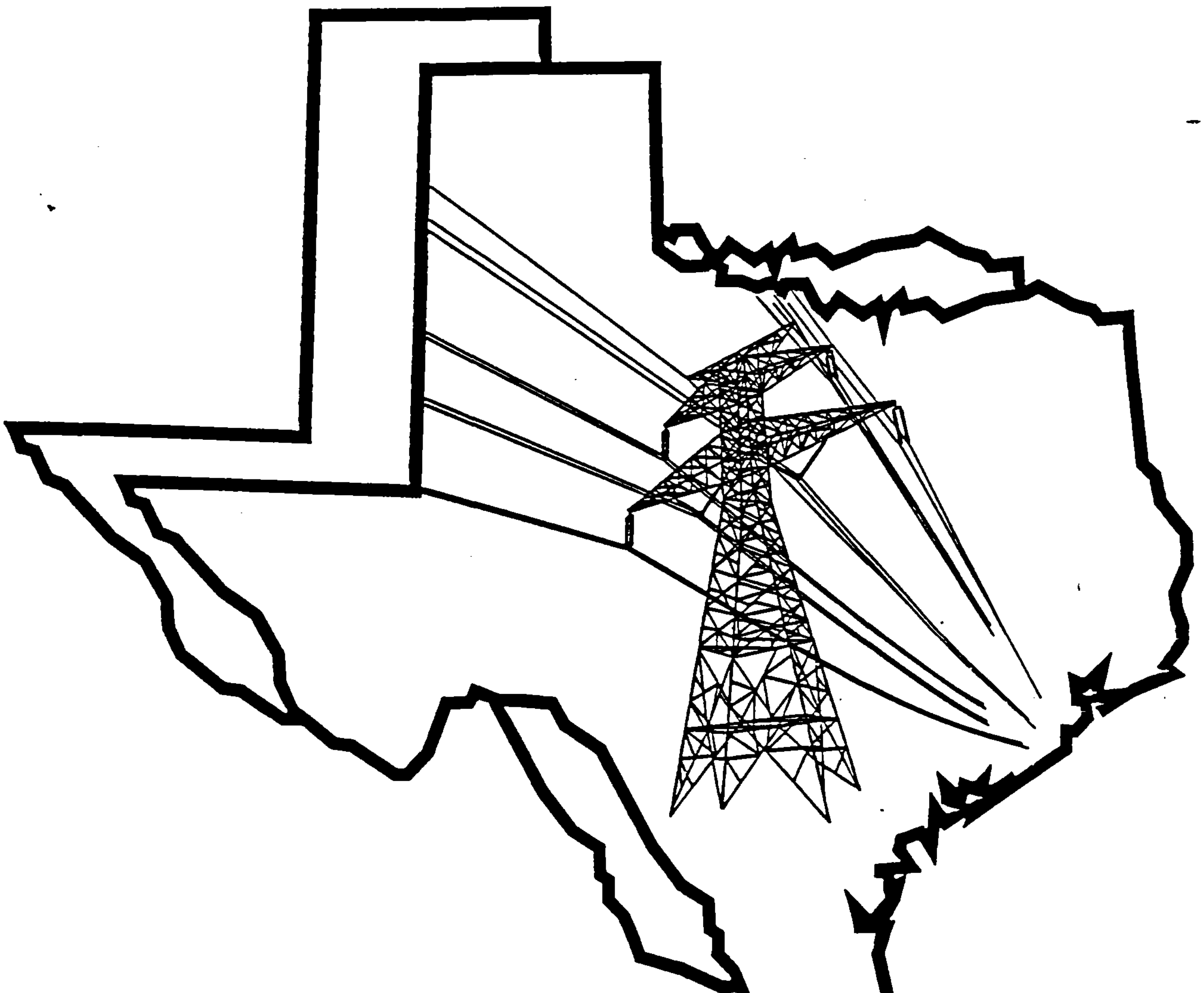
HEALTH EFFECTS OF EXPOSURE TO POWERLINE-FREQUENCY ELECTRIC AND MAGNETIC FIELDS

ELECTRO-MAGNETIC HEALTH EFFECTS COMMITTEE



PUBLIC UTILITY COMMISSION OF TEXAS

AUSTIN, TEXAS

MARCH, 1992

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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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TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

OVERVIEW

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).

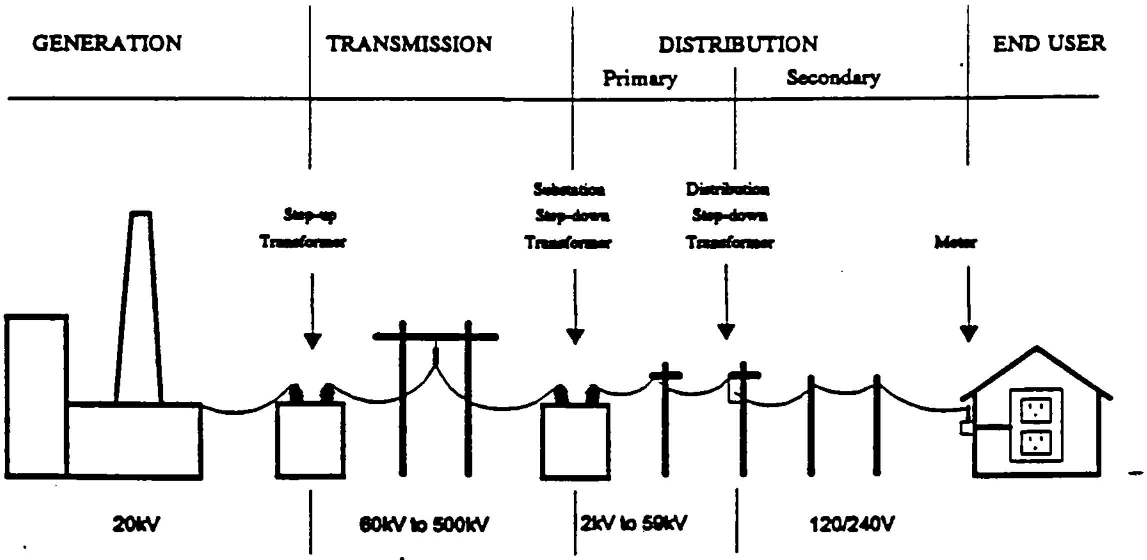

Figure 1-1. Schematic illustration of the stages in an electrical system used to transfer power from the generator via transmission and distribution lines to an end user. (Modified from Office of Technology Assessment Report-Biological Effects of Power Frequency Electric and Magnetic Fields).

