effects group contains four programs to calculate electric fields, magnetic fields, audible noise, and radio noise. The mechanical performance group features two programs to calculate conductor temperature rise and current carrying capacity, and conductor sag and blowout (i.e., physical displacement of the line due to wind loading). The electrical performance group contains six programs that calculate line electrical impedance and admittance parameters, line capability, line shield and insulator losses, switching surge performance, lightning performance, and tower footing resistance. These programs are independent of each other and can be run in any order, but they all use the same input data sets.

Input data to TRANSPAC are very similar to the input to the BPA's CORONA, although more straightforward. TRANSPAC accepts phase-to-phase voltages and allows the phase relationships between phases to be specified explicitly by a phase angle in degrees instead of using complex values for each phase's phase-to-neutral voltage. TRANSPAC is slightly limited because it allows only half the total number of phase and shield conductors as CORONA--25 versus 50. In most applications, problems seldom involve configurations of more than four or five separate circuits on a transmission right-of-way.

The electric field program's output report lists the average maximum subconductor surface gradient for each phase and shield group. It generates a tabular listing and graph of the magnitude of the maximum electric field strength that occurs at each increment along the lateral profile. Whereas CORONA lists the magnitude and angle for the maximum and the vertical and horizontal components of electric field strength, TRANSPAC lists only the magnitude of the maximum with no detail about its orientation. Both CORONA and TRANSPAC are limited to a maximum of 100 data points.

TRANSPAC's magnetic field calculation accounts for the effect of currents in the shield wires and ground return currents. Neither CORONA or EXPOCALC offer this capability. The user must supply earth resistivity and permeability to use this feature. Inclusion of the shield wires and ground return paths affect the contribution to the magnetic field results slightly as shown by comparison of the output in

Appendix A. Because of this ability TRANSPAC may be the program of choice when:

- Calculating magnetic fields at locations a great distance from the line, where contributions from ground return path can be significant; or
- Proving in regulatory and judicial proceeding that all effects (including shield wire and ground return currents) have been accounted for in the calculation of magnetic field levels.

The magnetic field report is similar in format to the electric field report. It lists the calculated currents in each shield wire and then features a tabular listing and graph of the magnitude of the maximum magnetic flux density in milligauss. Again CORONA provides more information by giving both the magnitude and angle of the maximum magnetic flux density and its vertical and horizontal components. TRANSPAC offers the choice of including or ignoring the effects of the currents in the shield wires and earth return currents.

TRANSPAC allows the reports to be sent to the printer or to a disk file. Unlike CORONA's DIF file option, TRANSPAC does not offer an easy method of transferring output data to other programs. It is possible to use a text editor to extract the data from the output file for "importing" into a spreadsheet program.

TRANSPAC is available to members through APPA for a nominal distribution fee of $150 and available to anyone else through David R. Brown, INC. for $2,995. Appendix A contains a sample run of a typical 345-kV transmission line.

<u>EPRI's *EXPOCALC*.</u> EPRI has sponsored the development of a computer model that assess personal exposure to the electric and magnetic fields of transmission lines. EXPOCALC (Enertech, 1988) combines field calculations similar to those performed by CORONA and TRANSPAC with activity modeling to estimate the time a person engaged in a particular activity spends in various levels of fields from nearby transmission lines. The program is designed for use on a microcomputer by persons with limited computer knowledge. The approach EXPOCALC uses is first to characterize the physical geography of the study area. Second, the subject's activity pattern is mapped to the physical geography to calculate time spent in each location. Third, electric and magnetic contours for the electric sources are calculated for the area of the physical geography. Fourth, the model calculates the equivalent field for the specific activity by applying an activity factor to the calculated unperturbed field. The activity factor describes a known physical reference condition (e.g., current induced into a body standing erect, with arms at side) to the condition occurring in the activity (e.g., percent of reference current for a body sitting on a tractor with arms raised). Fifth, the model calculates the index of exposure by summing the product of the time spent at each location and the value of the field at that location for all activities.

EXPOCALC features function menus, built in data editor, and graphical output directly to the screen or printer. The user has the options of creating a new case by entering data from the keyboard, or loading and modifying an existing case, or running an existing case by loading an existing data file.

EXPOCALC's input has the physical description of a study area surrounding the transmission line, the electrical description and physical orientation of the phase bundles and shield wires, and the phase-to-phase voltage and current for each phase. EXPOCALC assumes a three phase transmission line with each phase separated by 120 electrical degrees. EXPOCALC offers the unique capability to account for the shielding of the electric field by buildings, fences, vegetation and other objects. EXPOCALC also accounts for the sag in the transmission conductor between supports in calculating the electric and magnetic field contours.

Users can select to run an electric field analysis, magnetic field analysis, or both. They have the option of viewing the results graphically, through contour maps or histograms, or generating the results in a tabular format. They can direct the tabular results to the screen, printer, or a data file. Although EXPOCALC generates horizontal contour plots, it is unable to generate lateral profiles.

Like TRANSPAC, EXPOCALC calculates the magnitude of the maximum electric strength and magnetic flux density. It omits giving the angle of the magnitude. The program also does not support any data exchange formats, so transferring data to other programs requires editing the output files into a form other programs can accept. A copy of the input and output reports for the typical 345-kV transmission line are included in Appendix A.

EXPOCALC is available to EPRI members for a nominal distribution fee and available to anyone else under license from EPRI through Enertech Consultants for $1200.

Comparison of Results. The electric and magnetic fields for the same 345-kV transmission line were calculated by CORONA, TRANSPAC, and EXPOCALC and the results compared. The lateral profile was plotted by importing the results into MicroSoft's EXCEL spreadsheet. The profiles start at the center of the transmission line and extend out 500 feet. As the plots for both the electric and magnetic fields show (see Figures 2-24 and 2-25), all three programs give almost identical results–the three curves overlay each.

Other Programs. EPRI is developing another program called RESICALC (Sussman, 1988) that will calculate residential magnetic fields. RESICALC allows development of complex residential models that contain multiple line and point sources each having different electric phasing and temporal magnitudes. Sources of magnetic fields considered are distribution primary and secondary conductors, water pipes, household wiring, and other sources.

2.6.2. Spot Measurements

Another method (Silva, 1988a) of assessing exposure is to use a single point-in-space, instant-in-time value obtained from a survey measurement to represent the field at a location. The chief shortcoming of this procedure is that it ignores temporal variation of the fields. This may be acceptable for electric field exposure estimates, since the electric field from transmission and distribution lines are almost constant. However, magnetic fields vary constantly and such an approach prevents characterizing the magnetic field's spatial and temporal variability. The spot measurement approach can be improved by sampling the magnetic field over a period. But, that period (usually 24 hours) may not be long enough to capture weekly and seasonal variations. Also the method portrays the entire area's fields based on the field in only one location.

2.6.3. Surrogates

A common method to assess exposure to EMF is to choose a substitute physical quantity that may reliably indicate exposures. Use of a surrogate is often desirable because of economic and time constraints. Surrogates that have been used to estimate electric and magnetic field exposure are various wiring codes,

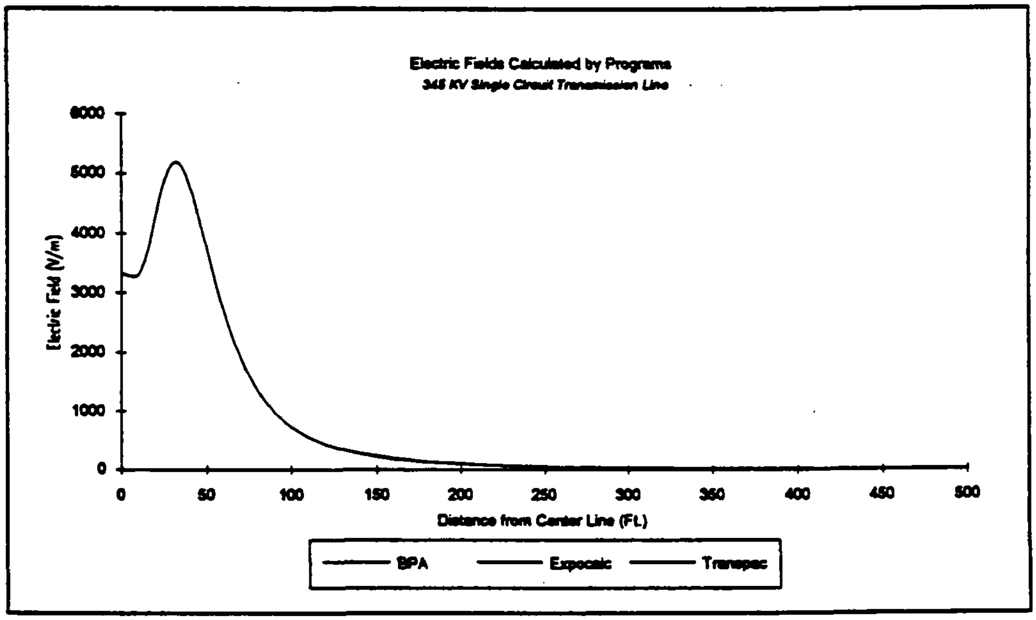


Figure 2-24. Comparison of electric field profile calculated by BPA's CORONA, EPRI's EXPOCALC and APPA's TRANSPAC. The three program yield almost identical values and the three curves overlay one another.

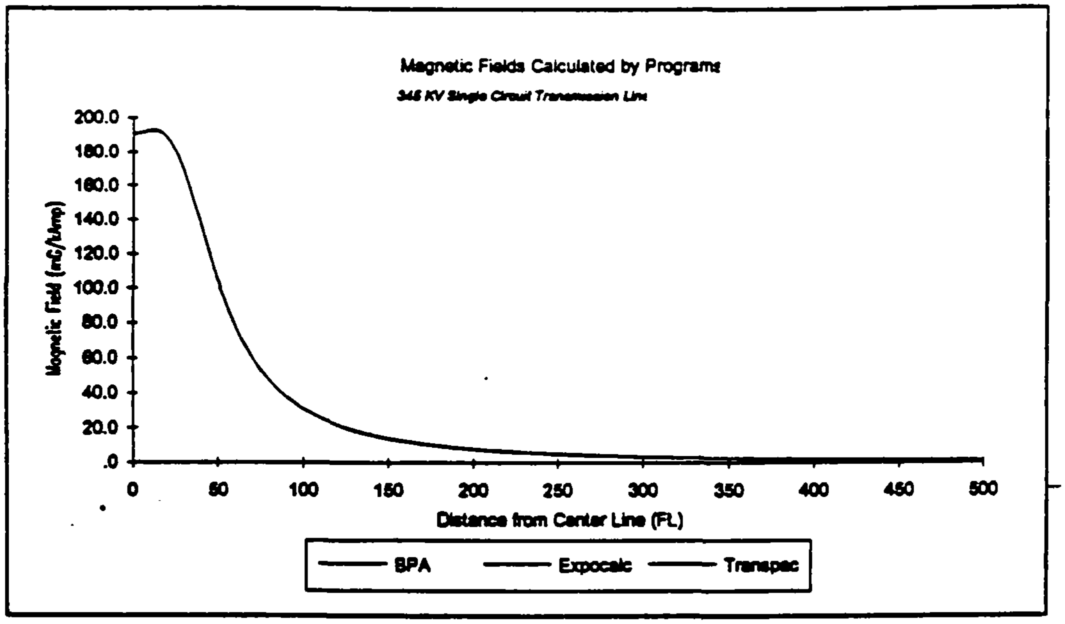


Figure 2-25. Comparison of magnetic field profile calculated by BPA's CORONA, EPRI's EXPOCALC and APPA's TRANSPAC. The three program yield almost identical values and the three curves overlay one another.

distance to powerlines, number of service drops, strength of the source, and occupational classification.

One wire code system developed by Wertheimer and Leeper (Wertheimer, 1979) attempts to characterize the historical exposure of a location to magnetic fields based on the amount of current the external wiring can carry and the proximity of the wiring to the location. Locations are divided into one of several categories such as:

VHCC - Very High Current Configuration

OHCC - Ordinary High Current Configuration

OLCC - Ordinary Low Current Configuration

VLCC - Very Low Current Configuration

The important factor in application of a surrogate is proper understanding of the accuracy of the indicator and whether the surrogate represents only the suspected quantity. For instance, Bracken (Bracken, 1988) noted that Wertheimer-Leeper code only accounted for about 20% of the variation found in one magnetic field measurement study. Keam (Keam, 1988) concluded, after reanalyzing the data from the various Denver epidemiological studies, that the Wertheimer-Leeper code is not a good surrogate for magnetic fields.

Also, critics (Wachtel, 1988) claim that wiring codes can confound the relationship between magnetic fields and cancer since they may be indicative of other factors (confounders) likely to be associated with causing cancer. Wachtel maintains that wiring codes may be surrogates for the age and type of housing construction, the density of housing, and the amount of vehicular traffic in an area.

Confounders associated with the age and type of housing construction may be: presence of toxic building material (e.g., formaldehyde, asbestos), seepage of radon gas, and proximity to toxic waste sites or contaminated water sources. The confounders associated with traffic and housing density may be air pollution and noise levels, and lack of recreational space. In fact, Savitz has recently analyzed the Denver locations (Savitz, 1989) for correlations between childhood cancer and traffic density and found risk ratios very similar to those associated with magnetic field exposure.

2.6.4 Conclusions

- Several computer programs are available to accurately calculate electric and magnetic fields.
- CORONA, TRANSPAC, and EXPOCALC are three programs in use by Texas utility companies. All three programs yielded almost identical results for the sample problem.
- Under controlled conditions, spot measurements may be combined with the

subject's activity patterns to estimate exposure.

- Surrogates must be used with great care since they can often be indicative of other factors besides power frequency EMF, which also may be associated with cancer.

2.7 Preliminary Field Measurements

Data have been collected that characterize field levels in residences and work places. Source characterizations have included measurements near appliances, as well as sources specific to certain occupations. The data collection procedures have ranged from spot, area measurements at one location, to continuous area monitoring of a location, to personal monitoring. The findings of many of these studies, were detailed in materials prepared by Robert M. Patterson, Temple University, for; Seminar on New EMF Epidemiologic Results and Their Implications, October 16-19, 1990, are summarized below.

2.7.1 Residential Exposure

Measurements of electric fields in 10 rural residences in Wisconsin and Michigan showed electric field intensities ranging from 2 to 65 V/m, with a mean value of 16 V/m and a median of 14 V/m. Magnetic field measurements at the same locations yielded a range of 0.07 to 1.6 mG, with a mean of 0.8 mG and a median intensity of 0.4 mG (IITRI, 1984).