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

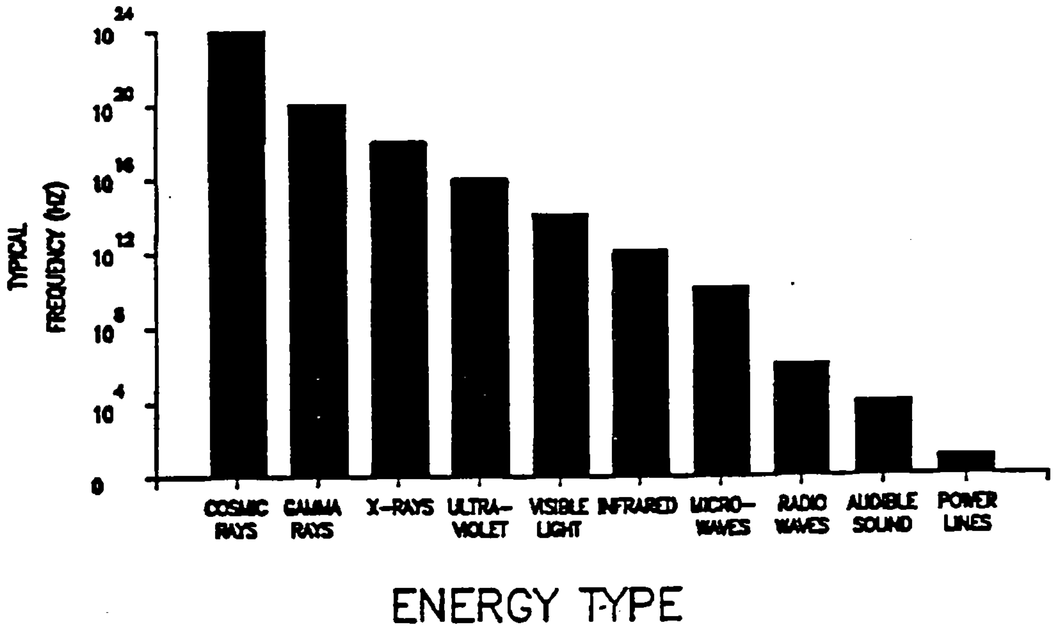

Figure 1-2 The electromagnetic spectrum

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.

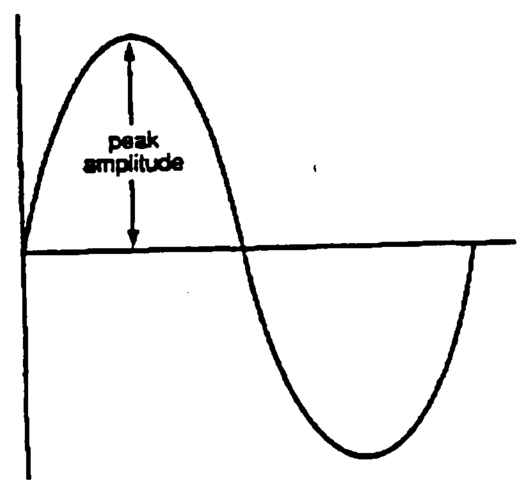

Figure 2-1. Alternating sinusoidal wave shape for current or voltage. The quantity flows one direction during the first half of the cycle and reverse direction during the second. (EPRI, 1989)

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.

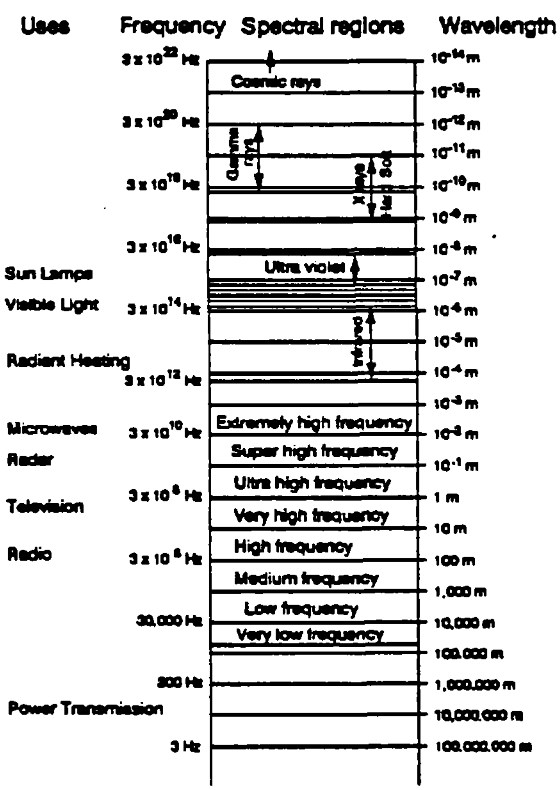

Figure 2-2. The electromagnetic spectrum shown by frequency and wavelength. At a frequency of 60 Hz and a wavelength of 5,000 km, powerlines are at the bottom of the figure. Frequencies less than 300 Hz are designated as extremely low frequency (ELF). (EPRI,1989)

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

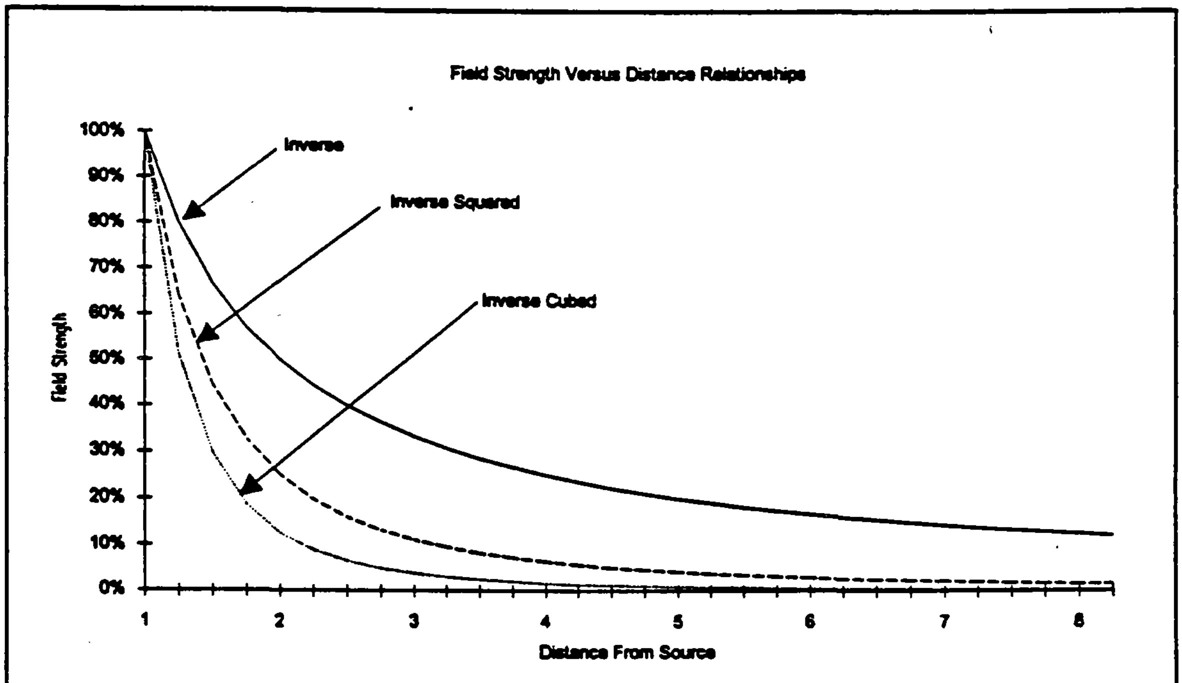

Figure 2-3. Field strength varies with distance from the source according to inverse, inverse-squared or inverse-cubed relationships.

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)

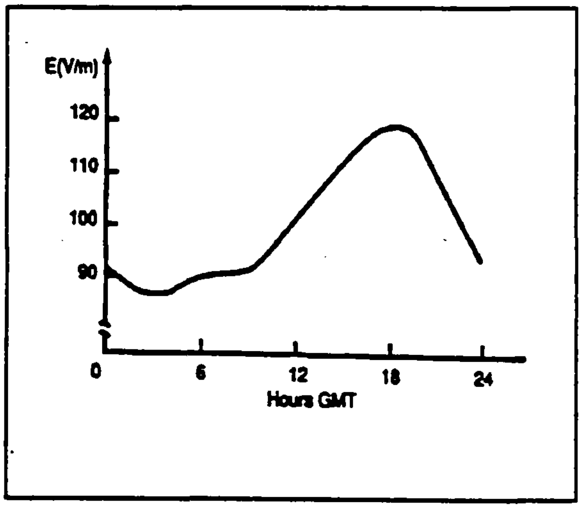

Figure 2-4. Average diurnal variation of the atmospheric potential gradient. The peak occurs near 7 p.m. Greenwich Mean Time (GMT) and is associated with peak thunderstorm activity around the globe (EPRI, 1989).

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

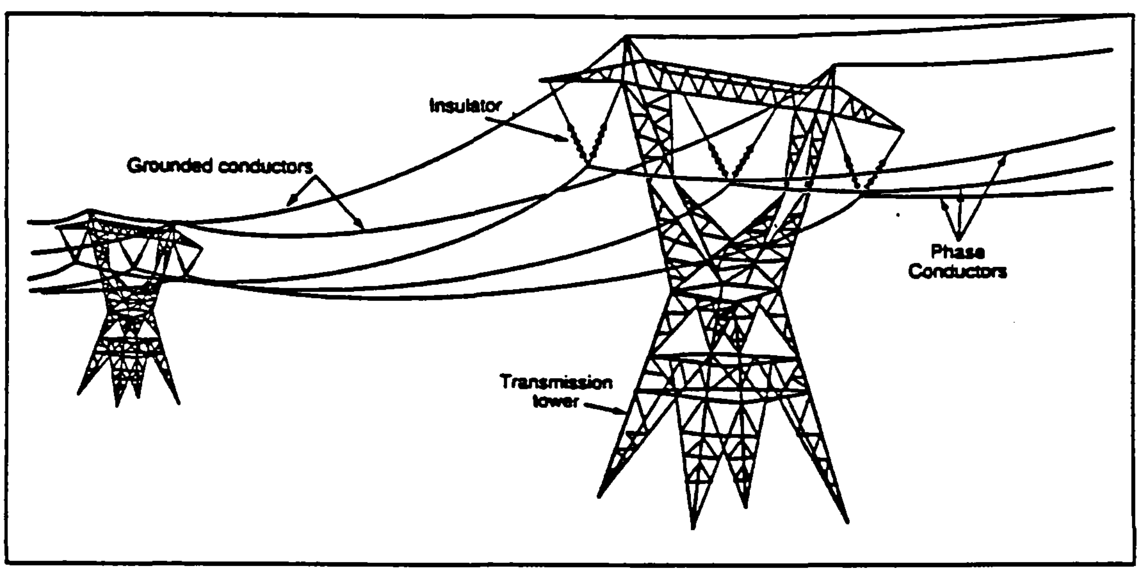

Figure 2-5. A typical three-phase single-circuit AC transmission line. (EPRI,1989)

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

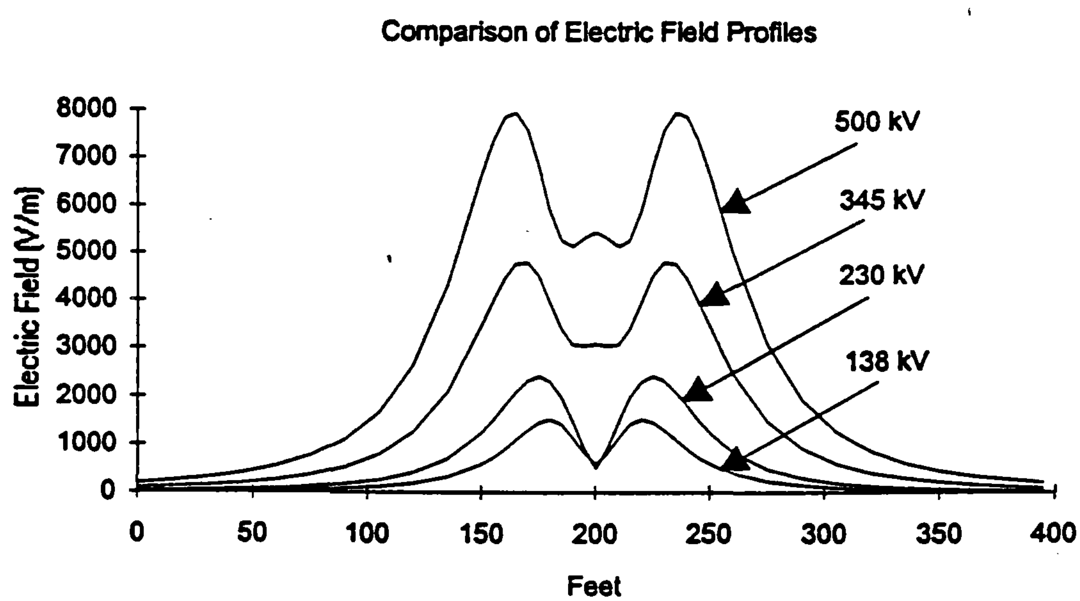

Figure 2-6. **The maximum electric field lateral profile for 500-kV, 345-kV, 230-kV, and 138-kV transmission lines. The profiles are symmetrical about center of the line (located at 200 ft.). Conductors are at minimum clearance conditions and the field measured at 1m above the ground.**

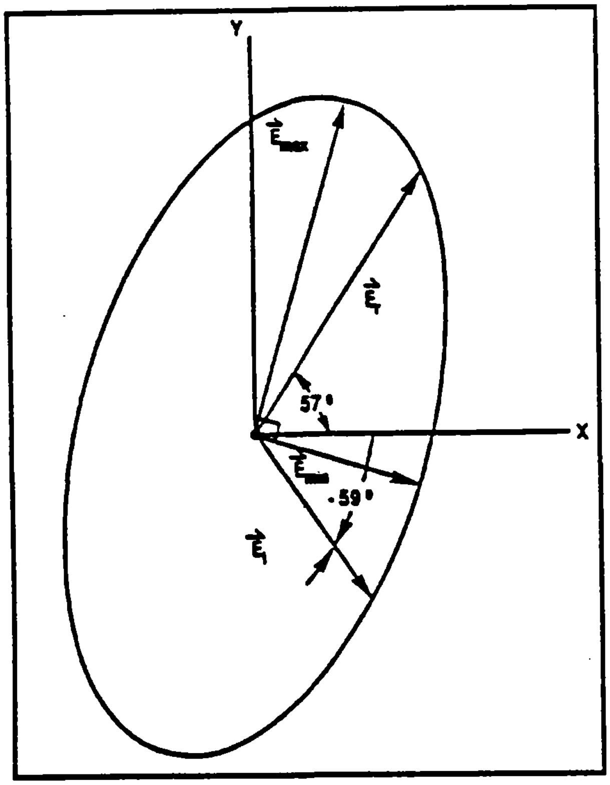

Figure 2-7. The electric field ellipse at a point in space. The maximum field occurs along the semi-major axis and the minimum along the semi-minor axis. The field vector rotates at the power frequency. (EPRI, 1982)

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.