The EPA measured 25 homes in Las Vegas and found an average of 5.8 V/m for the electric field and 2.5 mG for the magnetic field. The ranges were 2 to 12.7 V/m and 0.6 and 7.8 mG (Tell, 1983).

In New Jersey, Caola et al. (1983) measured the electric fields at homes that were 1610 m, 95 m, and 1682 m from a 500-kV transmission line and found a range of 1 to 20 V/m. Measurements in a Pittsburgh apartment revealed a non-uniform distribution of electric field levels throughout (Florig, 1986).

Barnes (1985) reported electric field levels measured in thirty-six homes in Denver under two conditions. Under "low power" conditions, with lights and appliances off, the mean value was 7.5 V/m. "High power" conditions, with lights and appliances on, produced a mean of 10.4 V/m.

As part of an epidemiologic study, magnetic field measurements were conducted in 483 Denver residences under low and high power conditions (Savitz, 1987). The mean low power value was 0.76 mG with a standard deviation of 0.79 mG, while the mean and standard deviation for high power were 1.05 and 1.3 mG. Wachtel (1986) pointed out that the difference is not statistically significant.

An epidemiologic study in Seattle incorporated electric and magnetic field measurements to assess residential exposures of cancer cases and controls (Kaune et al., 1987). Data were collected for 24 hours in 43 homes. The electric fields measured near a wall in the family rooms averaged 33 V/m, a value greater than the short-term measurements taken in the center of the room. The difference was attributed to differences in proximity to electrical wiring. The researchers found no relationship between electric and magnetic fields, between electric fields and wiring configurations, and between 24-hour and spot electric field measurements. They concluded that localized measurements are not useful for characterizing electric field exposures.

A somewhat different picture emerged from the magnetic field data in the Kaune study. The mean value in the family room was 1.0 mG, with a standard deviation of 1.2 mG and a median of 0.6 mG. Simultaneous measurements in the bedroom gave 1.0, 1.4, and 0.5 mG for the mean, standard deviation, and median, respectively. There was a diurnal variation that coincided with electric utility loads, peaking in the morning and evening, with low levels in the very early morning. For an individual residence, there was no correlation with power consumption. There was a significant correlation between twenty-four-hour and short-term levels. The researchers concluded that the predominant sources are external to the home and that ground return currents could be an important source.

Both the Denver and Seattle studies tested the Wertheimer-Leeper wire code against their measured data. Savitz (1987) found that the wire codes gave the correct average ranking of magnetic field levels among homes. Kaune et al. (1987) found some correlation between measured levels and wire codes, but the wire codes explained only 20% of the variance. As discussed earlier, he constructed a regression model of field levels. The most important predictor was the number of service drops near (within 43 m) of the residence. The presence and proximity of transmission lines were also important, as was the number of primary phase conductors. There was no significant correlation with distance to primary and secondary distribution lines.

Silva et al. (1988) measured magnetic fields in 91 buildings in six states and found the vertical component of the field to be dominant. Values measured at head level had a mean of 1.2 mG and a standard deviation of 2.5 mG. The maximum was 63 mG; the data appeared to follow a log normal distribution. In houses, they found that field levels depended on the method used for grounding. Of 31 homes with a local ground rod, the mean vertical magnetic field was 0.65 mG. It was 1.9 mG for homes grounded to the water system.

In other studies, a median level of 0.15 was found for 44 homes in the United Kingdom (Myers et al., 1985). Tomenius (1986) recorded an average of 0.7 mG at the front door of 2098 dwellings in Sweden. Measurements at 181 locations in 18 residences in Los Angeles had a geometric mean of 0.6 mG and a geometric standard deviation of 2.8 (Bowman et al., 1988). The ninety-fifth percentile was 3.4 mG. According to Stuchly (1986), levels of 80 to 120 mG have been reported in Germany in rooms where thermal storage electric heating is in use.

Figure 2-26 summarizes many of these data on a common plot (Bracken, 1988). Geometric means and standard deviations are shown when available. When these were missing, the data were assumed to be log-normally distributed and a transformation was made. Missing standard deviations were assumed to be 1.37 mG. The figure shows consistency among data in the United States and Sweden, with lower values recorded in the United Kingdom.

Electric fields near appliances average 30 to 60 V/m at one foot, but they fall off rapidly at greater distances. Levels can reach 960 V/m at the chest under an electric blanket (Florig, 1986). Preston-Martin et al. (1988) reported magnetic fields of about 24 mG under electric blankets. They estimated that electric blanket use increases "overall exposure" to electric fields by less than 50%, and to magnetic fields by less than 100%. Measurements of magnetic field exposure due to appliance use averaged 21 mG with a standard deviation of 76 mG for measurements taken at the belt (Silva et al., 1988). The high magnetic fields near

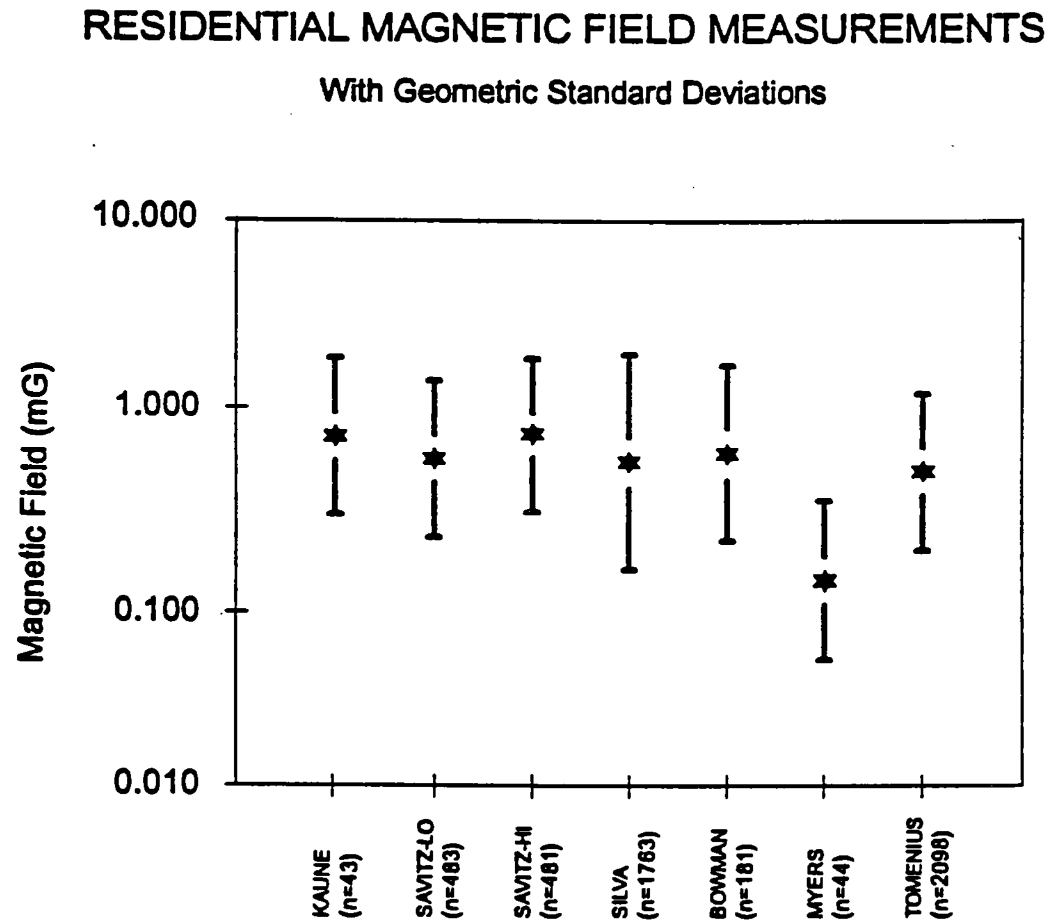


Figure 2-26.

appliances indicate that their contribution must be explicitly considered in any careful assessment of total exposure.

2.7.2 Occupational Exposure

Electric field measurements in fourteen commercial and retail locations in rural Wisconsin yielded a mean of 4.8 V/m and a standard deviation of 4.3 V/m, about one-third the values found in residences. The magnetic fields averaged 1.1 mG; the standard deviation was 2 mG (IITRI, 1984).

Bowman et al. (1988) sampled 114 work sites. "Electrical worker" environments had a geometric mean fields of 4.6 V/m and 5 mG. Secretaries had values of 2 to 5 V/m, 3.1 mG if they used a Video Display Terminal (VDT), and 1.1 mG if they did not. For powerline workers, the overhead line environment yielded geometric means of 160 V/m and 42 mG. A value of 57 mG was determined for underground lines. Other findings included 298 V/m and 39 mG at a distribution substation. Radio and television repair shops yielded 45 V/m, while AC welding produced 41 mG.

Swedish workers in a 400-kV substation spent most of their time in fields below 5 kV/m, with brief exposures above 15 kV/m (Knave et al., 1979). A study of Canadian linemen and substation workers used measurements and task activity patterns to estimate daily exposures (Stopps and Janischewskyj, 1979). Estimates ranged from 50 to 60 (kV/m)-hr for 500-kV linemen to 13 (kV/m)-hr for 115 to 230-kV lineman, and 12 (kV/m)-hr for substation workers. Using a personal exposure meter, which was worn on the arm, Male et al. (1984) measured exposures of electrical workers in the United Kingdom. The device had a threshold of 6.6 (kV/m)-hr. Among 166 transmission workers (equipment rated 132, 275, or 400 kV) and 121 distribution workers (equipment rated at 132 kV or below), only 26 transmission workers and two distribution workers had cumulative, 10-day exposures above the threshold. Among the 26 transmission workers with measurable exposures, the median daily exposure value was 1.5 (kV/m)-hr per day, and the maximum value was 24.3 (kV/m)-hr per day.

Farmers whose land is crossed by high-voltage transmission lines represent another exposed population with higher-than-normal peak exposures. Using a combination of measured and modeled concentration data, it was determined that the annual exposure of this group might range from 10 to 120 kV/m hr, with differences being attributed to the voltage of the lines (EPRI, 1985). Peak exposures ranged above 8 kV/m.

Bracken (1985) reported the use of personal electric field exposure monitors to measure cumulative exposures of utility employees. Highest exposures, 1.7 kV/m hr, occurred for linemen. Exposures generally rose with the voltage of the equipment, and daily maxima ranged from 5.1 to 7.6 kV/m hr.

Personal exposure data have been collected for work, non-work, and sleep periods in a study of 36 Canadians–20 utility workers and 16 office workers (Deadman, 1988). The time-weighted average of one week's data yielded a geometric mean-electric-field exposure of 3.1 mG. It was 1.9 mG for the office workers. Both groups had a level of 1.5 mG while sleeping. While at work, the utility workers' exposures averaged 48.3 V/m and 16.6 mG. Office workers were exposed to a geometric mean level of 4.9 V/m and 1.6 mG.

2.7.3 Exposure Summary

Bracken (1988) has summarized the characteristics of EMF exposure as follows:

- *Internal sources of electric field seem to predominate in residences. Electric fields in residences are highly variable, source dependent, and not easily predicated.*
- *Residential electric fields are in the range of 1 to 100 V/m, with area fields typically in the range of 5 to 20 V/m.*
- *Electric fields in public areas and occupational settings are comparable with residential exposures except when well-defined high-voltage sources are present.*
- *Transmission lines and other power transmission facilities represent sources of high electric field levels in outdoor areas, but levels are strongly dependent on shielding by objects.*
- *Residential magnetic fields are strongly influenced by external sources such as ground currents, transmission lines and nearby distribution lines. Appliances represent a source of highly variable fields, but predictive modeling of field levels may be possible.*
- *Domestic magnetic field levels are typically in the range of 0.5 to 1.0 mG but average levels can be much higher.*

- *Proximity to power transmission facilities is directly related to magnetic field levels in public areas and occupational settings. Higher fields are present for occupations that are associated with high-current facilities or equipment.*

Figure 2-27 depicts electric and magnetic field levels typical of various sources and environments.

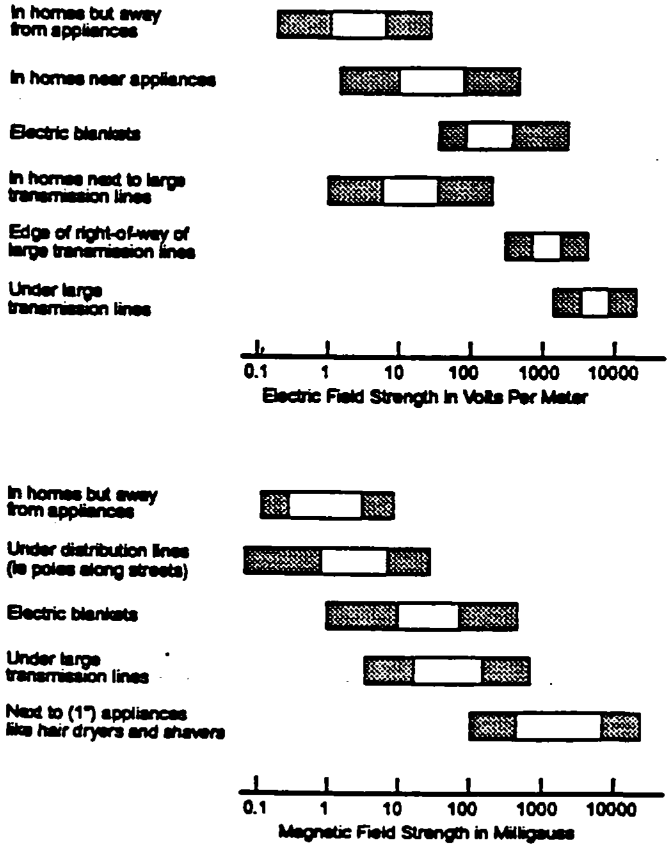


Figure 2-27.

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3.0 Epidemiology of Health Effects and Exposure to EMF

3.1 Introduction

Epidemiology is the study of the distribution and determinants of diseases and injuries in human populations. That is, epidemiology is concerned with the frequencies and types of illnesses and injuries in groups of people and with the factors that influence their distribution. This implies that disease is not randomly distributed throughout a population, but rather that subgroups differ in the frequency of different diseases. Knowledge of disease distributions can be used to investigate causal factors and thus to lay the groundwork for programs of prevention and control (Mausner and Kramer, 1985).