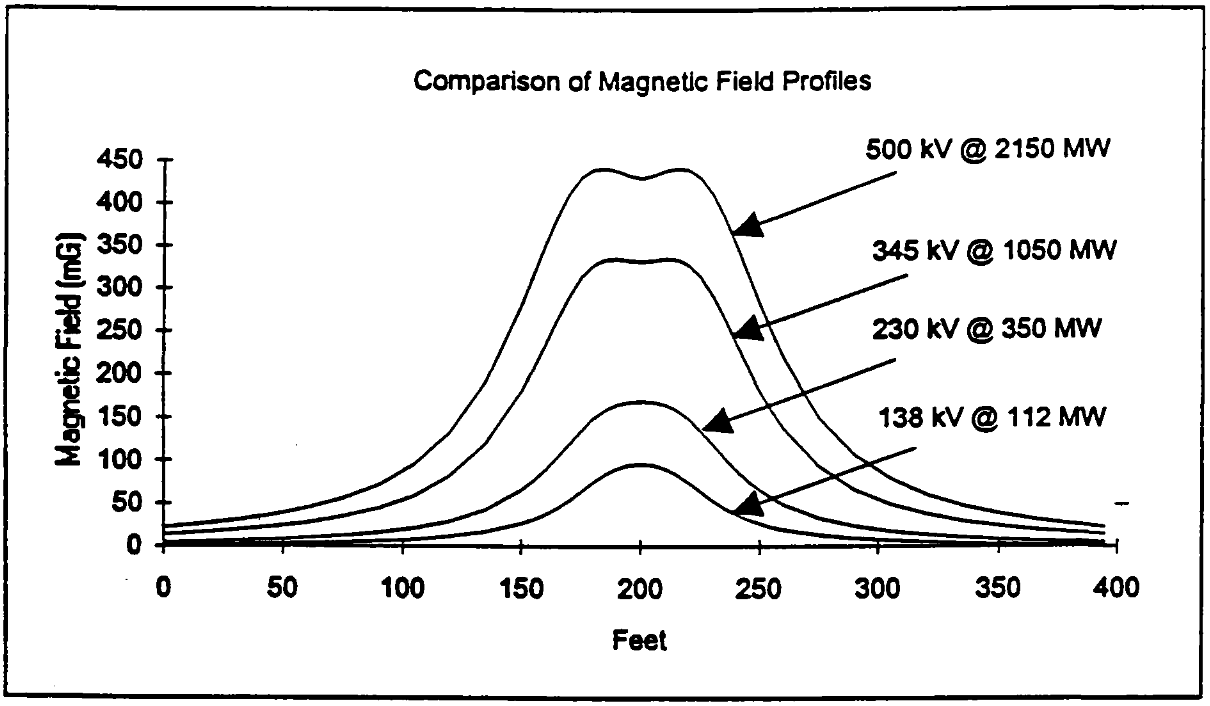

Figure 2-8. The maximum magnetic field lateral profile for 500-kV, 345-kV, 230-kV, and 138-kV transmission lines. Lines are at maximum operating load of 2150, 1050, 350, and 112 Megawatts, respectively. Conductors are at minimum clearance conditions and field measured at 1m above ground.

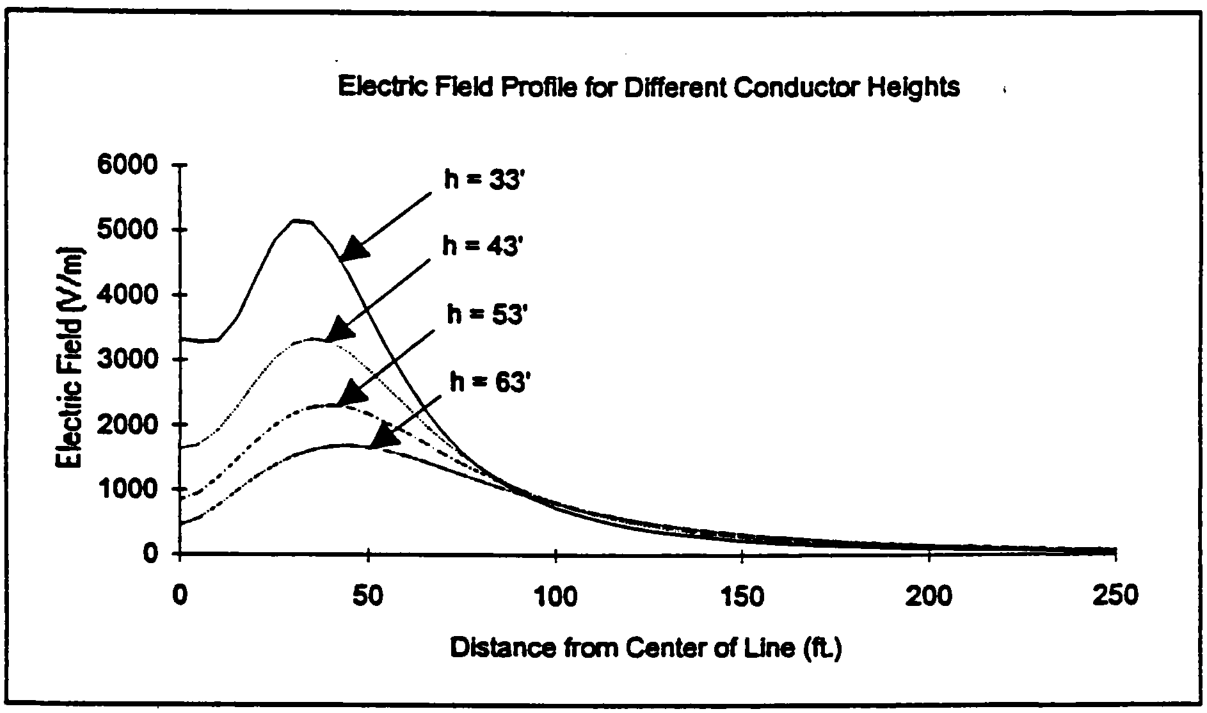

Figure 2-9. Electric field profiles at 1m above ground for single-circuit 345-kV transmission lines with conductors 63, 53, 43, and 33 feet above the ground. The profiles are symmetrical about center of line and only one side is shown.

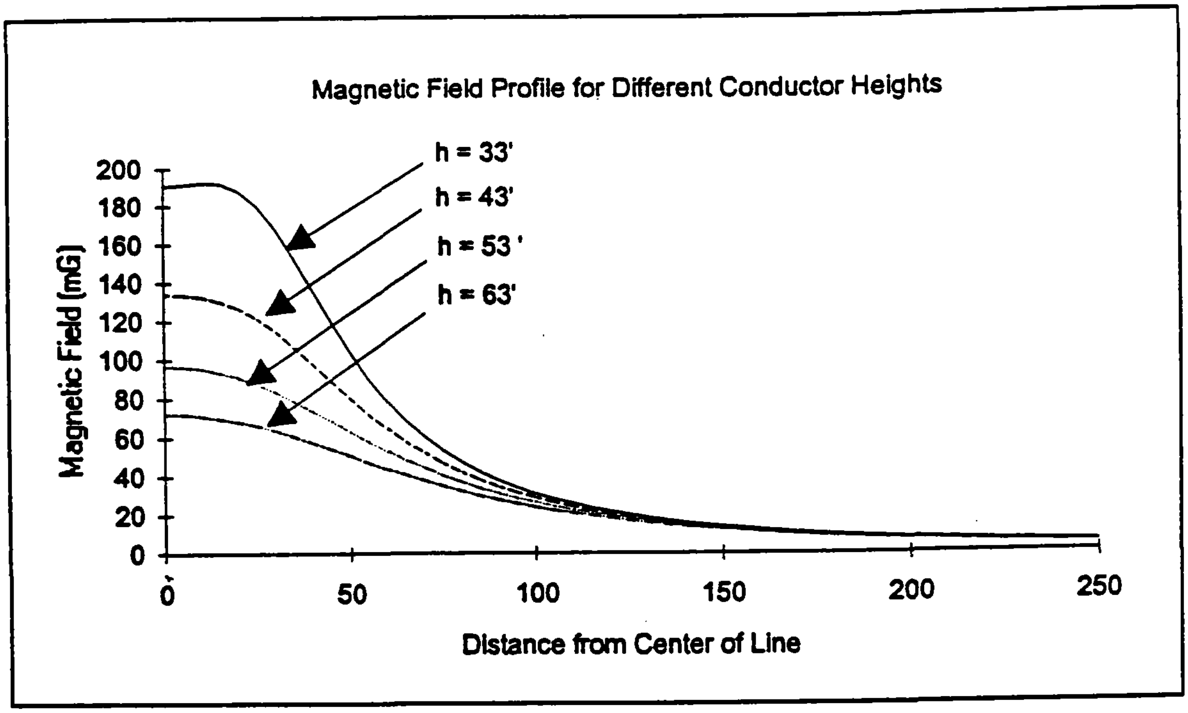

Figure 2-10. Magnetic field profiles at 1m above ground for single-circuit 345-kV transmission lines with conductors 63, 53, 43, and 33 feet above the ground. The profiles are symmetrical about center of line and only one side is shown.

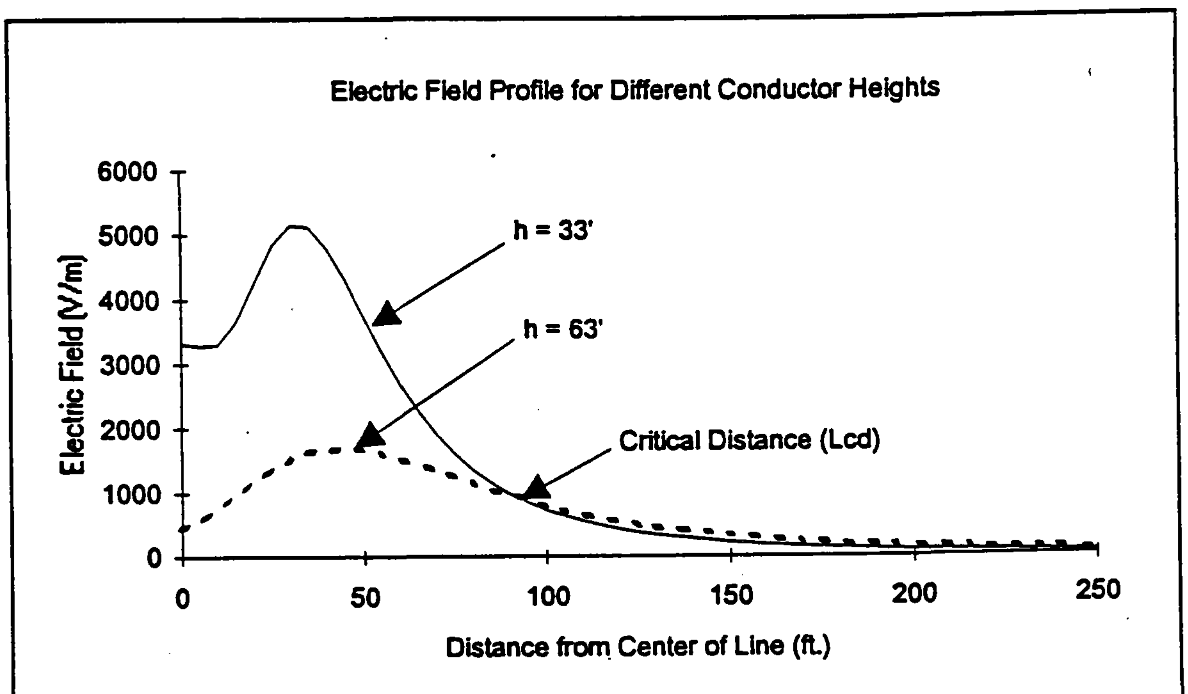

Figure 2-11. Critical distance (L_{cd}) for electric field from a 345-kV transmission line. The intersection of the field profiles occurs at L_{cd}. Increasing conductor height lowers E-field inside Lcd but raises E-field outside of L_{cd}.

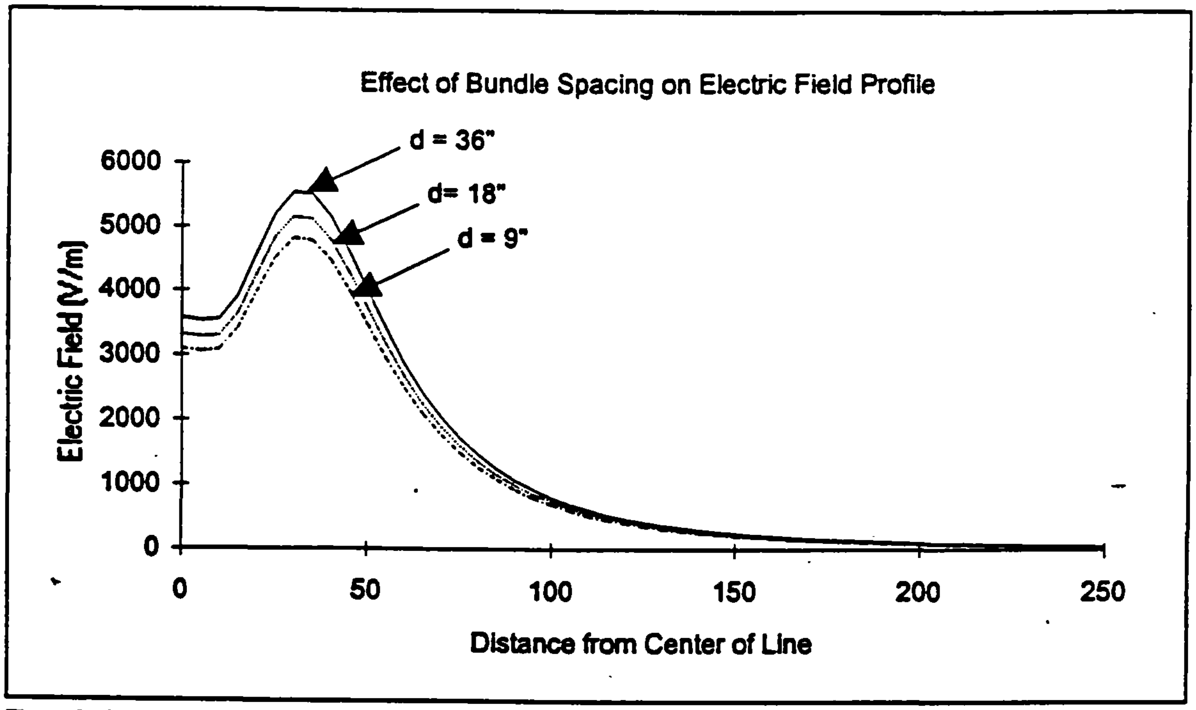

Figure 2-12. Electric field profiles for phase conductor bundle spacings of 9, 18, and 36 inches for a single-circuit 345-kV transmission line. Lines with smaller conductors (i.e., closer bundle spacing) have lower electric fields.