Epidemiologists have organized the complex processes that lead to disease in various ways. One useful way to view the causes of disease is in terms of the agent, the environment, and the host (Friedman, 1980). When a factor must be present for a disease to occur, it is called a necessary agent of that disease. An agent may be a necessary but not sufficient cause of disease because suitable conditions within the host and the environmental must be present for disease to develop. Host factors are usually intrinsic, whereas factors in the environment are extrinsic. Host factors affect susceptibility to disease; environmental factors influence exposure and may indirectly influence susceptibility as well. The interactions of these two sets of factors determine whether or not disease develops (Mausner and Kramer, 1985).

3.1.1 Types of Epidemiologic Studies

Epidemiologic study designs are more fully discussed in Appendix B (Fundamentals of Epidemiology, Section I), and are only briefly described below.

In general, epidemiologic studies (which undertake no manipulation of the study factor) may be categorized as either descriptive or analytic (i.e., etiologic). *Descriptive epidemiologic studies* are usually conducted when little is known regarding the occurrence, the natural history, or the risk factors for a particular disease (Kleinbaum et al., 1982). The objectives of such studies include identification of the patterns of disease occurrence in relation to variables such as person, place, or time and the generation of more specific hypotheses regarding etiologies. Descriptive studies provide essential data to public health administrators who use this information to plan programs for prevention and control of disease. Epidemiologists also rely on descriptive studies to lay the groundwork for hypothesis-testing etiologic studies (Hennekens and Buring, 1987).

Correlational studies, case reports or case series, and cross-sectional studies are included under the general category of descriptive epidemiologic studies. In *correlational studies*, measures that represent characteristics of entire populations are used to describe a particular disease in relation to some factor of interest, such as age, time, utilization of health services, or consumption of a food, medication, or other product. Instead of considering whole populations, as in correlational studies, *case reports* or *case series* describe the experience of a single patient or group of patients with a similar diagnosis. The third major type of descriptive study is the *cross-sectional* or *prevalence survey*, in which exposure and disease status are assessed simultaneously among individuals in a well defined population (Hennekens and Buring, 1987).

Once a disease has been identified and categorized with respect to person, place, and time, *analytic* or *etiologic epidemiologic studies* are often employed to test specific hypotheses, estimate chronic health effects, and to suggest potential means of disease prevention (Kleinbaum et al., 1982). The major types of analytic or etiologic epidemiologic studies include case-control and cohort or follow-up studies. In a *case-control study*, subjects are selected on the basis of whether they do (cases) or do not (controls) have a particular disease. The proportions of subjects within each group having histories of various exposures or other characteristics of interest are then compared. Case-control studies provide a solution to the problems inherent in the study of diseases with extended latency periods. Also, case-control studies permit the evaluation of a wide range of potential etiologic exposures that may be related to a specific disease and of the interrelationships among these factors. Case-control studies are particularly useful in the examination of rare diseases (Hennekens and Buring, 1987).

The second major type of analytic epidemiologic study is the *cohort* or *follow-up study*. In this type of study, a group (or several groups) of individuals is defined on the basis of the presence or absence of exposure to a suspected risk factor for a disease. There are two types of cohort or follow-up studies: *prospective* (or concurrent) and *retrospective* (or historical). These two types of cohort studies differ in terms of when exposure and disease occur in relation to the onset of the study. At the time exposure status is defined, all potential subjects must be free from the disease being studied, and all disease-free eligible participants are followed for a period of time to assess the occurrence of that disease. As a result of this design, cohort studies can provide information on the full range of health effects of a single exposure. When feasible, they are the preferred method of study since the results are less subject to bias than other study types. However, since cohort studies are generally very time-consuming and expensive, they are often conducted only after a hypothesized relationship has been explored and evaluated in a case-control study (Hennekens and Buring, 1987). Therefore, these two types of studies are complementary.

3.1.2 Estimates of Risk in Epidemiologic Studies

Rates of disease and ratios of rates derived from comparisons of exposed and unexposed groups in epidemiologic studies are used to provide estimates of risk. In a follow-up (cohort) study, an actual disease rate can be tabulated separately for both the exposed and nonexposed groups. These rates can then be compared in several ways to develop a quantified expression of risk in relative or absolute terms.

The most common measure of risk in a cohort follow-up study is the relative risk (RR). It is defined as the ratio of the incidence of disease in the exposed group divided by the incidence of disease in the nonexposed group. The relative risk is an indication of the degree of risk for disease (either increased or decreased) among the exposed relative to the nonexposed. This value, therefore, provides an estimate of the importance of the exposure under study. A relative risk of one (1.0) indicates no association between exposure and disease.

The standardized mortality ratio (SMR) is frequently used to estimate risk in epidemiologic studies when the only information available is the number of deaths that have been observed among the study population. It provides a means of comparing the mortality experiences of populations that have different distributions of important variables such as age, sex, or race. To assess whether the "observed" number of deaths is excessive, rates from a standard population are used to calculate the number of "expected" deaths for the study group had they succumbed to the disease at the same rate as the standard population.

The study group is first divided into a number of "strata," which usually include 5- or 10-year age groups within each sex and race or ethnicity category. The expected number of deaths for each stratum is calculated by multiplying the number of persons (or person-years of observation) in that stratum by the corresponding stratum-specific mortality rate in the standard population. The total "expected" number of deaths is then obtained by summing the expected numbers calculated for each stratum. Once this value has been obtained, the SMR is calculated by dividing the observed number of deaths by the expected number (occasionally, the resulting ratio is multiplied by 100 to eliminate the decimal places). When the observed and expected numbers are equal, the SMR is equal to 1.0 (or 100, if that multiplying factor has been used), and no excess (or decreased) risk is present. Values less than 1.0 (or 100) represent "decreased risk," and values greater than 1.0 (or 100) indicate "increased risk" for the study group compared to the standard population (see Appendix B).

A similar ratio can be calculated using morbidity or incidence data, thereby producing a standardized incidence ratio (SIR) which is interpreted in the same manner. An SIR that is equal to 1.0 (or 100) means that the observed and expected numbers of cases are equal, indicating no increased risk for the development of the particular disease. An SIR of 1.5 (or 150) means that there are 50% more cases in the study group than expected.

An entirely different ratio which appears frequently is the proportional mortality ratio (PMR). Although PMR and SMR studies appear superficially similar, they are quite different and are derived from different types of data. Proportional mortality expresses the proportion of all deaths that are due to a particular cause. For example, for deceased individuals who were employed in a particular industry, 20 percent of the deaths may have been due to cancer, whereas heart disease may have accounted for 35 percent of the deaths. Most PMR studies are done when the investigator only has information regarding the people who have died but does not have data on the total number of persons (or person-years) at risk. Under these circumstances, the only items that can be compared are the proportions of all deaths that were due to cancer in one occupation with the proportion due to cancer in another group. Since data for the total population at risk are not available, a mortality rate cannot be determined.

In contrast to *cohort* studies, which determine disease rates for exposed and nonexposed groups, *case-control* studies start with diseased and non-diseased groups and then determine exposure histories for individuals in the two groups. Since this approach does not permit the determination of actual disease rates, a relative risk cannot be determined. One can, however, compare "exposure ratios" between diseased and non-diseased groups and, under certain conditions, these "exposure ratios" can be used to estimate the relative risk by calculating the relative odds of exposure, or odds ratio (see Appendix B).

The odds ratio (OR) provides a reasonable estimate of the relative risk if the disease in question is relatively rare (e.g., specific cancers), if the exposure is relatively common, and if there are no serious biases in the design or conduct of the study. The odds ratio is interpreted exactly the same as the relative risk. If equal to one (1.0), the odds ratio suggests no association between the exposure and the disease.

3.1.3 Assessment of Validity in Epidemiologic Studies

In any scientific study, careful attention must be given to the validity and reliability of the data. All data collection methods involve some degree of inaccuracy and variability. Concern for these threats to data quality is more pronounced in observational studies of human populations, as is the case with most epidemiologic studies.

In assessing the results obtained from epidemiologic studies of human health effects thought to be associated with exposure to powerline-frequency electric and/or magnetic fields (EMF) (or any other suggested etiologic factor), two aspects of study validity must be considered: internal validity, as determined by accuracy and reliability of measurements, and external validity or the generalizability of the results.

INTERNAL VALIDITY

The concept of internal validity addresses the question, "Is this study capable of providing an unbiased and quantitatively accurate estimate of risk?" Threats to the internal validity of a study include: biases in the selection of study groups, errors and biases in measurements and classification of disease or exposure, confounding of the disease-exposure association by other risk factors, and the possibility that apparent associations may be due to chance. Each of these factors must be addressed in evaluating the internal validity of an epidemiologic study and weighing the credibility of any conclusions based thereon.

Bias in Epidemiologic Studies. *Bias* may be defined as a systematic error introduced into an epidemiologic study that results in an inaccurate estimate of the association between exposure and risk of disease (Hennekens and Buring, 1987). Since epidemiologic studies involve free-living human beings, even the most rigorously designed investigation will have the potential for one or more types of bias and/or confounding. A number of sources of bias may distort the association between exposure and disease observed in a particular study (Sackett, 1979). The major sources of bias resulting from the employed methods of study design and analysis may be conveniently grouped under the headings of selection bias, information bias, and confounding bias (Kleinbaum et al., 1982).

Selection bias refers to an error in the estimate of an effect that is due to systematic differences in the characteristics of those who are selected for study and those who are not (Hennekens and Buring, 1987). For instance, a telephone interview survey will exclude households that have no telephone. This exclusion may underestimate the proportions in the population with certain characteristics, such as age, ethnicity, and socioeconomic status; thus, the true proportions remain unknown (Corey and Freeman, 1990). In case-control studies, bias in the selection of study subjects can occur when the procedure used for the selection of cases is different from that used for selection of controls, as when the procedure used to identify disease status varies with exposure status. In cohort studies, selection bias occurs when the exposed group is selected from a population with a different overall probability of disease than that from which the unexposed group is selected. Systematic differences in the way cases and controls choose to participate in either a case-control or a cohort study also represent important sources of bias in epidemiologic studies.

Information bias refers to a distortion in the estimated effect that results from a random or systematic flaw in the measurement or classification of either the exposure status or the disease outcome. *Measurement error* can be either random (due to chance variations) or nonrandom (due to systematic bias). Random errors may be introduced into a study as a result of the variability inherent in most physical measurements. This form of error may be reduced to a certain extent by employing multiple measurements and using the resultant mean value. Nonrandom errors may occur as a result of the improper or inconsistent calibration of field measuring instruments or laboratory equipment. Other sources of nonrandom measurement errors include a defective questionnaire or an interview schedule that fails to elicit the intended responses or an inaccurate diagnostic procedure that either overestimates or underestimates disease status (Kleinbaum et al., 1982).

Misclassification bias is a form of information bias which typically affects the analysis of data in which both the disease and the exposure variables are dichotomous. As with measurement errors, misclassification bias may also be either random or nonrandom.

Random or *nondifferential misclassification* introduces imprecision but may also bias the association towards the null in a study seeking to evaluate an exposure-disease association. Thus, random errors in the estimation of exposure will generally lead to an underestimation of risk, and can introduce a spurious curvilinearity into the estimated dose-response function. For example, in the Radiation Effects Research Foundation (RERF) studies, random errors in the dose estimates resulted in a 10-15 percent underestimation of the relative risk (Schull, 1991). This type of error may be partially overcome by sufficiently increasing the sample size of the study.

By contrast, nonrandom errors in the estimation of exposure can distort or bias the relative risk either upward or downward, and, consequently, represent a serious threat to the validity of a study. *Differential misclassification* occurs when the errors in classifying individuals occur differentially among study groups, thus distorting the comparison of rates and the resulting rate ratios. Differential misclassification of the exposure or disease status may occur in epidemiologic studies, especially when surrogate measures or subjective estimates are used to determine exposure or disease status of the study subjects. This form of bias can occur when knowledge of the disease status of the cases and controls (in a case-control study) influences the exposure classification, or when knowledge of the exposure status of the study subjects (in a cohort study) influences the disease classification of the subjects.

To avoid or substantially reduce this type of bias, well designed studies generally employ some form of blinding to insure that the investigator is unaware of the disease status of the individual when the exposure status is being classified and vice versa. Also, when persons who become lost to follow-up differ, with respect to both exposure and outcome, from those who remain in the study, the observed association can be differentially biased. For instance, a statistically significant increase in lung cancer mortality was observed in a cohort of workers producing urea- and melamine-formaldehyde resins, but the increase could not be specifically attributed to formaldehyde exposure because of incomplete work histories for the workers lost to follow-up (Bertazzi et al. 1986).

Confounding bias in epidemiologic studies is a distortion in the apparent association between a disease and an exposure by a third factor that is causally related to the disease under study and is also associated with the exposure under study but is not a consequence of the exposure. Therefore, the disease may be either partially or totally attributable to the third factor and not to the exposure under investigation. The presence of confounding in a disease-exposure association can be assessed by controlling for the effect of any of the extraneous factors which may be associated with both disease and exposure. Unlike selection bias and information bias, which are primarily introduced by the investigator or study participants, confounding is a function of complex interrelationships between various exposures and disease (Hennekens and Buring, 1987).

Chance in Epidemiologic Studies. Before attempting to assess the causal nature of an association, it is necessary also to determine whether the difference in rates is likely to have been due to chance. Because of the random variations that occur in population samples, the case and control groups (in a case-control study) are unlikely to have exactly the same proportion of exposed and non-exposed persons, even when no association exists between exposure and disease. Likewise, the exposed and non-exposed groups in a cohort study are unlikely to have exactly the same incidence of (or mortality from) a particular disease even though there is no cause-and-effect (or protective) relationship. Determining how large a difference must be to establish convincingly that it is likely to be real and not due to chance, is accomplished through the use of appropriate statistical techniques such as significance testing with p-values and confidence intervals (CI). These techniques are discussed in the tutorial on epidemiologic methods in Appendix B.

EXTERNAL VALIDITY

Assessing the external validity of an epidemiologic study involves an evaluation of the generalizability of the association. It addresses two questions: (1) "Is the association of disease with exposure consistent with causality?" (2) "Is the disease-exposure association observed in a specific study likely to hold for other similarly exposed populations?" When bias, confounding, and chance have all been determined to be unlikely explanations of a particular finding in an epidemiologic study, it is then necessary to decide whether the observed association of disease with exposure can be considered to be causal (Kleinbaum et al., 1982; Hennekens and Buring, 1987). A number of guidelines to assist with the judgment of the causal nature of an environmental association were initially proposed by Hill (1965). These guidelines include the strength of the association, consistency of the data, specificity of the association, temporality of exposure and disease, dose-response gradient, biological plausibility, coherence of the evidence, and the effect of intervention.