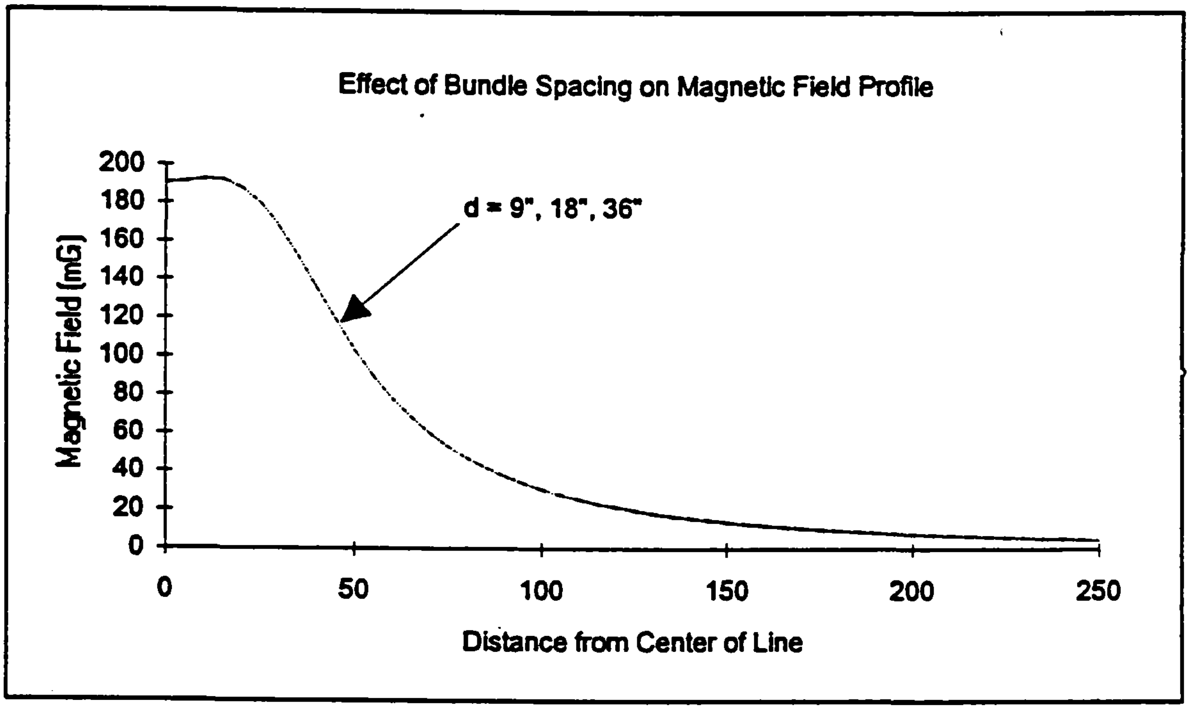

Figure 2-13. Magnetic field profiles for phase conductor bundle spacings of 9, 18, and 36 inches for a single-circuit 345-kV transmission line. Conductors size (i.e., bundle spacing) has no effect on magnetic field strength.

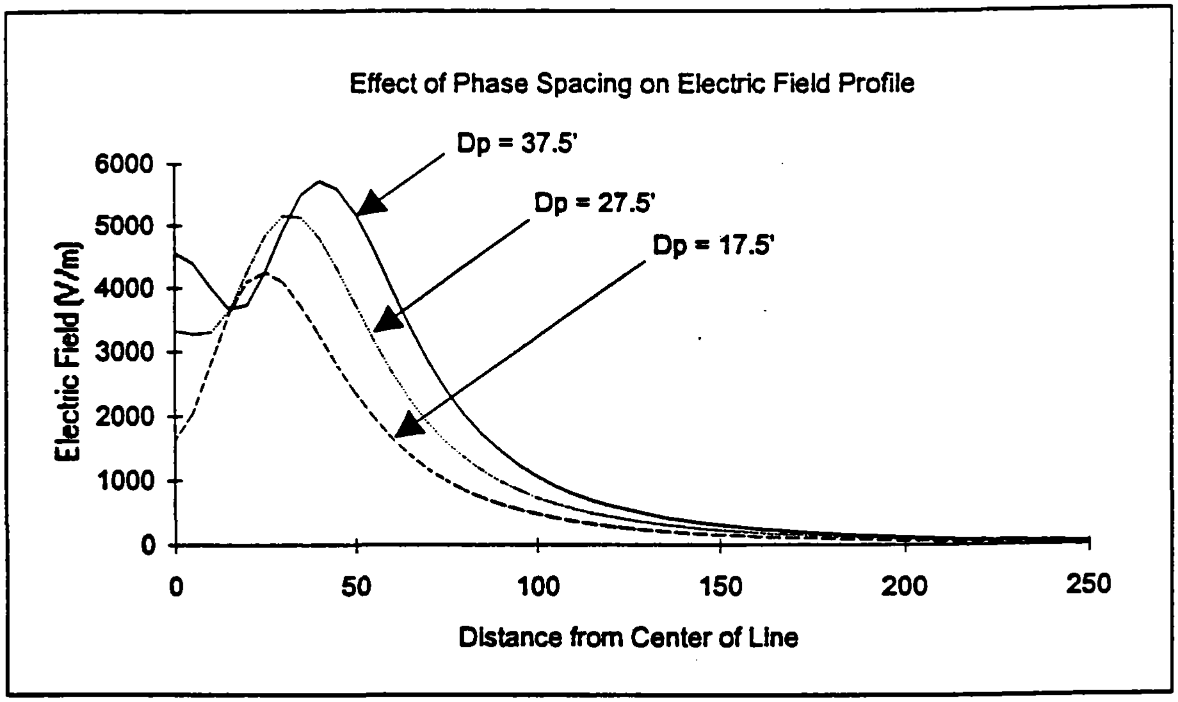

Figure 2-14. Electric field profiles for phase conductor spacings of 17.5, 27.5, and 37.5 feet for a single-circuit 345-kV transmission line. Compact transmission lines (narrower phase spacings) have lower electric fields.

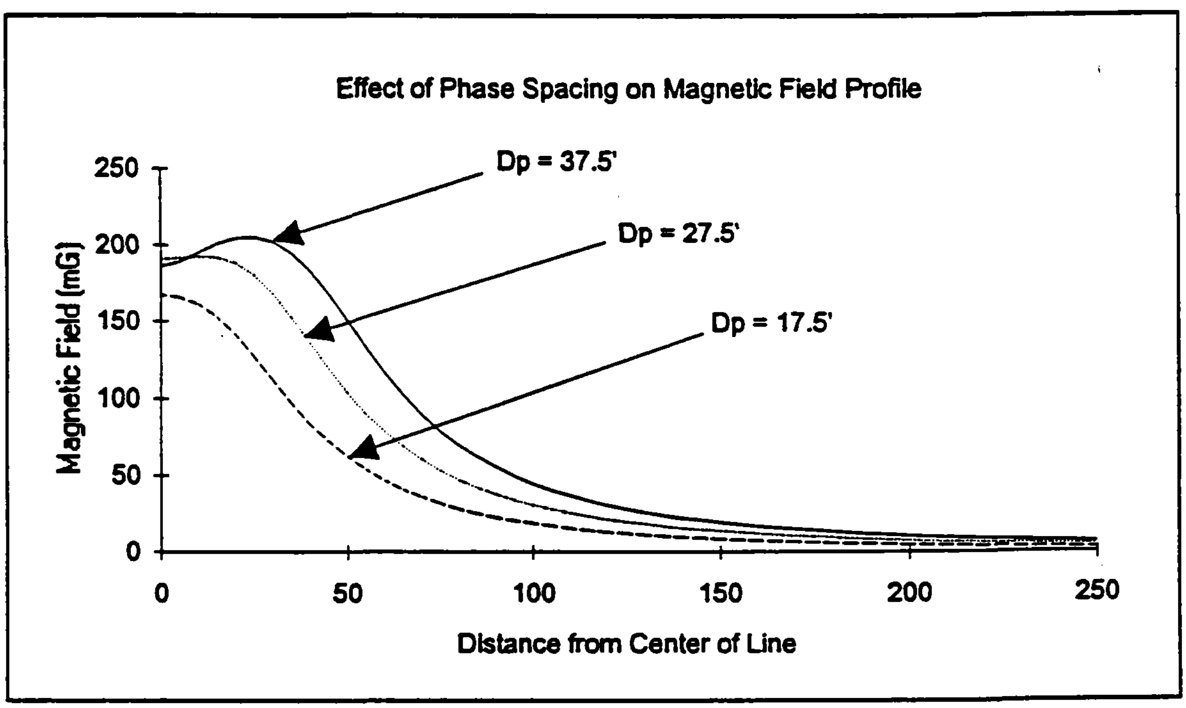

Figure 2-15. Magnetic field profiles for phase conductor spacings of 17.5, 27.5, and 37.5 feet for a single-circuit 345-kV transmission line. Compact transmission lines (narrower-phase spacings) have lower magnetic fields.

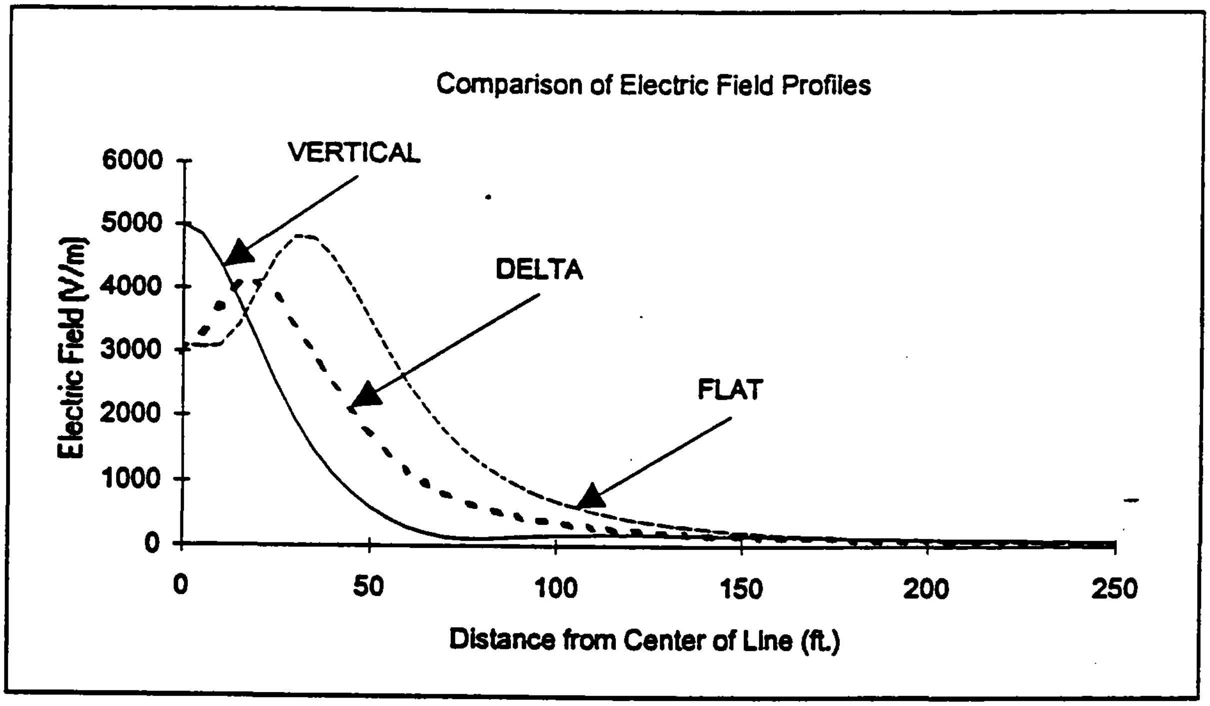

Figure 2-16. Electric field profiles for single-circuit 345-kV transmission lines with flat (horizontal), delta (equilateral) and vertical phase geometries. The phase spacing and minimum conductor height is the same for each configuration.

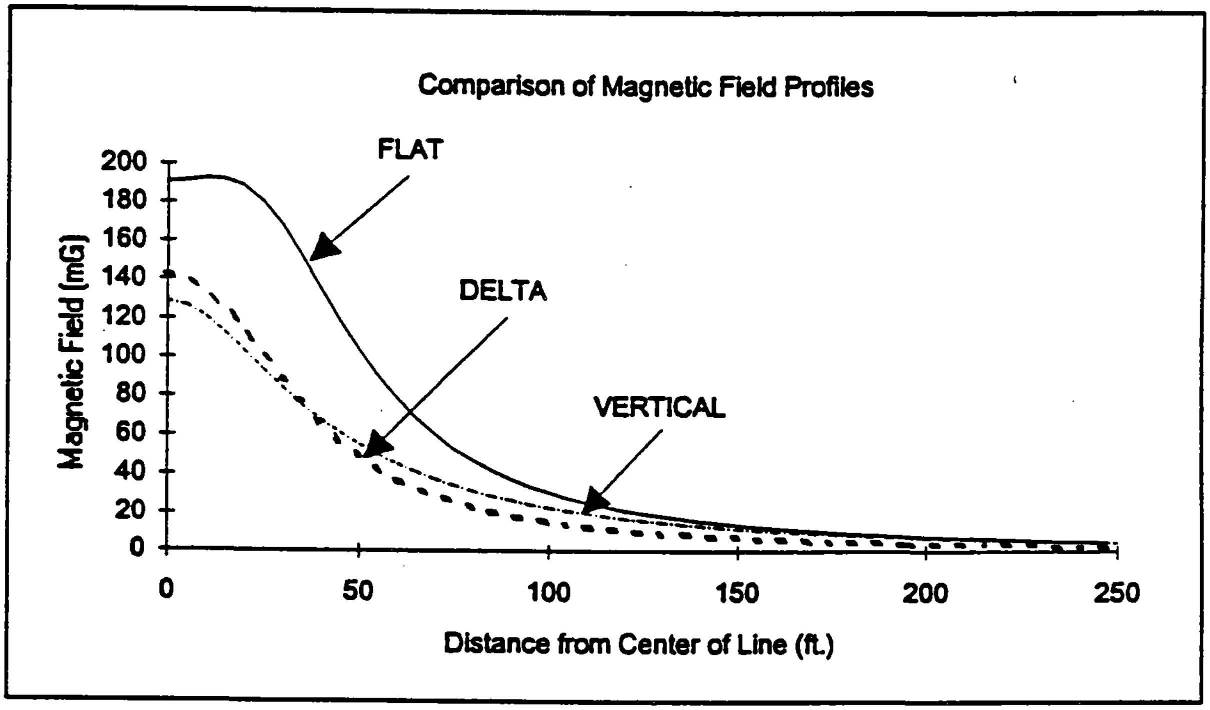

Figure 2-17. Magnetic field profiles for single-circuit 345-kV transmission lines with flat (horizontal), delta (equilateral) and vertical phase geometries. The phase spacing and minimum conductor height is the same for each configuration.