Strength of the Association. For epidemiologic evidence, the strength of the association, as measured by the magnitude of the risk ratio, is useful in determining whether the exposure affects the risk of developing the disease. Specifically, the stronger the association (or the greater the risk ratio), the more likely it is that the association is causal. In general, weaker associations do not lend as much support to a causal interpretation (Kleinbaum et al., 1982). Monson (1990) has proposed some guidelines for assessing the magnitude of relative risks. These guidelines suggest that relative risks of less than 2.0 are more likely to be due to bias or confounding, whereas relative risks greater than 5.0 (depending of course on sample size) are more likely to be reflective of a true increase in risk.

Consistency of the Data. Since epidemiology is by its nature observational, it is never possible to achieve the degree of control possible in experimental studies. Evidence to support a judgment of a cause-and-effect relationship cannot be persuasive unless the association is consistently observed in a number of studies. Consistency among multiple studies, conducted by different investigators, at various times, using alternative methods, in a variety of geographic or cultural settings, and among different populations, provides strong evidence for the generalizability of a cause-and-effect relationship (Hennekens and Buring, 1987). Conversely, when multiple studies seem to be producing inconsistent or contradictory results, chance associations, confounding factors, and/or study bias are more likely to be present, and the argument for a cause-and-effect relationship is weakened.

Specificity of the Association. Specificity of the association is another aspect to be considered in weighing the external validity of a study. If the association is limited to a specific exposure and/or to a particular disease, there is a strong argument in favor of causation. However, in chronic disease epidemiology, multiple-causation is generally more likely than single causation. Therefore, if specificity of the association has been demonstrated, a causal interpretation can be made with greater confidence; if specificity does not exist, a causal interpretation must be made more cautiously (Greenland, 1987).

Temporality of Exposure and Disease. The temporal relationship of an association is particularly relevant with diseases of slow development (Hill, 1971) or prolonged latency periods, such as cancer. Does a particular occupational or environmental exposure lead to an increase in some form of cancer? If the association is to be considered causal, then the relevant exposure must precede the occurrence of cancer by a sufficient interval of time to account for the disease latency period. This also holds for diseases with short incubation or latency periods (e.g., symptoms of acute toxicity). If the interval from exposure to onset of disease is too long, the argument for causation is weakened.

Dose-Response Gradient. If the association demonstrates a dose-response gradient, the cause-and-effect hypothesis is supported (Greenland, 1987). For example, the causal association of smoking and lung cancer was strongly supported by the evidence that the mortality rate from lung cancer increased linearly with the number of cigarettes smoked daily (Doll and Hill, 1950).

Biological Plausibility. The causal nature of an association is more readily accepted if there is a biologically plausible hypothesis to support causality. However, biological plausibility is determined, to a certain extent, by the current state of knowledge (Greenland, 1987). Consequently, such plausibility cannot always be demanded of a hypothesis, since the current state of knowledge may simply be inadequate to explain the observations. An impressive number of associations of environmental exposures with cancer was identified from epidemiologic studies prior to knowledge regarding the biological mechanisms. Notable examples include the association of cigarette smoking and lung cancer, and association of specific agents such as asbestos, benzene, and ultraviolet radiation with human cancer. Conversely, the less that is known regarding the etiology of a disease, the less confident one can be in rejecting a causal interpretation on the basis of this guideline (Kleinbaum et al., 1982).

Coherence of the Evidence. Coherence of the epidemiologic, biologic, and other evidence implies that a causal interpretation is not seriously in conflict with current knowledge of the natural history and biology of the disease (Greenland, 1987). For example, mortality from lung cancer was initially higher in males than in females because smoking was more common in males. As more females adopted the smoking habit, mortality rates for lung cancer among females have tended to approach those seen among males (Hammond, 1966).

The Effect of Intervention. The strongest support for the causation hypothesis is provided by experimental studies or intervention studies in human populations (Hill, 1971). If exposure to an agent is truly causal, then removal of the agent should result in a decrease in the disease rate. Since the association of smoking with lung cancer was recognized, many physicians have stopped smoking. This change was followed some 20 years later by a decrease in lung cancer mortality among physicians (Doll and Peto, 1976).

An expanded discussion of epidemiologic study methods is found in Appendix B.

3.1.4 EMF Exposure Assessment in Epidemiologic Studies

The assessment of EMF exposure seems to be the factor of greatest uncertainty in the epidemiologic studies of EMF and cancer. Many studies published to date have been somewhat flawed in methodology, in part due to the use of indirect, imprecise, and unverified surrogate measures of exposure. The possibility for misclassification of the exposure status of an individual can be random or systematic (i.e., nonrandom), thus resulting in either decreased precision or overt distortion in the assessment of an association.

In general, some form of exposure gradient or differential among study subjects is necessary for an effective environmental or occupational epidemiologic study. If exposures were homogeneous, it is unlikely that an exposure-disease association could be investigated. The choice of grouping subjects into dichotomous or multi-stage exposure classifications often influences the results of the statistical analyses (Flegal et al., 1986).

EXPOSURE METRIC

The appropriate direct measure of exposure in epidemiologic studies of EMF is still being debated, and this is an important area of ongoing research. The absence of a mechanism for a biologic effect to explain the EMF-cancer association creates uncertainty about what, exactly, should be the appropriate "exposure metric." Candidates for the exposure metric might include the magnetic field component, the electric field component, a combination of the two, or possibly the orientation of the EMF with respect to the earth's static magnetic field. Certain frequencies may be of greater or lesser significance. Transients (sudden changes in an electric or magnetic field) may be important, and certain field intensities (i.e., the window effect) have been suggested as possibilities to help explain some limited and apparently contradictory experimental data. To date, epidemiologic studies have not reported an association between directly-measured electric or magnetic fields (or other exposure metric) and health effects, but this may be because exposure assessment has been inadequate.

Magnetic fields have recently been regarded as the exposure component likely to be of greatest concern, but this emphasis is not based upon clear-cut epidemiologic evidence of an association between cancer and measured magnetic fields. Electric fields have received less attention in recent studies of cancer and residential exposure because few or no biologic effects have been demonstrated in experimental animal studies. In addition, while electric fields are relatively easily shielded by structures and other barriers, magnetic fields are not. In fact, wiring configuration codes were originally devised to predict magnetic fields rather than electric fields. Regardless, it is somewhat premature to dismiss electric fields as a possible agent, especially in the studies seeking to evaluate occupational EMF exposures.

EXPOSURE MODELS

Exposure models generally consist of some form of algorithm derived to estimate EMF exposure based on a set of known physical parameters such as wiring configuration, distance from wires, average voltage and current, and behavior patterns. The use of exposure models may be superior to the direct use of exposure measurements for current exposures because the influence of such factors as appliance use over time can be factored into a model. Exposure models using available historical information that can be validated using current measurement data are particularly useful for studies dealing with past unmeasured exposures.

EXPOSURE SURROGATES

In retrospective case-control studies, it is often necessary to establish or define certain surrogate measures of exposure which will help to quantitate a likely historical exposure which cannot be directly measured. The use of such surrogate measures to infer potential individual EMF exposure is not uncommon, but the process is fraught with uncertainty. On the other hand, surrogate measures, though potentially inaccurate, may result in less exposure misclassification than when inherently variable, short-term, spot measurements are used to estimate the unmeasurable historical exposure.

Wiring Configuration Codes. The most commonly employed surrogate measure for residential EMF exposure is the electric power transmission or power distribution line wiring configuration code (WCC). In the initial study of childhood cancer in Denver, Wertheimer and Leeper (1979) categorized high-current configuration (HCC) homes as those close to a number of specific types of wiring which had the potential to carry high currents. All other wiring configurations were considered low-current configurations (LCC). In their later study of cancer in adults, Wertheimer and Leeper (1982) expanded their wiring coding system to four categories: very high current configurations (VHCC), ordinary high current configurations (OHCC), ordinary low current configurations (OLCC), and end pole configurations. This latter category referred to houses situated beyond the pole at the end of a secondary line with no distribution wires running past.

In the case-control study of childhood cancer in Denver by Savitz et al. (1988) which attempted to replicate the Wertheimer and Leeper (1979) study, five categories were used for the wiring configuration codes: VHCC, OHCC, and OLCC, plus a very low current configuration (VLCC) and a buried category. Thus, these two studies used similar, but not completely comparable, coding systems.

Field Measurements and Their Correlation with Wire Configuration Codes. An estimate of the reliability of wiring configuration codes can be made by comparing the magnetic field measurements in 432 homes made by Savitz et al. (1988) at times of high and low power usage with the field measurements near 417 homes made by Wertheimer and Leeper (1982). The field measurements made by Savitz et al. (1988) were obtained in a number of rooms inside each house, and an average value for each house was used, while those made by Wertheimer and Leeper (1982) were obtained at a point close to the part of the house nearest the distribution wires. The percent of homes with measured fields greater than 3 milligauss (mG) and the median and maximum values for wire code categories suggest fairly good agreement between the two coding systems, but poor discrimination because of considerable overlap between categories.

Wertheimer and Leeper (1982) suggested that wire codes remain stable over long periods of time and, therefore, might provide better measures of historical field levels, but this suggestion is not based on quantitative evidence. The measurements made by Savitz et al. (1988) in the case-control study in Denver homes mentioned above appear to offer some support for this suggestion, as does the study in the Seattle area by Kaune et al. (1987). In their study, Kaune et al.

(1987) found a slightly stronger correlation between spot measurements and 24-hour averages for measured magnetic fields ($r=0.5$) than between wiring codes and 24-hour averages ($r=0.41$). Although this correlation has been interpreted as suggesting fairly good agreement, a very large percent of the actual variation remains unexplained (75-83% when $1-r^2$ is used to estimate the unexplained variation). Wire code surrogate data have recently been correlated with magnetic field levels in a relatively unsophisticated approach to modeling (Flynn, 1990). If magnetic fields are like other environmental agents, a single 24-hour measurement will be a very imprecise indicator of long-term or historical exposure levels at the measurement location. An exposure model based on specific measurement data combined with historical local power consumption trends might provide a better index of past exposure than isolated short-term measurements themselves.

Intuitively, one would expect that, if there is an association between magnetic fields and cancer, the association would be stronger for the more directly measured fields than for wiring codes. The fact that Savitz et al. (1988) found the reverse to be true in their study may suggest that the association of wiring codes with cancer may not be causal, or that spot measurement data do not provide accurate bases for exposure classification. In fact, none of the cancer odds ratios calculated for magnetic fields measured under high and low power usage conditions was statistically significant in the Savitz et al. (1988) study. This lack of association may be due to the smaller number of study subjects for whom data on measured magnetic fields were available, as well as to the variability in the measured data.

It was only when the wire code at the subject's residence two years before diagnosis was used in the analysis that the odds ratio for one category achieved statistical significance. This ratio is somewhat imprecise due to the small number of observations, which included only 8 cases and 2 controls in the VHCC category (Savitz et al., 1988). Since a lower participation rate was observed for controls in the VHCC category than other WCC categories, it has been suggested that the elevated risk ratio could have resulted from differential participation of controls by exposure status. The potential for this type of selection bias is now under study (Poole and Trichopoulos, 1991), as was strongly recommended by participants at the EPRI Workshop on EMF Epidemiology (EPRI Proceedings from Carmel Workshop, 1991).

Job Titles and Industry Codes. For occupational epidemiologic studies, job titles and industry codes are commonly used as surrogate measures for estimating potential occupational EMF exposure. However, the classification scheme has not yet been standardized (Lewis, 1990). Also, the duration of exposure has not been considered in most of the studies using these methods. In addition, potential confounding factors such as socioeconomic status have been described, but not carefully estimated or controlled in most studies.

De Guire et al. (1988) and Vågerö et al. (1985) selected subjects who had ever worked in the telecommunications industry. Olin et al. (1985) studied electrical engineers. Milham (1985b) and Pearce et al. (1989) chose several occupations which they considered to be exposed to EMF. However, Milham excluded electrical engineers because he thought the EMF exposure of electrical engineers was "infrequent" and their potential social class might bias the mortality ratio.

In epidemiologic studies where information was abstracted from death certificates, census codes for occupation were used (Thomas et al., 1986, 1987) to estimate EMF exposure. In the latter study, the job entry in a study subject's work history was assigned a three-digit standard industrial classification (SIC) code for industry (Office of Management and Budget, 1972) and a 1980 Census code for occupation (Bureau of the Census, 1982). In these studies, EMF exposure was estimated indirectly by using a surrogate measure without knowledge of actual EMF exposures. The occupational titles considered as surrogates were assumed to indicate a higher levels of EMF exposure than other job titles, but the intensities of individual exposures were unknown. In the study by Lin et al. (1985), occupations were grouped according to level of likely exposure to EMF. The exposure category for each occupation was determined in consultation with an industrial hygienist, an occupational physician, and a radiation physicist. However, data on duration of occupational exposure were not available.

Preliminary studies are underway to describe the correlation of job title surrogate data with measured occupational EMF exposures (Peters, 1990). In order to measure actual occupational EMF exposures, Peters et al. (1990) quantified exposure to EMF among the electrical occupations and among a representative sample of non-electrical occupations. An EMDEX dosimeter was used to measure electric and magnetic field exposures over an entire work shift at 2.5-second intervals. The study indicated considerable variability in magnetic field exposures within a single job category depending on the different tasks being performed. This finding demonstrated the importance of estimating the average exposure over a typical shift, as well as recording peak and transient exposure patterns. For each job category of non-electrical workers, the average magnetic field exposure over a shift was shown to be both lower and less variable than that for electrical workers.

CONFOUNDING IN EMF STUDIES

Study populations may be exposed to a variety of known or suspected carcinogens as well as to EMF. For example, in studies associating residential EMF exposure to the risk of cancer, some attention should be given to other residential exposures that are known to be associated with cancer, such as radon gas and benzene emissions, which may also be correlated with the estimate of EMF exposure used in the study.

Study of the same Denver subjects used in the Savitz et al. (1988) study of magnetic fields, for example, showed a weak, but statistically significant, association between cancer and traffic density, a surrogate for motor vehicle emissions and benzene exposure (Savitz and Feingold, 1989). Some attempt was made in the Savitz et al. (1988) study to evaluate the effects of other exposures on cancer risk, especially those exposures which may "confound" or distort the possible association between magnetic fields and cancer. A true confounding factor would be one that is related to both wiring codes and cancer. One suggested factor is traffic density, which Savitz et al. (1988) examined, concluding that "although traffic density did seem to be associated with both cancer incidence and wire codes, those associations were not strong enough to confound the association between wire codes and cancer." Although no data were provided to support this assertion, it seems likely that the elevated risk ratios may have resulted from some unrecognized bias, rather than confounding, which was better controlled in the study by Savitz et al. (1988) than in the study by Wertheimer and Leeper (1979).

In general, analysis for potential confounders would be limited by the small sample sizes available for specific cancers and would generally not be very informative. However, the "wire code effect" was reported to be most pronounced among females, older children, those who lived in multi-family housing, low social class, and those whose mothers smoked during pregnancy. These observations could imply effect modification or that other correlates of wire codes are responsible for the reported association.

Additional and expanded discussions of exposure assessment are found in section 2.0, Appendix A, and in the tutorial in Appendix B on exposure assessment in epidemiologic studies.

SELECTION OF CONTROLS IN EMF STUDIES

The published studies of EMF exposure and cancer emphasize the importance of selecting a control or reference population that is truly representative of the study population. The potential for bias due to differential patterns of response in the selection of controls can occur in case-control studies when the procedure for selecting controls does not ensure a representative sample from the underlying population from which the cases are drawn. The method of selecting controls by random digit dialing, as was done in the two major studies of childhood cancer and EMF exposure (Savitz et al., 1988; London et al., 1991), may result in under ascertainment of controls from the lower socioeconomic groups and controls with a greater stability of residence than cases. There is some evidence suggesting that such biases may have occurred in both studies; this possibility is being studied by several investigators (Poole and Trichoupoulos, 1991; EPRI Workshop Proceedings, 1991).

3.2 U.S. Cancer Mortality Rates and Trends

It is instructive at this point to examine the time trends for the various cancers of concern. In the subsequent review of the epidemiologic evidence regarding EMF exposure and adult or childhood cancers (see section 3.3), the sites of concern include: total cancer, leukemia, central nervous system (CNS) cancer, and, to a lesser extent, breast cancer. Since lung cancer has come to represent such a large percentage of total cancers and tends to dominate the overall trend, this site is also considered.

Much of the concern surrounding the EMF issue has arisen from reported increases in various childhood and/or adult cancers. Consequently, cancers have been examined dichotomously by age. For this analysis, the word "childhood" means persons of ages 0 through 19 years and the word "adult" means persons of age 20 and above. Age- and sex-specific cancer mortality rates for the United States were obtained from the American Cancer Society for each of the leading cancer sites and for each year back to 1930 (Silverberg, 1990). From these data, annual, age-adjusted mortality rates were calculated for (male and female) children and adults. A variety of additional terminology, analytical techniques, and data sources are typically utilized in the evaluation and quantification of morbidity and mortality data. Some of the more commonly used data sources and their limitations are reviewed in Appendix B. Also, a number of additional commonly used terms and techniques for analyzing morbidity and mortality data are briefly described in Appendix B or defined in the Glossary.

3.2.1 Total Cancer Mortality

From Figure 3-1, it can be seen that the crude cancer mortality rates in the U.S. for males and females combined have nearly doubled since 1930. However, when the shifting age distribution of the population at risk is taken into consideration through age-adjusted rates, it is apparent that the increase has been a much more modest 19 percent (Figure 3-2). The age-adjusted rates for females have actually decreased by about 10 percent over the period from 1930 to 1987, but the rates for males have gone up 64 percent. When adult cancers are examined separately from childhood cancers, the time-trend patterns are still very similar to the totals for all ages combined, but quantitatively, the adult-only, age-adjusted rates are approximately 60 percent higher (Figure 3-3). The age-adjusted rates for total cancers in children (Figure 3-4) increased 54 percent from 1930 to 1945, but leveled off and then began decreasing so that they are now about 30 to 40 percent lower than in 1930.

3.2.2 Lung Cancer Mortality

Lung cancer in males has been the leading form of cause- and sex-specific cancer mortality in the United States since it surpassed breast cancer in females in the early 1960's. Presently, lung cancers account for about 28 percent of all cancer deaths nationwide. From about 1950 to 1970, lung cancer among males underwent its period of most rapid growth, while the rates among females did not show appreciable increases until around 1965 (Figure 3-5). Over the 57-year period from 1930 to 1987, the age-adjusted lung cancer mortality rates among males and females have increased by 1510 and 1282 percent, respectively. However, since the early 1980's, the rates among males have shown a tendency to stabilize in the range of 72 to 74 deaths per 100,000 population. Lung cancer mortality among children (not shown) is generally very low (in the range of 0.05 to 0.15 deaths per 100,000).

3.2.3 Total Cancer Mortality (Excluding Lung Cancer)

When lung cancer deaths are subtracted from total cancers, the effect on the time trends is impressive (Figure 3-7). Total cancer (minus lung) among males has remained virtually unchanged since about 1945, while among females, the rates have decreased significantly by about 23 percent. Part of this declining trend is due to the steadily decreasing stomach cancer mortality rates, which, in 1930, accounted for about 28 to 38 deaths per 100,000 population for females and males, respectively, while by 1987 they had decreased to the range of 3 to 7 (data not shown).

3.2.4 Leukemia Mortality

Mortality from leukemia underwent a relatively steady increase from 1930 to 1960 (Figure 3-8). Since around 1968, the rates have gradually declined and, in 1987, they accounted for about 8.0 and 4.9 deaths per 100,000 in males and females, respectively. The time trends for adult-only leukemias are very similar to total leukemias except, quantitatively, they are about 30 to 40 percent higher (Figure 3-9). When childhood leukemias are examined separately, it can be seen (Figure 3-10) that mortality rates increased sharply (100 to 200 percent) over the period from 1930 to 1950, plateaued between 1950 and 1960, and then began a sharp and steady decline from 1960 to 1987. Part of this pattern was due to greatly improved chemotherapeutic measures for the childhood leukemias which have increased the expected five-year survival for this disease.

3.2.5 Brain Cancer Mortality

The time trend for brain and central nervous system (CNS) cancer is similar to that for leukemia, with a slightly more gradual rise from about 0.7 in 1930 to 3.2 in 1955 (Figure 3-11). At that point, the increase became even more gradual, with rates reaching 3.9 deaths per 100,000 in 1969. Since then, the rates have remained relatively stable in the range of 3.8 to 4.3 through 1987. There is a slight irregularity in the trend between the years 1978 and 1979. This occurred with the switch from the 8th Revision to the 9th Revision of the International Classification of Diseases (i.e., switching from ICD-8 to ICD-9). Prior to 1979, "Malignant Neoplasms of the Brain" included some secondary neoplasms; since then, only primary tumors have been included. If this is taken into account, there is still a gradual increase occurring (3.8 in 1979 to 4.1 in 1987).

When adult brain and CNS cancers (Figure 3-12) are examined independently of childhood cancers, the trend is similar to the combined rates, but they are about 43 to 51 percent higher. Childhood brain and CNS cancer mortality per 100,000 population increased from 0.25 for males and 0.21 for females in 1930 to about 1.73 for males and 1.28 for females in 1954 (Figure 3-13). The rates then began a gradually decreasing trend which has accelerated since about 1970. By 1987, childhood brain and CNS cancer mortality was back down to 0.75 and 0.60 for males and females, respectively. Whereas brain/CNS cancer and leukemia accounted for less than 10% of all cancer deaths in adults in the 1980's, these sites accounted for more than 50% of all cancer deaths among children.

3.2.6 Breast Cancer Mortality

Breast cancer mortality has remained remarkably stable for females, with only minor fluctuations in the range of 39.8 to 45.0 over the entire period from 1930 through 1987 (Figure 3-14). Male breast cancer mortality has always been below 0.75 deaths per 100,000, and the time-trend has shown a gradual but steady decline to the range of 0.35 to 0.42 in the mid-to-late 1980's.

3.2.7 Selected Cancer Mortality versus Electric Power Consumption

Electric power consumption in the United States is plotted along with cancer mortality for the selected sites of concern in Figures 3.15 through 3.18 in order to compare them with the temporal relationship of tobacco consumption versus lung cancer mortality shown in

Figure 3-6. This comparison provides a superficial, but useful, summary of the secular trends for electric power consumption and cancer mortality, even though it is not known whether electric power consumption is a good predictor of individual magnetic field exposures. In fact, in the United States it is unclear whether or not there has been an increase in exposure to EMF since 1950 concomitant with the increase in electric power consumption.

From Figure 3-15, we see that male adult leukemia and brain/CNS cancer mortality rates were increasing substantially before the exponential growth in U.S. electric power consumption was significantly underway. Then, as electric power consumption began its rapid increase, leukemia and brain/CNS cancer mortality began to level off. Male adult breast cancer mortality has continued a gradual but steady decline in spite of the rapid increases in electric power consumption (Figure 3-15). The mortality time-trends for female adult leukemia and brain/CNS cancer (Figure 3-16) show similar patterns. Female breast cancer mortality has remained relatively stable over the entire period of rapid growth in electric power consumption (Figure 3-16).

Leukemia, brain/CNS cancer, and total cancer mortality, for both male children (Figure 3-17) and female children (Figure 3-18), all show an increasing trend before electric power consumption had begun its major growth. Then, as power consumption rates increased significantly in the 1945 to 1950 time period, childhood leukemia, brain/CNS cancer, and total cancer all leveled off and began to decrease.

It should be emphasized that examination of mortality data is not the preferred method for examining secular changes in population risk for childhood cancers because of the impact of improved treatment for childhood cancers on the mortality rates. Examination of cancer incidence would be preferable, but reliable incidence data for childhood cancers are not available for the extended time period of interest (i.e., 1930 to 1987).

3.3 Epidemiologic Studies Involving EMF Exposures

In 1979, Wertheimer and Leeper published a study reporting a greater number of electrical wiring configurations that presumably carried high current near the former homes of children in Denver who had died of cancer when compared with the former homes of controls. In a second study, published in 1982, the same authors reported an increased cancer mortality among adults who resided at several locations in Colorado which appeared to be associated with high current wiring configurations. These two studies were the first to suggest possible human cancer risks associated with exposure to EMF. Subsequently, over 80 epidemiologic studies have been published which investigate the potential adverse health effects of residential and occupational EMF exposures. Studies of EMF and cancer reported through early 1991 (and subsequently published) were selected for the health effects literature review detailed in this section. Also reviewed were several unpublished studies for which full reports or manuscripts were available. In addition, several previous review articles on EMF were summarized.

3.3.1 Summary of Previous Reviews

Since the proliferation of epidemiologic studies of EMF and cancer began, an increasing number of review studies have also been published. Eight of these studies were included in our review of the EMF literature (Savitz and Calle, 1987; Aldrich and Easterly, 1987; Ahlbom, 1988; Coleman and Beral, 1988; Nair et al., 1989; Theriault, 1990; Hutchinson, 1991; Jauchem and Merritt, 1991).

Savitz and Calle (1987) reviewed 11 studies of leukemia and occupational exposure to EMF, reporting that there was a "modest" excess risk for total leukemia among men in exposed occupations and an "enhanced" risk elevation for acute leukemia, especially acute myelogenous leukemia. They concluded that, the studies were inherently limited because of the absence of exposure characterization, but that telegraph, radio, and radar operators; power and telephone linemen; and electrical and electronic engineers showed the most consistent results and warranted further study.

Aldrich and Easterly (1987), in addition to reviewing a number of experimental (i.e., animal, plant, and cell tissue) studies of EMF exposure, also reviewed and summarized 14 epidemiologic studies of cancer and birth defects associated with occupational EMF exposures. On the basis of the generally low risk levels observed in these studies, they concluded that if a human cancer risk does exist, it is likely to be very small, perhaps on the order of 2.0 or less, and then only for highly specific groups in the population. These authors suggested that future epidemiologic studies of the possible carcinogenic effects of EMF should take into account other potentially confounding exposures.

Ahlbom (1988) reviewed nine studies which focused primarily on residential EMF exposures, and he concluded that, although the childhood studies seem to indicate an increased risk for cancer, so many methodological and theoretical concerns have been raised against these studies that the findings must be considered highly uncertain. Ahlbom also concluded that the studies on adult cancer and residential exposures, provided little evidence for an association with all cancers together or with leukemia. While it was not possible to determine whether exposure to magnetic fields increases the risk of cancer, the information in this review did suggest that research in this area should be pursued.

Coleman and Beral (1988) reviewed seven studies of cancer and residential EMF exposure resulting from installations transmitting electricity and an additional 11 studies of cancer and occupational EMF exposure. They concluded that there was no clear association between cancer risk and residence near installations transmitting electricity. Combined data from the occupational studies indicated a significant excess of total leukemia and of acute myeloid leukemia, with risk estimates of 1.18 (95% CI, 1.09-1.27) and 1.46 (95% CI, 1.27-1.65), respectively. However, they reported that it was not clear whether the increase was specific to certain types of work within the electrical industry. They also concluded that, from the available data, it was not possible to determine whether the increases in leukemia were due to EMF or to other factors to which the electrical workers were exposed.

In an extensive review of the biologic effects of power-frequency electric and magnetic fields for the Office of Technology Assessment (OTA), Nair et al. (1989) reviewed five studies of childhood cancer and residential EMF exposure, three studies of adult cancer and residential exposure, and about 20 studies of leukemia, brain cancer, and total cancer in connection with occupational EMF exposures. They concluded that there was an indication that occupational exposure in "electrical occupations" was associated with enhanced leukemia risk, but they pointed out that "associated" means "occurs together with" and does not imply a causative link. With brain cancer and total cancer, the evidence was somewhat less substantial, and their overall conclusion was that the available evidence was too weak to allow any firm conclusions.

In a paper prepared for a plenary session of the NIOSH scientific workshop, Theriault (1990) reviewed the epidemiological evidence for the risks of cancer and other adverse health effects associated with occupational exposure to 60/50 Hz EMF. In his review, he grouped the studies into seven categories: 1) cancer hypothesis generating studies, 2) leukemia case-control studies, 3) brain cancer case-control studies, 4) cohort studies of electrical workers, 5) eye melanoma case-control studies, 6) welding and exposure to EMF, and 7) studies of male breast cancer. On the basis of these study groupings, Theriault concluded that:

1) Pooled analysis of 12 of the early proportional mortality ratio (PMR) studies has indicated minimal but significantly elevated risk estimates for total leukemia and acute myeloid leukemia. However, these exploratory studies were limited by study design, small numbers of observed deaths, weak statistical analyses, lack of controlling for confounders, and inaccurate exposure assessments (Theriault, 1990).