<u>Fields Near Underground Conductors.</u> 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.

<u>Fields in the Home Environment.</u> 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.

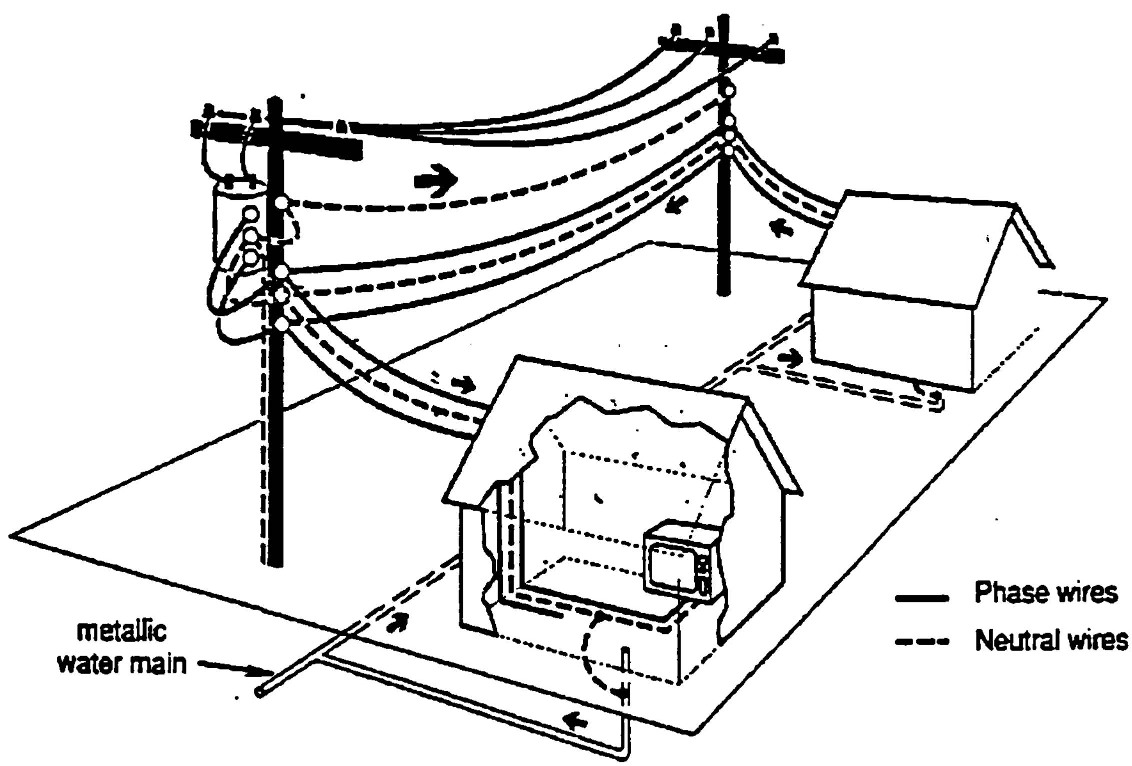

Figure 2-18. Residential magnetic field sources include appliances, grounding systems and overhead distribution lines (primary, secondary, and net current). Other possible sources are unusual wiring, underground cables and nearby transmission lines.(EPRI, 1989)

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 under-estimates 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.

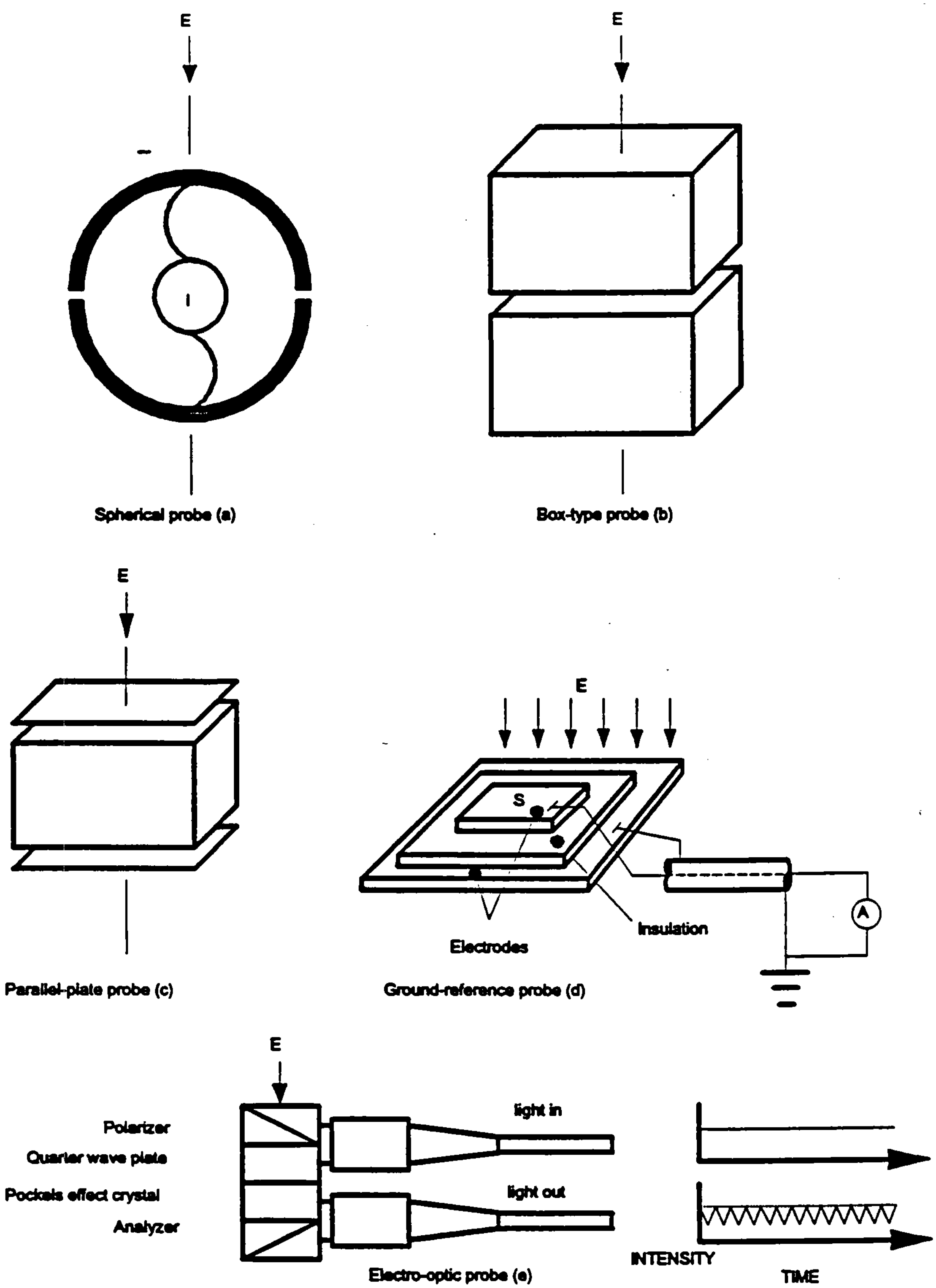

Figure 2-19. Illustrations of three types of electric field meters:

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

(IEC, 1987)