2) The five case-control studies of leukemia and occupational EMF exposures conducted subsequently were generally considered to be more informative because of improved study designs and larger numbers of leukemia cases studied. These studies provided support for the possible association of leukemia with occupational EMF exposure, but all were plagued with one major weakness: exposure assessment. EMF exposure was generally inferred from job titles and occupational histories secured through postal questionnaires or transcribed from registration forms rather than from actual measurement (Theriault, 1990).

3) Seven case-control studies on brain cancer and occupational exposures were reviewed; most showed elevated odds ratios for electricity-related occupations. In these studies, the numbers of cases were relatively large, and, in three of the studies, an apparent dose-response relationship was observed. However, as with the leukemia studies, exposures were estimated on the basis of the reported occupations or secured through postal questionnaires (Theriault, 1990).

4) The risk ratios in the cohort studies of electrical workers generally were not as highly elevated as in the case-control studies, and few excesses were statistically significant. Only one study (Milham, 1988) reported a significant excess of acute myeloid leukemia; only one (Matanowski et al., 1989) observed an excess of total leukemia; none reported significant excesses for brain cancer. However, skin melanoma appeared to be fairly consistently elevated in five of the cohort studies (Theriault, 1990).

5) Two case-control studies of eye melanoma were reviewed; Swerdlow (1983) reported an elevated odds ratio (reported as the proportional registration ratio)for electrical and electronic workers while Gallagher et al. (1985) did not find an excess in a similar group of workers (Theriault, 1990).

6) Occupational studies conducted among welders are important with respect to potential health effects of EMF exposure because of the presumably high electric and magnetic field exposures. Review of 15 cancer studies in welders indicated an excess of lung cancer but slightly decreased risk for leukemia (Theriault, 1990).

7) A cohort study of telephone workers by Matanoski (1989) reported a standardized incidence ratio of 6.5 (95% CI, 0.79-23.5) for male breast cancer based on 2 cases observed and 0.3 expected. Also reviewed was a case-control study by Demers et al. (1990) who noted elevated odds ratios for male breast cancer in workers potentially exposed to EMF (OR=1.8; 95% CI, 1.0-3.2). These findings were interpreted as lending support to the hypothesis that EMF may increase cancer risk by interfering with the melatonin hormonal system (Theriault, 1990).

In a review of cancer studies with residential EMF exposure, Hutchinson (1991) reported a statistically significant summary odds ratio of 1.33 (95% CI, 1.06-1.67) for childhood leukemia and a history of residential exposure to EMF. His analysis was based on five previous studies (Wertheimer and Leeper, 1979; Fulton et al., 1980; Tomenius, 1986; Savitz et al., 1988; Coleman et al., 1989). Among the five studies, only one (Wertheimer and Leeper, 1979) reported significant increases in leukemia. The statistical significance of the summary odds ratio (Mantel-Haenszel) may be due to significant heterogeneity of the component odds ratios (Hutchinson, 1991).

The summary odds ratio for childhood CNS cancer and a history of residential exposure to EMF was statistically significant, with an odds ratio of 2.44 (95% CI, 1.70-3.53) in Hutchinson's (1991) analysis. This analysis was based on three studies that examined brain cancer (Wertheimer and Leeper, 1979; Tomenius, 1986; Savitz et al., 1988).

Jauchem and Merritt (1991) reviewed a wide variety of epidemiologic studies and review articles addressing cancer and other effects reportedly associated with exposures to EMF. Because of the numerous inconsistencies and deficiencies of the studies reviewed, they concluded that there is currently no definitive evidence of an association between exposure to EMF and the alleged effects.

3.3.2 Review of Specific Studies

The studies reviewed for this report are divided into three sections according to the circumstances of the presumed EMF exposure: residential exposures and occupational exposures of the cases, and prenatal (or preconception) occupational exposures of the parent(s) of the childhood cases. Reported health consequences associated with exposure to EMF include various cancers in adults and children and adverse effects on the fetus or reproduction. Under residential EMF exposures, studies conducted among both children and adults were reviewed. Among occupational groups potentially exposed to EMF, total cancers (all sites combined), tumors of the brain/CNS, total and various specific leukemias, and other selected cancer types or sites such as melanoma, eye cancer, and breast cancer are reported. In terms of adverse effects on reproduction, a number of outcomes associated with residential and occupational exposure to EMF were reported in the studies reviewed. The following is an outline of this plan of review:

RESIDENTIAL EMF EXPOSURES

Childhood Cancers.

(6 studies, see Table 3.1)

Adult Cancers.

(5 studies, see Table 3.2)

OCCUPATIONAL EMF EXPOSURES

Total Cancer.

(10 studies, see Table 3.3)

Leukemia.

(28 studies, see Table 3.4)

Brain/CNS Cancer.

(18 studies, see Table 3.5)

Melanoma and Other Cancer Sites.

(22 studies, see Table 3.6)

PATERNAL/MATERNAL OCCUPATIONAL EMF EXPOSURES

Childhood Cancers.

(6 studies, see Table 3.7)

Congenital Malformations, Spontaneous Abortions, and/or Intrauterine Growth Retardation.

(6 studies, see Table 3.7)

RESIDENTIAL EMF EXPOSURES

Childhood Cancers. Six major epidemiologic studies examining various childhood cancers and residential EMF exposure were reviewed (Wertheimer and Leeper, 1979; Fulton et al., 1980; Myers et al., 1985; Tomenius, 1986; Savitz et al., 1988; London et al., 1991) (Table 3.1).

Four of these case-control studies examined at total cancers (Wertheimer and Leeper, 1979; Myers et al., 1985; Tomenius, 1986; Savitz et al., 1988). Three of the four studies reported statistically significant results for total cancer. Wertheimer and Leeper (1979) reported an excess in total cancers (OR=2.22; 95% CI, 1.58-3.12) for homes near electrical wiring configurations suggestive of high-current flow. The study further reported that the association "appeared to be dose-related." Tomenius (1986) reported significant results (OR=2.10; $p<0.05$) when magnetic fields at the dwelling were higher than 0.3 microtesla (μT) (i.e., 3.0 mG). Savitz et al., 1988) reported a slight excess for total cancer for HCC wiring codes (OR=1.53; 95% CI, 1.04-2.26) but non-significant results for measured magnetic fields _ 2.0 mG. Meyers et al. (1985) found no increased risk for total cancers.

All six of the studies examined childhood leukemia and residential EMF exposure, but the results appeared to be inconsistent. Two of the studies (Wertheimer and Leeper, 1979; London et al., 1991) reported statistical significance on the basis of wire code configurations with odds ratios of 2.35 (95% CI, 1.55-3.56) and 2.15 (95% CI, 1.08-4.26), respectively. However, when London et al. (1991) analyzed the data on the basis of the measured 24-hour average magnetic field strength in the child's bedroom, the results were not significant (p for trend = 0.74). The remaining studies did not report any significant associations of leukemia with EMF.

Among the six residential EMF studies reviewed, three had no data on childhood CNS or brain cancer, and three reported elevated odds ratios: Wertheimer and Leeper (1979) with an OR of 2.86 (95% CI, 1.64-4.98), Tomenius (1986) with an OR of 3.7 ($p<0.05$), and Savitz et al. (1988) with an OR of 2.04 (95% CI, 1.11-3.76) for high current configuration (HCC) wiring codes. When Savitz et al. (1988) analyzed on the basis of magnetic field strength _ 2.0 mG, the CNS/brain cancer results were not significant (OR, 1.04; 95% CI, 0.22-4.82)

Adult Cancers. Five epidemiologic studies of adult cancers and residential EMF exposure were reviewed(Wertheimer and Leeper, 1982; McDowall, 1986; Preston-Martin et al., 1988; Severson et al., 1988; Coleman and Bell, 1989) (Table 3.2).

Significant results for total cancer were reported in only one of the studies. The case-control study by Wertheimer and Leeper (1982) reported data which produces an odds ratio of 1.28 (95% CI, 1.08-1.52; $p<0.005$) for total cancer. They also reported "significantly high C-ratios" (i.e., the ratio of the number of case-control pairs with the case exposure higher to the number of pairs with the control exposure higher) for lymphomas and cancer of the nervous system, uterus, and breast, but the individual numbers were not presented.

The cohort study by McDowall (1986) reported a significant elevation for lung cancer (SMR, 2.15; 95% CI, 1.18-3.61) when the cohort was grouped by distance from electrical installations, but leukemias (SMR, 1.43; 95% CI, 0.04-7.96) and total cancers (SMR, 1.03; 95% CI, 0.68-1.50) were not significantly elevated.

Four of the five studies yielded inconsistent and weak associations of leukemia in adults with presumed residential EMF exposure (McDowall, 1986; Preston-Martin et al., 1988; Severson et al., 1988; Coleman and Bell, 1989). There was no consistency among studies for the examination of any specific type of leukemia. Two studies focused only on total leukemia (McDowall, 1986; Coleman and Bell, 1989), and the study conducted by Severson et al. (1988) was limited to non-lymphocytic leukemia. Preston-Martin et al. (1988) examined acute and chronic myeloid leukemias and observed non-significant odds ratios which were less than one.

OCCUPATIONAL EMF EXPOSURES

Fifty-one epidemiologic studies which were designed to detect possible associations between various cancer sites and occupational EMF exposure were reviewed (Tables 3.3, 3.4, 3.5, and 3.6). These studies focused on a variety of different occupational groups generally classified as electrical workers, including electricians, electrical engineers, electric power station operators, linemen, and others. They were carried out in different countries and employed a variety of different study designs, including cohort, case-control, and PMR studies.. The reported results were found to be generally inconsistent.

Total Cancer. Ten of the 51 epidemiologic studies examined total cancers associated with presumed occupational EMF exposure (Howe and Lindsay, 1983; Vågerö and Olin, 1983; Barregård et al., 1985; Milham, 1985b; Olin et al., 1985; Vågerö et al., 1985; Törnqvist et al., 1986; Lin, 1987; Milham, 1988; Gubéran et al., 1989) (Table 3.3). One study was based on proportional data (PMR), and the remaining nine studies were of a cohort design.

Of the ten studies examining total cancer, three cohort studies (Howe and Lindsay, 1983; Vågerö and Olin, 1983; Lin, 1987) and one PMR study (Milham, 1985b) showed a weak association between presumed occupational EMF exposure and total cancer. Although the risks were only slightly elevated, they were all statistically significant. One additional study (Törnqvist et al., 1986) demonstrated a weakly positive but non-significant SMR. Four studies (Barregård et al., 1985; Olin et al., 1985; Milham, 1988; Gubéran et al., 1989) reported risk estimates for total cancer and EMF exposure that were less than 1.00.

In comparing the results of the above ten studies, it is important to remember that the definitions for "total cancers" were not identical. In addition, industry codes and job titles for the "exposed" workers differed from study to study. These disparities in definition and methodology, combined with the inconsistencies of the data, make it impossible to determine whether there is a likely causal association between total cancers and occupational EMF exposure.

Leukemia. The possible association of leukemia with occupational EMF exposure has received considerable attention and stimulated numerous occupational epidemiologic studies. Twenty-eight studies which examined the association of leukemia with EMF exposure were reviewed (Table 3.4). Eight of these studies were based on proportional data (PMR or PIR studies), 11 were cohort studies, and 10 were case-control studies, one of which also reported PMR data (McDowell, 1983). Overall, the case-control studies tended to produce the greater number of significant findings (seven out of 10 studies) followed by the PMR/PIR studies (five out of eight) and the cohort studies (five out of 11).

Five of the eight PMR or PIR studies (Milham, 1982; Wright et al., 1982; Calle and Savitz, 1985; Milham, 1985a and 1985b) demonstrated weak, but statistically significant associations. Milham (1982) studied leukemia mortality among workers exposed to EMF and reported a PMR of 1.37 (95% CI, 1.15-1.62). Wright et al. (1982), in a similar study looking at incidence data, found a PIR of 1.73 (95% CI, 1.10-2.59) for acute leukemia and a PIR of 2.07 (95% CI, 1.30-3.14) for acute myelogenous leukemia. Calle and Savitz (1985) observed a PMR of 1.86 ($p<0.05$) for total leukemia and a PMR of 2.57 ($p<0.05$) for acute leukemia among electrical engineers. They also observed a PMR of 2.35 ($p<0.05$) for total leukemia among radio and telegraph operators. In a study of amateur radio operators, Milham (1985a) reported significant elevations in the PMR's for myeloid leukemia and total leukemia (2.81 and 1.91, respectively). In a death certificate study in Washington state, Milham (1985b) observed a PMR of 1.36 ($p<0.01$) for total leukemia and a PMR of 1.62 ($p<0.01$) for acute leukemia among all electrical occupations.

In general, the validity of the findings from a PMR study depends on whether the deaths included in the PMR are representative of all deaths in the total exposed population. A PMR study is a reliable indicator of risk only when the healthy worker effect is of equal strength for the disease of interest (e.g., leukemia) and for all causes of death in the exposed population (Checkoway et al., 1989). In addition, the potential for misclassification exists, in that the information used in most PMR studies is ascertained from death certificates or cancer registries. Accuracy of the information of exposure and case definition (diagnosis) are not guaranteed. PMR studies, therefore, are less reliable as a basis for estimating risks than are other types of epidemiologic studies.

Among the 11 cohort studies, five reported one or more significant finding (Lin, 1987; Törnqvist et al., 1987; Linet et al., 1988; Milham, 1988; Garland et al., 1990). The remaining six cohort studies reported non-significant risk estimates close to (or less than) 1.00. The sample sizes in the cohort studies were generally large enough to achieve adequate statistical power, but were marginal or insufficient when total leukemias were separated into the various leukemia subtypes and when exposed workers were segregated into different job categories.

In seven of the 10 case-control studies reviewed, statistically significant associations were observed in one or more of the specific occupational groups presumed to be exposed to EMF (McDowall, 1983; Gilman et al., 1985; Pearce et al., 1985; Floden et al., 1986; Stern et al., 1986; Preston-Martin and Peters, 1988; Pearce et al., 1989). Excesses for total leukemia were seen in four case-control studies (Gilman et al., 1985; Pearce et al., 1985; Stern, 1986; Pearce et al., 1989) and elevated risks for acute myeloid leukemia were reported in four studies (McDowall, 1983; Milham, 1985a; Flodin, 1986; Pearce et al., 1989).

McDowall (1983) studied acute myeloid leukemia in selected electrical workers and found a relative risk of 2.3 (95% CI, 1.4-3.7) for all electrical occupations. Gilman et al. (1985) observed elevated risks for total leukemia (OR=2.53; $p<0.05$), myelogenous leukemia (OR=4.74; $p<0.05$), and chronic lymphocytic leukemia (OR=6.33, $p<0.05$) among underground coal miners. Pearce et al. (1985) examined all adult male cancer cases in the New Zealand Cancer Registry. Their findings suggested an increase in the risk of leukemia among electronic equipment assemblers (OR, 8.17; 95% CI, 1.49-44.7) and radio/television repairmen (OR, 4.75; 95% CI, 1.59-14.2). Coggon et al. (1986b) noted that five out of 29 patients with acute myeloid leukemia had worked in electrical trades, but the statistical significance of this finding was not reported. Flodin et al. (1986) studied cases of acute myelogenous leukemia and reported an elevated odds ratio of 3.8 (95% CI, 1.5-9.5) for all electrical workers (a category which included electrical technicians, electrical welders, and computer-telephone mechanics). Stern et al. (1986) studied leukemia among naval shipyard workers and reported significantly increased odds ratios for total leukemia among electricians (OR, 3.0; 95% CI, 1.29-6.98) and for myeloid leukemia among welders (OR, 3.83; 95% CI, 1.28-11.5). In this study, a detailed history of occupational radiation exposure was obtained and the analysis controlled for these and other occupational exposures. Preston-Martin and Peters (1988) reported a highly elevated odds ratio (OR, 25.4; 95% CI, 2.78-232.5) for chronic myeloid leukemia associated with prior employment as a welder. Pearce et al. (1989) observed an elevated risk among radio/television repairmen (OR, 7.86; 95% CI, 2.20-28.1) and power station operators (OR, 3.89; 95% CI, 1.00-15.2) but not among electrical linemen.

In general, the case-control studies demonstrated a stronger and more consistent association between leukemia and occupational EMF exposure than did the cohort studies, although, in some cases, the high odds ratios were associated with wide confidence intervals (Pearce et al., 1985; Stern et al., 1986; Preston-Martin and Peters, 1988).

Preston-Martin and Peters (1988) reported a highly elevated odds ratio (OR=25.4) in a study of 137 chronic myeloid leukemia cases, 19 of whom reported prior employment as welders. However, based on an earlier review of 15 cancer studies in welders (with a pooled total of 146 leukemia cases) Stern (1987) described an excess for lung cancer but not for leukemia. The job title groupings used in these studies, however, were not comparable. In general, studies of welders suffer from a major confounding factor which arises from the concurrent exposure to high levels of metal fumes, a number of which are known human carcinogens. Furthermore, since some welders employ gas welding methods (e.g., acetylene, hydrogen, town gas, and propane) instead of arc welding, exposure to EMF in this occupational category may be highly variable.

Increased risks for several different types of leukemia were detected in a study of underground coal miners by Gilman et al. (1985). Törnqvist et al. (1987) also reported an elevated SMR of 2.1 for acute myeloid leukemia among miners and rockblasters. Miners are presumed to be exposed to EMF through overhead lines used for distribution of power to lights and mining equipment and through electrically operated trolleys used for transportation of men and materials. However, magnetic field exposure in underground coal mines is low compared to aboveground measurements in residential areas, and electric fields have not been measured in coal mines (Gilman et al., 1985). Also, a number of significant confounders for this occupational group, such as exposure to radioactive mineral dusts, radon and radon daughters, and diesel exhaust emissions, were not taken into account. Combined, the undocumented exposure levels and presence of possible confounders weaken the argument that the excess leukemias resulted from EMF exposure. Other studies which looked at leukemia mortality among a wide range of occupational groups (Howe and Lindsay, 1983; Blair et al., 1985; Linet et al., 1988) do not confirm the excesses in leukemia among miners.

The findings of an association between leukemia and potential occupational EMF exposures in the studies reviewed are modestly suggestive of a possible causal association. However, the conflicting data and the design limitations of the studies cannot be ignored. Most important among these limitations is the uncertainty of the exposure assessments. In most of the studies reviewed, exposure to EMF was inferred on the basis of job title and/or employment in a specific industry. Furthermore, most studies failed to carefully consider and control for potential confounding factors, such as specific relevant occupational exposures, which may have accounted for some or all of the apparent increases in morbidity or mortality. Most importantly, the majority of the studies with the strongest study design (i.e., the cohort studies) did not report a significant association of EMF exposure with leukemia risk. Few of the studies of electrical workers accounted for potential confounding factors such as exposure to polychlorinated biphenyls (PCB's), solvents (e.g., benzene), or ionizing radiation from radon or radon daughters, from diagnostic radiography, and from x-rays produced by high-voltage cathode ray tubes (CRT's) commonly used prior to the 1970's.

Brain/CNS Cancer. Following leukemia, brain or CNS cancer has been the second most frequent site to be investigated with respect to occupational EMF exposure. Eighteen occupational studies of brain/CNS cancer were reviewed and are listed in Table 3.5. Although different morphologic types were examined in some studies, most did not focus on a specific type of brain/CNS cancer. One of the studies reviewed used proportional (PMR) data, seven were cohort studies, and 10 were of a case-control design.

Milham (1985b), in a death certificate study in Washington state, found a PMR of 1.23 ($p<0.05$) for decedents with occupation coded as any one of nine electrical occupations.

Two of the seven cohort studies of brain/CNS cancer reported significant SMR's or SIR's (Lin, 1987; McLaughlin et al., 1987). In a study of Taiwan Electric Power Company employees, Lin (1987) observed an SMR of 4.10 (95% CI, 1.77-8.08) for brain/CNS cancer. McLaughlin et al. (1987) found an SIR of 1.4 (95% CI, 1.02-1.87) for intracranial gliomas among welders and metal cutters and an SIR of 1.1 (95% CI, 0.98-1.23) among workers in the machinery and electronics industry.

Six out of ten case-control studies reported statistically significant odds ratios (Lin et al., 1985; Thomas et al., 1987; Speers et al., 1988; Loomis and Savitz, 1989; Pearce et al., 1989; Preston-Martin et al., 1989). An exposure-response relationship between CNS cancer and presumed EMF exposure was observed in four of the six studies (Lin et al., 1985; Thomas et al., 1987; Speers et al., 1988; Preston-Martin et al., 1989).

In a study of glioblastoma multiforme and astrocytoma deaths, Lin et al. (1985) grouped occupations according to probability of exposure to EMF. An OR of 2.15 (95% CI, 1.10-4.06) was reported for the "definite" EMF exposure category, and lower OR's were found at the lower levels of probable EMF exposure. Electric and telephone linemen/servicemen seemed to have the highest mortality (SMR, 3.73; 95% CI, 2.24-5.82), but electricians and electronic engineers/technicians were also elevated (SMR's 2.28 and 2.50, respectively). In Thomas et al. (1987), microwave and radio frequency (MW/RF) EMF exposure was estimated on the basis of length of employment in various categories of electronics and electrical jobs. A significantly elevated odds ratio of 2.3 (95% CI, 1.3-4.2) was found among men presumed to be exposed to MW/RF EMF for 5-19 years.

In a study of east Texas residents by Speers et al. (1988), occupations were grouped according to probability of exposure to EMF. Electric and telephone company employees, electricians, electronic engineers, and railroad and telecommunication engineers were among the group categorized as having "definite exposure" to EMF. The OR for the "probable exposure" group was 2.86 ($p<0.04$), and there were six cases and no controls in the "definite exposure" group, producing a significant linear trend with $p<0.01$. In a death certificate study, Loomis and Savitz (1989) reported an OR of 1.5 (95% CI, 1.0-2.1) for brain cancer among all electrical workers combined. Pearce et al. (1989) found an OR of 4.74 (95% CI, 1.65-13.6) for brain cancer among electrical engineers, but the OR for electricians was not significantly elevated. Preston-Martin et al. (1989) examined the occupational and other risk factors for primary brain tumors (gliomas, including astrocytomas, and meningiomas) among males in Los Angeles County, 1980-1984. They found that the odds ratio for prior employment in jobs likely to involve high exposure to electric and magnetic fields was significant only for gliomas and that the risk was greatest for astrocytomas.

Half of the studies reviewed (Olin et al., 1985; Vågerö et al., 1985; Coggon et al., 1986b; Törnqvist et al., 1986; Magnani et al., 1987; Milham, 1988; Gubéran et al., 1989; Reif et al., 1989; Lewis, 1990) failed to demonstrate a statistically significant association between EMF exposure and cancer of the CNS. Furthermore, two case-control studies (Reif et al. 1989; Lewis, 1990) actually showed reduced odds ratios for brain/CNS cancer in the groups presumably exposed to EMF. As with the occupational studies of leukemia, the estimates of potential EMF exposure were based on job titles and/or industry codes. Consequently, the assessment of EMF exposure in the studies of CNS cancer was generally considered to be inadequate. While an apparent dose-response relationship between surrogate measures of EMF exposure and CNS cancer was observed in a few of the studies, the significance of these findings remains questionable, given the uncertainty of the exposure assessments.

Melanoma and Other Cancer Sites. With increasing attention being given to the possibility of an association between occupational EMF exposure and leukemia or brain/CNS cancer, more studies have begun looking for associations with other sites. Twenty-two occupational studies were reviewed which examined presumed EMF exposure and specific cancer sites other than leukemia and brain/CNS cancer (Table 3.6). Two studies used proportional data including PMR's and proportional registration ratios (PRR's), 12 were cohort studies, and eight employed case-control study designs.

Swerdlow (1983) studied total eye cancer as a surrogate for eye melanoma in England and Wales and reported significant PRR's for electrical and electronic workers in 3 out of 8 years studied. However, professional/technical workers (with no specific EMF exposures) were found to have significantly elevated PRR's for 5 out of the 8 years. In a case-control study in western Canada, Gallagher et al. (1985) examined ocular melanomas among electrical and electronic workers and found no increased risk. Significantly elevated SMR's for malignant melanoma (of the skin) were demonstrated in three out of four cohort studies (Vågerö and Olin, 1983; Vågerö et al., 1985; De Guire et al., 1988). Vågerö and Olin (1983) studied various cancers among workers in the electronics industry and reported a relative risk of 1.35 (95% CI, 1.05-1.76) for skin melanoma. Vågerö et al. (1985) examined various cancers among workers involved in the manufacture of telecommunications equipment and found an SMR of 2.6 (95% CI, 1.3-4.5) for melanoma among all workers. De Guire et al. (1988) found 10 cases of skin melanoma among telecommunication workers, producing an SIR of 2.7 (95% CI, 1.35-5.02) for males (no female cases were seen). None of the three case-control studies that examined malignant melanoma among electrical and electronic workers reported significantly increased risks.

Only two out of 11 studies looking at lung cancer among persons presumed exposed to higher-than-normal levels of EMF reported significantly elevated results (Vågerö and Olin, 1983; Milham, 1985b). Vågerö and Olin (1983) studied various cancers among workers in the electronics industry and reported a relative risk of 1.52 (95% CI, 1.35-1.72) for lung cancer in males among all electronics workers. Milham (1985b) examined death certificates in Washington state and observed a PMR of 1.14 ($p<0.01$) for cancer of the lung, trachea, and bronchus among all electrical occupations. Three of the studies reported significantly lower risk for lung cancer among various electrical occupations (Blair et al., 1985; Törnqvist et al. 1986; Milham, 1988).

Two studies examining female breast cancer and EMF exposure, one occupational (Vågerö et al., 1985) and one of home electric blanket use (Vena et al., 1991), reported no increased risk. Matanoski (1989,1991) reported a standardized incidence ratio of 6.5 (95% CI, 0.79-23.5) for male breast cancer among telephone workers. This finding was based on 2 cases observed and 0.3 cases expected. Demers et al. (1990,1991) noted elevated odds ratios for male breast cancer in workers potentially exposed to EMF (OR, 1.8; 95% CI, 1.0-3.2). Most important among the studies of male breast cancer is the study by Tynes and Andersen (1990) who observed 12 cases with 5.8 expected among Norwegian workers with potential EMF exposures (SIR, 2.07; 95% CI, 1.07-3.61). These findings have been interpreted as lending support to the hypothesis that EMF may increase cancer risk by interfering with melatonin production (Theriault, 1990). They may also be interpreted as suggesting the importance of shift-work and its effects on melatonin production as an independent risk factor for male breast cancer.

Only one study (Vågerö and Olin, 1983) out of five studies examining bladder cancer and occupational EMF exposure reported a minimally increased risk (RR, 1.22; 95% CI, 1.02-1.47). Of six studies looking at stomach cancer, only one (Howe and Lindsay, 1983) observed an increased risk (SMR, 2.33; $p<0,05$) for telephone, telegraph, and power linemen and servicemen. Two out of eight studies (Howe and Lindsay, 1983; Vågerö and Olin, 1983) examining cancer of the colon or intestine (excluding rectum) reported significant elevations. One study(Milham, 1985b) out of five considering cancer of the pancreas observed a very minimal but significant increase in risk (PMR, 1.17; $p<0.05$). None of the five studies with data on prostate cancer showed significant risks. Of three studies reviewing liver cancer data, only one (Lin, 1987) reported statistical significance (SMR, 1.54; $p<0.01$). Although not an occupational study, Verreault et al. (1990), in a case-control study of white males with testicular cancer in western Washington, found that the odds ratio for disease among electric blanket users was not elevated with respect to controls.

In general, the weight of evidence from studies examining "other cancer sites" is even weaker than that for leukemia and brain/CNS cancer. Many of the positive findings came out of hypothesis-generating studies which looked at dozens of different occupation or industry codes and possibly 10 to 20 different cancer sites. Under these conditions, statistically significant results are to be expected on the basis of chance alone, and are, at best, weak arguments for possible causation. As mentioned previously, lack of exposure assessment and failure to account for possible confounding factors also weaken the evidence for an association between EMF and "other cancer sites."

PATERNAL/MATERNAL EMF EXPOSURES

Childhood Cancers. Six studies exploring the possible association of childhood neuroblastoma or cancer of the CNS with presumed paternal EMF exposures were reviewed (Spitz and Johnson, 1985; Nasca et al., 1988; Wilkins and Koutras, 1988; Johnson and Spitz, 1989; Wilkins and Hundley, 1989; Bunin et al., 1990) (Table 3.7). Three of the six studies (Spitz and Johnson, 1985; Wilkins and Koutras, 1988; Johnson and Spitz, 1989) showed a statistically significant association between neuroblastoma or childhood cancer of the CNS and paternal occupations with potential EMF exposure. The magnitude of the association reported in these three studies was similar. Wilkins and Hundley (1989) calculated the odds ratios for childhood neuroblastomas using a variety of methods to estimate potential paternal EMF exposure based on occupation and industry codes. While the resulting odds ratios were generally comparable to the previously reported positive studies, they were not statistically significant. The studies associating paternal occupational EMF exposure with cancer in offspring are difficult to interpret since an effect, if real, would imply that EMF acts as a cancer initiating agent. To date, none has suggested a cancer initiating mechanism for EMF. Most investigators believe, instead, that if EMF affects cancer risk at all, it does so by cancer promotion or growth enhancement.

The magnitude of the association of childhood CNS tumors with paternal EMF exposure was not large enough to support a causal inference. In addition, the findings were inconsistent in the studies reviewed (Nasca et al., 1988; Wilkins and Koutras, 1988; Johnson and Spitz, 1989; Wilkins and Hundley, 1989; Bunin et al., 1990) (Table 3.7). Two studies of CNS tumors and one of neuroblastomas reported statistically significant results (Spitz and Johnson, 1985; Wilkins and Koutras, 1988; Johnson and Spitz, 1989). However, the observed paternal occupations thought to be associated with childhood cancer of the CNS in these studies were not specific electrical occupations, but instead represented various job titles. There were no exposure-response relationships observed in these studies.

Congenital Malformations, Spontaneous Abortions, and/or Intrauterine Growth Retardation. Five studies (Hemminki et al., 1980; Nordström et al., 1983; Wertheimer and Leeper, 1986; Nordström et al., 1987; Wertheimer and Leeper, 1989) (Table 3.7) have been conducted to evaluate the potential adverse effects of occupational exposure to EMF on reproduction. Three of these studies demonstrated a statistically significant association between presumed occupational exposure to EMF and adverse effects of reproduction, including spontaneous abortion, frequency of abnormal pregnancy, and congenital malformation (Hemminki et al., 1980; Nordström et al., 1985; Nordström et al., 1987). One study in Italy reported an odds ratio of 5.9 for oligospermia and azoospermia among radio electric workers, but the results were not statistically significant (95% CI, 0.86-40.2).

3.4 Discussion

3.4.1 Studies of EMF and Adverse Health Effects

Since the late 1960's, increasing public attention has been directed toward the electric power companies and the extra-high-voltage (EHV) transmission lines and the lower voltage distribution lines necessary to deliver that power from the generation facilities to the substations and on to the consumers. Initially, the concerns were focused primarily on the adverse aesthetic impact of having large, unsightly towers and wires cluttering the skylines. However, the electric and magnetic fields associated with EHV transmission lines also produced a number of nuisance effects such as audible noises, TV and radio signal interference, and unpleasant shocks when touching ungrounded metal objects (e.g., cars, trucks, or farm vehicles) while standing under the EHV transmission lines (Nair et al., 1989).

With the growth of the environmental movement in the late 1960's and early 1970's, attention began shifting more toward the possibility that power transmission or distribution lines might have an adverse effect on human and animal health. These fears were reinforced when Soviet and eastern European investigators reported an increased number of neurologic, cardiovascular, hematologic, and other nonspecific ailments among workers in EHV switchyards (Asanova, 1966; Sazonova, 1967; Filippov, 1972; Korobkova, 1972). Since negative studies are frequently ignored or minimized, it did little to ease the concerns of the public when Western scientists conducted similar studies and failed to confirm the earlier findings (Strumza, 1970; Roberge, 1976; Issel, 1977; Knave, 1978).

When Wertheimer and Leeper (1979) reported an elevation in leukemia, CNS tumors, and total cancer mortality among Denver children who lived in homes that were evaluated as near "high current configuration" power transmission or distribution lines, widespread attention became focused on the issue of cancer as a possible adverse health effect of exposure to ELF electric and/or magnetic fields. As before, the negative study of Fulton et al. (1980) (which used similar methods to study childhood leukemia cases in Rhode Island) did little to ease public concern over the EMF/cancer issue.

3.4.2 Historical Trends in the Cancer Mortality Ratio

Most authors who are knowledgeable about the historical trends of cancer recognize that the disease did not suddenly begin in the 20th century and that it is not limited to the United States and other technologically advanced countries. However, some tend to cite cancer statistics in a manner which appears to support the hypothesis that the U.S. and the rest of the technological world are in the midst of a cancer "epidemic." Ralph Nader (1981) reports that cancer in the U.S. has increased dramatically in this century. Such a conclusion is based on the changing percentage of all deaths that are attributable to cancer since 1900. The supporting figures are quoted as 3 percent in 1900, 9 percent in 1930, and 20 percent in 1975. Likewise, Larry Agran (1977) reports that only one in every 25 Americans died of cancer in 1900, while nearly one in every five died of cancer in 1975.

Changes in Cancer Mortality Ratio. In 1900, about 47 percent of all deaths were due to infectious diseases; by the 1970's, the proportion had dropped to only 6 percent (Figure 3-19). Over the time period in which the proportion of deaths due to cancer was showing a dramatic rise, influenza, pneumonia, tuberculosis, and other infectious disease causes of mortality were undergoing dramatic reductions. These decreases resulted from a number of factors including improved sanitation procedures, widespread purification of drinking water, and the development of antibiotics and vaccines for many of the potentially lethal childhood and adult infectious diseases. Thus, people who once would have died in childhood or in the prime of their lives as a result of some infectious disease had begun living to a much older age. The average life expectancy at birth increased from about 47 years in 1900 to over 75 years by 1987 (Figure 3-20). These factors resulted in a shift in the age distribution of the entire U.S. population, characterized by a disproportionate increase in the number of people in the older age groups (Figure 3-21). An inevitable consequence of such a shift is an increase in the percentage of people dying of diseases which are typically associated with older age such as heart disease and cancer, although since 1970, age-adjusted mortality due to coronary heart disease and stroke has decreased markedly.

Selecting a Morbidity/Mortality Data Set for Analysis. Since survival times for various cancers may differ considerably from site to site and (with improvements in treatment methods) over time as well, it is usually preferable to look at trends in cancer incidence rates as opposed to cancer mortality rates. However, historical trends in cancer incidence rates cannot be examined unless there has been some sort of long-term registration of all newly diagnosed cases of cancer from the geographical area in question. This long-term data collection process generally requires the extensive case-finding efforts of an active, population-based, cancer registry.

The National Cancer Institute's (NCI's) Surveillance, Epidemiology, and End Result (SEER) Registries (see Appendix B) have been collecting such cancer incidence data from selected geographical locations in the country since the early 1970's; a very few states have cancer registries that go further back than the SEER registries. Consequently, there are no available sources of cancer incidence data that would permit a meaningful time-trend analysis of a large segment of the population back to the early 1930's. The only feasible alternative, then, is to examine cancer mortality data, which are derived ultimately from death certificates, which in turn have been recorded with relative consistency across the U.S. since the early 1930's and, in some states and/or cities, as far back as the early 1900's. Despite the impact of improved treatment on the ratio of incidence to mortality rates, mortality data can be relied on for a useful analysis in this regard. Poole and Trichopoulos (1991) for instance demonstrated that data from the Connecticut Cancer Registry (considered to be the best long-term, population-based data on cancer incidence in the U.S.) do not show a secular increase for childhood leukemia or CNS tumors.

The Cause-Specific Mortality Ratio. In general, the examination of time trends for the various cause-specific mortality ratios (as employed by Agran, 1977 and Nader, 1981) is of limited usefulness. Since the sum of percentages for all causes of death must always equal 100 percent, when the percentage for one cause of death goes down, the percentage for one or more other causes of death must, of necessity, go up. When such a shift in the cause-specific mortality ratios occurs, it is not always clear which change is the cause and which is the effect. Consequently, it is necessary to utilize a more stable and meaningful measure for evaluating time trends for the various causes of death.

Annual or Crude Mortality Rate. One such measure is the annual mortality rate or cause-specific mortality rate which is expressed as the number of people dying from a particular cause per 100,000 population per year. Rather than being normalized to the total number of people who died in a particular year, the annual mortality rate for each cause of death is normalized to the total population from which the deaths occurred. This measure is often referred to as the crude mortality rate to distinguish between this figure and an age-adjusted mortality rate discussed below. However, annual mortality rates also have some weaknesses which can lead to misinterpretations of the mortality data.

The U.S. population has been shifting toward the older age groups (Figures 3.20 and 3.21). As this happens, the crude mortality rates for diseases which are characteristic of the older age groups will increase (Figure 3-1), and it may appear, on superficial analysis, that there is an emerging problem with those diseases (Figure 3-19). Thus, it is necessary to control for differences or changes in age distribution when comparing two different populations or when analyzing one population as it changes over long periods of time (Figure 3-4).

Age-Specific Mortality Rates. One method of controlling for changes in age distribution is to compare the age-specific mortality rates for a particular disease in the two populations. For this analysis, the annual deaths are generally tallied for each five-year or ten-year age group, and the number of deaths for each age group is divided by the population in that age group. The result for each age group is then multiplied by 100,000 and expressed as the number of deaths per 100,000 population per year. Thus, the age-specific mortality rates for any age group of one population can be compared appropriately with the same age group of any other population. However, when the mortality rates are likely to be different depending on race and/or sex, it may also be necessary to look at age-, race, and sex-specific mortality rates for the two populations before a valid comparison can be made.

Age-Adjusted Mortality Rates. Another method of controlling for age distribution differences is to calculate the age-adjusted mortality rate for each population. This method has some advantage over the age-specific mortality rates because the age-adjusted mortality rate is expressed as a single rate for the entire population. However, this characteristic may sometimes conceal a difference in the two populations that the age-specific mortality rates will reveal. For example, if a particular disease were occurring at a higher-than-expected rate for a particular age group in one of the populations, this effect could be canceled by a lower-than-expected rate in some other age group. In this situation, the age-adjusted mortality rates could be the same for the two populations, and the difference would become apparent only if the age-specific mortality rates were compared for each age group.

Interpretation of Observed Trends. When cancer mortality rates are properly adjusted for changes in population age distributions over time, the resulting trends become significantly more meaningful in an epidemiologic context. While the individual mortality rates for some of the cancer sites are in a state of flux, most of the changes are relatively small and have little impact on the total cancer mortality, as some are increasing while others are decreasing. One of the notable exceptions is the time-trend for lung cancer which has undergone a major increase over the past 50 years, placing this site on the top of the list for cancer mortality (Figure 3-5).

While the exact relationship between individual EMF exposure and the crude surrogate measure (total U.S. power consumption trends) has not been clearly established, it is not unreasonable to assume that there should be some degree of positive correlation between the two. If such exposures are indeed causing a significant increase in a number of different types of cancer, then there also should be some sign of correlation between power consumption and cancer mortality trends. In the preceding analysis, none of the long-term cancer mortality trends for the sites of concern show any patterns which would suggest an association with EMF exposure when plotted together with the surrogate measure, unlike the plot of cigarette consumption in pounds per capita together with lung cancer mortality (Figure 3-6). While this form of analysis does not disprove such a possible association, the inconsistency between the hypothesis and the observations suggests that the epidemiologic evidence should be somewhat more substantial before a causal association can be reasonably assumed.

3.4.3 Carcinogen Policy and Regulation

As early as 1964, the "WHO Expert Committee on the Prevention of Cancer," chaired by Sir Richard Doll, concluded "that the majority of human cancer is potentially preventable" (WHO, 1964). In 1969, Higginson estimated that 90 percent of cancers were influenced by "environmental factors" and, thus, were preventable (1969). Subsequently, writers have quoted Higginson's 90-percent figure and equated the term "environmental factors" with "man-made chemicals" or "environmental pollution." It is essential to note that Higginson used the word "environmental" in a much broader sense to indicate all external factors including tobacco and alcohol usage; dietary, social, and cultural habits; reproductive and infectious disease history; radiation exposures; occupational exposures; and exposure to either man-made or natural carcinogens in the air, water, or food.

In 1970, the Ad Hoc Committee on the Evaluation of Low Levels of Environmental Carcinogens made a number of recommendations to the Surgeon General that have since become almost axiomatic among most scientists and regulators when addressing the issue of environmental carcinogens:

1. Any substance that has been shown to cause cancer in animals should be considered carcinogenic and, therefore, a probable or possible cancer risk for humans;
2. No level of exposure to a known chemical carcinogen should be considered toxicologically insignificant for humans (i.e., no no-effect threshold can be assumed);
3. No chemical substance should be assumed safe for human consumption without proper negative lifetime carcinogenic bioassays;
4. In carcinogenic bioassays, negative results should be superseded by positive findings, and positive results should remain definitive unless new evidence conclusively proves prior results were in error; and
5. The principle of a zero tolerance for carcinogenic exposures should be established for all areas of legislation, and only in cases where carcinogenic contamination is unavoidable should exceptions be made to the zero tolerance rule.

These recommendations formed the basis for the FDA's "Delaney Clause" (which, in principle, bans every carcinogenic additive from the food supply) and also gave rise to the generally accepted philosophy that chemicals should be presumed "guilty until proven innocent." In the face of contradictory data (as when one study reports that a substance causes cancer while another reports that it does not), regulatory scientists maintain that "prudence" requires that the positive study should be accepted over the negative. This policy has been extended so that all that is required to establish the carcinogenicity of a chemical is a technically inadequate study, and that such a study may even outweigh a well done study which does not show a cancer effect.

While such a system for interpreting carcinogenic bioassays is not warranted on a strictly scientific basis, as it is clearly biased toward making Type I errors (i.e., taking regulatory action when none is needed), it is also clearly preferable to a system that fails to take any action until there is clear proof that a substance is having a detrimental effect on human health. However, full implementation of the "guilty until proven innocent" philosophy would be tantamount to ignoring the scientific basis for regulation, and it would render meaningless what is now, and has been, a prudent and effective system for protecting public health. Furthermore, it would seriously damage the credibility of regulatory scientists if every chemical that had not been tested for carcinogenicity were suddenly declared to be a suspected carcinogen and, therefore, were to be "banned" from food and drinking water supplies. In recent years, there has been growing recognition of the limitations of the rodent lifetime carcinogenisis bioassay (Lave et al., 1988). Even if all the testing could be done and all the positive substances identified, there would still be a tremendous technological gap which would make it virtually impossible to insure that all of the suspect substances were permanently eliminated from the food and water supplies. Unless all alcohol, tobacco, air pollution, and foods containing natural carcinogens were also banned or eliminated, it is highly unlikely that the removal from the food and water supply of all trace carcinogens that have resulted from humans and their technology would have any appreciable effect on cancer incidence or mortality rates.